Real-Time Operating Systems (Part II)

Embedded Software Design

熊博安
國立中正大學資訊工程研究所
pahsiung@cs.ccu.edu.tw

Textbooks: Embedded Software Primer, David E. Simon, Addison Wesley
Programming Embedded Systems with C and GNU Development Tools, Michael Barr & Anthony Massa

Contents

- Intertask Communication
- Timer Services
- Memory Management
- Events
- RTOS and ISR

Intertask Communication

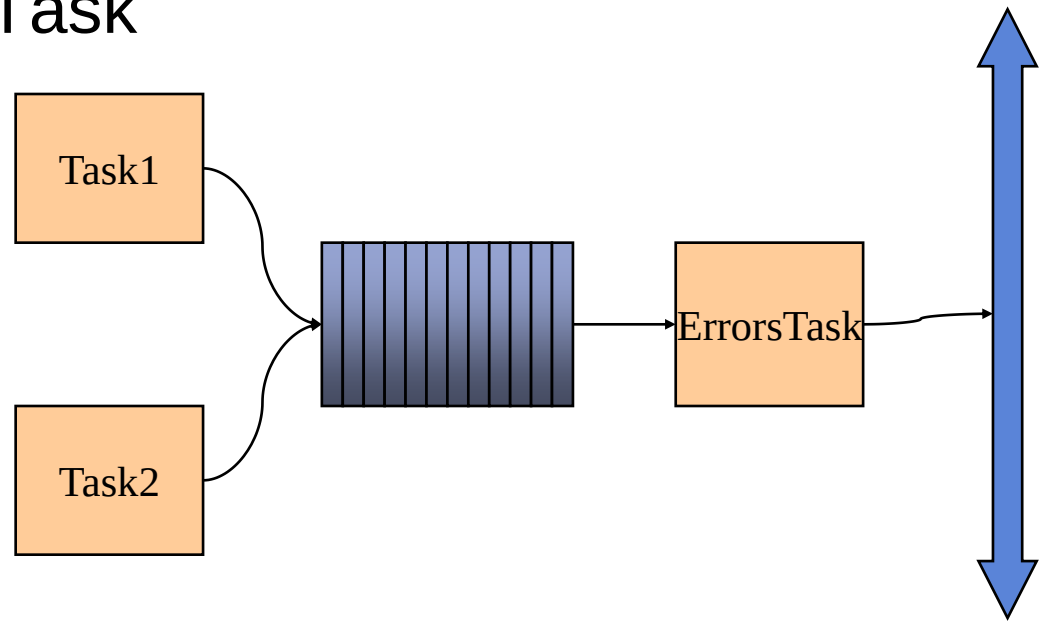
- Shared data
  - atomically-accessed variables
  - reentrant functions
- Semaphores
  - binary, counting semaphores
  - monitors
- Message Queues
- Mailboxes
- Pipes

Message Queues

- Simple Example:
  - 2 tasks discover error conditions that must be reported on the network (time consuming!)
  - 1 more task handles the error reporting
    - Task1 and Task2 report errors to ErrorsTask
- Qs: How to implement this in an RTOS?
  - Ans: Use an RTOS queue!

Message Queue Example

- Three tasks
  - Task1
  - Task2
  - ErrorsTask



Message Queue Example: Code

- Task1 and Task2

```
/* RTOS queue function prototypes */
void AddToQueue (int iData);
void ReadFromQueue (int *p_iData);
```

```
void Task1 (void)
{
    .
    .
    .
   if (!!problem arises)
      vLogError (ERROR_TYPE_X);

   !! Other things that need to be do
    .
    .
    .
}
```

```
void Task2 (void)
{
    .
    .
    .
   if (!!problem arises)
      vLogError (ERROR_TYPE_Y);

   !! Other things that need to be done soon.
    .
    .
    .
}
```

Message Queue Example: Code

- ErrorsTask

```
void vLogError (int iErrorType)
{
   AddToQueue (iErrorType);
}

static int cErrors;

void ErrorsTask (void)
{
   int iErrorType;

   while (FOREVER)
   {
      ReadFromQueue (&iErrorType);
      ++cErrors;
      !! Send cErrors and iErrorType out on network
   }
}
```

If the queue is empty, this function will block the calling task.

Message Queue Example

- AddtoQueue
  - add an integer to a queue in RTOS
- ReadFromQueue
  - read value from head of queue
- Both functions must be reentrant!

Message Queue Details

- Queues must be initialized before using
  - call an initialization function
  - must initialize before any task tries to use them
  - may have to allocate memory for queue
- RTOSs allow multiple queues
  - must identify queue in function calls
- Condition handler for full queue:
  - write operation failed error, OR
  - block until space available after some read

Message Queue Details

- Condition handler for empty queue:
  - queue empty error return, AND
  - block until data available in queue
- Write block size allowed by RTOS < Write block size desired by task
  - Qs: How to handle this situation?
  - Ans:
    - Write actual data to a buffer
    - Write buffer pointer, a (void *)-sized block, into queue

Message Queues & Pointers

```
/* Queue function prototypes */
OS_EVENT *OSQCreate (void **ppStart, BYTE bySize);
unsigned char OSQPost (OS_EVENT *pOse, void *pvMsg);
void *OSQPend (OS_EVENT *pOse, WORD wTimeout, BYTE *pByErr);
#define WAIT_FOREVER 0

static OS_EVENT *pOseQueueTemp;

void vReadTemperaturesTask (void)
{
   int *pTemperatures;

   while (TRUE)
   {
      !! Wait until it's time to read the next temperature

      /* Get a new buffer for the new set of temperatures. */
      pTemperatures = (int *) malloc (2 * sizeof *pTemperatures);

      pTemperatures[0] = !! read in value from hardware;
      pTemperatures[1] = !! read in value from hardware;

      /* Add a pointer to the new temperatures to the queue */
      OSQPost (pOseQueueTemp, (void *) pTemperatures);
   }
}
```

Message Queues & Pointers

```
void vMainTask (void)
{
   int *pTemperatures;
   BYTE byErr;

   while (TRUE)
   {
      pTemperatures =
         (int *) OSQPend (pOseQueueTemp, WAIT_FOREVER, &byErr);
      if (pTemperatures[0] != pTemperatures[1])
         !! Set off howling alarm;

      free (pTemperatures);
   }
}
```

Mailboxes

- Like queues
- Mailbox functions:
  - Create a mailbox
  - Write to a mailbox
  - Read from a mailbox
  - Check if a mailbox has any message
  - Destroy an unused mailbox

Mailboxes

- Variations
  - Mailbox size
    - One message: write only once, must read before next write
    - User-defined: size parameter in create mailbox function
    - Unlimited: each mailbox is not limited, but total size of all mailboxes is limited
  - Priority
    - higher-priority messages read before low-priority ones, regardless of write order

Mailbox Example in MultiTask!

