*u*C/OS-II – Real-Time Kernel

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• Slides come from my class notes, slides from graduates and students in my lab (Li-Pin Chang and Shi-Wu Lo), and slides contributed by Labrosse, the author of MicroC/OS-II.

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- Introduction
- Kernel Structure

Introduction

- Different ports from the official *u*C/OS-II Web site at http://www.uCOS-II.com.
- Neither freeware nor open source code.
- *u*C/OS-II is certified in an avionics product by FAA in July 2000.
- Text Book:
  - Jean J. Labresse, “MicroC/OS-II: The Real-Time Kernel,” CMP Book, ISBN: 1-57820-103-9

Introduction

- *u*C/OS-II
  - Micro-Controller Operating Systems, Version 2
  - A very small real-time kernel.
    - Memory footprint is about 20KB for a fully functional kernel.
    - Source code is about 5,500 lines, mostly in ANSI C.
    - It’s source is open but not free for commercial usages.

Introduction

- *u*C/OS-II
  - Preemptible priority-driven real-time scheduling.
    - 64 priority levels (max 64 tasks)
    - 8 reserved for *u*C/OS-II
    - Each task is an infinite loop.
  - Deterministic execution times for most *u*C/OS-II functions and services.
  - Nested interrupts could go up to 256 levels.

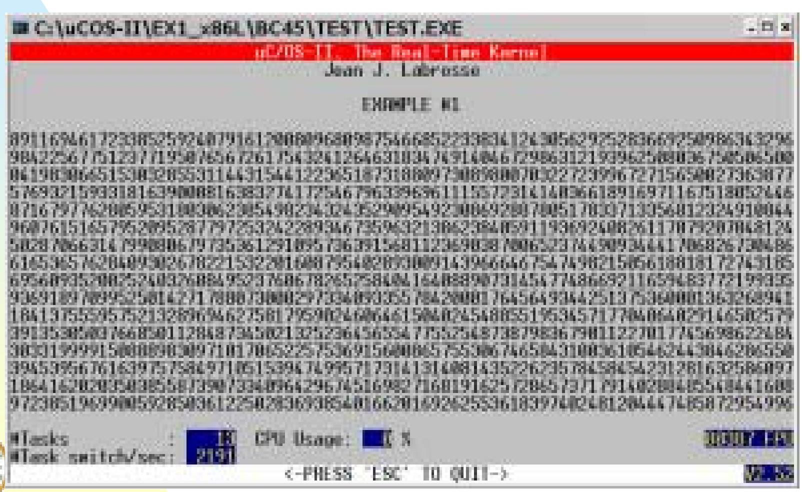
Introduction

- *u*C/OS-II
  - Supports of various 8-bit to 64-bit platforms: x86, 68x, MIPS, 8051, etc
  - Easy for development: Borland C++ compiler and DOS (optional).
- However, *u*C/OS-II still lacks of the following features:
  - Resource synchronization protocols.
  - Sporadic task support.
  - Soft-real-time support.

Introduction

- Getting started with *u*C/OS-II!
  - See how a *u*C/OS-II program looks like.
  - Learn how to write a skeleton program for *u*C/OS-II.
    - How to initialize *u*C/OS-II?
    - How to create real-time tasks?
    - How to use inter-task communication mechanisms?
    - How to catch system events?

Example 1: Multitasking



Example 1 : Multitasking

- 13 tasks run concurrently.
  - 2 internal tasks:
    - The idle task and the statistic task.
  - 11 user tasks:
    - 10 tasks randomly print numbers onto the screen.
- Focus: System initialization and task creation.

Example 1: Multitasking

- Files
  - The main program (test.c)
  - The big include file (includes.h)
  - The configuration of *u*C/OS-II (os_cfg.h) for each application
- Tools needed:
  - Borland C++ compiler (V3.1+)

Example 1

```
#include "includes.h"

/*
*********************************************************************************
    ********************************
*                                               CONSTANTS
*********************************************************************************
    ********************************
*/

#define  TASK_STK_SIZE                512       /* Size of each task's
    stacks (# of WORDs)             */
#define  N_TASKS                       10       /* Number of identical
    tasks                           */

/*
*********************************************************************************
    ********************************
*                                               VARIABLES
*********************************************************************************
    ********************************
*/

OS_STK        TaskStk[N_TASKS][TASK_STK_SIZE];        /* Tasks stacks
    */
OS_STK        TaskStartStk[TASK_STK_SIZE];
char          TaskData[N_TASKS];                      /* Parameters to
    pass to each task                */
OS_EVENT     *RandomSem;
```

A semaphore
(explain later)

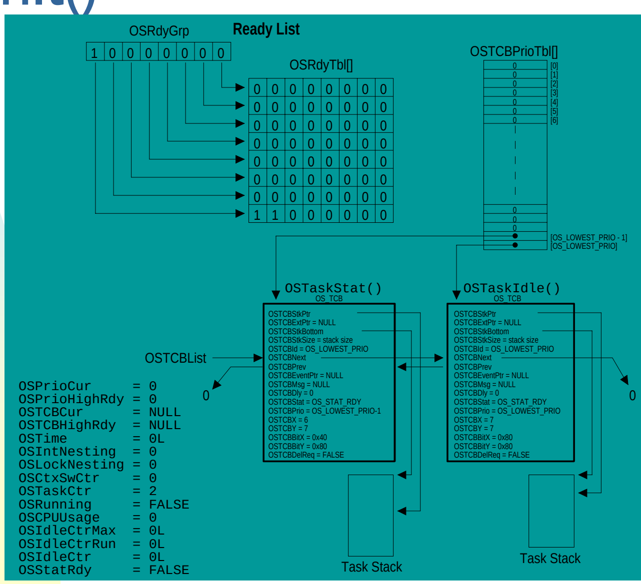
Main()

```
void main (void)
{
    PC_DispClrScr(DISP_FGND_WHITE + DISP_BGND_BLACK);
   (1)
    OSInit();
   (2)
    PC_DOSSaveReturn();
   (3)
    PC_VectSet(uCOS, OSCtxSw);
   (4)
    RandomSem = OSSemCreate(1);
   (5)
    OSTaskCreate(TaskStart,
   (6)
                 (void *)0,
                 (void *)&TaskStartStk[TASK_STK_SIZE-
   1],
                 0);
    OSStart();
   (7)
}
```

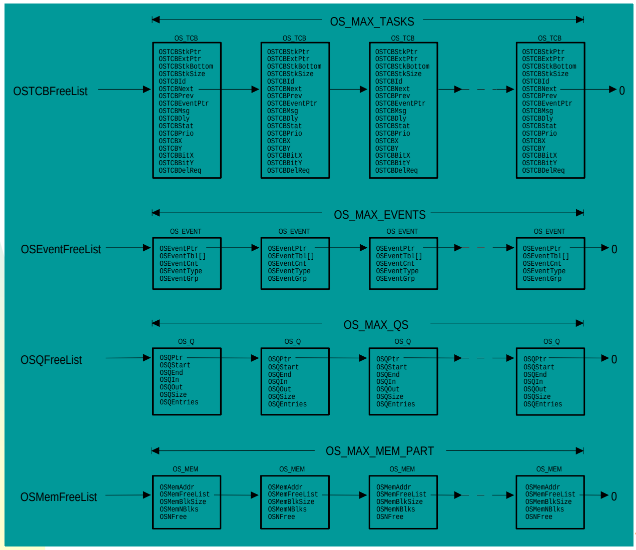
Main()

- OSinit():
  - internal structures of uC/OS-2.
    - Task ready list.
    - Priority table.
    - Task control blocks (TCB).
    - Free pool.
  - Create housekeeping tasks.
    - The idle task.
    - The statistics task.

OSinit()



OSinit()



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Main()

- PC_DOSSaveReturn()
  - Save the current status of DOS for the future restoration.
    - Interrupt vectors and the RTC tick rate.
  - Set a global returning point by calling setjump().
    - *u*C/OS-II can come back here when it terminates.
    - PC_DOSReturn()

PC_DOSSaveReturn()

```
void PC_DOSSaveReturn (void)
{
    PC_ExitFlag  = FALSE;                                          (1)
    OSTickDOSCtr =     8;                                          (2)
    PC_TickISR   = PC_VectGet(VECT_TICK);                          (3)

    OS_ENTER_CRITICAL();
    PC_VectSet(VECT_DOS_CHAIN, PC_TickISR);                        (4)
    OS_EXIT_CRITICAL();

    setjmp(PC_JumpBuf);                                            (5)
    if (PC_ExitFlag == TRUE) {
        OS_ENTER_CRITICAL();
        PC_SetTickRate(18);                                        (6)
        PC_VectSet(VECT_TICK, PC_TickISR);                         (7)
        OS_EXIT_CRITICAL();
        PC_DispClrScr(DISP_FGND_WHITE + DISP_BGND_BLACK);          (8)
        exit(0);                                                   (9)
    }
}
```

*

Main()

- PC_VectSet(uCOS,OSCtxSw)
  - Install the context switch handler.
  - Interrupt 0x08 under 80x86 family.
    - Invoked by INT instruction.
- OSStart()
  - Start multitasking of uC/OS-2.
  - It never returns to main().
  - *u*C/OS-II is terminated if PC_DOSReturn() is called. *

Main()

- OSSemCreate()
  - Create a semaphore for resource synchronization.
    - To protect non-reentrant codes.
  - The created semaphore becomes a mutual exclusive mechanism if "1" is given as the initial value.
  - In this example, a semaphore is created to protect the standard C library "random()".

Main()

- OSTaskCreate()
  - Create tasks with the given arguments.
  - Tasks become "ready" after they are created.
- Task
  - An active entity which could do some computations.
  - Priority, CPU registers, stack, text, housekeeping status.
- The *u*C/OS-II picks up the highest-priority task to run on context-switching.
  - Tightly coupled with RTC ISR.

