Inter-process communication

Wolf Text: Chapter 6.4

CMSIS-RTOS2: http://www.keil.com/pack/doc/CMSIS/RTOS2/html/index.html

uVision5 Books Pane: "MDK-ARM Getting Started" (PDF), CMSIS-RTOS2 (pp26-36)

Keil directory: *C:/Keil/ARM/PACK/ARM/CMSIS/5.3.0/CMSIS/RTOS2*

(user code templates, examples, documentation)

Interprocess communication

- Interprocess communication (IPC): OS provides mechanisms so that processes can pass data.
- Two types of semantics:
  - blocking: sending process waits for response;
    - time limit might be set in some cases
  - non-blocking: sending process continues.

Interprocess communication (IPC) mechanisms

- Semaphores
  - binary
  - counting
- Signals
- Mail boxes
- Queues
- Pipes

CMSIS-RTOS2 inter-thread communication

- **Thread flag** – for thread synchronization
  - Each thread has a pre-allocated 32-bit thread flag object.
  - A thread can wait for its TFs to be set by threads/interrupts.
- **Event flag** – for thread synchronization
  - Similar to thread flags, except dynamically created
- **Semaphores** – control access to common resource
  - Semaphore object contains tokens ("counting" semaphore)
  - Thread can request a token (put to sleep if none available)
- **Mutex** – mutual exclusion locks
  - "lock" a resource to use it, and unlock it when done
  - Kernel suspends threads that need the resource until unlocked
- **Message Queue** (Mail Queues eliminated in RTOS2)
  - Queue is a first-in/first-out (FIFO) structure
  - "Message" is an integer or a pointer to a message frame
  - Suspend thread if "put" to full queue or "get" from empty queue

Interprocess communication styles

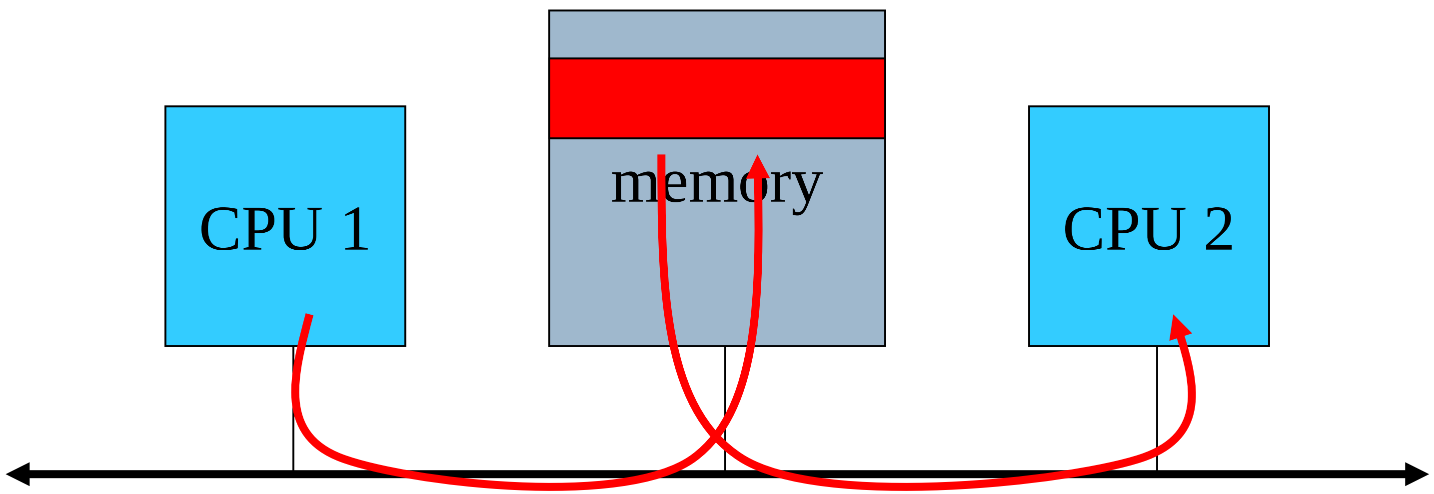
- Shared memory:
  - processes have some memory in common;
  - cooperate to avoid destroying/missing messages.
- Message passing:
  - processes send messages along a communication channel

    ---no common address space.
  - comm. channel may be physical or virtual

Shared memory

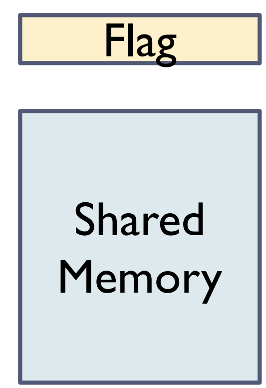
- CPUs could be separate processors and/or cores within a processor
- Multiple processes on the same CPU may also share memory

- Shared memory on a bus:



Race condition in shared memory

- Assume a "flag" used to synchronize access to shared memory
  - Flag = 1 when shared item is being used
  - Flag = 0 when shared item is not being used
  - To access the item: CPU must see flag = 0 and write flag = 1
- Problem when two CPUs try to write the same location:
  - CPU 1 reads flag and sees 0.
  - CPU 2 reads flag and sees 0.
  - CPU 1 sets flag to one and writes location.
  - CPU 2 sets flag to one and overwrites location.