- Each message is a void pointer
- Must create all mailboxes you need when you configure the system
- Three functions:
- int **sndmsg** (unsigned int *uMbId*, void **p_vMsg*, unsigned int *uPriority*);
- void ***rcvmsg** (unsigned int *uMbId*, unsigned int *uTimeout*);
- void ***chkmsg** (unsigned int *uMbId*);

Mailbox ID

Message

Msg Priority

Block Time

Return 1st Msg, or NULL

Mailbox Functions

- In all the three functions uMbId identifies the mailbox on which to operate. The sndmsg adds p_vMsg into the queue of messages held by the uMbId mailbox with the priority indicated by uPriority, it returns an error if uMbId is invalidor too many messages are pending in the queue. The rcvmsg returns the highest –priority message from the specified mailbox, it blocks the task that it called if the mailbox is empty. The task can use the uTimeout parameter to limit how long it will wait if there are no messages.The chkmsg returns the first message in the mailbox, it returns a NULL immediately if the mailbox is empty

Pipes

- Like queues
- Functions:
  - Create
  - Write to
  - Read from
  - …

Pipes

- Variations:
  - Varying lengths of write block size
  - Byte-oriented
    - Task 1 writes 11 bytes to pipe
    - Task 2 writes 19 bytes to pipe
    - Task 3 reads 14 bytes from pipe
      - 11 bytes from task 1
      - 3 bytes from task 2
    - 16 bytes remaining in pipe
  - Some RTOSs use C functions: fread, fwrite

Which Should I Use?

- Depends on RTOS
- Each RTOS has different implementations for message queues, mailboxes, and pipes.
- Trade-off among flexibility, speed, memory space, length of interrupt disabled time, …
- Read RTOS documents and decide which best meets your requirements

Pitfalls

1) No restrictions on reader/writer of queue, mailbox, or pipe
   - temperature data written to a queue read by task expecting error codes ➔ system failure
2) Data type mismatch between write and read
   - wrong interpretation of data
   - e.g.: write int, read pointer
   - compilers can find obvious errors, BUT
   - compilers cannot find interpretation errors

Pitfalls (Data type mismatch: caught by compiler)

```
/* Declare a function that takes a pointer parameter */
void vFunc (char *p_ch);

void main (void)
{
   int i;
   :
   :
   :
   /* Call it with an int, and get a compiler error */
   vFunc (i);
   :
   :
   :
}
```

Pitfalls (Data type mismatch: uncaught by compiler)

```
static OS_EVENT *pOseQueue;

void TaskA (void)
{
   int i;
   .
   .
   .
   /* Put an integer on the queue. */
   OSQPost (pOseQueue, (void *) i);
   .
   .
   .
}

void TaskB (void)
{
   char *p_ch;
   BYTE byErr;
   .
   .
   .
   /* Expect to get a character pointer. */
   p_ch = (char *) OSQPend (pOseQueue, FOREVER, byErr);
   .
   .
   .
}
```

Pitfalls

3) Running out of space in queues, mailboxes, or pipes is a disaster
   - Communication is not optional
   - Good solution: make it large enough in the first place
4) Passing pointers through queues, mailboxes, or pipes ➔ shared data problem!

Passing Pointers using Message Queue – Shared Data Problem

```
/* Queue function prototypes */
OS_EVENT *OSQCreate (void **ppStart, BYTE bySize);
unsigned char OSQPost (OS_EVENT *pOse, void *pvMsg);
void *OSQPend (OS_EVENT *pOse, WORD wTimeout, BYTE *pByErr);
#define WAIT_FOREVER 0

static OS_EVENT *pOseQueueTemp;

void vReadTemperaturesTask (void)
{
   int *pTemperatures;

   while (TRUE)
   {
      !! Wait until it's time to read the next temperature

      /* Get a new buffer for the new set of temperatures. */
      pTemperatures = (int *) malloc (2 * sizeof *pTemperatures);

      pTemperatures[0] = !! read in value from hardware;
      pTemperatures[1] = !! read in value from hardware;

      /* Add a pointer to the new temperatures to the queue */
      OSQPost (pOseQueueTemp, (void *) pTemperatures);
   }
}
```

With malloc and free

```
/* Queue function prototypes */
OS_EVENT *OSQCreate (void **ppStart, BYTE bySize);
unsigned char OSQPost (OS_EVENT *pOse, void *pvMsg);
void *OSQPend (OS_EVENT *pOse, WORD wTimeout,
      BYTE *pByErr);
#define WAIT_FOREVER 0
static OS_EVENT *pOseQueueTemp;

void vReadTemperaturesTask (void)
{
   int iTemperatures[2];

   while (TRUE)
   {
      !! Wait until it's time to read the next temperature

      iTemperatures[0] = !! read in value from hardware;
      iTemperatures[1] = !! read in value from hardware;

      /* Add to the queue a pointer to the temperatures
         we just read */
      OSQPost (pOseQueueTemp, (void *) iTemperatures);
   }
}
```

Without malloc and free

Passing Pointers using Message Queue – Shared Data Problem

```
void vMainTask (void)
{
   int *pTemperatures;
   BYTE byErr;

   while (TRUE)
   {
      pTemperatures =
         (int *) OSQPend (pOseQueueTemp, WAIT_FOREVER, &byErr);
      if (pTemperatures[0] != pTemperatures[1])
         !! Set off howling alarm;

      free (pTemperatures);
   }
}
```

With malloc and free

```
void vMainTask (void)
{
   int *pTemperatures;
   BYTE byErr;

   while (TRUE)
   {
      pTemperatures = (int *)
         OSQPend (pOseQueueTemp, WAIT_FOREVER, &byErr);
      if (pTemperatures[0] != pTemperatures[1])
         !! Set off howling alarm;
   }
}
```

Without malloc and free

Passing Pointers using Message Queue – Shared Data Problem

- Without malloc

When the vMainTask gets the value for pTemperatures from the queue, pTemperatures will point to the iTemperatures array in vReadTemperatures.

