FreeRTOS

A real time operating system for embedded systems

QUEUE MANAGEMENT

2.1 Queue Management

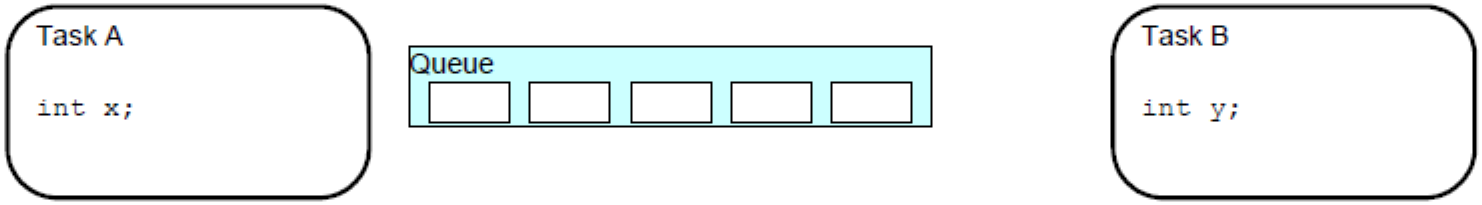
- FreeRTOS applications are structured as a set of independent tasks
  - Each task is effectively a mini program in its own right.
  - It will have to communicate with each other to collectively provide useful system functionality.
- Queue is the underlying primitive
  - Be used for communication and synchronization mechanisms in FreeRTOS.

Queue: Task-to-task communication

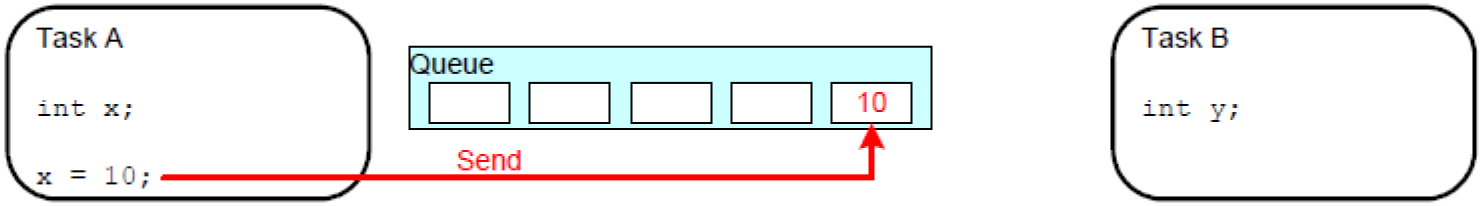
- Scope
  - How to create a queue
  - How a queue manages the data it contains
  - How to send data to a queue
  - How to receive data from a queue
  - What it means to block on a queue
  - The effect of task priorities when writing to and reading from a queue

2.2 Queue Characteristics – Data storage

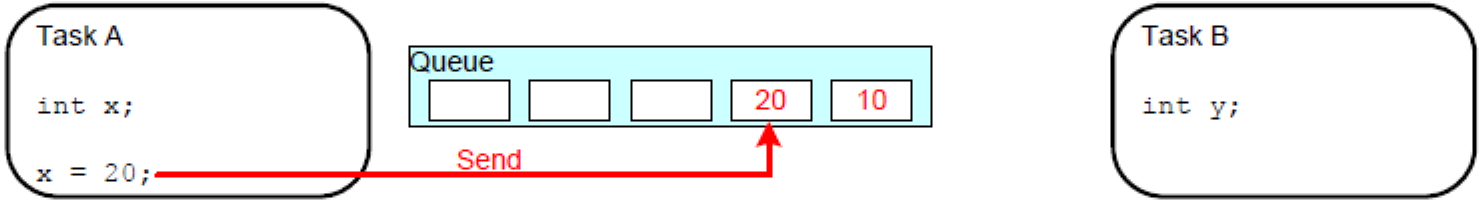
- A queue can hold a finite number of fixed size data items.
  - Normally, used as FIFO buffers where data is written to the end of the queue and removed from the front of the queue.
  - Also possible to write to the front of a queue.
  - Writing data to a queue causes a byte-for-byte copy of the data to be stored in the queue itself.
  - Reading data from a queue causes the copy of the data to be removed from the queue.



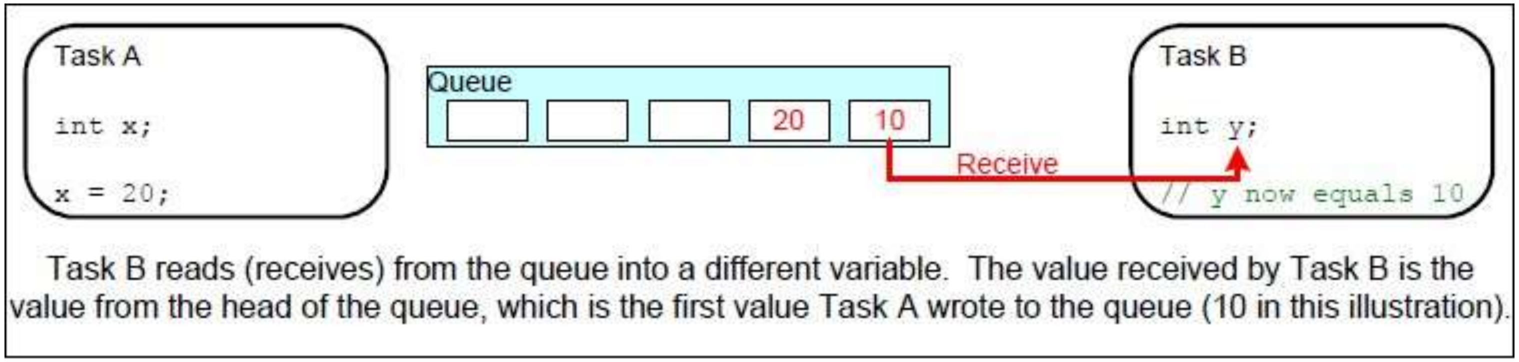
A queue is created to allow Task A and Task B to communicate. The queue can hold a maximum of 5 integers. When the queue is created it does not contain any values so is empty.



