Exercise 3: Threading, Tasking and Real Time Synchronization

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March 5th, 2016

Problem 1

3 points of Priority Inheritance

- Lemma 6 is huge because it tells us that a job can be blocked at most 1 time per semaphore it uses. This is key because the blocking time for each semaphore must be bounded assuming no job has infinite execution. This overall leads to a job that has a finite upper bound on its blocking time.
- Lemma 9 is an essential point of the priority ceiling protocol because it states that there can never be transitive blocking with this protocol. Thus, a job at low priority will be immediately pushed to the highest priority of all jobs it could block for any given semaphore.
- Lemma 11 is interesting, stating that a higher priority job can be blocked by a lower priority one for at most the duration of one critical section of all of the lower priority tasks critical sections

Position on Linux Priority Inheritance

Our group will be taking the opinion that Linux Priority Inheritance is a good thing, and can be extremely useful depending on the application. While Linus Torvalds seems to take the position that any priority inversion problem can be solved without Priority Inheritance, that is unrealistic in a development sense. The fact of the matter is that Priority Inheritance solves the problem of Priority Inversion. The main problem with Priority Inversion is that it gives a low priority task high priority. In Linux this might be bad because the low priority task could potentially write to locations where they shouldn't normally. That is overcome by running code in user space, and never giving high enough priority to a task so that it overwrites kernal space memory. The only other reason that Priority Inheritance is bad is because there are potentially other implementations that don't even require it. If one didn't use blocking then this would never happen, but that requires one to give each function a copy of the memory it works on which isn't efficient. It is generally possible to write code where Priority Inversion never happens, but that may require significant extra testing and work. By solving the problem with Priority Inheritance, we give a solution that, despite its drawbacks, can be made to work better and more easily than other solutions, which is what engineering is all about.

Does PI_Futex Fix it?

The PI_Futex does prevent a high priority task from unbounded priority inversion in the user space. By implementing the PI_Futexs largely the same as normal Futexs for the fast path, while not invoking any kernel calls for the short path, Ingo Molnar has made a safe implementation of Priority Inheritance locking. Similarly, the implementation for slow lock uses a minimal amount of kernel calls while looking up the priority of the highest waiting task. Overall, it seems like a very good implementation, but it isn't in the kernel.

Problem 2

Thread-Safe, and Reentrant

Thread-safe functions are functions that only ever access shared data safely, this means multiple calls to this function at the same time won't have any negative effect. A reentrant function is one that can be interrupted or preempted and then called again safely without finishing execution of the original call.

Three Solutions

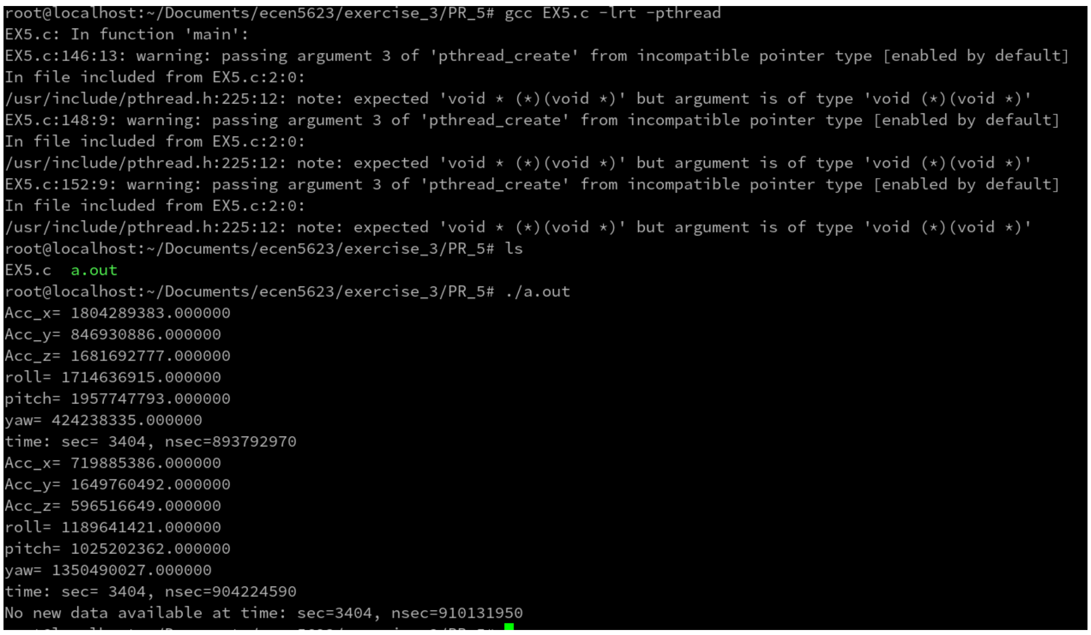
The first method of accomplishing this is by only using stack variables,and not using global data or dynamic memory. To do this, every single function must be passed all of the data it needs and must return all of the data it processes probably in the form of pointers to structures. It is often cumbersome to do this, and could potentially lead to over-sized structures getting passed in unnecessarily. The real issue is that one must copy all of the data every time a function call is made, which is extremely inefficient. Since the variables are declared locally to a function, it is thread safe as each thread working on the function will have a local copy of the variable unlike a global variable declaration which would result in race condition. But the threads must be executed in order (with proper priority assigned to each thread) so that we do not face issues with data forwarding.