If the RTOS switches from vMainTask to vReadTemperaturesTask while vMainTask is comparing the Temperatures values and if vReadTemperatures changes the values in iTemperatures – **Shared Data Problem.**

- With malloc

The iTemperatures variable in vReadTemperatures and pTemperatures in vMainTask won't share the same buffer at the same time when tasks are using the buffers – **No Shared Data Problem**

Timer Functions

- Most embedded systems must keep track of the passage of time
  - cordless bar-code scanner turns itself off after a certain number of seconds
  - wait for ack, re-transmit data on network
  - wait for robot arms to move
  - wait for motors to come up to speed
- RTOS provides a task delay function

VxWorks RTOS Delay Function

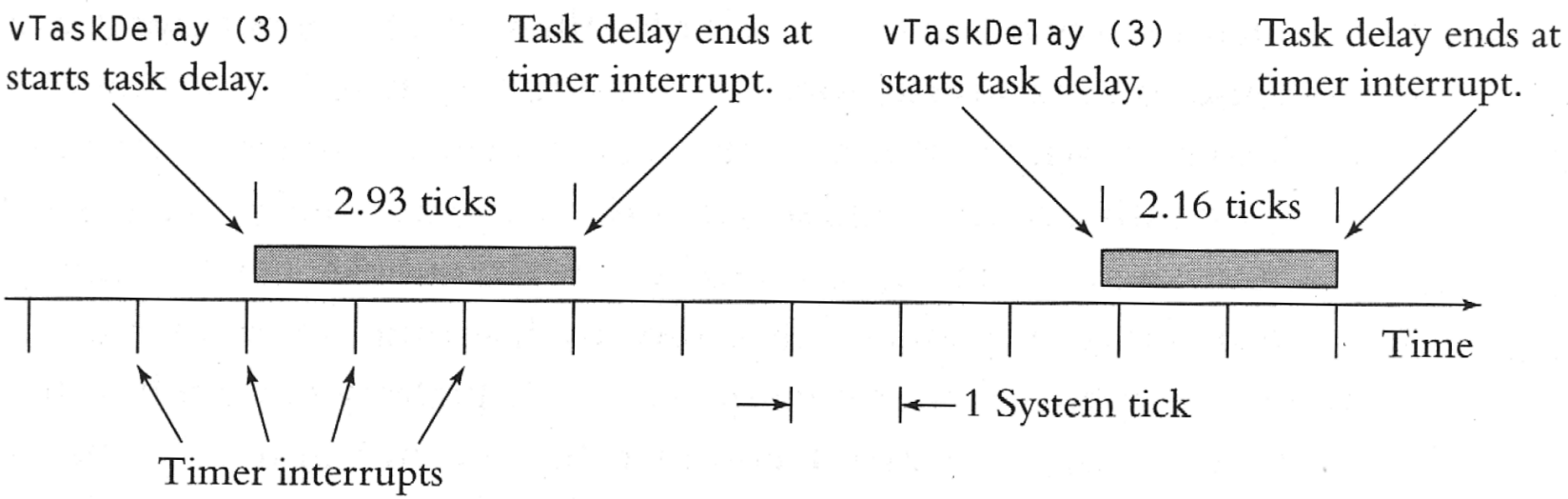
```
/* Message queue for phone numbers to dial. */
extern MSG_Q_ID queuePhoneCall;

void vMakePhoneCallTask (void)
{
   #define MAX_PHONE_NUMBER  11
   char a_chPhoneNumber[MAX_PHONE_NUMBER];
         /* Buffer for null-terminated ASCII number */
   char *p_chPhoneNumber;
         /* Pointer into a_chPhoneNumber */
   .
   .
   .
   while (TRUE)
   {
      msgQreceive (queuePhoneCall, a_chPhoneNumber,
         MAX_PHONE_NUMBER, WAIT_FOREVER);

      /* Dial each of the digits */
      p_chPhoneNumber = a_chPhoneNumber;
      while (*p_chPhoneNumber)
      {
         taskDelay (100);    /* 1/10th of a second silence */
         vDialingToneOn (*p_chPhoneNumber -'0');
         taskDelay (100);    /* 1/10th of a second with tone */
         vDialingToneOff ();

         /* Go to the next digit in the phone number */
         ++p_chPhoneNumber;
      }
      .
      .
      .
   }
}
```

Questions

- What is the unit of time for the taskDelay function? milliseconds?
  - No! It is the number of system ticks!
  - Length of one system tick can be controlled when you set up the system
- How accurate are the delays?
  - Accurate to the nearest system tick
  - Heartbeat timer: a hardware timer
  - taskDelay(n) ➔ n-1 < TimerExpires < n

Timer Function Accuracy

- vTaskDelay(3)



Questions

- How does RTOS know how to setup hardware timer?
  - RTOS is microprocessor dependent and so is the hardware timer, thus RTOS engineers know a priori how to setup the microprocessor hardware timer
  - Many RTOS vendors provide “board support packages” (BSPs), which contain driver software for common hardware components, such as timers, etc.

Questions

- What is the “normal length” for the system tick?
  - None!
  - If the system tick is made very small
    - accurate timing can be achieved
    - But frequent execution of timer interrupt routines ➔ decreased system performance
- What if I need extremely accurate timing?
  - Make system tick short enough
  - Use a separate hardware timer for those timings

Other Timing Services

1) To limit waiting time of a task for a message from a queue or a mailbox or for a semaphore

- **Issue**:
  - High-priority task attempts to get a semaphore
  - Time limit expires, task does not have the semaphore, task cannot access shared data
  - Need to write recovery code
- **Solution**:
  - High Priority Task can send instructions about using shared data through a mailbox to a low-priority task instead of Semaphore. So no need to wait for Semaphore.

