ENGG4420 -- CHAPTER 2 -- LECTURE 2

October-12-12
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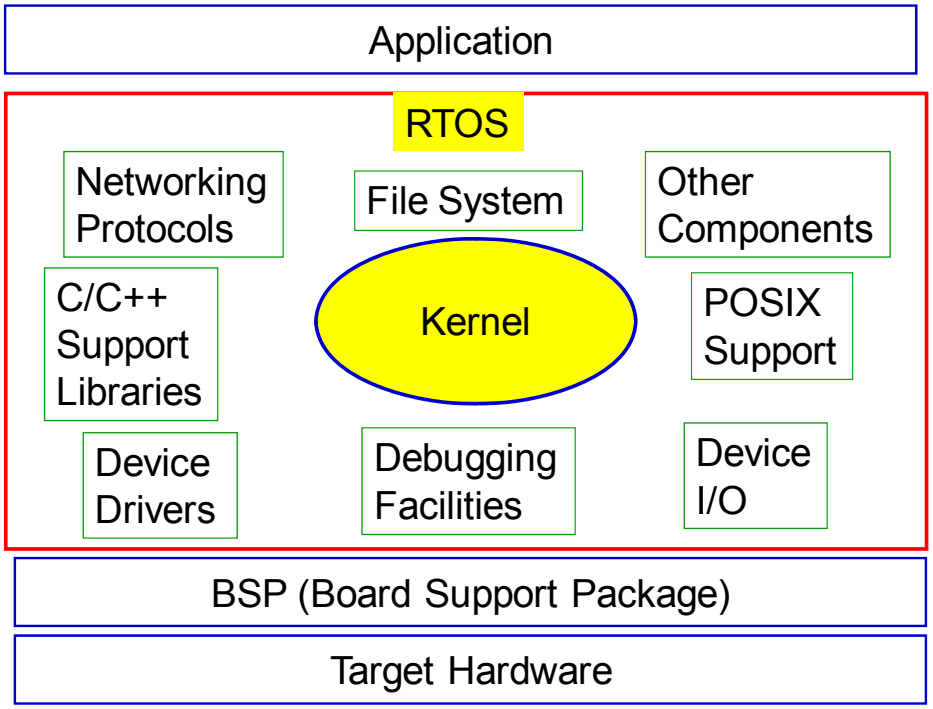
RTOS -- DEFINING AN RTOS

- A real-time operating system (RTOS) is a program that schedules execution in a timely manner, manages system resources, and provides a consistent foundation for developing application code.
- An RTOS contains a real-time kernel and high level services such as: file management, protocol stacks, graphical user interface, other device oriented services.

FIG. High level view of an RTOS.



Q: An RTOS should be scalable. So, what is a scalable RTOS?

- For example in some applications, an RTOS comprises only a kernel, which is the core supervisory software that provides minimal logic, scheduling, and resource-management algorithms -- every RTOS has a kernel.
- On the other hand, RTOS can be a combination of various modules, including the kernel, a file system, networking protocol stack, and others.

REAL-TIME KERNEL - software that manages the time and resources of a microprocessor, microcontroller, or a DSP.

- Considering the work job an applications needs to do, a task is a portion of that job to be done.
- From a software perspective a task or a thread is a simple program that can have the CPU to itself.
- A kernel is responsible for managing all the tasks of an application - thus we have a multitasking system.

MULTITASKING - is the process of scheduling and switching the CPU between several tasks.

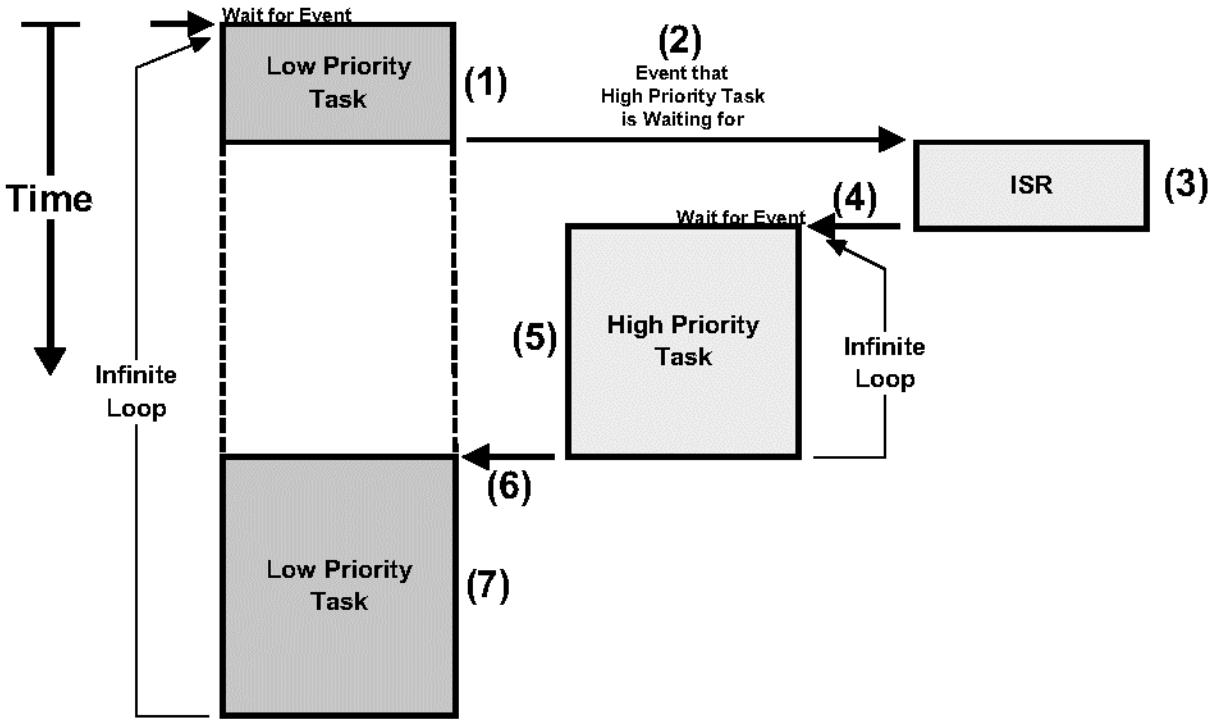
- In the context of one CPU the multitasking provides the illusion of having multiple CPUs and maximizes the CPU usage.
- Multitasking also helps in the creation of modular applications.
- Real time application programs are easier to design and maintain when multitasking is used.

KERNEL COMPONENTS - most RTOS kernel contain the following components:

- **Scheduler** -- implements a set of algorithms that determine which task executes and when.
- **Objects** -- are special kernel constructs that can be used to help developer to create applications.
- **Services** -- are operations that the kernel performs on an object, or general operations.

PREEMPTIVE KERNEL -- the kernel always runs the highest priority task that is ready to run.

- uC/OS-III is a preemptive kernel

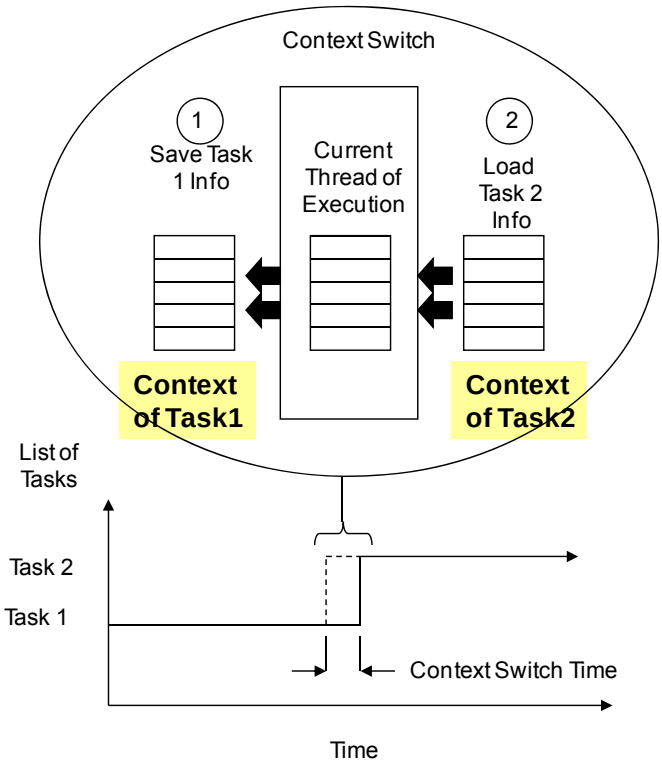


CONTEXT SWITCH

- Each task has its own context: the state of the CPU registers required each time it is scheduled to run.
- A context switch occurs when the scheduler switches from one task to another.
- Every time when a new task is created the kernel also creates and maintains an associated task control block (TCB) -- the context of a task is maintained in TCB.
  - TCB contains everything a kernel needs to know about a task.
- When a task is running, its context is highly dynamic.
- When the task is not running, its context is frozen in order that a restoration can be made when the scheduler switches back to the corresponding task.

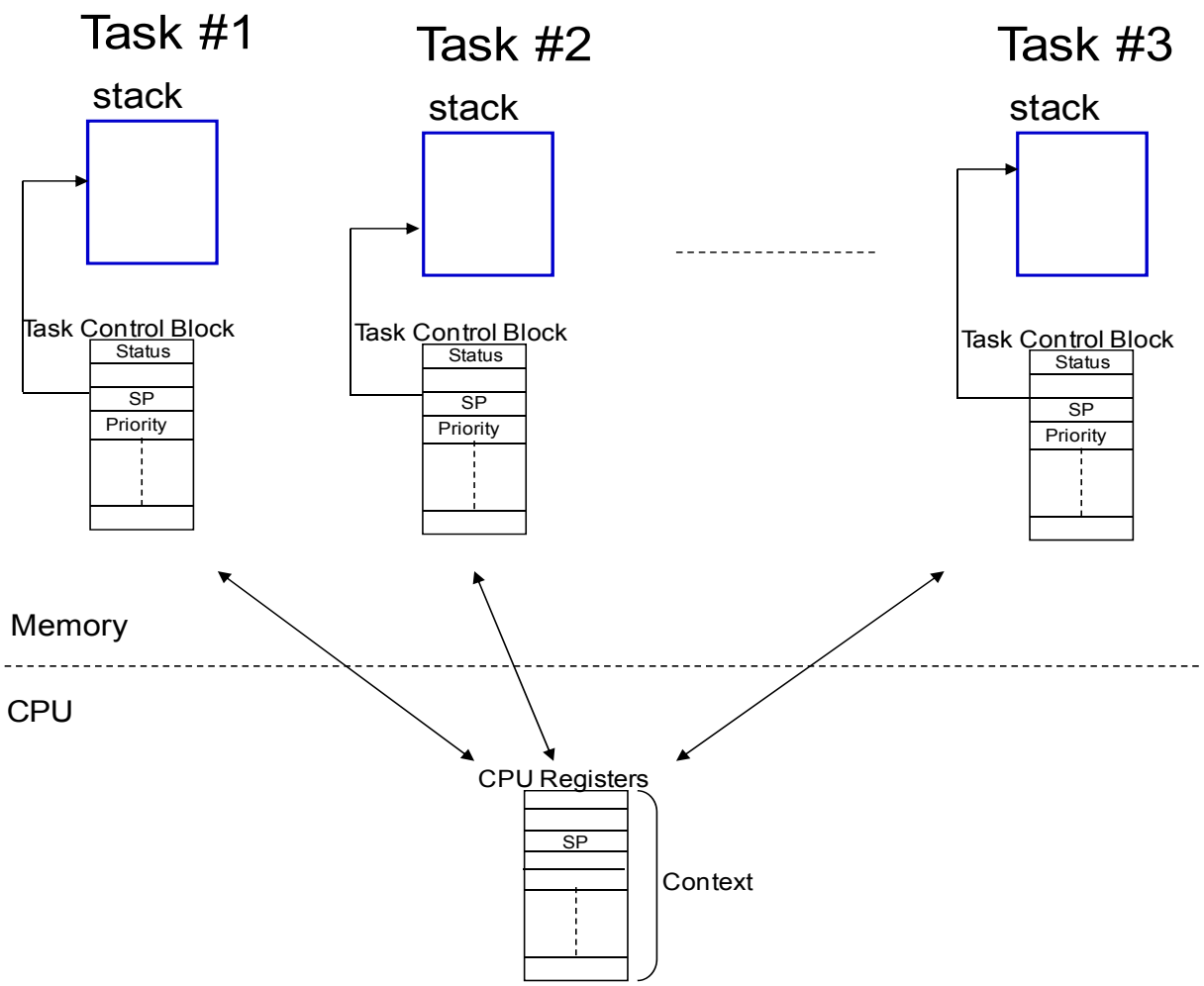
EXAMPLE -- Task 2 is scheduled to run.

- The kernel saves Task 1's context information in its TCB.
- It loads Task 2's context information from its TCB, which becomes the current thread of execution.
- The context of Task 1 is frozen while Task 2 executes.
- As a result, Task 1 can resume execution from where it left.



- There is a context switch time associated with the context switch -- this time is relatively insignificant ...

EXAMPLE OF CONTEXT SWITCH IN uC/OS-II

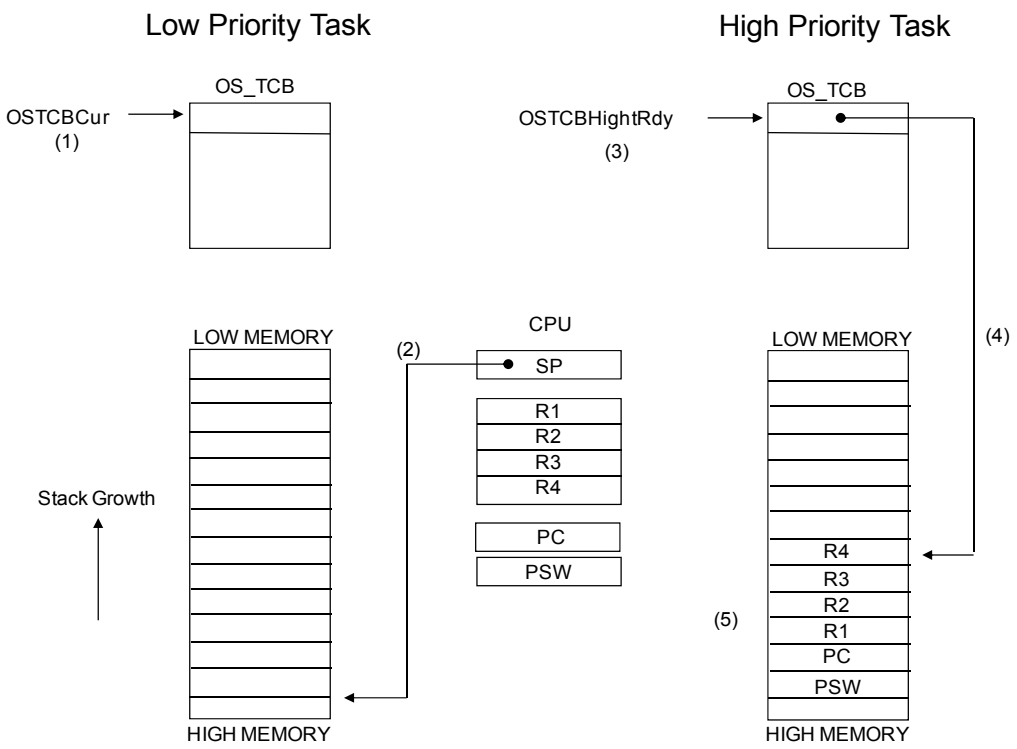


- In a RTOS, each task is assigned a priority, its own set of CPU registers, and its own stack area.
- When a multitasking kernel decides to run a different task, it saves the current task's context (CPU registers) in the current task's context storage area – its stack.
- After this operation is performed the new task's context is restarted from its storage area and resumes execution.
- Context switching adds overhead to the application. The more registers a CPU has the higher the overhead.

EXAMPLE FROM uC/OS-II -- DATA STRUCTURES

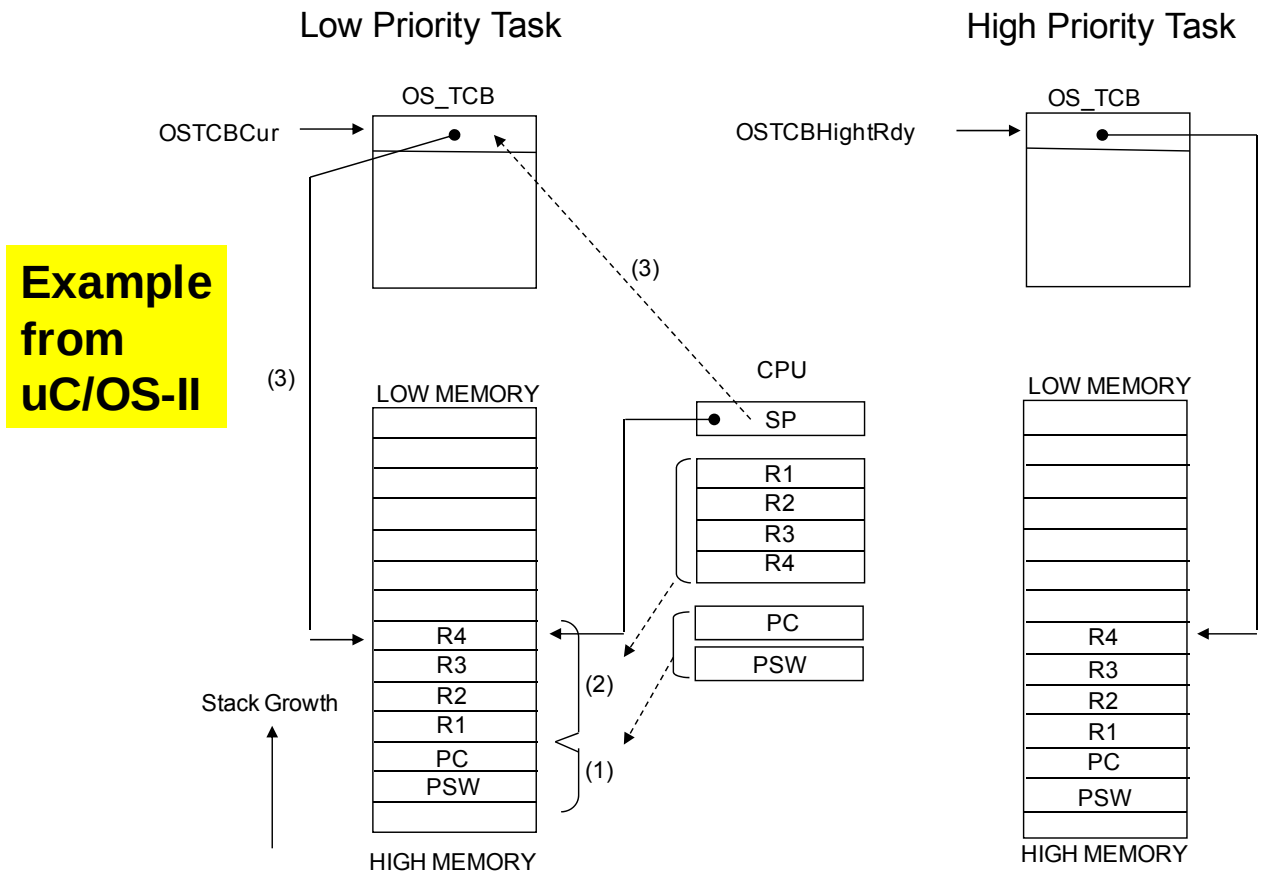
See uC/OS-II book for this example (pp. 92-96)

µC/OS-II structures when** 0S_TASK_SW() **is called.



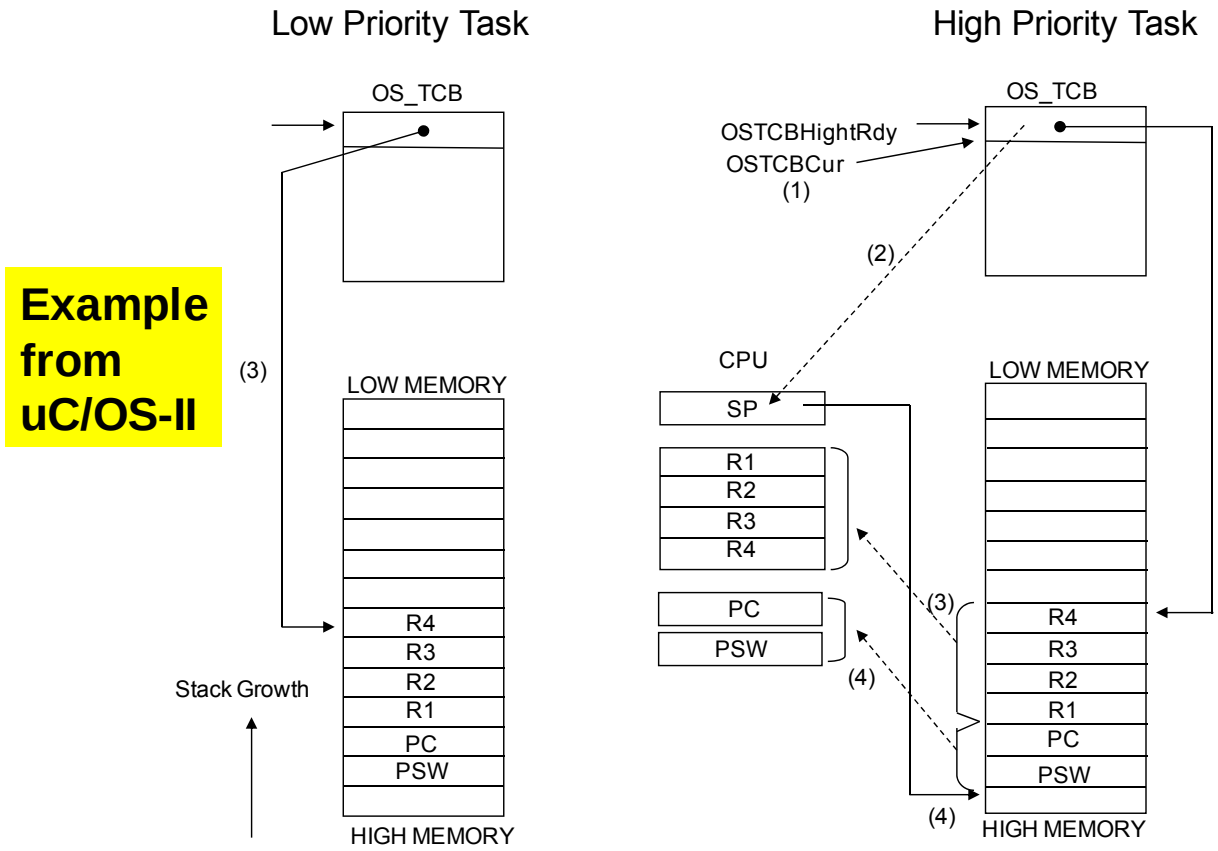
- OS_TASK_SW() is called to perform a context switch -- the context switch code needs to save the register values of the task being preempted and load into the CPU the values of the registers of the task to resume.
- OS_TASK_SW() is a macro that normally invokes a microprocessor software interrupt. **Q**: Why do we need a software interrupt here?
  - A: The interrupt triggers the hardware mechanism for saving the CPU's Program counter (PC), and Process Status Word (PSW) register at the switch time.
- HERE we created for this example **a fictional CPU** to show the process: SP –stack pointer; PC – program counter; PSW – processor status word; R1-R4 – four general purpose registers.
- **(1)**: OSTSBcur points to the OS-TSB of the task being suspended (the low priority task); **(2)**: The CPU's stack pointer register points to the current top-of-stack of the task being preempted; **(3)**: OSTCBHighRdy points to the OS-TCB task that will be executed after context switch; **(4)**: .OSTTCBStkPtr field in OS_TCB points to the top-of-stack of the task to resume; **(5)**: The stack of the task to resume contains the desired register values to load into CPU.

Saving the current task's context.



Example from uC/OS-II

- Step (1): Calling OS_TASK_SW() invokes the software interrupt instruction, which forces the processor to save the current value of PSW and the PC unto the current task's stack.
- The processor then vectors to the software interrupt handler which is responsible for completing the remaining steps of the context switch.
- Step (2): The software interrupt handler starts by saving the general purpose registers R1, R2, R3, and R4 in this order.
- Step (3): The stack pointer register is then saved into the current task's OS_TCB. At this point, both the CPU's SP register and OSTCBcur -> OSTCBStkPtr are pointing to the same location into the current task's stack.



- Step (1): Because the current task is now the task being resumed, the context switch code copies OSTCBHighRdy to OSTCBCur.
- Step (2): The stack pointer of the task to resume is extracted from the OS_TCB (from OSTCBHighRdy -> OSTCBStkPtr and loaded into the CPU's SP register. At this point, the SP register points to the stack location containing the value of register R4.
- Step (3): The general purpose registers are popped from stack in reverse order (R4 – R1).
- Step (4): The PC and PCW registers are loaded back into the CPU by executing a return from interrupt.
- Note: Because PC is changed, code execution resumes at this point to which PC is pointing, which happens to be in the new task's code.

THE DISPATCHER

- The dispatcher is the part of the scheduler that performs context switching and changes the flow of execution.
- At any time an RTOS is running, the flow of execution is passing through one of three areas:
  - through an application task, through an ISR, or through the kernel.
- When a task or ISR makes a system call, the flow of control passes to the kernel to execute one of the system routines provided by the kernel.
- When it is time to leave the kernel, the dispatcher is responsible for passing control to one of the tasks in the user's application.
- Depending on how the kernel is first entered, dispatching can happen differently:
  - Case 1: task makes a system call -- the dispatcher is used to exit the kernel after every system call completes. In this case, the dispatcher is used on a call-by-call basis so that it can coordinate task-state transitions that any of the system calls might have caused.
  - Case 2: ISR makes system calls -- the dispatcher is bypassed until the ISR fully completes its execution, then kernel exits through dispatcher so then it can dispatch the correct task.
    - this process is true even if some resources have been freed that would normally trigger a context switch between tasks.

SCHEDULING ALGORITHMS

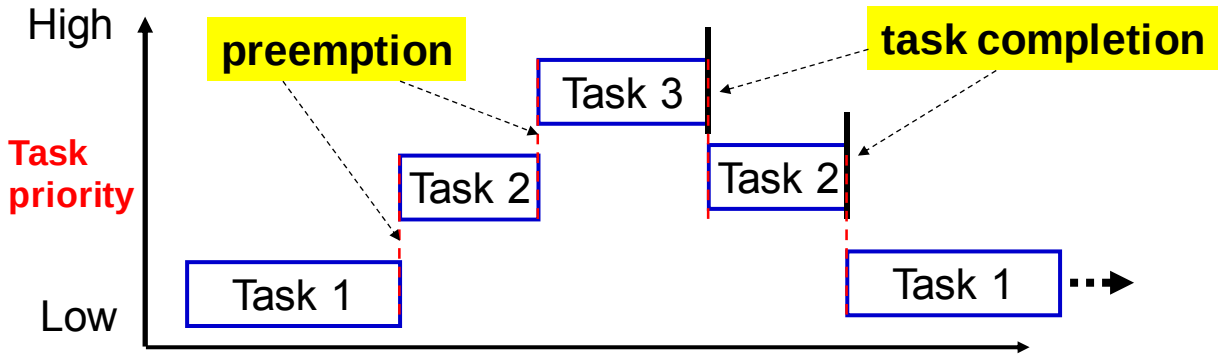
- The scheduler determines which task runs by following a scheduling algorithm (scheduling policy).
- Most kernels today support two common scheduling algorithms:
  - preemptive priority-based scheduling, and
  - round-robin scheduling
- The RTOS manufacturer typically predefines these algorithms. However, in some cases developers can create and define their own scheduling algorithm.

- NON-PREEMPTIVE kernels (also called cooperative multitasking) require that each task does something to explicitly give up control of the CPU. As a result, in order to maintain the illusion of concurrency the process of giving up control of the CPU by a task must be done frequently.
- **Advantages** of a non-preemptive kernel: a) interrupt latency is low; b) at the task level - non-reentrant functions possible; c) task level response is better than foreground/back systems; d) lesser need to guard shared data.
- **Disadvantages**: a) a higher priority task that has been made ready to run might have to wait a long time since the current task must give up the CPU; b) task level response is non-deterministic -- you never really know when the highest priority task will get control of the CPU.

  Note: A reentrant function can be used by more than one task without fear of data corruption.

PREEMPTIVE KERNELS

- A preemptive kernel is used when system responsiveness is important -- most commercial RT kernels are preemptive.
- The highest priority task ready to run is always given control of the CPU:
  - when a task makes a higher priority task ready to run, the current task is preempted and the higher priority task is immediately given control of CPU.
  - if an ISR makes a higher priority task ready, when the ISR completes, the interrupted task is suspended, and the new higher priority task runs.



- If a task with a priority higher than the current task becomes ready to run, the kernel immediately saves the current task's context in its TCB and switches to the higher priority task.
- With preemptive kernels, execution of the highest priority task becomes deterministic. As a result, task-level time is thus minimized.

OPERATION of a preemptive and non-preemptive kernel when a task is executed but is interrupted.

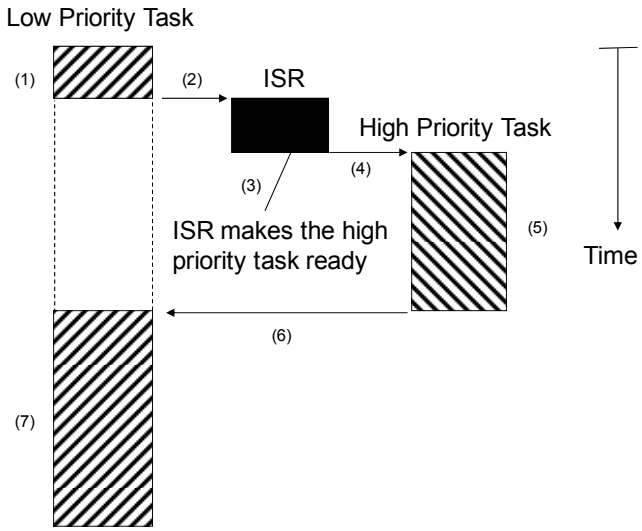


Fig. (a) Preemptive

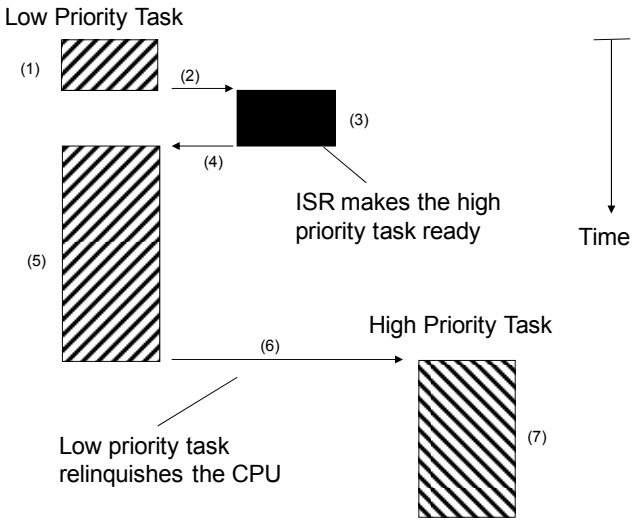


Fig. (b) Non-preemptive

PREEMPTIVE CASE

(1) A task is executing but is interrupted; (2) If interrupts are enabled, the CPU vector jumps to the ISR; (3) The ISR handles the event and makes a higher priority task ready to run. Upon completion of the ISR, a service provided by the kernel is invoked; (4) This function knows that a more important task has been made ready to run and thus, instead of returning to the interrupted task the kernel performs a context switch; (5) High priority task executes. (6) When done another function that the kernel provides is called to put the task to sleep waiting for the event -- the kernel then sees that a lower priority task needs to execute, and another context switch is done to resume execution of the interrupted task; (7) The lower priority task executes.

