CSS422 Final Project

Thumb-2 Implementation Work of Memory/Time-Related C Standard Library Functions.

1. Objective

You'll understand the following concepts at the ARM assembly language level through this final project that implements memory/time-related C standard library functions in Thumb-2.

- CPU operating modes: user and supervisor modes
- System-call and interrupt handling procedures
- C to assembler argument passing (APCS: ARM Procedure Call Standard)
- Stack operations to implement recursions at the assembly language level
- Buddy memory allocation

This document is quite dense. Please read it as soon as the final project spec. becomes available to you.

2. Project Overview

Using the Thumb-2 assembly language, you will implement several functions of the C standard library that will be invoked from a C program named driver.c. See Table 1. These functions must be code in the Thumb-2 assembly language. Some of them can be implemented in stdlib.s running in the unprivileged thread mode (=user mode), whereas the others need to be implemented as supervisor calls, (i.e., in the handler mode = supervisor mode). For more details, log in one of the CSS Linux servers and type from the Linux shell:

`man 3 function` where function is either bezro, strncpy, malloc, free, signal, or alarm

Table 1: C standard lib functions to be implemented in the final project

C standard lib functions	In stdlib.s *1	SVC *2
`bzero( void *s, size_t n )` writes n zeroed bytes to the setring s. If n is zero, bzero( ) does nothing.	Yes	
`strncpy(char *dst, const char *src, size_t len)` copies at most len characters from src into dst. It returns dst.	Yes	
`malloc( size_t size )` allocates size bytes of memory and returns a pointer to the allocated memory. If successful, it returns a pointer to allocated memory. Otherwise, it returns a NULL pointer.		Yes
`free( void *ptr )` Deallocates the memory allocation pointed to by ptr. If ptr is a NULL pointer, no operation is performed. If successful, it returns a pointer to allocated memory. Otherwise, it returns a NULL pointer.		Yes
`void (*signal( int sig, void (*func)(int)))(int);` Invokes the func procedure upon receipt of a signal. Our implementation focuses only on SIGALRM, (whose system call number is 14.)		Yes
`unsigned alarm( unsigned seconds )` sets a timer to deliver the signal SIGALRM to the calling process after the specified number of seconds. It returns the amount of time left on the timer from a previous call to alarm( ). If no alarm is currently set, the return value is 0.		Yes

*1: To be implemented in stdlib.s in the unprivileged thread mode
*2: To be passed as an SVC to SVC_Hander in the privileged handler mode

The driver.c we use is shown in listing 1. It tests all the above six stdlib functions. Please note that printf() in the code will be removed when you test your assembly implementation, because we won't implement the printf( ) standard function.

Listing 1: driver.c program to test your implementation

```
#include <strings.h> // bzero, strncpy
#include <stdlib.h>  // malloc, free
#include <signal.h>  // signal
#include <unistd.h>  // alarm
#include <stdio.h>   // printf

int* alarmed;

void sig_handler1( int signum ) {
      *alarmed = 2;
}

void sig_handler2( int signum ) {
      *alarmed = 3;
}

int main( ) {
 char stringA[40] = "0123456789ABCDEFGHIJKLMNOPQRSTUVWXYZabc\0";
 char stringB[40];

 bzero( stringB, 40 );
 strncpy( stringB, stringA, 40 );
 bzero( stringA, 40 );
 printf( "%s\n", stringA );
 printf( "%s\n", stringB );

 void* mem1 = malloc( 1024 );
 void* mem2 = malloc( 1024 );
 void* mem3 = malloc( 8192 );
 void* mem4 = malloc( 4096 );
 void* mem5 = malloc( 512 );
 void* mem6 = malloc( 1024 );
 void* mem7 = malloc( 512 );

 free( mem6 );
 free( mem5 );
 free( mem1 );
 free( mem7 );
 free( mem2 );

 void* mem8 = malloc( 4096 );

 free( mem4 );
 free( mem3 );
 free( mem8 );

 alarmed = (int *)malloc( 4 );
 *alarmed = 1;
 printf( "%d\n", *alarmed);

 signal( SIGALRM, sig_handler1 );
 alarm( 2 );
 while ( *alarmed != 2 ) {
  void* mem9 = malloc( 4 );
  free( mem9 );
 }
 printf( "%d\n", *alarmed);

 signal( SIGALRM, sig_handler2 );
```

```
    alarm( 3 );
    while ( *alarmed != 3 ) {
     void* mem9 = malloc( 4 );
     free( mem9 );
    }
    printf( "%d\n", *alarmed);

    return 0;
}
```

This driver program repeats allocating and deallocating memory space and thereafter sets the sig_handler1( ) function to be called upon receiving the first timer interrupt (in 2 seconds) and sig_ahndler2( ) function to be called upon the second timer interrupt (in 3 seconds).

3. System Overview and Execution Sequence

3.1. Memory overview

This project maps all code to 0x0000.0000 – 0x1FFF.FFFF in the ARM's usual ROM space (as the Keil C compiler/ARM assembler does) and defines a heap space; user and SVC stacks; memory control block (MCB) to manage the heap space; and all the SVC-related parameters over 0x2000.1000 – 0x2000.7FFF in the ARM's usual SRAM space. See table 2.

Table 2: Memory overview

Address	Size (hex)	Size (B)	Usage
0x400F.E600 – 0x400F.F028	0x0000.0A28	2.6KB	uDMA registers (memory mapped IO)
0x2000.7C00 – 0x2000.7FFF	0x0000.0400	1KB	uDMA memory map (ch 30)
0x2000.7B80 – 0x2000.7BFF	0x0000.0080	128B	System variables used by timer.s
0x2000.7B00 – 0x2000.7B7F	0x0000.0080	128B	System call table used by svc.s
0x2000.6C00 – 0x2000.7AFF	0x0000.0F00	3.8KB	Not used for now
0x2000.6800 – 0x2000.6BFF	0x0000.0400	1KB	Memory control block to manage in heap.s
0x2000.6000 – 0x2000.67FF	0x0000.0800	2KB	Not used for now.
0x2000.5800 – 0x2000.5FFF	0x0000.0800	2KB	SVC (handler) stack: used by all the others
0x2000.5000 – 0x2000.57FF	0x0000.0800	2KB	User (thread) stack: used by driver.c stdlib.s
0x2000.1000 – 0x2000.4FFF	0x0000.4000	16KB	Heap space controlled by malloc/free
0x2000.0000 – 0x2000.0FFF	0x0000.1000	4KB	Keil C compiler-reserved global data
0x0000.0000 – 0x1FFF.FFFF	0x2000.0000	512MB	ROM Space: all code mapped to this space

Since we compile driver.c together with our assembly programs, the Keil C compiler automatically reserves driver.c-related global data to some space within 0x2000.0000 – 0x2000.0FFF, which makes it difficult for us to start Master Stack Pointer (MSP) exactly at 0x2000.6000 toward to the lower address as well as to start Process Stack Pointer (PSP) at 0x2000.5800. So, it's sufficient to map MSP and PSP around 0x2000.6000 and 0x2000.5800 respectively. For the purpose of this memory allocation, you should declare the space as shown in listing 2:

Listing 2: The memory space definition in Thumb-2

```
Heap_Size             EQU      0x00005000
                      AREA     HEAP, NOINIT, READWRITE, ALIGN=3
__heap_base
Heap_Mem              SPACE    Heap_Size
__heap_limit

Handler_Stack_Size    EQU      0x00000800
Thread_Stack_Size     EQU      0x00000800
                      AREA     STACK, NOINIT, READWRITE, ALIGN=3
Thread_Stack_Mem      SPACE    Thread_Stack_Size
__initial_user_sp
Handler_Stack_Mem     SPACE    Handler_Stack_Size
__initial_sp
```

3.2. Initialization, system call, and interrupt sequences

(1) **Initialization:** the ARM processor reads the first 8 bytes to set MSP and the next 8 bytes to jump to the Reset_Handler routine (as you studied in the class). You don't have to change the original vector table. Reset_Handler initializes all the data structures you've developed and finally calls __main with listing 3.

