E4.52
ISE3.35

IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2007

EEE/ISE PART III/IV: MEng, BEng and ACGI

Corrected Copy

REAL-TIME OPERATING SYSTEMS

Tuesday, 8 May 10:00 am

Time allowed: 3:00 hours

There are SIX questions on this paper.

Answer FOUR questions.

All questions carry equal marks.

Any special instructions for invigilators and information for candidates are on page 1.

Examiners responsible First Marker(s) : T.J.W. Clarke
Second Marker(s) : Y.K. Demiris

Special instructions for invigilators

The booklet RTOS Exam Notes should be distributed with the paper.

Special instructions for students

You may use the booklet RTOS Exam Notes which is a reproduction of that published on the course web-site before the exam.

The Questions

1.

a) Write pseudo-code using the FreeRTOS API to illustrate mutually exclusive access to a shared resource using (i) critical sections and (ii) semaphores. When writing an application, how would you choose between these two methods?

[4]

b) In the FreeRTOS API critical sections can be enforced in two distinct ways. What are they, and what are their relative advantages and disadvantages?

[4]

c) Explain why priority inversion is a problem in real-time systems, illustrating your answer with an appropriate execution trace. How could an application under FreeRTOS overcome this problem?

[4]

d) "My RTOS application appears to have no liveness problems, therefore rate monotonic analysis is unnecessary". Discuss.

[4]

e) Under FreeRTOS, state giving reasons what is the expected sleep time from a single call of `TaskDelay(n)`? Under precisely what circumstances, and why, will use of `TaskDelayUntil()` lead to more accurate timing than `TaskDelay()`?

[4]

2.

a) Contrast the merits of writing real-time application code under a set of prioritised interrupts, or a set of prioritised tasks.

[4]

b) Using the FreeRTOS API, describe, with pseudo-code, two ways in which application code in a task could be synchronised with an interrupt, stating which you would prefer to use and why.

[4]

c) A priority-scheduled real-time system consists of four jobs with the characteristics shown in Figure 2.1 when run under CPU A.

(i)` How would you run these jobs under an RTOS with prioritised tasks?

(ii) Can you state with certainty whether or not all tasks will meet their deadlines, and if so will they, run under CPU A? Give reasons for your answer. You may assume RTOS task-switching overheads are negligible.

(iii) You are asked to choose a speed-rating for a CPU to run these jobs. What is the minimum speed, relative to A, that would guarantee all deadlines met?

[6]

d) Inter-task communication is introduced to the system of Figure 2.1 which results in the blocking specified in Figure 2.2 every job period. Answer the three parts of d) for the new system. How would your answers change if earliest deadline first scheduling were used?

[6]

Job	Job Time	Job Period
X	50us	220us
Y	1us	7us
Z	100us	300us
W	125us	250us

Figure 2.1

Job	Blocking Time
X	0
Y	0
Z	60us
W	5us

Figure 2.2

3. This question relates to the v4.0.5 FreeRTOS implementation of queues: source code for FreeRTOS v4.0.5 is contained in the booklet RTOS Exam Notes.

a) Discuss in detail how FreeRTOS implements copying of message data and the implications of this for the implementation, and the application programmer.

[4]

b) Explain the operation of **`xQueueReceive()`** when a task suspends waiting for a message from a queue, and then returns with a message posted from an ISR while the queue is locked . You may use the line numbers in the Exam Notes booklet to identify source code in your answer.

[4]

c) Describe the operation of **`QueueSend()`** and **`QueueReceive()`** during the sequence of events in Figure 3.1. What is problematic about FreeRTOS v4.0.5 behaviour under this sequence, and how could application code cope with this behaviour?

[6]

d) Describe one way in which the FreeRTOS v4.0.5 queue implementation might be improved to provide better behaviour under the case described in c).

[6]

Time	Event
Initially	Task priorities: D > C > B > A Two tasks A,B are waiting on messages from empty queue Q1, task C is running.
1	Task C calls **`QueueSend(Q1)`**
2	Task D preempts C
3	Task D calls **`QueueReceive(Q1)`**
4	Task D sleeps
5	Task B runs

Figure 3.1

4. This question relates to the FreeRTOS task list package implementation, source code for which can be found in the booklet RTOS Exam Notes.

a) Describe, with the aid of a suitable diagram, the data structures used in the FreeRTOS task list package.

[2]

b) What are the operations needed to implement a RTOS ready list, and how are these implemented by FreeRTOS using its task list package?

[4]

c) For each pointer field in the task list package, discuss what would be the consequences, good or bad, for the FreeRTOS ready task list implementation if the pointer field were omitted? Do not consider any other uses of task lists.

[6]

d) In FreeRTOS, detail for what purposes task lists are used, and discuss the merits of using a general purpose task list package.

[4]

e) MicroC/OS-II implements task lists using a bit array, packed 8 bits per byte, together with a 256 byte constant array to perform efficient selection of the most significant bit set within a byte. Describe briefly how a set of tasks is represented in this implementation. Discuss the advantages and disadvantages of this when compared with FreeRTOS.

[4]

5.

a) Describe and contrast the merits of priority inheritance protocol (PIP) and ceiling priority protocol (CPP) as solutions to priority inversion.

[4]

b) What conditions on the resource dependency graph are necessary and sufficient for a system to be deadlocked? How, writing code at the application level, can this situation be avoided?

[4]

c) Figure 5.1 describes three scenarios S1, S2, S3 in a real-time system. In each case state, giving reasons, what you can deduce about whether deadlock, starvation, or livelock might be responsible for the lack of progress.

[6]

d) Show how priority ceiling protocol (PCP) as defined in the Exam Notes eliminates priority inversion.

[4]

e) Does PCP implement deadlock prevention, avoidance, or recovery?

[2]

Task	Priority	S1	S2	S3
A	4	P	P	P
B	3	P	S	B
C	2	B	S	P
D	1	P	B	B

P= making progress, S = running, making no progress, B=permanently blocked

Figure 5.1

6. Answer **ONE only** of the following questions. Credit will be given for answers which are concise, clear, and complete.

(a) Real-time Operating Systems normally have a single frequency "tick" interrupt. What would be the consequences for RTOS implementation and usage if this were replaced by a variable-time interrupt?

(b) RTOS porting depends on both compiler and CPU architecture. Examine how each of these can influence the code necessary for an RTOS port giving (possibly hypothetical) examples, and a checklist of the issues that affect RTOS implementation, together with how easy it is for an RTOS implementation to incorporate their variability into configuration switches that do not require new code to be written.

(c) Discuss how the FreeRTOS API implements semaphores, and what are the merits of more complex implementations that incorporate solutions to priority inversion.

(d) Discuss ways in which an RTOS implementation could achieve faster task-level latency, and to what extent this is dependent on specific hardware or compiler features.