Atomic test-and-set

- Problem can be solved with an atomic test-and-set:
  - single bus operation reads memory location, tests it, writes it.
- ARM test-and-set provided by SWP (swap):

```
         ADR   r0,SEMAPHORE
         LDR   r1,#1
GETFLAG  SWP   r1,r1,[r0]
         BNZ   GETFLAG
```

Critical regions

- Critical region: section of code that cannot be interrupted by another process.
- Examples:
  - writing shared memory;
  - accessing I/O device.

Mutual Exclusion Example

System variables: Lock = 0;

while (1){

While (!Test-And-Set(&Lock));

Critical Region

Lock = 0;

Remainder

} /* end while (1) */

Process 1

while (1){

While (!Test-And-Set(&Lock));

Critical Region

Lock = 0;

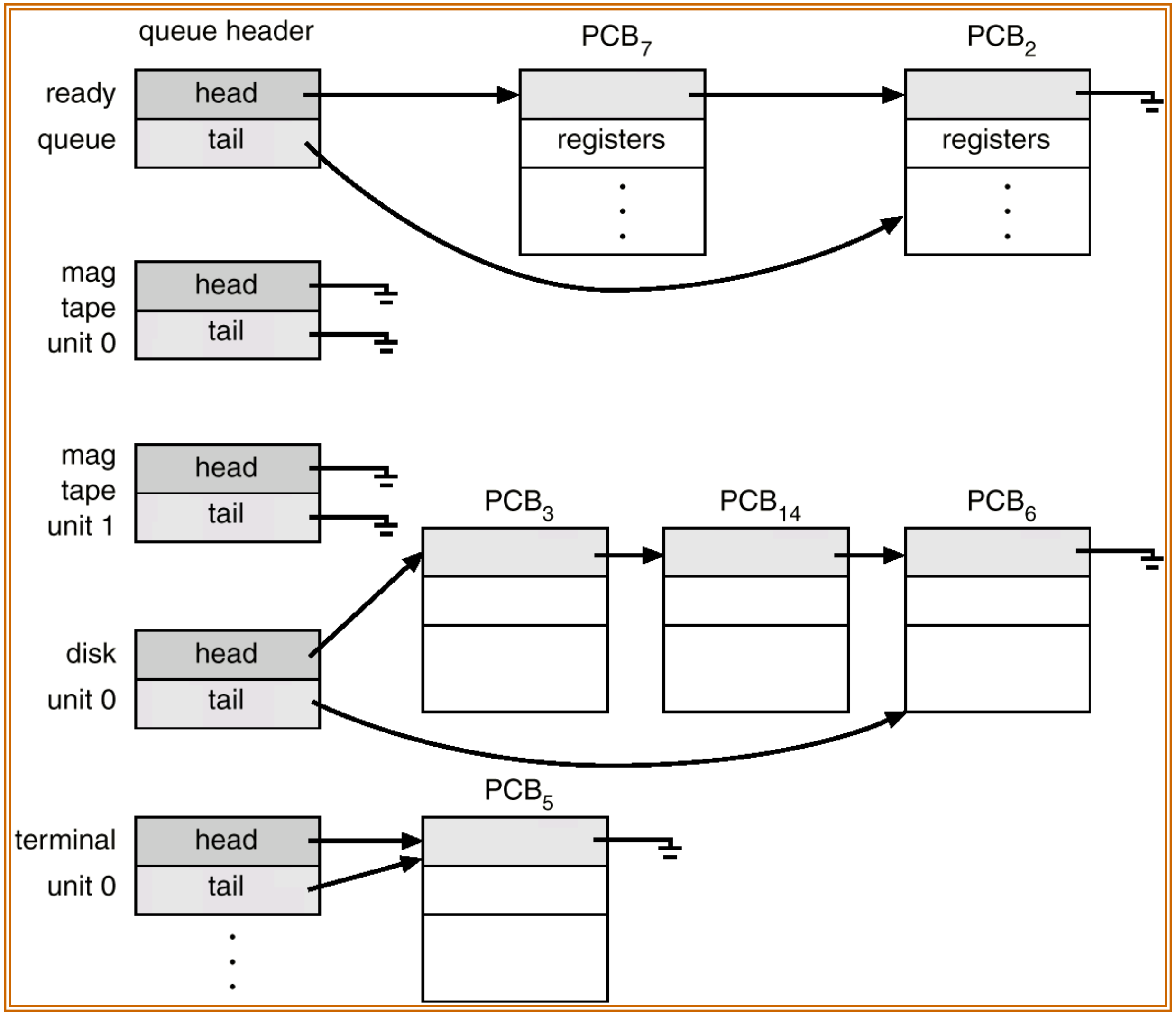
Remainder

} /* end while (1) */

Process 2

Task and Device Queues

Processes queued for shared device access



Semaphores

- Semaphore: OS primitive for controlling access to critical regions.
- Sempaphore can be "binary" or "counting"
- Protocol:
  1. Get access to semaphore with P() function.
     (Dutch "Proberen" – to test)
  2. Perform critical region operations.
  3. Release semaphore with V() function.
     (Dutch "Verhogen" – to increment)

