uC/OS-II Part 7: Mutual Exclusion Locks

Real-Time Compting
Prof. Li-Pin Chang
ESSLab@NYCU

Mutual Exclusion Locks

- A mutex synchronizes tasks with managed priority inversion
- If a LPT blocks a HPT, the priority of the LPT is boosted
  - Priority “inheritance”
  - Problem: tasks will have the same priority with inheritance, which is not allowed in uC/OS-2

Mutual Exclusion Locks

- uC/OS-II uses an alternative approach to work around the constraint of priority uniqueness
  - Reserve a priority for a mutex
  - The reserved priority (for the mutex) must be higher than all tasks that use the mutex
- Be careful about the priority for mutex!!
  - It should be immediately higher than the highest priority of all tasks use the mutex
  - To reduce the impact on unrelated tasks

Example1

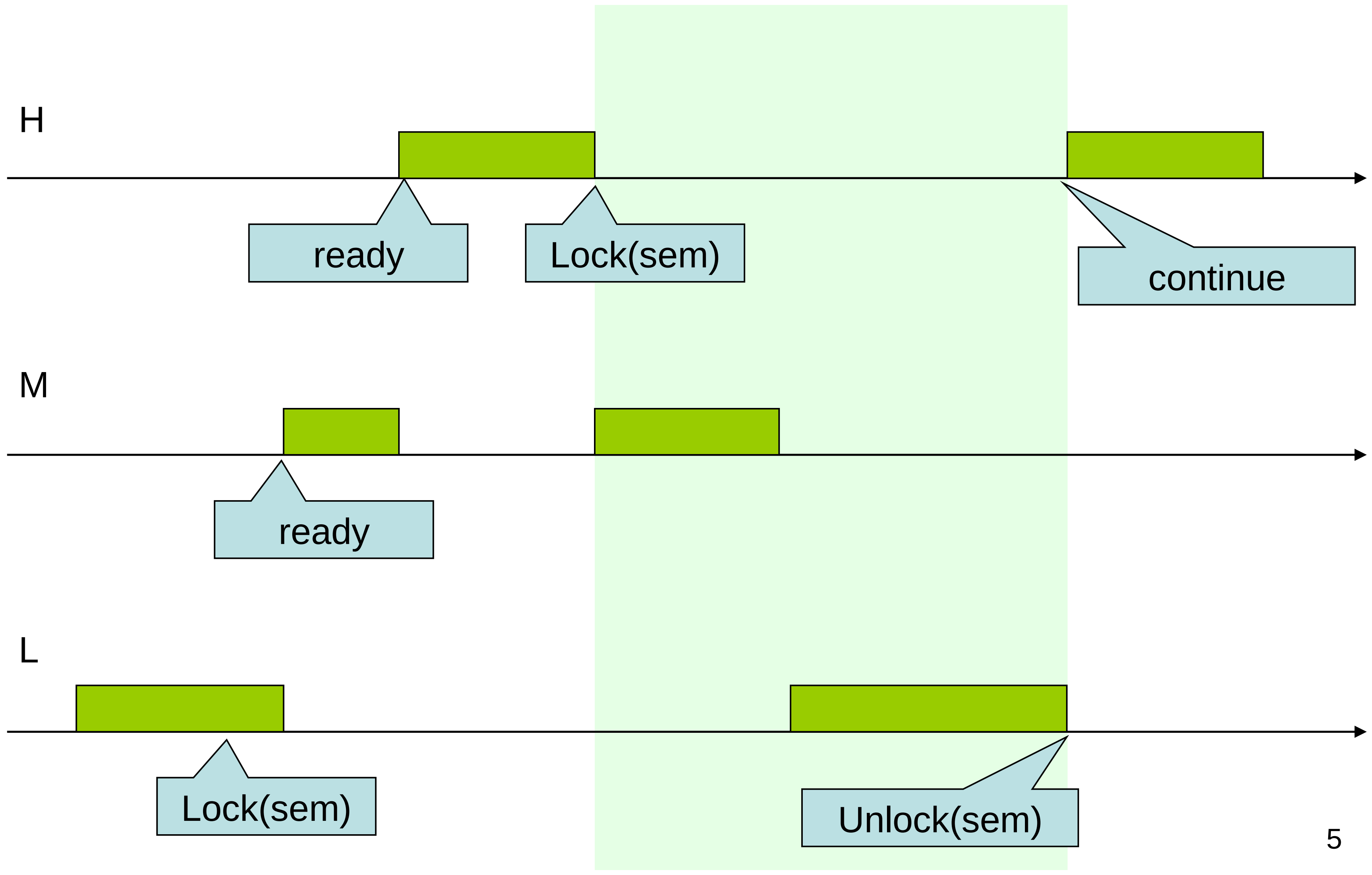
```
OSMutexCreate(VH, &err);

void taskPrioH {
        whle(1) {
                /*…*/
                OSMutexPend(mutex, 0, &err);
                /*…*/
                OSMutexPost(Mutex);
        }
}
```