OTHER FEATURES OF PREEMPTIVE KERNELS

- Real-time kernels generally support 256 priority levels, in which 0 is the highest and 255 is the lowest (some kernels have 255 as the highest priority and 0 as the lowest)
- In preemptive kernels each task has a priority
  - Task's priority is assigned when they are created.
- The task's priority can be changed dynamically using kernel-provided calls -- this allows an embedded application the flexibility to adjust to external events as they occur creating a true real-time, responsive system.
- Advantages of preemptive kernels:
  - the execution of the highest priority task is deterministic.
  - task-level response is minimized.
- Application code using preemptive kernel should not use non-reentrant functions unless exclusive access to these functions is controlled through mutual semaphores because both a low and a high priority task can use a common function.
  - As a result, corruption of data can occur if a higher priority task preempts a lower priority one.

ROUND ROBIN SCHEDULING OR TIME SLICING

- When two or more tasks have the same priority, the kernel allows one task to run for a predetermined amount of time (quantum or slice) and then selects another task.
- The kernel gives control to the next task in line if:
  - the current task has no work to do during its time slice, or
  - the current task completes before the end slice, or
  - the time slice ends.
- Note: uC/OS-II does not currently support round-robin scheduling. Each task must have a unique priority in the application.
- Preemptive, priority-based scheduling can be augmented with round-robin scheduling to achieve equal allocation of CPU for tasks of the same priority;

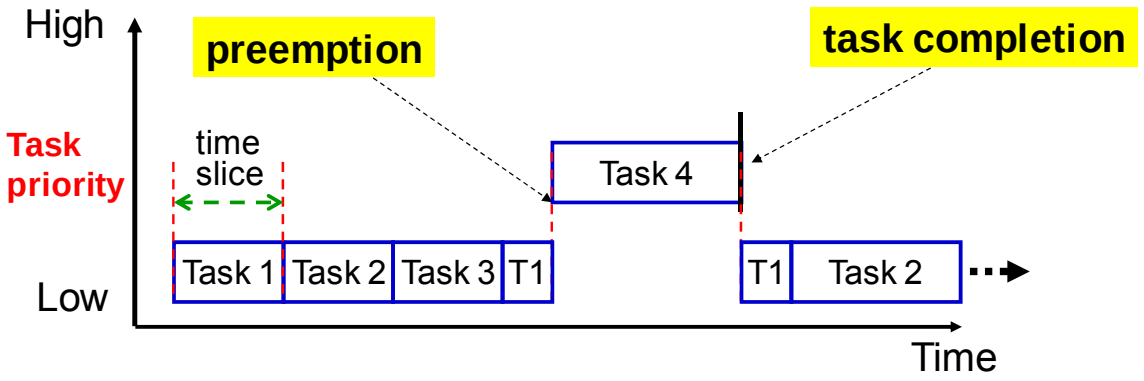


Figure. Case of the preemptive with round-robin. Note that T1 is preeemptied but after T4 finishes T1 starts from where it left in its slices. (T1-T3 have same priority.

- A run-time counter tracks the time slice for each task incrementing on every clock tick. When one task's time slice completes, the counter is cleared, and the task is placed at the end of the cycle.
- Newly added tasks of the same priority are placed at the end of the cycle with their run time initialized to 0.

OBJECTS

- Kernel objects are special constructs that form the building blocks for application development for real-time embedded systems;
- The most common RTOS kernel objects are:
  - Tasks – are concurrent and independent threads of execution that can compete for CPU execution time
  - Semaphores – are token-like objects that can be incremented or decremented by tasks for synchronization or mutual exclusion
  - Message Queues – are buffer-like data structures that can be used for synchronization, mutual exclusion, and data exchange.

... Q: Combining these basic kernel objects (and others) what common real-time design problems can be solved??

SERVICES

- Along with objects most kernels provide services that help developers create applications for real-time embedded systems.
- The most common services found comprise sets of API (Application Program Interface) calls that can be used to perform operations on kernel objects or can be used in general to facilitate timer management, interrupt handling, device I/O, and memory management.

KEY CHARACTERISTICS OF AN RTOS

- Applications define the requirements of its underlying RTOS. Some of the more common ones are:
  - Reliability -- depending on the application, the system might need to operate for long periods without human intervention.
  - Predictability -- meeting time requirements is key to real-time embedded systems -- the term deterministic describes RTOSs with predictable behavior, in which the completion of OS calls occurs within known timeframes.
  - Performance -- this requirement dictates that the embedded system must perform fast enough to fulfill its timing requirements.
  - Compactness -- application design constraints and cost constraints help determine how compact and embedded system needs to be.
  - Scalability -- because RTOSs can be used in a wide variety of applications, they must be able to scale up or down to meet application-specific requirements.

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SYSTEM INITIALIZATION AND STARTING

- Every RTOS has some specific steps for system initialization and starting. Here we present the initialization steps for the uC/OS-II.
- A requirement of uC/OS is that you call OSInit( ) before you call any of uC/OS's other services.
  - OSInit( ) initializes all uC/OS variables and data structures (see OS_CORE.C).
  - OSInit( ) creates the idle task OS_TaskIdle( ), which is always ready to run. The priority of OS_TaskIdle( ) is always set to OS_LOWEST_PRIO.
  - If OS_TASK_STAT_EN and OS_TASK_CREATE_EXT_EN (see OS_CFG.H) are both set to 1, OSInit( ) also creates the statistic task OS_TaskStat( ) and makes it ready to run. The priority of OS_TaskStat( ) is always set to OS_LOWEST_PRIO-1.

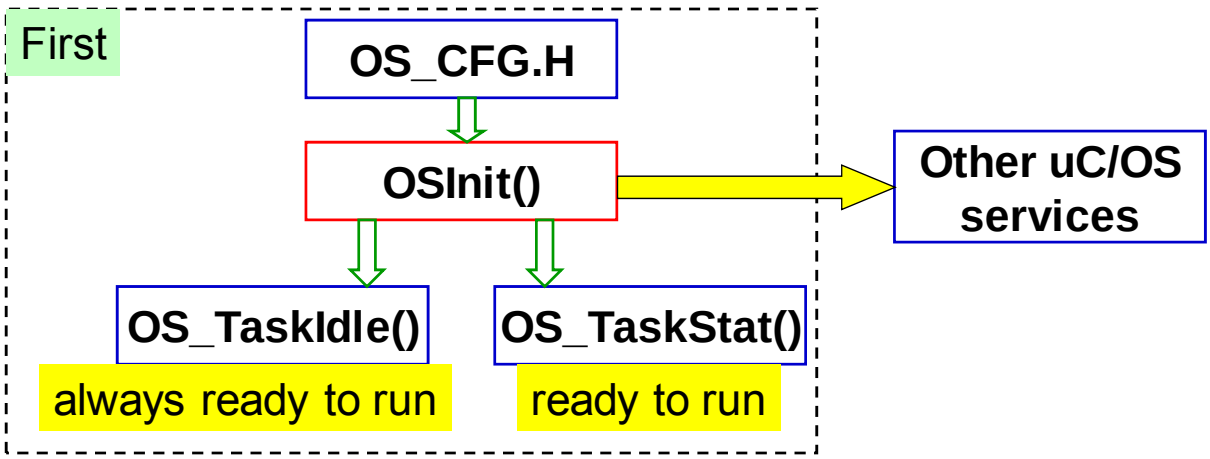
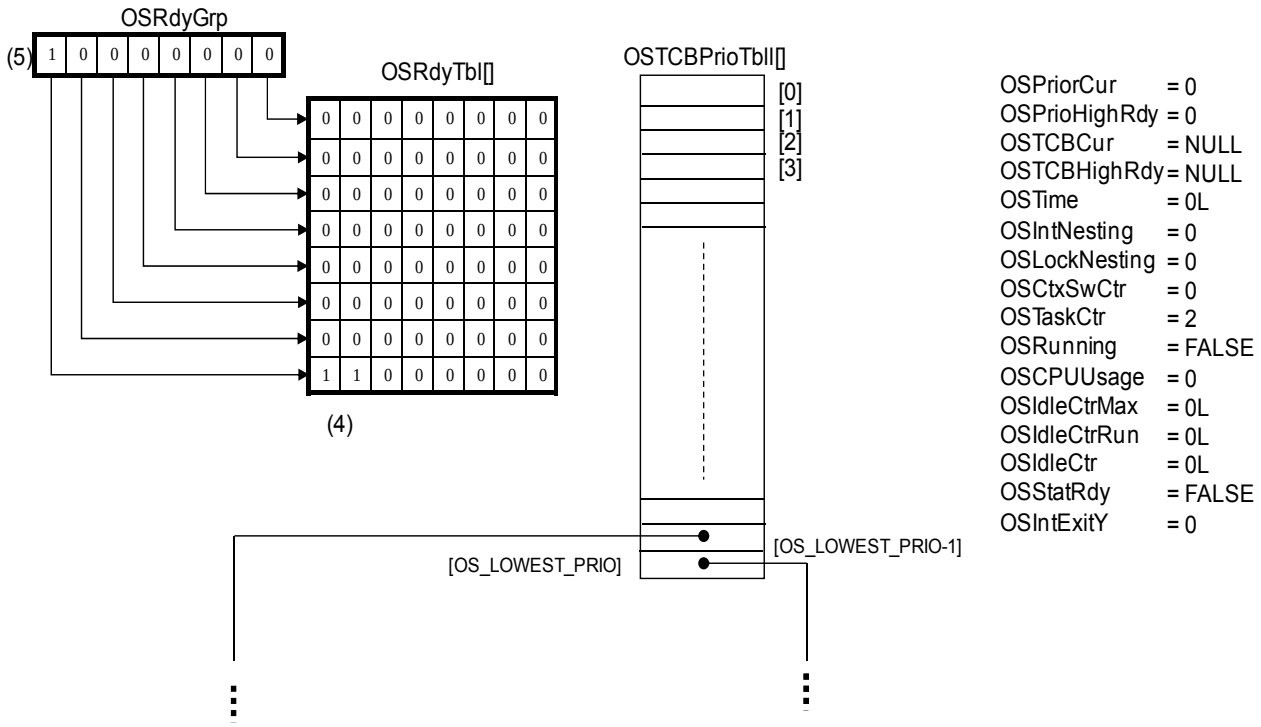
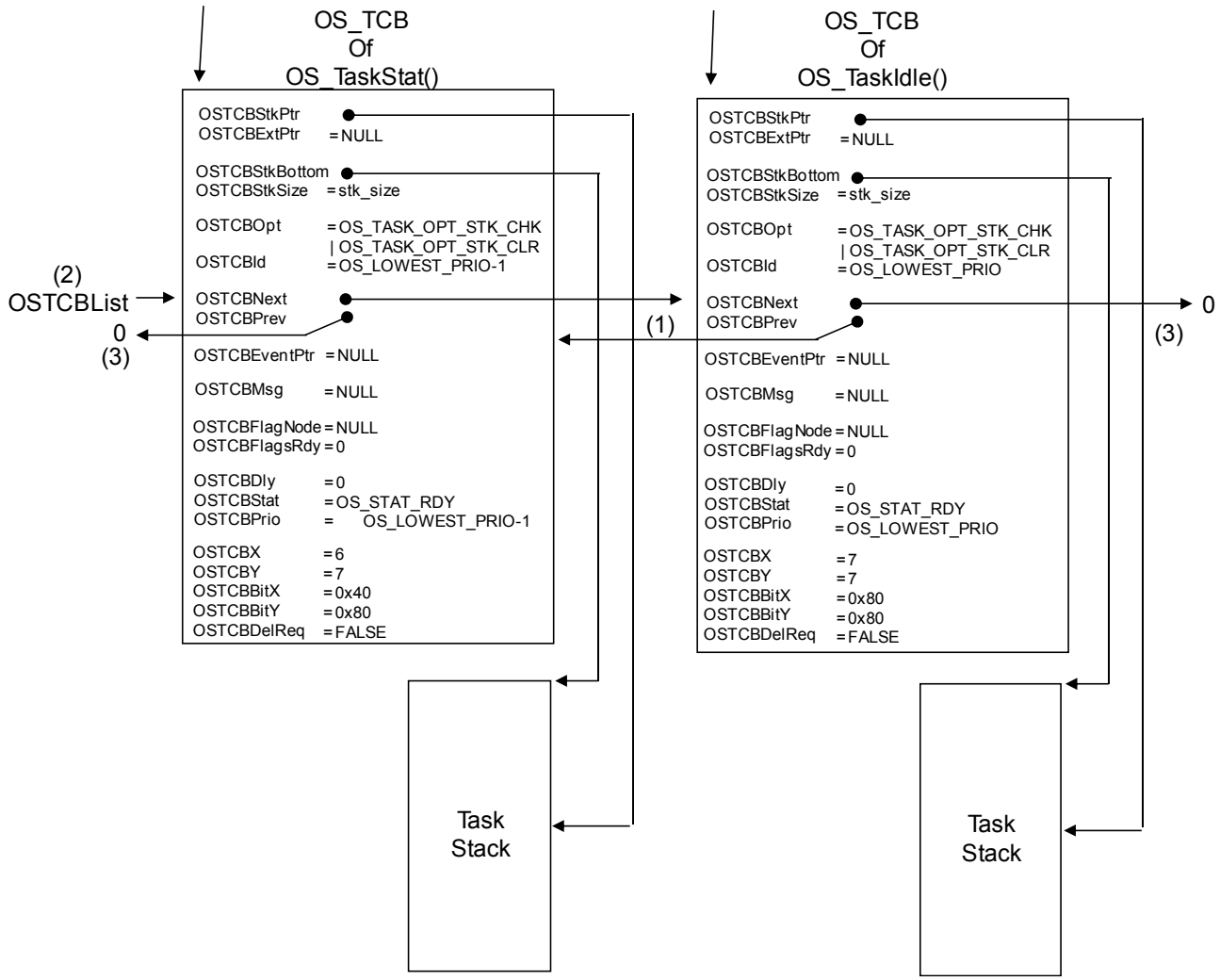


Figure Variables and data structures after calling *OSInit()*.



- This illustration assumes that the following #define constants are set as follows in OS_CFG.H: OS_TASK_STAT_EN = 1; OS_FLAG_EN = 1; OS_LOWEST_PRIO = 63; OS_LOWEST_PRIO1 = 62; OS_MAX_TASKS = 63.
- Here we see the values for OSRdyGrp, OSRdyTbl[], OSTCBPrioTbl[] and the initial variable values.
- (4) Because both tasks (Idle and Stat) are ready to run, their corresponding bits in OSRdyTbl[ ] are set to 1.
- (5) Also, because the bits of both tasks are on the same row in OSRdyTbl[ ] only one bit in OSRdyGrp is 1.

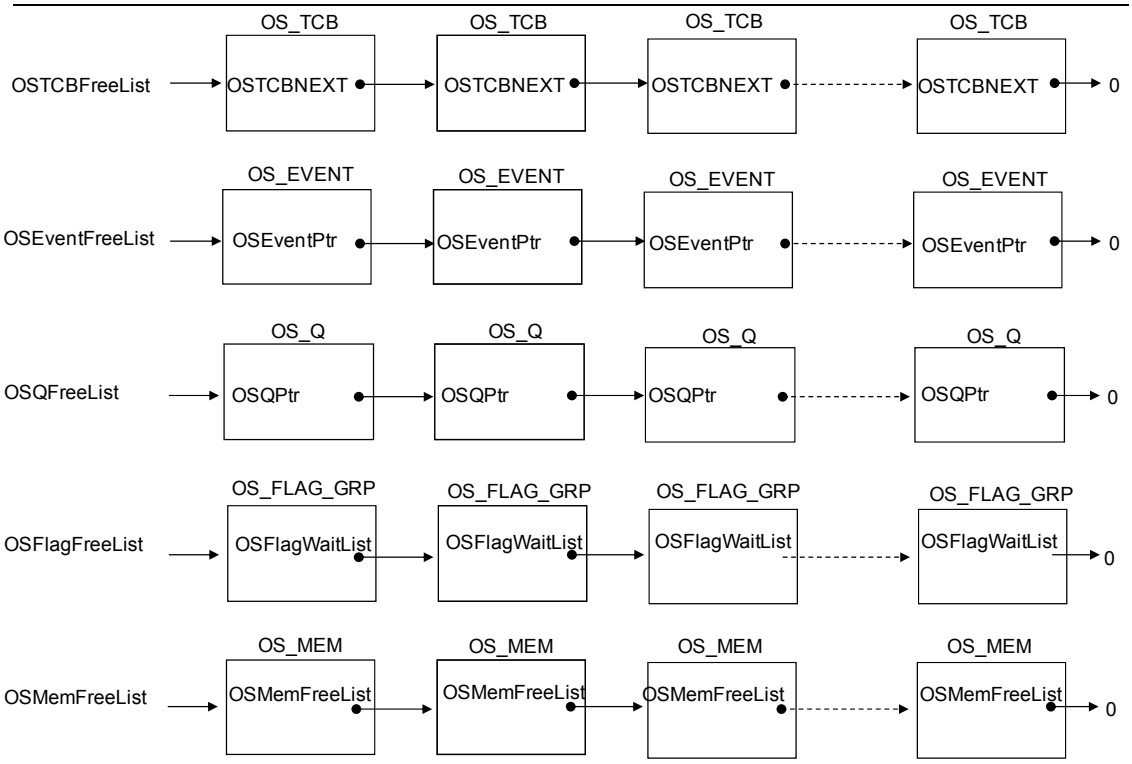


- (1) The task control blocks of the Idle and Stat tasks are chained together in a doubly linked list.
- (2) OSTCBList points to the beginning of this chain -- when a task is created, it is always placed at the beginning of the list.
- (3) both ends of the doubly linked list point to NULL (i.e., 0).
- Because both tasks are ready to run their corresponding bits in OSRdyTb[] are set to 1; also only one bit in OSRdyGrp is set to 1. ... Q: Why?

A: Each bit in OSRdyGrp corresponds to one row in OSRdyTbl[ ].

- uC/OS-II also initializes five pools of free data structure, as shown in the next slide. Each of these pools is a singly linked list and allows uC/OS-II to obtain and return an element from and to a pool quickly.

Figure: Free Pools



- After OSInit() has been called:
  - OS_TCB pool contains OS_MAX_TASKS entries
  - OS_EVENT pool contains OS_MAX_EVENTS entries
  - OS_Q pool contains OS_MAX_QS entries
  - OS_FLAG_GRP pool contains OS_MAX_FLAGS entries; and
  - OS_MEM pool contains OS_MAX_MEM_PART entries
- Each of the free pools are NULL-pointer terminated -- their size is defined in OS_CFG.H.

STARTING uC/OS-II MULTITASKING

- You start multitasking by calling OSStart( ).
- Before you start uC/OS you must create at least one of your application tasks, as shown below.

```
void main(void)
{
    OSInit( )            /* Initialize uC/OS */
    …
    Create at least 1 task using OSTaskCreate( ) or
    OSTaskCreateExt( );
    …
    OSStart( );     /*Start multitasking.  OSStart will not return */
}
```

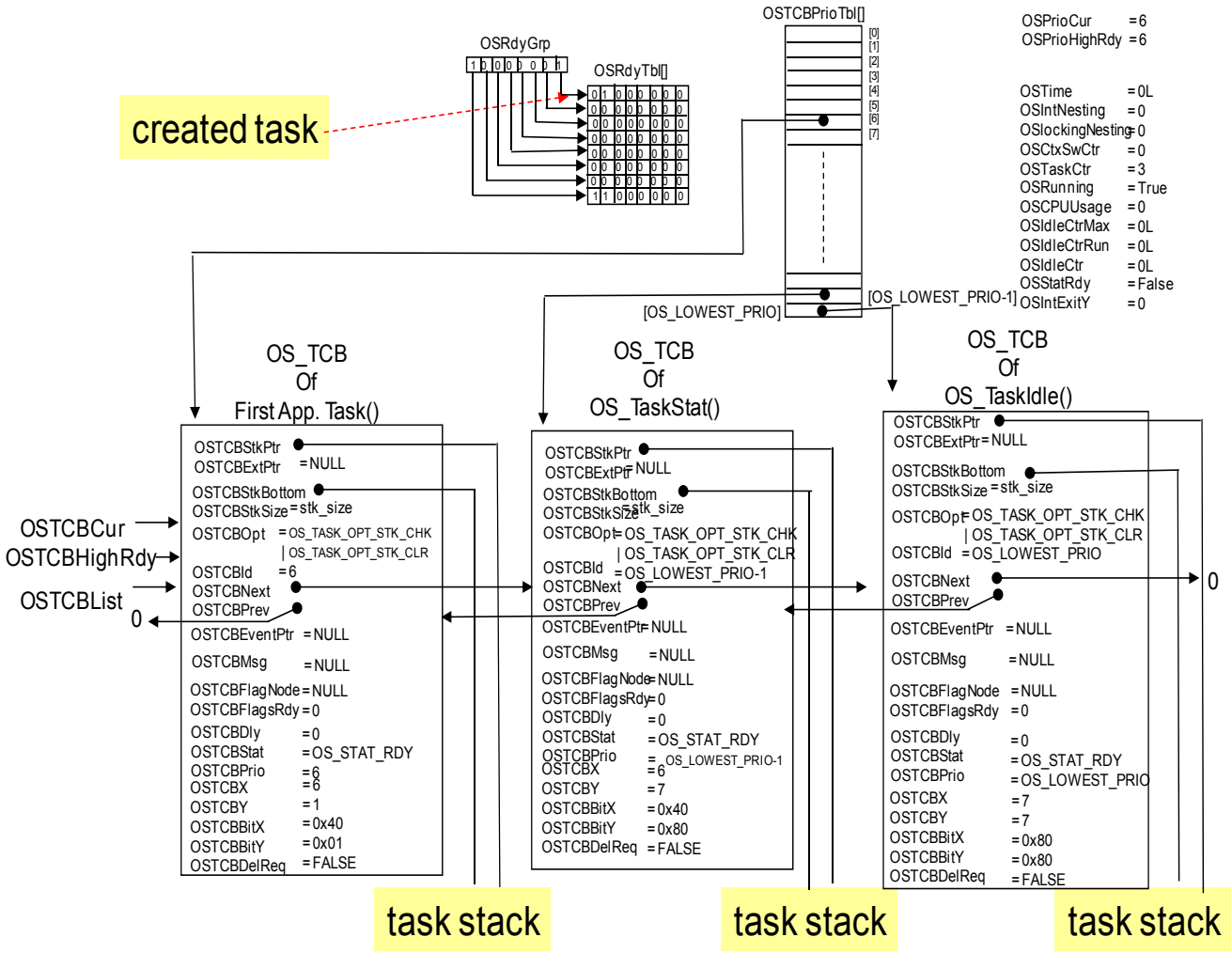
```
void OSStart (void)
{   INT8U y;    INT8U x;
    if (OSRunning == FALSE) {
        y = OSUnMapTbl[OSRdyGrp];
        x = OSUnMapTbl[OSRdyTbl[y]];
        OSPrioHighRdy = (INT8U)((y << 3) + x);
        OSPrioCur     = OSPrioHighRdy;
        OSTCBHighRdy =OSTCBPrioTbl[OSPrioHighRdy];   (1)
        OSTCBCur      = OSTCBHighRdy;
        OSStartHighRdy();    }                       (2)
}
```

(1) When called, OSStart() finds the OS_TCB from the ready list of the highest priority task you have created

(2) OSStart() calls OSStartHighRdy(), which is found in OS_CPU_A.ASM for the processor being used. Basically, OSStartHighRdy() restores the CPU registers by popping them off the task's stack and then executing a return from interrupt instruction, which forces CPU to execute your task's code

NOTE: OSStartHighRdy() never returns to OSStart() …Q?

Figure: *Variables and data structures after calling OSStart().*



- Here it is assumed that the task created has a priority of 6.
- Notice that OSTaskCtr indicates that three tasks have been created; OSRunning is set to TRUE, indicating that multitasking has started; OSPrioCur and OSPrioHighRdy contain the priority of your application task; and OSTCBCur and OSTCBHighRdy both point to the OS_TCB of your task.

PROGRAM ORGANIZATION EXAMPLE

- When writing a program for uC/OS, the main program module contains the main() function, a start-up task, and some or all the other tasks
- Additional tasks and support functions may be contained in separate modules.
- In the next example we consider that we have only one module in the project, and the module contains all the tasks.

EXAMPLE -- DECLARATIONS BEFORE main()

```
/*A simple uC/OS-II program demo*/
#include “includes.h”
/* Global event definition */
OS_EVENT *SecFlag;    /* A one-second flag semaphore */
/* Task functions prototype.
   -Private if in the same module as start-up task, otherwise public */
static void StartTask(void *pdata);
static void Task1(void *pdata);
static void Task2(void *pdata);
/*Allocate task stack space. (Must be public)
  - Private if in the same module as start-up task, otherwise public */
static OS_STK StartTaskStk[STARTTASK_STK_SIZE];
static OS_STK Task1Stk[TASK1_STK_SIZE];
static OS_STK Task2Stk[TASK2_STK_SIZE];
```

DECLARATIONS EXPLAINED

- The module starts by including the master header file include.h (to be presented later).
- Next, the program defines the uC/OS events and task functions contained in the module.
  - In this case, there is a single event, SecFlag, and three tasks, StartTask, Task1, and Task2.
  - Notice that the task functions are declared as private functions. “static” declaration indicates private to the module file (static variables are local but permanent – remain in existence). This is because task functions should never actually be called by another function. They are executed by the kernel, which knows about each task through the OSTaskCreate() service routine.
  - The event objects are handled like normal C resources. They may be private if only used in the current module, or they must be public if used by a task in another module.
- In a preemptive kernel each task uses its own stack space. So after the task functions are declared, the stack space for each task is allocated.
  - The size of each stack is defined in the include.h header file. The stack space should always be allocated in the same module as the task, so it too can be declared as a private resource.

EXAMPLE -- MAIN()

- The next item in the module is the main() function.
  - Recall that main() is the function called after the system is reset and the start-up code is completed.
  - Therefore, the main() it is the entry point for our application code.
- The following should be in main():
  - initialize the kernel with OSInit( ),
  - create the start-up task with OSTaskCreate( ),
  - create any kernel events,
  - start the kernel with OSStart( ).
- There is rarely anything else in the main() function. All the hardware and system initialization is completed in the start-up code before reaching main().
- The application wide initialization is completed in the start-up task and the task-specific initialization is completed in the tasks themselves.
- In our example, there are 3 tasks declared: StartTask, Task1, and Task2.

```
void main(void) {

    OSInit( );                          /* Initialize uC/OS-II*/
    OSTaskCreate(StartTask,       /*Create start-up task */
                 (void*)0,
                 (void*)&StartTaskStk[STARTTASK_STK_SIZE],
                 STARTTASK_PRIO);
     SecFlag = OSSemCreate(0);   /*Create a semaphore flag     */

     OSStart( );                         /*Start multitasking */
```

EXAMPLE -- START-UP TASK

- StartTask() is the start-up task, which is required in all programs using uC/OS.
- When we started the kernel in main(), the start-up task was the only task that had been created. Therefore it is guaranteed that the kernel will run the start-up task first.
- In the start-up task, we need to initialize the uC/OS timer service, create other tasks, and initialize application-wide resources that were not already initialized in the start-up code before main().
- Because, the start-up task creates other tasks, it must have the highest priority or the kernel may switch to another task before the initialization in the start-up task is complete.
- The uC/OS timer is initialized using the service OSTickInit(). The timer must be initialized before any timer services can be used but only after the kernel has been started. Therefore we could not move this to main().
- The start-up task is unique because it is meant to run only one time. As we have mentioned most tasks are endless loops. To make sure that the start-up task is executed only one time, it ends with a trap that calls the OSTaskSuspend() service. OSTaskSuspend() does stop the task, but just in case another task accidentally starts it up again with OSTaskResume(), it is contained in an endless trap.

START-UP TASK AND THE OTHER TASKS -- CODE

```
/*START-UP TASK   */
static void StartTask(void *pdata) {
      OSTickInit();                          /*Initialize the uC/OS ticker */
      DBUG_PORT_DIR = 0xff;          /*Initialize debug port */
      DBUG_PORT = 0xff;
      OSTaskCreate(Task1,
                  (void *)0,
                  (void *)&Task1Stk[TASK1_STK_SIZE],
                   TASK1_PRIO);
      OSTaskCreate(Task2,
                  (void *)0,
                  (void *)&Task2Stk[TASK2_STK_SIZE],
                  TASK2_PRIO);
       FOREVER() {                          /*Start-up task ending trap */
                  DBUG_PORT ^= DBUG_STSK;
                  OSTaskSuspend(STARTTASK_PRIO);
        }
}                                                                    Q...??


/*TASK #1          */
static void Task1(void *pdata) {
    INT8U TimCntr = 0;          /* Counter for one-second flag */
  while (1) {                        /*Endless loop  */
       OSTimeDly(10);               /* Task period = 10 ms       */
       DBUG_PORT ^= DBUG_TSK1;
       TimCntr++;
       if(TimCntr == 100) {
            OSSemPost(SecFlag);          /* Signal one second  */
            TimCntr = 0;
       }
  }
}
```

```
/*TASK #2                    */
static void Task2(void *pdata) {
        INT8U err;                  /* Storage for error codes */
      while (1) {
          OSSemPend(SecFlag, 0, &err);   /*Wait for 1-second event */
          DBUG_PORT ^= DBUG_TSK2;   /*Toggle task 2 debug bit */
       }
}
```

- Notice that Task1 and Task2 appear never to exit. They are designed as endless independent tasks. When the delay is completed the task code is executed.
- Task1 is a timed loop with a loop period of 10ms.
- The task toggles a general purpose output bit and increments a counter TimCntr.
- If TimCntr reaches to 100 then Task1 signals an event flag to communicate to Task2 that 1 second passed.

