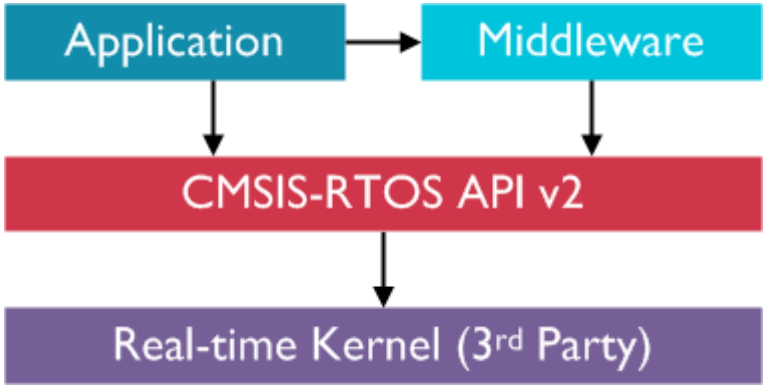
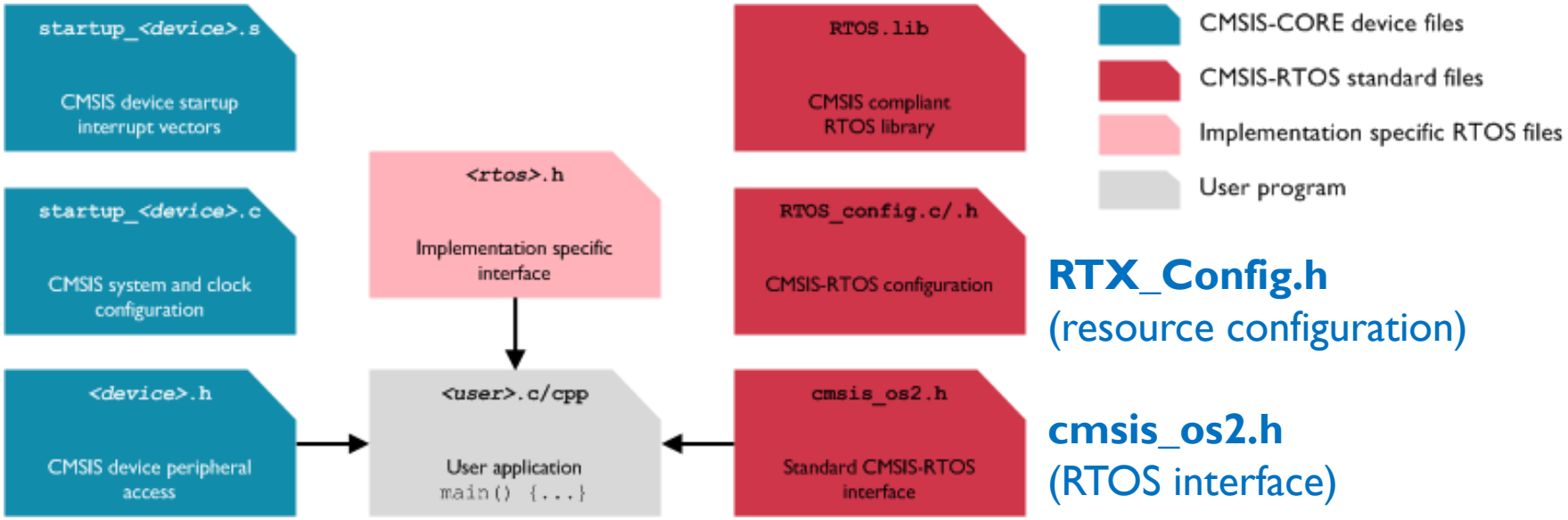
CMSIS Real Time Operating System (Based on Free RTOS)

References: HTTPS://developer.mbed.org/handbook/CMSIS-RTOS
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)

CMSIS-RTOS2 Implementation (v2.x)





RTX_Config.h
(resource configuration)