(e) Event registers are often provided in an RTOS API. List a set of features that could be implemented in an event register API. For each feature, summarise, with reasons, the costs of implementation, and state with examples how it might enable better application programming.

[20]

[END]

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Priority Ceiling Protocol definition

B. Definition

Having illustrated the basic idea of the priority ceiling protocol and its properties, we now present its definition.

1) Job J, which has the highest priority among the jobs ready to run, is assigned the processor, and let S^* be the semaphore with the highest priority ceiling of all semaphores currently locked by jobs other than job J. Before job J enters its critical section, it must first obtain the lock on the semaphore S guarding the shared data structure. Job J will be blocked and the lock on S will be denied, if the priority of job J is not higher than the priority ceiling of semaphore S^*.[4] In this case, job J is said to be blocked on semaphore S^* and to be blocked by the job which holds the lock on S^*. Otherwise job J will obtain the lock on semaphore S and enter its critical section. When a job J exits its critical section, the binary semaphore associated with the critical section will be unlocked and the highest priority job, if any, blocked by job J will be awakened.

2) A job J uses its assigned priority, unless it is in its critical section and blocks higher priority jobs. If job J blocks higher priority jobs, J *inherits* P_H, the highest priority of the jobs blocked by J. When J exits a critical section, it resumes the priority it had at the point of entry into the critical section.[5] Priority inheritance is transitive. Finally, the operations of priority inheritance and of the resumption of previous priority must be indivisible.

3) A job J, when it does not attempt to enter a critical section, can preempt another job J_L if its priority is higher than the priority, inherited or assigned, at which job J_L is executing.

Task.h

```
typedef void * xTaskHandle;
#define taskYIELD()                     portYIELD()
#define taskENTER_CRITICAL()            portENTER_CRITICAL()
#define taskEXIT_CRITICAL()             portEXIT_CRITICAL()
#define taskDISABLE_INTERRUPTS()        portDISABLE_INTERRUPTS()
#define taskENABLE_INTERRUPTS()         portENABLE_INTERRUPTS()

/*-----------------------------------------------------------
 * TASK CREATION API
 *----------------------------------------------------------*/

signed portBASE_TYPE xTaskCreate(     pdTASK_CODE pvTaskCode, const signed portCHAR * const pcName,
                                      unsigned portSHORT usStackDepth, void *pvParameters,
                                      unsigned portBASE_TYPE uxPriority, xTaskHandle *pvCreatedTask );

void vTaskDelete( xTaskHandle pxTask );

/*-----------------------------------------------------------
 * TASK CONTROL API
 *----------------------------------------------------------*/

void vTaskDelay( portTickType xTicksToDelay );
void vTaskDelayUntil( portTickType *pxPreviousWakeTime, portTickType xTimeIncrement );
unsigned portBASE_TYPE uxTaskPriorityGet( xTaskHandle pxTask );
void vTaskPrioritySet( xTaskHandle pxTask, unsigned portBASE_TYPE uxNewPriority );
void vTaskSuspend( xTaskHandle pxTaskToSuspend );
void vTaskResume( xTaskHandle pxTaskToResume );
portBASE_TYPE xTaskResumeFromISR( xTaskHandle pxTaskToResume );

/*-----------------------------------------------------------
 * SCHEDULER CONTROL
 *----------------------------------------------------------*/

void vTaskStartScheduler( void );
void vTaskEndScheduler( void );
void vTaskSuspendAll( void );
signed portBASE_TYPE xTaskResumeAll( void );

/*-----------------------------------------------------------
 * TASK UTILITIES
 *----------------------------------------------------------*/

portTickType xTaskGetTickCount( void );
unsigned portBASE_TYPE uxTaskGetNumberOfTasks( void );
void vTaskPlaceOnEventList( xList *pxEventList, portTickType xTicksToWait );
signed portBASE_TYPE xTaskRemoveFromEventList( const xList *pxEventList );
void vTaskCleanUpResources( void );
inline void vTaskSwitchContext( void );
xTaskHandle xTaskGetCurrentTaskHandle( void );
```

Semaphr.c

```
#define vSemaphoreCreateBinary( xSemaphore )        {                                                   \
        xSemaphore = xQueueCreate( ( unsigned portCHAR ) 1, semSEMAPHORE_QUEUE_ITEM_LENGTH );           \
        if( xSemaphore != NULL )                                                                        \
        {                                                                                               \
                xSemaphoreGive( xSemaphore );                                                           \
        }                                                                                               \
}

#define xSemaphoreTake( xSemaphore, xBlockTime )                                                        \
                        xQueueReceive( ( xQueueHandle ) xSemaphore, NULL, xBlockTime )

#define xSemaphoreGive( xSemaphore ) xQueueSend( ( xQueueHandle ) xSemaphore, NULL, semGIVE_BLOCK_TIME )

#define xSemaphoreGiveFromISR( xSemaphore, xTaskPreviouslyWoken )                                       \
                        xQueueSendFromISR( ( xQueueHandle ) xSemaphore, NULL, xTaskPreviouslyWoken )
```

From Task.h - related to lists package

```
signed portBASE_TYPE xTaskRemoveFromEventList( const xList *pxEventList )
{
tskTCB *pxUnblockedTCB;
portBASE_TYPE xReturn;

        /* THIS FUNCTION MUST BE CALLED WITH INTERRUPTS DISABLED OR THE
        SCHEDULER SUSPENDED.  It can also be called from within an ISR. */

        /* The event list is sorted in priority order, so we can remove the
        first in the list, remove the TCB from the delayed list, and add
        it to the ready list.

        If an event is for a queue that is locked then this function will never
        get called - the lock count on the queue will get modified instead.  This
        means we can always expect exclusive access to the event list here. */
        pxUnblockedTCB = ( tskTCB * ) listGET_OWNER_OF_HEAD_ENTRY( pxEventList );
        vListRemove( &( pxUnblockedTCB->xEventListItem ) );

        if( uxSchedulerSuspended == ( unsigned portBASE_TYPE ) pdFALSE )
        {
                vListRemove( &( pxUnblockedTCB->xGenericListItem ) );
                prvAddTaskToReadyQueue( pxUnblockedTCB );
        }
        else
        {
                /* We cannot access the delayed or ready lists, so will hold this
                task pending until the scheduler is resumed. */
                vListInsertEnd( ( xList * ) &( xPendingReadyList ), &( pxUnblockedTCB->xEventListItem ) );
        }

        if( pxUnblockedTCB->uxPriority >= pxCurrentTCB->uxPriority )
        {
                /* Return true if the task removed from the event list has
                a higher priority than the calling task.  This allows
                the calling task to know if it should force a context
                switch now. */
                xReturn = pdTRUE;
        }
        else
        {
                xReturn = pdFALSE;
        }

        return xReturn;
}
```