Listing 3: The last two instructions in Reset_Handler (startup_TM4C129.s)

```
LDR     R0, =__main
BX      R0
```

These last two statements are from the original startup_TM4C129.s. Then, the main( ) function in driver.c is invoked.

(2) **System calls:** whenever main( ) calls any of stdlib functions including bzero, strncpy, malloc, free, signal, and alarm, the control needs to move to strlib.s. In other words, you need to define these function protocols in strlib.s, as shown in listing 4:

Listing 4: The framework of stdlib.s

```
              AREA    |.text|, CODE, READONLY, ALIGN=2
              THUMB
              EXPORT  _bzero
_bzero
              ; Implement the body of bzero( )
              MOV             pc, lr  ; Return to main( )
              EXPORT  _strncpy
_strncpy
              ; Implement the body of strncpy( )
              MOV             pc, lr  ; Return to main( )
              EXPORT  _malloc
_malloc
              ; Invoke the SVC_Handler routine in startup_TM4C129.s
              MOV             pc, lr  ; Return to main( )
              EXPORT  _free
_free
              ; Invoke the SVC_Handler routine in startup_TM4C129.s
              MOV             pc, lr  ; Return to main( )
              EXPORT  _signal
_signal
              ; Invoke the SVC_Handler routine in startup_TM4C129.s
              MOV             pc, lr  ; Return to main( )
              EXPORT  _alarm
_alarm
              ; Invoke the SVC_Handler routine in startup_TM4C129.s
              MOV             pc, lr  ; Return to main( )
              END
```

Among these six stdlib functions, you'll implement the entire logic of bzero( ) and strncpy( ) as they may be executed in the user mode. However, the other four functions must be handled as a system call. You need to invoke SVC_Handler in startup_TM4C129.s. Based on the Linux system call convention, use R7 to maintain the system call number. Arguments to a system call should follow ARM Procedure Call Standard, as summarized in table 3.

Table 3: System Call Parameters

System Call Name	R7	R0	R1
alarm	1	arg0: seconds	
signal	2	arg0: sig	arg1: func
malloc	3	arg0: size	
free	4	arg0: ptr	

SVC_Handler must invoke _systemcall_table_jump in svc.s. This in turn means you must prepare the svc.s file to implement _systemcall_table_jump. This function initializes the system call table in _systemcall_table_init as shown in Table 4:

Table 4: System Call Jump Table

Memory address	System Calls	Jump destination
0x2000.7B10	#4: free( )	_kfree in heap.s
0x2000.7B0C	#3: malloc( )	_kalloc in heap.s
0x2000.7B08	#2: signal( )	_signal_handler in timer.s
0x2000.7B04	#1: alarm( )	_timer_start in timer.s
0x2000.7B00	#0	Reserved

Each table entry records the routine to jump. For this purpose, svc.s needs to import the addresses of these routines, using the code snippet shown in listing 5:

Listing 5: Entry points to kernel functions imported in svc.s

```
IMPORT  _kfree
IMPORT  _kalloc
IMPORT  _signal_handler
IMPORT  _timer_start
```

When called from SVC_Handler, _system_call_table_jump checks R7, (i.e., the system call#) and refers to the corresponding jump table entry, and invokes the actual routine. The merit of using svc.c is to minimize your modifications onto startup_TM4C129.s.

(3) **Interrupts:** This final project only handles SysTick interrupts. The SysTick timer gets started with _timer_start that was invoked when main( ) calls alarm( ). Note that SysTick timer can count down up to 1 second. Therefore, if main( ) calls alarm(2) or alarm(3), you'll get a SysTick interrupts at least twice or three times. Upon receiving a SysTick interrupt, the control jumps to SysTick_Handler in startup_TM4C129.s. The handler routine will invoke _timer_update in timer.s to decrement the count provided by alarm( ), to check if the count reached 0, and if so to stop the timer as well as invoke func specified by signal(SIG_ALRM, func).

3.3. Structure of your library implementation

The software components you need for this final project are summarized in table 5.

Table 5: A summary of software components implemented in this final project

Source files	Functions to implement	Control[1:0]	Functions/routines to call
driver.c	main( )	11 User/PSP*[1]	→ bzero( ) → strncpy( ) → malloc( ) → free( ) → signal( ) → alarm( )

stdlib.s	bzero( ): entirely implemented here strncpy( ): entirely implemented here malloc( ): invokes an SVC free( ): invokes an SVC signal( ): invokes an SVC alarm( ): invokes and SVC	11 User/PSP*1	 → SVC_Handler → SVC_Handler → SVC_Handler → SVC_Handler
startup_TM4C129.s	Reset_Handler SVC_Handler SysTick_Handler	00 PriThr/MSP*2 00 Handler/MSP*3 00 Handler/MSP*3	→ _kinit → _systemcall_table_init → _timer_init → __main →_systemcall_table_jump → _timer_update
svc.s	_systemcall_table_init: see 3.2.(2) _systemcall_table_jump: see 3.2.(2)	00 Handler/MSP*3	 → _kalloc → _free → _signal_handler → _timer_start
timer.s	_timer_init: initializes SysTick here _timer_update: see 3.2.(3) _timer_start: see 3.2.(3) _signal_handler: see 3.2.(3)	00 Handler/MSP*3	
heap.s	_kinit: initializes memory ctl blocks. _kalloc: buddy allocation coded _kfree: buddy de-allocation coded	00 Handler/MSP*3	

*1: running under the unprivileged thread mode, using process stack pointer
*2: running under the privileged thread mode, using master stack pointer
*3: running under the privileged handler mode, using master stack pointer

4. Buddy Memory Allocation and Test Scenario

The final project implements the buddy memory allocation in Thumb-2.

4.1. Algorithms

If you have already taken CSS430: Operating Systems, have your OS textbook in your hand and read Section 10.8.1 Buddy System. Since the CSS ordinary course sequence assumes CSS422 taken before CSS430, here is a copy of Section 10.8.1:

10.8.1 Buddy System
The buddy system allocates memory from a fixed-size segment consisting of physically contiguous pages. Memory is allocated from this segment using a power-of-2 allocator, which satisfies requests in units sized as a power of 2 (4 KB, 8 KB, 16 KB, and so forth). A request in units not appropriately sized is rounded up to the next highest power of 2. For example, a request for 11 KB is satisfied with a 16-KB segment.