- Sempaphore may be "binary" or "counting"

Binary semaphore

- Semaphore S values
  - S=1 : resource in use
  - S=0 : resource not in use
- Semaphore S actions
  - wait(&S) : test & set (read S, set S=1)

    use resource if S was read as 0

    wait if S was read as 1
  - signal(&S) : write S=0 to free up resource

Counting semaphore

- Semaphore S values
  - S=1 : resource free
  - S=0 : resource in use, no others waiting
  - S<0 : resource in use, others waiting
- Semaphore S actions
  - wait(&S) : S--, use resource if S=0, o/w wait
  - signal(&S) : S++, wake up other task if S<1

Also use for access to N copies of a resource
– semaphore indicates number of copies free

Example

- Access critical region

  wait(&S); //continue if read S=1, o/w wait

  //execute "critical region"

  signal(&S); //free the resource

- Task synchronization

Task1	Task2
signal(&S1)	signal(&S2)
wait (&S2)	wait(&S1)

  tasks synchronize at this point

Potential deadlock

- Tasks 1 and 2 each require two resources, R1 and R2, with access controlled by S1 and S2, respectively

Task1	Task2
wait(&S1)	wait(&S2)
//have R1	//have R2
wait (&S2)	wait(&S1)
//wait for R2	//wait for R1

DEADLOCK!!

Mutual Exclusion (MUTEX)

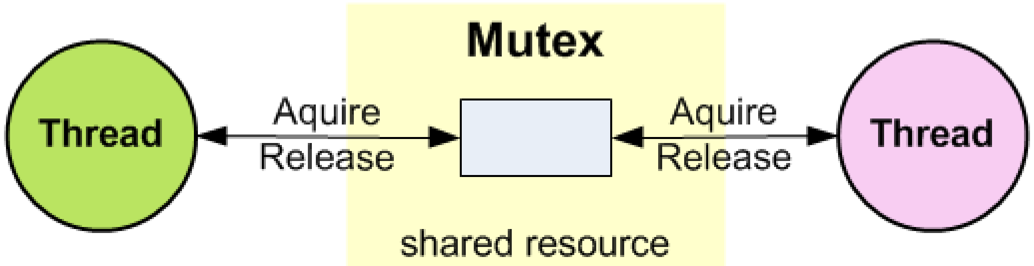
- **Binary semaphore**
- **Provide exclusive access to a resource**
- *osMutexId_t m_id;* //MUTEX ID

  m_id = osMutexNew(attr); //create MUTEX obj
  - attr = osMutexAttr_t structure or NULL for default
- *status = osMutexAcquire(m_id, timeout);*
  - Wait until MUTEX available or until time = "timeout"
    - timeout = 0 to return immediately
    - timeout = osWaitForever for infinite wait

    Timeout arguments for other objects have same options
  - "status" = osOK if MUTEX acquired

    osErrorTimeout if not acquired within timeout

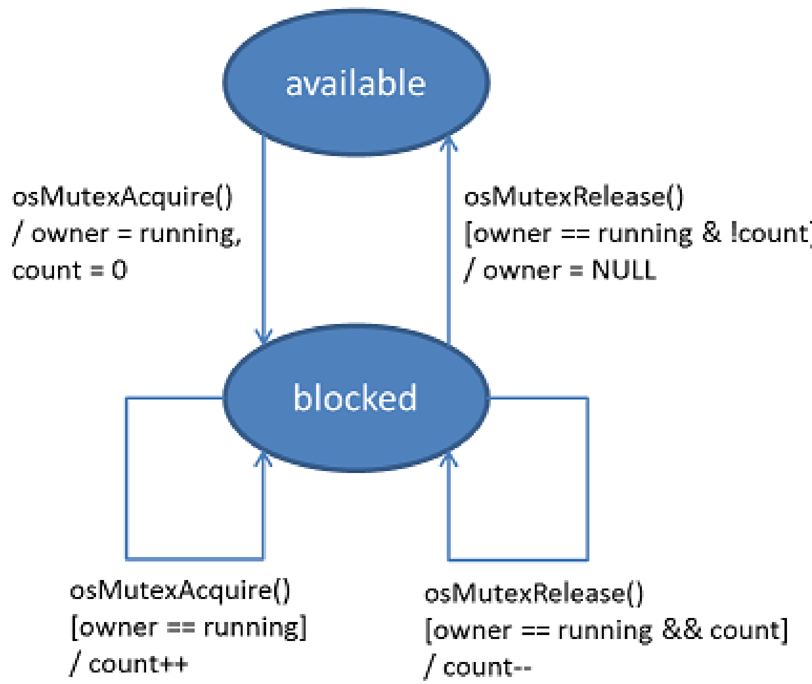
    osErrorResource if not acquired when timeout=0 specified
- *status = osMutexRelease(m_id);* //release the MUTEX
  - status = osOK if released, osErrorResource if invalid operation (not owner)



osMutexAcquire(mutex_id, timeout)
osMutexRelease(mutex_id)

Limit access to shared resource to one thread at a time.