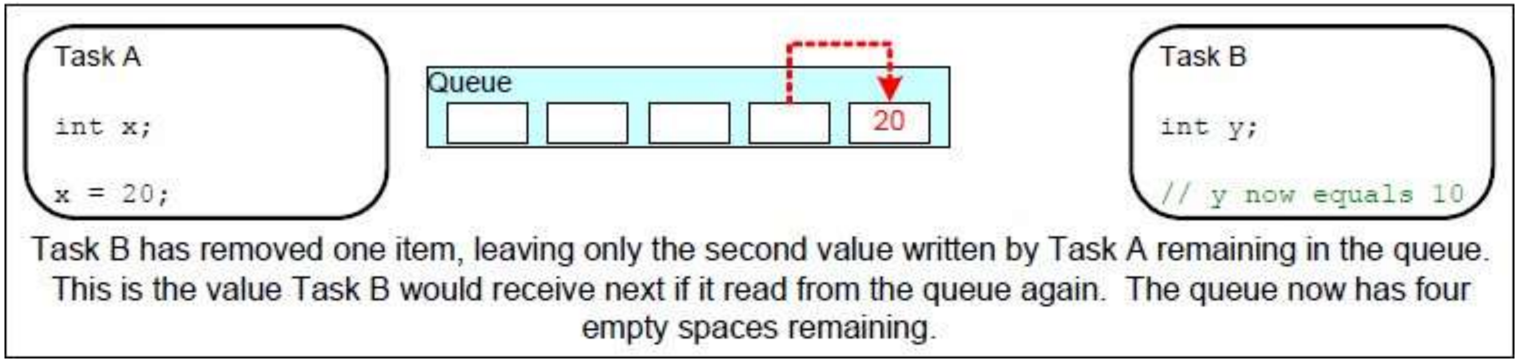
Task A writes (sends) the value of a local variable to the back of the queue. As the queue was previously empty the value written is now the only item in the queue, and is therefore both the value at the back of the queue and the value at the front of the queue.



Task A changes the value of its local variable before writing it to the queue again. The queue now contains copies of both values written to the queue. The first value written remains at the front of the queue, the new value is inserted at the end of the queue. The queue has three empty spaces remaining.



Task B reads (receives) from the queue into a different variable. The value received by Task B is the value from the head of the queue, which is the first value Task A wrote to the queue (10 in this illustration).



Task B has removed one item, leaving only the second value written by Task A remaining in the queue. This is the value Task B would receive next if it read from the queue again. The queue now has four empty spaces remaining.

- Queues are objects in their own right
  - Not owned by or assigned to any particular task
  - Any number of tasks can write to the same queue and any number of tasks can read from the same queue.
  - Very common to have multiple writers, but very rare to have multiple readers.

Blocking on Queue Reads

- When a task attempts to read from a queue it can optionally specify a ‘block’ time
  - The maximum time that the task should be kept in the Blocked state to wait for data to be available from the queue should the queue already be empty.
  - It is automatically moved to the Ready state when another task or interrupt places data into the queue.
  - It will also be moved automatically from the Blocked state to the Ready state if the specified block time expires before data becomes available.
  - Queues can have multiple readers, so it is possible for a single queue to have more than one task blocked on it waiting for data. When this is the case:

Blocking on Queue Reads

- Only one task will be unblocked when data becomes available.
  - Queue can have multiple readers.
    - So, it is possible for a single queue to have more than one task blocked on it waiting for data.
  - The task that is unblocked will always be the highest priority task that is waiting for data.
  - If the blocked tasks have equal priority, the task that has been waiting for data the longest will be unblocked.

Blocking on Queue Writes

- A task can optionally specify a ‘block’ time when writing to a queue.
  - The maximum time that task should be held in the Blocked state to wait for space to be available on the queue, should the queue already be full.

Blocking on Queue Writes

- Queue can have multiple writers.
  - It is possible for a full queue to have more than one task blocked on it waiting to complete a send operation.
- Only one task will be unblocked when **space** on the queue becomes available.
  - The task that is unblocked will always be the highest priority task that is waiting for **space**.
  - If the blocked tasks have equal priority, the task that has been waiting for **space** the longest will be unblocked.

2.3 Using a Queue

- A queue must be explicitly created before it can be used.
  - FreeRTOS allocates RAM from the heap when a queue is created.
  - RAM holds both the queue data structures and the items that are contained in the queue.

- xQueueCreate() API Function
  - Be used to create a queue and returns an xQueueHandle to reference the queue it creates.

- Function Prototype

  ```
  xQueueHandle xQueueCreate(
                      unsigned portBASE_TYPE uxQueueLength,
                      unsigned portBASE_TYPE uxItemSize);
  ```

  – xQueueLength: The maximum number of items that the queue being created can hold at any one time.

  – uxItemSize: the size in bytes of each data item that can be stored in the queue.