List.h

```
/*
 * Definition of the only type of object that a list can contain.
 */
struct xLIST_ITEM
{
	portTickType xItemValue;			/*< The value being listed.  In most cases this is
                                                    used to sort the list in descending order. */
	volatile struct xLIST_ITEM * pxNext;	/*< Pointer to the next xListItem in the list. */
	volatile struct xLIST_ITEM * pxPrevious;/*< Pointer to the previous xListItem in the list. */
	void * pvOwner;				/*< Pointer to the object (normally a TCB) that contains the list item. */
	void * pvContainer;			/*< Pointer to the list in which this list item is placed (if any). */
};
typedef struct xLIST_ITEM xListItem;  /* For some reason lint wants this as two separate definitions. */

struct xMINI_LIST_ITEM
{
	portTickType xItemValue;
	volatile struct xLIST_ITEM *pxNext;
	volatile struct xLIST_ITEM *pxPrevious;
};
typedef struct xMINI_LIST_ITEM xMiniListItem;

/*
 * Definition of the type of queue used by the scheduler.
 */
typedef struct xLIST
{
	volatile unsigned portBASE_TYPE uxNumberOfItems;
	volatile xListItem * pxIndex;		/*  Used to walk through the list */
	volatile xMiniListItem xListEnd;	/*  List item that contains the maximum possible item value */
} xList;

#define listSET_LIST_ITEM_OWNER( pxListItem, pxOwner ) ( pxListItem )->pvOwner = ( void * ) pxOwner

#define listSET_LIST_ITEM_VALUE( pxListItem, xValue )		( pxListItem )->xItemValue = xValue

#define listGET_LIST_ITEM_VALUE( pxListItem )			( ( pxListItem )->xItemValue )

#define listLIST_IS_EMPTY( pxList )	( ( pxList )->uxNumberOfItems == ( unsigned portBASE_TYPE ) 0 )

#define listCURRENT_LIST_LENGTH( pxList )		( ( pxList )->uxNumberOfItems )

#define listGET_OWNER_OF_NEXT_ENTRY( pxTCB, pxList )                                    \
	/* Increment the index to the next item and return the item, ensuring */            \
	/* we don't return the marker used at the end of the list.  */                      \
	( pxList )->pxIndex = ( pxList )->pxIndex->pxNext;                                  \
	if( ( pxList )->pxIndex == ( xListItem * ) &( ( pxList )->xListEnd ) )              \
	{                                                                                   \
		( pxList )->pxIndex = ( pxList )->pxIndex->pxNext;                          \
	}                                                                                   \
	pxTCB = ( pxList )->pxIndex->pvOwner


#define listGET_OWNER_OF_HEAD_ENTRY( pxList )  ( ( pxList->uxNumberOfItems != ( unsigned portBASE_TYPE ) 0 ) ?
( (&( pxList->xListEnd ))->pxNext->pvOwner ) : ( NULL ) )

#define listIS_CONTAINED_WITHIN( pxList, pxListItem ) ( ( pxListItem )->pvContainer == ( void * ) pxList )

void vListInitialise( xList *pxList );

void vListInitialiseItem( xListItem *pxItem );

void vListInsert( xList *pxList, xListItem *pxNewListItem );

void vListInsertEnd( xList *pxList, xListItem *pxNewListItem );

void vListRemove( xListItem *pxItemToRemove );
```

List.c

```
#include <stdlib.h>
#include "FreeRTOS.h"
#include "list.h"

/*-----------------------------------------------------------
 * PUBLIC LIST API documented in list.h
 *----------------------------------------------------------*/

void vListInitialise( xList *pxList )
{
        /* The list structure contains a list item which is used to mark the end of the list.  To initialise
           the list the list end is inserted as the only list entry. */
        pxList->pxIndex = ( xListItem * ) &( pxList->xListEnd );

        /* The list end value is the highest possible value in the list to ensure it
                remains at the end of the list. */
        pxList->xListEnd.xItemValue = portMAX_DELAY;

        /* The list end next and previous pointers point to itself so we know when the list is empty. */
        pxList->xListEnd.pxNext = ( xListItem * ) &( pxList->xListEnd );
        pxList->xListEnd.pxPrevious = ( xListItem * ) &( pxList->xListEnd );

        pxList->uxNumberOfItems = 0;
}

void vListInitialiseItem( xListItem *pxItem )
{
        /* Make sure the list item is not recorded as being on a list. */
        pxItem->pvContainer = NULL;
}

void vListInsertEnd( xList *pxList, xListItem *pxNewListItem )
{
volatile xListItem * pxIndex;

        /* Insert a new list item into pxList, but rather than sort the list, makes the new list item the last
           item to be removed by a call to pvListGetOwnerOfNextEntry.  This means it has to be the item
           pointed to by the pxIndex member. */
        pxIndex = pxList->pxIndex;

        pxNewListItem->pxNext = pxIndex->pxNext;
        pxNewListItem->pxPrevious = pxList->pxIndex;
        pxIndex->pxNext->pxPrevious = ( volatile xListItem * ) pxNewListItem;
        pxIndex->pxNext = ( volatile xListItem * ) pxNewListItem;
        pxList->pxIndex = ( volatile xListItem * ) pxNewListItem;

        /* Remember which list the item is in. */
        pxNewListItem->pvContainer = ( void * ) pxList;

        ( pxList->uxNumberOfItems )++;
}
```

```
67  void vListInsert( xList *pxList, xListItem *pxNewListItem )
68  {
69  volatile xListItem *pxIterator;
70  portTickType xValueOfInsertion;
71
72          /* Insert the new list item into the list, sorted in ulListItem order. */
73          xValueOfInsertion = pxNewListItem->xItemValue;
74
75          /* If the list already contains a list item with the same item value then the new list item should be
76          placed after it.  This ensures that TCB's which are stored in ready lists (all of which have the same
77          ulListItem value) get an equal share of the CPU.  However, if the xItemValue is the same as the back
78          marker the iteration loop below will not end.  This means we need to guard against this by checking
79          the value first and modifying the algorithm slightly if necessary. */
80          if( xValueOfInsertion == portMAX_DELAY )
81          {
82                  pxIterator = pxList->xListEnd.pxPrevious;
83          }
84          else
85          {
86                  for( pxIterator = ( xListItem * ) &( pxList->xListEnd );
87                       pxIterator->pxNext->xItemValue <= xValueOfInsertion;
88                           pxIterator = pxIterator->pxNext )
89                  {
90                  /* There is nothing to do here, we are just iterating to the wanted insertion position. */
91                  }
92          }
93
94          pxNewListItem->pxNext = pxIterator->pxNext;
95          pxNewListItem->pxNext->pxPrevious = ( volatile xListItem * ) pxNewListItem;
96          pxNewListItem->pxPrevious = pxIterator;
97          pxIterator->pxNext = ( volatile xListItem * ) pxNewListItem;
98
99          /* Remember which list the item is in.  This allows fast removal of the item later. */
00          pxNewListItem->pvContainer = ( void * ) pxList;
01
02          ( pxList->uxNumberOfItems )++;
03  }
04
05  void vListRemove( xListItem *pxItemToRemove )
06  {
07          xList * pxList;
08          pxItemToRemove->pxNext->pxPrevious = pxItemToRemove->pxPrevious;
09          pxItemToRemove->pxPrevious->pxNext = pxItemToRemove->pxNext;
10
11          /* The list item knows which list it is in.  Obtain the list from the list item. */
12          pxList = ( xList * ) pxItemToRemove->pvContainer;
13
14          /* Make sure the index is left pointing to a valid item. */
15          if( pxList->pxIndex == pxItemToRemove )
16          {
17                  pxList->pxIndex = pxItemToRemove->pxPrevious;
18          }
19
20          pxItemToRemove->pvContainer = NULL;
21          ( pxList->uxNumberOfItems )--;
22  }
23  /*-----------------------------------------------------------*/
```