OSTaskCreate()

- OSTaskCreate(
  TaskStart,
  (void *)0,
  &TaskStartStk[TASK_STK_SIZE-1],
   0
  );

Entry point of the task (a pointer to function)

User-specified data

Top of Stack

Priority (0=hightest)

TaskStart()

```
void  TaskStart (void *pdata)
{
#if OS_CRITICAL_METHOD == 3                          /* Allocate storage for CPU status register */
    OS_CPU_SR  cpu_sr;
#endif
    char       s[100];
    INT16S     key;

    pdata = pdata;                                   /* Prevent compiler warning                 */

    TaskStartDispInit();                             /* Initialize the display                   */

    OS_ENTER_CRITICAL();
    PC_VectSet(0x08, OSTickISR);                     /* Install uC/OS-II's clock tick ISR        */
    PC_SetTickRate(OS_TICKS_PER_SEC);                /* Reprogram tick rate                      */
    OS_EXIT_CRITICAL();

    OSStatInit();                                    /* Initialize uC/OS-II's statistics         */

    TaskStartCreateTasks();                          /* Create all the application tasks         */

    for (;;) {
        TaskStartDisp();                             /* Update the display                       */


        if (PC_GetKey(&key) == TRUE) {               /* See if key has been pressed              */
            if (key == 0x1B) {                       /* Yes, see if it's the ESCAPE key          */
                PC_DOSReturn();                      /* Return to DOS                            */
            }
        }

        OSCtxSwCtr = 0;                              /* Clear context switch counter             */
        OSTimeDlyHMSM(0, 0, 1, 0);                   /* Wait one second                          */
    }
}
```

Change the ticking rate

TaskStart()

- OS_ENTER_CRITICAL()/OS_EXIT_CRITICAL()
  - Enable/disable most interrupts.
  - An alternative way to accomplish mutual exclusion.
    - No rescheduling is possible during the disabling of interrupts. (different from semaphores)
  - Processor specific.
    - CLI/STI (x86 real mode)
    - Interrupt descriptors (x86 protected mode)

TaskStartCreateTasks()

Entry point of the created task

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

    for (i = 0; i < N_TASKS; i++) {

        TaskData[i] = '0' + i;

        OSTaskCreate(
        Task,
        (void *)&TaskData[i],
        &TaskStk[i][TASK_STK_SIZE - 1],
        i + 1);
    }
}
```

Argument: character to print

Stack

Priority

Task()

```
void  Task (void *pdata)
{
    INT8U  x;
    INT8U  y;
    INT8U  err;


    for (;;) {
        OSSemPend(RandomSem, 0, &err);/* Acquire semaphore to perform random numbers
    */
        x = random(80);               /* Find X position where task number will appear
    */
        y = random(16);               /* Find Y position where task number will appear
    */
        OSSemPost(RandomSem);         /* Release semaphore
    */
                                      /* Display the task number on the screen
    */
        PC_DispChar(x, y + 5, *(char *)pdata, DISP_FGND_BLACK + DISP_BGND_LIGHT_GRAY);
        OSTimeDly(1);                 /* Delay 1 clock tick
    */
    }
}
```

Semaphore operations.

Semaphores

- A semaphore consists of a wait list and an integer counter.
  - OSSemPend():
    - Counter--;
    - If the value of the semaphore <0, then the task is blocked and moved to the wait list immediately.
    - A time-out value can be specified.
  - OSSemPost():
    - Counter++;
    - If the value of the semaphore >= 0, then a task in the wait list is removed from the wait list.
      - Reschedule if needed.

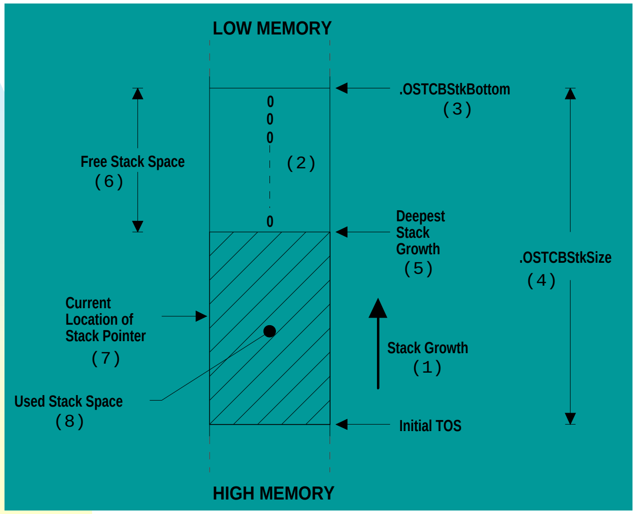
Example 1: Multitasking

- Summary:
  - *u*C/OS-II is initialized and started by calling OSInit() and OSStart(), respectively.
  - Before *u*C/OS-II is started,
    - The DOS status is saved by calling PC_DOSSaveReturn().
    - A context switch handler is installed by calling PC_VectSet().
    - User tasks must be created first!
  - Shared resources can be protected by semaphores.
    - OSSemPend(),OSSemPost().

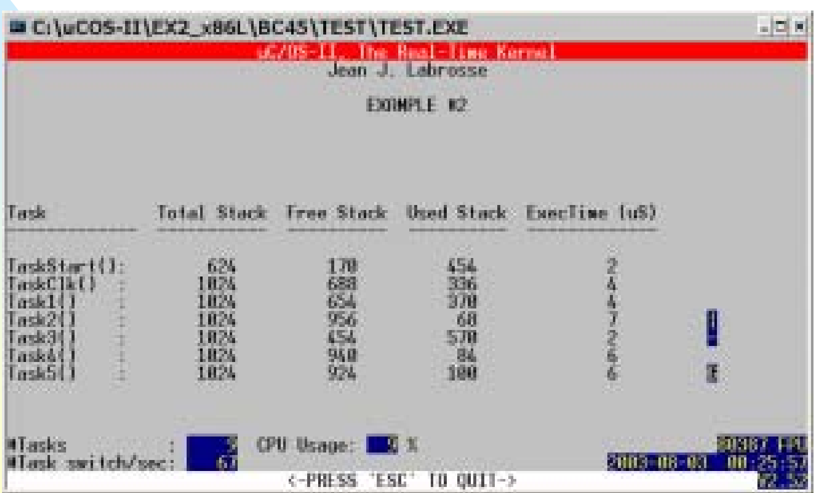
Example 2: Stack Checking

- Five tasks do jobs on message sending/receiving, char-displaying with wheel turning, and char-printing.
  - More task creation options
    - Better judgment on stack sizes
  - Stack usage of each task
    - Different stack sizes for tasks
  - Emulation of floating point operations
    - 80386 or lower-end CPU's
  - Communication through mailbox
    - Only the pointer is passed.

The Stack Usage of a Task



Example 2: Stack Checking



```
#define         TASK_STK_SIZE     512             /* Size of each task's stacks (# of WORDs)
    */

#define         TASK_START_ID       0             /* Application tasks IDs
    */
#define         TASK_CLK_ID         1
#define         TASK_1_ID           2
#define         TASK_2_ID           3
#define         TASK_3_ID           4
#define         TASK_4_ID           5
#define         TASK_5_ID           6

#define         TASK_START_PRIO    10             /* Application tasks priorities
    */
#define         TASK_CLK_PRIO      11
#define         TASK_1_PRIO        12
#define         TASK_2_PRIO        13
#define         TASK_3_PRIO        14
#define         TASK_4_PRIO        15
#define         TASK_5_PRIO        16

OS_STK       TaskStartStk[TASK_STK_SIZE];         /* Startup    task stack
    */
OS_STK       TaskClkStk[TASK_STK_SIZE];           /* Clock      task stack
    */
OS_STK       Task1Stk[TASK_STK_SIZE];             /* Task #1    task stack
    */
OS_STK       Task2Stk[TASK_STK_SIZE];             /* Task #2    task stack
    */
OS_STK       Task3Stk[TASK_STK_SIZE];             /* Task #3    task stack
    */
OS_STK       Task4Stk[TASK_STK_SIZE];             /* Task #4    task stack
    */
OS_STK       Task5Stk[TASK_STK_SIZE];             /* Task #5    task stack
    */

OS_EVENT     *AckMbox;                            /* Message mailboxes for Tasks #4 and #5
    */
OS_EVENT     *TxMbox;
```

2 Mailboxes

Main()

```
void main (void)
{
    OS_STK *ptos;
    OS_STK *pbos;
    INT32U  size;

    PC_DispClrScr(DISP_FGND_WHITE);                /* Clear the screen          */
    OSInit();                                      /* Initialize uC/OS-II       */
    PC_DOSSaveReturn();                            /* Save environment to return to
    DOS        */
    PC_VectSet(uCOS, OSCtxSw);                     /* Install uC/OS-II's context
    switch vector */
    PC_ElapsedInit();                              /* Initialized elapsed time
    measurement     */
    ptos        = &TaskStartStk[TASK_STK_SIZE - 1]; /* TaskStart() will use Floating-
    Point      */
    pbos        = &TaskStartStk[0];
    size        = TASK_STK_SIZE;
    OSTaskStkInit_FPE_x86(&ptos, &pbos, &size);
    OSTaskCreateExt(TaskStart,
                   (void *)0,
                   ptos,
                   TASK_START_PRIO,
                   TASK_START_ID,
                   pbos,
                   size,
                   (void *)0,
                   OS_TASK_OPT_STK_CHK | OS_TASK_OPT_STK_CLR);

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

TaskStart()

```
void  TaskStart (void *pdata)
{
#if OS_CRITICAL_METHOD == 3                          /* Allocate storage for CPU status register */
    OS_CPU_SR  cpu_sr;
#endif
    INT16S     key;


    pdata = pdata;                                   /* Prevent compiler warning                 */

    TaskStartDispInit();                             /* Setup the display                        */

    OS_ENTER_CRITICAL();                             /* Install uC/OS-II's clock tick ISR        */
    PC_VectSet(0x08, OSTickISR);
    PC_SetTickRate(OS_TICKS_PER_SEC);                /* Reprogram tick rate                      */
    OS_EXIT_CRITICAL();

    OSStatInit();                                    /* Initialize uC/OS-II's statistics         */

    AckMbox = OSMboxCreate((void *)0);               /* Create 2 message mailboxes               */
    TxMbox  = OSMboxCreate((void *)0);

    TaskStartCreateTasks();                          /* Create all other tasks                   */

    for (;;) {
        TaskStartDisp();                             /* Update the display                       */

        if (PC_GetKey(&key)) {                       /* See if key has been pressed              */
            if (key == 0x1B) {                       /* Yes, see if it's the ESCAPE key          */
                PC_DOSReturn();                      /* Yes, return to DOS                       */
            }
        }

        OSCtxSwCtr = 0;                              /* Clear context switch counter             */
        OSTimeDly(OS_TICKS_PER_SEC);                 /* Wait one second                          */
    }
}
```

Create 2 mailboxes

The dummy loop wait for 'ESC'

Timer drifting

Task1()

```
void  Task1 (void *pdata)
{
    INT8U       err;
    OS_STK_DATA data;                       /* Storage for task stack data    */
    INT16U      time;                       /* Execution time (in uS)  */
    INT8U       i;
    char        s[80];


    pdata = pdata;
    for (;;) {
        for (i = 0; i < 7; i++) {
            PC_ElapsedStart();
            err  = OSTaskStkChk(TASK_START_PRIO + i, &data);
            time = PC_ElapsedStop();
            if (err == OS_NO_ERR) {
                sprintf(s, "%4ld        %4ld        %4ld        %6d",
                        data.OSFree + data.OSUsed,
                        data.OSFree,
                        data.OSUsed,
                        time);
                PC_DispStr(19, 12 + i, s, DISP_FGND_BLACK +
                    DISP_BGND_LIGHT_GRAY);
            }
        }
        OSTimeDlyHMSM(0, 0, 0, 100);            /* Delay for 100 ms */
    }
}
```

Extra overheads on measurement

Task1: total 1024 Free 654 Used 370

Task2() & Task3()

```
void  Task2 (void *data)
{
    data = data;
    for (;;) {
        PC_DispChar(70, 15, '|',  DISP_FGND_YELLOW + DISP_BGND_BLUE);
        OSTimeDly(10);
        PC_DispChar(70, 15, '/',  DISP_FGND_YELLOW + DISP_BGND_BLUE);
        OSTimeDly(10);
        PC_DispChar(70, 15, '-',  DISP_FGND_YELLOW + DISP_BGND_BLUE);
        OSTimeDly(10);
        PC_DispChar(70, 15, '\\', DISP_FGND_YELLOW + DISP_BGND_BLUE);
        OSTimeDly(10);
    }
}
```