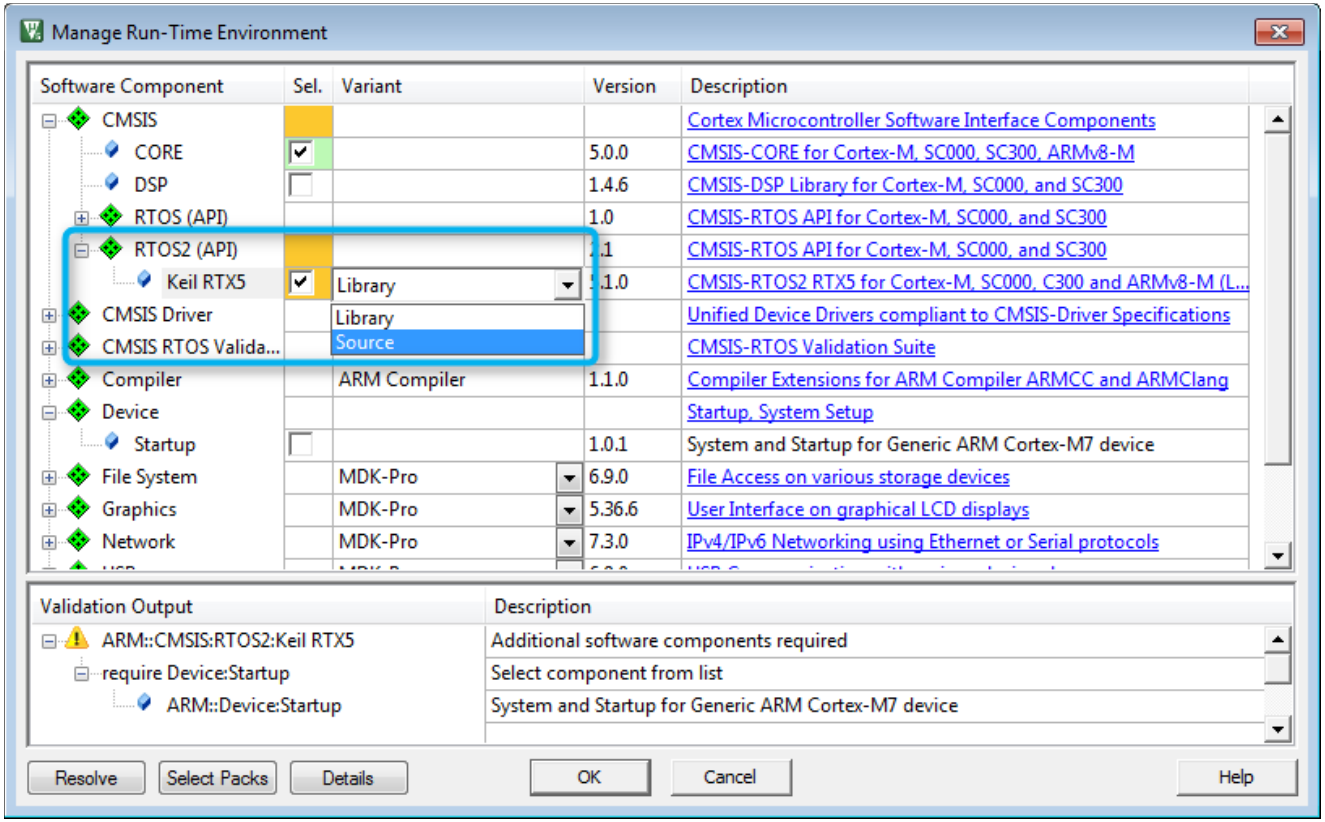
cmsis_os2.h
(RTOS interface)

CMSIS-RTOS2 *(RTOS version 2)* API

- **Thread Management** allows you to define, create, and control threads.
- **Interrupt Service Routines** (ISR) can call some CMSIS-RTOS functions.
  - When a CMSIS-RTOS function cannot be called from an ISR context, it rejects the invocation and returns an error code.
- Three event types support communication between multiple threads and/or ISR:
  - **Thread Flags**: may be used to indicate specific conditions to a thread.
  - **Event Flags**: may be used to indicate events to a thread or ISR.
  - **Messages**: can be sent to a thread or an ISR. Messages are buffered in a queue.
- **Mutex Management** and **Semaphores** are incorporated.
- CPU time can be scheduled with the following functionalities:
  - A *timeout* parameter is incorporated in many CMSIS-RTOS functions to avoid system lockup. When a timeout is specified, the system waits until a resource is available or an event occurs. While waiting, other threads are scheduled.
  - The **osDelay** and **osDelayUntil** functions put a thread into the **WAITING** state for a specified period of time.
  - The **osThreadYield** provides co-operative thread switching and passes execution to another thread of the same priority.
- **Timer Management** functions are used to trigger the execution of functions.

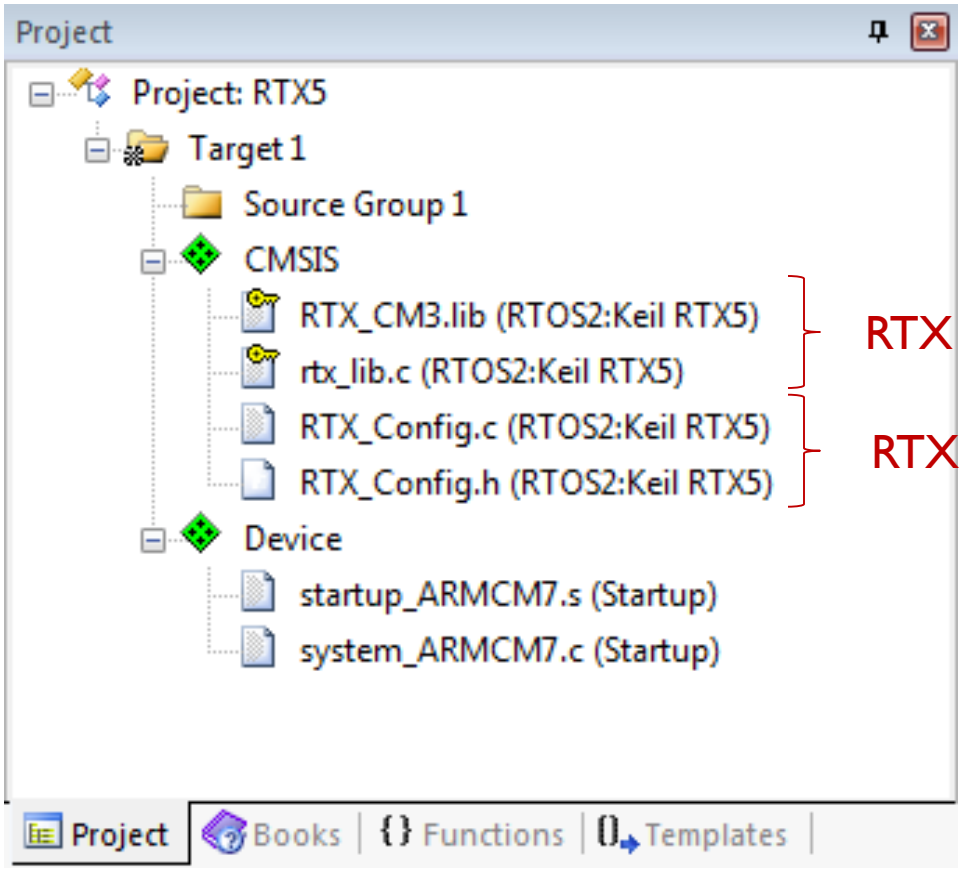
Using CMSIS-RTOS2 in a project

Create the project and add RTOS2 from *Manage Run-Time Environment* during project creation or from *Project > Manage > Run-Time Environment*