Queue.h

```
typedef void * xQueueHandle;

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

signed portBASE_TYPE xQueueSend( xQueueHandle xQueue, const void * pvItemToQueue, portTickType xTicksToWait );

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

unsigned portBASE_TYPE uxQueueMessagesWaiting( xQueueHandle xQueue );

void vQueueDelete( xQueueHandle xQueue );

signed portBASE_TYPE xQueueSendFromISR( xQueueHandle pxQueue, const void *pvItemToQueue, signed portBASE_TYPE
xTaskPreviouslyWoken );

signed portBASE_TYPE xQueueReceiveFromISR( xQueueHandle pxQueue, void *pvBuffer, signed portBASE_TYPE
*pxTaskWoken );
```

Queue.c

```
/*-----------------------------------------------------------
 * PUBLIC LIST API documented in list.h
 *----------------------------------------------------------*/

/* Constants used with the cRxLock and cTxLock structure members. */
#define queueUNLOCKED	( ( signed portBASE_TYPE ) -1 )

/*
 * Definition of the queue used by the scheduler.
 * Items are queued by copy, not reference.
 */
typedef struct QueueDefinition
{
	signed portCHAR *pcHead;	/*< Points to the beginning of the queue storage area. */
	signed portCHAR *pcTail;	/*< Points to the byte at the end of the queue storage area.
                                    Once more byte is allocated than necessary to store the queue items,
                                    this is used as a marker. */

	signed portCHAR *pcWriteTo;	/*< Points to the free next place in the storage area. */
	signed portCHAR *pcReadFrom;	/*< Points to the last place that a queued item was read from. */

	xList xTasksWaitingToSend;		/*< List of tasks that are blocked waiting to post onto this queue.
                                            Stored in priority order. */
	xList xTasksWaitingToReceive;	/*< List of tasks that are blocked waiting to
                                            read from this queue.  Stored in priority order. */

	unsigned portBASE_TYPE uxMessagesWaiting;/*< The number of items currently in the queue. */
	unsigned portBASE_TYPE uxLength;	/*< The length of the queue defined as the number
                                            of items it will hold, not the number of bytes. */
	unsigned portBASE_TYPE uxItemSize;	/*< The size of each items that the queue will hold. */

	signed portBASE_TYPE xRxLock;		/*< Stores the number of items received from the queue
                                            (removed from the queue) while the queue was locked.
                                            Set to queueUNLOCKED when the queue is not locked. */
	signed portBASE_TYPE xTxLock;		/*< Stores the number of items transmitted to the queue
                                            (added to the queue) while the queue was locked.
                                            Set to queueUNLOCKED when the queue is not locked. */
} xQUEUE;
/*-----------------------------------------------------------*/

/*
 * Inside this file xQueueHandle is a pointer to a xQUEUE structure.
 * To keep the definition private the API header file defines it as a
 * pointer to void.
 */
typedef xQUEUE * xQueueHandle;
```

```
368  /*
369   * Unlocks a queue locked by a call to prvLockQueue.  Locking a queue does not
370   * prevent an ISR from adding or removing items to the queue, but does prevent
371   * an ISR from removing tasks from the queue event lists.  If an ISR finds a
372   * queue is locked it will instead increment the appropriate queue lock count
373   * to indicate that a task may require unblocking.  When the queue in unlocked
374   * these lock counts are inspected, and the appropriate action taken.
375   */
376  static signed portBASE_TYPE prvUnlockQueue( xQueueHandle pxQueue );
377
378  /*
379   * Uses a critical section to determine if there is any data in a queue.
380   *
381   * @return pdTRUE if the queue contains no items, otherwise pdFALSE.
382   */
383  static signed portBASE_TYPE prvIsQueueEmpty( const xQueueHandle pxQueue );
384
385  /*
386   * Uses a critical section to determine if there is any space in a queue.
387   *
388   * @return pdTRUE if there is no space, otherwise pdFALSE;
389   */
390  static signed portBASE_TYPE prvIsQueueFull( const xQueueHandle pxQueue );
391
392  /*
393   * Macro that copies an item into the queue.  This is done by copying the item
394   * byte for byte, not by reference.  Updates the queue state to ensure it's
395   * integrity after the copy.
396   */
397  #define prvCopyQueueData( pxQueue, pvItemToQueue )                                          \
398  {                                                                                           \
399          memcpy( ( void * ) pxQueue->pcWriteTo, pvItemToQueue, ( unsigned ) pxQueue->uxItemSize ); \
400          ++( pxQueue->uxMessagesWaiting );                                                   \
401          pxQueue->pcWriteTo += pxQueue->uxItemSize;                                          \
402          if( pxQueue->pcWriteTo >= pxQueue->pcTail )                                         \
403          {                                                                                   \
404                  pxQueue->pcWriteTo = pxQueue->pcHead;                                       \
405          }                                                                                   \
406  }
407
408  /*
409   * Macro to mark a queue as locked.  Locking a queue prevents an ISR from accessing the queue event lists.
410   */
411  #define prvLockQueue( pxQueue )                         \
412  {                                                       \
413          taskENTER_CRITICAL();                           \
414                  ++( pxQueue->xRxLock );                 \
415                  ++( pxQueue->xTxLock );                 \
416          taskEXIT_CRITICAL();                            \
417  }
418  /*-----------------------------------------------------------
419   * PUBLIC QUEUE MANAGEMENT API documented in queue.h
420   *----------------------------------------------------------*/
421
422  xQueueHandle xQueueCreate( unsigned portBASE_TYPE uxQueueLength, unsigned portBASE_TYPE uxItemSize )
423  {
424  xQUEUE *pxNewQueue;
425  size_t xQueueSizeInBytes;
426
427          /* Allocate the new queue structure. */
428          if( uxQueueLength > ( unsigned portBASE_TYPE ) 0 )
429          {
430                  pxNewQueue = ( xQUEUE * ) pvPortMalloc( sizeof( xQUEUE ) );
431                  if( pxNewQueue != NULL )
432                  {
433                          /* Create the list of pointers to queue items.  The queue is one byte
434                          longer than asked for to make wrap checking easier/faster. */
435                          xQueueSizeInBytes = ( size_t ) ( uxQueueLength * uxItemSize ) + ( size_t ) 1;
436
437                          pxNewQueue->pcHead = ( signed portCHAR * ) pvPortMalloc( xQueueSizeInBytes );
438                          if( pxNewQueue->pcHead != NULL )
439                          {
440                                  /* Initialise the queue members as described above where the
441                                  queue type is defined. */
442                                  pxNewQueue->pcTail = pxNewQueue->pcHead + ( uxQueueLength * uxItemSize );
443                                  pxNewQueue->uxMessagesWaiting = 0;
444                                  pxNewQueue->pcWriteTo = pxNewQueue->pcHead;
445                                  pxNewQueue->pcReadFrom = pxNewQueue->pcHead + ( ( uxQueueLength - 1 ) *
446                                                                   uxItemSize );
447                                  pxNewQueue->uxLength = uxQueueLength;
448                                  pxNewQueue->uxItemSize = uxItemSize;
449                                  pxNewQueue->xRxLock = queueUNLOCKED;
450                                  pxNewQueue->xTxLock = queueUNLOCKED;
```

```
451
452                             /* Likewise ensure the event queues start with the correct state. */
453                             vListInitialise( &( pxNewQueue->xTasksWaitingToSend ) );
454                             vListInitialise( &( pxNewQueue->xTasksWaitingToReceive ) );
455
456                             return  pxNewQueue;
457                         }
458                         else
459                         {
460                             vPortFree( pxNewQueue );
461                         }