  – Return Value:

    - if NULL is returned, the queue cannot be created as there is insufficient heap memory available for FreeRTOS to allocate the queue data structures and storage.
    - A non-NULL value returned indicates that the queue has been created successfully. The returned value should be stored as the handle to the created queue.

xQueueSendToBack() and xQueueSendToFront() API Functions

- xQueueSendToBack()
  - Be equivalent to xQueueSend()
  - Be used to send data to the back (tail) of a queue
- xQueueSendToFront()
  - Be used to send data to the front (head) of a queue
- Please note, never call these two API functions from an interrupt service routine (ISR).
  - Interrupt-safe versions will be used in their place and described in next chapter.

- Function prototypes

```
portBASE_TYPE    xQueueSendToBack (
                     xQueueHandle  xQueue,
                     const void * pvItemToQueue,
                     portTickType xTicksToWait);

portBASE_TYPE   xQueueSendToFront(
                     xQueueHandle xQueue,
                     const void * pvItemToQueue,
                     portTickType xTicksToWait);
```

  – xQueue: The handle of the queue to which the data is being send (written). It will have been returned from the call to xQueueCreate() used to create the queue.

- pvItemToQueue: a pointer to the data to be copied into the queue.
  - The size of each item that the queue can hold is set when the queue is created, so the data will be copied from *pvItemToQueue* into the queue storage area.
- xTicksToWait: the maximum amount of time the task should remain in the Blocked state to wait for the space to become available on the queue, should the queue already be full.
  - if xTicksToWait is zero, both APIs will return immediately in case the queue is already full.
  - The block time is specified in tick periods, so the absolute time it represents is dependent on the tick frequency. The constant portTICK_PERIOD_MS can be used to convert a time specified in MS into ticks.

- Returned value: two possible return values.
  - pdPASS will be returned if data was successfully sent to the queue.
    - If a block time was specified, it is possible that the calling task was placed in the Blocked state to wait for another task or interrupt to make room in the queue, before the function returned,
    - Data was successfully written to the queue before the block time expired.
  - errQUEUE_FULL will be returned if data could not be written to the queue as the queue was already full.
    - In a similar scenario that a block time was specified, but it expired before space becomes available in the queue.

xQueueReceive() and xQueuePeek() API Function

- xQueueReceive()
  - Be used to receive (consume) an item from a queue. The item received is removed from the queue.
- xQueuePeek()
  - Be used receive an item from the queue without the item being removed from the queue.
  - Receives the item from the head of the queue.
- Please note, never call these two API functions from an interrupt service routine (ISR).

•Function prototypes

```
portBASE_TYPE   xQueueReceive (
                    xQueueHandle  xQueue,
                    const void  *pvBuffer,
                    portTickType   xTicksToWait);

portBASE_TYPE   xQueuePeek(
                    xQueueHandle xQueue,
                    const void * pvBuffer,
                    portTickType xTicksToWait);
```

– xQueue: The handle of the queue from which the data is being received (read). It will have been returned from the call to xQueueCreate().

- pvBuffer: a pointer to the memory into which the received data will be copied.
    - The memory pointed to by pvBuffer must be at least large enough to hold the data item held by the queue.
- xTicksToWait: the maximum amount of time the task should remain in the Blocked state to wait for the data to become available on the queue, should the queue already be empty.
    - if xTicksToWait is zero, both APIs will return immediately in case the queue is already empty.
    - The block time is specified in tick periods, so the absolute time it represents is dependent on the tick frequency. The constant portTICK_RATE_MS can be used to convert a time specified in MS into ticks.

- Returned value: two possible return values.
  - pdPASS will be returned if data was successfully read from the queue.
    - If a block time was not zero, it is possible that the calling task was placed in the Blocked state to wait for another task or interrupt to send the data to the queue before the function is returned,
    - data was successfully read from the queue before the block time expired.
  - errQUEUE_EMPTY will be returned if data could not be read from the queue as the queue was already empty.
    - In a similar scenario that a block time was not zero, but it expired before data was sent.

uxQueueMessageWaiting() API Function

- Be used to query the number of items that are currently in a queue.
- Prototype

```
unsigned portBASE_TYPE  uxQueueMEssagesWaiting (
                                    xQueueHandle  xQueue);
```

  – Returned value: the number of items that the queue being queried is currently holding. If zero is returned, the queue is empty.

Example 10. Blocking when receiving from a queue

- To demonstrate
  - a queue being created,
    - Hold data items of type *long*
  - data being sent to the queue from multiple tasks,
    - Sending tasks do not specify a block time, lower priority than receiving task.
  - And data being received from the queue
    - Receiving task specifies a block time 100ms
- So, queue never contains more than one item
  - Once data is sent to the queue, the receiving task will unblock, pre-empt the sending tasks, and remove the data – leaving the queue empty once again.

```
static void vSenderTask( void *pvParameters )
{
long lValueToSend;
long xStatus;

lValueToSend = ( long ) pvParameters;
  Serial.print("lValueToSend = ");
  Serial.println(lValueToSend);

  /* As per most tasks, this task is implemented within an infinite loop. */
  for( ;; )
  {
    xStatus = xQueueSendToBack( xQueue, &lValueToSend, 0 );

    if( xStatus != pdPASS )
    {
        Serial.print( "Could not send to the queue.\r\n" );
    }

    /* Allow the other sender task to execute. */
    //taskYIELD();
  }
}
```

```
static void vReceiverTask( void *pvParameters )
{
long lReceivedValue;
long xStatus;
const TickType_t xTicksToWait = 100 / portTICK_PERIOD_MS;
for( ;; )
  {
    if( uxQueueMessagesWaiting( xQueue ) != 0 )
    {
      Serial.print( "Queue should have been empty!\r\n" );
    }
    xStatus = xQueueReceive( xQueue, &lReceivedValue, xTicksToWait );

    if( xStatus == pdPASS )
    {
      Serial.print("Received = ");
      Serial.println(lReceivedValue);
    }
    else
    {
        Serial.print( "Could not receive from the queue.\r\n" );
    }
  }
}
```