Select CMSIS-RTOS2 Library
or
Source (all .c files)

Created CMSIS-RTOS2 project



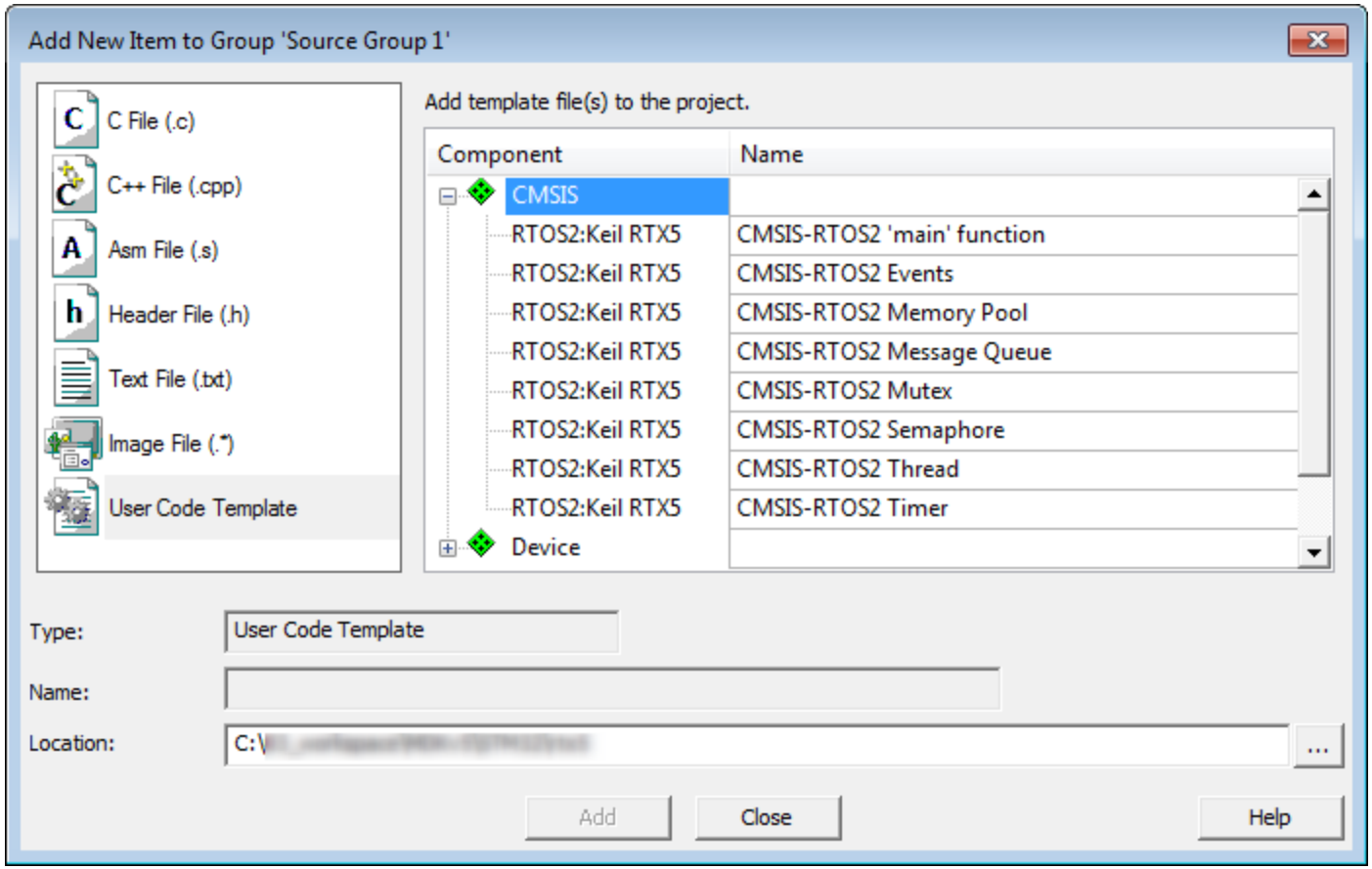
RTX function library

RTX configuration file

Edit RTX_Config.h to configure RTX kernel for this particular application.

#include “cmsis_os2.h” in source (RTOS2 API)

Templates can used to create sources



Recommended order of program operations

In **main()**:

1. Initialize/configure hardware:
   - Peripherals, memory, pins, clocks, interrupts.
2. Configure system core clock
   - Optional: **SystemClock_Config()** for 80MHz clock
   - **SystemCoreClockUpdate();** sets global variable SystemCoreClock used to configure SysTick timer.
3. Run **osKernelInitialize** to initialize CMSIS-RTOS kernel.
4. Run **osThreadNew** to create at least one thread ***app_main***
   - RTOS scheduler will execute this thread when Kernel starts.
   - Use ***app_main*** to create “application” threads.
   - Alternatively, can create all threads in **main()**.
5. Run **osKernelStart** to start RTOS scheduler.
   - This function does not return in case of successful execution.
   - Any application code after **osKernelStart** will not be executed unless **osKernelStart** fails.