462                 }
463         }
464
465         /* Will only reach here if we could not allocate enough memory or no memory
466         was required. */
467         return NULL;
468 }
469
470 signed portBASE_TYPE xQueueSend( xQueueHandle pxQueue, const void *pvItemToQueue, portTickType xTicksToWait )
471 {
472 signed portBASE_TYPE xReturn;
473
474         /* Make sure other tasks do not access the queue. */
475         vTaskSuspendAll();
476
477         /* Make sure interrupts do not access the queue event list. */
478         prvLockQueue( pxQueue );
479
480         /* If the queue is already full we may have to block. */
481         if( prvIsQueueFull( pxQueue ) )
482         {
483                 /* The queue is full - do we want to block or just leave without
484                 posting? */
485                 if( xTicksToWait > ( portTickType ) 0 )
486                 {
487         /* We are going to place ourselves on the xTasksWaitingToSend event list, and will get woken should
488         the delay expire, or space become available on the queue. As detailed above we do not require mutual
489         exclusion on the event list as nothing else can modify it or the ready lists while we have the
490         scheduler suspended and queue locked.
491
492         It is possible that an ISR has removed data from the queue since we checked if any was available.  If
493         this is the case then the data will have been copied from the queue, and the queue variables updated,
494         but the event list will not yet have been checked to see if anything is waiting as the queue is
495         locked. */
496                         vTaskPlaceOnEventList( &( pxQueue->xTasksWaitingToSend ), xTicksToWait );
497
498         /* Force a context switch now as we are blocked.  We can do this from within a critical section as the
499         task we are switching to has its own context.  When we return here (i.e. we unblock) we will leave the
500         critical section as normal.
501
502         It is possible that an ISR has caused an event on an unrelated and unlocked queue.  If this was the
503         case then the event list for that queue will have been updated but the ready lists left unchanged -
504         instead the readied task will have been added to the pending ready list. */
505                         taskENTER_CRITICAL();
506                         {
507         /* We can safely unlock the queue and scheduler here as interrupts are disabled.  We must not yield
508         with anything locked, but we can yield from within a critical section.
509
510         Tasks that have been placed on the pending ready list cannot be tasks that are waiting for events on
511         this queue.  See in comment xTaskRemoveFromEventList(). */
512                             prvUnlockQueue( pxQueue );
513
514                             /* Resuming the scheduler may cause a yield.  If so then there
515                             is no point yielding again here. */
516                             if( !xTaskResumeAll() )
517                             {
518                                     taskYIELD();
519                             }
520
521         /* Before leaving the critical section we have to ensure exclusive access again. */
522                             vTaskSuspendAll();
523                             prvLockQueue( pxQueue );
524                         }
525                         taskEXIT_CRITICAL();
526                 }
527         }
528
529         /* When we are here it is possible that we unblocked as space became available on the queue.
530         It is also possible that an ISR posted to the queue since we left the critical section, so it may be
531         that again there is no space.  This would only happen if a task and ISR post onto the same queue. */
532         taskENTER_CRITICAL();
533         {
```

```
534                 if( pxQueue->uxMessagesWaiting < pxQueue->uxLength )
535                 {
536                         /* There is room in the queue, copy the data into the queue. */
537                         prvCopyQueueData( pxQueue, pvItemToQueue );
538                         xReturn = pdPASS;
539
540                         /* Update the TxLock count so prvUnlockQueue knows to check for
541                         tasks waiting for data to become available in the queue. */
542                         ++( pxQueue->xTxLock );
543                 }
544                 else
545                 {
546                         xReturn = errQUEUE_FULL;
547                 }
548         }
549         taskEXIT_CRITICAL();
550
551         /* We no longer require exclusive access to the queue.  prvUnlockQueue will remove any tasks suspended
552         on a receive if either this function or an ISR has posted onto the queue. */
553         if( prvUnlockQueue( pxQueue ) )
554         {
555         /* Resume the scheduler - making ready any tasks that were woken by an event while the scheduler was
556         locked.  Resuming the scheduler may cause a yield, in which case there is no point yielding again
557         here. */
558                 if( !xTaskResumeAll() )
559                 {
560                         taskYIELD();
561                 }
562         }
563         else
564         {
565         /* Resume the scheduler - making ready any tasks that were woken
566         by an event while the scheduler was locked. */
567                 xTaskResumeAll();
568         }
569
570         return xReturn;
571 }
572
573 signed portBASE_TYPE xQueueSendFromISR( xQueueHandle pxQueue, const void *pvItemToQueue, signed portBASE_TYPE
574 xTaskPreviouslyWoken )
575 {
576         /* Similar to xQueueSend, except we don't block if there is no room in the queue.  Also we don't
577         directly wake a task that was blocked on a queue read, instead we return a flag to say whether a
578         context switch is required or not (i.e. has a task with a higher priority than us been woken by this
579         post). */
580         if( pxQueue->uxMessagesWaiting < pxQueue->uxLength )
581         {
582                 prvCopyQueueData( pxQueue, pvItemToQueue );
583
584                 /* If the queue is locked we do not alter the event list.  This will
585                 be done when the queue is unlocked later. */
586                 if( pxQueue->xTxLock == queueUNLOCKED )
587                 {
588                         /* We only want to wake one task per ISR, so check that a task has
589                         not already been woken. */
590                         if( !xTaskPreviouslyWoken )
591                         {
592                                 if( !listLIST_IS_EMPTY( &( pxQueue->xTasksWaitingToReceive ) ) )
593                                 {
594                                         if( xTaskRemoveFromEventList( &( pxQueue->xTasksWaitingToReceive ) )
595                                                         != pdFALSE )
596                                         {
597                                                 /* The task waiting has a higher priority so record that a
598                                                 context switch is required. */
599                                                 return pdTRUE;
600                                         }
601                                 }
602                         }
603                 }
604                 else
605                 {
606                 /* Increment the lock count so the task that unlocks the queue
607                 knows that data was posted while it was locked. */
608                         ++( pxQueue->xTxLock );
609                 }
610         }
611
612         return xTaskPreviouslyWoken;
613 }
614
```

```
615 signed portBASE_TYPE xQueueReceive( xQueueHandle pxQueue, void *pvBuffer, portTickType xTicksToWait )
616 {
617 signed portBASE_TYPE xReturn;
618
619         /* This function is very similar to xQueueSend().  See comments within
620         xQueueSend() for a more detailed explanation.*/
621
622         /* Make sure other tasks do not access the queue. */
623         vTaskSuspendAll();
624
625         /* Make sure interrupts do not access the queue. */
626         prvLockQueue( pxQueue );
627
628         /* If there are no messages in the queue we may have to block. */
629         if( prvIsQueueEmpty( pxQueue ) )
630         {