Other Timing Services

2) To call a function after a given number of system ticks

- An Example:
- Handle radio hardware: turn on & off from time to time
- Turn radio off:
  - cut the power
- Turn radio on:
  - turn on power to basic radio hardware
  - after waiting 12 ms, set radio frequency
  - after waiting 3 ms, turn on transmitter / receiver
  - radio is ready to function

Timer Callback Functions

Figure 7.7 Using Timer Callback Functions

```
/* Message queue for radio task. */
extern MSG_Q_ID queueRadio;

/* Timer for turning the radio on. */
static WDOG_ID wdRadio;

static int iFrequency;      /* Frequency to use. */

void vSetFrequency (int i);
void vTurnOnTxorRx (int i);

void vRadioControlTask (void)
{
   #define MAX_MSG 20
   char a_chMsg[MAX_MSG + 1];  /* Message sent to this task */

   enum
   {
      RADIO_OFF,
      RADIO_STARTING,
```

(continued)

Timer Callback Functions

Figure 7.7 *(continued)*

```
    RADIO_TX_ON,
    RADIO_RX_ON,
} eRadioState;   /* State of the radio */
eRadioState = RADIO_OFF;

/* Create the radio timer */
wdRadio = wdCreate ();

while (TRUE)
{
    /* Find out what to do next */
    msgQReceive (queueRadio, a_chMsg, MAX_MSG, WAIT_FOREVER);

    /* The first character of the message tells this task what
       the message is. */
    switch (a_chMsg[0])
    {
        case 'T':
        case 'R':
            /* Someone wants to turn on the transmitter */
            if (eRadioState == RADIO_OFF)
            {
                !! Turn on power to the radio hardware.

                eRadioState = RADIO_STARTING;
```

Turn On Tx after few operations

(continued)

Timer Callback Functions

Figure 7.7 *(continued)*

```
            /* Get the frequency from the message */
            iFrequency = * (int *) a_chMsg[1];

            !! Store what needs doing when the radio is on.
            /* Make the next step 12 milliseconds from now. */
            wdStart (wdRadio, 12, vSetFrequency,
               (int) a_chMsg[0]);
         }
         else
            !! Handle error.  Can't turn radio on if not off
         break;

      case 'K':
         /* The radio is ready. */
         eRadioState = RADIO_TX_ON;
         !! Do whatever we want to do with the radio
         break;

      case 'L':
         /* The radio is ready. */
         eRadioState = RADIO_RX_ON;
         !! Do whatever we want to do with the radio
         break;
```

First ch. tells what the message is (T, R, K, etc.)

Parameter to function vSetFrequency

Timer Callback Functions

```
            case 'X':
               /* Someone wants to turn off the radio. */
               if (eRadioState == RADIO_TX_ON ||
                     eRadioState == RADIO_RX_ON)
               {
                  !! Turn off power to the radio hardware.
                  eRadioState = RADIO_OFF;
               }
               else
                  !! Handle error.  Can't turn radio off if not on
               break;
            .
            .
            .
            default:
               !! Deal with the error of a bad message
               break;
         }
      }
   }
```

(continued)

i repesents First ch. from messageQ tells what the message type is (T, R, K, etc.)

```
void vSetFrequency (int i)
{
   !! Set radio frequency to iFrequency;

   /* Turn on the transmitter 3 milliseconds from now. */
   wdStart (wdRadio, 3, vTurnOnTxorRx, i);
}
```

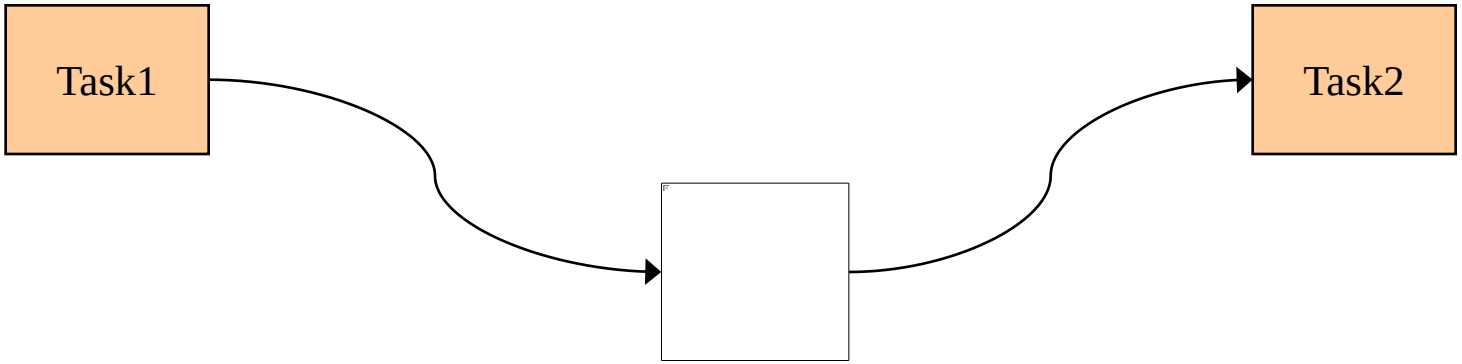
i repesents First ch. from messageQ tells what the message type is (T, R, K, etc.)

Timer Callback Functions

```
void vTurnOnTxorRx (int i)
{
   if (i == (int) 'T')
   {
      !! Turn on the transmitter

      /* Tell the task that the radio is ready to go. */
      msgQSend (queueRadio, "K", 1,
         WAIT_FOREVER, MSG_PRI_NORMAL);
   }
   else
   {
      !! Turn on the receiver

      /* Tell the task that the radio is ready to go. */
      msgQSend (queueRadio, "L", 1,
         WAIT_FOREVER, MSG_PRI_NORMAL);
   }
}
```

Events

- Event = a Boolean flag that tasks can
  - set, reset, and wait for



- Example: cordless bar-code scanner
  - user pulls trigger ➔
  - laser scanning mechanism must start

Features of Events

- More than one task can block/wait for an event, when event occurs
  - all blocked tasks are unblocked, and
  - RTOS executes them in priority order
- RTOS forms groups of events:
  - tasks can wait for any subset of an event group
  - Example: {key-press on scanner keypad, trigger-pull} ➔ start scanning
- Resetting of events:
  - automatically done by RTOS
  - done by user task software

Using Event in AMX

```
/* Handle for the trigger group of events. */
AMXID amxidTrigger;

/* Constants for use in the group. */

#define TRIGGER_MASK  0x0001
#define TRIGGER_SET   0x0001
#define TRIGGER_RESET 0x0000
#define KEY_MASK      0x0002
#define KEY_SET       0x0002
#define KEY_RESET     0x0000

void main (void)
{
   .
   .
   .
   /* Create an event group with
      the trigger and keyboard events reset */
   ajevcre (&amxidTrigger, 0, ''EVTR'');
   .
   .
   .
}
```