Timer drifting

```
void  Task3 (void *data)
{
    char    dummy[500];
    INT16U  i;


    data = data;
    for (i = 0; i < 499; i++) {        /* Use up the stack with 'junk'
 */
        dummy[i] = '?';
    }
    for (;;) {
        PC_DispChar(70, 16, '|',  DISP_FGND_YELLOW + DISP_BGND_BLUE);
        OSTimeDly(20);
        PC_DispChar(70, 16, '\\', DISP_FGND_YELLOW + DISP_BGND_BLUE);
        OSTimeDly(20);
        PC_DispChar(70, 16, '-',  DISP_FGND_YELLOW + DISP_BGND_BLUE);
        OSTimeDly(20);
        PC_DispChar(70, 16, '/',  DISP_FGND_YELLOW + DISP_BGND_BLUE);
        OSTimeDly(20);
    }
}
```


Task4() and Task5()

```
void  Task4 (void *data)
{
    char   txmsg;
    INT8U  err;


    data  = data;
    txmsg = 'A';
    for (;;) {
        OSMboxPost(TxMbox, (void *)&txmsg);      /* Send message to Task #5   */
        OSMboxPend(AckMbox, 0, &err);            /* Wait for acknowledgement from Task #5 */
        txmsg++;                                 /* Next message to send      */
        if (txmsg == 'Z') {
            txmsg = 'A';                         /* Start new series of messages */
        }
    }
}

void  Task5 (void *data)
{
    char  *rxmsg;
    INT8U  err;


    data = data;
    for (;;) {
        rxmsg = (char *)OSMboxPend(TxMbox, 0, &err);          /* Wait for message from Task #4 */
        PC_DispChar(70, 18, *rxmsg, DISP_FGND_YELLOW + DISP_BGND_BLUE);
        OSTimeDlyHMSM(0, 0, 1, 0);                            /* Wait 1 second                 */
        OSMboxPost(AckMbox, (void *)1);                       /* Acknowledge reception of msg  */
    }
}
```

Mail Box

- A mailbox is for data exchanging between tasks.
  - A mailbox consists of a data pointer and a wait-list.
- OSMboxPend():
  - The message in the mailbox is retrieved.
  - If the mailbox is empty, the task is immediately **blocked** and moved to the wait-list.
  - A time-out value can be specified.
- OSMboxPost():
  - A message is posted in the mailbox.
  - If there is already a message in the mailbox, then an error is returned (not overwritten).
  - If tasks are waiting for a message from the mailbox, then the task with the highest priority is removed from the wait-list and scheduled to run.

OSTaskStkInit_FPE_x86()

- OSTaskStkInit_FPE_x86(&ptos, &pbos, &size)
  - Pass the original top address, the original bottom address, and the size of the stack.
  - On the return, arguments are modified, and some stack space are reserved for the floating point library.

OSCreateTaskExt()

```
OSTaskCreateExt(
  TaskStart,
  (void *)0,
  ptos,
  TASK_START_PRIO,
  TASK_START_ID,
  pbos,
  size,
  (void *)0,
  OS_TASK_OPT_STK_CHK |
  OS_TASK_OPT_STK_CLR
  );
```


OSTaskStkCheck()

- Check for any stack overflow
  - bos < (tos – stack length)
  - Local variables, arguments for procedure calls, and temporary storage for ISR’s.
  - *u*C/OS-II can check for any stack overflow for the creation of tasks and when OSTaskStkCheck() is called.
  - *u*C/OS-II does not automatically check for the status of stacks.

Example2: Stack Checking

- Summary:
  - Local variable, function calls, and ISR's will utilize the stack space of user tasks.
    - ISR will use the stack of the interrupted task.
  - If floating-point operations are needed, then some stack space should be reserved.
  - Mailboxes can be used to synchronize the work of tasks.

Example 3: Extension of *u*C/OS-II

- A Pointer to from the TCB of each task to a user-provided data structure
  - Passing user-specified data structures on task creations or have application-specific usage.
- Message queues
  - More than one potiners
- Demonstration on how to use OS hooks to receive/process desired event from the *u*C/OS-II

Example 3: Extension of *u*C/OS-II


```
#define         TASK_STK_SIZE     512               /* Size of each task's stacks (# of WORDs)       */

#define         TASK_START_ID       0               /* Application tasks                             */
#define         TASK_CLK_ID         1
#define         TASK_1_ID           2
#define         TASK_2_ID           3
#define         TASK_3_ID           4
#define         TASK_4_ID           5
#define         TASK_5_ID           6

#define         TASK_START_PRIO    10               /* Application tasks priorities                  */
#define         TASK_CLK_PRIO      11
#define         TASK_1_PRIO        12
#define         TASK_2_PRIO        13
#define         TASK_3_PRIO        14
#define         TASK_4_PRIO        15
#define         TASK_5_PRIO        16

#define         MSG_QUEUE_SIZE     20               /* Size of message queue used in example         */

typedef struct {
    char    TaskName[30];
    INT16U  TaskCtr;
    INT16U  TaskExecTime;
    INT32U  TaskTotExecTime;
} TASK_USER_DATA;


OS_STK          TaskStartStk[TASK_STK_SIZE];        /* Startup    task stack                         */
OS_STK          TaskClkStk[TASK_STK_SIZE];          /* Clock      task stack                         */
OS_STK          Task1Stk[TASK_STK_SIZE];            /* Task #1    task stack                         */
OS_STK          Task2Stk[TASK_STK_SIZE];            /* Task #2    task stack                         */
OS_STK          Task3Stk[TASK_STK_SIZE];            /* Task #3    task stack                         */
OS_STK          Task4Stk[TASK_STK_SIZE];            /* Task #4    task stack                         */
OS_STK          Task5Stk[TASK_STK_SIZE];            /* Task #5    task stack                         */

TASK_USER_DATA  TaskUserData[7];

OS_EVENT       *MsgQueue;                           /* Message queue pointer                         */
void           *MsgQueueTbl[20];                    /* Storage for messages                          */
```

User-defined data structure to pass to tasks

Message queue and an array of event

```
void  Task1 (void *pdata)
{
   char  *msg;
   INT8U  err;


   pdata = pdata;
   for (;;) {
      msg = (char *)OSQPend(MsgQueue, 0, &err);
      PC_DispStr(70, 13, msg, DISP_FGND_YELLOW + DISP_BGND_BLUE);
      OSTimeDlyHMSM(0, 0, 0, 100);
   }
}


void  Task2 (void *pdata)
{
   char  msg[20];


   pdata = pdata;
   strcpy(&msg[0], "Task 2");
   for (;;) {
      OSQPost(MsgQueue, (void *)&msg[0]);
      OSTimeDlyHMSM(0, 0, 0, 500);
   }
}
```

Task 2, 3, 4 are functionally identical.

Message Queues

- A message queue consists of an array of elements and a wait-list.
- Different from a mailbox, a message queue can hold many data elements (in a FIFO basis).
- As same as mailboxes, there can be multiple tasks pend/post to a message queue.
- OSQPost(): a message is appended to the queue. The highest-priority pending task (in the wait-list) receives the message and is scheduled to run, if any.
- OSQPend(): a message is removed from the array of elements. If no message can be retrieved, the task is moved to the wait-list and becomes blocked.

Hooks

- A hook function will be called by *u*C/OS-II when the corresponding event occurs.
  - Event handlers could be in user programs.
  - For example, OSTaskSwHook () is called every time when context switch occurs.
- The hooks are specified in the compiling time in *u*C/OS-II:
  - *u*C/OS-II is an embedded OS.
    - OS_CFG.H (OS_CPU_HOOKS_EN = 0)
  - Many OS's can register and un-register hooks.

User Customizable Hooks for ***u*C/OS-II**

void OSInitHookBegin (void)
void OSInitHookEnd (void)
void OSTaskCreateHook (OS_TCB *ptcb)
void OSTaskDelHook (OS_TCB *ptcb)
void OSTaskIdleHook (void)
void OSTaskStatHook (void)
void OSTaskSwHook (void)
void OSTCBInitHook (OS_TCB *ptcb)
void OSTimeTickHook (void)

```
void  OSTaskStatHook (void)
{
    char    s[80];
    INT8U   i;
    INT32U  total;
    INT8U   pct;


    total = 0L;                                     /* Totalize TOT. EXEC. TIME for each task */
    for (i = 0; i < 7; i++) {
        total += TaskUserData[i].TaskTotExecTime;
        DispTaskStat(i);                            /* Display task data                      */
    }
    if (total > 0) {
        for (i = 0; i < 7; i++) {                   /* Derive percentage of each task         */
            pct = 100 * TaskUserData[i].TaskTotExecTime / total;
            sprintf(s, "%3d %%", pct);
            PC_DispStr(62, i + 11, s, DISP_FGND_BLACK + DISP_BGND_LIGHT_GRAY);
        }
    }
    if (total > 1000000000L) {                      /* Reset total time counters at 1 billion */
        for (i = 0; i < 7; i++) {
            TaskUserData[i].TaskTotExecTime = 0L;
        }
    }
}

void  OSTaskSwHook (void)
{
    INT16U          time;
    TASK_USER_DATA  *puser;


    time  = PC_ElapsedStop();                   /* This task is done                          */
    PC_ElapsedStart();                          /* Start for next task                        */
    puser = OSTCBCur->OSTCBExtPtr;              /* Point to used data                         */
    if (puser != (TASK_USER_DATA *)0) {
        puser->TaskCtr++;                       /* Increment task counter                     */
        puser->TaskExecTime     = time;         /* Update the task's execution time           */
        puser->TaskTotExecTime += time;         /* Update the task's total execution time     */
    }
}
```

Elapsed time for the current task

OSTCBCur → TCB of the current task
OSTCBHighRdy → TCB of the new task

Example 3: Extension of *u*C/OS-II

- Summary:
  - Message queues can be used to synchronize among tasks.
    - Multiple messages can be held in a queue.
    - Multiple tasks can “pend”/“post” to message queues simultaneously.
  - Hooks can be used to do some user-specific computations on certain OS events occurs.
    - They are specified in the compiling time.
- A Pointer to from the TCB of each task to a user-provided data structure

Introduction

- Getting Started with *u*C/OS-II:
  - How to write a dummy *u*C/OS-II program?
  - How the control flows among procedures?
  - How tasks are created?
  - How tasks are synchronized by semaphore, mailbox, and message queues?
  - How the space of a stack is utilized?
  - How to capture system events?

Contents

- Introduction
- Kernel Structure

Objectives

- To understand what a task is.
- To learn how *u*C/OS-II manages tasks.
- To know how an interrupt service routine (ISR) works.
- To learn how to determine the percentage of CPU that your application is using.

The *u*C/OS-II File Structure

Application Code (Your Code!)

Processor independent implementations

•Scheduling policy
•Event flags
•Semaphores
•Mailboxes
•Event queues
•Task management
•Time management
•Memory management

Application Specific Configurations

OS_CFG.H

•Max # of tasks
•Max Queue length
•…

uC/OS-2 port for processor specific codes

Software

Hardware

CPU

Timer

Source Availability

- Download the “Ports” of *u*C/OS-II from the web site http://www.ucos-II.com/
  - Processor-independent and dependent code sections (for Intel 80x86) are contained in the companion CD-ROM of the textbook

Critical Sections

- A *critical section* is a portion of code that is not safe from race conditions because of the use of shared resources.
- They can be protected by interrupt disabling/enabling interrupts or semaphores.
  - The use of semaphores often imposes a more significant amount of overheads.
  - A RTOS often use interrupts disabling/ enabling to protect critical sections.
- Once interrupts are disabled, neither context switches nor any other ISR’s can occur.