Let's consider a simple example. Assume the size of a memory segment is initially 256 KB and the kernel requests 21 KB of memory. The segment is initially divided into two buddies—which we will call AL and AR—each 128 KB in size. One of these buddies is further divided into two 64-KB buddies—BL and BR. However, the next-highest power of 2 from 21 KB is 32 KB so either BL or BR is again divided into two

32-KB buddies, CL and CR. One of these buddies is used to satisfy the 21-KB request. This scheme is illustrated in Figure 10.26, where CL is the segment allocated to the 21-KB request.
An advantage of the buddy system is how quickly adjacent buddies can be combined to form larger segments using a technique known as coalescing. In Figure 10.26, for example, when the kernel releases the CL unit it was allocated, the system can coalesce CL and CR into a 64-KB segment. This segment, BL, can in turn be coalesced with its buddy BR to form a 128-KB segment. Ultimately, we can end up with the original 256-KB segment.

The obvious drawback to the buddy system is that rounding up to the next highest power of 2 is very likely to cause fragmentation within allocated segments. For example, a 33-KB request can only be satisfied with a 64-KB segment. In fact, we cannot guarantee that less than 50 percent of the allocated unit will be wasted due to internal fragmentation. In the following section, we explore a memory allocation scheme where no space is lost due to fragmentation.

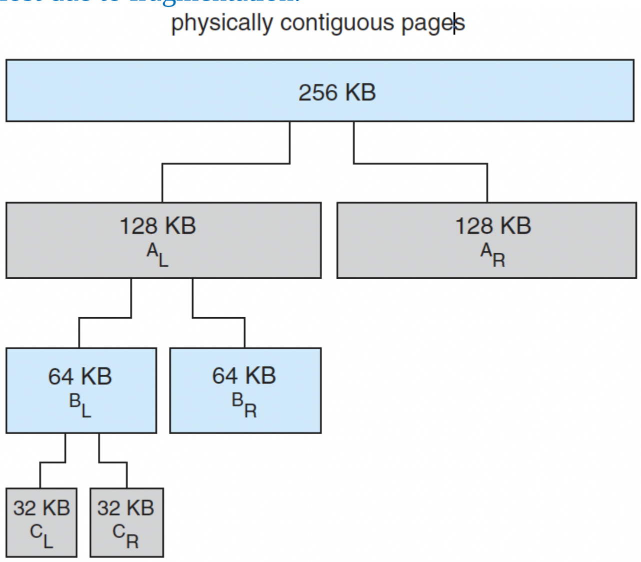


Figure 10.26 Buddy system allocation.

4.2. Implementation over 0x20001000 – 0x20004FFF

As the memory range we use is 0x20001000 – 0x20004FFF, the entire contiguous size is 16KB. This space will be recursively divided into 2 subspaces of 8KB, each further divided into 2 pieces of 4KB, all the way to 32B. Therefore, one extreme allocates 16KB entirely at once, whereas the other extreme allocates 512 different spaces, each with 32 bytes. To address this finest case, (i.e., handling 512 spaces), we allocate a memory control block (MCB) of 512 entries, each with 2 bytes, in the 1KB space over 10x20006800 – 0x20006BFF. Each entry corresponds to a different 32-byte heap space. For instance, let MCB entries are defined as

```
short mcb[512];
```

Then, mcb[0] points to the heaps space at 0x20001000, whereas mcb[511] corresponds to 0x20004FE0. However, each mcb[i] does not have to manage only 32 bytes. It can manage up to a contiguous 16KB space. Therefore, each mcb[i] has the size information of a heap space it is currently managing. The size can be 32 bytes to 16KB and thus be represented with 5 to16 bits, in other words with mcb[i]'s bits #15 - #4. We also use mcb[i]'s LSB, (i.e., bit #0) to indicate if the given heap space is available (= 0) or in use (= 1). Table 6 shows each mcb[i]'s bit usage:

Table 6: each mcb entry's bit usage

bits	descriptions
#15 – #4	The heap size this mcb entry is currently managing
#3 – #1	Reserved
#0	0: available, 1: in use

Let's consider a simple memory allocation scenario where main( ) requests 4KB and thereafter 8KB heap spaces with malloc(4096) and malloc(8192). Based on the buddy system algorithm, this scenario allocates 0x2000100 – 0x20001FFF for the first 4KB request and 0x20003000 – 0x20004FFF for the second 8KB request. Figure 1 shows this allocation. Only mcb[0], mcb[128], and mcb[256] are used to indicate in-use or available spaces. All the other mcb entries are not used yet.

Heap Address	Memory Availability		MCB	MCB Address	Contents
0x20001000 – 0x20001FFF	4KB in use		mcb[0]	0x20006800	4097_{10} (0x1001)
0x20002000 – 0x20002FFF	4KB available		mcb[128]	0x20006900	4096_{10} (0x1000)
0x20003000 – 0x20003FFF	8KB in use		mcb[256]	0x20006A00	8193_{10} (0x2001)
0x20004000 – 0x20004FFF					

Figure 1: heap space and mcb contents

4.3. Implementation

For each implementation of _kinit, _kalloc, and _kfree, refer to figure 2 that illustrates how mcb entries are updated.

(1) **_kinit:** The initialization must writes 16384_{10} (0x4000) onto mcb[0] at 0x20006800-0x20006801, indicating that the entire 16KB space is available. All the other mcb entries from 0x20006802 to 0x20006BFE must be zero-initialized (step 1 in figure 2).

(2) **_kalloc:** Your implementation must use recursions. When _kalloc(size) is called with a size requested, it should call a helper function, say _ralloc, as recursively choosing the left half or the right half of the current range until the requested size fits in a halved range. For instance in figure 1, the first malloc(4096) call is relayed to _kalloc(4096) that then calls _ralloc(4096, mcb[0], mcb[511]) or _ralloc(4096, 20006800, 20006BFE). See step 2 in figure 2. The _ralloc call finds mcb[0] at 0x20006800 has 16384B available, halves it, and chooses the left half by calling itself with _ralloc(4096, mcb[0], mcb[255]) or _ralloc(4096, 2006800, 200069FE). At this time, make sure that the right half managed by mcb[256] at 0x20006A00 must be updated with 8192 as its available space (step 3). Since the range is still 8192 bytes > 4096 bytes, _ralloc chooses the left by calling itself with _ralloc(4096, mcb[0], mcb[127]) or _ralloc(4096, 20006800, 200068FE). Make sure that the right half managed by mcb[128] at 0x2006900 is updated to 4096. The left half in the range between mcb[0]-mcb[127] or 0x20006800-200068FF fits the requested size of 4096. Therefore, ralloc( ) records 4097_{10} (0x1001) into mcb[0] at 0x20006800-0x20006801. This is step 4 in figure 2.

The second malloc(8192) is handled as follows: _kalloc(8192) calls _ralloc(8192, mcb[0], mcb[511]) or _ralloc(8192, 20006800, 20006BFE) as in step 5 that needs to choose the right half with _ralloc(8192, 20006A00, 20006BFE), because mcb[0] at 0x20006800-0x2006801 has a value of 4097 indicating that the left half (20006800 – 200069FE) is in use. Since mcb[256] at 0x20006A00-0x20006A01 is available, _ralloc saves 8193 (0x2001) there (step 6).