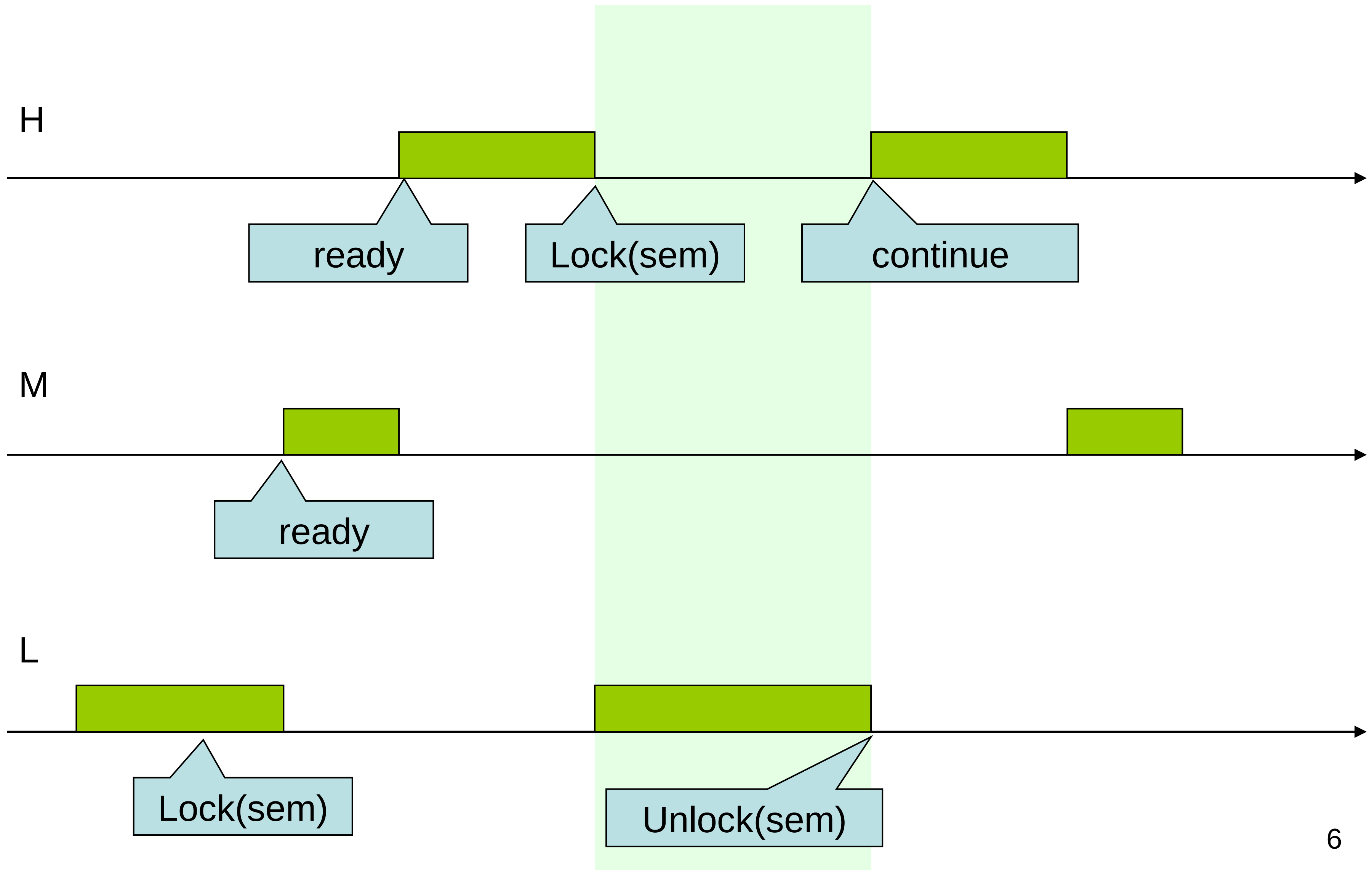
```
void taskPrioM {
        while(1) {
                /*…*/
        }
}
```

```
void taskPrioL {
        whle(1) {
                /*…*/
                OSMutexPend(mutex, 0, &err);
                /*…*/
                OSMutexPost(Mutex);
        }
}
```