Critical Sections

```
...
OS_ENTER_CRITICAL();
/* Critical Section */
OS_EXIT_CRITICAL();
...
```

- Interrupt latency is vital to an RTOS!
  - Interrupts should be disabled as short as possible to improve the responsiveness.
  - It must be accounted as a blocking time in the schedulability analysis.
- Interrupt disabling must be used carefully:
  - E.g., if OSTimeDly() is called with interrupt disabled, the machine might hang!

Critical Sections

- The states of the processor must be carefully maintained across multiple calls of OS_ENTER_CRITICAL() and OS_EXIT_CRITICAL().
- There are three implementations in *u*C/OS-II:
  - Interrupt enabling/disabling instructions.
  - Interrupt status save/restore onto/from stacks.
  - Processor Status Word (PSW) save/restore onto/from memory variables.
- Interrupt enabling/disabling can be done by various way:
  - In-line assembly.
  - Compiler extension for specific processors.

Critical Sections

- OS_CRITICAL_METHOD=1
  - Interrupt enabling/disabling instructions.
  - The simplest way! However, this approach does not have the sense of “save” and “restore”.
  - Interrupt statuses might not be consistent across kernel services/function calls!!

```
{
    .
    disable_interrupt();
    a_kernel_service();
    .
    .
}
```

```
{
    .
    disable_interrupt();
    critical section
    enable_interrupt();
    .
}
```

Interrupts are now implicitly re-enabled!

Critical Sections

- OS_CRITICAL_METHOD=2
- Processor Status Word (PSW) can be saved/restored onto/from stacks.
  - PSW’s of nested interrupt enable/disable operations can be exactly recorded in stacks.

```
#define OS_ENTER_CRITICAL() \
        asm(“PUSH    PSW”) \
        asm(“DI”)

#define OS_EXIT_CRITICAL() \
        asm(“POP     PSW”)
```

Some compilers might not be smart enough to adjust the stack pointer after the processing of in-line assembly.

Critical Sections

- OS_CRITICAL_METHOD=3
- The compiler and processor allow the PSW to be saved/restored to/from a memory variable.

```
void foo(arguments)
{
    OS_CPU_SR cpu_sr;
    .
    cpu_sr = get_processor_psw();
    disable_interrupts();
    .
    /* critical section */
    .
    set_processor_psw(cpu_sr);
    .
}
```

OS_ENTER_CRITICAL()

OS_EXIT_CRITICAL()

Tasks

- A task is an active entity which could do some computations.
- Under real-time *u*C/OS-II systems, a task is typically an infinite loop.

```
void YourTask (void *pdata)                    (1)
{
   for (;;) {                                  (2)
      /* USER CODE */
      Call one of uC/OS-II's services:
      OSMboxPend();
      OSQPend();
      OSSemPend();
      OSTaskDel(OS_PRIO_SELF);
      OSTaskSuspend(OS_PRIO_SELF);
      OSTimeDly();
      OSTimeDlyHMSM();
      /* USER CODE */
   }
}
```

Delay itself for the next event/period, so that other tasks can run.

Tasks

- *u*C/OS-II can have up to 64 priorities.
  - Each task must be associated with an unique priority.
  - 63 and 62 are reserved (idle, stat).
- An insufficient number of priority might damage the schedulability of a real-time scheduler.
  - The number of schedulable task would be reduced.
    - Because there is no distinction among the tasks with the same priority.
    - For example, under RMS, tasks have different periods but are assigned with the same priority.
    - It is possible that all other tasks with the same priority are always issued before a particular task.
  - Fortunately, most embedded systems have a limited number of tasks to run.

Tasks

- A task is created by OSTaskCreate() or OSTaskCreateExt().
- The priority of a task can be changed by OSTaskChangePrio().
- A task could delete itself when it is done.

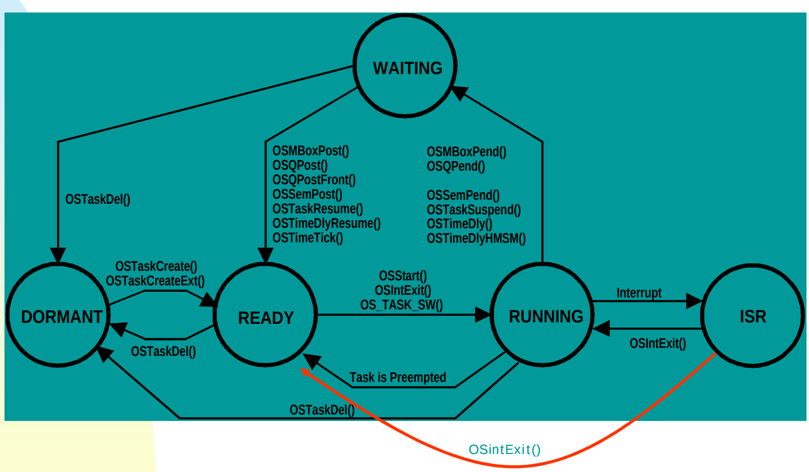
```
void YourTask (void *pdata)
{
   /* USER CODE */
   OSTaskDel(OS_PRIO_SELF);
}
```

The priority of the current task

Task States

- Dormant: Procedures residing on RAM/ROM is not an task unless you call OSTaskCreate() to execute them.
  - No tasks correspond to the codes yet!
- Ready: A task is neither delayed nor waiting for any event to occur.
  - A task is ready once it is created.
- Running: A ready task is scheduled to run on the CPU .
  - There must be only one running task.
  - The task running might be preempted and become ready.
- Waiting: A task is waiting for certain events to occur.
  - Timer expiration, signaling of semaphores, messages in mailboxes, and etc.
- ISR: A task is preempted by an interrupt.
  - The stack of the interrupted task is utilized by the ISR.

Task States



Task States

- A task can delay itself by calling OSTimeDly() or OSTimeDlyHMSM().
  - The task is placed in the waiting state.
  - The task will be made ready by the execution of OSTimeTick().
    - It is the clock ISR! You don't have to call it explicitly from your code.
- A task can wait for an event by OSFlagPend(), OSSemPend(), OSMboxPend(), or OSQPend().
  - The task remains waiting until the occurrence of the desired event (or timeout).

Task States

- The running task could be preempted by an ISR unless interrupts are disabled.
  - ISR's could make one or more tasks ready by signaling events.
  - On the return of an ISR, the scheduler will check if rescheduling is needed.
- Once new tasks become ready, the next highest priority ready task is scheduled to run (due to occurrences of events, e.g., timer expiration).
- If no task is running, and all tasks are not in the ready state, the idle task executes.

Task Control Blocks (TCB)

- A TCB is a main-memory-resident data structure used to maintain the state of a task, especially when it is preempted.
- Each task is associated with a TCB.
  - All valid TCB's are doubly linked.
  - Free TCB's are linked in a free list.
- The contents of a TCB is saved/restored when a context-switch occurs.
  - Task priority, delay counter, event to wait, the location of the stack.
  - CPU registers are stored in the stack rather than in the TCB.


```
typedef struct os_tcb {
    OS_STK        *OSTCBStkPtr;
#if OS_TASK_CREATE_EXT_EN
    void          *OSTCBExtPtr;
    OS_STK        *OSTCBStkBottom;
    INT32U         OSTCBStkSize;
    INT16U         OSTCBOpt;
    INT16U         OSTCBId;
#endif
    struct os_tcb *OSTCBNext;
    struct os_tcb *OSTCBPrev;
#if (OS_Q_EN && (OS_MAX_QS >= 2)) || OS_MBOX_EN || OS_SEM_EN
    OS_EVENT      *OSTCBEventPtr;
#endif
#if (OS_Q_EN && (OS_MAX_QS >= 2)) || OS_MBOX_EN
    void          *OSTCBMsg;
#endif

    INT16U         OSTCBDly;
    INT8U          OSTCBStat;
    INT8U          OSTCBPrio;
    INT8U          OSTCBX;
    INT8U          OSTCBY;
    INT8U          OSTCBBitX;
    INT8U          OSTCBBitY;
#if OS_TASK_DEL_EN
    BOOLEAN        OSTCBDelReq;
#endif
} OS_TCB;
```

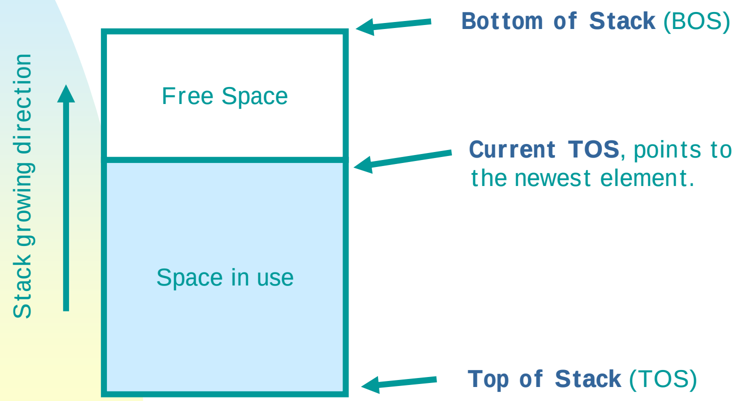
Task Control Blocks (TCB)

- .OSTCBStkPtr contains a pointer to the current TOS for the task.
  - It is the first entry of TCB so that it can be accessed directly from assembly language. (offset=0)
- .OSTCBExtPtr is a pointer to a user-definable task control block extension.
  - Set OS_TASK_CREATE_EXT_EN to 1.
  - The pointer is set when OSTaskCreateExt( ) is called
  - The pointer is ordinarily cleared in the hook OSTaskDelHook().

Task Control Blocks (TCB)

- .OSTCBStkBottom is a pointer to the bottom of the task's stack.
- .OSTCBStkSize holds the size of the stack in the number of elements, instead of bytes.
  - The element size is a macro OS_STK.
  - The total stack size is OSTCBStkSize*OS_STK bytes
  - .OSTCBStkBottom and .OSTCBStkSize are used to check up stacks (if OSTaskCreateExt( ) is invoked).

Task Control Blocks (TCB)



Task Control Blocks (TCB)

- **.OSTCBOpt** holds "options" that can be passed to OSTaskCreateExt( )
  - OS_TASK_OPT_STK_CHK: stack checking is enabled for the task .
  - OS_TASK_OPT_STK_CLR: indicates that the stack needs to be cleared when the task is created.
  - OS_TASK_OPT_SAVE_FP: Tell OSTaskCreateExt() that the task will be doing floating-point computations. Floating point processor's registers must be saved to the stack on context-switches.
- **.OSTCBId**: hold an identifier for the task.
- **.OSTCBNext** and **.OSTCBPrev** are used to doubly link OS_TCB's

Task Control Blocks (TCB)

- **.OSTCBEVEventPtr** is pointer to an event control block.
- **.OSTCBMsg** is a pointer to a message that is sent to a task.
- **.OSTCBFlagNode** is a pointer to a flagnode.
- **.OSTCBFlagsRdy** maintains info regarding which event flags make the task ready**.**
- **.OSTCBDly** is used when
  - a task needs to be delayed for a certain number of clock ticks, or
  - a task needs to wait for an event to occur with a timeout.
- **.OSTCBStat** contains the state of the task (0 is ready to run).
- **.OSTCBPrio** contains the task priority.