(3) **_kfree:** Your _kfree implementation must use recursions, too. The _kfree(*ptr) function calls a helper function, _rfree(the corresponding mcb[]). If main( ) calls free(20001000), it is relayed to _kfree(20001000) that calls _rfree(mcb[0]) or _rfree(20006800) to reset its bit #0 from in-use to available (step 7). Then, check its right buddy at mcb[128] (or 0x20006900). If its bit #0 is 0, indicating the availability, zero-reinitialize mcb[128] at 0x20006900 and make sure that mcb[0] at

0x20006800 shows an availability of 8192 bytes (step 8). Recursively check the buddy at higher layers. So, the next higher layer's buddy is mcb[256]-mcb[511] at 0x2006A00-0x2006BFE. Check mcb[256]'s contents, (at 0x20006A00-0x20006A01). In figure 2, the content is 8193 or (0x2001), showing that 8KB is being occupied. Therefore, stop _kfree's recursive calls.

		step 1	step 2	step 3	step 4	step 5	step 6	step 7	step 8
		_kinit( )	_kalloc(4096)			_kalloc(8192)		_kfree(20001000)	
			_ralloc(4096, 2006800, 2006BFE)	_ralloc(4096, 2006800, 20069FE)	_ralloc(4096, 2006800, 20068FE)	_ralloc(8192, 20068, 2006BFE)	_ralloc(8192, 2006A00, 2006BFE)	_rfree(20006800)	recursive _rfee(20006800)
mcb[ ]	MCB Address								
mcb[0]	0x20006800	0x4000	0x4000	0x2000	0x1001	0x1001	0x1001	0x1000	0x2000
	:	0x0000	0x0000						
mcb[127]	0x200068FE	0x0000	0x0000						
mcb[128]	0x20006900	0x0000	0x0000		0x1000	0x1000	0x1000	0x1000	0x0000
	:	0x0000	0x0000						
mcb[255]	0x200069FE	0x0000	0x0000						
mcb[256]	0x20006A00	0x0000	0x0000	0x2000	0x2000	0x2000	0x2001	0x2001	0x2001
	:	0x0000	0x0000						
mcb[383]	0x20006AFE	0x0000	0x0000						
mcb[384]	0x20006B00	0x0000	0x0000						
	:	0x0000	0x0000						
mcb[511]	0x200006BFE	0x0000	0x0000						

Figure 2: Recursive _ralloc/_rfree calls, each updating mcb entries

4.4. Test Scenario

Looking back to listing 1. "driver.c", you are supposed to verify your Thumb-2 implementation of malloc( ) and free( ) with repetitive system call invocations that allocate/deallocate mem1 – mem8 spaces. Figure 2 illustrates how the heap space is allocated and deallocated when you run driver.c. Orange indicates allocated spaces and green means de-allocated spaces.

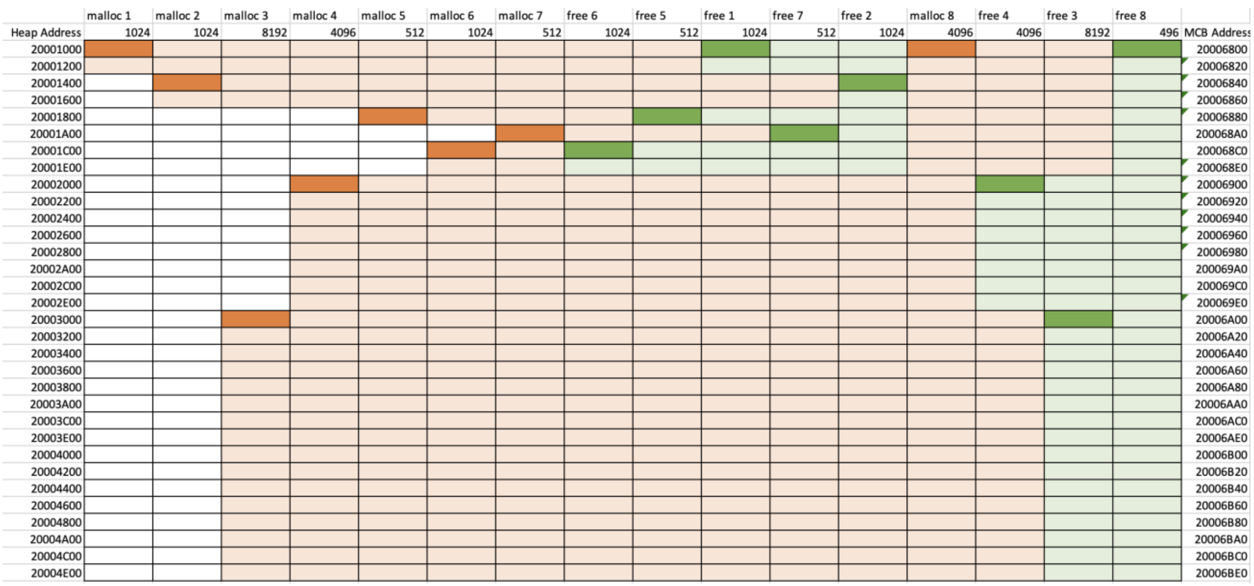


Figure 2: Test scenario and memory allocation

5. Signal and Alarm

The time management you will implement in your final project includes signal(sig, *func) and alarm(seconds). The parameters *func and seconds should be memorized in memory address at 0x20007B84 and 0x20007B80, as shown in table 7.

Table 7: Signal/alarm parameters to be stored in memory

Memory address	Parameters to store
0x2000.7B84	*func
0x2000.7B80	seconds

5.1. SysTick Initialization

The ARM system timer, SysTick's description can be found at:
https://developer.arm.com/documentation/dui0552/a/cortex-m3-peripherals/system-timer--systick

Table 8 is a copy of Table 4.32. System timer register summary on that URL. Among four SysTick registers, you will use the first three registers: (1) SysTick Control and Status Register, (2) SysTick Relaod Value Register, and (3) SysTick Current Value Register.

Table 8: A copy from Cortex-M3 Devices Generic User Guide URL's Table 4.32.

Table 4.32. System timer registers summary

Address	Name	Type	Required privilege	Reset value	Description
`0xE000E010`	SYST_CSR	RW	Privileged	[a]	*SysTick Control and Status Register*
`0xE000E014`	SYST_RVR	RW	Privileged	UNKNOWN	*SysTick Reload Value Register*
`0xE000E018`	SYST_CVR	RW	Privileged	UNKNOWN	*SysTick Current Value Register*
`0xE000E01C`	SYST_CALIB	RO	Privileged	- [a]	*SysTick Calibration Value Register*

[a] See the register description for more information.

Please click each register's hyperlink from table 4.32 to understand how the SysTick registers work.

For initialization in _timer_init,

(1) Make sure to stop SysTick:
Set SYST_CSR's Bit 2 (CLK_SRC) = 1, Bit 1 (INT_EN) = 0, Bit 0 (ENABLE) = 0
(2) Load the maximum value to SYST_RVR:
The value should be 0x00FFFFFF which means MAX Value = 1/16MHz * 16M = 1 second

5.2. Signal

The signal(sig, *func) function assumes only SIG_ALRM as the sig argument, while it accepts any address of *func (Keil C compiler automatically maps to memory). These sig and *func arguments must be relayed from signal(sig, *func) all the way to _signal_handler in timer.s as keeping sig in R0 and *func in R1 respectively (based on APCS, see table 3). If R0 is SIG_ALRM, (i.e., 14), save it in memory address at 0x20007B84. Return the previous value of 0x2007B84 to main( ) through R0.

5.3. Alarm

The alarm(seconds) function relays this seconds argument in R0 from main( ) all the way to _timer_start in timer.s. Retrieve the previous value at 0x20007B80 that is recognized as the previous time valuve and returned to main( ) through R0, save the new seconds value to 0x20007B80, and start the SysTick timer.