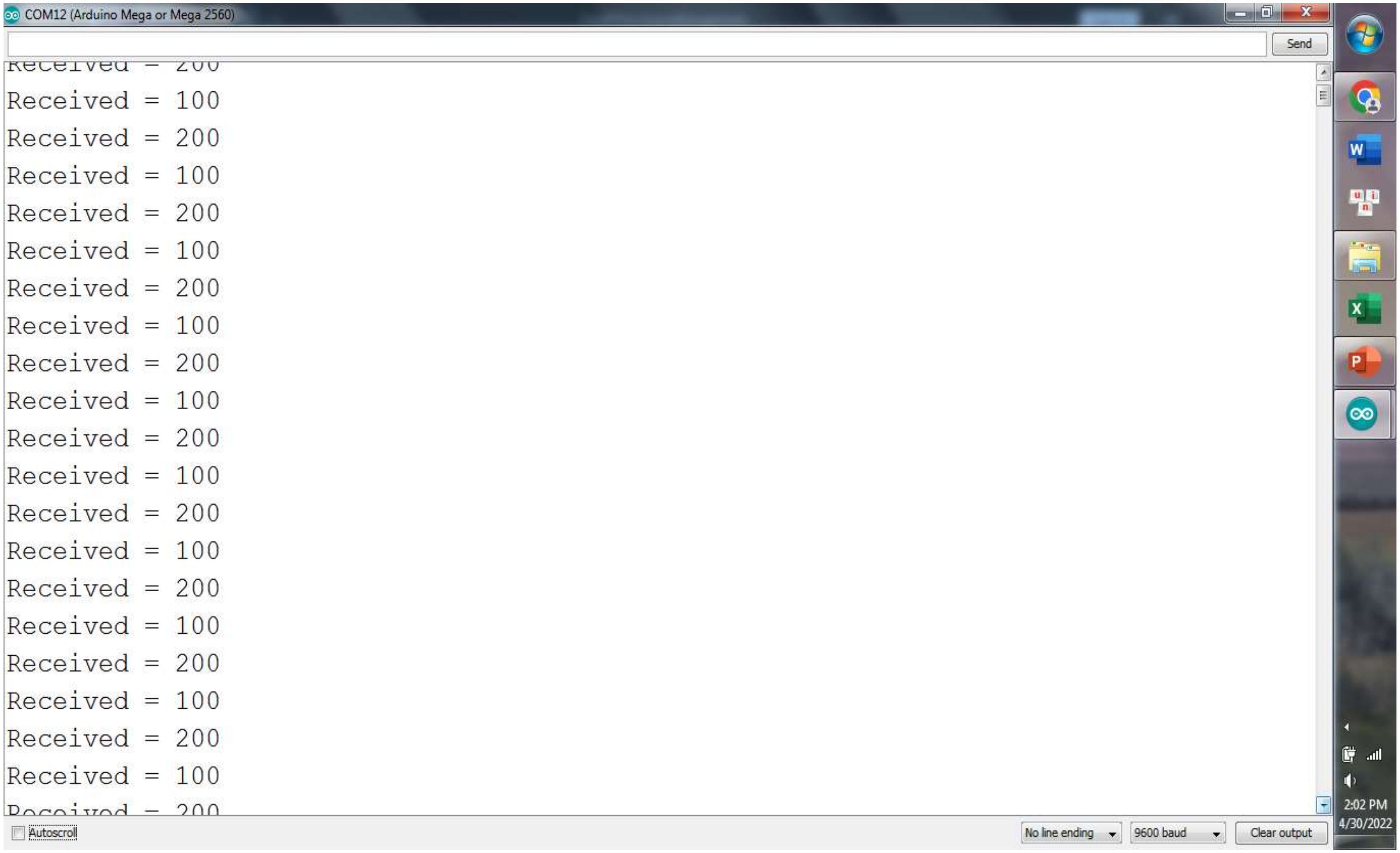
- vSenderTask() does not specify a block time.
  - continuously writing to the queue

```
xStatus = xQueueSendToBack(xQueue, pvParameters, 0);
If (xStatus != pdPASS) {
          Serial.print("Could not send to the queue.\n"); }
//taskYIELD();
```

- vReceiverTask() specifies a block time 100ms.
  - Enter the Blocked state to wait for data to be available, leaves it when either data is available on the queue, or 100ms expires, which should never occur.

```
xStatus = xQueueReceive(xQueue,
          &xReceivedValue, 100/portTICK_RATE_MS);
          if (xStatus == pdPASS) {  Serial.print("Received = ");
          Serial.println(lReceivedValue );
          }
```

```
/* Declare a variable of type QueueHandle_t.  This is used to store the queue
that is accessed by all three tasks. */
QueueHandle_t xQueue;
void setup( void )
{
  Serial.begin(9600);

    /* The queue is created to hold a maximum of 5 long values. */
    xQueue = xQueueCreate( 5 , sizeof( long ) );

  if( xQueue != NULL )
{

    xTaskCreate( vSenderTask, "Sender1", 1000, ( void * ) 100, 1, NULL );
    xTaskCreate( vSenderTask, "Sender2", 1000, ( void * ) 200, 1, NULL );

    /* Create the task that will read from the queue.  The task is created with
    priority 2, so above the priority of the sender tasks. */
    xTaskCreate( vReceiverTask, "Receiver", 1000, NULL, 2, NULL );

    /* Start the scheduler so the created tasks start executing. */
    vTaskStartScheduler();
  }
  else
  {
    /* The queue could not be created. */
    Serial.println("The queue could not be created.");
  }

for( ;; );
//  return 0;
}
```



```
Received = 200
Received = 100
Received = 200
Received = 100
Received = 200
Received = 100
Received = 200
Received = 100
Received = 200
Received = 100
Received = 200
Received = 100
Received = 200
Received = 100
Received = 200
Received = 100
Received = 200
Received = 100
Received = 200
Received = 100
Received = 200
```