Starting the RTOS2 Kernel and Scheduler

```
#include "cmsis_os2.h"
osThreadId_t  tid_phaseA;                  // Thread id of thread "phaseA"

void phaseA (void *argument) {             //Some application thread
   …some processing
}

void app_main (void *argument) {
   tid_phaseA = osThreadNew (phaseA, NULL, NULL);    //Create thread "phaseA"
   osDelay(osWaitForever);                           //app_main never ready again
   while (1);
}

int main (void) {
// System Initialization
SystemCoreClockUpdate();                   // Set SystemCoreClock variable
osKernelInitialize();                      // Initialize CMSIS-RTOS2
osThreadNew(app_main, NULL, NULL);         // Create application main thread
if (osKernelGetState() == osOK) {          // Kernel OK to run?
            osKernelStart();               //Start thread execution
   }
 while(1);   //will not execute unless above fails
}
```

RTX_Config.h – Kernel configuration

Edit RTX parameters to tailor the kernel to the application

- *OS_TICK_FREQ* = kernel tick frequency [Hz] (SysTick interrupts)
  - Uses **SystemCoreClock** variable to set up SysTick timer.
- *OS_ROBIN_ENABLE* = 1 enable round-robin thread switching
  = 0 disable round-robin & use timer/event scheduling
- *OS_ROBIN_TIMEOUT* = # kernel ticks to execute before thread switch
- *OS_THREAD_NUM* = max # active use threads (in any state)
- *OS_THREAD_DEF_STACK_NUM* = *#user thread with default stack size*
- *OS_THREAD_USER_STACK_SIZE* = *total stack size (bytes) for user-provided stacks*
- *OS_STACK_SIZE* = default thread stack size if not specified
- *OS_STACK_CHECK* = enable/disable status checking (of stack)
- *OS_EVFLAGS_NUM* = # event flag objects
- *OS_MUTEX_NUM* = # Mutex objects
- *OS_SEMAPHORE_NUM* = # Semaphore objects
- *OS_MSGQUEUE_NUM* = # Message Queue objects
- *OS_MSGQUEUE_OBJ_MEM* = Enable allocation of Message Queue memory
- *OS_MSGQUEUE_DATA_SIZE* = combined data storage (#bytes) for message objects

RTX Threads

- The scheduling unit is the **thread**
  - Threads are dynamically created, started, stopped, etc.
- Create and put each thread into the Thread List
  - Each assigned a "thread ID" to be used for scheduling, messages, flags, events, etc.

```
osThreadId_t tid_ralph;          //thread ID of thread "ralph"
void ralph ( void ) { … }        //thread function "ralph"
tid_ralph = osThreadNew( ralph, argument, attr);
```

    - *ralph* = function name
    - *argument* - passed to function as start argument (default NULL)
    - attr = thread attribute structure: priority, stack size, mem'y alloc, etc.
      (NULL to use default structure values)
  - *osThreadGetId();* //return thread ID of current thread if not known

Thread attributes

- Each thread has an attribute record structure of type **osThreadAttr_t**
  - name - char* string thread name (ex. "MyThread")
  - cb_mem/cb_size – memory and size of thread control block
  - stack_mem/stack_size – memory and size of thread stack
  - priority – thread priority (initially *osPriorityNormal*)
  - *several other less-used fields*

Thread function

- Attribute record structure may be passed to **osThreadNew()**
  - If NULL parameter passed, default values are assigned

Thread priorities

- Priority levels
  - osPriorityIdle (1) – lowest priority
  - osPriorityLow (8)
  - osPriorityBelowNormal (16)
  - osPriorityNormal (24) – default priority
  - osPriorityAboveNormal (32)
  - osPriorityHigh (40)
  - osPriorityRealTime (48)
  - osPriorityISR (56) – highest priority

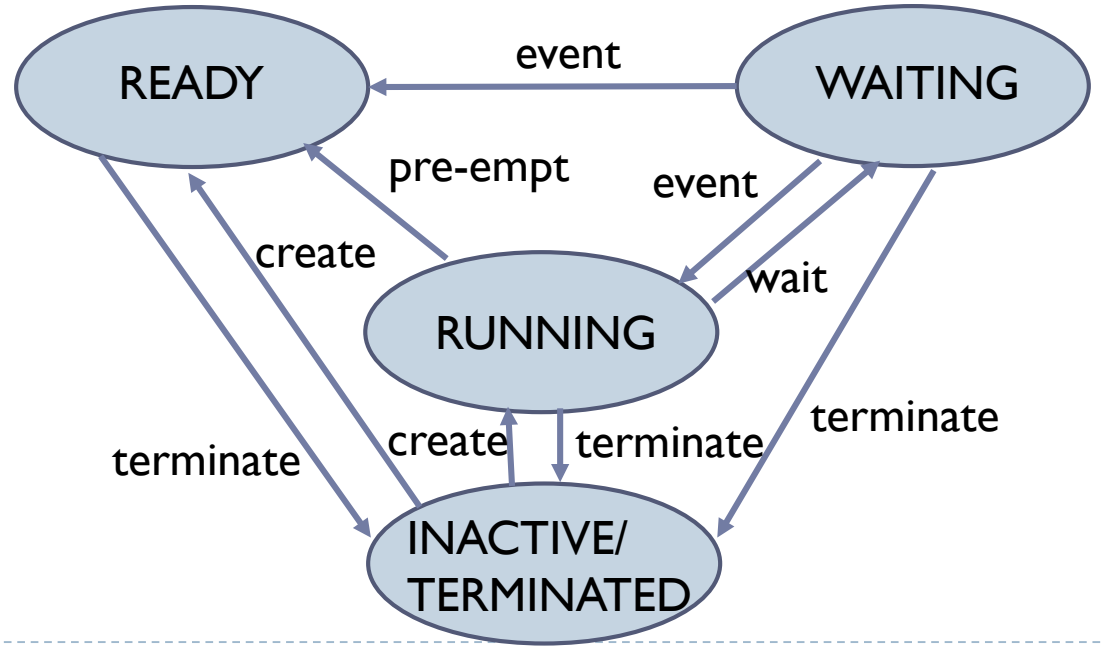
7 more levels for each:
Example:
LowN (N=1..7) = 8+N