- Task 2 is configured as an event loop -- it waits for a TimCntr event from Task1 and then runs the task code.
- The task code toggles another general purpose output bit. Therefore the output bit is toggled every second.
  - One significant difference in this case is that the event signal does not have to be polled.
  - The task is placed in a waiting state when it calls OSSemPend(), and then when the event occurs, the kernel makes the task ready to run.

Q: Why don't we need to poll the signal event?
A: The task is in waiting list and waits for the event. When Task1 signals the event the kernel makes Task2 ready.

TYPICAL TASK STRUCTURES

- When writing code for tasks, the code is structured in one of two ways:
  - run to completion, or
  - endless loop.

```
RunToCompletionTask() {
  Initialize application
  Create 'endless loop tasks'
  Create kernel objects
  Delete or suspend this task
}
```

```
EndlessLoopTask()  {
    Initialization code
    Loop forever
    {
        Body of the loop
        Make one or more blocking calls
    }
}
```

EXAMPLE -- HEADER FILE

- For small projects, the header file should include all your definitions + the uC/OS definitions such as:
  - the task priorities, the task stack sizes, and message queue sizes.
- By putting these definitions here, we can look in one place to see what tasks are used in the project, what priority each task has and how much RAM space is used for the stacks.
- For larger projects the uC/OS definitions could be placed in a separate header file.

- For the header file for this example check Morton's book pp. 601-602.There are: Project type definitions; General defined constants; General defined macros; MCU specific configurations; Task priorities (such as: #define STARTTASK_PRIO 4; #define TASK1_PRIO 6; #define TASK2_PRIO 10); Task stack sizes; System header files.

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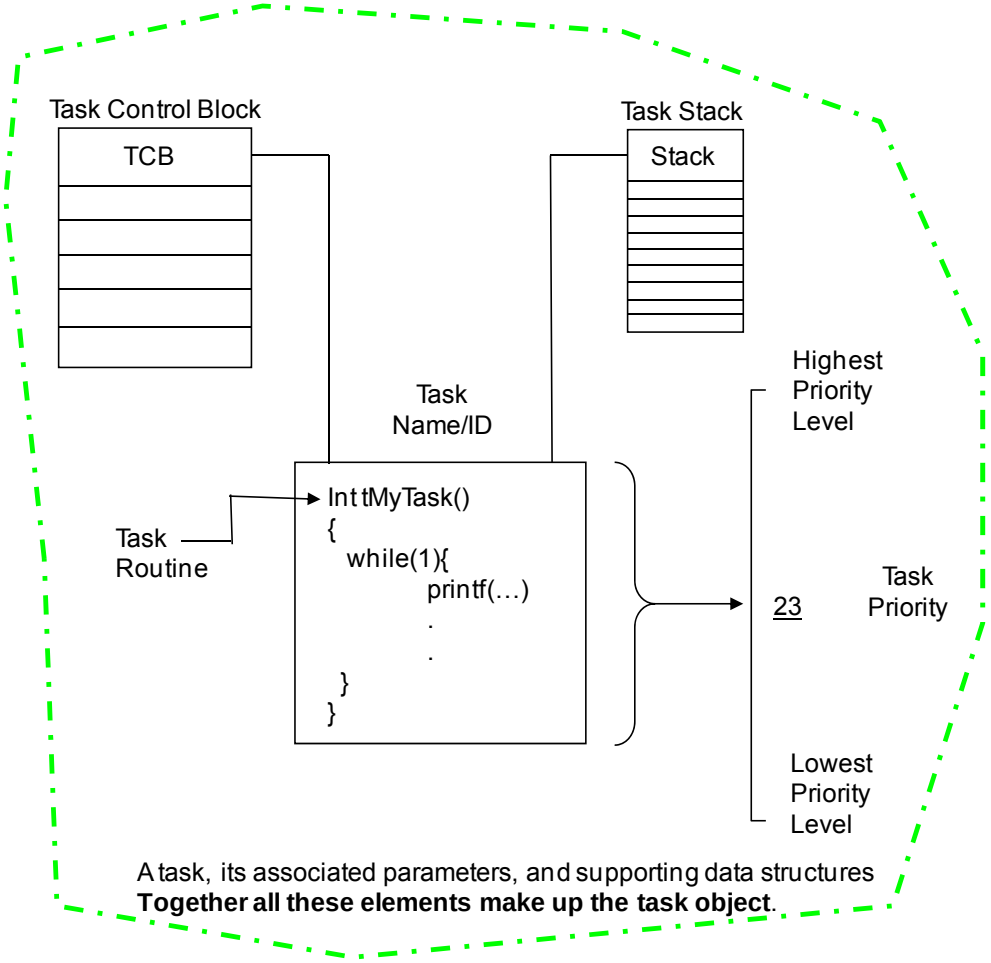
TASK OBJECT

- Upon creation, each task has an associated name, a unique ID, a priority (if part of a preemptive scheduling plan), a task control block (TCB), a stack, and a task routine. Together, these components make up what is known as the task object.

Figure. Task Object



- Task: an independent thread of execution that can compete with other concurrent tasks for processor execution time.
- A task is schedulable and is defined by its distinct set of parameters and supporting data structures.

SYSTEMS TASKS

- When the kernel first starts, it creates its own set of system tasks and allocates the appropriate priority for each from a set of reserved priority levels. The reserved priority levels refer to the priorities used internally by the RTOS for its system tasks.
- An application should avoid using the reserved priority levels for its tasks because running application tasks at such level may affect the overall system performance or behaviour.
- For most RTOSs, these reserved priorities are not enforced. The kernel needs its system tasks and their reserved priority levels to operate. These priorities should not be modified.
- Examples of uC/OS-II system tasks include:
  - initialization or startup task OSInit() – initializes the system and creates and starts system tasks,
  - idle task – uses up processor idle cycles
    - It is set to the lowest priority, typically executes in an endless loop, and runs when either no other task can run or when no other task exists, for the sole purpose of using idle processor cycles. The idle task is necessary because the processor executes the instruction to which the program counter register points while it is running. Unless the processor can be suspended, the program counter must still point to valid instructions even when no task exists in the system or when no task can run.
  - logging task – logs system messages,
  - exception handling task – handles exceptions,
  - debug agent task – allows debugging with a host debugger, and
  - Statistics task -- generates execution statistics.

TASK CONTROL BLOCK (TCB)

- A task control block is a data structure.
- All OS_TCBs reside in RAM. The following are some members of the structure for uC/OS:
  - .OSTCBStkPtr: contains a pointer to the current top-of-stack for the task
  - .OSTCBStkBottom: is a pointer to the bottom of the task's stack
  - .OSTCBStkSize: holds the size of the stack in number of elements instead of bytes,
  - .OSTCBId; .OSTCBNext; .OSTCBPrev; .OSTCBEventPtr; .OSTCBMsg; .OSTCBFlagNode; .OSTCBFlagsRdy; .OSTCBDly; .OSTCBStat (contains the state of the task); OSTCBPrio (contains the task priority); ...
- OS_TCB is initialized by the function OS_TCBInit() when a task is created.

Note: A dot at the beginning of a variable indicates that the variable is an element of a structure.
OS_TCBInit() is called by either OSTaskCreate() or OSTaskCreateExt().
OS_TCBInit() receives seven arguments:

- prio: is the task priority;
- ptos: is a pointer to the top of stack after the stack frame has been built by OSTaskStkInit() and is stored in the .OSTCBStkPtr field of the OS_TCB
- pbos: is a pointer to the stack bottom and is stored in the .OSTCBStkBottom field of the OS_TCB
- id: is the task identifier and is saved in the .OSTCBId field;
- stk_size: is the total size of the stack and is saved in the .OSTCBStkSize field of the OS_TCB;
- pext: is the value to place in the .OSTCBExtPtr field of the OS_TCB;
- opt: are the OS_TCB options and are saved in the .OSTCBOpt field.

A TASK AS AN INFINITE LOOP -- EXAMPLE

```
void YourTask (void *pdata)  /*return type must be declared void*/
{
   for (;;) {              /* you could also use a while (1) statement */
       /* USER CODE */
       Call one of uC/OS-II's services:
       OSFlagPend();
       OSMutexPend();
       OSQPend();
       OSSemPend();
       OSTaskDel(OS_PRIO_SELF);
       OSTaskSuspend(OS_PRIO_SELF);
       OSTimeDly();
       OSTimeDlyHMSM();
       /*USER CODE*/
    }
)
```

NOTE: A task can delete itself upon completion

- The return type must always be declared void.
- An argument is passed to your task code when the task first starts executing. Notice that the argument is a pointer to a void, which allows your application to pass just about any kind of data to your task.
  - The pointer is a universal vehicle used to pass your task the address of a variable, a structure, or even the address of a function if necessary.
- It is possible to create many identical tasks, all using the same function (or task body). For example, you could have four asynchronous serial ports that each are managed by their own task. However, the task code is actually identical.
  - Instead of copying the code four times, you can create a task that receives a pointer to a data structure that defines the serial port's parameters (for example, baud rate, I/O port address, and interrupt vector number) as an argument (See uC/OS examples in the book).

TASK PRIORITIES IN uC/OS-II

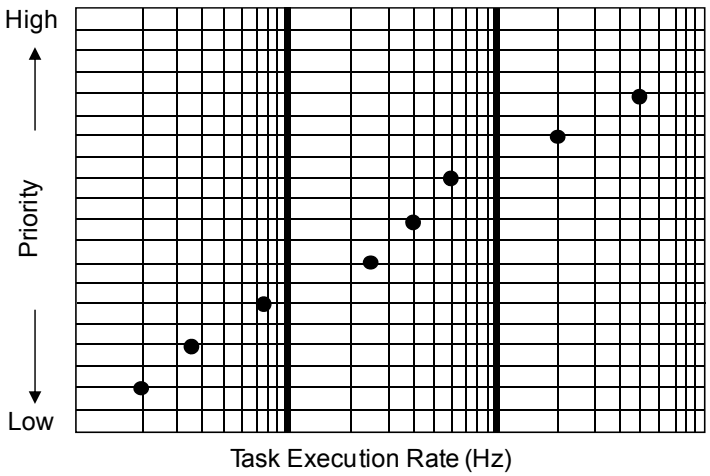
- uC/OS can manage up to 64 tasks;
- The current version uses two tasks for system use.
- It is recommended that you don't use priorities 0, 1, 2, 3, OS_LOWEST_PRIO-3, OS_LOWEST_PRIO-2, OS_LOWEST_PRIO-1, OS_LOWEST_PRIO
- OS_LOWEST_PRIO is a #define constant defined in file OS_CFG.H
- Each task must be assigned a unique priority level. The lower the priority number the higher the priority of the task.
- uC/OS always executes the highest priority task ready to run, the task priority serve as task ID as well.
- A task must be created by passing its address along with other arguments to one of two functions:
  - OSTaskCreate(), or
  - OSTaskCreateExt() -- this is an extended version with more features.

ASSIGNING TASK PRIORITIES

- Assigning task priorities in a complex real-time system is a difficult job -- noncritical tasks should obviously be given low priorities
- Most real-time systems have a combination of soft and hard requirements
  - in soft real time systems, tasks are performed as quickly as possible but they don't have to finish by specific times
  - in hard real-time systems, tasks have to be performed not only correctly but on time

RATE MONOTONIC SCHEDULING (RMS)

Assigning task priorities base on task execution rate.



- RMS - assigns task priorities based on how often tasks execute (other technique will be presented later):
  - tasks with the highest rate of execution are given the highest priority

RMS THEOREM

- RMS theorem makes a number of assumptions:
  - all tasks are periodic (occur at regular intervals),
  - tasks do not synchronize with one another, share resources, or exchange data,
  - the CPU must always execute the highest priority task that is ready to run. ... Q: What type of scheduling we need to use in this case? A: Preemptive.
- Given a set of n tasks that are assigned RMS priorities, the basic RMS theorem states that all task hard-real time deadlines are always met if the following inequality holds:

$$\sum_i \frac{E_i}{T_i} \leq n(2^{1/n} - 1)$$

Allowable CPU use on number of tasks

Number of Tasks	n[2^(1/n) – 1]
1	1.000
2	0.828
3	0.779
4	0.756
...	
infinite	0.693

- Where:
  - Ei: maximum execution time of task *i*,
  - Ti: execution period of task *i*,
  - Ei/Ti: the fraction of CPU time required to execute task *i.*
- NOTE: Using 100% of your CPU is not a desirable goal because it does not allow for code changes and added features.
- As a rule of thumb, you should always design a system to use less than 60 to 70% of your CPU.

SPECIAL SYSTEM TASKS

- **IDLE TASK** -- OS_TaskIdle(): the idle task is always the lowest priority task -- See uC/OS book pp. 98-101.

```
void OS_TaskIdle (void *pdata) {
#if OS_CRITICAL_METHOD == 3
    OS_CPU_SR  cpu_sr;
#endif

  pdata = pdata;
  for (;;) {
      OS_ENTER_CRITICAL();     /* interrupts are disabled */
      OSIdleCtr++;             /* counter used for the statistics task */
      OS_EXIT_CRITICAL();
      OS_TaskIdleHook();  }   /* it is a function that you can write to do
anything you want. You can use this function for power saving*/
}
```

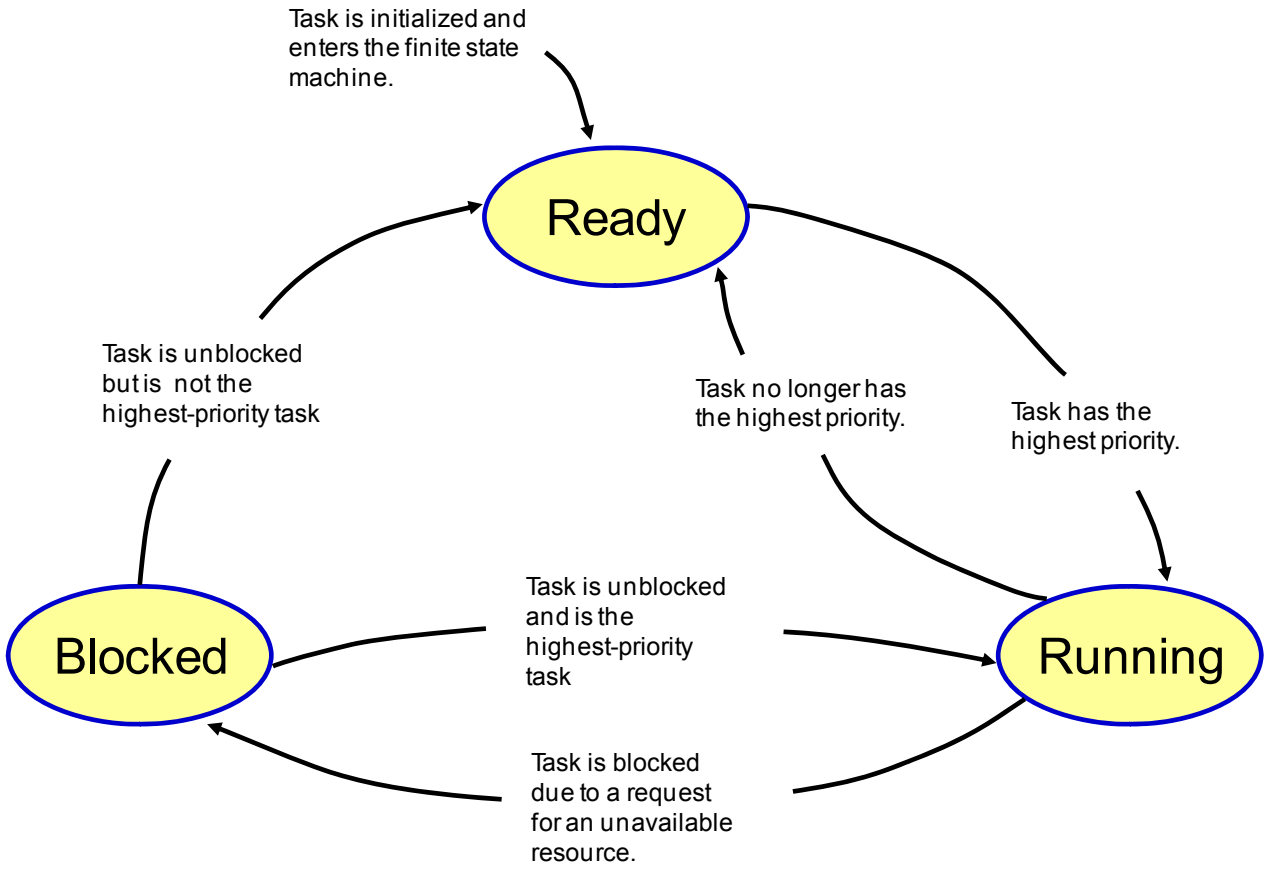
- The idle task executes when none of the other tasks are ready to run.
- Note that: OSIdleCrt is a 32 bit counter that is used by the statistics task.
- OS_TaskIdleHook( ) is a function that you can write to do anything you want. It can be used for testing, power conservation, etc.

STATISTICS TASK -- OS_TaskStat() -- is a special task that provides run-time statistics and it is created by uC/OS.

  - executes every second and computes the percentage of CPU usage by your application.
  - the percentage value is placed in the signed 8-bit integer value OSCPUUsage; the resolution is 1%
- OSCPUsage% = (100 – OSIdleCrt/(OSIdleCrtMax/100)).
- See also the uC/OS book (pages 99 – 103) for the usage of this task.

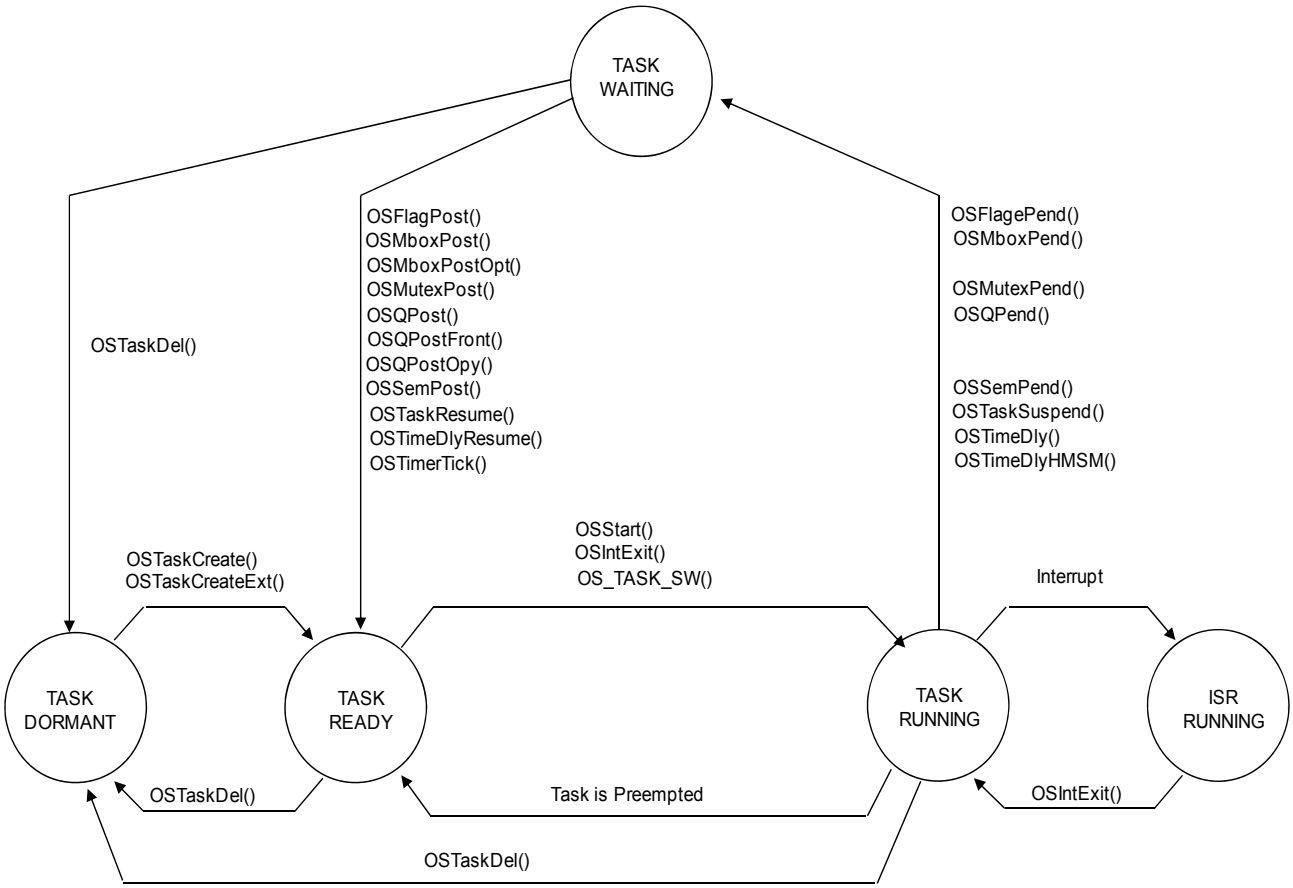
TASKS STATES AND SCHEDULING

- Whether it's a system task or an application task, at any time each task exists in one of a small number of states including *ready, running, or blocked*.
- As the real-time embedded system runs, each task moves from one state to another according to the logic of a simple finite state machine (FSM).
- Kernels can define task-state grouping differently, however, there are 3 main states that are most used in typical preemptive kernels.



A typical state machine for task execution states.

Figure: Task States. uC/OS Example



- The TASK DORMANT state corresponds to a task that resides in program space (ROM or RAM) but has not been made available to uC/OS:
  - a task is made available to uC/OS by calling either OSTaskCreate( ) or OSTaskCreateExt( ).
  - A task can return itself or another task to the dormant state by calling OSTaskDel( ).
- When a task is created, it is made ready to run and placed in the TASK READY state.
- Tasks can be created before multitasking starts or dynamically by a running task.

- If multitasking has started and a task created by another task has a higher priority than its creator, the created task is given control of the CPU immediately.
- OSStart() must only be called once during startup and the highest priority task is placed in the TASK RUNNING state.
- Only one task can be running at any given time -- a ready task does not run until all higher priority tasks are either placed in the TASK WAITING state or are deleted.
- The running task can delay itself for a certain amount of time by calling either OSTimeDly( ) or OSTimeDlyHMSM( ).
  - This task would be placed in the TASK WAITING state until the time specified in the call expires.
  - Both of these functions force an immediate context switch to the next highest priority task that is ready to run.
  - The delayed task is made ready to run by OSTimeTick( ) when the desired time delay expires (pp.108).
- OSTimeTick( ) is an internal function to uC/OS-II and thus, you don't have to actually call this function from your code.
- When all the tasks are waiting either for events or for time to expire, uC/OS executes an internal task called the idle task, OS_TaskIdle().

- RUNNING tasks are placed in the TASK WAITING state when calling event functions. The running task may also need to wait until an event occurs by calling either OSFlagPend(), OSSemPend(), OSMutexPend(), OSQPend(), OSMboxPend().
  - If the event did not already occur, the task that calls one of these functions is placed in the TASK WAITING state until the occurrence of the event.
  - When a task pends on an event the next highest priority task is immediately given control of the CPU. The task is made ready when the event happens or when a timeout expires.
  - The occurrence of an event can be signaled by either another task or an ISR.
- A running task can always be interrupted, unless uC/OS disables the interrupts. When interrupted the task enters the ISR RUNNING state.
- ISRs are treated differently by the kernel. When an interrupt occurs, execution of the task is suspended, and the ISR takes control of the CPU.
- The ISR can make one or more tasks ready to run by signalling one or more events. In this case, before returning from the ISR, uC/OS determines if the interrupted task is still the highest priority task ready to run. If the ISR makes a higher priority task ready to run, the new highest priority task is resumed; otherwise, the interrupted task is resumed.

BASIC TASK OPERATIONS

- In addition to providing a task object, kernels also provide task-management services -- task management services include actions that a kernel performs behind the scenes to support tasks:
  - For example: creating and maintaining the TCB and task stacks, etc.
- A kernel also provides an API (Application Program Interface) that allows developers to manipulate tasks. Common operations are:
  - creating and deleting tasks; controlling task scheduling; and obtaining task information.

EXAMPLE OF TASK CREATION IN uC/OS-II

- You create a task with uC/OS by passing its address and other arguments to one of two functions:
  - OSTaskCreate() or OSTaskCreateExt().
- A task can be created prior to the start of multitasking or by another task. You must create at least one task before OSStart(). An ISR cannot create a task.

INT8U OSTaskCreate
(void (*task)(void *pd), void *pdata, OS_STK *ptos, INT8U prio)

task is a pointer to the task code	pdata is a pointer to an argument that is passed to your task when it starts executing	ptos is a pointer to the top of the stack that is assigned to the task	prio is the desired task priority

DECLARATION of a task in uC/OS -- task is declared as:

static void Task(void *pd);

- Here, (void *pd) – is the argument of the task which is of type void.

Example #1, TaskStartCreateTask()
NOTE: In this application, N_TASKS = 10.

```
static void TaskStartCreateTasks (void)  {          1
INT8U i;

  for (i = 0; i < N_TASKS; i++) {
2   TaskData[i] = '0' + i;   /*array initialized to contain ASCII char 0 to 9*/
    OSTaskCreate(Task, /*N_TASKS identical tasks called Task(), created */
3           (void*)&TaskData[i], /*each task receives a pointer to an array el.*/
            &TaskStk[i][TASK_STK_SIZE – 1], /*each task need stack space*/
             i+1);  /*each task must have unique priority, 1 to 10*/
  }
}
```

- Example 1 is found in the uC/OS book pp. 4-10. The book has other interesting examples.
- The function of statement 1 is called from TaskStart(). Q: How does the statement 2 work? A: '0' = 0x30;
- The for loop initializes n identical tasks called Task(). Each instance of task will place a different ASCII character on the display.
- In statement 3, (void *)… is a pointer to the argument passed to the task.
- Note: Even if the tasks have identical code they need to have their own stack space and individual ID (See how OS_TCBInit() works).

TYPICAL TASK OPERATIONS SUPPORTING MANUAL TASK SCHEDULING

- Many Kernels provide a set of API calls that allow the control of task moves.
- Operations for task scheduling: suspend; resume; delay; restart – fresh initialized (not resumed); get priority; set priority - dynamically sets a task's priority; preemption lock – locks the scheduler; preemption unlock – unlocks the scheduler.
- By using manual scheduling, developers can suspend and resume tasks from within an application.

EXAMPLE OF OPERATIONS SUPPORTING DYNAMIC SCHEDULING FROM uC/OS-II

Changing a Task's Priority:

```
INT8U OSTaskChangePrio (INT8U oldprio, INT8U newprio)
/*At runtime you can change the priority of any task by
calling OSTaskChangePrio()*/
```

Suspending a Task:

```
INT8U OSTaskSuspend (INT8U prio)
/*A suspended task can only be resumed by calling
OSTaskResume() function call. Task suspension is additive
which means that if a task is also waiting for time to expire,
the suspension needs to be removed and the time needs to
expire before the task is ready to run */
```

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INTERRUPTS

- Interrupts allow a microprocessor to process events when they occur, which prevents the microprocessor from continually polling an event to see if it has occurred.
- Microprocessors allow the interrupts to be ignored and recognized through the use of two special instructions: disable interrupts (DI) and enable interrupts (EI), respectively.
- In a real-time environment, interrupts should be disabled as little as possible. Disabling interrupts affects interrupt latency and can cause interrupts to be missed.
- Processors generally allow interrupts to be nested.
- An interrupt is a HW mechanism used to inform the CPU that an asynchronous event has occurred.
- When an interrupt is recognized, the CPU saves part (or all) of its context (i.e. registers) and jumps to a special subroutine, called an ISR.
- The ISR processes the event, and, upon completion of the ISR, the program returns to:
  - the background for a foreground/background system; Q …Why to background? A: Because the foreground is the ISR.
  - the interrupted task for a non-preemptive kernel, or
  - the highest priority task ready to run for a preemptive kernel.

INTERRUPT LATENCY

- An important specification of a real-time kernel is the amount of time interrupts are disabled.
- All real-time systems disable interrupts to manipulate critical sections of code and re-enable interrupts when the critical sections have been executed.
- The longer the interrupts are disabled, the higher the interrupt latency.

(interrupt latency) = (maximum amount of time interrupts are disabled) + (time to start executing the first instruction in the ISR) (2.2)

- Note that the time to start executing the first instruction in the ISR is composed of the time required to save the PC and Status Word (SW) plus the execution time of the longest instruction (here we assume worst case scenario, such that the interrupt comes during the longest instruction).
  - Also note that some processors will save more than the PC and SW when the interrupt is acknowledged.

INTERRUPT RESPONSE

- Interrupt response is defined as the time between the reception of the interrupt and the start of the user code that handles the interrupt.
  - the interrupt response time accounts for all of the overhead involved in handling an interrupt.
  - typically, the processor's context (CPU registers) is saved on the stack before the user code is executed.

- The interrupt response includes the latency time plus the time needed to save the CPU's context (other savings besides the ones saved automatically by the processor) which is normally done before the application code starts.
- Normally, at the beginning of the ISR you will have some context saving instructions. The application code starts after this. Also, you might have some kernel calls.
- As a result, we will have different interrupt response calculations depending on the type of kernel used.
- In FOREGROUND/BACKGROUND and NON-PREEMPTIVE systems ISR code is executed immediately after saving the processor's context, so:

interrupt response = interrupt latency + time to save CPU's context

- In PREEMPTIVE kernels a special function provided by the kernel needs to be called to notify the kernel that an ISR is starting. This function allows to keep track of interrupt nesting. As a result:

interrupt response = interrupt latency + time to save CPU's context + execution time of the kernel ISR entry function

- Note that, in all cases you must consider the system's worst case interrupt response time.
- Your system might respond to interrupts in 50us 99% or the time, but, if it responds to interrupts in 250us the other 1%, you must assume a 250us interrupt response time.