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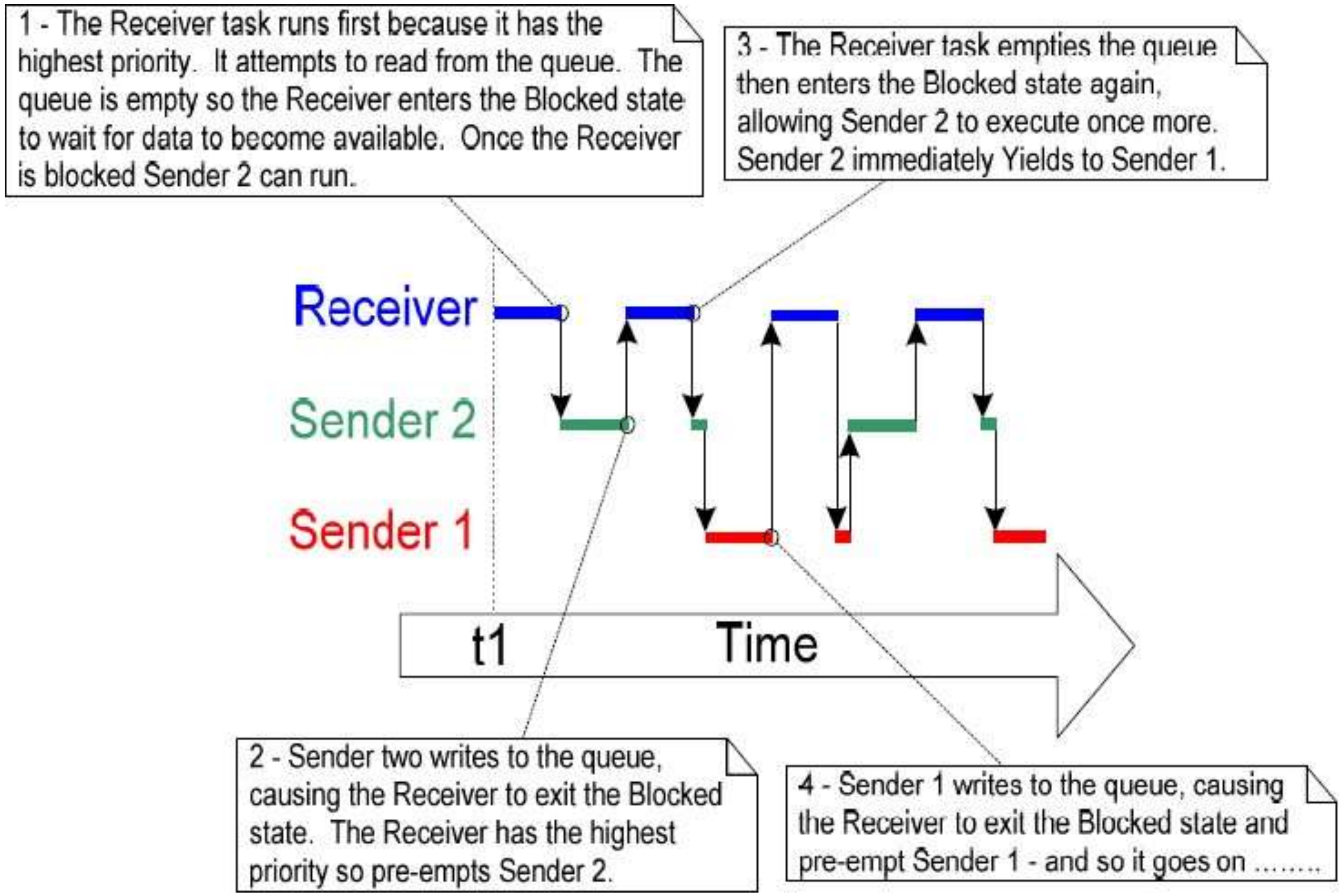
Execution sequence



1 - The Receiver task runs first because it has the highest priority. It attempts to read from the queue. The queue is empty so the Receiver enters the Blocked state to wait for data to become available. Once the Receiver is blocked Sender 2 can run.

3 - The Receiver task empties the queue then enters the Blocked state again, allowing Sender 2 to execute once more. Sender 2 immediately Yields to Sender 1.