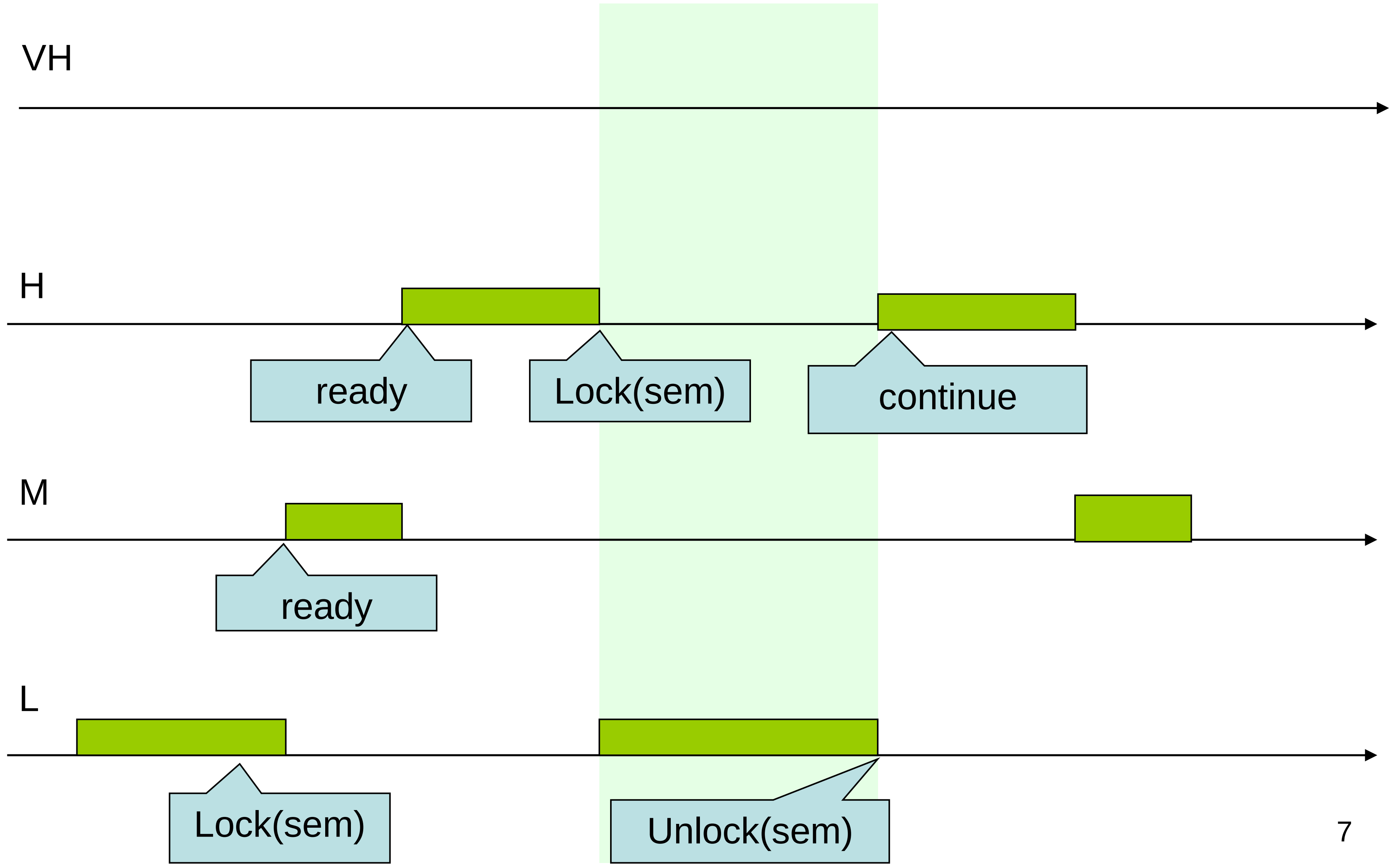
Example - without PIP



Example - with PIP



Example - μC/OS-II



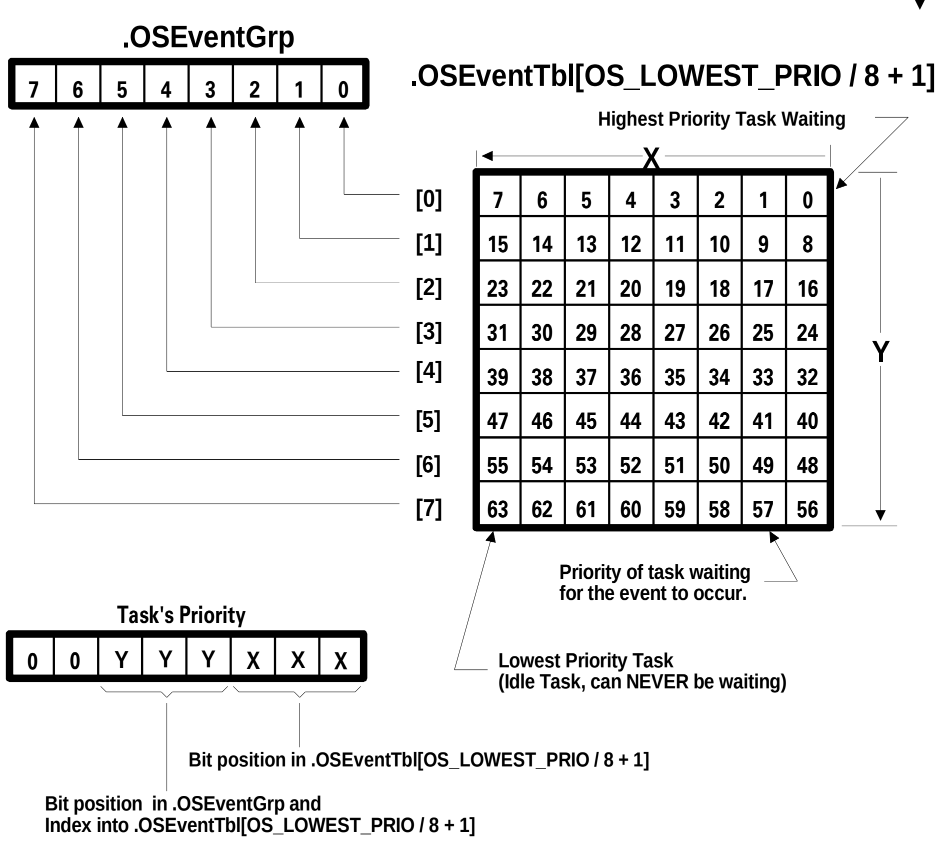
Mutual Exclusion Locks

- uC/OS-II’s mutex locks are
  - different from NPCS
    - LPT does not become non-preemptible
  - different from priority-inheritance protocol (PIP)
    - LPT’s priority is raised to the reserved priority
  - different from ceiling priority protocol (CPP)
    - CPP raises priority on locking
    - uC/OS-II raises on blocking