INTERRUPT RECOVERY

- Interrupt recovery is defined as the time required for the processor to return to the interrupted code or to a higher priority task, in the case of a preemptive kernel.

foreground/background and non-preemptive kernels

interrupt recovery = time to restore the CPU's context + time to execute the return from interrupt instruction (2.6)

preemptive kernels

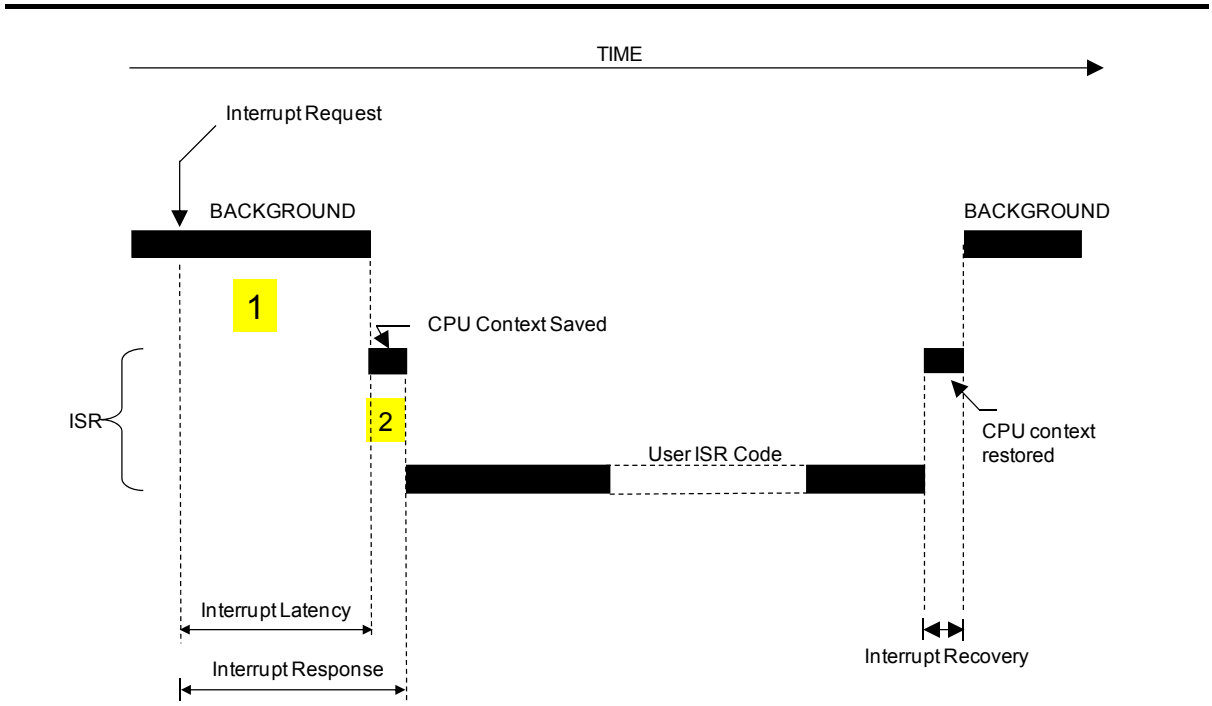
interrupt recovery = time to determine if a higher priority task is ready + time to restore the CPU's context of the high priority task + time to execute the return from interrupt instruction (2.8)

- For a preemptive kernel, interrupt recovery is more complex. Typically, a function provided by the kernel is called at the end of the ISR.
- For uC/OS, this function is called OSIntExit() and allows the kernel to determine if all interrupts have nested. If they have nested (i.e., a RTI would return to task-level code), the kernel determines if a higher priority is ready to run as a result of an ISR, this task is resumed.
- Note that in this case, the interrupted task resumes only when it again becomes the highest priority task ready to run.
- For a preemptive kernel, interrupt recovery is given by Eq. (2.8).

INTERRUPT LATENCY, RESPONSE, AND RECOVERY FOR VARIOUS TYPES OF SYSTEMS

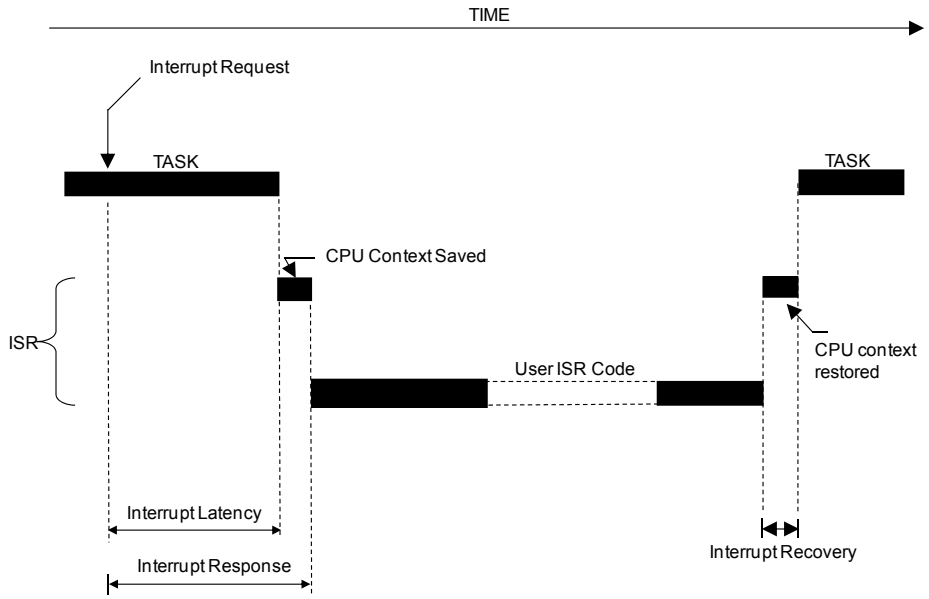
- You should note that for a preemptive kernel, the exit function decides to return either to the interrupted task or to a higher priority task that the ISR has made ready to run.
  - ...Q? What happens to the execution time in the case when the exit functions decides to return to a higher priority task?
  - A: The execution time is slightly longer because the kernel has to perform a context switch to this high priority task.

Interrupt latency, response, and recovery (foreground/background)

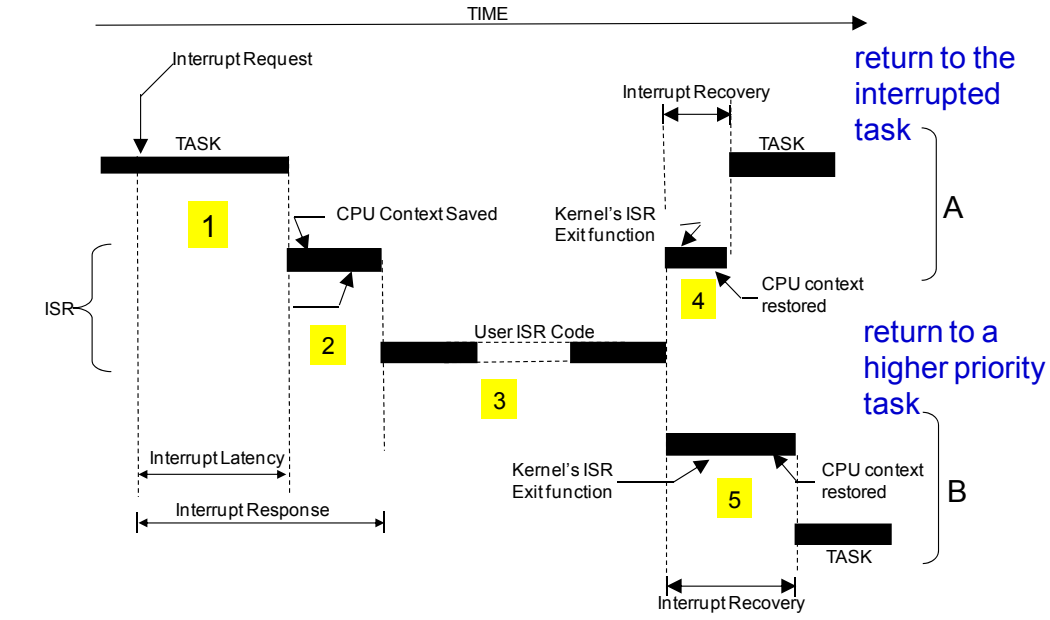


- 1 – includes the DI + the execution of the longest instruction before ISR + saving of PC and SW.
- 2 – includes the time to save all the CPU registers and all other system and kernel calls before the user ISR code.

Interrupt latency, response, and recovery (non-preemptive kernel)



Interrupt latency, response, and recovery (preemptive kernel)



- 2 – includes context saved + execution of the Kernel's ISR entry function (i.e., OSIntEntry ( ) for uC/OSS);
- 4 – Kernel's ISR exit function to decide the nesting level. If the nesting complete, and interrupted task is the highest priority then restore the CPU context.
- 5 – context switch to a higher priority task is longer than CPU context restore.

ISR PROCESSING TIME

- Although ISRs should be as short as possible, no absolute limits on the amount of time exist for an ISR. One cannot say that an ISR must always be less than 100us, 500us, or 1 ms.
- If the ISR code is the most important code that needs to run at any given time, it could be as long as it needs to be.
- In most cases, however, the ISR should recognize the interrupt, obtain data or a status from the interrupting device, and signal a task to perform the actual processing.
- You should also consider whether the overhead involved in signalling a task is more than processing of the interrupt. Signalling a task from an ISR (i.e., through a semaphore, a mailbox, or a queue) requires some processing time.
- If processing your interrupt requires less than the time required to signal a task, you should consider processing the interrupt in the task itself and possibly enabling interrupts to allow higher priority interrupts to be recognized and serviced.

INTERRUPTS UNDER uC/OSS

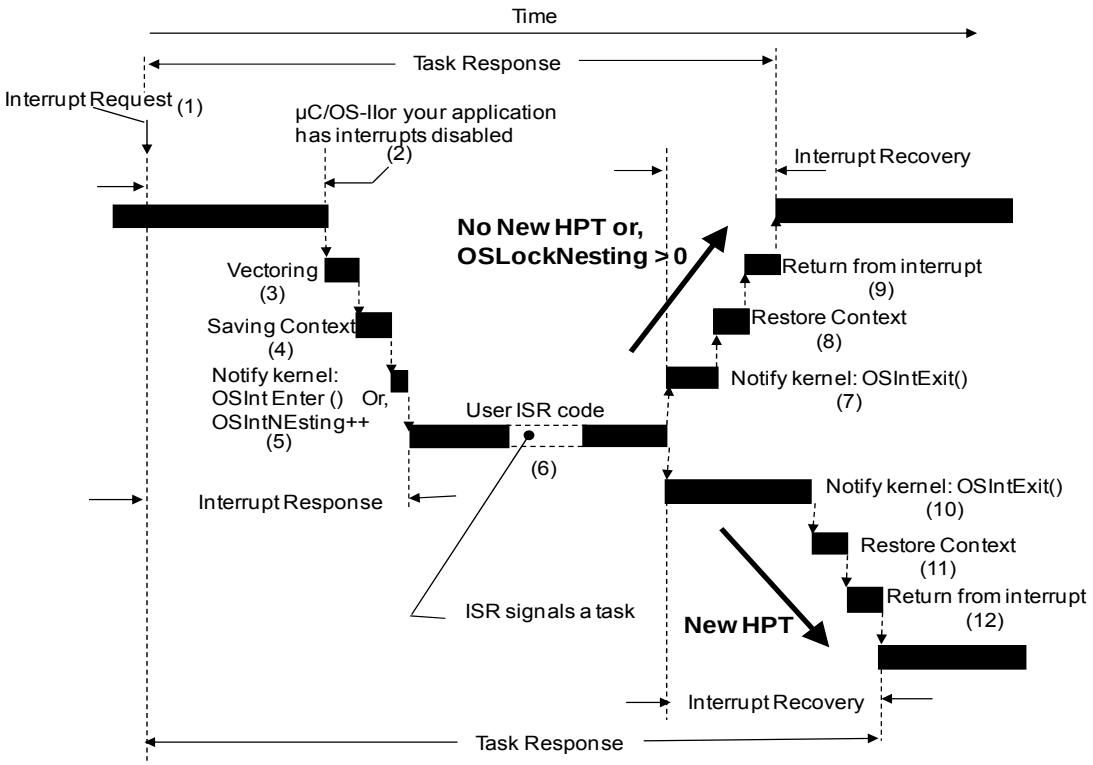
```
Your ISR:
    Save all CPU  registers;                                  (1)
    Call OSIntEnter() or, increment OSIntNesting directly;    (2)
    if (OSIntNesting == 1)  {                                 (3)
        OSTCBCur -> OSTCBStkPtr = SP;                         (4)
    }
    Clear interrupting device;                                (5)
    Re-enable interrupts (optional);                          (6)
    Execute user code to service ISR;                         (7)
    Call OSIntExit();                                         (8)
    Restore all CPU registers;                                (9)
    Execute a return from interrupt instruction;              (10)
```

- uC/OS requires that an ISR be written in assembly language. However, if your C compiler supports in-line assembly you can put the ISR code directly in a C source file.
- (1) Your code should save all CPU registers unto the current stack; this time is part of the response time.
- (2) uC/OS needs to know that you are servicing an ISR, so you need to either call OSIntEnter() or increment the global variable OSIntNesting. Incrementing OSIntNesting directly is much faster than calling OSIntEnter() and is thus the preferred way; This time is part of the response time.
- (4) We check to see if this level is the first interrupt level, and, if it is, we immediately save the stack pointer into the current task's OS_TCB.
- (5) you must clear the interrupt source because you stand the chance or re-entering the ISR if you decide to re-enable interrupts.
- (8) the conclusion of the ISR is marked by calling OSIntExit(), which decrements the interrupt nesting counter. When the nesting counter reaches to 0, all nested interrupts are complete, and uC/OS needs to determine whether a higher priority task has been awakened by the ISR (or any other nested ISR). If a higher priority task is ready to run, uC/OS returns to the higher priority task rather than to the interrupted task.
- (9) if the interrupted task is still the most important task to run, OSIntExit() returns to the ISR.
- NOTE: uC/OS returns to the interrupted task if scheduling has been disabled.

  Q: What sections within the ISR are part of the latency time, response time, and recovery time?

  A: Latency: none; Response: 1, 2, 3, 4, 5, and 6; Recovery: 8, 9, and 10.

Figure Servicing an interrupt in uC/OS II.



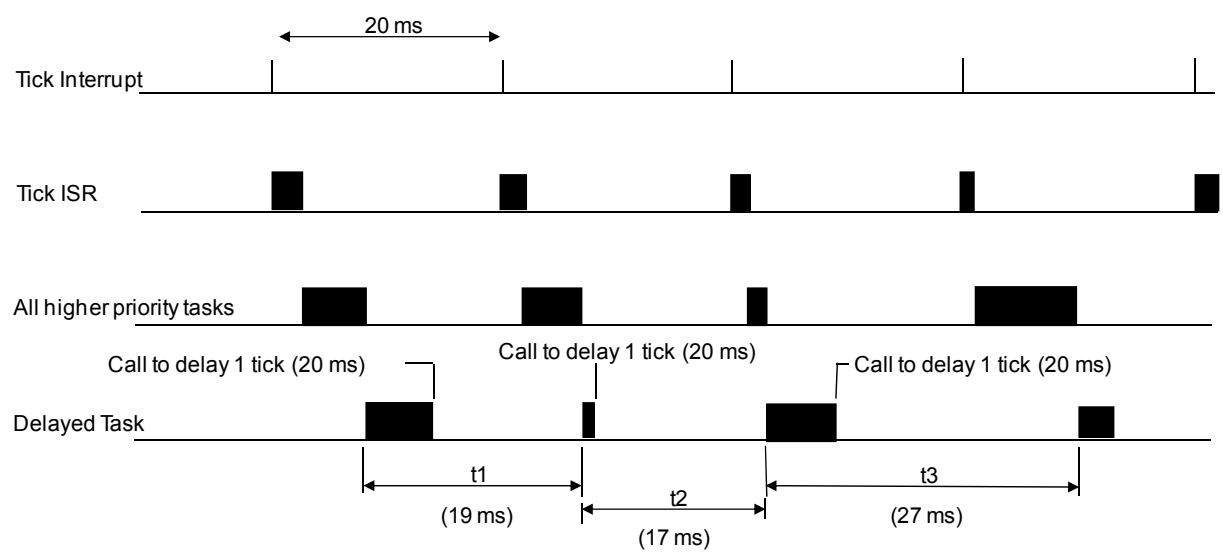
(1) the interrupt is received but is not recognized by the CPU, either because interrupts have been disabled by uC/OS or your application, or because the CPU has not completed executing the current instruction. **(3)** After the CPU recognizes the interrupt, the CPU vectors (at least on most microprocessors) to the ISR. **(4)** the ISR saves the CPU registers (i.e., the CPU's context). **(5)** ISR notifies uC/OS by calling OSIntEnter() or by incrementing OSIntNesting. You also need to save the stack pointer into the current task's OS_TCB. **(6)** your ISR code executes. Your ISR should do as little work as possible and defer most of the work at the task level. A task is notified from the ISR by calling OSFlagPost(), OSMboxPost(), OSQPost(), OSQPostFront(), or OSSemPost(). The receiving task might or might not be pending at the event flag, mailbox, queue, or semaphore when the ISR occurs and the post is made. **(7)** after the ISR code is completed you need to call OSIntExit(). As can be seen from the timing diagram, OSIntExit() takes less time to return to the interrupted task when there is not higher priority task (HPT) readied by the ISR. **(9)** in this case, the CPU registers are then simply restored and a return from interrupt instruction is executed. **(10)** Q: Why if a HPT is made ready the OSIntExit() takes longer to execute? A: Because the OSIntExit() must execute a context switch to HPT. **(12)** the registers of the new task are restored, and a return from interrupt instruction is executed.

CLOCK TICK

- A clock tick is a special interrupt that occurs periodically. Clock tick interrupt usage:
  - allows a kernel to delay tasks for an integral number of clock ticks,
    … Q: How? A delay time value is stored on the TCB variable. Every time the tick interrupt is serviced by the kernel this value is decremented.
  - provide timeouts when tasks are waiting for events to occur.
- NOTE: the faster the tick rate, the higher the overhead imposed on the system.
- uC/OS REQUIRES that you provide a periodic time source to keep track of time delays and timeouts.
  - a tick should occur between 10 and 100 times per second, or Hertz,
  - the actual frequency of the clock tick depends on the desired tick resolution of your application,
  - Generally, you can obtain a tick source by dedicating a hardware timer.
- You must enable the ticker interrupts by calling OSTickInit() after multitasking has started (OSStart()). As a result, you should initialize ticker interrupts in the first task that executes following a cal to OSStart().
- The uC/OS clock tick is serviced by calling OSTimeTick () from a tick ISR or from a task -- OSTimeTick() keeps track of all the task timers and timeouts.
- The tick ISR follows all the rules described for interrupts under uC/OS. The code for the tick ISR must be written in assembly language because you cannot access CPU registers directly from C. Because the tick ISR is always needed, it is generally provided with a port.

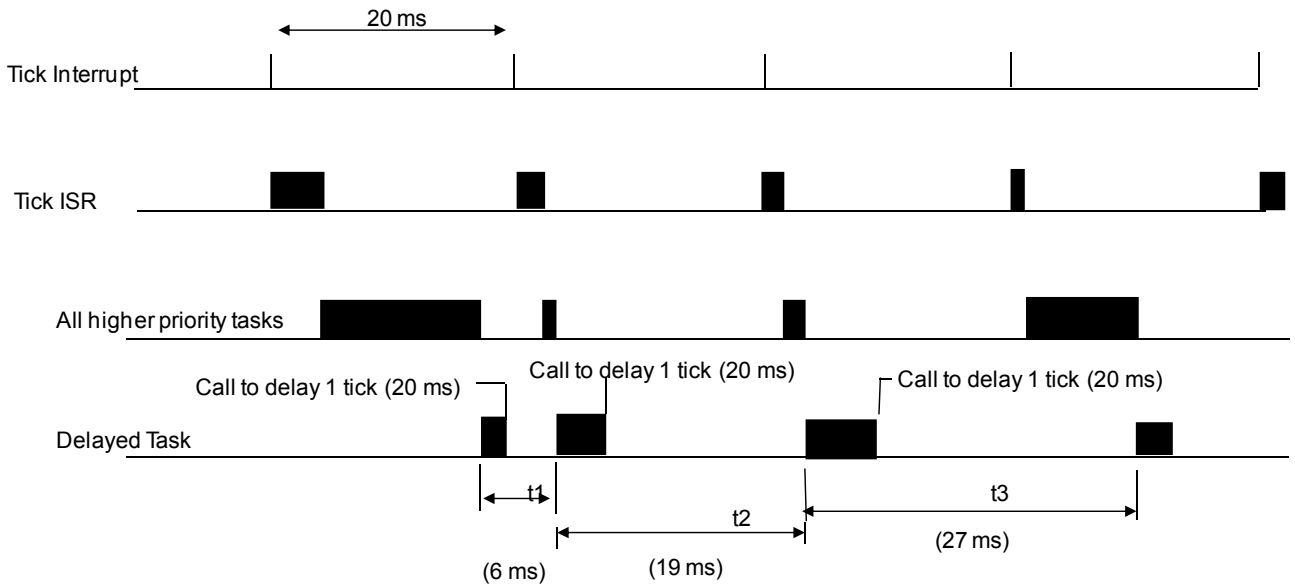
- THE RESOLUTION of delayed tasks is 1 clock tick -- however, this does not mean that its accuracy is 1 clock tick.
- CASES 1, 2, and 3 present situations of task jitter related to clock tick delay.

Delaying a task for one tick (Case 1)



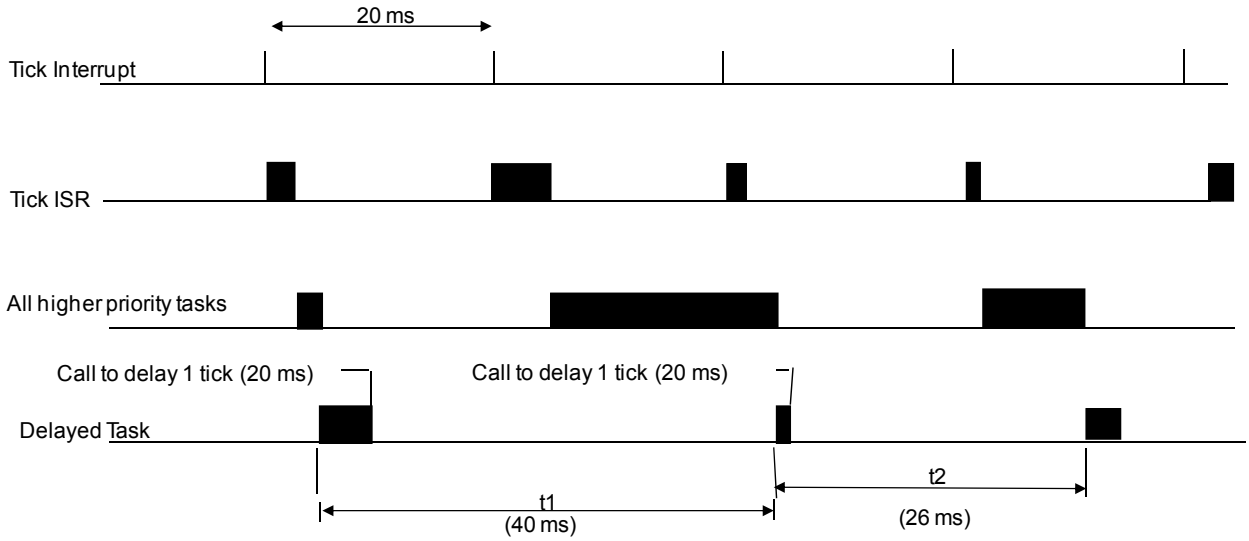
- CASE 1 shows a situation where higher priority tasks and ISRs execute prior to the task, which needs to delay for one tick.
- As you can see, the task attempts to delay for 20 ms but because of its priority, actually executes at varying intervals.
  - The variable execution time causes the execution of the task to jitter.
- The shaded areas indicate the execution time for each operation performed. The processing time of the tick ISR has been exaggerated to show that it is subject to varying execution time -- Note: Time for each operation varies to reflect typical processing which would include loops and conditional statements.
- In this case, due to variable execution time of HPT (High Priority Task) the period of the delay is less than or greater than 20 ms.

Delaying a task for one tick (Case 2)



- CASE 2 shows a situation where the execution times of all higher priority tasks and ISRs are slightly less than one tick.
- If the task delays itself just before a clock tick, the task executes again almost immediately.
- As a result of this, if you need to delay a task at least one clock tick, you must specify one extra tick.
  - In other words, if you need to delay a task for at least 5 ticks, you must specify 6 ticks.

Delaying a task for one tick (Case 3)

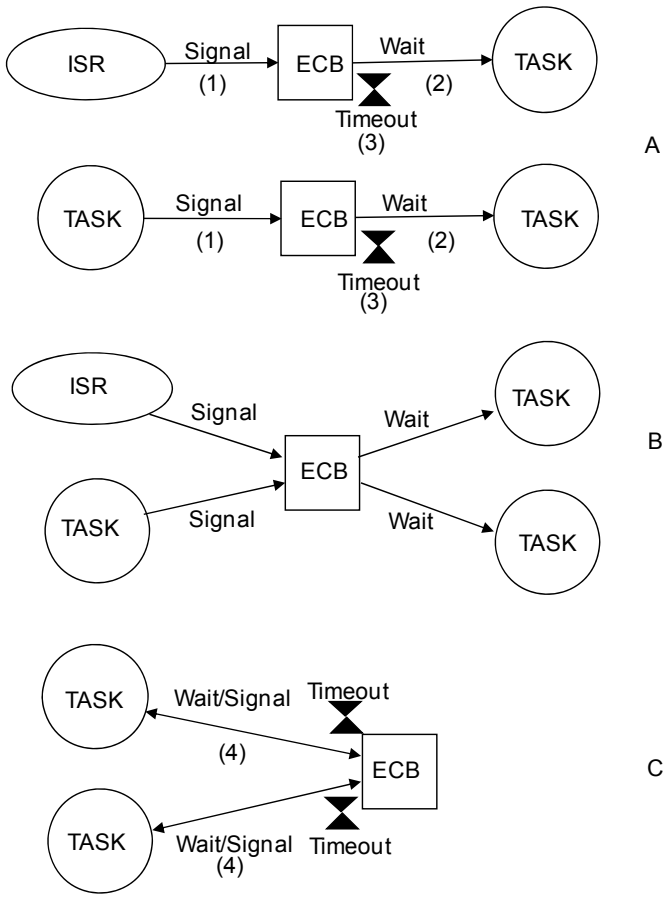


- CASE 3 shows a situation in which the execution times of all higher priority tasks and ISRs extend beyond one clock tick.
  - In this case, the task that tries to delay for one tick actually executes two ticks later and misses its deadline. Missing the deadline might be acceptable in some applications, but in most cases it isn't.
- CASE 1, 2, and 3 situations exist in all real-time kernels. They are related to the CPU processing load and possibly incorrect system design
- Possible solutions to these problems:
  - increase the clock rate of your microprocessor,
  - increase the time between tick interrupts,
  - rearrange task priorities,
  - avoid using floating-point math (if you must, use single precision),
  - get a compiler that performs better code optimization,
  - write a time-critical code in assembly language,
  - if possible upgrade to a faster processor in the same family.

ENGG4420 -- CHAPTER 2 -- LECTURE 6
EVENT CONTROL BLOCK (ECB) FOR uC/OS

- A task or an ISR signals a task through a kernel object called an event control block (ECB) – the signal is considered to be event.
- An ECB can be a semaphore, a message mailbox, or a message queue, as discussed later.

Use of event control blocks.



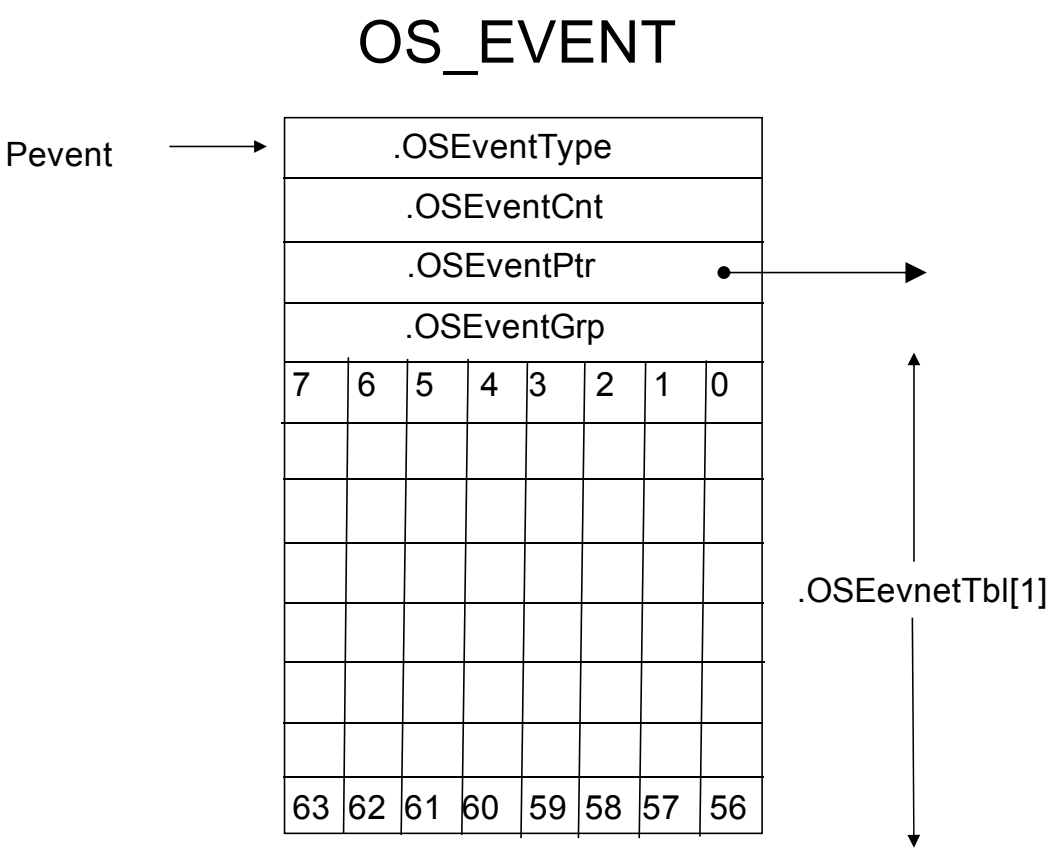
- (1) an ISR or a task can signal an ECB.
- (2) only a task can wait for another task or an ISR to signal the ECB. An ISR is not allowed to wait on an ECB.
- (3) an optional timeout can be specified by the waiting task in case the object is not signalled within a specified time period.
- (B) multiple tasks can wait for a task or an ISR to signal an ECB. When the ECB is signalled, only the highest priority task waiting on the ECB is signalled and made ready to run.
- (4) when an ECB is used as a semaphore, tasks can both wait on and signal the ECB.