Using Events in AMX

```
void interrupt vTriggerISR (void)
{
   /* The user pulled the trigger.  Set the event. */
   ajevsig (amxidTrigger, TRIGGER_MASK, TRIGGER_SET);
}

void interrupt vKeyISR (void)
{
   /* The user pressed a key.  Set the event. */
   ajevsig (amxidTrigger, KEY_MASK, KEY_SET);

   !! Figure out which key the user pressed and store that value
}
```

(continued)

Using Events in AMX

Figure 7.8 *(continued)*

```
void vScanTask (void)
{
   .
   .
   .
   while (TRUE)
   {
      /* Wait for the user to pull the trigger. */
      ajevwat (amxidTrigger, TRIGGER_MASK, TRIGGER_SET,
         WAIT_FOR_ANY, WAIT_FOREVER);

      /* Reset the trigger event. */
      ajevsig (amxidTrigger, TRIGGER_MASK, TRIGGER_RESET);

      !! Turn on the scanner hardware and look for a scan.
      .
      .
      .
      !! When the scan has been found, turn off the scanner.
   }
}
```

Using Events in AMX

```
void vRadioTask (void)
{
   .
   .
   .
   while (TRUE)
   {
      /* Wait for the user to pull the trigger or press a key. */
      ajevwat (amxidTrigger, TRIGGER_MASK | KEY_MASK,
         TRIGGER_SET | KEY_SET, WAIT_FOR_ANY,
         WAIT_FOREVER);

      /* Reset the key event.  (The trigger event will be reset
         by the ScanTask.) */
      ajevsig (amxidTrigger, KEY_MASK, KEY_RESET);

      !! Turn on the radio.
      .
      .
      .
      !! When data has been sent, turn off the radio.
   }
}
```

AMX Event Functions

Figure 7.9 *AMX* Event Functions

The *AMX* functions used in Figure 7.8 are the following:

```
ajevcre (AMXID *p_amxidGroup, unsigned int uValueInit,
   char *p_chTag)
```

The `ajevcre` function creates a group of 16 events, the handle for which is written into the location pointed to by `p_amxidGroup`. The initial values of those events—set and reset—are contained in the `uValueInit` parameter. *AMX* assigns the group a four-character name pointed to by `p_chTag`; this is a special feature of *AMX*, which allows a task to find system objects by name if it does not have access to the handle.

```
ajevsig (AMXID amxidGroup, unsigned int uMask,
   unsigned int uValueNew)
```

The `ajevsig` function sets and resets the events in the group indicated by `amxidGroup`. The `uMask` parameter indicates which events should be set or reset, and the `uValueNew` parameter indicates the new values that the events should have.

AMX Event Functions

```
ajevwat (AMXID amxidGroup, unsigned int uMask,
   unsigned int uValue, int iMatch, long lTimeout)
```

The `ajevwat` function causes the task to wait for one or more events within the group indicated by `amxidGroup`. The `uMask` parameter indicates which events the task wants to wait for, and `uValue` indicates whether the task wishes to wait for those events to be set or reset. The `iMatch` parameter indicates whether the task wishes to unblock when *all* of the events specified by `uMask` have reached the values specified by `uValue` or when *any one* of the events has reached the specified value. The `lTimeout` parameter indicates how long the task is willing to wait for the events.

AMX also includes functions to delete a group of events that are no longer needed, to read the current values of all the events in a group and to read the values of all the events in a group as of the moment that a task unblocked because an event occurred for which it was waiting.

Comparison: Semaphores, Events

- Semaphores are usually the fastest and simplest methods.
  - However, not much information can pass through a semaphore.
- Events are a little more complicated than semaphores and take up just a hair more microprocessor time than semaphores.

Advantages

- A task can wait for any one of several events at the same time, whereas it can only wait for one semaphore.
- Some RTOSs make it convenient to use events and make it inconvenient to use semaphores.

Comparison: Queues

- Queues allow you to send a lot of information from one task to another.
  - The drawbacks
    - putting messages into and taking messages out of queues is more microprocessor-intensive
    - that queues offer you many more opportunities to insert bugs into your code.

Memory Management

- RTOS have memory management
- But, not malloc() and free():
  - slow
  - unpredictable execution times
- Solution:
  - allocate and free **fixed-size buffers**
  - fast and predictable functions
- Example:
  - MultiTask! RTOS

MultiTask! Memory Management

- Pool = a collection of memory buffers of the same size
- Users can declare and use different pools
- void *reqbuf(unsigned int uPoolId);
  - request a buffer from pool uPoolId,
  - return NULL if no buffer available
- void *getbuf(unsigned int uPoolId, unsigned int uTimeout);
  - get a buffer from pool uPoolId
  - block wait for uTimeout

MultiTask! Memory Management

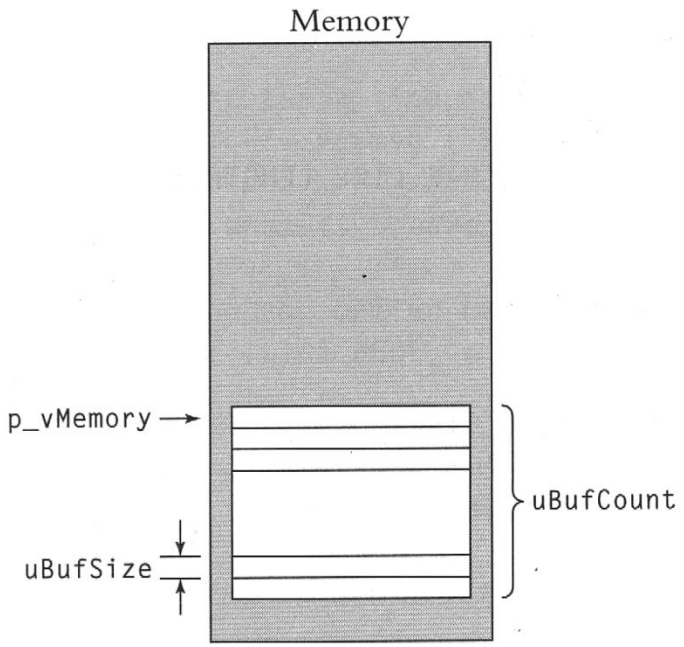
- void relbuf (unsigned int uPoolId,
  void *p_vBuffer);
  - release buffer *p_vBuffer into pool uPoolId
  - RTOS does not check if buffer belongs to pool
    - for efficiency,
    - drastic consequence on error
- RTOS does not know where is free memory
  - Application needs to tell RTOS!
  - Initialize memory pool init_mem_pool()

MultiTask! Memory Management

```
int init_mem_pool (
    unsigned int uPoolId,
    void *p_vMemory,
    unsigned int uBufSize,
    unsigned int uBufCount,
    unsigned int uPoolType
);
```

used by functions

used by task or ISR



Example of Memory Management in MultiTask!