Functions

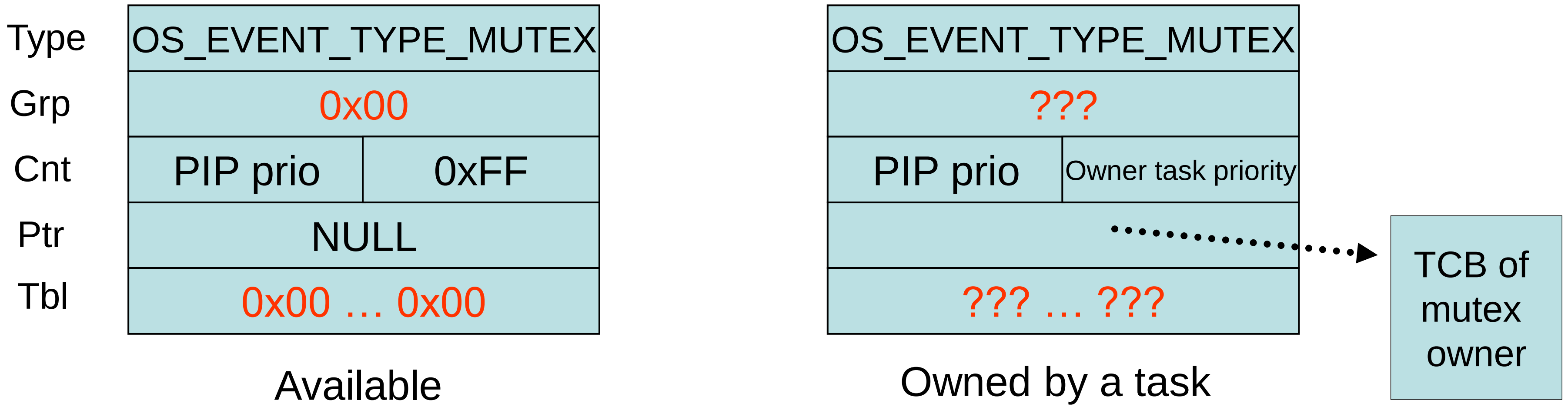
- OSMutexCreate()
- OSMutexPend()
- OSMutexPost()
- OSMutexDel()
- OSMutexAccept()
- OSMutexQuery()

```
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;
```


.OSEventGrp
7 6 5 4 3 2 1 0
.OSEventTbl[OS_LOWEST_PRIO / 8 + 1]
Highest Priority Task Waiting
X
Y
[0] [1] [2] [3] [4] [5] [6] [7]
7 6 5 4 3 2 1 0
15 14 13 12 11 10 9 8
23 22 21 20 19 18 17 16
31 30 29 28 27 26 25 24
39 38 37 36 35 34 33 32
47 46 45 44 43 42 41 40
55 54 53 52 51 50 49 48
63 62 61 60 59 58 57 56
Priority of task waiting for the event to occur.
Lowest Priority Task (Idle Task, can NEVER be waiting)
Task's Priority
0 0 Y Y Y X X X
Bit position in .OSEventTbl[OS_LOWEST_PRIO / 8 + 1]
Bit position in .OSEventGrp and Index into .OSEventTbl[OS_LOWEST_PRIO / 8 + 1]

OSMutexCreate()