Task Control Blocks (TCB)

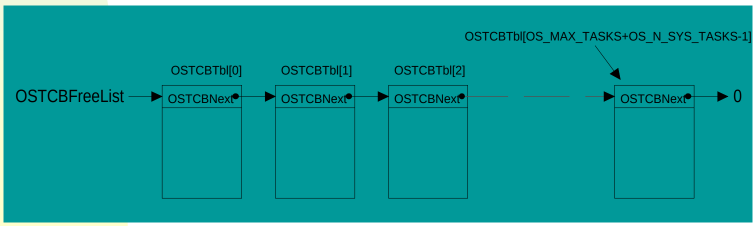
- **.OSTCBX .OSTCBY .OSTCBBitX** and **.OSTCBBitY**
  - They are used to accelerate the process of making a task ready to run or make a task wait for an event.

```
OSTCBY = priority >> 3;
OSTCBBitY     = OSMapTbl[priority >> 3];
OSTCBX = priority & 0x07;
OSTCBBitX     = OSMapTbl[priority & 0x07];
```

- **.OSTCBDelReq** is a boolean used to indicate whether or not a task requests that the current task to be deleted.
- OS_MAX_TASKS is specified in OS_CFG.H
  - # OS_TCB's allocated by *u*C/OS-**II**
- **OSTCBTbl**[ ] : where all OS_TCB's are placed.
- When *u*C/OS-II is initialized, all OS_TCB's in the table are linked in a singly linked list of free OS_TCB's.

Task Control Blocks (TCB)

- When a task is created, the OS_TCB pointed to by OSTCBFreeList is assigned to the task, and OSTCBFreeList is adjusted to point to the next OS_TCB in the chain.
- When a task is deleted, its OS_TCB is returned to the list of free OS_TCB.
- An OS_TCB is initialized by the function OS_TCBInit(), which is called by OSTaskCreate().




```
INT8U  OS_TCBInit (INT8U prio, OS_STK *ptos, OS_STK *pbos, INT16U id, INT32U stk_size, void *pext, INT16U
opt)
{
#if OS_CRITICAL_METHOD == 3                               /* Allocate storage for CPU status register */
    OS_CPU_SR  cpu_sr;
#endif
    OS_TCB    *ptcb;


    OS_ENTER_CRITICAL();
    ptcb = OSTCBFreeList;                                 /* Get a free TCB from the free TCB list    */
    if (ptcb != (OS_TCB *)0) {
        OSTCBFreeList        = ptcb->OSTCBNext;           /* Update pointer to free TCB list          */
        OS_EXIT_CRITICAL();
        ptcb->OSTCBStkPtr    = ptos;                      /* Load Stack pointer in TCB                */
        ptcb->OSTCBPrio      = (INT8U)prio;               /* Load task priority into TCB              */
        ptcb->OSTCBStat      = OS_STAT_RDY;               /* Task is ready to run                     */
        ptcb->OSTCBDly       = 0;                         /* Task is not delayed                      */

#if OS_TASK_CREATE_EXT_EN > 0
        ptcb->OSTCBExtPtr    = pext;                      /* Store pointer to TCB extension           */
        ptcb->OSTCBStkSize   = stk_size;                  /* Store stack size                         */
        ptcb->OSTCBStkBottom = pbos;                      /* Store pointer to bottom of stack         */
        ptcb->OSTCBOpt       = opt;                       /* Store task options                       */
        ptcb->OSTCBId        = id;                        /* Store task ID                            */
#else
        pext                 = pext;                      /* Prevent compiler warning if not used     */
        stk_size             = stk_size;
        pbos                 = pbos;
        opt                  = opt;
        id                   = id;
#endif

#if OS_TASK_DEL_EN > 0
        ptcb->OSTCBDelReq    = OS_NO_ERR;
#endif

        ptcb->OSTCBY         = prio >> 3;                 /* Pre-compute X, Y, BitX and BitY          */
        ptcb->OSTCBBitY      = OSMapTbl[ptcb->OSTCBY];
        ptcb->OSTCBX         = prio & 0x07;
        ptcb->OSTCBBitX      = OSMapTbl[ptcb->OSTCBX];
```

Get a free TCB from the free list

```
#if OS_EVENT_EN > 0
        ptcb->OSTCBEventPtr  = (OS_EVENT *)0;             /* Task is not pending on an event         */
#endif

#if (OS_VERSION >= 251) && (OS_FLAG_EN > 0) && (OS_MAX_FLAGS > 0) && (OS_TASK_DEL_EN > 0)
        ptcb->OSTCBFlagNode  = (OS_FLAG_NODE *)0;         /* Task is not pending on an event flag    */
#endif

#if (OS_MBOX_EN > 0) || ((OS_Q_EN > 0) && (OS_MAX_QS > 0))
        ptcb->OSTCBMsg       = (void *)0;                 /* No message received                     */
#endif

#if OS_VERSION >= 204
        OSTCBInitHook(ptcb);
#endif

        OSTaskCreateHook(ptcb);                           /* Call user defined hook                  */

        OS_ENTER_CRITICAL();
        OSTCBPrioTbl[prio] = ptcb;
        ptcb->OSTCBNext    = OSTCBList;                   /* Link into TCB chain                     */
        ptcb->OSTCBPrev    = (OS_TCB *)0;
        if (OSTCBList != (OS_TCB *)0) {
            OSTCBList->OSTCBPrev = ptcb;
        }
        OSTCBList              = ptcb;
        OSRdyGrp              |= ptcb->OSTCBBitY;         /* Make task ready to run                  */
        OSRdyTbl[ptcb->OSTCBY] |= ptcb->OSTCBBitX;
        OS_EXIT_CRITICAL();
        return (OS_NO_ERR);
    }
    OS_EXIT_CRITICAL();
    return (OS_NO_MORE_TCB);
}
```

User-defined hook is called here.

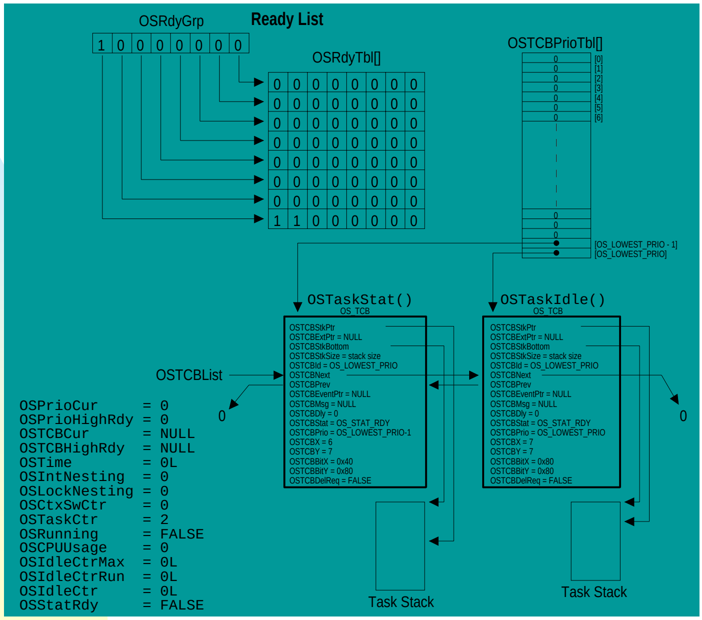
Priority table

TCB list

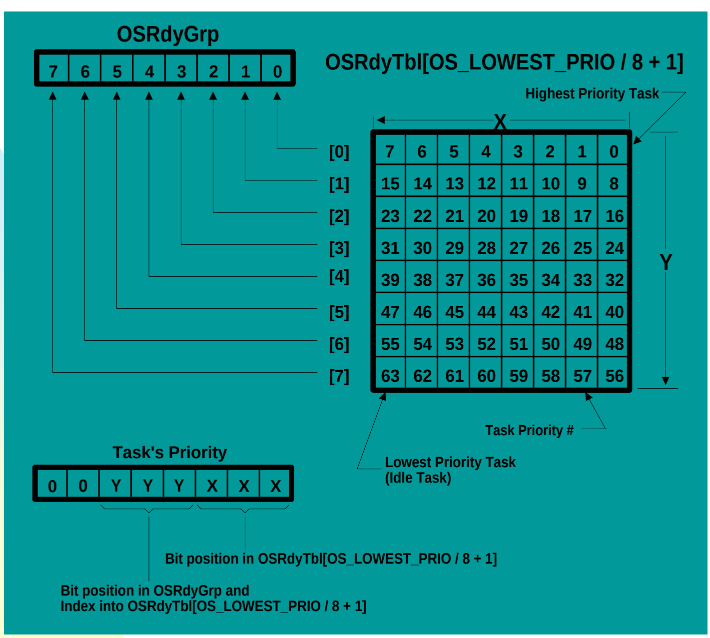
Ready list

Ready List

- Ready list is a special bitmap to reflect which task is currently in the ready state.
  - Each task is identified by its unique priority in the bitmap.
- A primary design consideration of the ready list is how to efficiently locate the highest-priority ready task.
  - The designer could trade some ROM space for an improved performance.
- If a linear list is adopted, it takes O(n) to locate the highest-priority ready task.
  - It takes O(log n) if a heap is adopted.
  - Under the design of ready list of *u*C/OS-II, it takes only O(1).
    - Note that the space consumption is much more than other approaches, and it also depends on the bus width.



Ready List
OSRdyGrp
OSRdyTbl[]
OSTCBPrioTbl[]
[OS_LOWEST_PRIO - 1]
[OS_LOWEST_PRIO]
OSTaskStat()
OSTaskIdle()
OS_TCB
OSTCBList
OSPrioCur = 0
OSPrioHighRdy = 0
OSTCBCur = NULL
OSTCBHighRdy = NULL
OSTime = 0L
OSIntNesting = 0
OSLockNesting = 0
OSCtxSwCtr = 0
OSTaskCtr = 2
OSRunning = FALSE
OSCPUUsage = 0
OSIdleCtrMax = 0L
OSIdleCtrRun = 0L
OSIdleCtr = 0L
OSStatRdy = FALSE
Task Stack
Task Stack



OSRdyGrp
OSRdyTbl[OS_LOWEST_PRIO / 8 + 1]
Highest Priority Task
X
Y
Task Priority #
Lowest Priority Task
(Idle Task)
Task's Priority
0 0 Y Y Y X X X
Bit position in OSRdyTbl[OS_LOWEST_PRIO / 8 + 1]
Bit position in OSRdyGrp and
Index into OSRdyTbl[OS_LOWEST_PRIO / 8 + 1]

OSMapTbl

Index	Bit mask (Binary)
0	00000001
1	00000010
2	00000100
3	00001000
4	00010000
5	00100000
6	01000000
7	10000000

Bit 0 in **OSRdyGrp** is 1 when any bit in **OSRdyTbl[0]** is 1.
Bit 1 in **OSRdyGrp** is 1 when any bit in **OSRdyTbl[1]** is 1.
Bit 2 in **OSRdyGrp** is 1 when any bit in **OSRdyTbl[2]** is 1.
Bit 3 in **OSRdyGrp** is 1 when any bit in **OSRdyTbl[3]** is 1.
Bit 4 in **OSRdyGrp** is 1 when any bit in **OSRdyTbl[4]** is 1.
Bit 5 in **OSRdyGrp** is 1 when any bit in **OSRdyTbl[5]** is 1.
Bit 6 in **OSRdyGrp** is 1 when any bit in **OSRdyTbl[6]** is 1.
Bit 7 in **OSRdyGrp** is 1 when any bit in **OSRdyTbl[7]** is 1.