- Underground tank monitoring system
- Slow thermal printer prints a few lines per second
- 2 tasks
  - high priority task: formats report
  - low priority task: feeds lines to printer
    - one line at a time
    - 40-character line ➔ buffer-size = 40 bytes ➔ waste of memory ➔ solution: use diff pools

Example of Memory Management in MultiTask!

Figure 7.11 Using Memory Management Functions

```
#define LINE_POOL           1
#define MAX_LINE_LENGTH     40
#define MAX_LINES           80

static char a_lines[MAX_LINES][MAX_LINE_LENGTH];

void main (void)
{
    .
    .
    .
   init_mem_pool (LINE_POOL, a_lines,

      MAX_LINES, MAX_LINE_LENGTH, TASK_POOL);
    .
    .
    .
}
```

Example of Memory Management in MultiTask!

```
void vPrintFormatTask (void)
{
   char *p_chLine;       /* Pointer to current line */
   .
   .
   .
   /* Format lines and send them to the vPrintOutputTask */
   p_chLine = getbuf (LINE_POOL, WAIT_FOREVER);
   sprintf (p_chLine, "INVENTORY REPORT");
   sndmsg (PRINT_MBOX, p_chLine, PRIORITY_NORMAL);
   p_chLine = getbuf (LINE_POOL, WAIT_FOREVER);
   sprintf (p_chLine, "Date: %02/%02/%02",
      iMonth, iDay, iYear % 100);
   sndmsg (PRINT_MBOX, p_chLine, PRIORITY_NORMAL);
   p_chLine = getbuf (LINE_POOL, WAIT_FOREVER);
   sprintf (p_chLine, "Time: %02:%02", iHour, iMinute);
   sndmsg (PRINT_MBOX, p_chLine, PRIORITY_NORMAL);
   .
   .
   .
}
```

Example of Memory Management in MultiTask!

```
void vPrintOutputTask (void)
{
    char *p_chLine;
    while (TRUE)
    {
        /* Wait for a line to come in. */
        p_chLine = rcvmsg (PRINT_MBOX, WAIT_FOREVER);

        !! Do what is needed to send the line to the printer

        /* Free the buffer back to the pool */
        relbuf (LINE_POOL, p_chLine);
    }
}
```

Interrupt Routines in an RTOS

- Rules for ISR (not for tasks):
- Rule 1: ISR must not call any RTOS function that might block the caller
  - Must NOT:
    - get semaphores
    - read from empty queues, mailboxes, etc.
    - wait for event, …
  - Must run to completion to reset hardware to be ready for next interrupt

Interrupt Routines in an RTOS

- Rule 2: ISR may not call any RTOS function that cause task switching, unless RTOS knows that it is an ISR (& thus will not switch task)
  - May not
    - write to mailboxes, queues on which tasks may be waiting
    - set events
    - release semaphores, …

Rule 1: No Blocking

Figure 7.12 Interrupt Routines *Cannot* Use Semaphores

ISR should not get semaphore!!!

```
static int iTemperatures[2];

void interrupt vReadTemperatures (void)
{
   GetSemaphore (SEMAPHORE_TEMPERATURE);   /***NOT ALLOWED***/
   iTemperatures[0] = !! read in value from hardware;
   iTemperatures[1] = !! read in value from hardware;
   GiveSemaphore (SEMAPHORE_TEMPERATURE);
}

void vTaskTestTemperatures (void)
{
   int iTemp0, iTemp1;

   while (TRUE)
   {
      GetSemaphore (SEMAPHORE_TEMPERATURE);
      iTemp0 = iTemperatures[0];
      iTemp1 = iTemperatures[1];
      GiveSemaphore (SEMAPHORE_TEMPERATURE);
      if (iTemp0 != iTemp1)
         !! Set off howling alarm;
   }
}
```

Rule 1: No Blocking

- Task is running (semaphore held)
- Interrupt occurs, ISR tries to get semaphore
- ISR is blocked, task is blocked
- Semaphore is never released
- All lower-priority tasks are also blocked
- One-armed deadly embrace
  - ISR vReadTemperatures() interrupts task vTaskTestTemperatures()

Post Queue in ISR? (Eg in VRTX)

Figure 7.13 Legal Uses of RTOS Functions in Interrupt Routines

```
/* Queue for temperatures. */
int iQueueTemp;

void interrupt vReadTemperatures (void)
{
   int aTemperatures[2];      /* 16-bit temperatures. */
   int iError;

   /* Get a new set of temperatures. */
   aTemperatures[0] = !! read in value from hardware;
   aTemperatures[1] = !! read in value from hardware;

   /* Add the temperatures to a queue. */
   sc_qpost (iQueueTemp,
      (char *) ((aTemperatures[0] << 16) | aTemperatures[1]),
      &iError);
}
```

Post Queue in ISR? (Eg in VRTX)