(1) Retrieve the seconds parameter from memory address 0x20007B80, which is the previous time value and should be returned to main( ).
(2) Save a new seconds parameter from alarm( ) to memory address 0x20007B80.
(3) Enable SysTick:
Set SYST_CSR's Bit 2 (CLK_SRC) = 1, Bit 1 (INT_EN) = 1, Bit 0 (ENABLE) = 1
(4) Clear SYST_CVR:
Set 0x00000000 in SYST_CVR.

5.4. SysTick Interrupt

A SysTick interrupt is caught at SysTick_Handler in startup_TM4C129.s. It is relayed to _timer_update in timer.s

This is the same as HW7-Q4.

The timer_update( ) function reads the value at address 0x20007B80, decrements the value by 1 (second), checks the value, branches to _timer_update_done if the value hasn't reached 0, otherwise it needs to stop the timer and to invoke a user function whose address is maintained in 0x20007B84. To stop the timer, write "Bit 2 (CLK_SRC) = 1, Bit 1 (INT_EN) = 0, Bit 0 (ENABLE) = 0" to SYST_CSR. (Don't forget to save back a decremented value into 0x20007B80.)

6. Implementation Steps, Timeline, and Submissions

Since it is definitely hard to implement everything in assembly code at once, the final project will take the following two steps. To work on your project, distinguish the following three versions of driver.c program. They are all available from Canvas→files→final project.

Table 9: driver programs

Files you will work on	Tasks
driver.c	This is a complete C program that can be compiled with gcc and executable on Linux.
driver_cpg.c	This is a C program that should be used for testing your heap.c in step 1 toward your midpoint report. The difference from driver.c is: - malloc( ) and free( ) are renamed _malloc( ) and _free( ), so that the compiler can use your own implementation of _malloc( ) and _free( ). - prinf( ) are included to verify your implementation. - alarm( ) and signal( ) are commented out as you will implement in step 2.
driver_keil.c	This is a C program that can be compiled with Keil C compiler and executable with your ARM/THUMB-2 assembly code. The difference from driver.c is: - all stdlib functions bzero( ), strncpy( ), malloc( ), free( ), alarm( ), and signal( ) are renamed _bzero( ), _strncpy( ), _malloc( ), _free( ), _alarm( ), and _signal( ), so that the compiler can use your own implementation.

6.1. Step 1 toward the midpoint report (due on 2nd class date in week 8)

Step 1 intends to understand and develop the following two features:

(1) The reset sequence from the assembly language level all the way to main( ) in C which calls back down to stdlib.s in the assembly language level.

startup_tm4c129.s → main( ) in driver.c → stdlib.s

Your actual work on Keil uVersion is summarized below in table 10.

Table 10: Keil uVersion work toward the midpoint report

Files you will work on	Tasks
startup_tm4c129.s	Revise the Reset_Handler routine as follows: - Set up and switch PSP (Process Stack Pointer) - Call __main.

driver_keil.c	Comment out the two while-loops, so that main( ) can complete with your stdlib.s partial implementation.
stdlib.s	bzero and strcpy: Receive arguments from main( ), based on APCS, and complete the entire implementation within stdlib.s. malloc, free, signal, and alarm: Receive arguments from main( ), based on APCS, but does nothing by simply returning back to main( ).

In Keil uVersion, start the debugger and take a memory snap of stringA and stringB after an execution.

(2) A C-based implementation of the buddy memory allocation

Use driver_cpg.c that calls _malloc( ) and _free( ) in heap.c. You can also find heap_template.c in Canvas→files→final project folder. This is a template that hopefully makes it easy for you to implement the buddy memory allocation in C. Your C implementation must use a recursion. When you complete your C programs, rename this file "heap.c". Table 11 summarizes your C implementation in step 1.

Table 11: Linux C programming work toward the midpoint report

Files you will work on	Tasks
driver_cpg.c	No need to change. But, if you like, you can include more printf or test statements.
heap.c	_malloc( ) and _free( ) in heap.c will internally call _kinit( ), _kalloc( ), and _kfree( ). As mentioned in section 4.3, _kalloc( ) and _kfree( ) will use recursive _ralloc( ) and _rfree( ) helper functions. In your step 2, _kinit( ), _kalloc( ), _ralloc( ), _kfree( ), and _rfreee( ) will be implemented in ARM/THUMB-2 in heap.s.

Compile and run with:
gcc *.c
a.out

Submission Items:
Please submit the following materials listed in table 12.

Table 12: Step-1 Submission

Materials	Remarks	Grade points (out of 25pts)
startup_tm4c129.s	From your Keil uVersion project	2pts
stdlib.s	From your Keil uVersion project	5pts
Two memory snapshots: stringA and stringB	From your Keil uVersion project	4pts
heap.c	From your Linux C program	10pts
a.out execution results	From your Linux C execution	4pts

6.2. Step 2 toward the final report (due on 2nd class date in week 11, i.e., final's week)

After the midpoint report, the professor will disclose startup_tm4c129.s, stdlib.s, and heap.c. You may refer to and use them to continue working on the rest of your final project. Step 2 intends to complete all assembly components in ARM/THUMB-2. Your work items in step 2 are summarized below in table 13.

Table 13: Step-2 Work Items

Files you will work on	Tasks
startup_tm4c129.s	Correct the Reset_Handler routine if necessary, (based on the midpoint report feedback). Thereafter add subroutine calls such as: - _kinit: initialization in heap.s - _timer_init: initialization in timer.s - _systemcall_table_init: initialization in svc.s (table 4 in section 3.2.(2)) Implement the following two routines: - SVC_Handler: invoke _system_call_table_jump in svc.s - SysTick_Handler: invoke _timer_update in timer.s
driver_keil.c	No more comment-out of the two while-loops. We entirely run driver_keil.c.
stdlib.s	bzero and strcpy: Correct them if necessary, (based on the midpoint report feedback). malloc, free, signal, and alarm: Receive arguments from main( ), based on APCS and rely each call to SVC_Handler.
svc.s	Refer to section 3.2.(2). Based on the system call # in R7, jump to the corresponding function through the system call jump table in table 4.
heap.s	Implement the following 5 routines, based on your C implementation in heap.c. _kinit: mcb initialization _kalloc: the entry point to invoke the _ralloc recursive helper function _ralloc: a recursive helper function to allocate a space _kfree: the entry point to invoke the _rfree recursive helper function _rfree: a recursive helper function to free the space and merge the buddy space if possible
timer.s	Implement the following 4 routines, based on the specification in section 5. _timer_init: initialize SysTick. _timer_start: start SysTick. _timer_update: decrement seconds at 0x2000.7B80 and invokes *func at 0x2000.7B84. _signal_handler: register a user-provided *func at 0x2000.7B84.

Test all your assembly language implementation with driver_keil.c on Keil uVersion's debugger session. Take all memory snapshots of mcb addresses corresponding to mem1 – mem8 upon their allocation and deallocation as well as mem9's contents that should change from 1 to 2 and from 2 to 3.

Submission Items:
Please submit the following materials listed in table 14.