Likewise for all but
IDLE and ISR

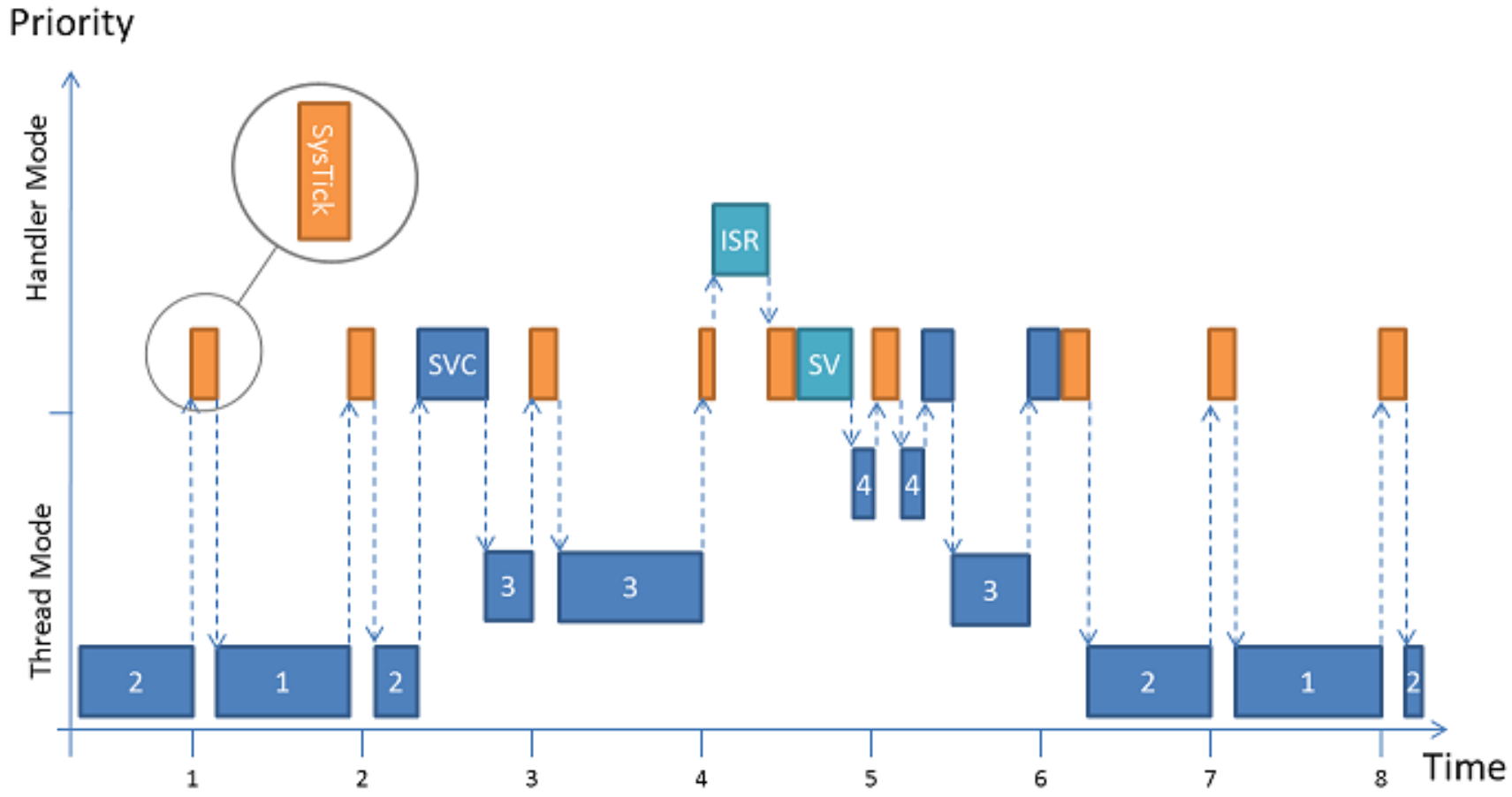
- Thread priority set to default when thread created:
  - Initial default priority osPriorityNormal
  - If Thread Attribute record specified for new thread, use its priority field.
- Change priorities:
  - osThreadSetPriority(tid, p); //tid = task id, new priority p
  - osThreadGetPriority(); //return current task priority

Thread states

- RUNNING – thread currently running
- READY to run, RTX chooses highest-priority
- BLOCKED – waiting for some event to occur
- INACTIVE – thread created but not active, or terminated