- ECB is used as a building block to implement services, such as semaphore management, mutual exclusion semaphores, message mailbox management, and message queue management.
- uC/OS maintains the state of an ECB in a data structure called OS_EVENT.

```
typedef struct {
  INT8U OSEventType;          /* Event type          */
  INT8U  OSEventGrp;          /* Group for wait list */
  INT16U OSEventCnt;          /* Count (when event is a semaphore)*/
  void  *OSEventPtr;          /* Ptr to message or queue structure */
  INT8U OSEventTbl[OS_EVENT_TBL_SIZE]; /*wait list for event
                                         to occur  */
} OS_EVENT;
```

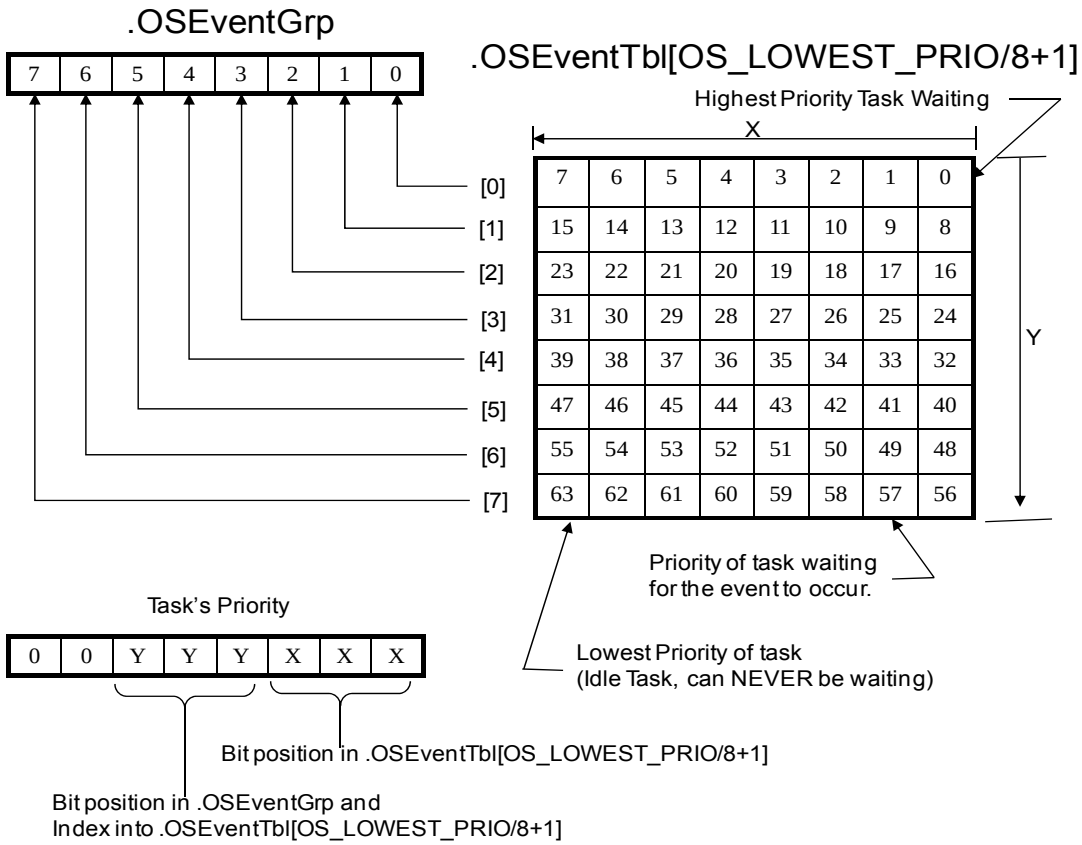
- NOTE: A dot in front of a variable name indicates that the variable is part of a data structure.
- .OSEventType contains the type associated with the ECB and can have the following vaues: OS_EVENT_TYPE_SEM, OS_EVENT_TYPE_MUTEX, OS_EVENT_TYPE_MBOX, or OS-EVENT_TYPE_Q. This field is used to make sure that you are accessing the proper object when you perform operations on these objects through the uC/OS service calls.

Event Control Block (ECB)



- .OSEventPtr: is only used when ECB is assigned to a message mailbox or a message queue. It points to a message when used for a mailbox or to a data structure when used for a queue.
- .OSEventTbl[] and .OSEventGrp: are similar to OSRdyTbl[] and OSRdyGrp, respectively, except that they contain a list of tasks waiting on the event instead of a list of tasks ready to run.
- .OSEventCnt: is used to hold the semaphore count when the ECB is used for a semaphore or the mutex and PIP when the ECB is used for a mutex.

Figure: Wait list for task waiting for an event to occur.



- Each task that needs to wait for the event to occur is placed in the wait list, which consists of the two variables: .OSEventGrp and .OSEventTbl[].
- Task priorities are grouped (eight tasks per group). Each bit in ...Grp is used to indicate when any task in a group is waiting for the event to occur. When a task is waiting, its corresponding bit is set in the wait table, ...Tbl[].
- The size (in bytes) of ...Tbl[] depends on OS_LOWEST_PRIO (which indicates the lowest task priority that your tasks can take – the maximum number of tasks in the system). As a result, OS_LOWEST_PRIO/8 +1 represent the size of OSEventTbl[].
- The task that is resumed when the event occurs is the highest priority task waiting for the event and corresponds to the lowest priority number that has a bit set in ..Tbl[].

OPERATIONS ON ECBs

- Four common operations can be performed on ECBs
  - Initialize an ECB: OS_EventWaitListInit(),
    - This is a function called when a semaphore, mutex, message queue, or message mailbox is created.
    - All that is accomplished by this function is to indicate that no task is waiting on the ECB.
  - Make a task ready: OS_EventTaskRdy(),
    - This function is called by the POST functions for a semaphore, a mutex, a message mailbox, or a message queue when an ECB is signaled and the highest priority task waiting on the ECB needs to be made ready to run.
    - In other words, OS_EventTaskRdy() removes the highest priority task (HPT) form the waiting list of the ECB and makes this task ready to run.
  - Make a task wait for an event: OS_EventWait(),
    - This function is called by the PEND functions of a semaphore, mutex, message mailbox, and message queue when a task must wait on an ECB. As a result, OS_EventTaskWait() **removes the current task from the ready list** and places it in the wait list of the ECB.
  - Make a task ready because a timeout occurred while waiting for an event: OS_EventTO().
    - This function is called by PEND functions for a semaphore, mutex, message queue, and message mailbox when OSTimeTick() has readied a task to run, which means that the ECB was not signaled within the specified timeout period.

MEMORY REQUIREMENTS FOR REAL-TIME SYSTEMS

- The size of a kernel is from 1K to 100K bytes.
  - A minimal kernel for an 8-bit CPU that provides only scheduling, context switching, semaphore management, delays, and timeouts is 1K to 3K bytes.
- Total code space = application space + kernel space.
- Total RAM if the kernel does not support a separate interrupt stack is:
  - application code requirements + data space needed by the kernel itself + SUM (task staks + MAX(ISR nesting)).
- If the kernel supports a separate stack for interrupts is:
  - application + data space needed by the kernel + SUM(task stacks) + MAX(ISR nesting).

SYNCHRONIZATION, COMMUNICATION, AND CONCURRENCY

TOPICS COVERED IN THIS SECTION ARE:

1. Synchronization and communication
2. Objects used for synchronization, communication and signaling (semaphores, mutexes, mailboxes, message queues, etc.)
3. Pattern designs for inter-task synchronization and communication
4. Common design problems (deadlocks, priority inversion)

SYNCHRONIZATION

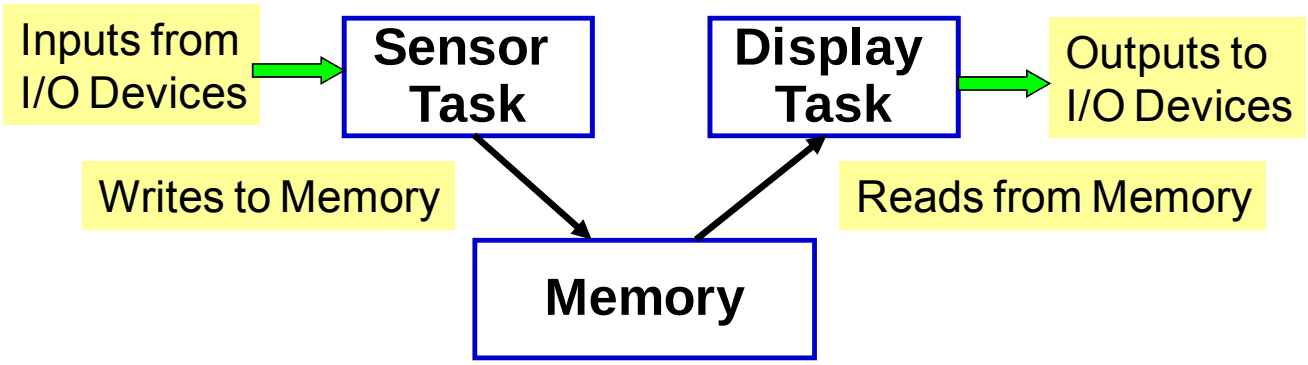
- Real time system applications use multiple concurrent tasks to maximize efficiency -- coordinating these activities requires inter-task synchronization and communication.
- Synchronization is classified in two categories:
  - resource synchronization -- determines whether access to a shared resource is safe, and, if not, when it will be safe.
  - activity synchronization -- determines whether the execution of a multithreaded program has reached a certain state, and, if it hasn't, how to wait for and be notified when this state is reached.

RESOURCE SYNCHRONIZATION

- Access by multiple tasks must be synchronized to maintain the integrity of a shared resource.
  - **Shared Resource**: is a resource that can be used by more than one task. Each task should gain exclusive access to the shared resource to prevent data corruption. This process is called mutual exclusion.
- Resource synchronization is closely associated with critical sections and mutual exclusions.
- Mutual exclusion is a provision by which only one task at a time can access a shared resource.
- A critical section is the section of code from which the shared resource is accessed.
  - **Critical section**: a critical section of code, also called a critical region, is code that needs to be treated indivisibly. After the section of code starts executing, it must not be interrupted. To ensure that execution is not interrupted, interrupts are typically disabled before the critical code is executed and enabled when the critical code is finished.

EXAMPLE OF TWO TASKS TRYING TO ACCESS SHARED MEMORY

- Problem arises if access to the shared memory is not exclusive, and multiple tasks can simultaneously access it -- As an example, consider two tasks trying to access shared memory.



- One task (the sensor task) periodically receives data from a sensor and writes the data to shared memory.
- Meanwhile, a second task (display task) reads the data from the memory and displays it.
- Erroneous data interpretation can take place. ...Q1? ... Q2?
- Q1: How can we get erroneous data in this scenario?

  A: One task (the sensor task) periodically receives data from a sensor and writes the data to the shared memory. If the sensor task has not completely written the data to the shared memory area before the display task tries to display the data, the display would contain a mixture of data extracted at different times, leading to erroneous data interpretation.
- Q2: Identify the critical sections of code in this example.

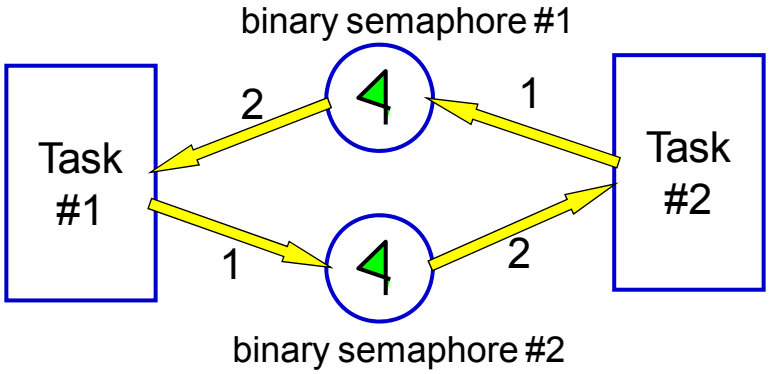
  A: The section of code in the sensor task that writes input data to the shared memory is a critical section of the sensor task. The section of code in the display task that reads data from the shared memory is a critical section of the display task. These two critical sections are called competing critical sections because they access the same shared resource.

ACTIVITY SYNCHRONIZATION

- Activity synchronization, also called condition synchronization or sequence control, ensures that the correct execution order among cooperating tasks is used. ...Q?
  - Q: What types of activity synchronization do you think we can have? A: activity synchronization can be either synchronous or asynchronous.
- Methods of activity synchronization: 1) rendezvous synchronization; 2) barrier synchronization.

RENDEZVOUS SYNCHRONIZATION

- A simple rendezvous method can use kernel primitives such as semaphores or message queues, instead of entry calls.

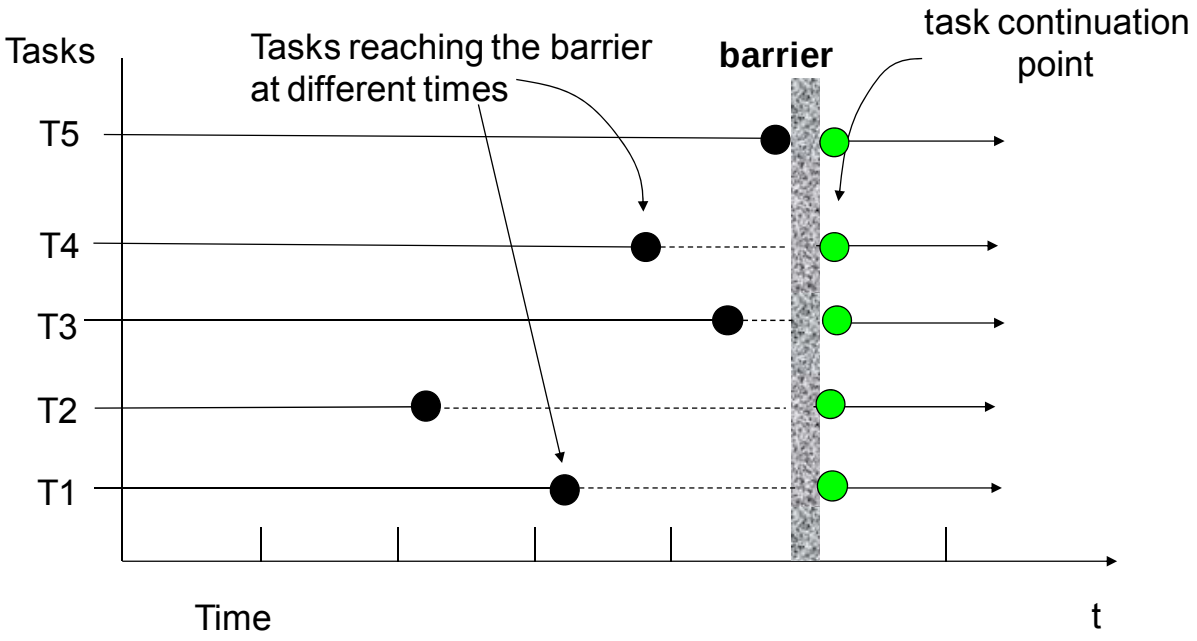


Simple rendezvous without data passing

- Both binary semaphores are initialized to 0.
- When task 1 reaches the rendezvous point, it gives semaphore #2, and then it gets on semaphore #1.
- When task 2 reaches the rendezvous point, it gives semaphore #1, and it gets on semaphore #2.
- Task 1 has to wait on semaphore #1 before task 2 arrives, and vice versa, thus achieving rendezvous synchronization.

BARRIER SYNCHRONIZATION

A barrier is a point where some tasks need to present some results that must be analyzed before the decision on the next execution path can be made.



Barrier synchronization comprises three actions:

1. A task posts its arrival at the barrier,
2. The task waits for other participants to reach the barrier,
3. The task receives notification to proceed beyond the barrier.

- **EXAMPLE** of barrier: In an embedded control system, a complex computation can be divided and distributed among multiple tasks. Some parts of this complex computations are I/O bound, other parts are CPU intensive, and still others are mainly floating point operations that rely heavily on specialized floating-point coprocessor hardware. These partial results must be collected from the various tasks for the final calculation. The result determines what other partial computations each task is to perform next.

Pseudo code for barrier synchronization

```
typedef struct {
   mutex_t   br_lock;  /*guarding mutex */
   cond_t    br_cond; /* condition variable */
   int       br_count;  /* number of tasks at the barrier */
   int       br_n_threads; /*number of task participating in the sync. */
} barrier_t;

barrier (barrier_t *br)  {                                  1
    mutex_lock (&br ->br_lock);                             2
    br-> br_count ++;                                       3
    if (br-> br_count < br->br_n_threads)                   4
        cond_wait(&br->br_cond, &br->br_lock);              5
    else {
        br-> br_count = 0;                                  6
        cond_broadcast (&br->br_cond);                      7
    }
    mutex_unlock(&br->br_lock);                             8
}
```

Associated with the shared resource

- This is a barrier synchronization mechanism implementation that uses a mutex and a condition variable.
- Each participating task invokes the function barrier for barrier synchronization -- which is part of posting its arrival.
- The guarding mutex for br_count and br_n_threads is acquired on line 2 (makes the task wait). The number of waiting tasks on the barrier is updated on line 3. Line 4 checks to see if all of the participants have reached the barrier.
- If more tasks are to arrive, the caller waits at the barrier (the blocking wait on the condition variable at line 5). If the caller is the last task of the group to enter the barrier, this task resets the barrier on line 6 and notifies all other tasks that the barrier synchronization is complete.
- Broadcasting on the condition variable on line 7 completes the barrier synchronization -- notification part.

COMMUNICATION

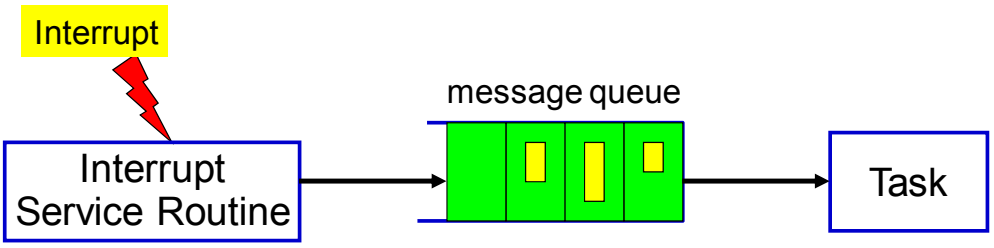
- Tasks in a multitasking environment communicate with one another so they can pass information to each other and coordinate their activity.
- Types of communications are:
  - signal-centric -- all necessary information is conveyed within the event signal itself.
  - data-centric -- the information is carried within the transferred data.
  - or both -- data transfer accompanies event notification.

COMMUNICATION PURPOSES

- Transferring data from one task to another,
- signaling the occurrences of events between tasks,
- allowing one task to control the execution of other tasks,
- synchronizing activities, and
- implementing custom synchronization protocols for resource sharing

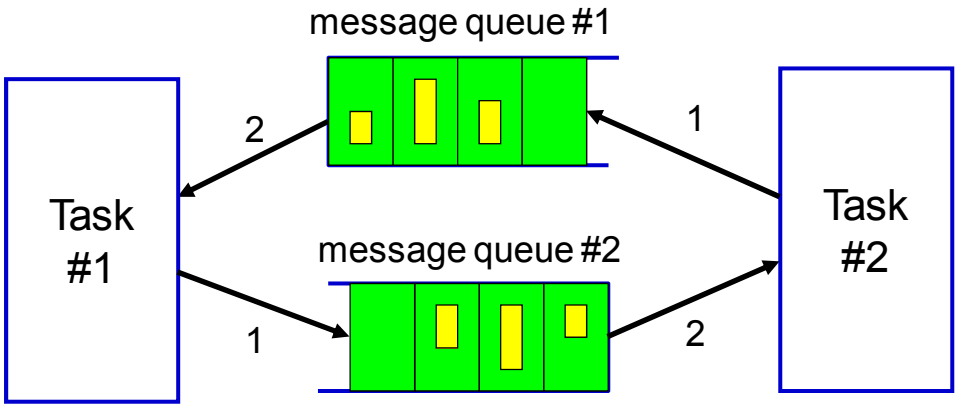
The main kernel objects used for task communications are **message mailboxes and message queues**

Loosely coupled communication – when communication involves unidirectional data flow.



In this ISR-to-task communication using message queue, the ISR (data producer) does not require response from the consumer.

Tightly coupled communication – the data movement is bidirectional.



- The data producer synchronously waits for a response to its data transfer before resuming execution, or the response is returned asynchronously while the data producer continue its function.
- Example: Task 1 sends data to task 2 using message queue #2 and waits for confirmation to arrive at message queue #1.
- The communication is bidirectional. It is necessary to use a message queue for confirmation because the confirmation should contain enough information in case task #1 can continue sending messages while waiting for confirmation to arrive on message queue #2.

RESOURCE SYNCHRONIZATION METHODS IN RTOS

- Resource synchronization or mutual exclusion methods are: 1) interrupt locking (disabling system interrupts), 2) preemptive locking (disabling the kernel scheduler); 3) performing test-and-set operations; 4) using semaphores and event flags (semaphores, event flags and other kernel objects are described in the next section)

DISABLING SYSTEM INTERRUPTS

```
Disable interrupts;
   Access the resource (read/write from/to variable);
Reenable interrupts;
```

NOTE: most of the kernels (including uC/OS) use this method

```
/*using uC/OS macros to disable and enable interrupts */

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

- Interrupt locking (disabling system interrupts) is the method used to synchronize exclusive access to shared resources between tasks and ISRs. This process guarantees that the current task continues to execute until it voluntarily relinquishes control. As such, interrupt locking can also be used to synchronize access to shared resources between tasks. Interrupt locks, although the most powerful and the most effective synchronization method, can introduce indeterminism into the system when used indiscriminately. Therefore, the duration of interrupt locks should be short, and interrupt locks should be used only when necessary to guard a task-level critical region from interrupt activities.

DISABLING AND ENABLING THE SCHEDULER

- Can be used when a task is not sharing variables or data structures with an ISR. NOTE that while the scheduler is locked, interrupts are enabled, but the behavior of the scheduler is very similar with that of a non-preemptive kernel.

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

Disadvantage: introduces the possibility for priority inversion (discussed later)

The scheduler is invoked when OSSchedUnlock() is called to see if a higher priority task has been made ready to run by the task or an ISR

If your task is not sharing variables or data structures with an ISR, you can disable and enable scheduling (lock and unlock the scheduler). In this case, two or more tasks can share data without the possibility of contention. You should note that while the scheduler is locked, interrupts are enabled, and, if an interrupt occurs while in the critical region, the ISR is executed immediately. At the end of ISR, the kernel always returns to the interrupted task, even if the ISR has made a higher priority task ready to run. Because the ISR returns to the interrupted task, the behaviour of the kernel is very similar to that of a non-preemptive kernel (at least, while the scheduler is locked). The scheduler is invoked when OSSchedUnlock() is called to see if a higher priority task has been made ready to run by the task or an ISR. A context switch results if a higher priority task is ready to run. Although this method works well you should avoid disabling the scheduler because it defeats the purpose of having a kernel in the first place. Also, preemptive locking (disabling and enabling the scheduler) introduces the possibility for priority inversion. Even though interrupts are enabled while preemption locking is in effect, actual servicing of the event is usually delayed to a dedicated task outside the context of the ISR. The ISR must notify that task that such an event has occurred. The dedicated task usually executes at a high priority. This higher priority task, however, cannot run while another task is inside a critical region that a preemption lock is guarding. In this case, the result is not much different from using an interrupt lock. The priority inversion, however, is bounded.
The method that uses semaphores should be chosen instead.

USING TEST-AND-SET OPERATIONS

- Global variable combined with a test-and-set (or TAS) operation can be used to access shared resources.

```
Disable interrupts:
if ('Access Variable' is 0) {
        Set variable to 1;
        reenable interrupts;
        access the resource;
        disable interrupts;
        set the 'Access Variable' back to 0;
        reenable interrupts;
} else {
        reenable interrupts;
        /* you don't have access to the resource, try back later */
}
```

- If you are not using a kernel, two functions could agree that to access a resource, they must check a global variable and if the variable is 0, the function has access to the resource. To prevent the other function from accessing the resource the first function that gets the resource sets the variable to 1, which is called a test-and-set (or TAS) operation.
- NOTE: A TAS operation must be performed indivisibly (by the processor) or you must disable the interrupts when doing the TAS on the variable.
- Processors actually implement a TAS operation in hardware (e.g., the 68000 family, ARM cores have TAS instruction).

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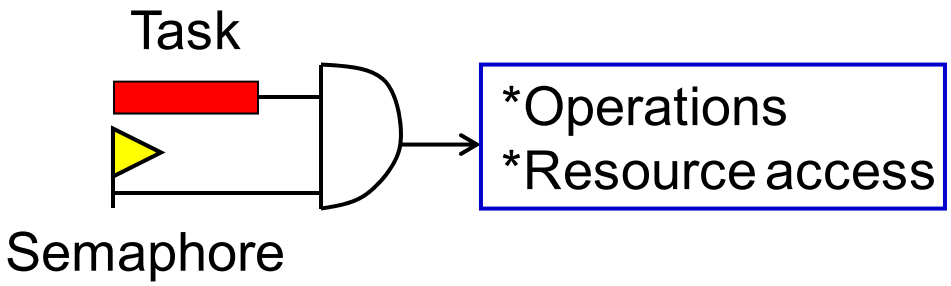
- Synchronization and mutual exclusion objects covered: semaphores, mutex.
- Communication objects covered: mail boxes, message queues.

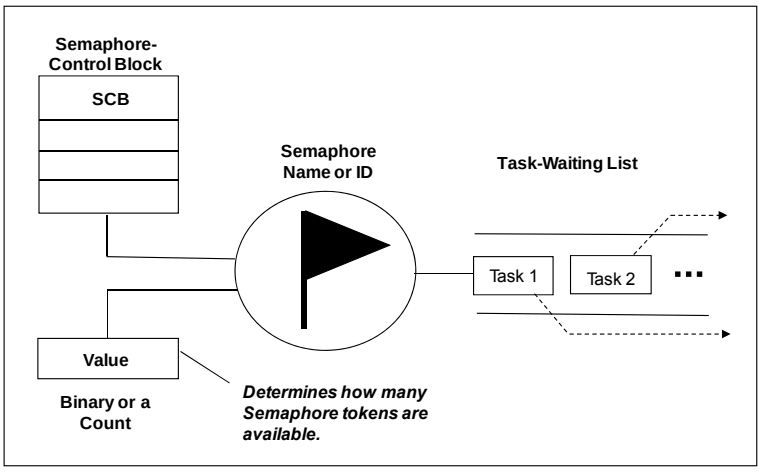
DEFINING A SEMAPHORE

- A semaphore (sometimes called a semaphore token) is a kernel object that one or more tasks can acquire or release for the purpose of synchronization or mutual exclusion
- Types of semaphores:
  - a) binary semaphores, b) counting semaphores, c) mutual exclusion (mutex) semaphores.
- A semaphore is like a key when used for mutual exclusion and like a flag when used for synchronization -- if a task can acquire the semaphore, it can carry out the intended operation or access the resource.



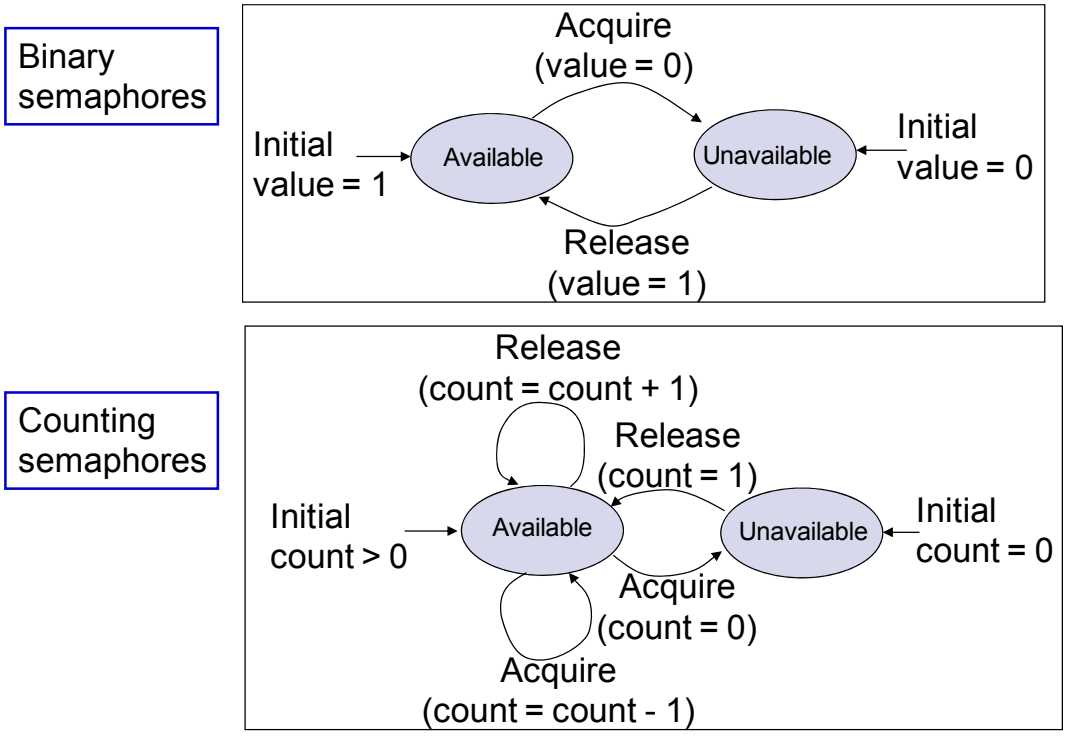
DEFINING SEMAPHORES -- IN COMMON KERNELS

- When a semaphore is first created, the kernel assigns to it an associated semaphore control block (SCB), a unique ID, a value (binary or count), and a task-waiting list.



- A single semaphore can be acquired a finite number of times. The kernel tracks the number of times a semaphore has been acquired or released by maintaining a token count, which is initialized to a value when the semaphore is created.
- As a task acquires the semaphore, the token is decremented; as a task releases the semaphore, the count is incremented.
- If the token count reaches 0, the semaphore has no tokens left. A requesting task, therefore, cannot acquire the semaphore, and the task blocks if it chooses to wait for the semaphore to become available.
- The task waiting list tracks all tasks blocked. These blocked tasks are kept in the task waiting list in either first in/first out (FIFO) order or highest priority first order.
- When an unavailable semaphore becomes available, the kernel allows the first task in the task-waiting list to acquire it. The kernel moves this unblocked task either to the running state, if it is highest priority task, or to the ready state, until it becomes the highest priority task and is able to run.
- Note that the exact implementation of a task-waiting list can vary from one kernel to another.

BINARY AND COUNTING SEMAPHORES



- A binary semaphore has a value of either 0 or 1. Note that when the binary semaphore is created it can be initialized to either available or unavailable (1 or 0) state.
- Binary semaphores are treated as global resources, which means that they are shared among all tasks that need them. Making the semaphore a global resource allows any task to release it, even if the task didn't initially acquire it – this sometimes becomes a problem.
- A counting semaphore uses a count to allow it to be acquired or released multiple times.

MUTUAL EXCLUSION SEMAPHORE (MUTEX)

- Special binary semaphore that supports ownership, recursive access, task deletion safety, and one or more protocols for avoiding problems inherent to mutual exclusion.
- Mutex ownership -- when task owns the mutex and as a result, no other task can lock or unlock that mutex.
  - Ownership of a mutex is gained when a task first locks the mutex by acquiring it. Conversely, a task loses ownership of the mutex when it unlocks it by releasing it (In contrast binary semaphores can be released by any task).
- Recursive locking -- task that owns a mutex can acquire the mutex multiple times in the lock state.
  - recursive mutex is useful when a task requiring exclusive access to a shared resource calls one or more routines that also require access to the same resource – avoids deadlock creation.
- Task deletion safety -- premature task deletion is avoided by using the built in *task deletion locks.*
  - Task deletion feature ensures that while a task owns the mutex, the task cannot be deleted.
- Priority inversion avoidance -- protocols such as: PIP (priority inversion protocol) and CPP(ceiling priority protocol) are build into mutexes to help avoid priority inversion:
  - PIP ensures that the priority level of the lower priority task that has acquired the mutex is raised to that of the highest priority task that has requested the mutex when inversion happens.
  - CPP ensures that priority level of the task that acquires the mutex is automatically set to the highest priority of all possible tasks that might request the mutex when it is first acquired until is released.

OPERATIONS PERFORMED ON A SEMAPHORE

- The operations performed on a semaphore are:
  - INITIALIZE (also called CREATE)
  - WAIT (also called PEND)
  - SIGNAL (also called POST)
- The initial value of the semaphore must be provided when the semaphore is initialized.
- The waiting list of tasks is always initially empty.

ACQUIRING A SEMAPHORE

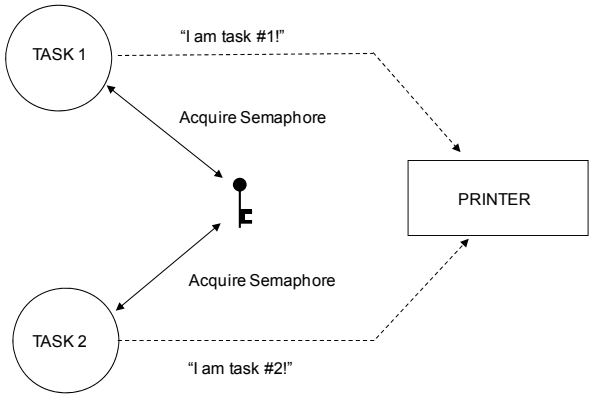
- A task desiring a semaphore performs a WAIT operation.
  - if the semaphore is available (the semaphore value is greater than 0) the semaphore value is decremented and the task continue execution.
  - if semaphore's value is 0, the task performing WAIT is placed in a waiting list.
- most kernels allow to specify a timeout for the wait

RELEASING A SEMAPHORE

- A task releases a semaphore by performing a SIGNAL (POST) operation
  - If no task is waiting for the semaphore, the semaphore value is simply incremented
  - If any task is waiting, one of the tasks is made ready to run and the semaphore value is not incremented - depending on the kernel.
- the task that receives the semaphore is the highest priority task waiting or, the first task that requested the semaphore -- uC/OS supports the first method

Q: What is the semaphore used for here?

Using a Semaphore




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

- Semaphores are useful when task share I/O devices. Note: a timeout value of 0 indicates that the task is willing to wait forever.
- Example: Two tasks need to access the same printer. Solution: The resource (device) has a semaphore associated to it. Initialize the semaphore to 1.
- Rules to access the printer: each task must first obtain the semaphore.

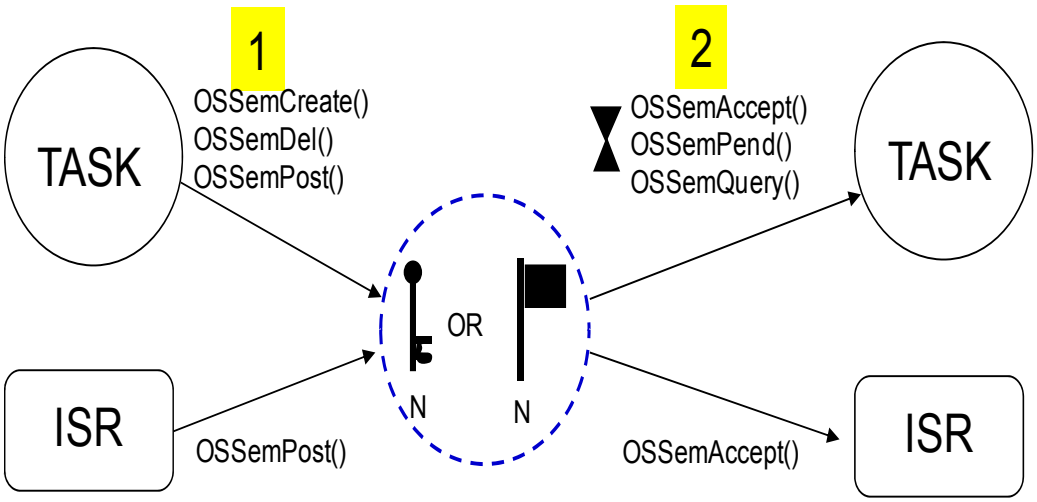
EXAMPLE OF SEMAPHORE MANAGEMENT AND OPERATIONS FOR uC/OS

- uC/OS semaphores consist of two elements:
  - a 16-bit unsigned integer used to hold the semaphore count (0 to 65,535),
  - a list of tasks waiting for the semaphore count to be greater than 0.
- uC/OS provides 6 services to access semaphores: OSSemAccept(), OSSemCreate(), OSSemDel(), OSSemPend(), OSSemPost() and OSSemQuery().
- FUNCTION CALLS