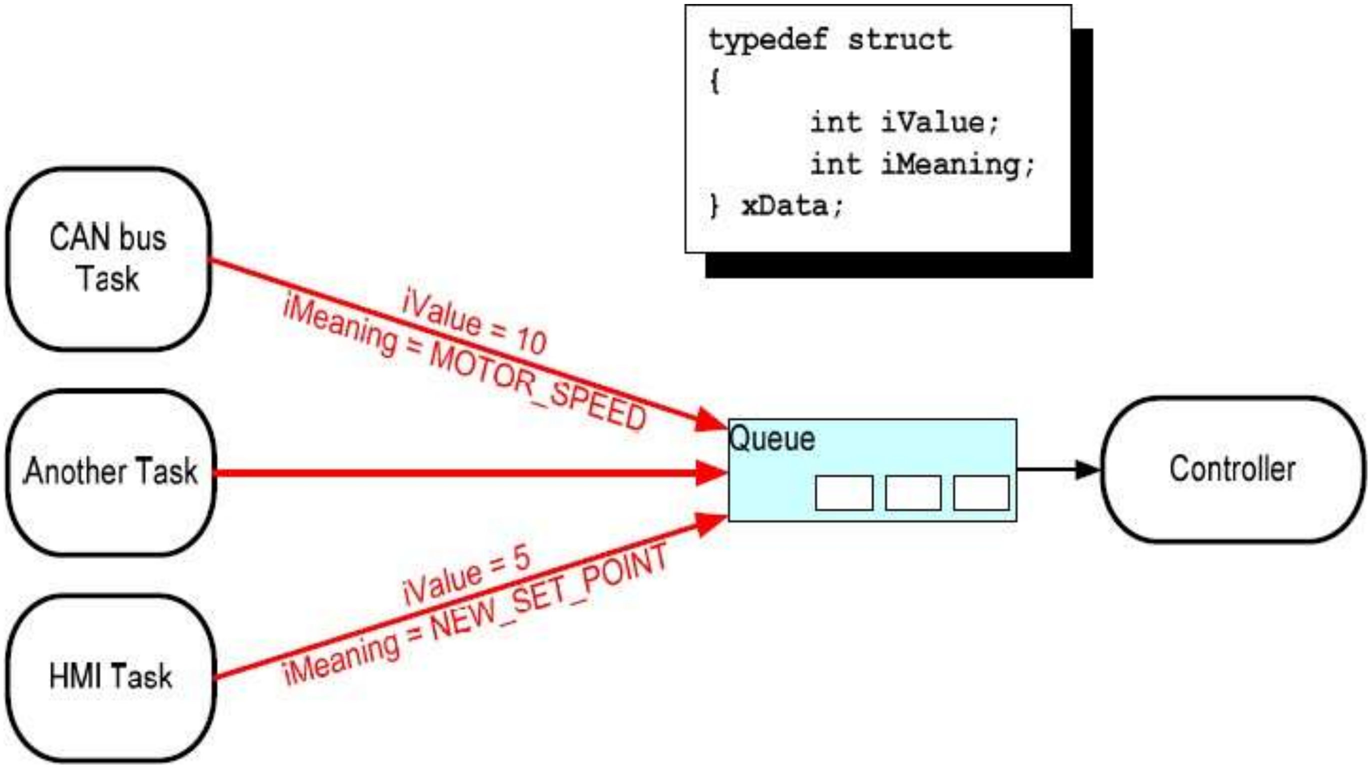
2 - Sender two writes to the queue, causing the Receiver to exit the Blocked state. The Receiver has the highest priority so pre-empts Sender 2.

4 - Sender 1 writes to the queue, causing the Receiver to exit the Blocked state and pre-empt Sender 1 - and so it goes on ....

Using Queues to transfer compound types

- It is common for a task to receive data from multiple sources on a single queue.
  - Receiver needs to know the data source to allow it to determine how to process the data.
  - Use the queue to transfer structures which contain both data value and data source, like

```
typedef struct {
  int iValue; // a data value
  int iMeaning; // a code indicating data source
} xData;
```



```
typedef struct
{
        int iValue;
        int iMeaning;
} xData;
```

- Controller task performs the primary system function.
  - React to inputs and changes to the system state communicated to it on the queue.
  - A CAN bus task encapsulates the CAN bus interfacing functionality, like the actual motor speed value.
  - A HMI task encapsulates all the HMI functionality, like the actual new set point value.

Example 11

- Two differences from Example 10
  - Receiving task has a **lower** priority than the sending tasks.
  - The queue is used to pass structures, rather than simple long integers between the tasks.
- The Queue will normally be full because
  - Once the receiving task removes an item from the queue, it is pre-empted by one of the sending tasks which then immediately refills the queue.
  - Then sending tasks re-enters the Blocked state to wait for space to become available on the queue again.

Structure Type

```
/* Define the structure type that will be passed on the queue. */
typedef struct
{
  unsigned char ucValue;
  unsigned char ucSource;
} xData;

/* Declare two variables of type xData that will be passed on the queue. */
static const xData xStructsToSend[ 2 ] =
{
  { 100, mainSENDER_1 }, /* Used by Sender1. */
  { 200, mainSENDER_2 }  /* Used by Sender2. */
};
```

```
static void vSenderTask( void *pvParameters )
{
portBASE_TYPE xStatus;
const TickType_t xTicksToWait = 100 / portTICK_PERIOD_MS;

  /* As per most tasks, this task is implemented within an infinite loop. */
  for( ;; )
  {
    xStatus = xQueueSendToBack( xQueue, pvParameters, xTicksToWait );

    if( xStatus != pdPASS )
    {
      /* We could not write to the queue because it was full - this must
      be an error as the receiving task should make space in the queue
      as soon as both sending tasks are in the Blocked state. */
      Serial.print( "Could not send to the queue.\r\n" );
    }

    /* Allow the other sender task to execute. */
    taskYIELD();
  }
}
```

```
static void vReceiverTask( void *pvParameters )
{
/* Declare the structure that will hold the values received from the queue. */
xData xReceivedStructure;
portBASE_TYPE xStatus;

 /* This task is also defined within an infinite loop. */
 for( ;; )
 {
  /* As this task only runs when the sending tasks are in the Blocked state,
  and the sending tasks only block when the queue is full, this task should
  always find the queue to be full.  3 is the queue length. */
  if( uxQueueMessagesWaiting( xQueue ) != 3 )
  {
   Serial.print( "Queue should have been full!\r\n" );
  }
xStatus = xQueueReceive( xQueue, &xReceivedStructure, 0 );

    if( xStatus == pdPASS )
    {
      /* Data was successfully received from the queue, print out the received
      value and the source of the value. */
      if( xReceivedStructure.ucSource == mainSENDER_1 )
      {
        Serial.print( "From Sender 1 = ");
        Serial.println(xReceivedStructure.ucValue );
      }
      else
      {
        Serial.print( "From Sender 2 = ");
        Serial.println(xReceivedStructure.ucValue );
      }
    }
    else
    {
Serial.print( "Could not receive from the queue.\r\n" );
    }
  }
}
```