Special version of a "semaphore"

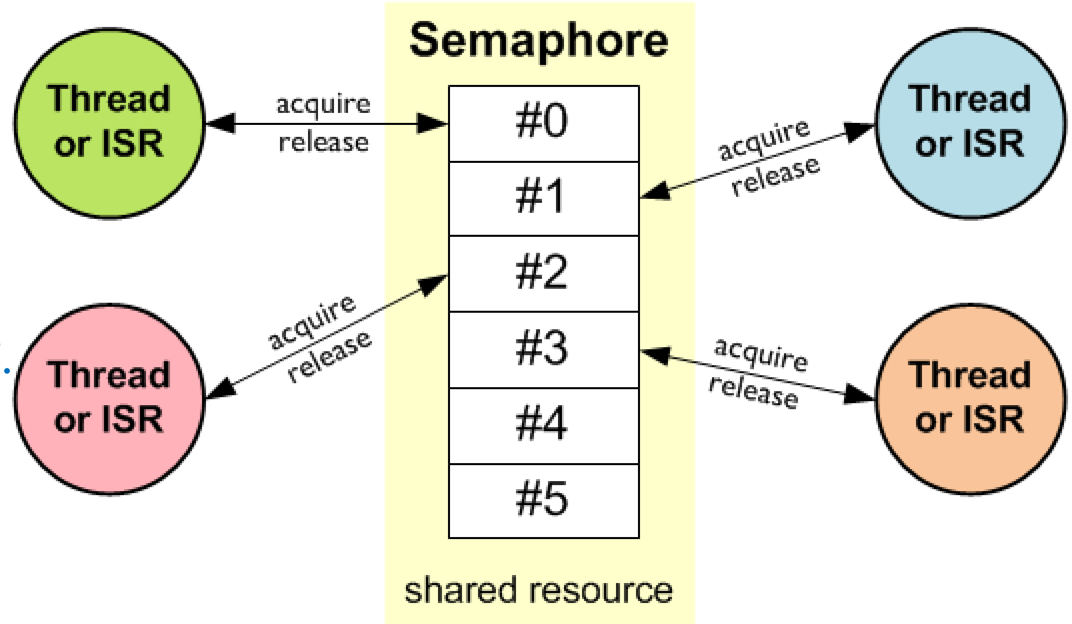


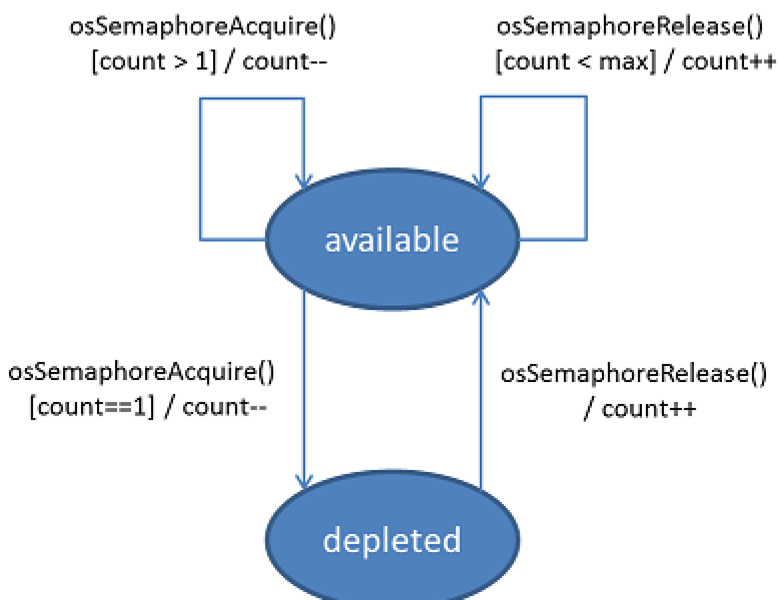
CMSIS-RTOS2 Semaphores

- **Counting semaphore**
- **Allow up to t threads to access a resource**
- osSemaphoreId s_id; //semaphore ID
  s_id = osSemaphoreNew(max_tokens, init_tokens, attr);
  - Create s1; set max and initial #tokens
  - attr osSemaphoreAttr_t structure or NULL for defaults
- status = osSemaphoreAcquire(s_id, timeout);
  - Wait until token available or timeout
  - status = osOK if token obtained (#tokens decremented)
    osErrorTimeout if token not obtained before timeout
    osErrorResouce if token not obtained and timeout=0
- status = osSemaphoreRelease(s_id);
  - Release token
  - status = osOK if token released (#tokens incremented)
    osErrorResouce if max token count reached
    osErrorParameter if s_id invalid

Permit fixed number of threads/ISRs to access a pool of shared resources.