Table 14: Step-2 Submission

Materials	Remarks	Grade points (out of 75pts)
Your zipped Keil uVersion project (35pts)	startup_tm4c129.s (5pts) Reset_Handler SVC_Handler SysTick_Handler	 1pt 2pts 2pts
	driver_keil.c	
	stdlib.s (6pts) _bzero( ) _strncpy( )	 1pt 1pt

	_malloc( ) _free( ) _alarm( ) _signal( )	1pt 1pt 1pt 1pt
	svc.s (3pts) _systemcall_table_init( ) _systemcall_table_jump( )	 1pt 2pts
	heap.s (16pts) _kinit( ) _kalloc( ) _ralloc( ) _kfree( ) _rfree( )	 2pts 1pt 6pts 1pt 6pts
	timer.s (5pts) _timer_init( ) _timer_start( ) _timer_update( ) _signal_handler( )	 1pt 1pts 2pts 1pts

Execution snapshots (26pts)	_strncpy(stringB, stringA, 40);
	_bzero(stringA, 40);
	void* mem1 = _malloc(1024);
	void* mem2 = _malloc(1024);
	void* mem3 = _malloc(8192);
	void* mem4 = _malloc(4096);
	void* mem5 = _malloc(512);
	void* mem6 = _malloc(1024);
	void* mem7 = _malloc(512);
	_free(mem6);
	_free(mem5);
	_free(mem1);
	_free(mem7);
	_free(mem2);
	void* mem8 = _malloc(4096);
	_free(mem4);
	_free(mem3);
	_free(mem8);
	
	alarmed = (int *)_malloc(32);
	*alarmed = 1;
	_signal(SIG_ALRM, sig_handler1);
	_alarm(2);
	while (*alarmed != 2) {
	    void* mem9 = _malloc(32);
	        _free(mem9);
	    }
	
	_signal(SIG_ALRM, sig_handler2);
	_alarm(3);
	while (*alarmed != 3) {
	    void* mem9 = _malloc(4);
		1pt
		1pt
		1pt
		1pt
		1pt
		1pt
		1pt
		1pt
		1pt
		1pt
		1pt
		1pt
		1pt
		1pt
		1pt
		1pt
		1pt
		1pt
		
		1pt
		1pt
		1pt
		1pt
		
		1pt
		1pt

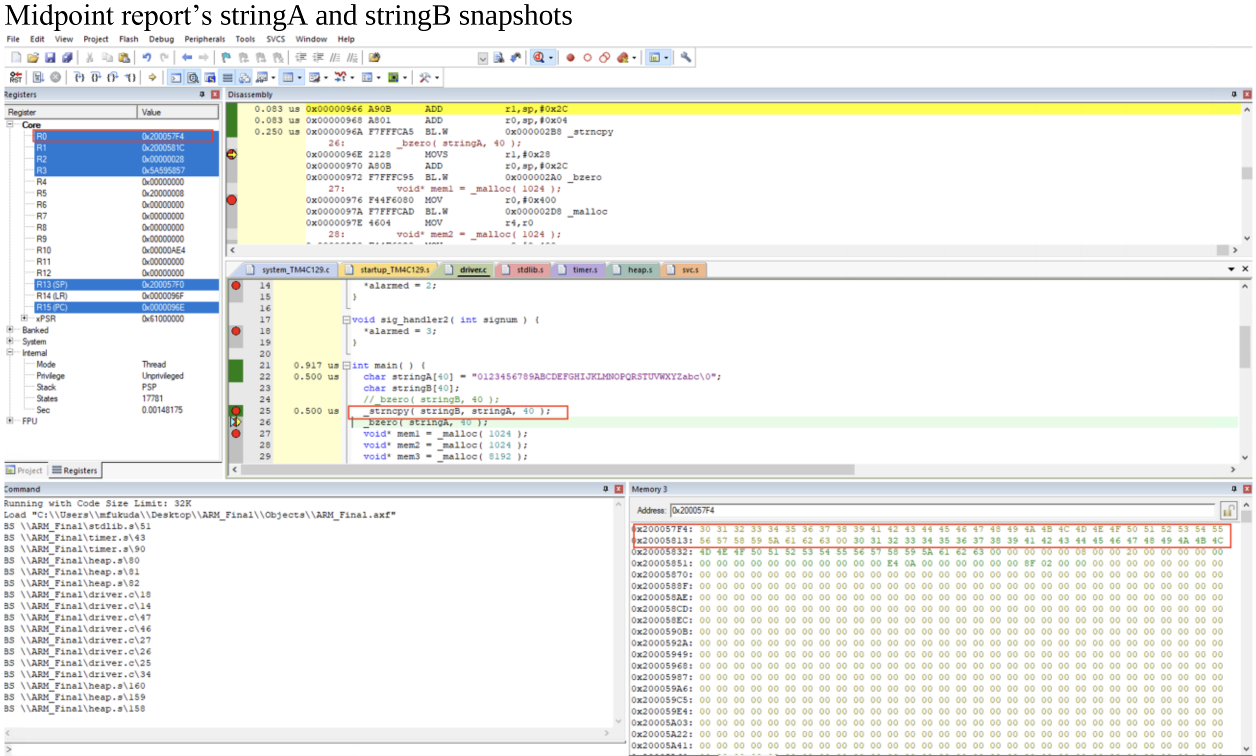
	_free(mem9);
	}
	
	void sig_handler1(int signum) {
	*alarmed = 2;
	}
	
	void sig_handler2(int signum) {
	*alarmed = 3;
	}
		
		1pt
		
		1pt

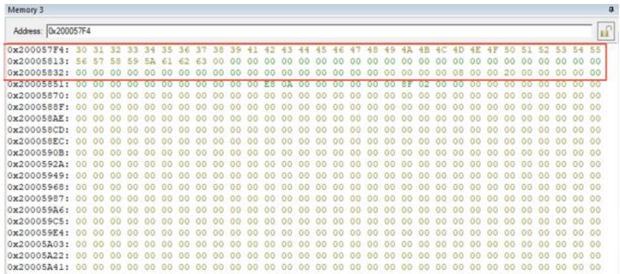
Documentation (14pts)	A two-page summary of your implementation - Narratives o What you implemented. o What was missing. - Any Diagrams (at least one)	 6pts 6pts 2pts
Extra credits (5pts)	If you implemented additional stdlib functions in ARM/THUMB-2, please write about them and highlight your narratives in our documentation.	

6.3. Execution Snapshots

To clarify what you need to turn in execution results, sample snapshots from the key answer are given below. Don't reuse them. **Any reuse of these snapshots below will result in an academic misconduct.**