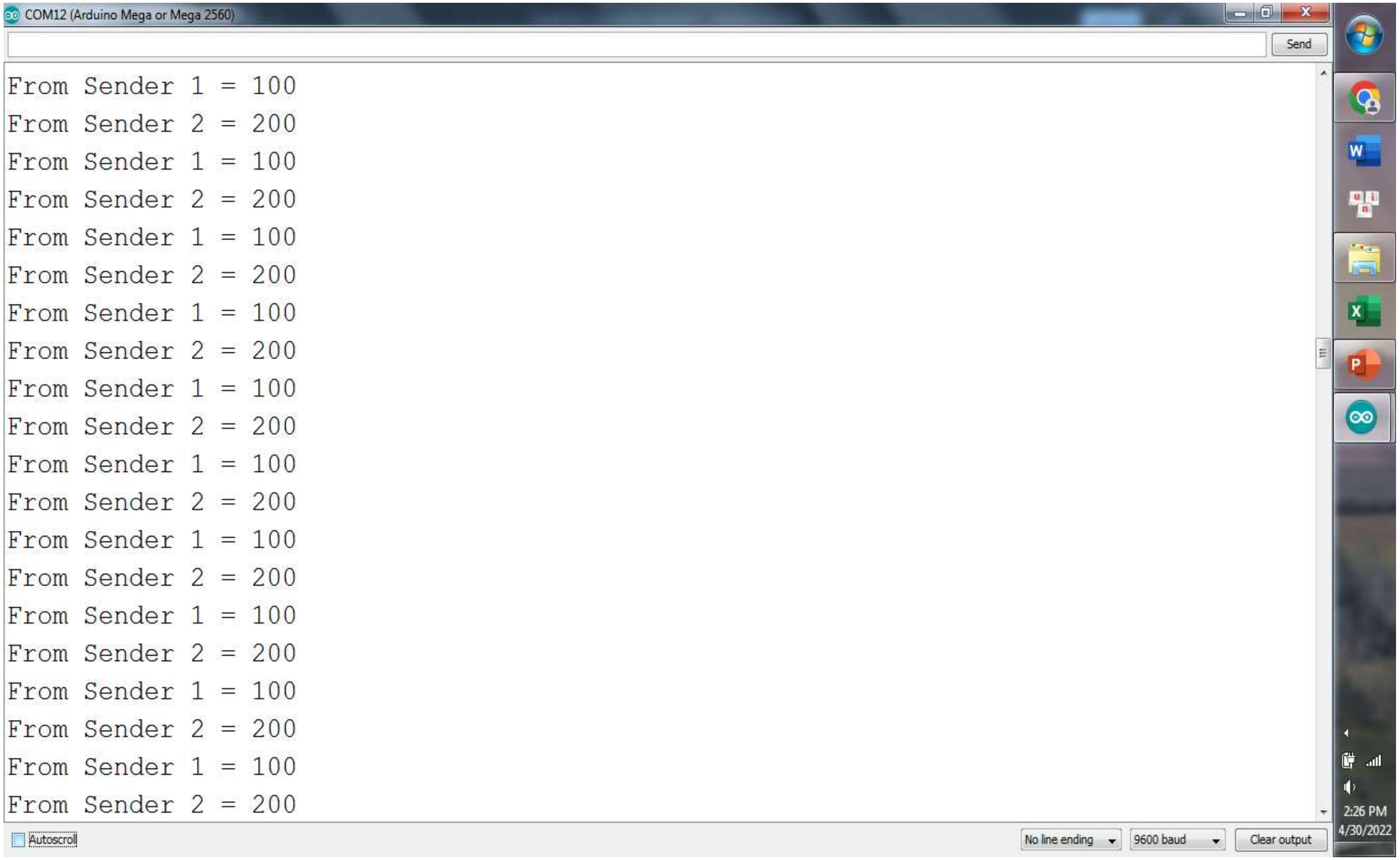
```
void setup( void )
{
 Serial.begin(9600);
   /* The queue is created to hold a maximum of 3 structures of type xData. */
   xQueue = xQueueCreate( 3, sizeof( xData ) );

 if( xQueue != NULL )
 {
   xTaskCreate( vSenderTask, "Sender1", 200, ( void * ) &( xStructsToSend[ 0 ] ), 2, NULL );
   xTaskCreate( vSenderTask, "Sender2", 200, ( void * ) &( xStructsToSend[ 1 ] ), 2, NULL );

   xTaskCreate( vReceiverTask, "Receiver", 200, NULL, 1, NULL );

   /* Start the scheduler so the created tasks start executing. */
   vTaskStartScheduler();
 }
 else
 {
   /* The queue could not be created. */
 }

for( ;; );
}
```



```
From Sender 1 = 100
From Sender 2 = 200
From Sender 1 = 100
From Sender 2 = 200
From Sender 1 = 100
From Sender 2 = 200
From Sender 1 = 100
From Sender 2 = 200
From Sender 1 = 100
From Sender 2 = 200
From Sender 1 = 100
From Sender 2 = 200
From Sender 1 = 100
From Sender 2 = 200
From Sender 1 = 100
From Sender 2 = 200
From Sender 1 = 100
From Sender 2 = 200
From Sender 1 = 100
From Sender 2 = 200
```