```
OS_EVENT *OSSemCreate (INT16U cnt)
OS_EVENT *OSSemDel (OS_EVENT *pevent,
                    INT8U opt, INT8U *err)
void OSSemPend (OS_EVENT *pevent, INT16U timeout,
                INT8U *err)
INT8U  OSSemPost (OS_EVENT *pevent)
INT16U OSSemAccept (OS_EVENT *pevent)
INT8U OSSemQuery (OS_EVENT *pevent,
                  OS_SEM_DATA *pdata)
```

- The above services are enabled when OS_SEM-EN is set to 1 -- Note that the underlined services can be individually disabled.
  - OSSemCreate(), OSSemPend(), and OSSemPost() cannot be individually disabled as can the other services. That's because they are always needed when you enable uC/OS semaphore management.
  - To enable the other services individually you must set the corresponding constant to 1, specifically: OS_SEM_ACCEPT_EN, OS_SEM_DEL_EN, OS_SEM_QUERRY_EN.

Figure: Relationships between tasks, ISRs, and a semaphore



- The key symbol indicates that the semaphore protects a shared resource and the N next to the key represents how many resources are available.
- A flag symbol indicates that a semaphore is used to signal the occurrence of an event. ...Q?
  - Q: What represents N under the flag? A: N in this case represents the number of times the event can be signalled. N is 1 for a binary semaphore.
- The hourglass represents a timeout that can be specified by OSSemPend() call.
- On the diagram marked by 1 we have functions targeting the object semaphore,
- And marked by 2 we have functions accessing the object semaphore.

MUTEX IN uC/OS

- In general, a mutex is used by an application to avoid the priority inversion problem
  - a priority inversion occurs when a low priority task owns a resource needed by a high priority task,
  - In order to avoid the priority inversion, the kernel can increase the priority of the lower priority task to the priority of the higher priority task until the lower priority tasks is done with the resource.
- A real-time kernel supporting mutex objects needs to provide the ability to support multiple tasks at the same priority. Unfortunately, uC/OS doesn't allow multiple tasks at the same priority.
- Q: How does uC/OS implement mutexes? The example below shows a solution of using mutexes for uC/OS. In this example, we have 3 tasks with access a common resource.

```
OS_EVENT *ResourceMutex;
OS_STK  TaskPrio10Stk[1000];
OS_STK  TaskPrio15Stk[1000];
OS_STK  TaskPrio20Stk[1000];

void main (void)  {
  INT8U err;

  OSInit();                                                          1
/* Application initialization */
  OSMutexCreate(9, &err);                                            2
  OSTaskCreate(TaskPrio10, (void *)0, &TaskPrio10Stk[999], 10);      3
  OSTaskCreate(TaskPrio15, (void *)0, &TaskPrio10Stk[999], 15);
  OSTaskCreate(TaskPrio20, (void *)0, &TaskPrio10Stk[999], 20);
/* Application initialization */
  OSStart();                                                         4
}
```

Mutex is OS_EVENT type object

NOTE: the other tasks have the same structure as TaskPrio10

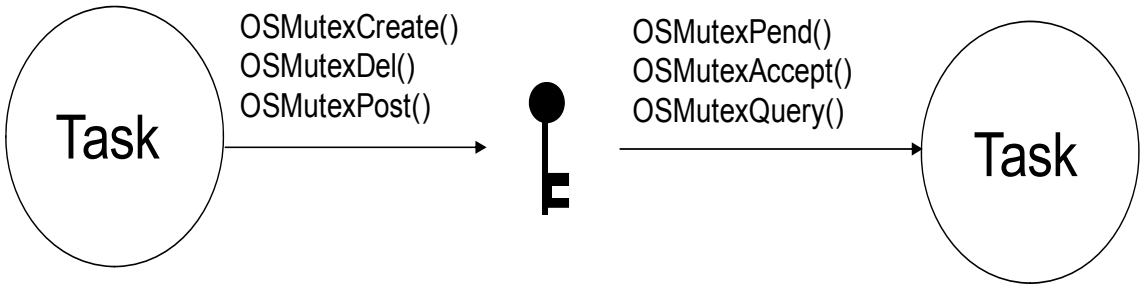
```
void TaskPrio10 (void *pdata)  {
   INT8U  err;

   pdata = pdata;
   while (1) {
      /* Application code */
      OSMuxPend(ResourceMutex, 0, &err);
      /* access common resource */
      OSMutexPost(ResourceMutex);
      /* application code */
   }
}
```

- To access the resource each task must pend on the mutex ResourceMutex.
- An unused priority just above the highest task priority (i.e., priority 9) is reserved as the priority inheritance priority (PIP).
- (2) As shown in main(), uC/OS is initialized and a mutex is created by calling OSMutexCreate(); note that OSMutexCreate() is passed the PIP = 9.
- (4) the 3 tasks are then created, and the uC/OS is started.
- Suppose that this application has been running for a while and at some point, task #3 accesses the common resource first and thus acquires the mutex; Task #3 runs for a while and then gets preempted by task #1.
- Task #1 needs the resource and thus attempts to acquire the mutex (by calling OSMutexPend()):
  - In this case, OSMutexPend() notices that a higher priority task needs the resource and thus raises the priority of task #3 to 9, which forces a context switch back to task #3,
  - When done with the resource, task #3 calls OSMutexPost() to release the mutex. OSMutexPost() notices that the mutex was owned by a lower priority task that got its priority raised and thus, returns task #3 to its original priority. OSMutexPost() notices that a higher priority task (i.e., task #1) needs access to the resource, gives the resource to task #1, and performs a context switch to task #1.

SERVICES SUPPORTED BY MUTEX OBJECTS IN uC/OS

A mutex consists of 3 elements: a flag, a priority, a task list

Figure: Relationship between tasks and a mutex

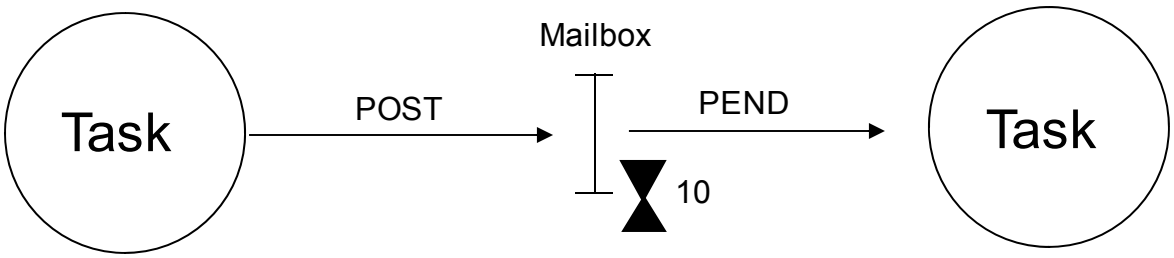



```
OS_EVENT *OSMutexCreate (INT8U prio, INT8U *err)
OS_EVENT *OSMutexDel (OS_EVENT *pevent, INT8U opt, INT8U *err)
void OSMutexPend (OS_EVENT *pevent, INT16U timeout, INT8U *err)
INT8U OSMutexPost (OS_EVENT *pevent)
INT8U OSMutexAccept (OS_EVENT *pevent, INT8U *err)
INT8U OSMutexQuerry (OS_EVENT *pevent, OS_MUTEX_DATA *pdata)
```

- uC/OS mutexes consist of 3 elements: a flag indicating whether the mutex is available (0 or 1), a priority to assign to the task that owns the mutex in case a higher priority task attempts to gain access to the mutex, and a list of tasks waiting for the mutex.
- uC/OS provides 6 services to access the mutexes. These services follow the same principles as the semaphore services.
- The initial value of a mutex is always ‘1’ indicating that the resource is available.

COMMUNICATION OBJECTS -- MASSAGE MAILBOXES

- Messages can be sent to a task through kernel services. A message mailbox, also called a message exchange, is typically a pointer-size variable.
- Through a service provided by the kernel, a task or an ISR can deposit a message (the pointer) into this mailbox.
- Similarly, one or more tasks can receive messages through a service provided by the kernel. Both the sender and receiving task agree on what the pointer is actually pointing to.
- A waiting list is associated with each mailbox in case more than one task wants to receive messages through the mailbox.
- A task desiring a message from an empty mailbox is suspended and placed on the waiting list until a message is received.
- Typically, the kernel allows the task waiting for a message to specify a timeout. If a message is not received before the timeout expires, the requesting task is made ready to run, and an error code (indicating that a timeout has occurred) is returned to it.
- When a message is deposited into the mailbox, either the highest priority task waiting for the message is given the message (priority-based), or the first task to request a message is given the message (FIFO).
- uC/OS support the highest priority mechanism.

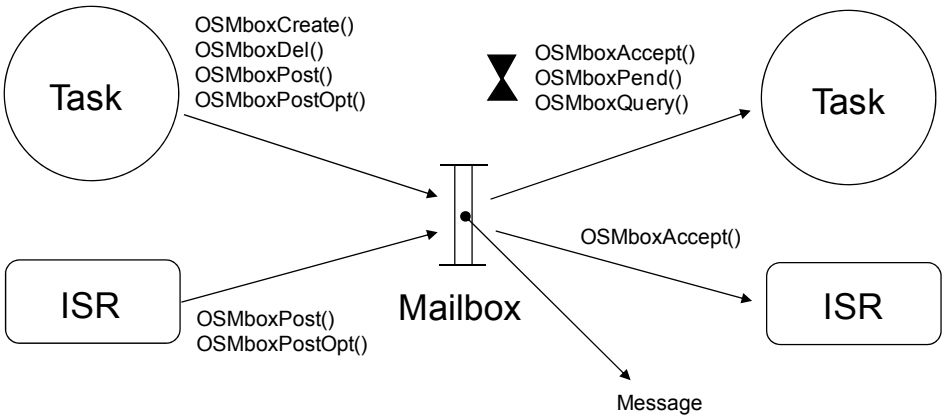


OPERATIONS ON THE MAILBOXES

- Kernels typically provide the following mailbox services
  - initialize the content of a mailbox.
  - deposit a message into the mailbox (POST).
  - wait for a message to be deposited into the mailbox (PEND).
  - get a message from a mailbox, if one is present, but do not suspend the caller if the mailbox is empty (ACCEPT).

uC/OS MAILBOX MANAGEMENT AND SERVICES

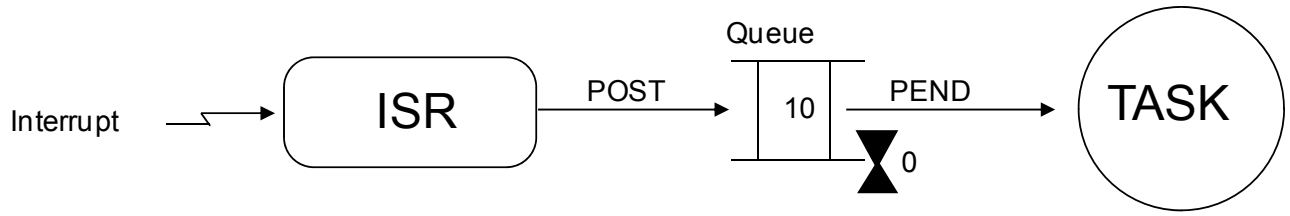
Figure: *Relationship between tasks, ISRs, and a message mailbox.*