Initialize with max# of "tokens".





osSemaphoreAcquire(sem_id,timeout)
osSemaphoreRelease(sem_id)

osSemaphoreGetCount(sem_id)

CMSIS-RTOS semaphore example

```
osSemaphoreId_t sid_Thread_Semaphore;            // semaphore id

// Main thread: Create the semaphore
  sid_Thread_Semaphore = osSemaphoreNew(2, 2, NULL);   //init with 2 tokens
  if (!sid_Thread_Semaphore)  {     ; // Semaphore object not created, handle failure  }


// Application thread:   Acquire semaphore - perform task - release semaphore
osStatus_t val;
val = osSemaphoreWait (sid_Thread_Semaphore, 10);          // wait up to 10 ticks
switch (val) {
      case osOK:                                            //Semaphore acquired
            // Use protected code here...
            osSemaphoreRelease (sid_Thread_Semaphore);      // Return token back to a semaphore
            break;
      case osErrorTimeout:     break;                  // Not acquired within timeout
      case osErrorResource:    break;                  // Not acquired and timeout=0 ("just checking")
      default:                 break;                  // Other errors
   }
```

POSIX semaphores

- POSIX supports counting semaphores with _POSIX_SEMAPHORES option.
  - Semaphore with N resources will not block until N processes hold the semaphore.
- Semaphores are given name:
  - Example: /sem1
- P() is sem_wait()
- V() is sem_post()

Semaphore example (1)

```
int i, oflags;
sem_t *my_semaphore; //descriptor for sem.

//create the semaphore
my_semaphore = sem_open("/sem1",oflags);
  /* do useful work here */

//destroy the semaphore if no longer needed
i = sem_close(my_semaphore);
```

Semaphore example (2)

```
int i;

i = sem_wait(my_semaphore);   // P()
 // wait for semaphore, block if not free
 // now do useful work
i = sem_post(my_semaphore);   // V()


// test without blocking
i = sem_trywait(my_semaphore);
```

Signals

- Originally, a Unix mechanism for simple communication between processes.
- Analogous to an interrupt---forces execution of a process at a given location.
  - But a signal is generated by one process with a function call.
- No data---can only pass type of signal.

CMSIS-RTOS2 Thread Flags

- Thread flags not "created" – a 32-bit word with 31 thread flags; exists automatically within each thread.

0	TF_{30}	….	TF_2	TF_1	TF_0

- One thread sets TFs in another thread (addressed by its thread ID)
- osThreadFlagsSet(tid, flags) – set TFs of thread tid
  - flags = int32_t; each "1" bit in "flags" sets the corresponding TF
  - Example: flags=0x8002 => set/clear TF #15 and TF #1
- osThreadFlagsWait(flags, option, timeout)
  - Wait for TFs corresponding to "1" bits in "flags" to be set
  - Option = osFlagsWaitAny or osFlagsWaitAll = wait for <u>any</u> or <u>all</u> of the flags
  - Timeout = 0 (check and return), osWaitForever, or time T
  - Return 32-bit value of flags (and then clear them)

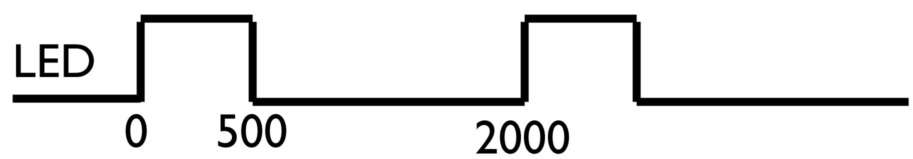
    osFlagsErrorTimeout if TFs are set before timeout T

    osFlagsEventTimeout if no flag before timeout

- osThreadFlagsClear(tid, flags) – clear TFs of thread, return current flags set
- osThreadFlagsGet( ) – return flags currently set in this thread

CMSIS-RTOS thread flags example

```
//Thread 1
void ledOn (void constant *argument) {
  for (;;) {
        LED_On(0);
        osThreadFlagsSet(tid_ledOff, 0x0001);  //signal ledOff thread
        osDelay(2000);
  }
}
```




```
// Thread 2
void ledOff (void constant *argument) {
  for (;;) {
        // wait for signal from ledOn thread
        osThreadFlagsWait(0x0001, osFlagsWaitAny, osWaitForever);
        osDelay(500);
        LED_Off(0);
  }
}
```

```
// Thread Flag Example – Thread3 must wait for signals from both Thread1 and Thread2
#include "cmsis_os2.h"
osThreadId_t tid1;              //three threads
osThreadId_t tid2;
osThreadId_t tid3;

void thread1 (void *argument) {
    while (1) {
            osThreadFlagsSet(tid3, 0x0001);   /* signal thread 3 */
            ….

void thread2 (void *argument) {
    while (1) {
            osThreadFlagsSet(tid3, 0x0002);   /* signal thread 3 */
            ….

void thread3 (void *argument) {
uint32_t flags;
   while (1) {
      //wait for signals from both thread1 and thread2
      flags = osThreadFlagsWait(0x0003, osFlagsWaitAll, osWaitForever);
      … //continue processing
```