631                 /* There are no messages in the queue, do we want to block or just leave with nothing? */
632                 if( xTicksToWait > ( portTickType ) 0 )
633                 {
634                         vTaskPlaceOnEventList( &( pxQueue->xTasksWaitingToReceive ), xTicksToWait );
635                         taskENTER_CRITICAL();
636                         {
637                                 prvUnlockQueue( pxQueue );
638                                 if( !xTaskResumeAll() )
639                                 {
640                                         taskYIELD();
641                                 }
642
643                                 vTaskSuspendAll();
644                                 prvLockQueue( pxQueue );
645                         }
646                         taskEXIT_CRITICAL();
647                 }
648         }
649
650         taskENTER_CRITICAL();
651         {
652                 if( pxQueue->uxMessagesWaiting > ( unsigned portBASE_TYPE ) 0 )
653                 {
654                         pxQueue->pcReadFrom += pxQueue->uxItemSize;
655                         if( pxQueue->pcReadFrom >= pxQueue->pcTail )
656                         {
657                                 pxQueue->pcReadFrom = pxQueue->pcHead;
658                         }
659                         --( pxQueue->uxMessagesWaiting );
660                         memcpy( ( void * ) pvBuffer, ( void * ) pxQueue->pcReadFrom,
661                                                                 ( unsigned ) pxQueue->uxItemSize );
662
663                         /* Increment the lock count so prvUnlockQueue knows to check for
664                         tasks waiting for space to become available on the queue. */
665                         ++( pxQueue->xRxLock );
666                         xReturn = pdPASS;
667                 }
668                 else
669                 {
670                         xReturn = pdFAIL;
671                 }
672         }
673         taskEXIT_CRITICAL();
674
675         /* We no longer require exclusive access to the queue. */
676         if( prvUnlockQueue( pxQueue ) )
677         {
678                 if( !xTaskResumeAll() )
679                 {
680                         taskYIELD();
681                 }
682         }
683         else
684         {
685                 xTaskResumeAll();
686         }
687
688         return xReturn;
689 }
690
```

```
signed portBASE_TYPE xQueueReceiveFromISR( xQueueHandle pxQueue, void *pvBuffer, signed portBASE_TYPE
*pxTaskWoken )
{
signed portBASE_TYPE xReturn;

        /* We cannot block from an ISR, so check there is data available. */
        if( pxQueue->uxMessagesWaiting > ( unsigned portBASE_TYPE ) 0 )
        {
                /* Copy the data from the queue. */
                pxQueue->pcReadFrom += pxQueue->uxItemSize;
                if( pxQueue->pcReadFrom >= pxQueue->pcTail )
                {
                        pxQueue->pcReadFrom = pxQueue->pcHead;
                }
                --( pxQueue->uxMessagesWaiting );
                memcpy( ( void * ) pvBuffer, ( void * ) pxQueue->pcReadFrom,
                                             ( unsigned ) pxQueue->uxItemSize );

                /* If the queue is locked we will not modify the event list.  Instead we update the lock count
                so the task that unlocks the queue will know that an ISR has removed data while the queue was
                locked. */
                if( pxQueue->xRxLock == queueUNLOCKED )
                {
                /* We only want to wake one task per ISR, so check that a task has not already been woken. */
                        if( !( *pxTaskWoken ) )
                        {
                                if( !listLIST_IS_EMPTY( &( pxQueue->xTasksWaitingToSend ) ) )
                                {
                                        if( xTaskRemoveFromEventList( &( pxQueue->xTasksWaitingToSend ) )
                                                        != pdFALSE )
                                        {
                                        /* The task waiting has a higher priority than us so
                                        force a context switch. */
                                                *pxTaskWoken = pdTRUE;
                                        }
                                }
                        }
                }
                else
                {
                /* Increment the lock count so the task that unlocks the queue
                        knows that data was removed while it was locked. */
                        ++( pxQueue->xRxLock );
                }

                xReturn = pdPASS;
        }
        else
        {
                xReturn = pdFAIL;
        }

        return xReturn;
}

unsigned portBASE_TYPE uxQueueMessagesWaiting( xQueueHandle pxQueue )
{
unsigned portBASE_TYPE uxReturn;

        taskENTER_CRITICAL();
                uxReturn = pxQueue->uxMessagesWaiting;
        taskEXIT_CRITICAL();

        return uxReturn;
}

void vQueueDelete( xQueueHandle pxQueue )
{
        vPortFree( pxQueue->pcHead );
        vPortFree( pxQueue );
}
```

```
763 static signed portBASE_TYPE prvUnlockQueue( xQueueHandle pxQueue )
764 {
765 signed portBASE_TYPE xYieldRequired = pdFALSE;
766
767         /* THIS FUNCTION MUST BE CALLED WITH THE SCHEDULER SUSPENDED. */
768
769         /* The lock counts contains the number of extra data items placed or
770         removed from the queue while the queue was locked.  When a queue is
771         locked items can be added or removed, but the event lists cannot be
772         updated. */
773         taskENTER_CRITICAL();
774         {
775                 --( pxQueue->xTxLock );
776
777                 /* See if data was added to the queue while it was locked. */
778                 if( pxQueue->xTxLock > queueUNLOCKED )
779                 {
780                         pxQueue->xTxLock = queueUNLOCKED;
781
782                         /* Data was posted while the queue was locked.  Are any tasks
783                         blocked waiting for data to become available? */
784                         if( !listLIST_IS_EMPTY( &( pxQueue->xTasksWaitingToReceive ) ) )
785                         {
786                                 /* Tasks that are removed from the event list will get added to
787                                 the pending ready list as the scheduler is still suspended. */
788                                 if( xTaskRemoveFromEventList( &( pxQueue->xTasksWaitingToReceive ) ) != pdFALSE
789 )
790                                 {
791                                         /* The task waiting has a higher priority so record that a
792                                         context switch is required. */
793                                         xYieldRequired = pdTRUE;
794                                 }
795                         }
796                 }
797         }
798         taskEXIT_CRITICAL();
799
800         /* Do the same for the Rx lock. */
801         taskENTER_CRITICAL();
802         {
803                 --( pxQueue->xRxLock );
804
805                 if( pxQueue->xRxLock > queueUNLOCKED )
806                 {
807                         pxQueue->xRxLock = queueUNLOCKED;
808
809                         if( !listLIST_IS_EMPTY( &( pxQueue->xTasksWaitingToSend ) ) )
810                         {
811                                 if( xTaskRemoveFromEventList( &( pxQueue->xTasksWaitingToSend ) ) != pdFALSE )
812                                 {
813                                         xYieldRequired = pdTRUE;
814                                 }
815                         }
816                 }
817         }
818         taskEXIT_CRITICAL();
819
820         return xYieldRequired;
821 }
822
823 static signed portBASE_TYPE prvIsQueueEmpty( const xQueueHandle pxQueue )
824 {
825 signed portBASE_TYPE xReturn;
826
827         taskENTER_CRITICAL();
828                 xReturn = ( pxQueue->uxMessagesWaiting == ( unsigned portBASE_TYPE ) 0 );
829         taskEXIT_CRITICAL();
830
831         return xReturn;
832 }
833
834 static signed portBASE_TYPE prvIsQueueFull( const xQueueHandle pxQueue )
835 {
836 signed portBASE_TYPE xReturn;
837
838         taskENTER_CRITICAL();
839                 xReturn = ( pxQueue->uxMessagesWaiting == pxQueue->uxLength );
840         taskEXIT_CRITICAL();
841
842         return xReturn;
843 }
```