- Make a task ready to run:

```
OSRdyGrp            |= OSMapTbl[prio >> 3];
OSRdyTbl[prio >> 3] |= OSMapTbl[prio & 0x07];
```

- Remove a task from the ready list:

```
if ((OSRdyTbl[prio >> 3] &= ~OSMapTbl[prio & 0x07]) == 0)
    OSRdyGrp &= ~OSMapTbl[prio >> 3];
```

What does this code do?

Coding Style

The author writes:

```
if ((OSRdyTbl[prio >> 3] &= ~OSMapTbl[prio & 0x07]) == 0)
    OSRdyGrp &= ~OSMapTbl[prio >> 3];
```

How about this:

```
char x,y,mask;

    x = prio & 0x07;
    y = prio >> 3;
    mask = ~(OSMapTbl[x]);          // a mask for bit clearing
    if((OSRdyTbl[x] &= mask) == 0) // clear the task's bit
    {                        // the group bit should be cleared too
        mask = ~(OSMapTbl[y]);      // another bit mask…
        OSRdyGrp &= mask;           // clear the group bit
    }
```

Coding Style

```
mov     al,byte ptr [bp-17]
mov     ah,0
and     ax,7
lea     dx,word ptr [bp-8]
add     ax,dx
mov     bx,ax
mov     al,byte ptr ss:[bx]
not     al
mov     dl,byte ptr [bp-17]
mov     dh,0
sar     dx,3
lea     bx,word ptr [bp-16]
add     dx,bx
mov     bx,dx
and     byte ptr ss:[bx],al
mov     al,byte ptr ss:[bx]
or      al,al
jne     short @1@86
mov     al,byte ptr [bp-17]
mov     ah,0
sar     ax,3
lea     dx,word ptr [bp-8]
add     ax,dx
mov     bx,ax
mov     al,byte ptr ss:[bx]
not     al
and     byte ptr [bp-18],al
```

```
mov     al,byte ptr [bp-17]
and     al,7
mov     byte ptr [bp-19],al
mov     al,byte ptr [bp-17]
mov     ah,0
sar     ax,3
mov     byte ptr [bp-20],al
mov     al,byte ptr [bp-19]
mov     ah,0
lea     dx,word ptr [bp-8]
add     ax,dx
mov     bx,ax
mov     al,byte ptr ss:[bx]
not     al
mov     cl,al
mov     al,byte ptr [bp-19]
mov     ah,0
lea     dx,word ptr [bp-16]
add     ax,dx
mov     bx,ax
and     byte ptr ss:[bx],cl
mov     al,byte ptr ss:[bx]
or      al,al
jne     short @1@142
mov     al,byte ptr [bp-20]
mov     ah,0
lea     dx,word ptr [bp-8]
add     ax,dx
mov     bx,ax
mov     al,byte ptr ss:[bx]
not     al
mov     cl,al
and     byte ptr [bp-18],cl
```



```
INT8U const OSUnMapTbl[] = {
    0, 0, 1, 0, 2, 0, 1, 0, 3, 0, 1, 0, 2, 0, 1, 0,    /* 0x00 to 0x0F    */
    4, 0, 1, 0, 2, 0, 1, 0, 3, 0, 1, 0, 2, 0, 1, 0,    /* 0x10 to 0x1F    */
    5, 0, 1, 0, 2, 0, 1, 0, 3, 0, 1, 0, 2, 0, 1, 0,    /* 0x20 to 0x2F    */
    4, 0, 1, 0, 2, 0, 1, 0, 3, 0, 1, 0, 2, 0, 1, 0,    /* 0x30 to 0x3F    */
    6, 0, 1, 0, 2, 0, 1, 0, 3, 0, 1, 0, 2, 0, 1, 0,    /* 0x40 to 0x4F    */
    4, 0, 1, 0, 2, 0, 1, 0, 3, 0, 1, 0, 2, 0, 1, 0,    /* 0x50 to 0x5F    */
    5, 0, 1, 0, 2, 0, 1, 0, 3, 0, 1, 0, 2, 0, 1, 0,    /* 0x60 to 0x6F    */
    4, 0, 1, 0, 2, 0, 1, 0, 3, 0, 1, 0, 2, 0, 1, 0,    /* 0x70 to 0x7F    */
    7, 0, 1, 0, 2, 0, 1, 0, 3, 0, 1, 0, 2, 0, 1, 0,    /* 0x80 to 0x8F    */
    4, 0, 1, 0, 2, 0, 1, 0, 3, 0, 1, 0, 2, 0, 1, 0,    /* 0x90 to 0x9F    */
    5, 0, 1, 0, 2, 0, 1, 0, 3, 0, 1, 0, 2, 0, 1, 0,    /* 0xA0 to 0xAF    */
    4, 0, 1, 0, 2, 0, 1, 0, 3, 0, 1, 0, 2, 0, 1, 0,    /* 0xB0 to 0xBF    */
    6, 0, 1, 0, 2, 0, 1, 0, 3, 0, 1, 0, 2, 0, 1, 0,    /* 0xC0 to 0xCF    */
    4, 0, 1, 0, 2, 0, 1, 0, 3, 0, 1, 0, 2, 0, 1, 0,    /* 0xD0 to 0xDF    */
    5, 0, 1, 0, 2, 0, 1, 0, 3, 0, 1, 0, 2, 0, 1, 0,    /* 0xE0 to 0xEF    */
    4, 0, 1, 0, 2, 0, 1, 0, 3, 0, 1, 0, 2, 0, 1, 0     /* 0xF0 to 0xFF    */
};
```

- Finding the highest-priority task ready to run:

```
y    = OSUnMapTbl[OSRdyGrp];
x    = OSUnMapTbl[OSRdyTbl[y]];
prio = (y << 3) + x;
```

This matrix is used to locate the first LSB which is '1', by given a value.

For example, if 00110010 is given, then '1' is returned.

Task Scheduling

- The scheduler always schedules the highest-priority ready task to run .
- Task-level scheduling and ISR-level scheduling are done by OS_Sched() and OSIntExit(), respectively.
  - The difference is the saving/restoration of PSW (or CPU flags).
- *u*C/OS-II scheduling time is a predictable amount of time, i.e., a constant time.
  - For example, the design of the ready list intends to achieve this objective.

Task Scheduling

```
void OSSched (void)
{
    INT8U y;
    OS_ENTER_CRITICAL();
    if ((OSLockNesting | OSIntNesting) == 0) {                          (1)
        y             = OSUnMapTbl[OSRdyGrp];                           (2)
        OSPrioHighRdy = (INT8U)((y << 3) + OSUnMapTbl[OSRdyTbl[y]]);    (2)
        if (OSPrioHighRdy != OSPrioCur) {                               (3)
            OSTCBHighRdy = OSTCBPrioTbl[OSPrioHighRdy];                 (4)
            OSCtxSwCtr++;                                               (5)
            OS_TASK_SW();                                               (6)
        }
    }
    OS_EXIT_CRITICAL();
}
```

(1) Rescheduling will not be done if the scheduler is locked or an ISR is currently serviced.

(2) Find the highest-priority ready task.

(3) If it is not the current task, then skip!

(4) (4)~(6) Perform a context-switch.

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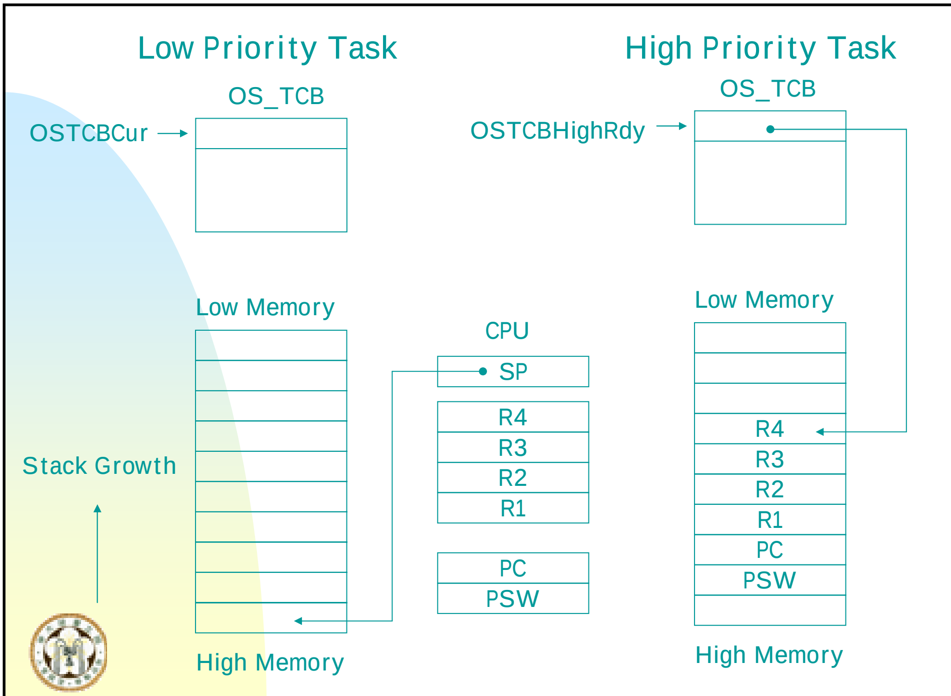
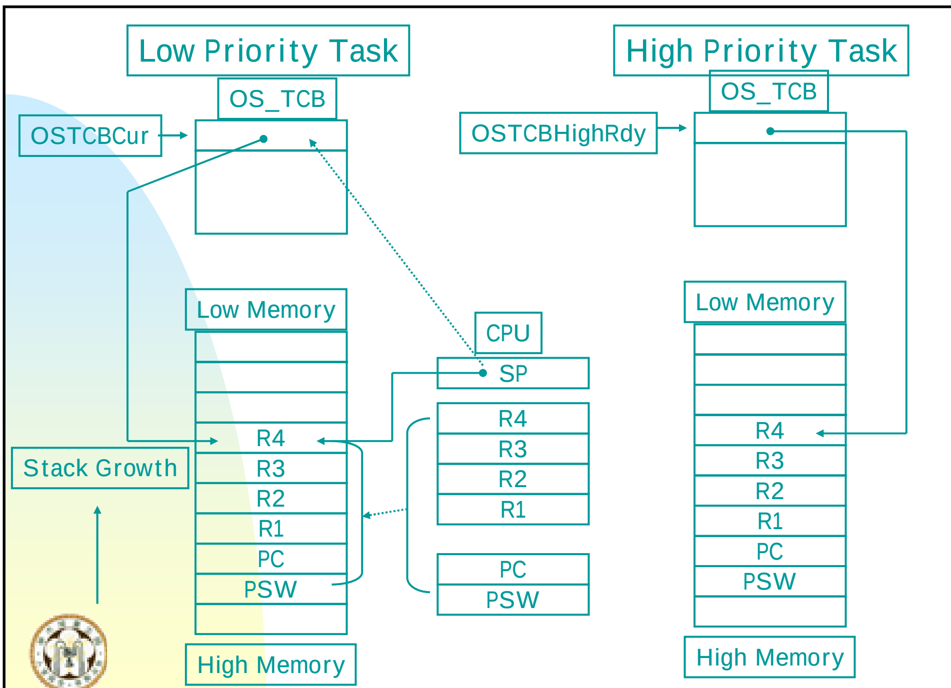
Task Scheduling

- A context switch must save all CPU registers and PSW of the preempted task onto its stack, and then restore the CPU registers and PSW of the highest-priority ready task from its stack.
- Task-level scheduling will emulate that as if preemption/scheduling is done in an ISR.
  - OS_TASK_SW() will trigger a software interrupt.
  - The interrupt is directed to the context switch handler OSCtxSw(), which is installed when *u*C/OS-II is initialized.
- Interrupts are disabled during the locating of the highest-priority ready task to prevent another ISR's from making some tasks ready.