The problem with the second method would be synchronization between threads. If the threads need to share data, then a shared memory has to be used again with semaphores and mutexs. Care must be taken in assigning priorities to each thread. Transferring data from global memory for the computation will result in lesser throughput due to high latency. Since the data is thread indexed, one is either going to have to make many copies of the same memory or implement proper locking mechanisms to prevent shared memory errors.

The final method of accomplishing this is to use shared memory global data, but to use locking mechanisms to synchronize access. This method can be implemented with semaphores and mutexs like the POSIX standard ones. The idea is to allow only one thread to work on the shared memory at a time by implementing a type of counter (note mutexs and semaphores aren't necessarily implemented as counters). If that counter is zero then that thread must wait, if it is one or more than it can execute on the shared memory. It does have drawbacks, like unbounded priority inversion or unbounded blocking, but these can generally be overcome fixed with proper coding techniques.

An Implementation with Pthreads

Here is a screencapture of our implementation of code to randomly generate data and a timestamp in one thread and then print it out safely in another. A makefile is included in the folder PR_2 that allows one to build and clean this.



```
root@localhost:~/Documents/ecen5623/exercise_3/PR_5# gcc EX5.c -lrt -pthread
EX5.c: In function 'main':
EX5.c:146:13: warning: passing argument 3 of 'pthread_create' from incompatible pointer type [enabled by default]
In file included from EX5.c:2:0:
/usr/include/pthread.h:225:12: note: expected 'void * (*)(void *)' but argument is of type 'void (*)(void *)'
EX5.c:148:9: warning: passing argument 3 of 'pthread_create' from incompatible pointer type [enabled by default]
In file included from EX5.c:2:0:
/usr/include/pthread.h:225:12: note: expected 'void * (*)(void *)' but argument is of type 'void (*)(void *)'
EX5.c:152:9: warning: passing argument 3 of 'pthread_create' from incompatible pointer type [enabled by default]
In file included from EX5.c:2:0:
/usr/include/pthread.h:225:12: note: expected 'void * (*)(void *)' but argument is of type 'void (*)(void *)'
root@localhost:~/Documents/ecen5623/exercise_3/PR_5# ls
EX5.c  a.out
root@localhost:~/Documents/ecen5623/exercise_3/PR_5# ./a.out
Acc_x= 1804289383.000000
Acc_y= 846930886.000000
Acc_z= 1681692777.000000
roll= 1714636915.000000
pitch= 1957747793.000000
yaw= 424238335.000000
time: sec= 3404, nsec=893792970
Acc_x= 719885386.000000
Acc_y= 1649760492.000000
Acc_z= 596516649.000000
roll= 1189641421.000000
pitch= 1025202362.000000
yaw= 1350490027.000000
time: sec= 3404, nsec=904224590
No new data available at time: sec=3404, nsec=910131950
```

Figure 1: Code that writes and reads some data safely

Problem 3

Deadlock

Deadlock is what happens when threads are looking for more than one shared piece of memory. If one thread takes shared memory A, and another thread takes shared memory B, then the first thread asks for shared memory B and the second thread asks for shared memory A execution of each thread will stop indefinitely. One solution to this, known as random backoff, is to give up the resource a thread owns when it tries and fails to get the other resource. Then, wait a psuedo-random amount of time, and try to grab each resource again. In that period of wait time the other thread will hopefully get both pieces of memory and finish with shared memory. This is what we implemented on the deadlock code given to us for the problem.

Priority Inversion

Priority Inversion is another effect of having multiple priority level tasks/services and shared resources. When a low priority and high priority task both share data, the low priority task might end up blocking the high priority task. Basically, the low priority task will have the shared memory and be executing on it, the high priority task will need to wait for that to finish, but a medium priority task could preempt the low priority task and force the high priority task to wait for many lower priority tasks to finish while waiting for the shared memory. This kind of inversion was demonstrated by the code given to us and can be seen running below.