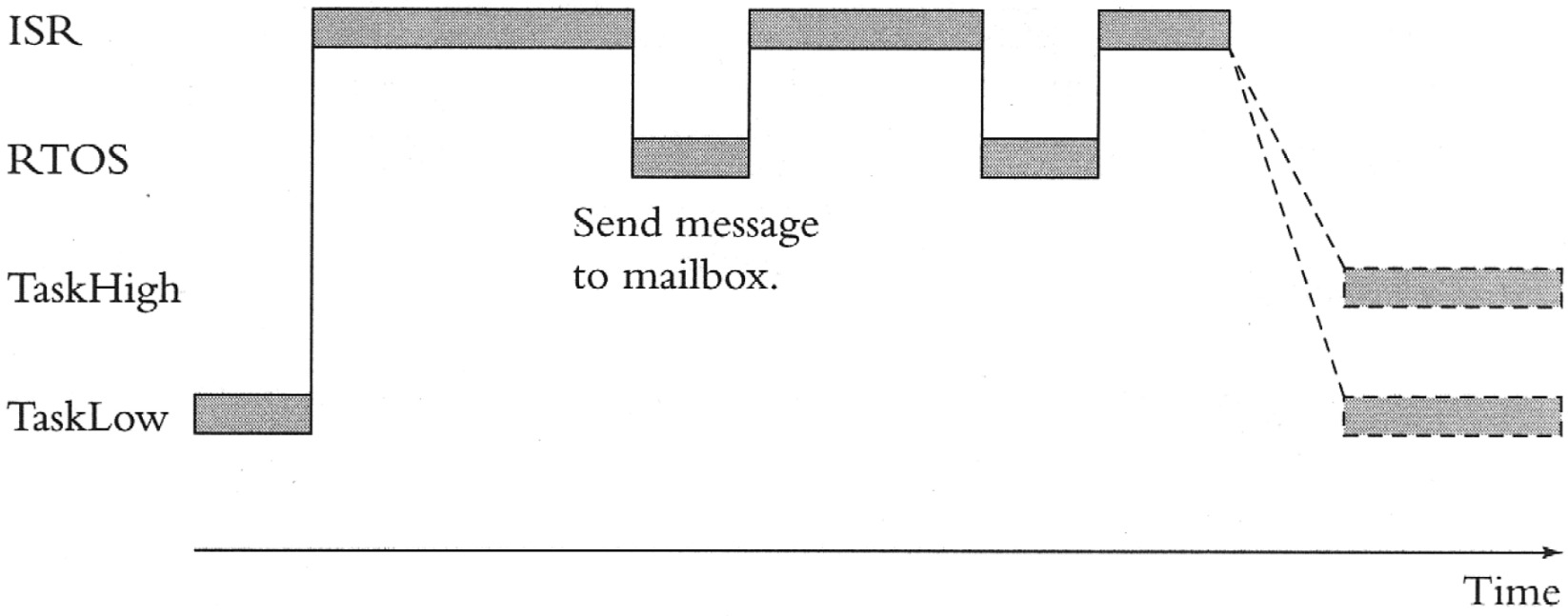
```
void vMainTask (void)
{
   long int lTemps;   /* 32 bits; the same size as a pointer. */
   int aTemperatures[2];
   int iError;

   while (TRUE)
   {
      lTemps = (long) sc_qpend (iQueueTemp, WAIT_FOREVER,
         sizeof(int), &iError);
      aTemperatures[0] = (int) (lTemps >> 16);
      aTemperatures[1] = (int) (lTemps & 0x0000ffff);
      if (aTemperatures[0] != aTemperatures[1])
         !! Set off howling alarm;
   }
}
```

Post Queue in ISR?

- No problem!
- Posting to a queue is non-blocking!
- ISR can post a queue

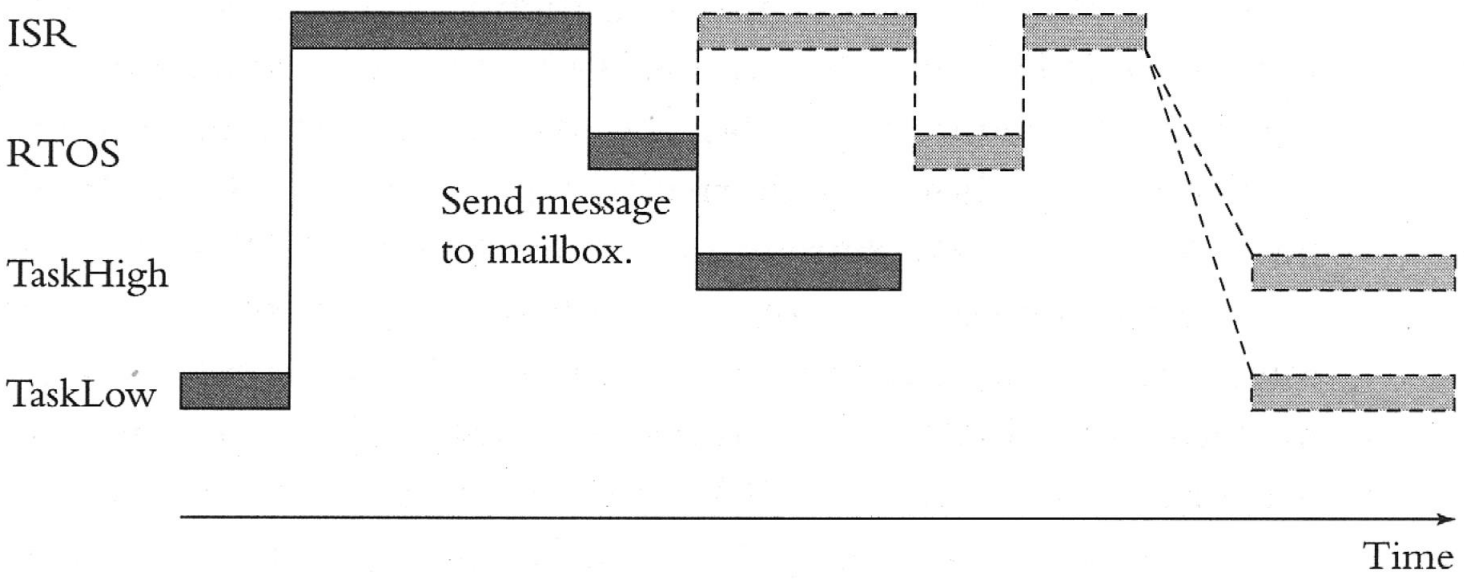
Rule 2: No RTOS Calls without Fair Warning

- A naïve view



Rule 2: No RTOS Calls without Fair Warning

What would really happen!