Thread scheduling and interrupts



Threads 1 & 2 have same priority; Thread 3 higher; Thread 4 highest

Controlling thread states

- Running thread BLOCKED if it must wait for an event
  - Thread flag, event signal, semaphore, mutex, message, etc.
- osThreadYield() – move to READY and pass control to next READY thread of same priority (continue if no ready threads)
- osThreadSuspend(tid) – move thread tid -> BLOCKED
- osThreadResume(tid) – move thread tid -> READY
- osThreadTerminate(tid) – move thread tid -> INACTIVE
  - Remove from list of active threads (terminate if running)

- Function return values:
  - osOK - successful
  - osError – unspecified error
  - osErrorISR – cannot call function from an ISR
  - osErrorResource – thread in wrong state for attempted action

```
/*----------------------------------------------------------------------
 *      Thread 1 'MyThread': Sample thread
 *----------------------------------------------------------------------*/

#include <cmsis_os2.h>     // CMSIS RTOS2 header file

void MyThread (void * argument);                 // thread function prototype
osThreadId_t tid_MyThread;                       // thread id variable

/* Define the thread function */
void MyThread (void const *argument) {
  while (1) {
    ; // Insert thread code here...
    osThreadYield();    // suspend thread
  }

/* Created before and executed after kernel initialized */
void main_thread (void) {
   tid_MyThread = osThreadCreate (MyThread, NULL, NULL);  //create thread MyThread
   if(!tid_MyThread) return(-1);  //error if thread ID is NULL
   // …. create other new threads …..
   osDelay(osWaitForever);          //suspend this thread
   while (1);
}
```

```
/* Simple program using round-robin schedule with two threads */
#include "cmsis_os2.h"    // CMSIS-RTOS2 header file

int counter1, counter2;
osThreadId_t tid_job1;              //thread IDs
osThreadId_t tid_job2;

void job1 (void const *arg) {    //First thread
   while (1) { // loop forever
      counter1++; // update the counter
   }
}
void job2 (void const *arg) {    //Second thread
  while (1) { // loop forever
     counter2++; // update the counter
   }
}

int main (void) {        //executed at startup
   osKernelInitialize ();                                    // set up kernel
   tid_job1 = osThreadCreate (job1, NULL, NULL);   // create and add thread "job1" to Thread List
   tid_job2 = osThreadCreate (job2, NULL, NULL);   // create and add thread "job2" to Thread List
   osKernelStart ();                                          // start kernel
}
```

ARM CMSIS-RTOS scheduling policies

- Round robin schedule (OS_ROBIN_ENABLE = 1)
  - All threads assigned *same priority*
  - Threads allocated a fixed time
    - OS_ROBIN_TIMEOUT = ticks allocated to each thread
    - OS_TICK_FREQ = frequency (in Hz) of SysTick timer interrupts
  - Thread runs for designated time or until blocked/yield
- Round robin with preemption (OS_ROBIN_ENABLE = 1)
  - Threads assigned *different priorities*
  - Higher-priority thread becoming ready preempts (stops) a lower-priority running thread
- Pre-emptive (OS_ROBIN_ENABLE = 0)
  - Threads assigned *different priorities*
  - Thread runs until blocked, or executes osThreadYield(), or higher-priority thread becomes ready (no time limit)
- Co-operative Multi-Tasking (OS_ROBIN_ENABLE = 0)
  - All threads assigned *same priority*
  - Thread runs until blocked (no time limit) or executes osThreadYield();
  - Next ready thread executes

Preemptive multitasking

- *#define OS_ROBIN_ENABLE 0* in *RTX_Config.h*
- RTX suspends running thread if a higher priority thread (HPT) becomes READY
- Thread scheduler executes at system tick timer interrupt.
- Thread context switch occurs when:
  - Event set for a HPT by the running thread or by an interrupt service routine (event for which the HPT was waiting)
  - Token returned to a semaphore for which HPT is waiting
  - Mutex released for which HPT is waiting
  - Message posted to a message queue for which HPT is waiting
  - Message removed from a full message queue, with HPT waiting to send another message to that queue
  - Priority of the current thread reduced and a HPT is ready to run

Round-Robin Multitasking

- RTX gives a time slice to each thread (OS_ROBIN_TIMEOUT)
- Thread executes for duration of time slice, unless it voluntarily stops (via a system delay or yield function)
- RTX changes to next READY thread with same priority
  - if none – resume current thread

- Configure in *RTX_Config.h*
  - #define OS_ROBIN_ENABLE 1
  - #define OS_ROBIN_TIMEOUT n

    n = #kernel ticks given to each thread ("timeout" value)

Basic wait/delay function

- Suspend a thread for a designated amount of time
- *osStatus_t osDelay (uint32_t T);*
  - Change thread state to WAITING
  - Change thread state back to READY after T kernel ticks
  - Return status = *osOK* if delay properly executed
    = *osErrorISR* if osDelay() called from an ISR (not permitted)

```
#include "cmsis_os2.h“

void Thread_1 (void const *arg) { // Thread function
      osStatus_t status;         // capture the return status
      uint32_t delayTime;        // delay time in milliseconds
      delayTime = 1000;          // delay 1 second
       :
       status = osDelay (delayTime); // suspend thread execution
}
```

- Also available: *osStatus_t osDelayUntil (uint32_t T); //delay until time=T*

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
- **Semaphore** – 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 Queue 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