- PIP prio = the “resvd. priority” for the mutex
- Owner = the locker task



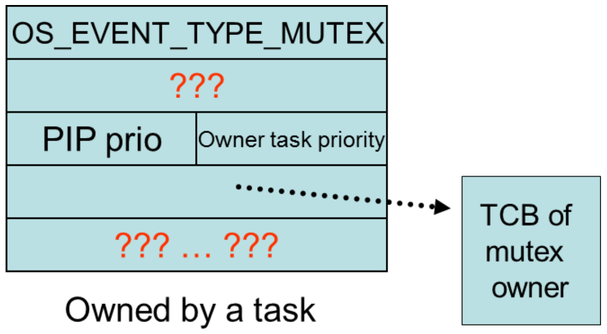
```
OS_EVENT  *OSMutexCreate (INT8U prio, INT8U *err)
{
#if OS_CRITICAL_METHOD == 3                           /* Allocate storage for CPU status register */
    OS_CPU_SR  cpu_sr;
#endif
    OS_EVENT  *pevent;


    if (OSIntNesting > 0) {                           /* See if called from ISR ...               */
        *err = OS_ERR_CREATE_ISR;                     /* ... can't CREATE mutex from an ISR       */
        return ((OS_EVENT *)0);
    }
#if OS_ARG_CHK_EN > 0
    if (prio >= OS_LOWEST_PRIO) {                     /* Validate PIP                             */
        *err = OS_PRIO_INVALID;
        return ((OS_EVENT *)0);
    }
#endif
    OS_ENTER_CRITICAL();
    if (OSTCBPrioTbl[prio] != (OS_TCB *)0) {          /* Mutex priority must not already exist    */
        OS_EXIT_CRITICAL();                           /* Task already exist at priority ...       */
        *err = OS_PRIO_EXIST;                         /* ... inheritance priority                 */
        return ((OS_EVENT *)0);
    }
    OSTCBPrioTbl[prio] = (OS_TCB *)1;                 /* Reserve the table entry                  */
    pevent             = OSEventFreeList;             /* Get next free event control block        */
    if (pevent == (OS_EVENT *)0) {                    /* See if an ECB was available              */
        OSTCBPrioTbl[prio] = (OS_TCB *)0;             /* No, Release the table entry              */
        OS_EXIT_CRITICAL();
        *err               = OS_ERR_PEVENT_NULL;      /* No more event control blocks             */
        return (pevent);
    }
    OSEventFreeList       = (OS_EVENT *)OSEventFreeList->OSEventPtr;    /* Adjust the free list   */
    OS_EXIT_CRITICAL();
    pevent->OSEventType = OS_EVENT_TYPE_MUTEX;
    pevent->OSEventCnt  = (prio << 8) | OS_MUTEX_AVAILABLE;/* Resource is available              */
    pevent->OSEventPtr  = (void *)0;                  /* No task owning the mutex                 */
    OS_EventWaitListInit(pevent);
    *err                = OS_NO_ERR;
    return (pevent);
}
```

OSMutexPend()

```
void  OSMutexPend (OS_EVENT *pevent, INT16U timeout, INT8U *err) {
    INT8U      pip;                                        /* Priority Inheritance Priority (PIP)      */
    INT8U      mprio;                                      /* Mutex owner priority                     */
    BOOLEAN    rdy;                                        /* Flag indicating task was ready           */
    OS_TCB    *ptcb;
    if (OSIntNesting > 0) {                                /* See if called from ISR ...               */
        *err = OS_ERR_PEND_ISR;                            /* ... can't PEND from an ISR               */
        return;
    }
    OS_ENTER_CRITICAL();                                                                /* Is Mutex available?
    if ((INT8U)(pevent->OSEventCnt & OS_MUTEX_KEEP_LOWER_8) == OS_MUTEX_AVAILABLE) {
        pevent->OSEventCnt &= OS_MUTEX_KEEP_UPPER_8;       /* Yes, Acquire the resource                */
        pevent->OSEventCnt |= OSTCBCur->OSTCBPrio;         /*      Save priority of owning task        */
        pevent->OSEventPtr  = (void *)OSTCBCur;            /*      Point to owning task's OS_TCB       */
        OS_EXIT_CRITICAL();
        *err  = OS_NO_ERR;
        return;
    }
    pip   = (INT8U)(pevent->OSEventCnt >> 8);                    /* No, Get PIP from mutex          */
    mprio = (INT8U)(pevent->OSEventCnt & OS_MUTEX_KEEP_LOWER_8); /*     Get priority of mutex owner */
    ptcb  = (OS_TCB *)(pevent->OSEventPtr);                      /*     Point to TCB of mutex owner */
```