```
OS_EVENT *OSMboxCreate (void *msg)
OS_EVENT *OSMboxDel (OS_EVENT *pevent,
                     INT8U opt, INT8U *err)
void *OSMboxPend (OS_EVENT *pevent,
                  INT16U timeout, INT8U *err)
INT8U OSMboxPost (OS_EVENT *pevent, void *msg)
INT8U OSMboxPostOpt (OS_EVENT *pevent, void *msg,
                     INT8U opt)
void *OSMboxAccept (OS_EVENT *pevent)
INT8U OSMboxQuery (OS_EVENT *pevent,
                   OS_MBOX_DATA *pdata)
```

MESSAGE QUEUES

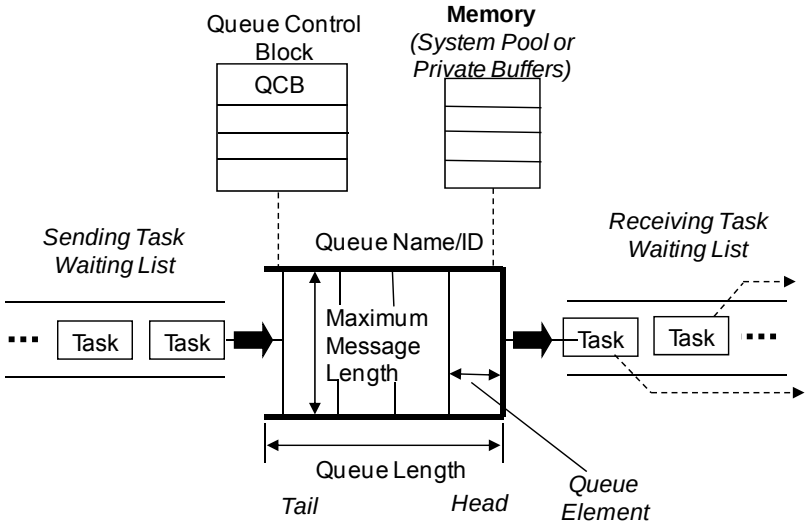
- A message queue is used to send one or more messages to a task – is an array of mailboxes.
- The messages are extracted in FIFO fashion or LIFO fashion.
- A waiting list is associated with the queue -- highest priority task waiting or FIFO will get the message.



- Kernels typically provide these message queue services:
  - initialize the queue (queue empty after initialization).
  - deposit a message into the queue (POST).
  - wait for a message to be deposited into the queue (PEND).
  - get a message from a queue, if one is present, but do not suspend the caller if the mailbox is empty (ACCEPT).

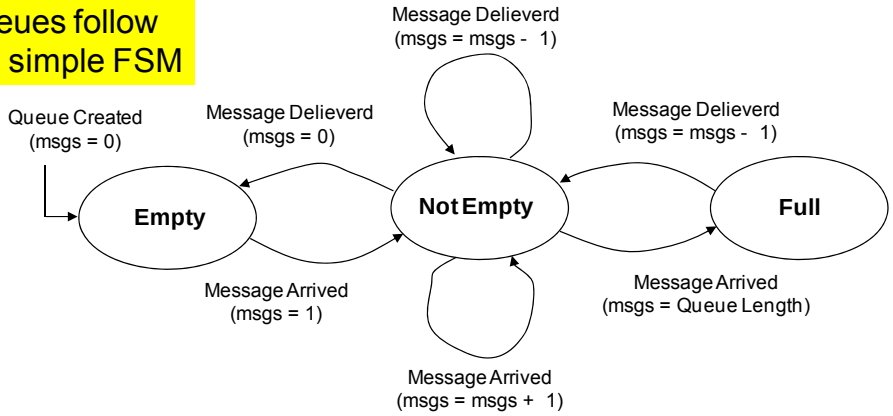
Defining Message Queues

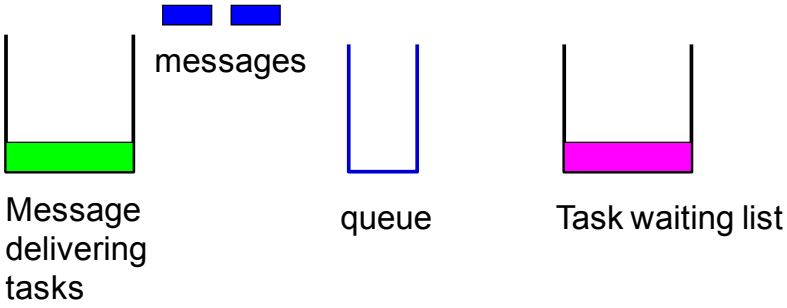
Message queue created: an associated queue control block (QCB), a message queue name, a unique ID, memory buffers, a queue length, a maximum message length, and one or more task-waiting lists



- A message queue in any kernel is a buffer-like object through which a task and ISRs send and receive messages to communicate and synchronize with data.
- A message queue temporarily holds messages from sender until the intended receiver is ready to read them -- this temporary buffering decouples a sending and receiving task; that it frees the tasks from having to send and receive messages simultaneously.
- The message queue itself consists of a number of elements, each of which can hold a single message.

Message queues follow the logic of a simple FSM





uC/OS MESSAGE QUEUE MANAGEMENT

Figure: *Relationship between tasks, ISRs, and a message queue.*

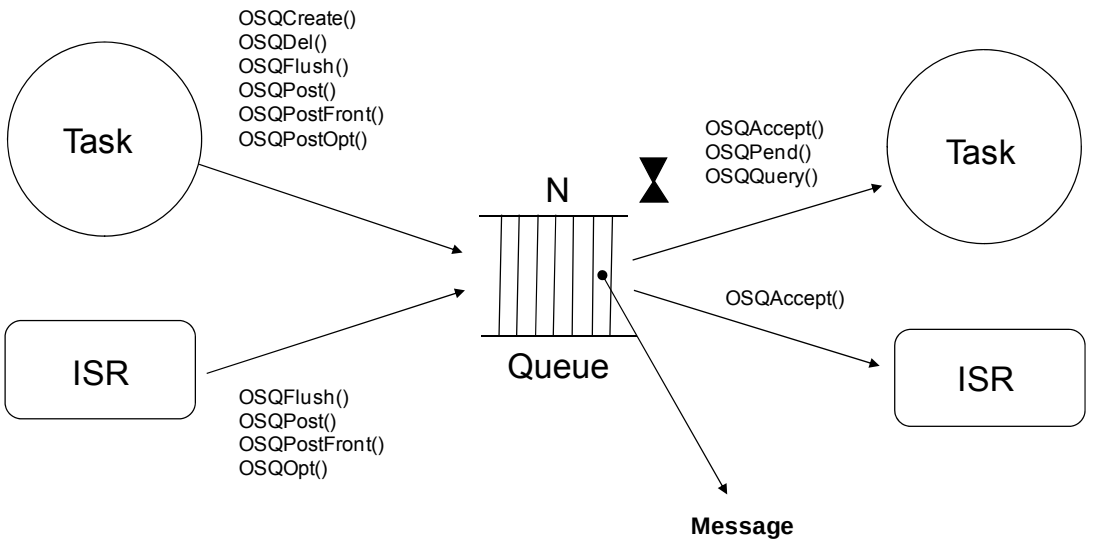
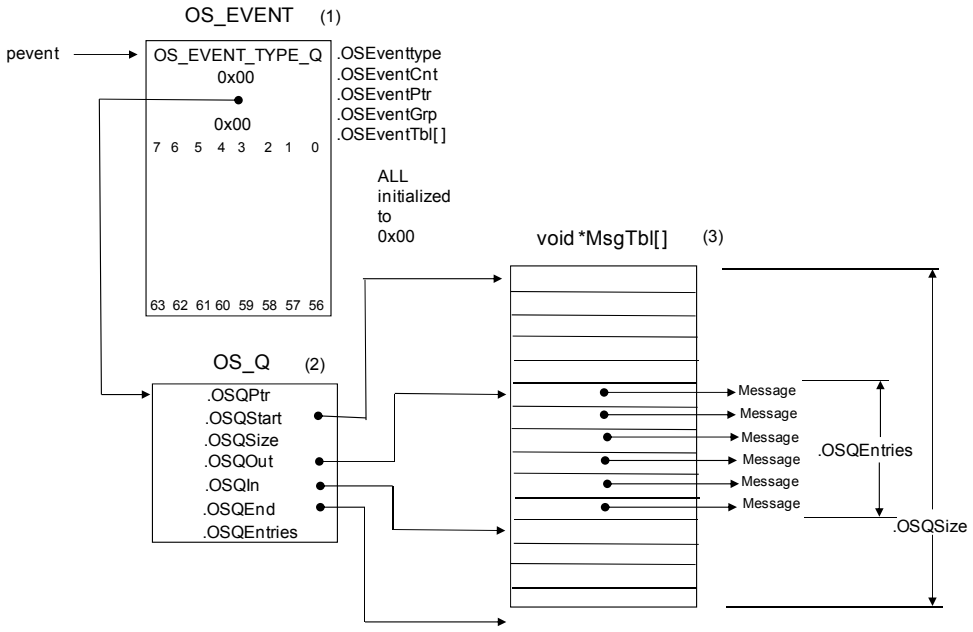


Figure: *Data structures used in a message queue*



- (1) An ECB (event control block) is required since you need a waiting list.
- (2) A queue control block (i.e., an OS_Q see OS_Q.C) is allocated and linked to the ECB using .OSEventPtr field.
- (3) Before you create a queue you need to allocate an array of pointers that contains the desired number of queue entries. The number of elements in the array = number of entries in the queue.
- The starting address of the array is passed to OSQCreate(), as well as the size (in number of elements) of the array.
- OS_MAX_OS in OS_CFG.H must be > 0 so it will allow to create a list of free queue control blocks.

Figure: List of free queue control blocks.

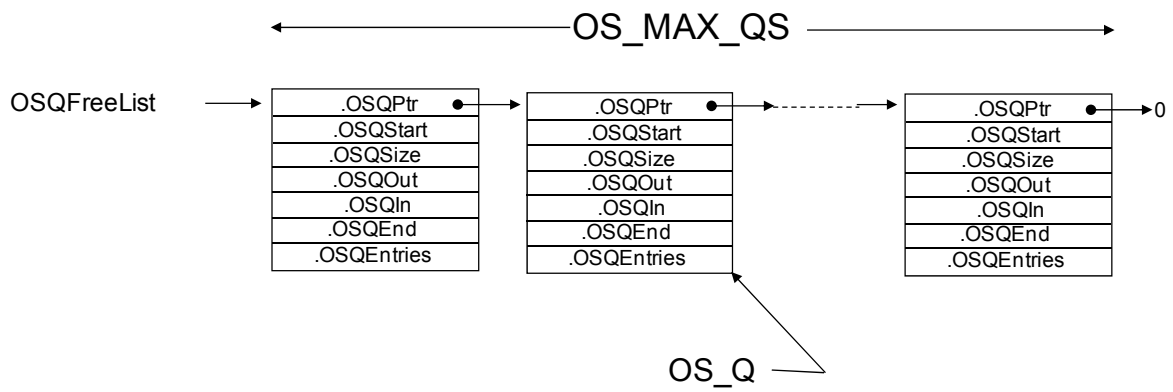
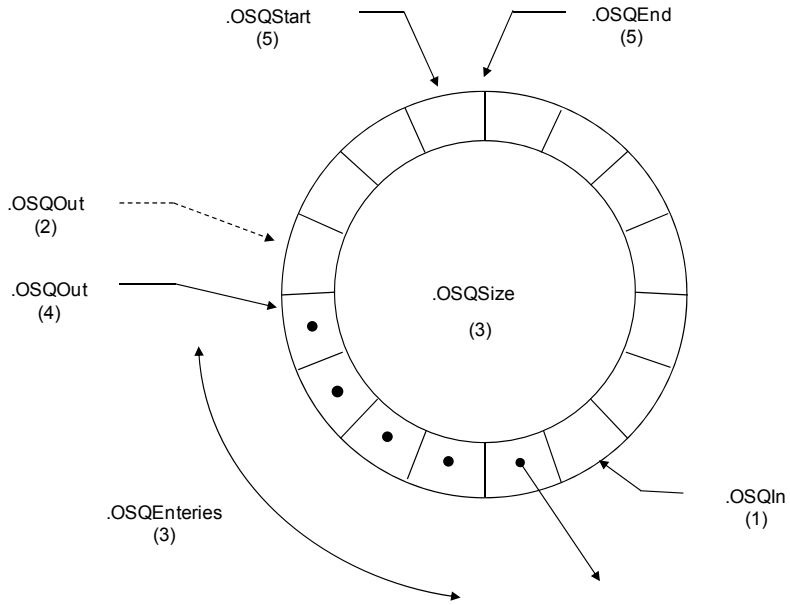


Figure: A message queue as a circular buffer of pointers

- (3) Each entry contains a pointer. The pointer to the next message is deposited at the entry to which . OSQIn points unless the queue is full (i.e., .OSQEntries == .OSQSize).



- Depositing the pointer at .OSQIn implements FIFO queue which is what OSQPost() does.
- (2) ucOS-II implements a LIFO queue by pointing to the entry preceding .OSQOut and depositing the pointer at that location (See OSQPostFront() and OSQPostOpt().
- (4) The pointer is also considered full when .OSQEntries == .OSQSize. Message pointers are always extracted from the entry to which .OSQOut points.
- (5) The pointers .OSQStart and .OSQEnd are simply markers used to establish the beginning and the end of the array so that .OSQIn and .OSQOut can wrap around to implement this circular motion.

ENGG4420 -- CHAPTER 2 -- LECTURE 8

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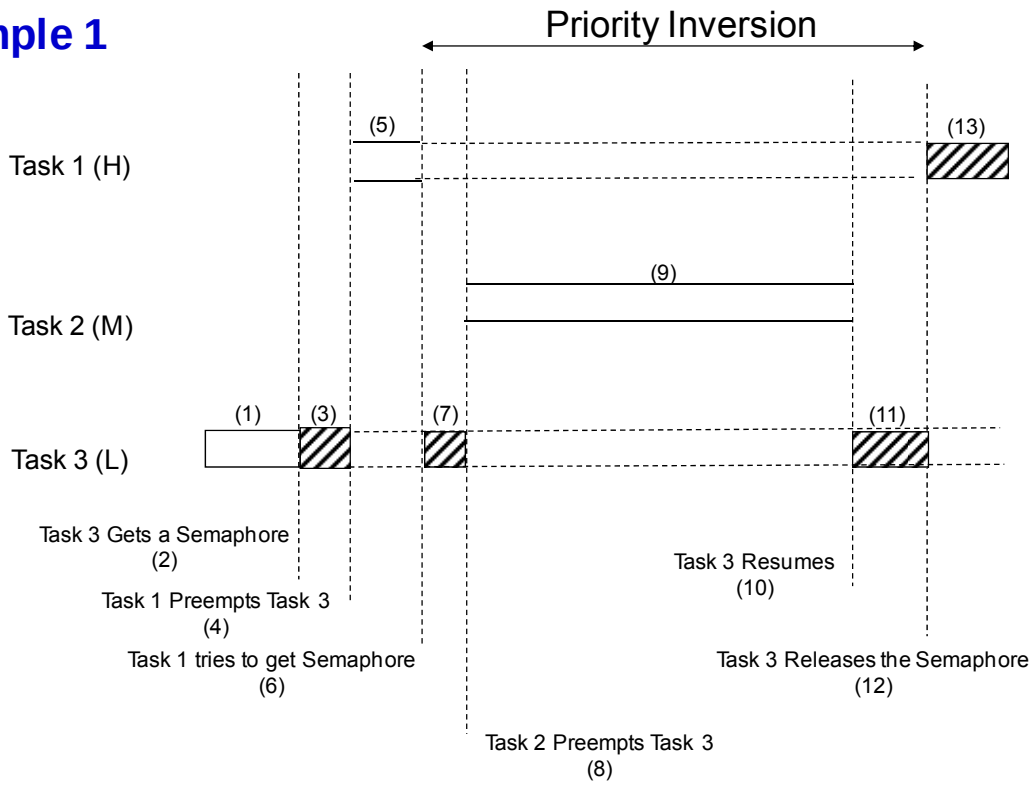
PRIORITY INVERSION PROBLEM IN RTOS

- A priority is assigned to each task -- the more important the task, the higher the priority given to it.
- The application designer is responsible for deciding what priority each task gets.
- STATIC PRIORITIES -- task priorities are static when the priority of each task does not change during the application's execution -- all the tasks and their timing constraints are known at compile time and each task gets a fixed priority at compile time.
- DYNAMIC PRIORITIES -- Task priorities are dynamic if the priority of tasks can be changed during the application's execution -- each task can change its priority at run time. This feature is desirable to have in real-time kernels to avoid priority inversions.

PRIORITY INVERSION PROBLEM --

- Priority inversion is a situation in which a low-priority task executes while a higher priority task waits on it due to resource contentions.
  - Priority inversion is a problem in real-time system and occurs mostly when you use a real-time kernel.
  - May be caused by semaphore usage, device conflicts, bad design of interrupt handlers, poor programming and system design.

Example 1

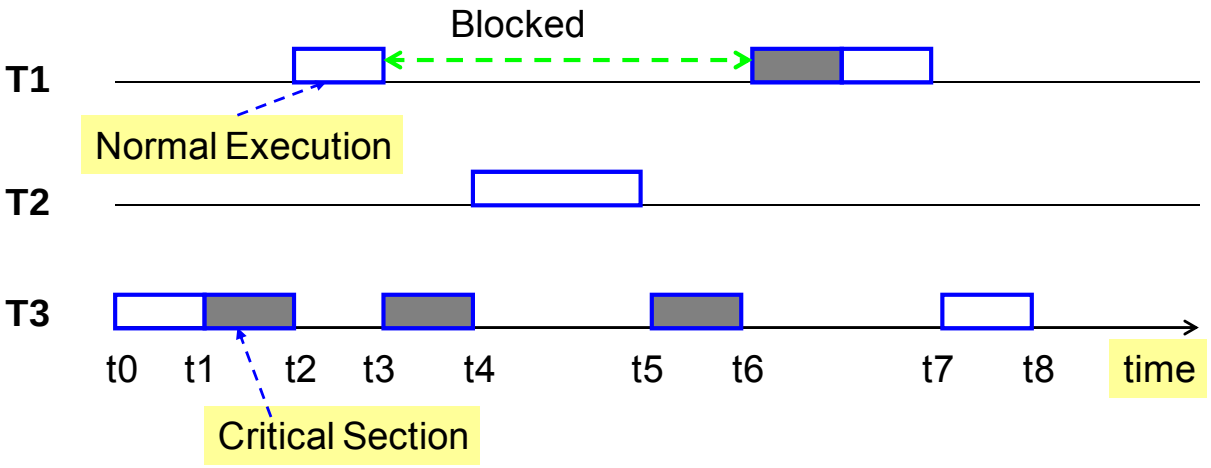


Task 1 has a higher priority than Task 2, which in turn has a higher priority than Task 3.

- (1) Task 1 and Task 2 are both waiting for an event to occur and Task 3 is executing. (2) At some point, Task 3 acquires a semaphore, which the task needs before it can access a shared resource. (3) Task 3 performs some operations on the acquired resource. (4) The event for which Task 1 was waiting occurs, and thus the kernel suspends Task 3 and starts executing Task 1 because Task 1 has a higher priority. (5) Task 1 executes for a while until it also wants to access the resource at (6) (i.e. it attempts to get the semaphore that Task 3 owns). Because Task 3 owns the resource, Task 1 is placed in a list of tasks waiting for the kernel to free the semaphore. (7) Task 3 resumes and continues execution until it is preempted by Task 2 at (8) because the event for which Task 2 was waiting occurred. (9) Task 2 handles the event for which it was waiting, and when it's done, the kernel relinquishes the CPU back to Task 3 at (10). During (11) Task 3 finishes working with the resource and releases the semaphore at (12). At this point, the kernel knows that a higher priority task is waiting for the semaphore and performs a context switch to resume Task 1. During (13) Task 1 has the semaphore and can access the shared resource.
- **In this scenario the priority of Task 1 has been virtually reduced to that of Task 3.**

PRIORITY INVERSION EXAMPLE 2

- Three tasks T1, T2 and T3 have decreasing priorities (T1 has the highest priority) and T1 and T3 share some data or resource that require exclusive access, while T2 does not interact with either of the other tasks. Access to the critical section is done through the P (WAIT, PEND) and V (SIGNAL, POST) operations on semaphore S.



- Consider the following execution scenario -- the tasks are preemptable and the release times (the time when the tasks start executing) of the 3 tasks are:
  - T1: t2; T2: t4; and T3: t0
- A priority inversion is said to occur between time interval [t3, t6] during which the highest priority task T1 has been unduly prevented from execution by a medium-priority task.
- Note that the blocking of T1 during the periods [t3, t4] and [t5, t6] by T3 which has the lock, is preferable to maintain the integrity of the shared resource while blocking due to T2 is not preferred since it can result in an unbounded or excessive blocking.

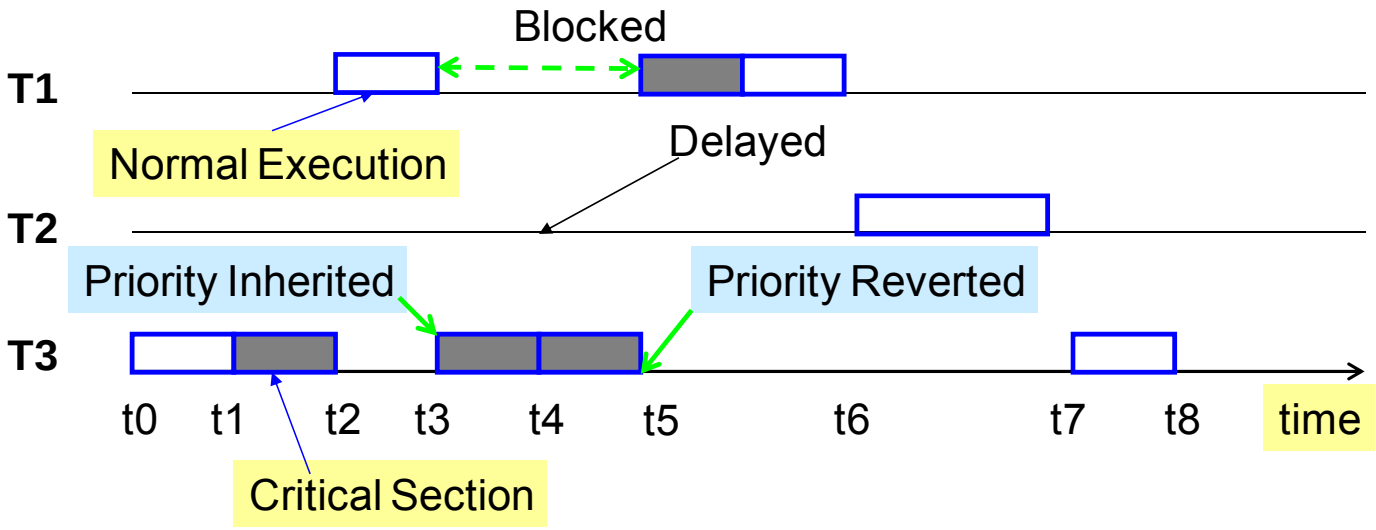
PRIORITY INHERITANCE PROTOCOL (PIP)

- The problem of priority inversion in real-time systems has been studied intensively for both fixed-priority and dynamic-priority scheduling.
- **One result is**: the **priority inheritance protocol** that offers a simple solution to the problem of ***unbounded priority inversion.***
- In the PIP the priority of tasks are dynamically changed so that the priority of any task in a critical region gets the priority of the highest task pending on that same critical region. In particular when a task T blocks one or more higher-priority tasks, it temporarily inherits the highest priority of the blocked tasks.

HIGHLIGHTS OF THE PIP

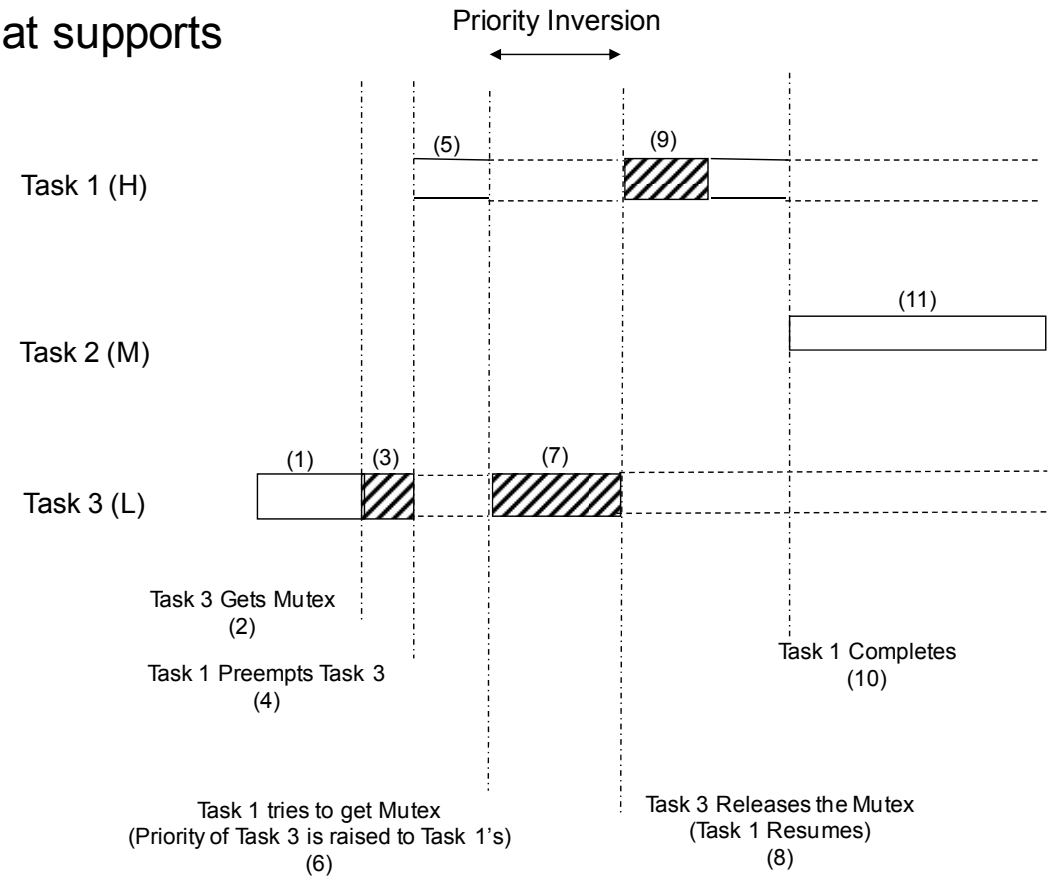
- The highest-priority task T gives up the processor whenever it seeks to lock the semaphore guarding a critical section that is already locked by some other task.
- If a task T1 is blocked by T2 and , T1 > T2 (i.e., T1 has precedence over task T2), task T2 inherits the priority of T1 as long as it blocks T1.
  - When T2 exits the critical section that caused the block, it reverts to the priority it had when it entered that section.
- Priority inheritance is transitive.
  - If T3 blocks T2, which blocks T1, (with T1 > T2 > T3) then T3 inherits the priority of T1 via T2.

PIP APPLIED TO EXAMPLE 2



- Thus, in Example 2, T3 priority would be temporarily raised to that of T1 at time t3 => the preemption of T3 at t4 by T2 is prevented
- At time t5, T3 reverts to its original priority and T2 gets to execute only after T1 completes its computations

Kernel that supports PIP



uC/OS-II solve the priority inversion problem by providing the mutex objects that implement the PIP protocol.
(1) Task 3 executes. (2) As with Example 1, Task 3 is running but, this time, acquires a mutual exclusion semaphore (mutex) to access a shared resource. (3) - (4) Task 3 accesses the resource and then is preempted by Task 1. (5) – (6) Task 1 executes and tries to obtain the mutex. The kernel sees that Task 3 has the mutex and knows that Task 3 has a lower priority than Task 1. In this case, the kernel raises the priority of Task 3 to the same level as Task 1 (mutex priority which is greater than T1 priority). (7) The kernel places Task 1 in mutex wait list and then resumes execution of Task 3 so that this task can continue with the resource. (8) When Task 3 is done with the resource, it releases the mutex. At this point, the kernel reduces the priority of Task 3 to its original value and looks in the mutex waiting list to see if a task is waiting for th mutex. The kernel sees that Task 1 is waiting and gives it the mutex. (9) Task 1 is now free to access the resource. (10) – (11) When Task 1 is done executing, the medium priority task (i.e. Task 2) gets the CPU. Note that Task 2 could have been ready to run any time between points (3) and (10) without affecting the outcome. Some level of priority inversion cannot be avoided but far less is present than in the previous scenario.

DEADLOCK

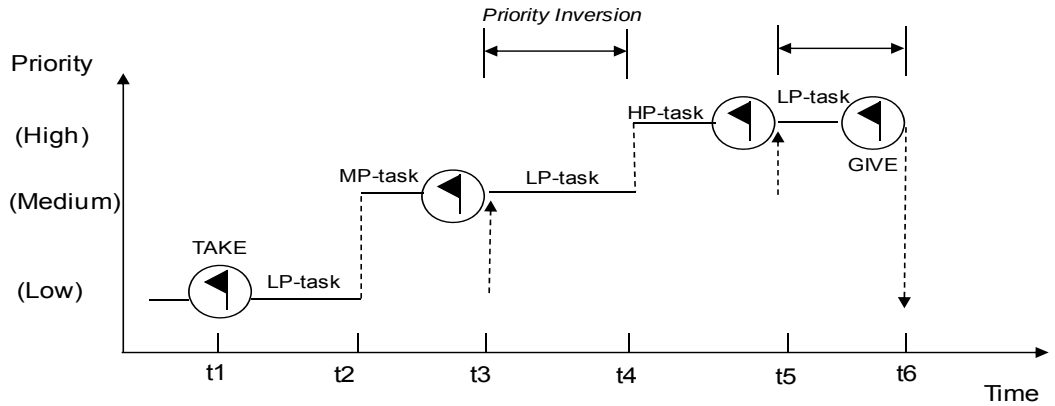
- A deadlock also called a deadly embrace, is a situation in which two tasks are each unknowingly waiting for resources held by the other.
  - Assume task T1 has exclusive access to resource R1 and task T2 has exclusive access to resource R2. If T1 needs exclusive access to R2 and T2 needs exclusive access to R1, neither task can continue – they are deadlocked.
- (1) The simplest way to avoid deadlock is for tasks to:
  - acquire all resources before proceeding,
  - acquire the resources in the same order, and release resources in the reverse order. …Q1?
- Most kernels allow you to specify a timeout when acquiring a semaphore so the deadlock can be broken. …Q2?

- **Q1:** How do the techniques presented at (1) solve the deadlock problem?
  A. Tasks don't lock when they are in the wait state; In the example if we acquire, release resources in order R1, R2. This makes the tasks acquire and release the resources in the same order and as a result the tasks can't deadlock.
- **Q2:** How the deadlock is broken by having the timeout specified, and what are the implications of this method?
  A: If the semaphore is not available within a certain amount of time, the task requesting the resource resumes execution. Some form of error code must be returned to the task to notify it that a timeout occurred. A return error code prevents the task from thinking it has obtained the resource. Deadlocks generally occur in multitasking systems, not in embedded systems.

PROBLEMS WITH THE PIP

- PIP does not prevent deadlock. In fact, PIP can cause deadlock or multiple blocking. It also cannot prevent other problems induced by semaphores.
  - Ex. Consider the following sequence with T1 > T2:
    T1: Lock S1; Lock S2; Unlock S2; Unlock S1
    T2: Lock S2; Lock S1; Unlock S1; Unlock S2
  - Here two semaphores are used in a nested fashion, but reverse order. Although the deadlock does not depend on the PIP (it is caused by an erroneous use of a semaphore), the PIP does not prevent the problem.
- Priority Ceiling Protocol (PCP) solves some of these problems by imposing a total ordering of the S access.

TRANSITIVE EXAMPLE: the PIP is dynamic and the priority promotion for a task during PIP is transitive but deadlock can take place -- 3 tasks share a common resource



Transitive priority promotion example.

- In the transitive example above deadlock situation can take place -- MP-task can hold some additional resources required by HP-task. HP-task can also acquire some other resources needed by MP before HP-task is blocked.
- When LP task releases the resource and HP task immediately gets to run, it is deadlocked with the MP-task.
- **Therefore, the PIP protocol does not eliminate deadlock.**

PRIORITY CEILING PROTOCOL (PCP)

- The Priority Ceiling Protocol extends the Priority Inheritance Protocol through chained blocking in such a way that no task can enter a critical section in a way that leads to blocking it.
  - To achieve this, each resource is assigned a priority (the priority ceiling) equal to the priority of the highest priority task that can use it.
- The Priority Ceiling Protocol is the same as the Priority Inheritance Protocol, except that a task, T, can also be blocked from entering a critical section if there exists any semaphore currently held by some other task whose priority ceiling is greater than or equal to the priority of T.
- In the PCP, the priority of every task is known, as are the resources required by every task.
- For a given resource the priority ceiling is the highest priority of all possible tasks that might require the resource.
  - Example 1: R is required by 4 tasks (T1 of priority 4, T2 of priority 9, T3 of priority 10 and T4 of priority 8). As a result the priority ceiling of R is 4.
- The current priority ceiling for a running system at any given time is the highest priority ceiling of all of resources in use at that time
  - Example 2: A system has 4 resources. R1: PC=4, R2: PC= 9, R3: PC=10; R4: PC=8. As a result the current priority ceiling of the system is 4.

PRIORITY CEILING PROTOCOL RULES

- The following rules apply when a task T requests a resource R:
  - (1) If R is in use, T is blocked,
  - (2) If R is free and if the priority of T is higher than the current priority ceiling, R is allocated to T,
  - (3) If the current priority ceiling belongs to one of the resources that T currently holds, R is allocated to T, and otherwise T is blocked,
  - (4) The task that blocks T inherits T's priority if it is higher and executes at this priority until it releases every resource whose priority ceiling is higher than or equal to T's priority. The task then returns to its previous priority.

- In PCP a requesting task can be blocked for one of 3 causes.

1. The first cause is when the resource is currently in use, which is direct resource contention blocking, and is the result of rule (1).
2. The second cause is when the blocking task has inherited a higher priority and its current execution priority is higher than that of the requesting task. This cause is priority inheritance blocking and is the result of rule (4).
3. A task can be blocked when its priority is lower than the current priority ceiling even when the requested resource if free. This cause is priority ceiling blocking and is a direct consequence of the "otherwise" clause of rule (3). Rule (3) prevents a task from blocking itself if it holds a resource that has defined the current priority ceiling.

PCP CHARACTERISTICS

- The PCP has 3 characteristics:

1. A requesting task can be blocked by only one task; therefore, the blocking interval is at most the duration of the critical section,
2. Transitive blocking never occurs under the PCP,
3. Deadlock never occurs under the PCP.

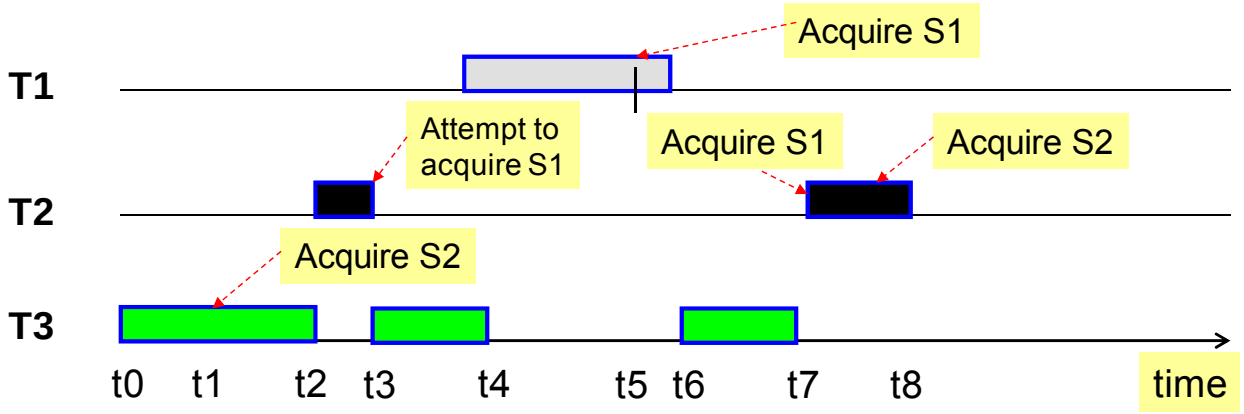
- One of the deadlock preventions strategies is to impose ordering on the resources.
- The resource ordering can be realized by using the priority ceilings of the resources. Rule (2) says if the priority of T is higher than the current priority ceiling, T does not require any resources that are in use.
  - This issue occurs because otherwise the current priority ceiling would be either equal to or higher than the priority of T, which implies that tasks with a priority higher than T's do not require the resources currently in use.
  - Consequently, none of the tasks that are holding resources in use can inherit a higher priority, preempt task T, and then request a resource that T holds. This feature prevents the circular-wait condition. This feature is also why deadlock cannot occur when using the PCP as an access control protocol.
  - The same induction process shows that the condition in which a task blocks another task but is in turn blocked by a third task, transitive blocking, does not occur under the PCP.

PRIORITY CEILING PROTOCOL EXAMPLES

- Scenario Example:
- T2 executes and holds a lock on S2;
- T1 is initiated:
  - T1 will be blocked from entering S1 ?
  - A: P(T1) is not strictly greater than the PC(S2) = P(T1);

Critical Section	Accessed by	Priority Ceiling
S1	T1, T2	P(T1)
S2	T1,T2,T3	P(T1)
S3	T3	P(T3)
S4	T2,T3	P(T2)

Priority Ceiling. Protocol Example Scheduling



- T1,T2, T3 (decreasing priorities) with the following sequence of op:
  - **T1**: Lock S1; Unlock S1 **T2**: Lock S1; Lock S2; Unlock S2; Unlock S1 **T3**: Lock S2; Unlock S2; Semaphores ceiling priorities for S1 and S2 are P(T1) and P(T2), respectively.
- Suppose that T3 starts executing first, locks the semaphore S2 at time t1 and enters the critical section.
- At time t2, T2 starts executing, preempts T3, and attempts to lock semaphore S1 at time t3. At this time, T2 is suspended because its priority is not higher than priority ceiling of semaphore S2 (it is equal only), currently locked by T3.
- Task T3 temporarily inherits the priority of T2 and resumes execution.
- At time t4, T1 enters, preempts T3, and executes until t5, where it tries to lock S1. Note that T1 is allowed to lock S1 at time t5, as its priority is greater than the priority ceiling of all the semaphores currently being locked (in this case, it is compared with S2). Task T1 completes its execution at t6 and lets T3 execute to completion at t7. Task T2 is then allowed to lock S1, and subsequently S2, and completes at t8.

ENGG4420 -- CHAPTER 2 -- HOMEWORK

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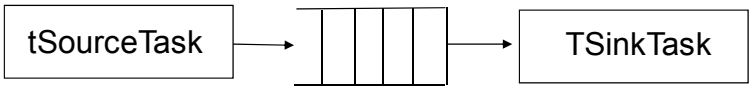
TYPICAL MESSAGE QUEUE USE

- The following are typical ways to use message queues within an application: 1) non-interlocked, one-way data communication; 2) interlocked, one-way data communication; 3) interlocked, two-way data communication; 4) broadcast communication

- One of the simplest scenarios for message-based communications requires a sending task (also called the message source), a message queue, and a receiving task (also called a message sink), as illustrated in this figure.

Non-interlocked, one-way data communication



The activities of tSourceTask and tSinkTask are not synchronized

```
tSourceTask ()
{
    ...
    Send message to
      message queue
    ...
}
```

Sending task

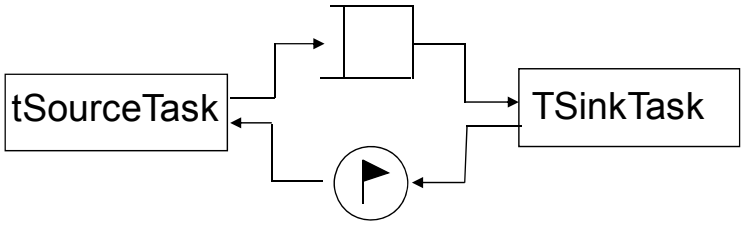
```
tSinkTask ()
{
    ...
    Receive message from
      message queue
    ...
}
```

Receiving task

- The type of communication is also called non-interlocked (or loosely coupled), one-way data communication. The activities of tSourceTask and tSinkTask are not synchronized. tsourceTask simply sends a message; it does not require acknowledgment from tSinkTask.
- Q: What happen if tSinkTask has a higher or a lower priority? A: If tSinkTask is set to a higher priority, it runs first until it blocks on an empty message queue. As soon as tSourceTask sends a message to the queue, tSinkTask receives the message and starts to execute again.
- If tSinkTask is set to a lower priority, tSourceTask fills the message queue with messages. Eventually, tSourceTask can be made to block when sending a message to a full message queue.
- ISRs typically use non-interlocked, one-way communication. Remember, when ISRs send messages to the message queue, they must do so in a non-blocking way. If the message queue becomes full, any additional messages that the ISR sends tot the message queue are lost.

Interlocked, one-way data communication

Interlocked communication is based on the handshake process



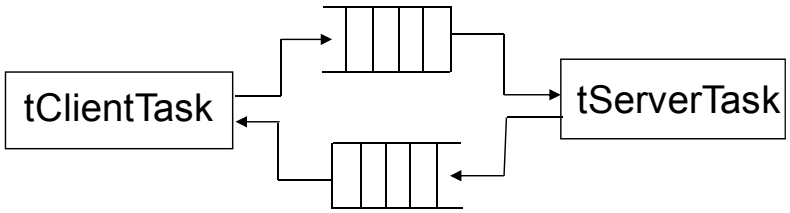

```
tSourceTask ()
{
    ...
    Send message to
      message queue
    Acquire binary semaphore
    ...
}
```
Sending task

```
tSinkTask ()
{
    ...
    Receive message from
      message queue
    Give binary semaphore
    ...
}
```
Receiving task

- In some designs, a sending task might require a handshake (acknowledgement) that the receiving task has been successful in receiving the message. This process is called interlocked communication, in which the sending task sends a message and waits to see if the message is received. This requirement can be useful for reliable communication or task synchronization.
- For example, if the message for some reason is not received correctly, the sending task can resend it. Using interlock communication can close a synchronization loop. To do so, you can construct a continuous loop in which sending and receiving tasks operate in lockstep with each other.
- An example is presented in this figure, where tSourceTask and tSinkTask use a binary semaphore initially set to 0 and a message queue with a length of 1 (mailbox).
    - The semaphore in this case acts as a simple synchronization object that ensures that tSourceTask and tSinkTask are in lockstep. This synchronization mechanism also acts as a simple acknowledgement to tSourceTask that it's okay to send the next message.

Interlocked, two-way data communication

Full-duplex or tightly coupled communication (bidirectional)



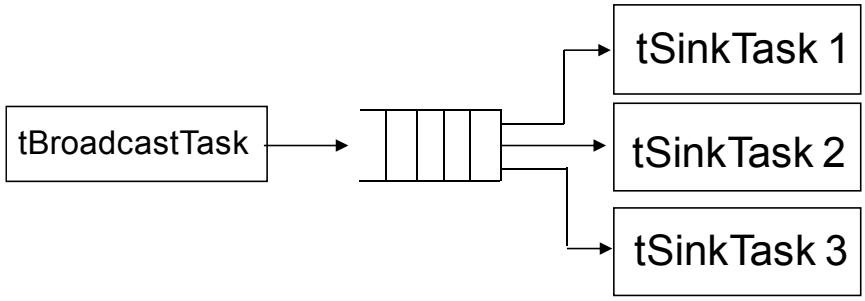