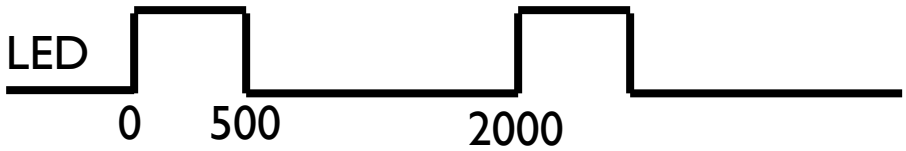
Thread Flags

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

- 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 any or all 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
    - osFlagsErrorResource if TFs not set and timeout = 0
    - osFlagsErrorUnknown unspecified error (not called from correct context)
- 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

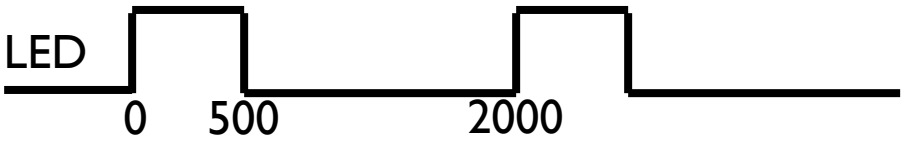
  osEventFlagsClear(evt_id, flags) – clear EFs of evt_id
  - flags = int32_t; each "1" bit in "flags" sets/clears the corresponding EF
  - Return int32_t = flags after executing the set/clear (or error code)
- osEventFlagsWait(evt_id, flags, options, timeout)
  - Wait for EFs corresponding to "1" bits 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 awaited flags not set and timeout = 0