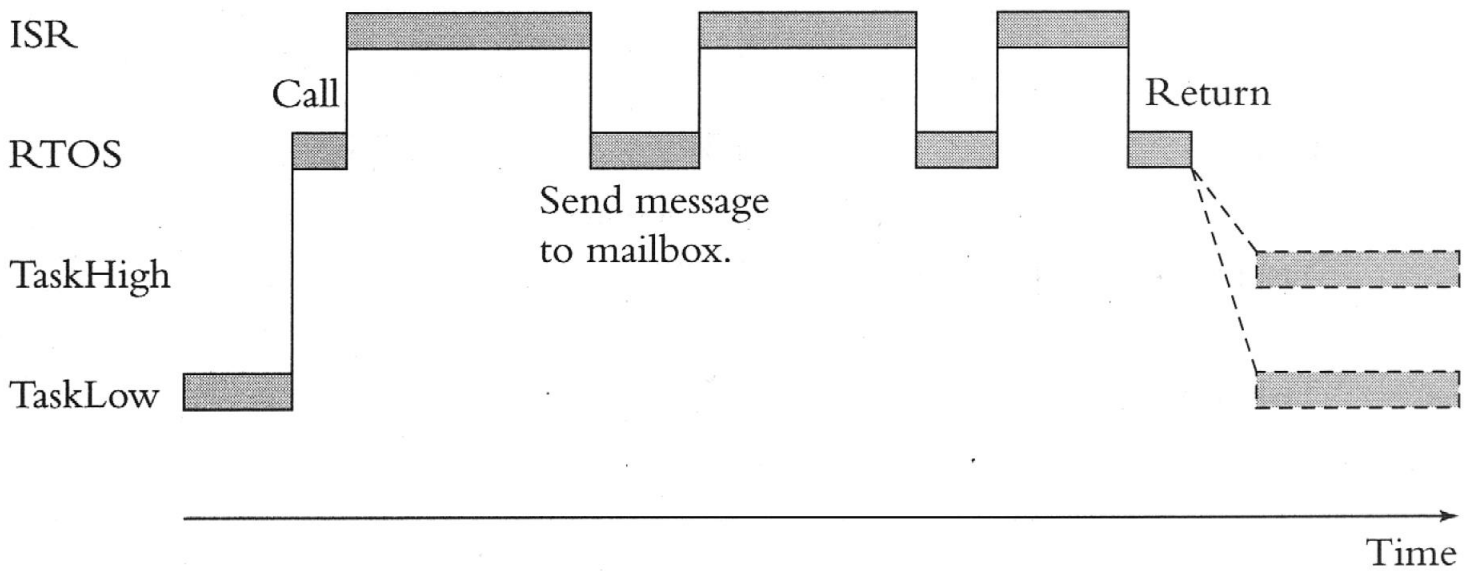


RTOS unblocks a high priority task (which was waiting for a message in mailbox), is unaware of ISRs, switches to high priority task, ISR is delayed!

Rule 2: No RTOS Calls without Fair Warning

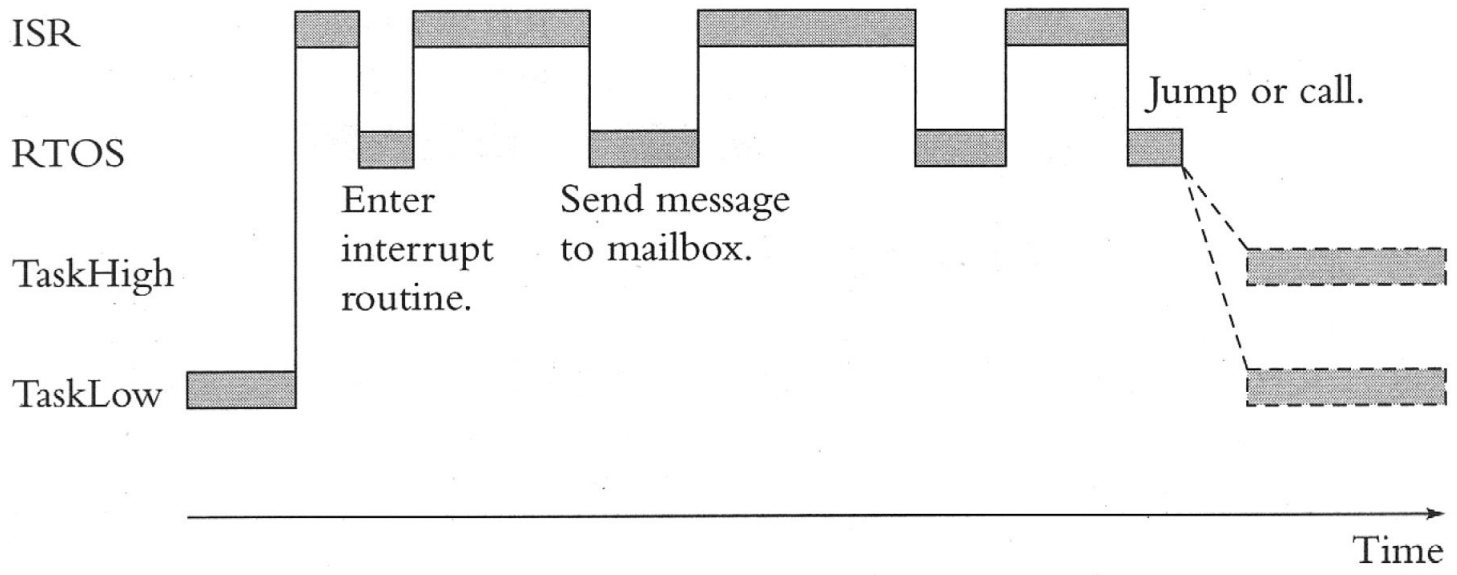
- Solutions:
- **Plan A**: Let RTOS know those functions are ISRs, need to register ISRs and which hardware interrupt corresponds to which ISR
- **Plan B**: In ISR, call a function to let RTOS know that we're in ISR (suspend task switching temporarily), jump or call at end of ISR (to switch to tasks)
- **Plan C**: Separate set of functions (Semaphores) to ISR, which always return to ISR

Rule 2: No RTOS Calls without Fair Warning



Plan A: let RTOS know about ISRs, hardware interrupts

Rule 2: No RTOS Calls without Fair Warning



Plan B: suspend scheduler in ISR

Rule 2: No RTOS Calls without Fair Warning

- Plan C:
- Call **OSISRSemPost()** instead of **OSSemPost()**
- OSISRSemPost() always return to ISR

Rule 2 and Nested Interrupts

- **Nest Interrupts**: Higher priority interrupt interrupts low-priority ISR
- When higher priority ISR finishes, it must return to low-priority ISR and not to another ready task (otherwise low priority ISR will be delayed!)
- Must suspend scheduler until all nested ISRs have finished execution

Rule 2 and Nested Interrupts