CMSIS-RTOS2 Event Flags

- Each "signal" has up to 31 "event flags" (bits 30-0 of the signal word)
- Similar to Thread Flags, but Event Flags do not "belong" to any thread
  - Wait (in BLOCKED state) for an event flag to be set
  - Set/Clear one or more event flags
- osEventFlagsId_t evt_id;

  evt_id = osEventFlagsNew(*attr) – create & initialize event flags
  - NULL argument for default values (or pointer to osEventFlagsAttr_t structure)
  - Return event flags id (evt_id)
- osEventFlagsSet(evt_id, **flags**) – set EFs in evt_id

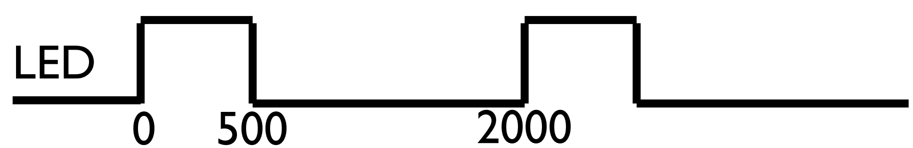
  osEventFlagsClear(evt_id, **flags**) – clear EFs of evt_id
  - flags = int32_t; each "1" bit in "flags" sets/clears the corresponding EF
  - Return int32_t = flags after executing the set/clear (or error code)
- osEventFlagsWait(evt_id, **flags**, options, timeout)
  - Wait for EFs corresponding to "1" bits in "flags" to be set, or until timeout
  - Options – osFlagsWaitAny or osFlagsWaitAll (any or all of the indicated flags)
  - Return current event flags or error code

    osFlagsErrorTImeout if awaited flags not set before timeout

    osFlagsErrorResouce if evt_id not ready to be used

Event flags example

```
osEventFlagsId_t  led_flag;
void main_app (void constant *argument) {
        led_flag = osEventFlagsNew(NULL);  //create the event flag
}
void ledOn (void constant *argument) {
  for (;;) {
        LED_On(0);
        osEventFlagsSet(led_flag, 0x0001);    //signal ledOff thread
        osDelay(2000);
  }
}
void ledOff (void constant *argument) {
  for (;;) { // wait for signal from ledOn thread
         osEventFlagsWait(led_flag, 0x0001, osFlagsWaitAny, osWaitForever);
         osDelay(500);
         LED_Off(0);
  }
}
```



POSIX signals

- Must declare a signal handler for the process using sigaction().
  - what to do when signal received
  - handler is called when signal is received

```
retval=sigaction(SIGUSR1,&act,&oldact);
```

- Send signal with sigqueue():

```
sigqueue(destpid,SIGRTMAX-1,sval);
```

signal type

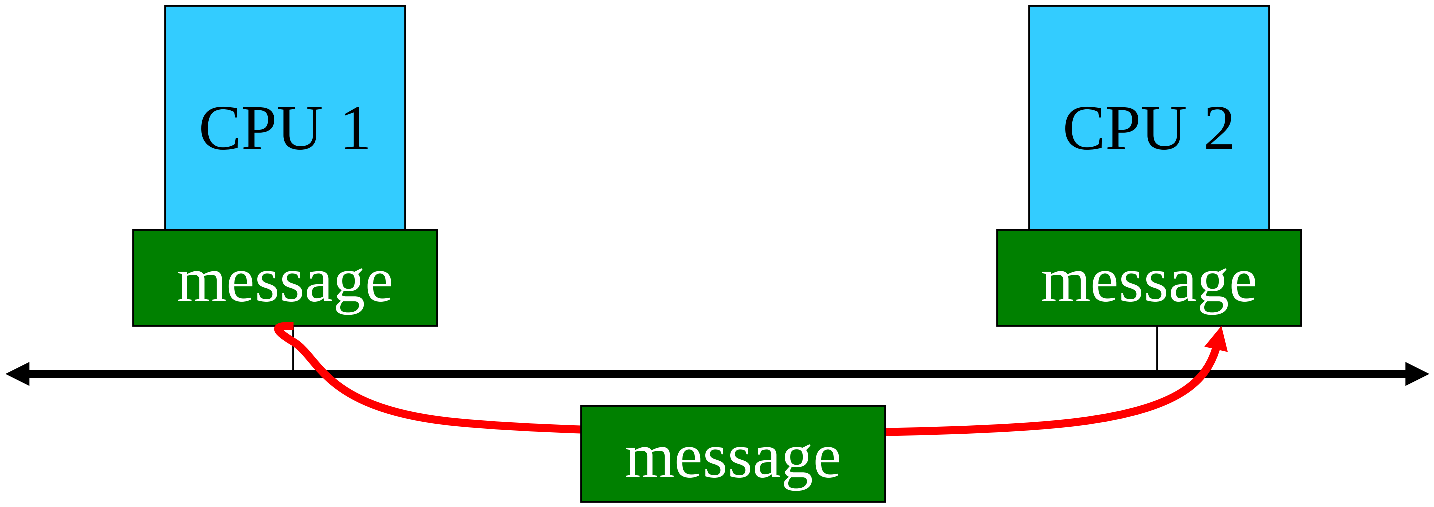
send to process

POSIX signal types (partial list)