Task-Level Context Switch

- By default, context switches are handled at the interrupt-level. Therefore task-level scheduling will invoke a software interrupt to emulate that effect:
  - Hardware-dependent! Porting must be done here.


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


Low Priority Task
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R2
R1
PC
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R4
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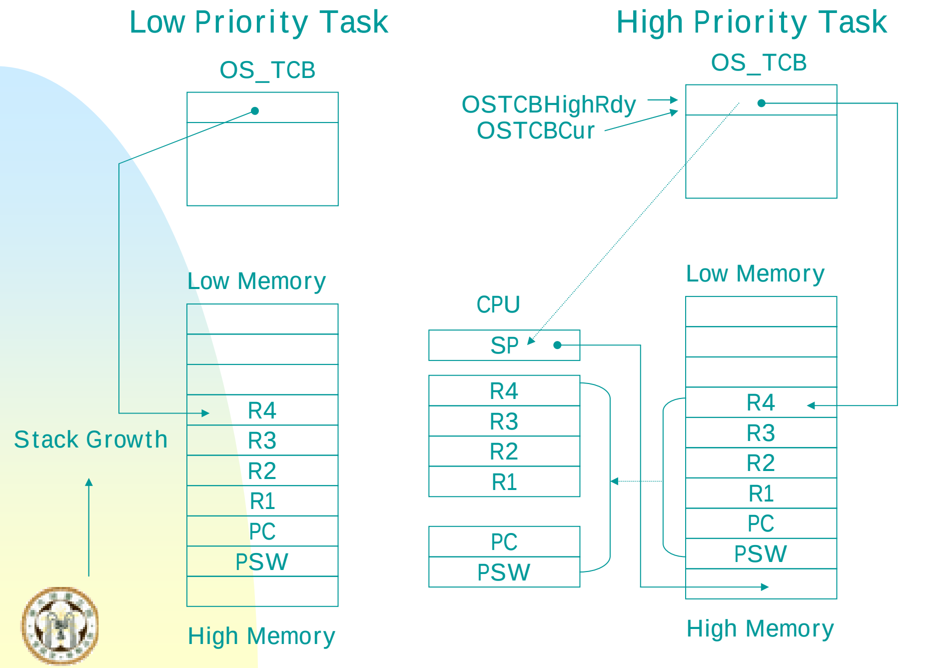
Stack Growth
High Memory
High Memory



Locking and Unlocking the Scheduler

- OSSchedLock() prevents high-priority ready tasks from being scheduled to run while interrupts are still recognized.
  - OSSchedLock() and OSSchedUnlock() must be used in pairs.
  - After calling OSSchedLock(), you must not call kernel services which might cause context switch, such as OSFlagPend(), OSMboxPend(), OSMutexPend(), OSQPend(), OSSemPend(), OSTaskSuspend(), OSTimeDly, OSTimeDlyHMSM(), until OSLockNesting == 0. Otherwise, the system will be locked up.
- Sometimes we disable scheduling (but with interrupts still recognized) because we hope to avoid lengthy interrupt latencies without introducing race conditions.
- OSLockNesting keeps track of the number of OSSchedLock() has been called.

OSSchedLock()

```
void  OSSchedLock (void)
{
#if OS_CRITICAL_METHOD == 3       /* Allocate storage for CPU status register  */
    OS_CPU_SR  cpu_sr;
#endif


    if (OSRunning == TRUE) {      /* Make sure multitasking is running
*/
        OS_ENTER_CRITICAL();
        if (OSLockNesting < 255) {/* Prevent OSLockNesting from wrapping back to
0*/
            OSLockNesting++;      /* Increment lock nesting level
*/
        }
        OS_EXIT_CRITICAL();
    }
}
```


OSSchedUnlock()

```
void  OSSchedUnlock (void)
{
#if OS_CRITICAL_METHOD == 3           /* Allocate storage for CPU status register */
    OS_CPU_SR  cpu_sr;
#endif


    if (OSRunning == TRUE) {         /* Make sure multitasking is running    */
        OS_ENTER_CRITICAL();
        if (OSLockNesting > 0) {     /* Do not decrement if already 0        */
            OSLockNesting--;         /* Decrement lock nesting level         */
            if ((OSLockNesting == 0) &&
              (OSIntNesting == 0)) { /* See if sched. enabled and not an ISR */
                OS_EXIT_CRITICAL();
                OS_Sched();          /* See if a HPT is ready                */
            } else {
                OS_EXIT_CRITICAL();
            }
        } else {
            OS_EXIT_CRITICAL();
        }
    }
}
```

Idle Task

- The idle task is always the lowest-priority task and can not be deleted or suspended by user-tasks.
- To reduce power dissipation, you can issue a HALT-like instruction in the idle task.
  - Suspend services in OSTaskIdleHook()!!

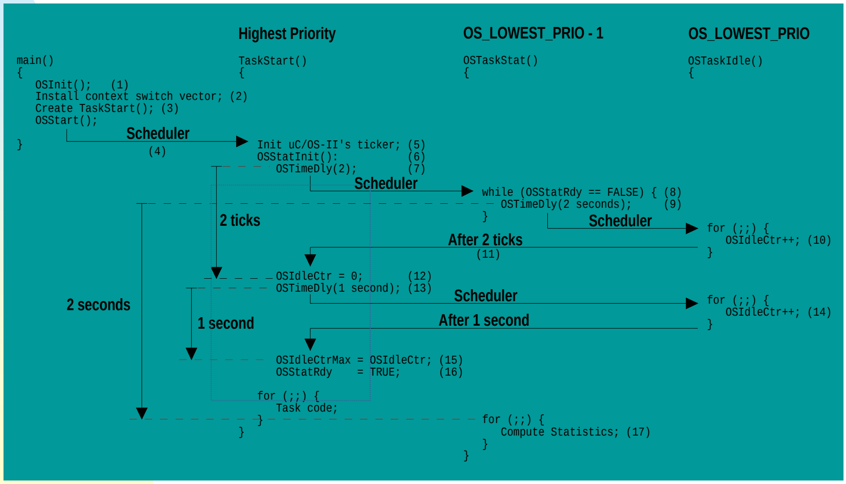
```
void  OS_TaskIdle (void *pdata)
{
#if OS_CRITICAL_METHOD == 3
   OS_CPU_SR  cpu_sr;
#endif


   pdata = pdata;
   for (;;) {
      OS_ENTER_CRITICAL();
      OSIdleCtr++;
      OS_EXIT_CRITICAL();
      OSTaskIdleHook();
   }
}
```


Statistics Task

- It is created by *u*C/OS-II. It executes every second to compute the percentage of the CPU usage.
  - It is with the OS_LOWEST_PRIO – 1 priority.
- OSStatInit() must be called before OSStart() is called.

```
void main (void)
{
    OSInit();                 /* Initialize uC/OS-II                  (1)*/
    /* Install uC/OS-II's context switch vector                          */
    /* Create your startup task (for sake of discussion, TaskStart())  (2)*/
    OSStart();                /* Start multitasking                   (3)*/
}
void TaskStart (void *pdata)
{
    /* Install and initialize µC/OS-II’s ticker                       (4)*/
    OSStatInit();             /* Initialize statistics task           (5)*/
    /* Create your application task(s)                                   */
    for (;;) {
        /* Code for TaskStart() goes here!                               */
    }
}
```

Statistics Task



Statistics Task

(7) TaskStart: Delay for 2 ticks→ transfer CPU to the statistics task to do some initialization.

(9) OS_TaskStat: Delay for 2 seconds→ Yield the CPU to the task TaskStart and the idle task.

(13) TaskStart: Delay for 1 second→ Let the idle task count OSIdleCtr for 1 second.

(15) TaskStart: When the timer expires in (13), OSIdleCtr contains the value of OSIdleCtr can be reached in 1 second.

Notes:

- Since OSStatinit() assume that the idle task will count the OSOdleCtr at the full CPU speed, you must not install an idle hook before calling OSStatInit()!!!
- After the statistics task is initialized, it is OK to install a CPU idle hook and perform some power-conserving operations! Note that the idle task consumes the CPU power just for the purpose of being idle.

Statistics Task

- With the invocation of OSStatInit(), we have known how large the value of the idle counter can reach in 1 second (OSIdleCtrMax).
- The percentage of the CPU usage can be calculated by the actual idle counter and the OSIdleCtrMax.

$$OSCPUUsage_{(\%)} = 100 \times \left(1 - \frac{OSIdleCtr}{OSIdleCtrMax}\right)$$

This term is always 0 under an integer operation

$$OSCPUUsage_{(\%)} = \left(100 - \frac{100 \times OSIdleCtr}{OSIdleCtrMax}\right)$$

$$OSCPUUsage_{(\%)} = \left(100 - \frac{OSIdleCtr}{\left(\frac{OSIdleCtrMax}{100}\right)}\right)$$

This term might overflow under fast processors! (42,949,672)

Statistics Task

```
#if OS_TASK_STAT_EN > 0
void  OS_TaskStat (void *pdata)
{
#if OS_CRITICAL_METHOD == 3
   OS_CPU_SR  cpu_sr;
#endif
   INT32U     run;
   INT32U     max;
   INT8S      usage;


   pdata = pdata;
   while (OSStatRdy == FALSE) {
      OSTimeDly(2 * OS_TICKS_PER_SEC);
   }
   max = OSIdleCtrMax / 100L;
   for (;;) {
      OS_ENTER_CRITICAL();
      OSIdleCtrRun = OSIdleCtr;
      run          = OSIdleCtr;
      OSIdleCtr    = 0L;
      OS_EXIT_CRITICAL();
      if (max > 0L) {
         usage = (INT8S)(100L - run / max);
         if (usage >= 0) {
            OSCPUUsage = usage;
         } else {
            OSCPUUsage = 0;
         }
      } else {
         OSCPUUsage = 0;
         max        = OSIdleCtrMax / 100L;
      }
      OSTaskStatHook();
      OSTimeDly(OS_TICKS_PER_SEC);
   }
}
```

Interrupts under *u*C/OS-II

- *u*C/OS-II requires an ISR being written in assembly if your compiler does not support in-line assembly!

An ISR Template:

```
Save all CPU registers;                                  (1)
Call OSIntEnter() or, increment OSIntNesting directly;   (2)
If(OSIntNesting == 1)                                    (3)
    OSTCBCur->OSTCBStkPtr = SP;                          (4)
Clear the 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)
```


Interrupts under *u*C/OS-II

(1) In an ISR, *u*C/OS-II requires that all CPU registers are saved onto the stack of the interrupted task.
- For processors like Motorola 68030_, a different stack is used for ISR.
- For such a case, the stack pointer of the interrupted task can be obtained from OSTCBCur (offset 0).

(2) Increase the interrupt-nesting counter counter.