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);
  }
}
```



Mutual Exclusion (MUTEX)

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

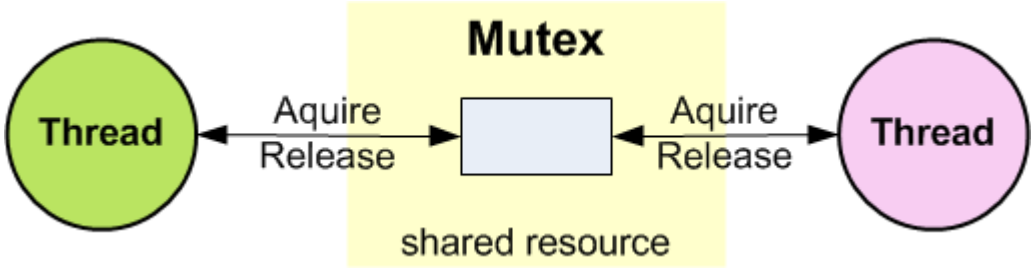
  m_id = osMutexNew(attr); //create MUTEX obj
  - attr = osMutexAttr_t structure or NULL for default
- *status = osMutexAcquire(m_id, timeout);*
  - Wait until MUTEX available or until time = "timeout"
    - timeout = 0 to return immediately
    - timeout = osWaitForever for infinite wait
  - "status"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

    osErrorTimeout if not acquired within timeout

    osErrorResource if not acquired when timeout=0 specified

Timeout arguments for other objects have same options

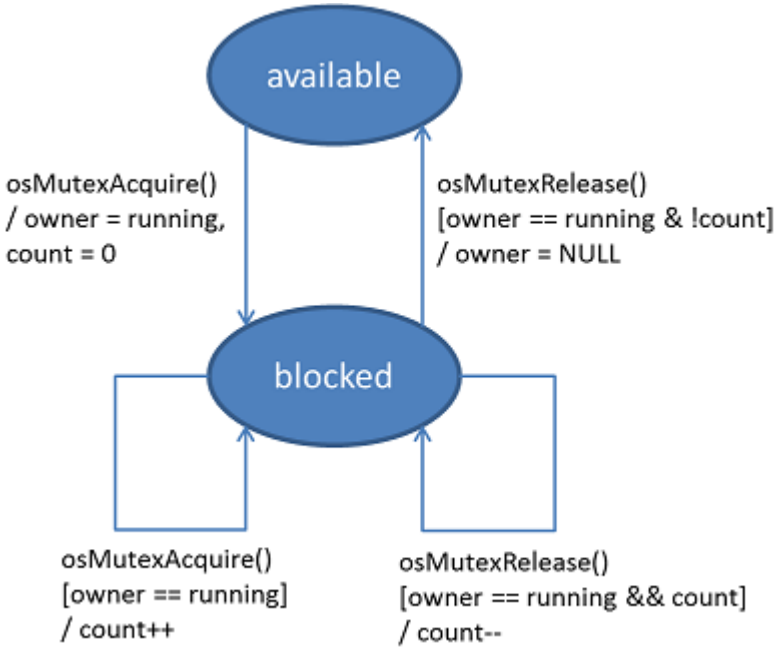
- *status = osMutexRelease(m_id);* //release the MUTEX
  - status = osOK if released, osErrorResource if invalid operation (not owner)



osMutexAcquire(mutex_id, timeout)
osMutexRelease(mutex_id)

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

Special version of a "semaphore"

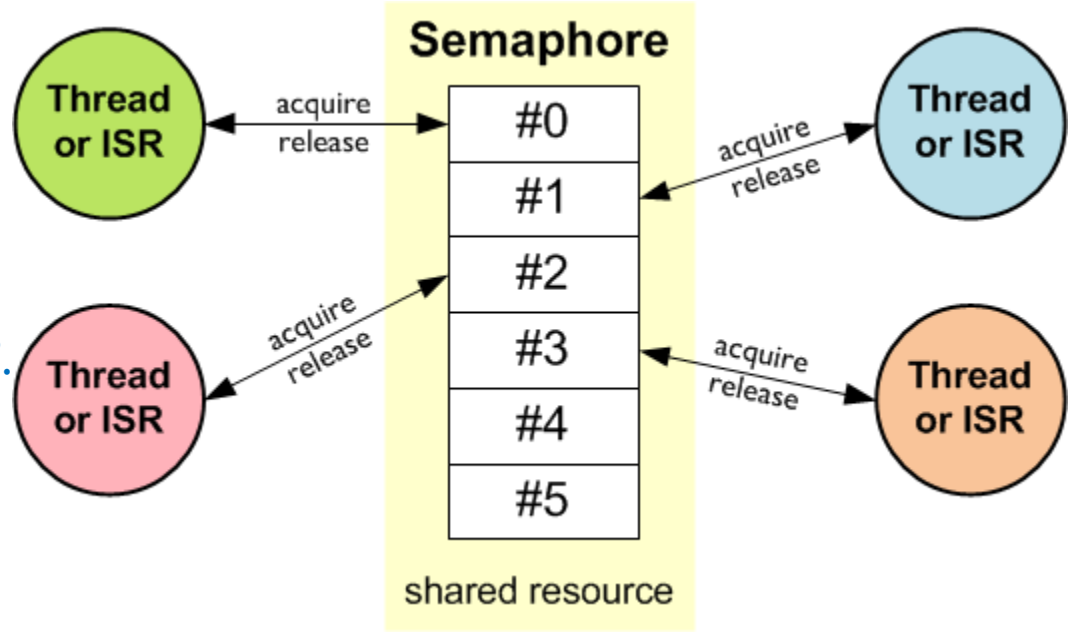


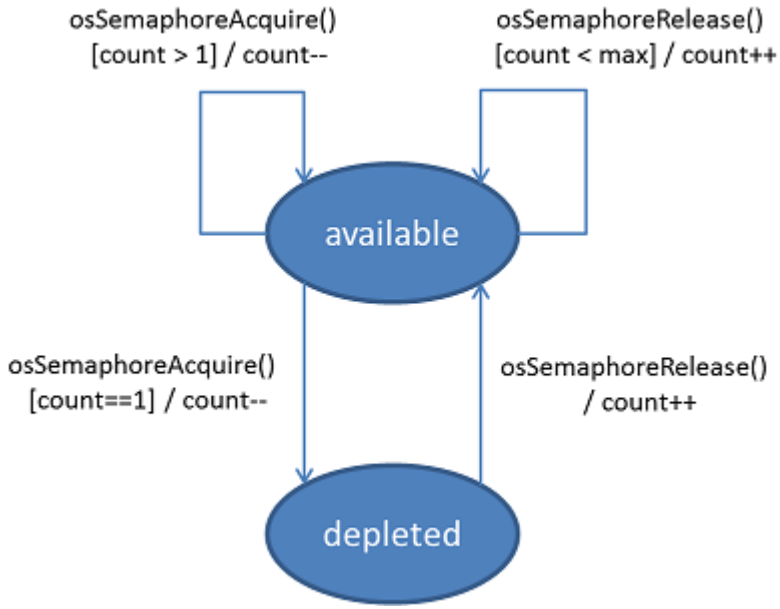
Semaphores

- **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".





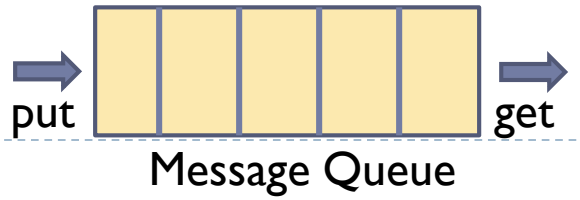
osSemaphoreAcquire(sem_id)
osSemaphoreRelease(sem_id)

osSemaphoreGetCount(sem_id)

CMSIS-RTOS semaphore example

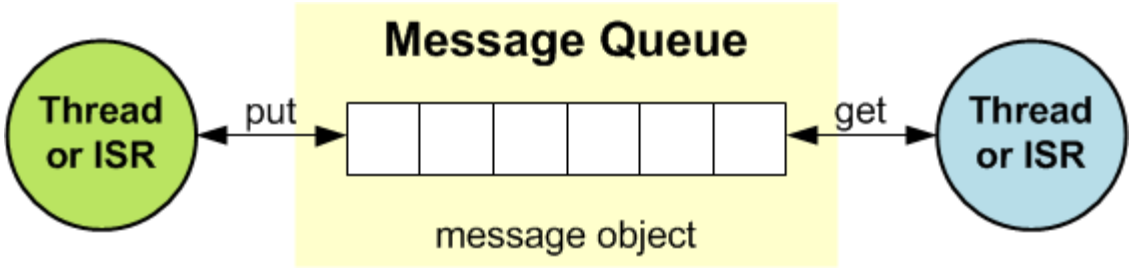
```
osSemaphoreId_t sid_Thread_Semaphore;            // semaphore id

// 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) {   //check result of wait
      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
    }
```

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 and put in *msg-ptr; wait for "timeout" if no message
  - Status = *osOK* : no msg available and timeout=0
    = *osEventTimeout* : no message available before timeout
    = *osEventMessage* : msg received *("status" is a "union" structure)*



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

/* 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]
   }   } }
```

Additional examples

- Examples provided in CMSIS-RTOS2 Documentation

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

- Examples provided in Keil installation directory

C:/Keil_v5/ARM/PACK/ARM/CMSIS/5.4.0/CMSIS/RTOS2/RTX/Examples

(Locate on your PC)