- SIGABRT: abort process
- SIGTERM: terminate process
- SIGFPE: floating point exception
- SIGILL: illegal instruction
- SIGKILL: unavoidable process termination
- SIGALRM: real-time clock expired
- SIGUSR1, SIGUSR2: user defined

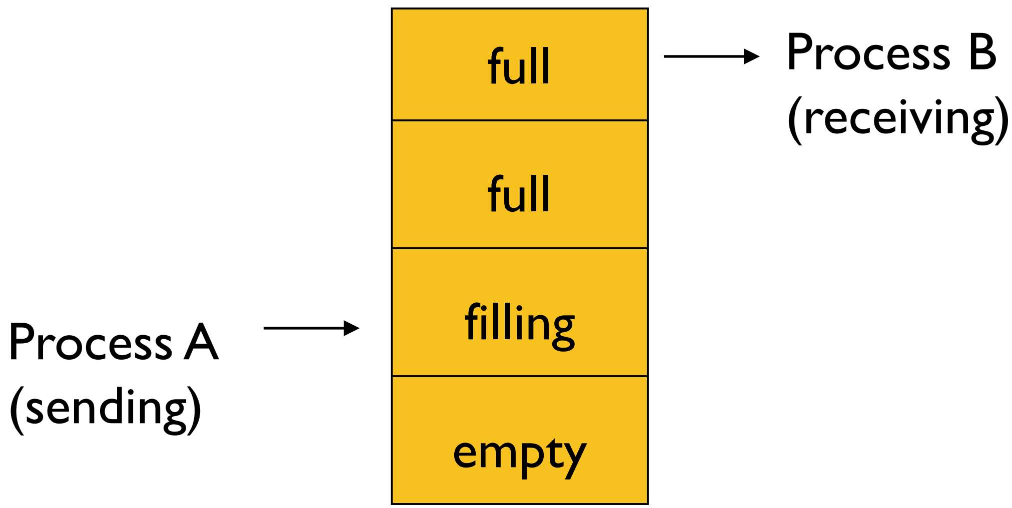
Message passing

- Message passing on a network:



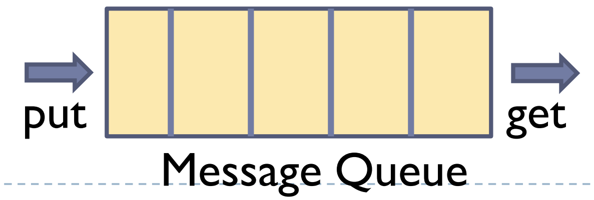
Message passing via mailboxes

- Mailbox = message buffer between two processes (FIFO)



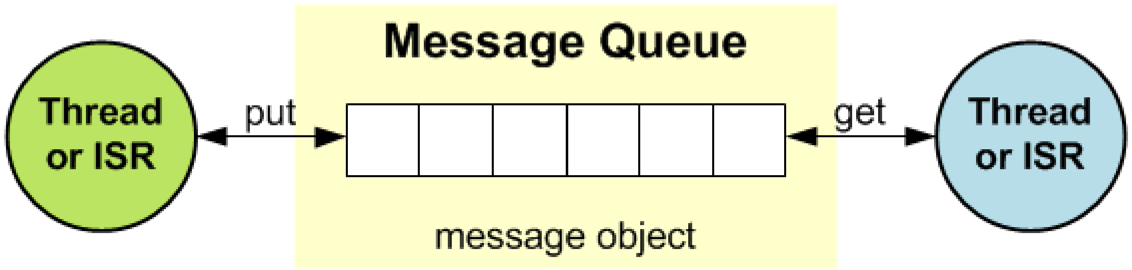
Use semaphore to lock buffer during read/write

CMSIS-RTOS2
Message queues



"Message" = information to be sent

- *osMessageQueueId q_id;* *// ID of queue object*
- *q_id = osMessageQueueNew(msg-count, msg-size, attr);*
  - Create and initialize a message queue, return queue ID
  - Specify: max #msgs, max msg size, attributes (or NULL for defaults)
- *status = osMessageQueuePut(q_id, msg-ptr, msg-priority, timeout);*
  - Add message to queue; wait for "timeout" if queue full
  - msg-ptr = pointer to message data structure
  - Status = *osOK* : msg was put into the queue
    = *osErrorResource* : not enough space for msg
    = *osErrorTimeout* : no memory available at timeout
- *status = osMessageQueueGet(q_id, msg-ptr, msg-priority, timeout);*
  - Get msg from queue, put it in *msg-ptr and put priority in *msg-priority;
  - Wait for "timeout" if no message
  - Status = *osOK* : message was retrieved from the queue
    = *osErrorResource* : no message available and timeout=0
    = *osErrorTimeout* : no message available before timeout



osMessageQueuePut(mq_id, *msg_ptr, msg_prio, timeout)
osMessageQueueGet(mq_id, *msg_ptr, *msg_prio, timeout)

osMessageQueueGetCapacity(mq_id) - max #msgs in the queue
osMessageQueueGetMsgSize(mq_id) - max msg size in memory pool
osMessageQueueGetCount(mq_id) - # queued msgs in the queue
osMessageQueueGetSpace(mq_id) - # available slots in the queue
osMessageQueueReset(mq_id) - reset to empty