```
tClientTask ()
{
    ...
    Send message to the
      requests queue
    Wait for message from
      the server queue
    ...
}
```
Client task

```
tServerTask ()
{
    ...
    Receive message from
      the requests queue
    Send a message to
      the client queue
    ...
}
```
Sever task

- Sometimes data must flow bidirectionally between tasks, which is called interlocked, two-way data communication (also called full-duplex or tightly coupled communication). This form of communication can be useful when designing a client/server-based system.
- A diagram is provided in this figure. In this case, tClientTask sends a request to tServerTask via a message queue. tServerTask fulfills that request by sending a message back to tClientTask. Note that two separate message queues are required for full-duplex communication.
- If any kind of data needs to be exchanged, message queues are required; otherwise, a simple semaphore can be used to synchronize acknowledgement.
- In the simple client/server example, tServerTask is typically set to a higher priority, allowing it to quickly fulfill client requests.
- Q: How do we deal with a situation where we have multiple clients? A: All clients can use the client message queue to post requests, while tServerTask uses a separate message queue to fulfill the different client's requests.

Broadcast communication

Broadcast communication is a one-to-many-task relationship




```
tBroadcastTask ()
{
    ...
    Send broadcast
        message to queue
    ...
}
```
Sending task

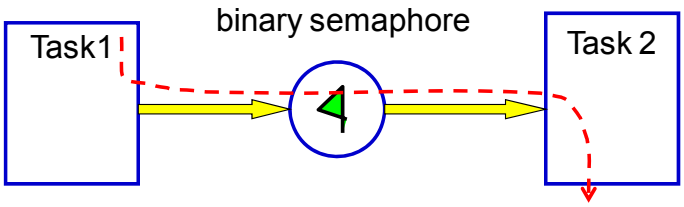
```
tSignalTask ()
{
    ...
    Receive message on
        queue
    ...
}
```
Receiving task

- Some message-queue implementations allow developers to broadcast a copy of the same message to multiple tasks, as shown in this figure.
- Message broadcasting is a one-to-many-task relationship. tBroadcastTask sends the message on which multiple tSinkTask are waiting.
- In this figure scenario, tSinkTask 1, 2, and 3 have all made calls to block on the broadcast message queue, waiting for the message. When tBroadcastTask executes, it sends one message to the message queue, resulting in all three waiting tasks exiting the blocked state.
- Note that not all message queue implementations might support the broadcasting facility.

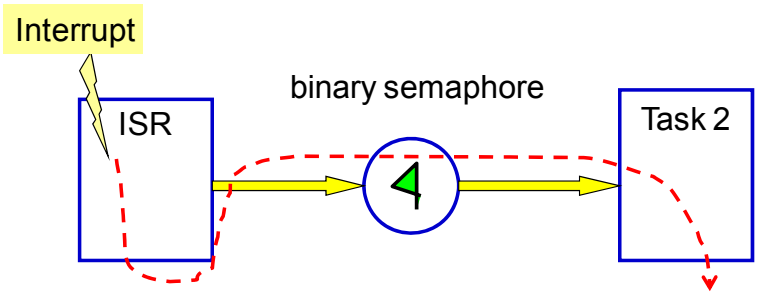
SUMMARY OF COMMON PRACTICAL DESIGN PATTERNS -- HOMEWORK

1. Synchronous activity synchronization
2. Asynchronous event notification using signals
3. Resource synchronization

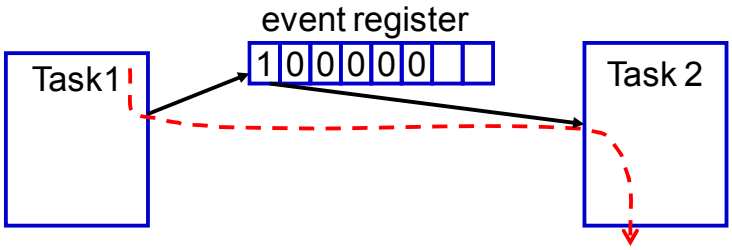
(1) Synchronous activity synchronization



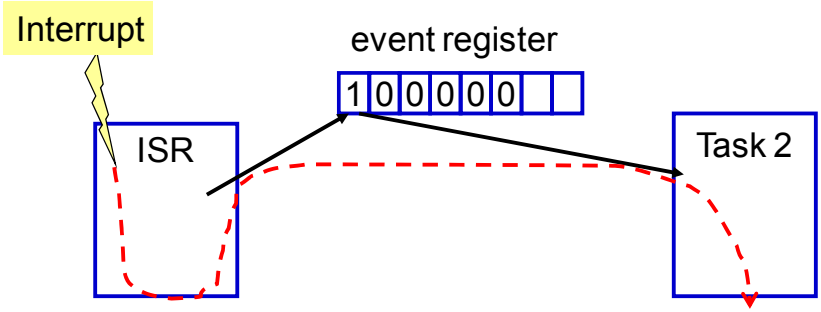
Task-to-task synchronization using binary semaphores



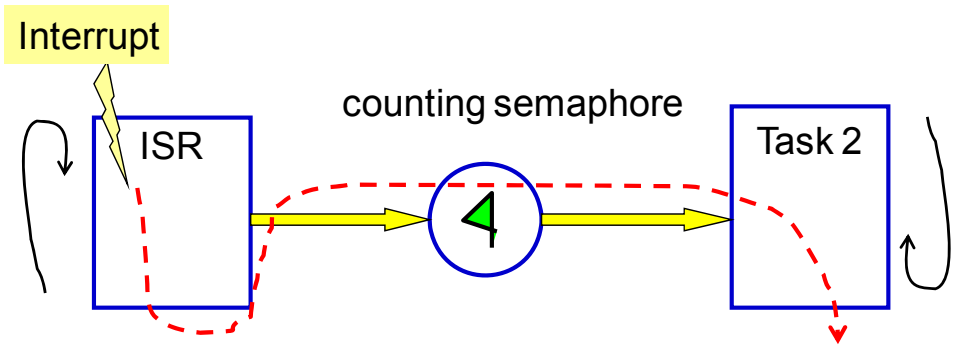
ISR-to-task synchronization using binary semaphores



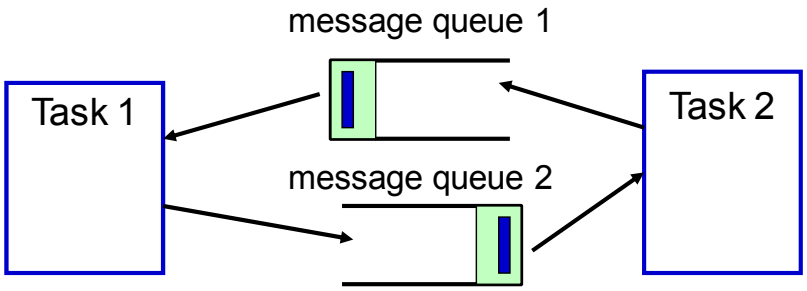
Task-to-task synchronization using event registers



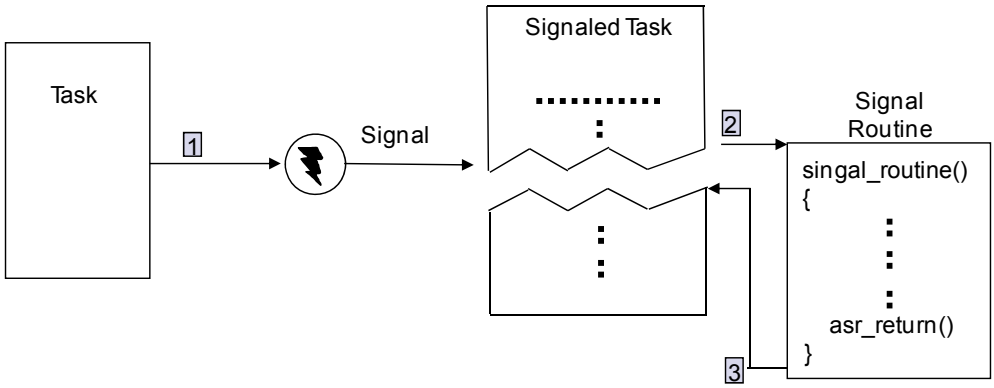
ISR-to-task synchronization using event registers



ISR-to-task synchronization using counting semaphores

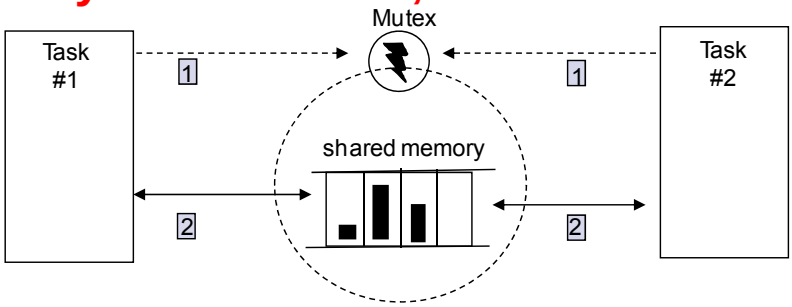


Task-to-task rendezvous using two message queues

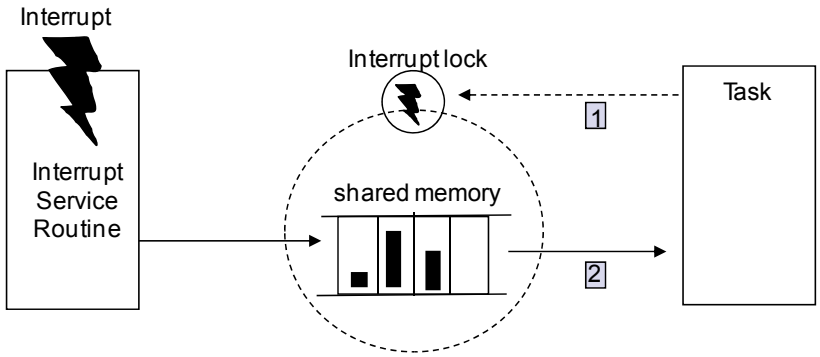


(2) Asynchronous event notification using signals

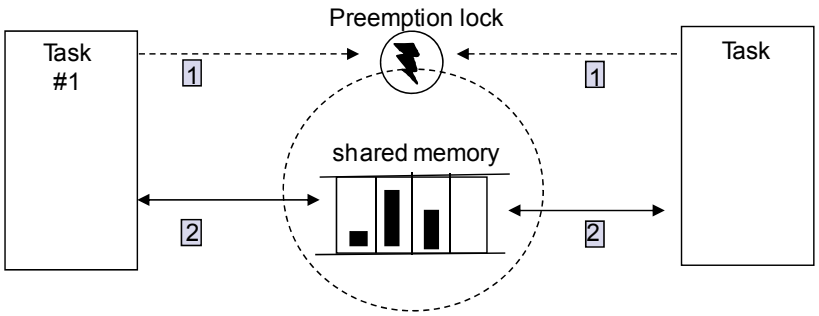
(3) Resource Synchronization;



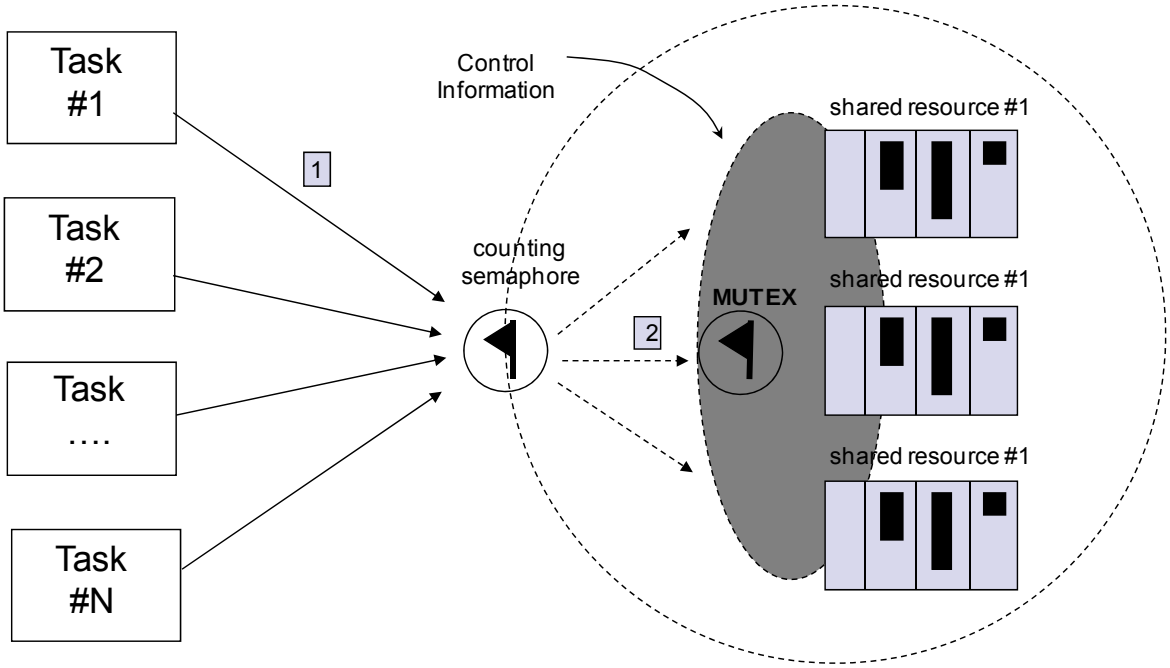
Shared Mem with Mutexes



ISR-to-task resource synchronization – shared mem guarded by interrupt lock



Shared memory guarded by preemption lock



Sharing multiple instances of resource using counting semaphores and mutexes

ENGG4420 -- CHAPTER 2 -- ASSIGNMENTS

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PROBLEM. In a real-time kernel, the tasks can be at any given time in one state determined by the kernel. Present the finite state machine (FSM) diagram for the task states supported by the uC/OS-II kernel. Place all the functions presented in the Functions List bellow on the corresponding arcs of your FSM.
Functions List: OSSemPend(), OSTimeDly(), OSIntExit(), OSStart(), OSTaskDel(), OSTaskCreate, OSSemPost(), OSTaskResume(), OSTimeDlyResume().
NOTE: In order to get full marks for this problem make sure that you present the uC/OS-II state machine not the general 3 states FSM.

PROBLEM. A real-time application uses tasks T1, T2, T3, Idle and an ISR. The task priorities are: T1_prio = 4; T2_prio = 6; and T3_prio = 8. At a particular moment in time t0, the tasks T1, T2 and T3 are waiting for an event E that needs to be set upon the arrival of an interrupt signal.
Knowing the following:

- the interrupt system is enabled;
- the interrupt signal arrives at time t1 = t0 + 100 ms;
- the interrupt service routing (ISR) sets the event E at time t2 = t0 + 150 ms;
- the user code of the ISR executes for 70 ms;
- interrupt vectoring takes 1 ms;
- saving the CPU context takes 3 ms;
- OSIntEnter() function executes for 2 ms;
- a context restore takes 4 ms;
- the return from interrupt (RTI) takes 2 ms;
- OSIntExit() without context switch takes 3 ms;
- OSIntExit() with context switch takes 9 ms;

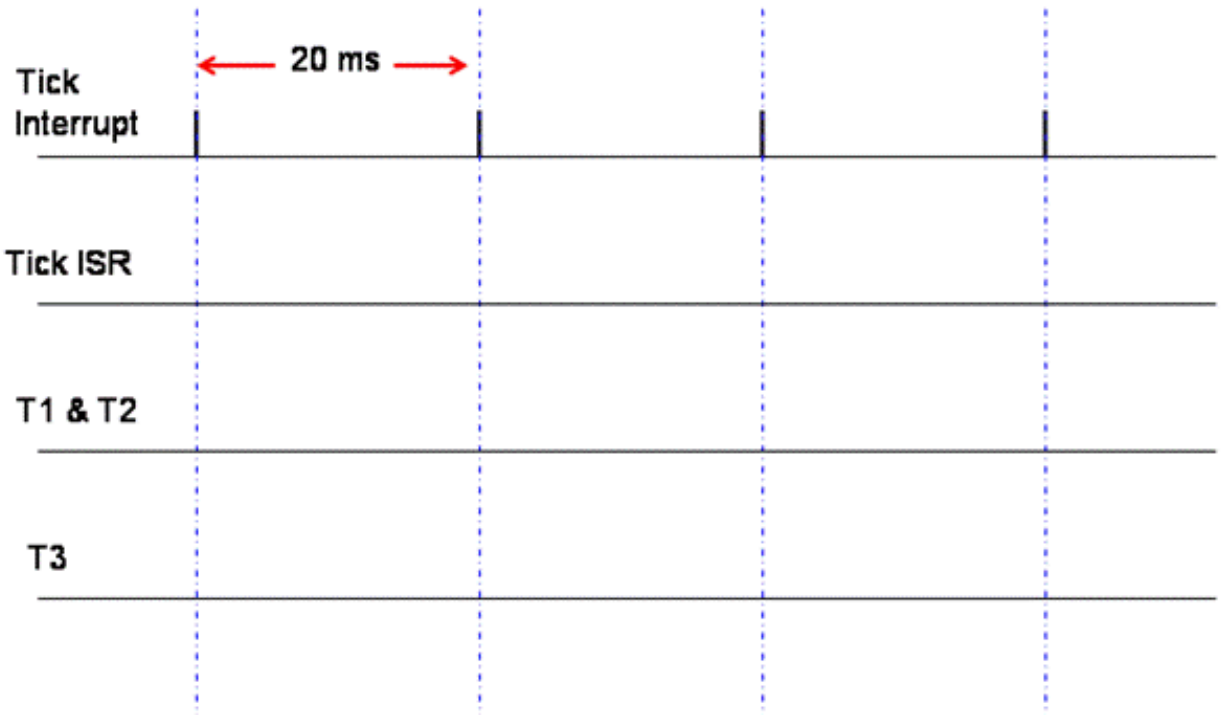
(Note: The time values presented above are given only for calculation purposes and are not necessarily realistic)
Answer the following questions:

a) [1 marks] What task is executing at time t1?
b) [1.5 marks] What is the interrupt response time? Show your calculation by indicating all the times included in the interrupt response time.
c) [1 marks] What task executes shortly after the event E is set and why, specifically, at time t0 + 158 ms?
d) [1.5 marks] What is the task response time for this interrupt scenario and what task executes at the end of the time response? Show your calculation by indicating all the times included in the task response time.
e) [2 marks] Draw the diagram that captures the service interrupt scenario presented in this problem. Indicate on your diagram the actions taken by the system that correspond to each time step.

PROBLEM. A clock tick is a special interrupt that occurs periodically. The interrupt can be viewed as the system's heartbeat. All kernels allow tasks to be delayed for a certain number of clock ticks. The resolution of delayed tasks is one clock tick; however, this does not mean that its accuracy is one clock tick.
Consider a system that has 3 tasks T1, T2, and T3 with priorities P1 > P2 > P3, respectively. We want to introduce a delay of one tick for task T3. For this analysis consider the following scenario:

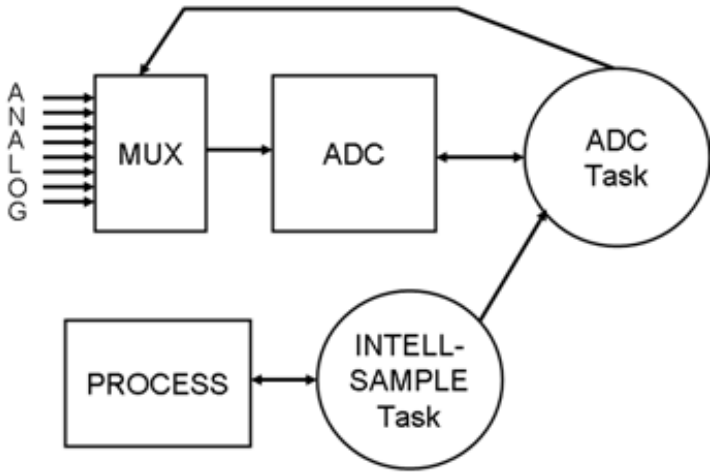
- The tick interrupt takes place at every 20 ms;
- The tick ISR has a maximum execution time of 2 ms;
- Tasks T1 and T2 execute each 20 ms cycle for a minimum time of 3 ms and a maximum time of 12 ms;
- Task T3 has a maximum execution time of 6 ms per 20 ms cycle;
- Task T3 has a system call to delay for 1 tick (20 ms) that is executed at 2 ms time after task T3 took hold of the CPU;
- Assume that the release time of all tasks is at the beginning of the tick cycle.

(a) Present on Figure 2.1 the worst case scenarios that capture the maximum and minimum delay that can be incurred by task T3 when we consider the execution times described above. Show the times on the diagram in ms and show on your diagram the maximum and minimum delays in ms. Show the execution times for ISR, Tasks T1&T2 combined, and T3.



DESIGN PROBLEM. Figure below presents a system level diagram for a data acquisition module. Within this system, the analog inputs must be read at regular intervals and offer the flexibility of adaptive acquisition. The ADC (Analog to Digital Conversion) Task is responsible for sampling the data and the INTELL-SAMPLE Task is responsible for adding intelligence to the system acquisition. The ADC Task must be able to sample data at regular fixed intervals and at variable intervals controlled dynamically be the Intelligent Sampling Task (INTELL-Sample). The INTELL-Sample Task must communicate to the ADC Task the inputs to be sampled, the rate increase in the sampling interval, and conversion parameters when necessary.
A simple way to accomplish regular interval sampling within a uC/OS-II environment is by using the OSTimeDly() function. However, in order to implement the intelligence capability of the module, you are required to use a message queue instead of the OSTimeDly() function.
(a) Present a message queue based design for this acquisition module. The message queue must be used to solve the sample delay problem and to communicate the intelligent services that are required.

- Note that the OSQPend service call has a timeout parameter that can be used to solve the time delay sample problem.
- **The design should show the main structure of the main function, and the tasks ADC and INTELL-SAMPLE. You are required to use the proper uC/OS-II system functions that relate to creating the tasks and creating and using the message queue. Use the example programs shown in the lectures and your labs.**




```
//variable declarations that you can use, you can add more if needed
void *QueueArray [10];
OS_EVENT *QueueSample;
OS_STK ADC_Task_S [1000];
OS_STK INTELL_Sample_Task_S [1000]

// Continue with the program showing the main program and the two tasks
```

uC/OS PROBLEM. When a resource is shared in a preemptive kernel, we need to make sure that only one task has access to the resource at a time. In this problem, you need to develop a multitask uC/OS-II application with 2 tasks (Task 1 and Task 2) that need to write an LCD display.

- The first task (Task 1) is an ADC (Analog to Digital Conversion) task that needs to display a processed ADC sample on the first row starting at the first column of an LCD.
- The second task (Task 2) is used to display the elapsed time on the first column of the second row.

The Task1 and Task2 can use the following LCD functions:
static void LcdMoveCursor(UBYTE row, UBYTE col); /* this function moves the moves the cursor to the specified (row, col) position */
static void LcdDispDecByte(UBYTE data); /* this function displays the sample in decimal */
static void LcdDispTime(UBYTE hours, UBYTE minutes, UBYTE seconds); /* this function formats and displays the time */
In order to avoid display errors in this multitask application use a uC/OS-II object that can allow proper sharing of the resource LCD. Show the structure of the application by completing the application program including all system initialization, multitasking start-up, the tasks programs, and correct object usage for resource sharing.

/* PROGRAM APPLICATION. YOU NEED TO FILL IN THE DOTTED LINES WITH PROPER FUNCTION CALLS */
#include “includes.h”
/* Public event declaration section. Use this to declare all your event objects */

…….

/* Task declaration section. Use this section to declare all your tasks */

……..

……..

……..

/* Allocate task stack space in this section */

……..

……..

……..

void main(void) {

……..

……

……..

…… /* Start multitasking here */

}

```
/* START-UP TASK */
static void StartTask(void *pdata) {

OSTickInit(); /* Initialize the uC/OS ticker */

Other initialization can take place here
/* Fill the next lines with the appropriate uC/OS functions */

……..

……..

FOREVER() { OSTaskSuspend(START_TASK_PRIO); }

}


/* Use the section on the next page to show your two tasks.
The tasks need to show the proper real time task structure but you don't need to provide
complete application code.
The only code required is function calls related to managing the object used for sharing the LCD
and the related function for the LCD */

 static void AtoDProcTask(void *pdata) {

/*extra application code*/

……..

……

……..

…….

…….

 }

static void ETimeTask(void *pdata) {

/*extra application code*/

……..

……

……..

…….

…….


}
```

PROBLEM (PIP, PCP). Consider the following tasks with their resource requirements given as:

- T3 = (0, 10, 3; [S1; 7]), where the task executes for two time units, then requests the resource (critical section) S1.
- T2 = (4, 8, 2; [S2; 5 [S1; 2][S3; 1]]), where the task executes for one time unit, then requests the resource (critical section) S2 and holds it for one time unit and makes a nested request for S1. After finishing with S1 the task makes a nested request (from S2) for S3.
- T1 = (8, 10, 1; [S3; 7 [S1; 3][S2; 2]]), where the task executes for one time unit, then requests the resource (critical section) S3 and holds it for one time unit and makes a nested request for S1. After finishing with S1 the task makes a nested request (from S3) for S2.

Here, the notation Ti = (ri, ei, πi, [R; t]) indicates that the task Ti is released at time ri, has the execution time ei, priority πi (the lower the value of πi, the higher the priority), and the critical section [R; t] for the resource R and the execution time t (total hold time of R).

- ***Note that ei is the total execution time including the times that the task holds the resources;***
- And the representation [R; t [S; w][U;v]] denotes nested critical sections, that is, the usage of resource R includes the usage of resource S and U, and time t includes the time w and v of the critical sections S and U, respectively. Also, this notation indicates that S and U are nested within critical section R and execute sequentially in this order.

(a). [3 marks]. Using the grid in Table 4.1 present the schedule of the above tasks based on the priority inversion protocol (PIP).
(b). [1 mark]. What is the task status within the PIP schedule at time 20?
(c). [1 mark]. Propose a solution to the problem that you identified at **(b)**.

TABLE

Time:	2	4	6	8	10	12	14	16	18	20	22	24	26	28
T1														
T2														
T3														
Time:	2	4	6	8	10	12	14	16	18	20	22	24	26	28

1. What are the three scenarios in which a running task can be preempted?
2. Although we do not use *cooperative tasks* for a preemptive kernel, we still need to design tasks that cooperate to some extent. What is the "cooperation" required by the tasks designed for a preemptive kernel? Which kernel services can be used to realize this cooperation?
3. A project uses µC/OS for six tasks with priorities 4 through 9 available. Given the following tasks and task execution rates, assign priority values based on the rate monotonic scheduling rule:

Task	Task Period
StartTask()	One time only
TaskA()	1ms
TaskB()	20ms
TaskC()	500ms
TaskD()	10ms
TaskE()	1/keypress

4. After the system in Exercise 3 was tested, it was determined that *TaskD* had to have an exact period of 10ms, and with the current priorities, it was longer than 10ms. Readjust the priorities so *TaskD* will have an exact period of 10ms. Assume its execution time is just under one tick period.
5. Replace the *OSTimeDly()* call in Source 16.8 with the equivalent *OSTimeDlyHMSM()* call.
6. An on-chip input capture is to be used to count pulses on *Timer Channel 1*. Design the input capture's interrupt service routine so it will run under µC/OS and will signal the semaphore, *NewPulse,* every time a pulse is received. Include the code required to create the semaphone.
7. Design a task that increments a 16-bit variable, *PulseCnt,* to count the pulses from Exercise 6. Use the *NewPulse* semaphore for intertask communications.
8. Expand on the task in Exercise 7 to include a timeout so that the function *PulseError()* will be called if a pulse is not received within two seconds.

9. The following definition is used for a message to be displayed by a µC/OS program:

```
UBYTE HelloMsg[] = {"Hello Happy User"};
```

(a) Show the code required in a sender task and a receiver task to send a pointer to this message as a global variable. The receiver task waits for the pointer and displays it using the Basic I/O routine, *PUTSTRG()*. Include the code required to define and initialize the variable.

(b) Show the code required in the two tasks to send the message through a µC/OS mailbox. Include the code required to create and initialize the mailbox.

(c) Show the code required in the two tasks to send the message through a µC/OS queue. Include the code required to create and initialize a queue that can hold eight messages.

(d) Revise the code in Exercise 9a so the tasks use a semaphore as a resource key to access the global variable. Include the code required to create and initialize the semaphore.

10. The following two tasks send messages to the *OutStrgSrvrTask()* in Source 16.15. Assuming *Sendr1Tsk()* has priority 5, *Sendr2Tsk()* has priority 6, and *OutStrgSrvrTsk()* has a priority of 10, what should the resulting display look like? (Assume *OutStrgQ* can hold eight messages.)

```
/*********************************************************************
* Sendr1Task - A task that sends a message to the serial output server
*********************************************************************/
static void Sendr1Task(void *pdata){
    FOREVER() {
        OSQPost(OutStrgQ, (void *)"MESSAGES");
        OSTimeDly(10);
        OSSemPost(OutFlag);
        OSQPost(OutStrgQ, (void *)"Sendr1, Msg1");
        OSQPost(OutStrgQ, (void *)"Sendr1, Msg2");
        OSQPost(OutStrgQ, (void *)"Sendr1, Msg3");
        OSTaskSuspend(SENDR1_PRIO);
    }
}
/*********************************************************************
* Sendr2Task - A task that sends a message to the serial output server
*********************************************************************/
static void Sendr2Task(void *pdata){
    UBYTE err;
    FOREVER() {
        OSSemPend(OutFlag, 0, &err);
        OSQPost(OutStrgQ, (void *)"Sendr2, Msg1");
        OSQPostFront(OutStrgQ, (void *)"Sendr2, Msg2");
        OSQPost(OutStrgQ, (void *)"Sendr2, Msg3");
        OSTaskSuspend(SENDR2_PRIO);
    }
}
/*********************************************************************/
```

11. A new design has the following requirements: 5 tasks, 4 semaphores, and 2 message queues. What are the minimum values for the following configuration constants to build • C/OS specifically for this project? Assume that the four highest priorities and four lowest priorities are reserved for the kernel.

```
OS_MAX_EVENTS
OS_MAX_QS
OS_MAX_TASKS
OS_LOWEST_PRIO
```

END OF CHAPTER 2