If the mutex is free, grab it



```
if (ptcb->OSTCBPrio != pip && mprio > OSTCBCur->OSTCBPrio) {  /*     Need to promote prio of owner?*/
    if ((OSRdyTbl[ptcb->OSTCBY] & ptcb->OSTCBBitX) != 0x00) { /*     See if mutex owner is ready   */
                                                              /*     Yes, Remove owner from Rdy ...*/
                                                              /*          ... list at current prio */
        if ((OSRdyTbl[ptcb->OSTCBY] &= ~ptcb->OSTCBBitX) == 0x00) {
            OSRdyGrp &= ~ptcb->OSTCBBitY;
        }
        rdy = TRUE;
    } else {
        rdy = FALSE;                                          /* Ma                                */
    }
    ptcb->OSTCBPrio          = pip;                     /* Change owner task prio to PIP           */
    ptcb->OSTCBY             = ptcb->OSTCBPrio >> 3;
    ptcb->OSTCBBitY          = OSMapTbl[ptcb->OSTCBY];
    ptcb->OSTCBX             = ptcb->OSTCBPrio & 0x07;
    ptcb->OSTCBBitX          = OSMapTbl[ptcb->OSTCBX];
    if (rdy == TRUE) {                                  /* If task was ready at owner's priority ...*/
        OSRdyGrp               |= ptcb->OSTCBBitY;      /* ... make it ready at new priority.      */
        OSRdyTbl[ptcb->OSTCBY] |= ptcb->OSTCBBitX;
    }
    OSTCBPrioTbl[pip]        = (OS_TCB *)ptcb;
}
OSTCBCur->OSTCBStat |= OS_STAT_MUTEX;               /* Mutex not available, pend current task       */
OSTCBCur->OSTCBDly   = timeout;                     /* Store timeout in current task's TCB          */
OS_EventTaskWait(pevent);                           /* Suspend task until event or timeout occurs   */
OS_EXIT_CRITICAL();
OS_Sched();                                          /* Find next highest priority task ready        */
OS_ENTER_CRITICAL();
if (OSTCBCur->OSTCBStat & OS_STAT_MUTEX) {          /* Must have timed out if still waiting for event*/
    OS_EventTO(pevent);
    OS_EXIT_CRITICAL();
    *err = OS_TIMEOUT;                              /* Indicate that we didn't get mutex within TO  */
    return;
}
OSTCBCur->OSTCBEventPtr = (OS_EVENT *)0;
OS_EXIT_CRITICAL();
*err = OS_NO_ERR;
}
```

- If the owner's priority has not been raised, do it.
- If the owner's is current ready, change its bit from the ready-list bitmap

Set the ECB bitmap & clear itself from RdyMap

Locked the mutex without timed-out

pip = mutex's PIP priority
mprio = mutex owner's priority (original)
ptcb→OSTCBPrio = mutex owner's priority (current)

OSMutexPost()

```
INT8U  OSMutexPost (OS_EVENT *pevent) {
    INT8U      pip;                                   /* Priority inheritance priority           */
    INT8U      prio;
    if (OSIntNesting > 0) {                           /* See if called from ISR ...              */
        return (OS_ERR_POST_ISR);                     /* ... can't POST mutex from an ISR        */
    }
    OS_ENTER_CRITICAL();
    pip  = (INT8U)(pevent->OSEventCnt >> 8);          /* Get priority inheritance priority of mutex   */
    prio = (INT8U)(pevent->OSEventCnt & OS_MUTEX_KEEP_LOWER_8);  /* Get owner's original priority    */
    if (OSTCBCur->OSTCBPrio != pip &&
        OSTCBCur->OSTCBPrio != prio) {                /* See if posting task owns the MUTEX      */
        OS_EXIT_CRITICAL();
        return (OS_ERR_NOT_MUTEX_OWNER);
    }
```

The task posting the mutex must be the task that owns (has acquired) the mutex!!

OSMutexPost()

```
    if (OSTCBCur->OSTCBPrio == pip) {                         /* Did we have to raise current task's priority? */
                                                              /* Yes, Return to original priority              */
                                                              /*      Remove owner from ready list at 'pip'    */
        if ((OSRdyTbl[OSTCBCur->OSTCBY] &= ~OSTCBCur->OSTCBBitX) == 0) {
            OSRdyGrp &= ~OSTCBCur->OSTCBBitY;
        }
        OSTCBCur->OSTCBPrio         = prio;
        OSTCBCur->OSTCBY            = prio >> 3;
        OSTCBCur->OSTCBBitY         = OSMapTbl[OSTCBCur->OSTCBY];
        OSTCBCur->OSTCBX            = prio & 0x07;
        OSTCBCur->OSTCBBitX         = OSMapTbl[OSTCBCur->OSTCBX];
        OSRdyGrp                   |= OSTCBCur->OSTCBBitY;
        OSRdyTbl[OSTCBCur->OSTCBY] |= OSTCBCur->OSTCBBitX;
★       OSTCBPrioTbl[prio]          = (OS_TCB *)OSTCBCur;
    }
    OSTCBPrioTbl[pip] = (OS_TCB *)1;                          /* Reserve table entry                           */
    if (pevent->OSEventGrp != 0x00) {                         /* Any task waiting for the mutex?               */
                                                              /* Yes, Make HPT waiting for mutex ready         */
★       prio                   = OS_EventTaskRdy(pevent, (void *)0, OS_STAT_MUTEX);
        pevent->OSEventCnt &= OS_MUTEX_KEEP_UPPER_8;          /*      Save priority of mutex's new owner       */
        pevent->OSEventCnt |= prio;
        pevent->OSEventPtr  = OSTCBPrioTbl[prio];             /*      Link to mutex owner's OS_TCB             */
        OS_EXIT_CRITICAL();
★       OS_Sched();                                           /*      Find highest priority task ready to run  */
        return (OS_NO_ERR);
    }
    pevent->OSEventCnt |= OS_MUTEX_AVAILABLE;                 /* No,  Mutex is now available                   */
    pevent->OSEventPtr  = (void *)0;
    OS_EXIT_CRITICAL();
    return (OS_NO_ERR);
}
```