CMSIS-RTOS message queue example

```
// "Message" will be a 32-bit integer
osMessageQueueId_t mid_MyQueue;        // message queue id
// Thread 1 code
    uint32_t n;
    n = something;
    osMessageQueuePut (mid_MyQueue, &n, 0, osWaitForever);  //send n as the message
    …
// Thread 2 code
    osStatus_t status;                                       //function call status
    uint32_t msg;                                            //variable for received "message"
    status = osMessageQueueGet(qid_MyQueue, &msg, 0, 0)      //return immediately if no message
    if (status == osOK)        //was there a message?
      {    //process its data        }
    ….
// Main creates threads, message queues, etc.
    int main (void )
    {
      qid_MyQueue = osMessageQueueNew(16, sizeof(uint32_t), NULL);
```

/* Message Queue creation & usage example */

```
// message object data type
typedef struct {
  uint8_t Buf[32];
  uint8_t Idx;
} MSGQUEUE_OBJ_t;

// message queue id
osMessageQueueId_t mid_MsgQ;

// thread creates a message queue for 12 messages
int Init_MsgQueue (void) {
   mid_MsgQ = osMessageQueueNew(12, sizeof(MSGQUEUE_OBJ_t), NULL);
   ….
}
```

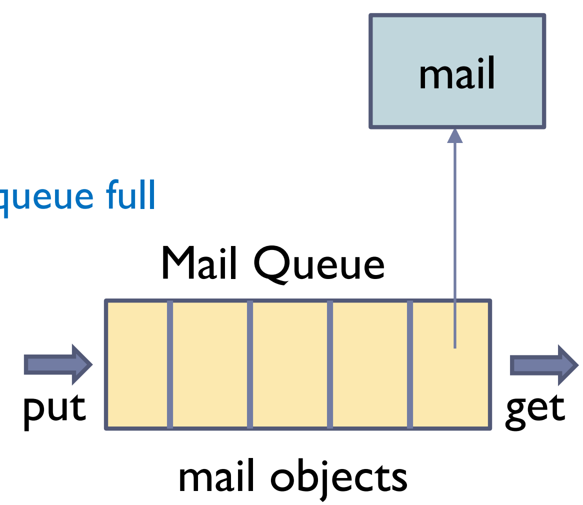
Continued on next slide

```
/* Message Queue Example Continued */

void Thread1 (void *argument) {    // this threads sends data to Thread2
  MSGQUEUE_OBJ_t msg;
  while (1) {
    ; // Insert thread code here...
    msg.Buf[0] = 0x55;                                       // data to send
    msg.Idx    = 0;                                          // index of data in Buf[]
    osMessageQueuePut (mid_MsgQ, &msg, 0, NULL);             // send the message
    osThreadYield ();                                        // suspend thread
  } }

void Thread2 (void *argument) {   //This thread receives data from Thread1
  MSGQUEUE_OBJ_t msg;
  osStatus_t status;
  while (1) {
    ; // Insert thread code here...
    status = osMessageQueueGet (mid_MsgQ, &msg, NULL, NULL);  // wait for message
    if (status == osOK) {
        ; // process data in msg.Buf[msg.Idx]
   }  } }
```

CMSIS-RTOS mail queues (eliminated in RTOS2)

- *osMailQId q_id;* // ID of ***mail queue*** object
- *osMailQDef (name, queue_size, type);* // Macro: mail queue name, # entries, mail type
- *q_id = osMailCreate(osMailQ(name), NULL);*
  - Create and initialize a message queue, return queue ID
- *mptr = osMailAlloc(q_id, timeout);* *(osMailCAlloc() – allocate and clear memory)*
  - *Allocate a memory block in the queue that can be filled with mail info*
  - *"mptr" = pointer to the memory block (NULL if no memory can be obtained)*
  - *Wait, with timeout, if necessary for a mail slot to become available*
- *status = osMailFree(q_id, mptr); - free allocated memory*

- *status = osMailPut(q_id, mptr);*
  - Add mail (pointed to by mptr) to queue; wait for "timeout" if queue full
  - Status = *osOK* : mail was put into the queue
    = *osErrorValue* : mail was not allocated as a memory slot
- *status = osMailGet(q_id, timeout);*
  - Get mail from queue; wait for "timeout" if no mail available
  - Status = *osOK* : no mail available and timeout=0
    = *osEventTimeout* : no mail available before timeout
    = *osEventMail* : mail received, pointer = value.p



MicroC/OS-II Mailboxes

- OSMboxCreate(msg)
  - create mail box & insert initial msg
- OSMboxPost(box, msg)
  - add msg to box
- OSMboxAccept(box)
  - get msg if there, o/w continue
- OSMboxPend(box,timeout)
  - get msg if there, o/w wait up to timeout
- OSMboxQuery(box,&data)
  - return information about the mailbox