(4) If it is the first interrupt-nesting level, we immediately save the stack pointer to OSTCBCur.
- We do this because a context-switch might occur.

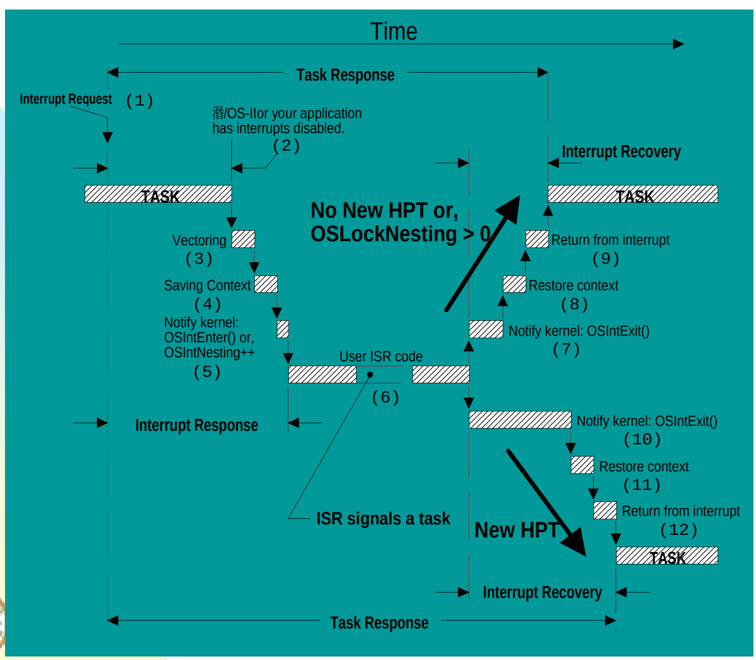
Interrupts under *u*C/OS-II

(8) Call OSIntExit(), which checks if we are in the inner-level of nested interrupts. If not, the scheduler is called.

- A potential context-switch might occur.
- The Interrupt-nesting counter is decremented.

(9) On the return from this point, there might be several high-priority tasks since *u*C/OS-II is a preemptive kernel.

(10) The CPU registers are restored from the stack, and the control is returned to the interrupted task.



Interrupts under uC/OS-2

```
void OSIntExit (void)
{
    OS_ENTER_CRITICAL();
    if ((--OSIntNesting | OSLockNesting) == 0) {
        OSIntExitY    = OSUnMapTbl[OSRdyGrp];
        OSPrioHighRdy = (INT8U)((OSIntExitY << 3) +
                        OSUnMapTbl[OSRdyTbl[OSIntExitY]]);
        if (OSPrioHighRdy != OSPrioCur) {
            OSTCBHighRdy  = OSTCBPrioTbl[OSPrioHighRdy];
            OSCtxSwCtr++;
            OSIntCtxSw();
        }
    }
    OS_EXIT_CRITICAL();
}
```

If no scheduler locking and no interrupt nesting

If there is another high-priority task ready

A context switch is executed.

Note that OSIntCtxSw() is called, instead of OS_TASK_SW(), because the ISR already saves the CPU registers onto the stack.

```
void OSIntEnter (void)
{
    OS_ENTER_CRITICAL();
    OSIntNesting++;
    OS_EXIT_CRITICAL();
}
```


Clock Tick

- A time source is needed to keep track of time delays and timeouts.
- You must enable ticker interrupts after multitasking is started.
  - In the TaskStart() task of the examples.
  - Do not do this before OSStart().
- Clock ticks are serviced by calling OSTimeTick() from a tick ISR.
- Clock tick ISR is always a port (of uC/OS-2) of a CPU since we have to access CPU registers in the tick ISR.

Clock Tick

```
void OSTickISR(void)
{
    Save processor registers;
    Call OSIntEnter() or increment OSIntNesting;
    If(OSIntNesting == 1)
            OSTCBCur->OSTCBStkPtr = SP;
    Call OSTimeTick();
    Clear interrupting device;
    Re-enable interrupts (optional);
    Call OSIntExit();
    Restore processor registers;
    Execute a return from interrupt instruction;
}
```


Clock Tick

```
void  OSTimeTick (void)
{
   OS_TCB    *ptcb;


   OSTimeTickHook();

   if (OSRunning == TRUE) {
     ptcb = OSTCBList;
     while (ptcb->OSTCBPrio != OS_IDLE_PRIO) {
        OS_ENTER_CRITICAL();
        if (ptcb->OSTCBDly != 0) {
           if (--ptcb->OSTCBDly == 0) {
              if ((ptcb->OSTCBStat & OS_STAT_SUSPEND) == OS_STAT_RDY) {
                 OSRdyGrp              |= ptcb->OSTCBBitY;
                 OSRdyTbl[ptcb->OSTCBY] |= ptcb->OSTCBBitX;
              } else {
                 ptcb->OSTCBDly = 1;
              }
           }
        }
        ptcb = ptcb->OSTCBNext;
        OS_EXIT_CRITICAL();
     }
   }
}
```

For all TCB's

Decrement delay-counter if needed

If the delay-counter reaches zero, make the task ready. Or, the task remains waiting.

Clock Tick

- OSTimeTick() is a hardware-independent routine to service the tick ISR.
- A callout-list is more efficient on the decrementing process of OSTCBDly.
  - Constant time to determine if a task should be made ready.
  - Linear time to put a task in the list.
  - Compare it with the approach of *u*C/OS-II?

Clock Tick

- You can also move the bunch of code in the tick ISR to a user task:

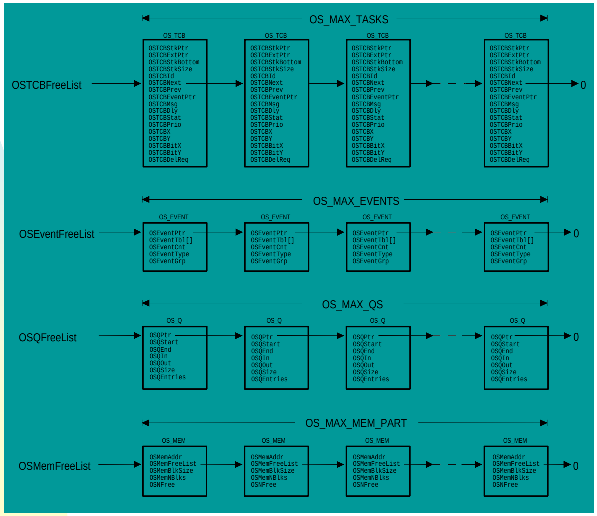
```
void OSTickISR(void)
{
    Save processor registers;
    Call OSIntEnter() or increment OSIntNesting;
    If(OSIntNesting == 1)
    OSTCBCur->OSTCBStkPtr = SP;

    Post a 'dummy' message (e.g. (void *)1)
      to the tick mailbox;

    Call OSIntExit();
    Restore processor registers;
    Execute a return from interrupt instruction;
}
```

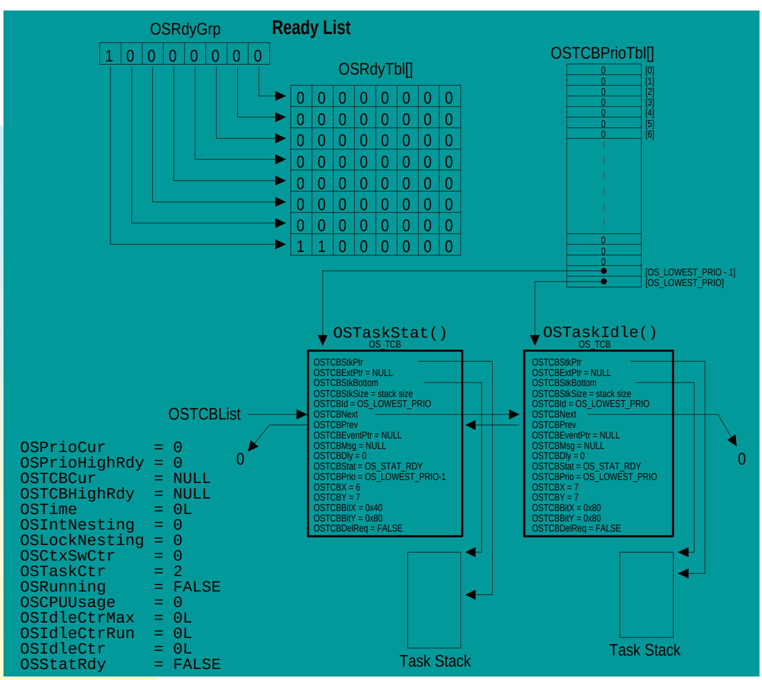
Post a message

```
void TickTask (void *pdata)
{
   pdata = pdata;
   for (;;) {
     OSMboxPend(...);
     OSTimeTick();
     OS_Sched();
   }
}
```

Do the rest of the job!

*u*C/OS-II Initialization





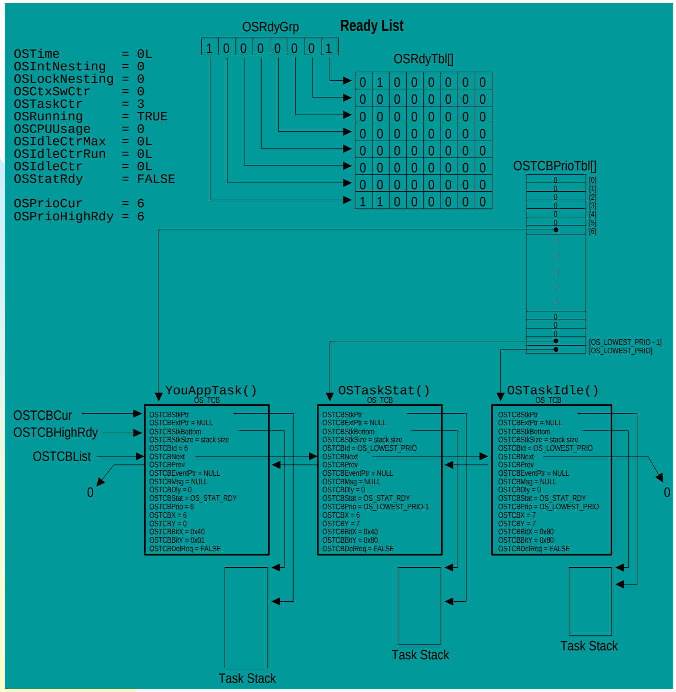
Starting of *u*C/OS-II

- OSInit() initializes data structures for *u*C/OS-II and creates OS_TaskIdle().
- OSStart() pops the CPU registers of the highest-priority ready task and then executes a return from interrupt instruction.
  - It never returns to the caller of OSStart() (i.e., main()).

Starting of *u*C/OS-II

```
void main (void)
{
    OSInit();        /* Initialize uC/OS-II                    */
    .
    Create at least 1 task using either 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];
                OSTCBCur      = OSTCBHighRdy;
                OSStartHighRdy();
            }
        }
```

Start the highest-priority ready task



Summary

- The study of the *u*C/OS-II kernel structure, we learn something:
  - What a task is? How *u*C/OS-II manages a task and related data structures.
  - How the scheduler works, especially on detailed operations done for context switching.
  - The responsibility of the idle task and the statistics task! How they works?
  - How interrupts are serviced in *u*C/OS-II.
  - The initialization and starting of *u*C/OS-II.