Ex 3.35
Ex. 52

Solutions 2007

FOUR Questions in 180 minutes => 45 min per question

Answer codes: A=analysis, B=bookwork, D=design, C= new application of learnt theory

1. *This question tests whether the students understand some of the issues when writing application code for RTOS*

a)

```
taskENTER_CRITICAL()
/*access resource*/
taskEXIT_CRITICAL()
```

```
xQueueHandle sema;
vSemaphoreCreateBinary( sema);
xSemaphoreTake(sema);
/*access resource*/
xSemaphoregive(sema);
```

[3B]

b)

(1) interrupt disable [ENTER/EXIT]_CRITICAL_SECTION() as above

Benefit: fast, no priority inversion

disadvantage: may increase global interrupt latency

(2) scheduler locking:

```
vTaskSuspendAll()
/*critical section*/
vTaskResumeAll()
```

Benefit: allows interrupts while locked, no priority inversion

Disadvantage: can't be used to share resource with interrupt

[4B]

c) PI can increase the delay of a high priority task when it is sharing a resource with a low priority task. Specifically:

LPT runs and takes S

HPT runs & waits on S

LPT continues

MPT preempts LPT

MPT blocks

LPT runs and gives S

HPT takes S

In this trace any number of tasks with priority greater than LPT and less than HPT can delay progress of HPT

Mend the problem by implementing priority inheritance protocol (PIP) using FreeRTOS dynamic task priorities:

vTaskPrioritySet()

uxTaskPriorityGet()

increase the priority of LPT to that of HPT for the length of time that LPT holds S and HPT is waiting on S

[4B]

d) Strictly speaking, CPU starvation (which may happen if RMA analysis does not guarantee deadlines) is a form of starvation and therefore liveness problem. However just because it does not happen, it does not mean that it is guaranteed not to happen given future minor changes in conditions or code. therefore RMA is still useful because it guarantees no CPU starvation (though does not say anything about other liveness problems).

[4A]

e) Single call results in wait for n clock ticks => time of min(0, (n-1))*tick-time to n*tick-time

TaskDelayUntil is useful for repeated delays where the time from one call to the next is critical. This will be precise providing the total task (+ higher priority task) execution time is less than the specified delay. This is better than TaskDelay() – which will go wrong if the above total time is greater than one time-tick.

[4A]

2.

a)

Interrupts: no RTOS required => more compact code, faster switching.

Disadvantages: Prioritised interrupts are required. Code must be written as separate ISRs with no state preserved in ISR between calls. RTOS communication & synchronisation primitives can't be used.

RTOS: reverse of above.

[4B]

b) EITHER use a binary semaphore, posting from the ISR and taking the semaphore in the task to implement wait for next interrupt.:

SemaphoreGiveFromISR(sema)--> SemaphoreTake(sema)

OR use task suspend resume:

vTaskSuspend(0) – will suspend current task

xtaskResumeFromISR(taskH) – will restart task from ISR

Note task handle must be stored after task creation.

The suspend/resume solution does not require a semaphore (queue) and is therefore both more compact and faster.

[4B/A]

c)

(i)` Y,X,W,Z (decreasing priority order)

(ii) Utilisation = 50/220+1/7+30/300+40/250=0.63

RMA limit n(2^(1/n)-1) for 4 tasks = 0.757

RMA theorem => all tasks meet deadlines with certainty

(iii) 0.63/0.757=0.83 that have A is minimum speed

[6C]

d) Add blocking time to CPU time so: (i) no change, (ii)+0.22=> RMA conditions not met. CANT TELL whether deadlines will be met. (iii) 0.85/0.757= 1.12X speed of A. With EDF scheduling, assuming CPU+blocking is less than 100%, can guarantee all deadlines. speed 0.85/1 would be minimum.