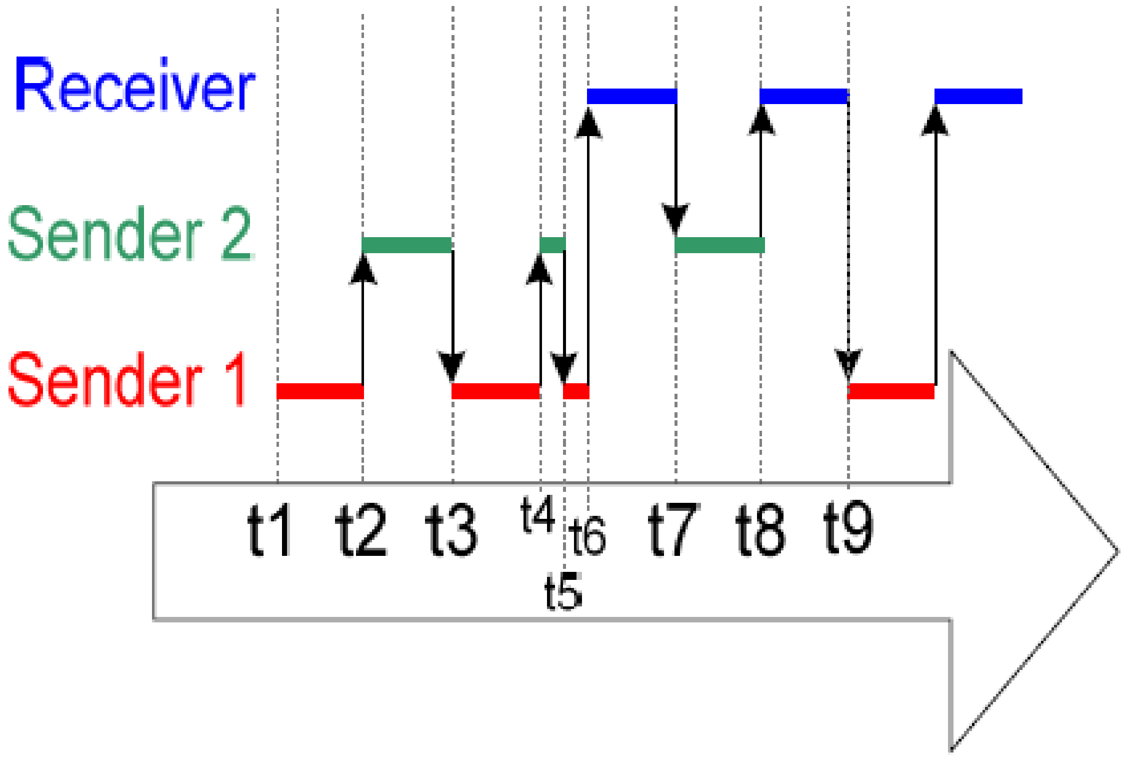
- In vSenderTask(), the sending task specifies a block time of 100ms.
  - So, it enters the Blocked state to wait for space to become available each time the queue becomes full.
  - It leaves the Blocked state when either the space is available on the queue or 100ms expires without space be available (should never expire as receiving task is continuously removing items from the queue).

```
xStatus = xQueueSendToBack(xQueue,
          pvParameters,
          100/portTICK_PERIOD_MS);
If (xStatus != pdPASS) {
      Serial.print("Could not send to the queue.\n");
}
taskYIELD();
```

- vReceiverTask() will run only when both sending tasks are in the Blocked state.
  - Sending tasks will enter the Blocked state only when the queue is full as they have higher priorities.
  - The receiving task will execute only when the queue is already full. -> it always expects to receive data even without a 'block' time.

```
xStatus = xQueueReceive(xQueue,
                        &xReceivedStructure, 0);
if (xStatus == pdPASS) {
        // print the data received
}
```

Execution sequence – Sender 1 and 2 have higher priorities than Receiver



2.4 Working with large data

- It is not efficient to copy the data itself into and out of the queue byte by byte, when the size of the data being stored in the queue is large.
- It is preferable to use the queue to transfer pointers to the data.
  - More efficient in both processing time and the amount of RAM required to create the queue.
- But, when queuing pointers, extreme care must be taken to ensure that:

1. The owner of the RAM being pointed to is clearly defined.
   - When multiple tasks share memory via a pointer, they do not modify its contents simultaneously, or take any other action that cause the memory contents invalid or inconsistent.
     - Ideally, only the sending task is permitted to access the memory until a pointer to the memory has been queued, and only the receiving task is permitted to access the memory after the pointer has been received from the queue.

2. The RAM being pointed to remains valid.
   - If the memory being pointed to was allocated dynamically, exactly one task be responsible for freeing the memory.
   - No task should attempt to access the memory after it has been freed.
   - A pointer should never be used to access data that has been allocated on a task stack. The data will not be valid after the stack frame has changed.