(a) Midpoint report's stringA and stringB snapshots



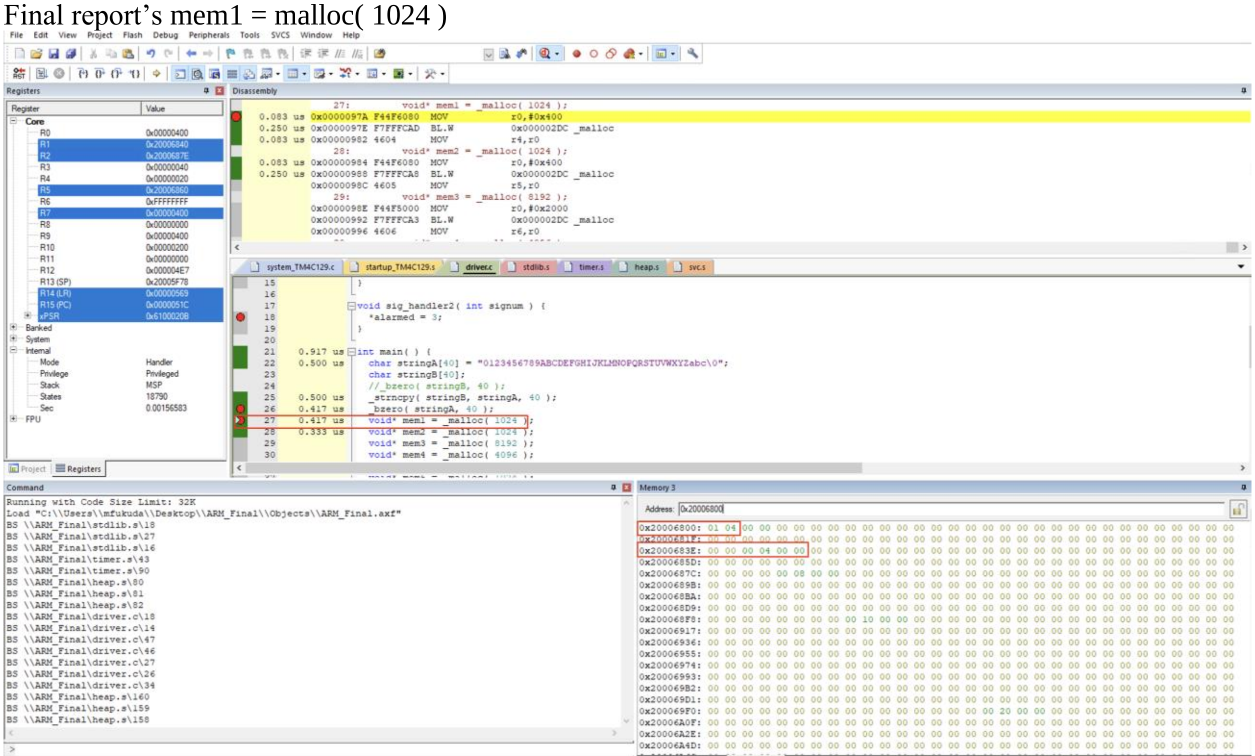


(b) Midpoint report's a.out's outputs

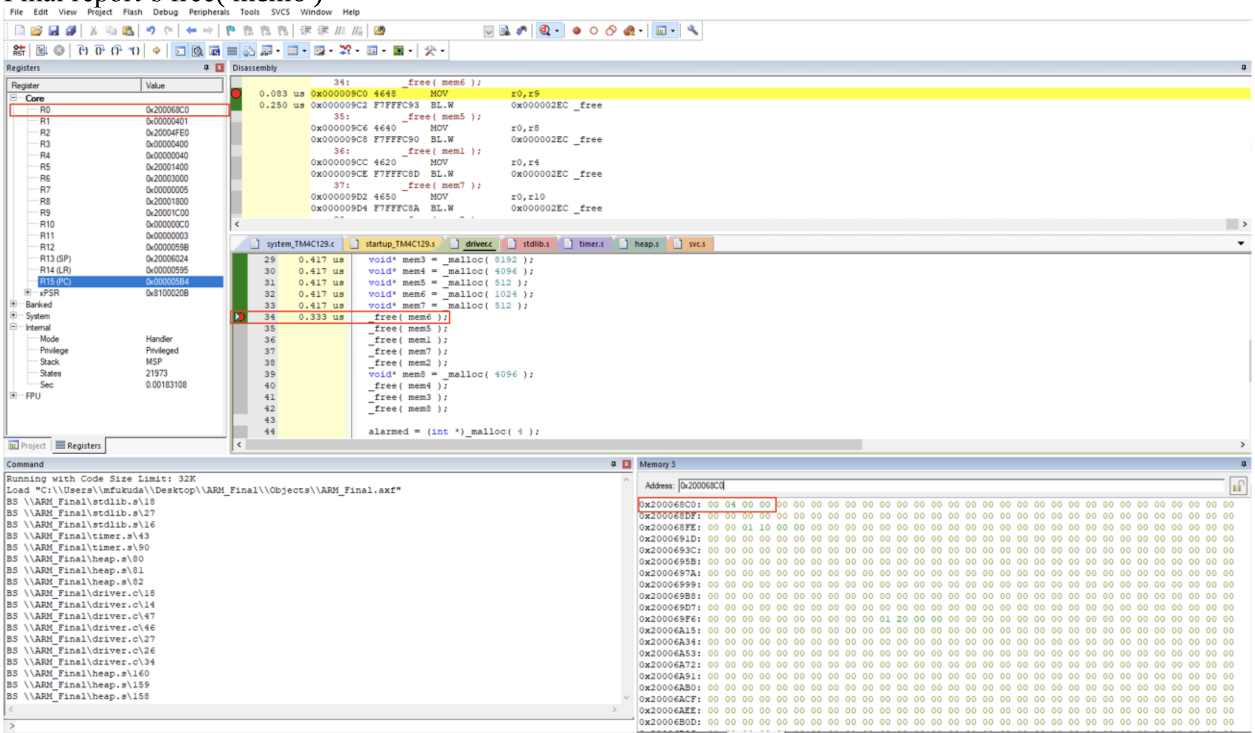
```
andromeda:C_Programs munehiro$ ./driver_cpg

0123456789ABCDEFGHIJKLMNOPQRSTUVWXYZabc
mem1 = 20001000
mem2 = 20001400
mem3 = 20003000
mem4 = 20002000
mem5 = 20001800
mem6 = 20001c00
mem7 = 20001a00
mem8 = 20001000
andromeda:C_Programs munehiro$ 
```

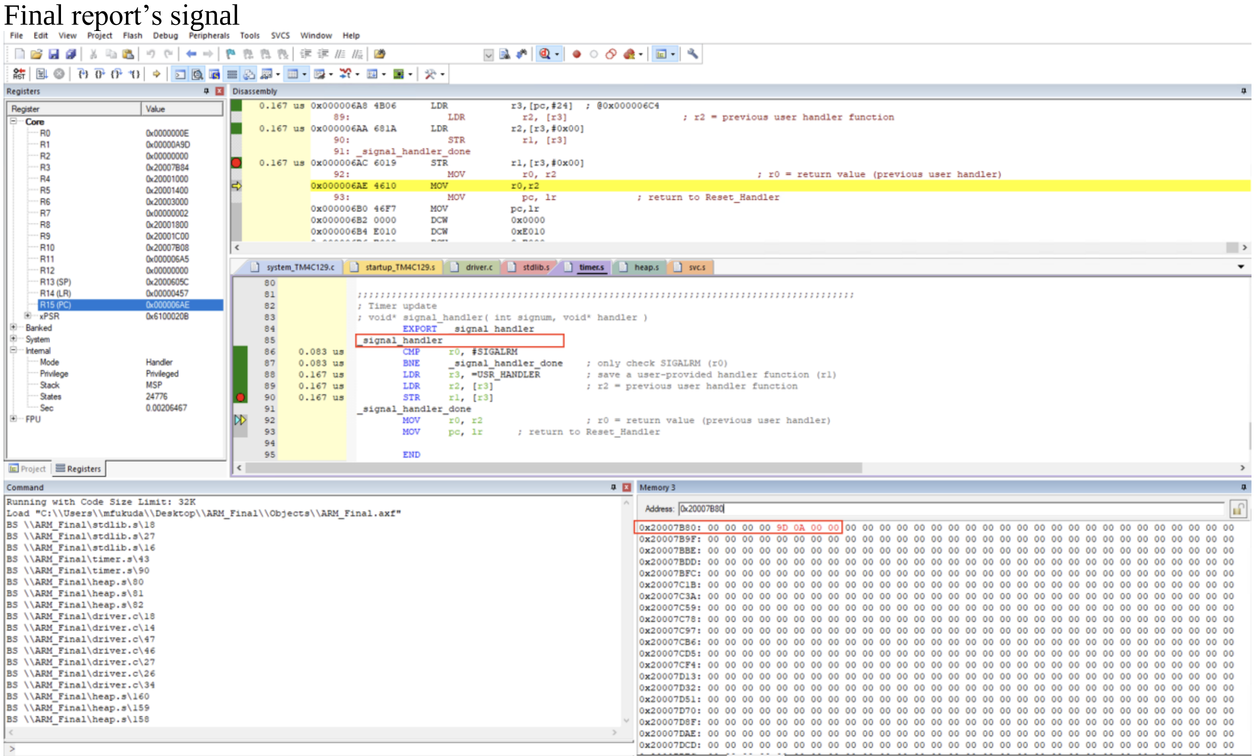
(c) Final report's mem1 = malloc(1024)