[6C]

3. *This question tests whether students understand the implementation of RTOSes by examining in detail the behaviour of some real (but not ideal, and hence now replaced) code.*

This question relates to the v4.0.5 FreeRTOS implementation of queues: source code for FreeRTOS v4.0.5 is contained in the booklet RTOS Exam Notes.

a) Discuss in detail how FreeRTOS implements copying of message data and the implications of this for the implementation, and the application programmer.

[4B]

b) line 629 IF is true since Q is empty. Line 634 If is true since timeout must be non-zero for task to wait. Line 640 – task suspends.

ISR posts message and rewakes task, which continues from line 640.

643: scheduler is locked

Line 652 test is true, since message is waiting to be picked up

Message is extracted from queue (with possible read pointer wrap-around (line 657)

Line 665: Lock count is incremented in case Q was previously full

666: set pdPass return value

668-671 skipped

678 – scheduler unlocked, causes no change of task

680 – taskYield() does not result in change of task.

return pdPass (set from 666)

[4A]

c) See below for details. Problem: task B returns early with a failure when it has not timed out. Application code could check whether timeout was real and if not try again to receive a message by calling QueueReceive() again with an adjusted timeout. This must be implemented with a loop, since spurious wakeup can happen at any time.

[6A]

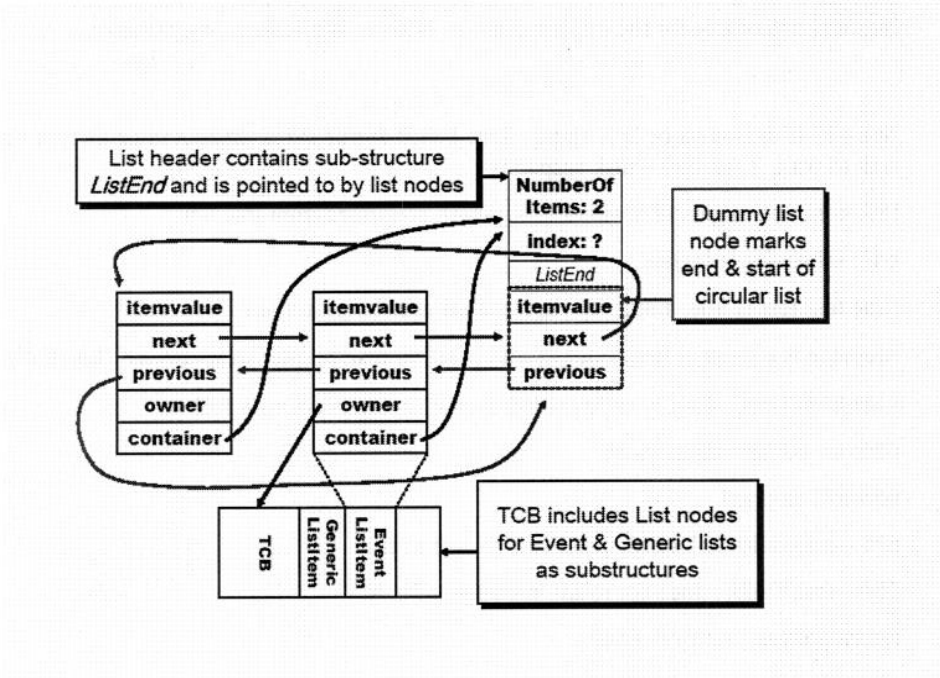
Time	Event	Details
1	task C calls QueueSend(Q1)	In QueueSend(), from prvUnlockQueue, B, the highest priority waiter, is awoken but does not yet run
2	task D preempts C	
3	task D calls QueueReceive(Q1)	D finds the message that was posted in Q1, and returns immediately with this.
4	task D sleeps	
5	task B runs	B runs inside QueueReceive and finds that no message is available, it returns with a failure (as from timeout)

d) Solution: Distinguish between a timeout wakeup and a (perhaps spurious) event wakeup by checking timeout value (which is a local variable) and go back to sleep if the latter has not elapsed. Can distinguish because the wakeup time can be calculated on QueueReceive() entry and stored in local variable for reference.

[6D]

4. This question relates to the FreeRTOS task list package implementation, source code for which can be found in the booklet RTOS Exam Notes.

a)



[2]

[2B]

b)

add task to ready list

delete task from ready list

find & remove highest priority task from ready list

move to next task (round-robin) of set of tasks of identical priority in ready list.

ready list is implemented as array of (circular) task lists, one for each priority. add & delete task from task list functions are used as necessary. All tasks within one list are same priority so ordering is not relevant, tasks are added to end of list (different from start in the case that there are multiple tasks of same priority). List of traversed continuously in case time-slicing is needed.

[4B]

c) next & previous. Could delete one of these to make singly-linked. Delete task would take longer, other operations (except move to next task) would be quicker.

container – not needed for ready list, since know what it is

owner – not needed for ready list, since know offset between listitem node and task TCB so can reconstruct this.

[6A]

d) Used for ready list, suspended task list, delayed task list, overflow delayed task list, event lists (two per message queue). General package considerably reduces RTOS code size, however not all features are used in all cases, so separate code would be slightly more efficient.

[4B]

e) Each separate priority is represented by one bit. Fixed number of priorities allowed (e.g. 64) => 8 bytes needed for table. Must have unique task per priority. Tasks are represented as in list by setting appropriate bit. This means that dynamic priority would require changes to task lists (all of them containing the task).

[4A]

5.

a) Both stop priority inversion from time that a HPT is waiting by ensuring task with lock on resource is same priority as HPT. CPP requires static analysis of code (which may be additional burden for programmer). It has advantage that low priority tasks will have high priority whenever they lock the resource. this makes no difference to worst case HPT delay. However it reduces average case HPT delay by making it less likely that another lower priority task will have resource locked when HPT requests lock.

[4B]

b) A cycle in the graph <=> deadlock

This can be avoided by ordering resources and making sure all tasks claim shared resources in the same (global) order. (resources can be released in any order).

[4B]

c) S1. only one task is blocked, so can't be deadlock. Task is blocked, so can't be livelock. Must be starvation. Two higehr priority tasks must be hogging some resource.

S2. B,C are running & making no progress – they must be livelocked.

S3. B & D are blocked. B cannot be starved since only one higher prio task, hence it must be deadlocked. D cannot be blocked because B must be deadlocked with D. Hence B,D are deadlocked.

[6A]

d) Condition 2 of PCP means that any task locking a resource will inherit dynamically the priority of any task waiting on the lock. Condition 3 means that this will allow preemption if necessary of a lower priority task.

[4A]

e) Prevention, since it constrains resource lockers to wait until such time as deadlock is no longer possible.

[2A]

6.

This question tests whether the student have deeper understanding of some aspect of the topic. All students have RTOS implementation coursework relating to one of these five options. The given question tests whether they understand the wider issues relating to their implementation. The answers will depend on the precise coursework topic.

[20]