Move the ready bit of the current task back to its original position

Release the highest waiting task and transfer the ownership of the mutex to the task

OSMutexDel()

```
OS_EVENT  *OSMutexDel (OS_EVENT *pevent, INT8U opt, INT8U *err) {
    BOOLEAN    tasks_waiting;
    INT8U      pip;
    if (OSIntNesting > 0) {                                   /* See if called from ISR ...          */
        *err = OS_ERR_DEL_ISR;                                /* ... can't DELETE from an ISR        */
        return (pevent);
    }
    OS_ENTER_CRITICAL();
    if (pevent->OSEventGrp != 0x00) {                         /* See if any tasks waiting on mutex   */
        tasks_waiting = TRUE;                                 /* Yes                                 */
    } else {
        tasks_waiting = FALSE;                                /* No                                  */
    }

    switch (opt) {
        case OS_DEL_NO_PEND:                                  /* Delete mutex only if no task waiting    */
             if (tasks_waiting == FALSE) {
                 pip                = (INT8U)(pevent->OSEventCnt >> 8);
                 OSTCBPrioTbl[pip]  = (OS_TCB *)0;            /* Free up the PIP                     */
                 pevent->OSEventType = OS_EVENT_TYPE_UNUSED;
                 pevent->OSEventPtr  = OSEventFreeList;       /* Return Event Control Block to free list */
                 OSEventFreeList     = pevent;
                 OS_EXIT_CRITICAL();
                 *err = OS_NO_ERR;
                 return ((OS_EVENT *)0);                      /* Mutex has been deleted              */
             } else {
                 OS_EXIT_CRITICAL();
                 *err = OS_ERR_TASK_WAITING;
                 return (pevent);
             }
```

OSMutexDel()

```
        case OS_DEL_ALWAYS:                                    /* Always delete the mutex                */
             while (pevent->OSEventGrp != 0x00) {              /* Ready ALL tasks waiting for mutex      */
                 OS_EventTaskRdy(pevent, (void *)0, OS_STAT_MUTEX);
             }
             pip                   = (INT8U)(pevent->OSEventCnt >> 8);
             OSTCBPrioTbl[pip]     = (OS_TCB *)0;              /* Free up the PIP                        */
             pevent->OSEventType = OS_EVENT_TYPE_UNUSED;
             pevent->OSEventPtr    = OSEventFreeList;          /* Return Event Control Block to free list */
             OSEventFreeList       = pevent;                   /* Get next free event control block      */
             OS_EXIT_CRITICAL();
             if (tasks_waiting == TRUE) {                      /* Reschedule only if task(s) were waiting */
                 OS_Sched();                                   /* Find highest priority task ready to run */
             }
             *err = OS_NO_ERR;
             return ((OS_EVENT *)0);                           /* Mutex has been deleted                 */

        default:
             OS_EXIT_CRITICAL();
             *err = OS_ERR_INVALID_OPT;
             return (pevent);
    }
}
```

Summary

- In realistic systems, compromise exists between simplicity and performance
  - [PCP]→[PIP]→[CPP]→[NPCS]

- uC/OS-II implements a variant of PIP but this approach has some drawbacks, which is to be addressed later