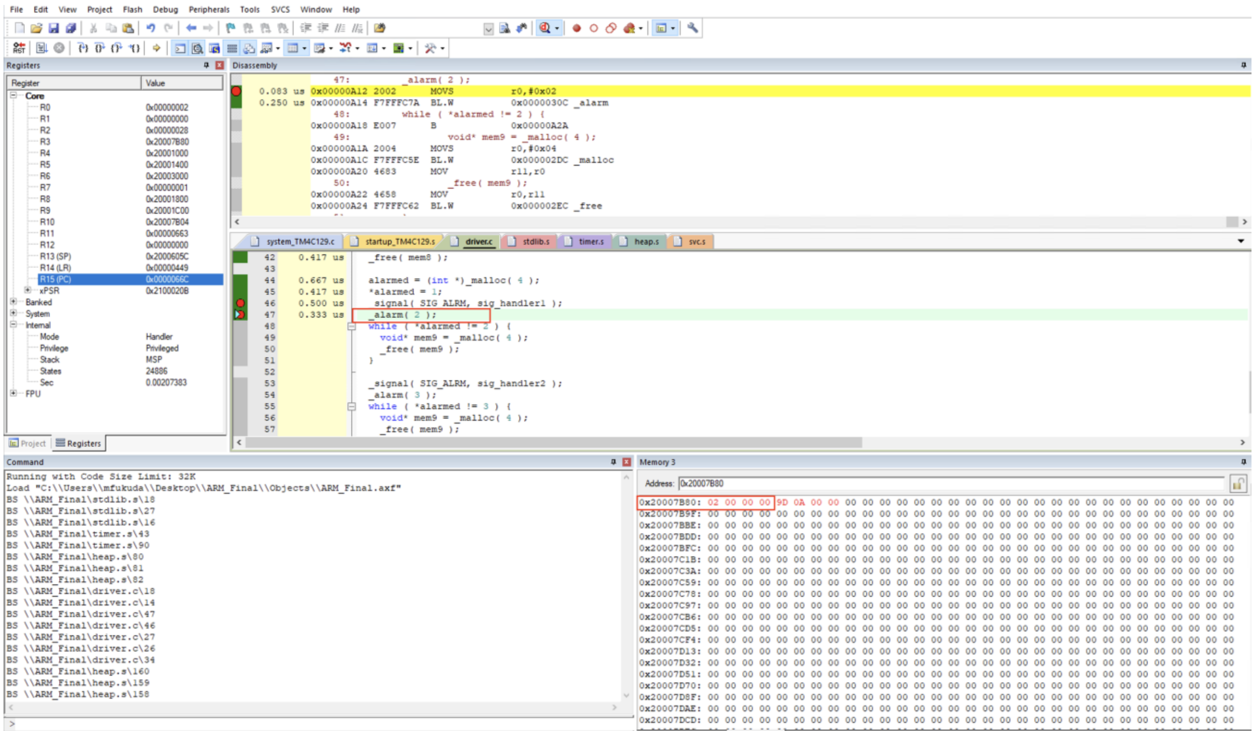
(d) Final report's free(mem6)



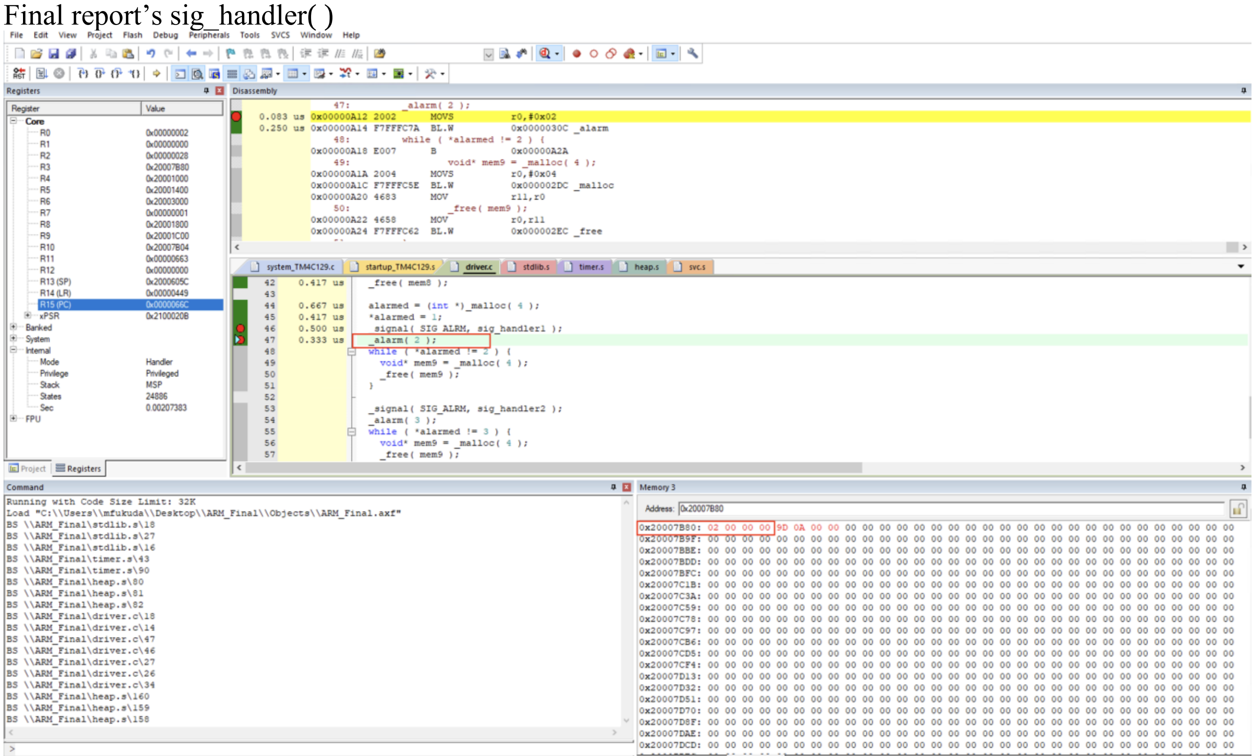
(e) Final report's signal



(f) Final report's alarm



(g) Final report's sig_handler( )



7. Final notes

(1) Follow the final project specification.

   a. Use the memory spaces exactly specified in this document.
   b. Use the function and routine names specified in this document.
   c. Attach the execution results as specified in this document (see tables 12 and 14).

(2) Start your implementation early and keep up your plan.