Linux RT Preempt Patch

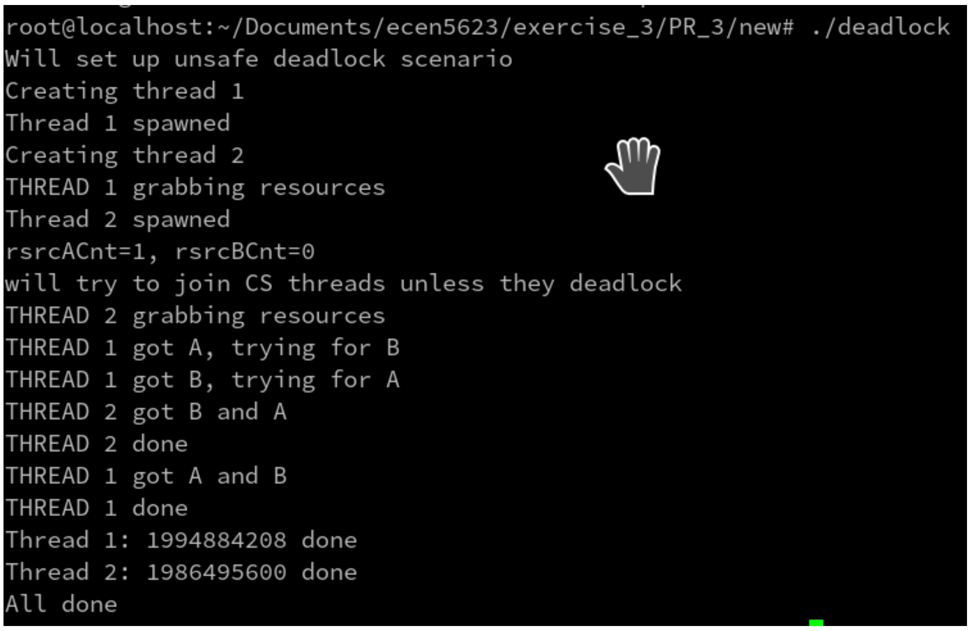
The Linux real-time preempt patch is a patch that exists to fix the issues of Linux only being able to meat soft real-time deadlines. This patch attempts to address priority inversion by creating priority inheritance. This means that when a high priority thread is blocked because a low priority thread is using shared memory the low priority thread will inherit the high priority thread's priority for the duration of its use of shared memory. Thus, the low priority thread can no longer be preempted by medium priority ones.

This method does address the unbounded priority inversion because the high priority thread can no longer be stuck behind infinite medium priority threads. With this technique, the high priority thread is blocked for only the duration the low priority thread is using shared memory. The downside of this technique is that the low priority thread gets high priority for much of its execution, which isn't necessarily desirable. If the high priority thread is using the shared memory of an even higher priority thread, the low priority thread could even be pushed all the way up to that higher priority. A developer might pursue a different implementation where the low priority thread simply never executes its critical section if it would preempt in any way the higher priority thread. A system like that might limit blocking time for high priority tasks, but would likely be harder to implement. That is where something like priority inversion becomes useful. While it doesn't address the entire issue of priority inversion it does address the problem of unbounded priority inversion.

The question of switching to a RTOS because of the problems of priority inversion in Linux is an interesting one. A RTOS might address the issues of priority inversion a lot better than Linux does even with the preempt patch, but probably does not come with the same community and sheer amount of code that has gone into Linux. For projects from companies where much of the code will be written from scratch anyway, a RTOS will probably be the better solution because it is more specifically tailored to real-time applications than Linux will ever be. On the other hand, Linux does provide a lot of non-embedded system tools that might be extraordinarily useful for some applications.

Deadlock and PI Code Running

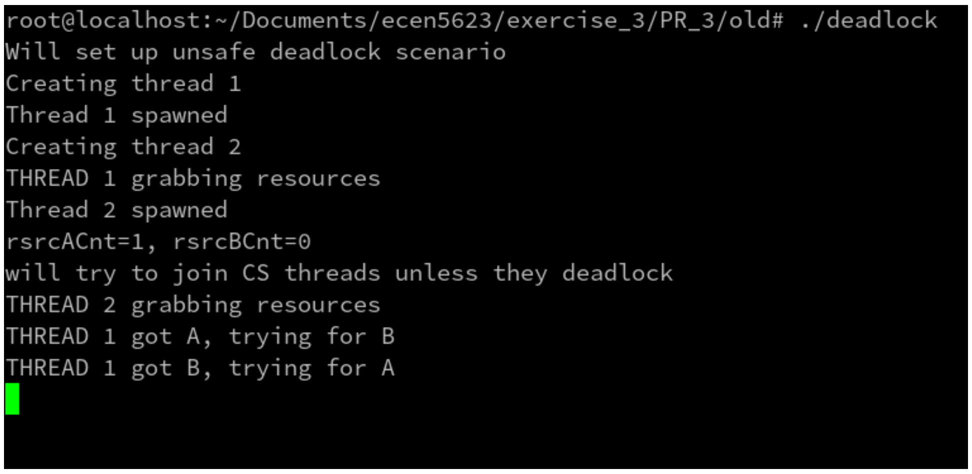
Here is the proof of execution of our code to fix the deadlock with a random backoff scheme. There is a makefile in the PR_2/new folder which will allow one to run this code after running ./deadlock as an executable.



```
root@localhost:~/Documents/ecen5623/exercise_3/PR_3/new# ./deadlock
Will set up unsafe deadlock scenario
Creating thread 1
Thread 1 spawned
Creating thread 2
THREAD 1 grabbing resources
Thread 2 spawned
rsrcACnt=1, rsrcBCnt=0
will try to join CS threads unless they deadlock
THREAD 2 grabbing resources
THREAD 1 got A, trying for B
THREAD 1 got B, trying for A
THREAD 2 got B and A
THREAD 2 done
THREAD 1 got A and B
THREAD 1 done
Thread 1: 1994884208 done
Thread 2: 1986495600 done
All done
```

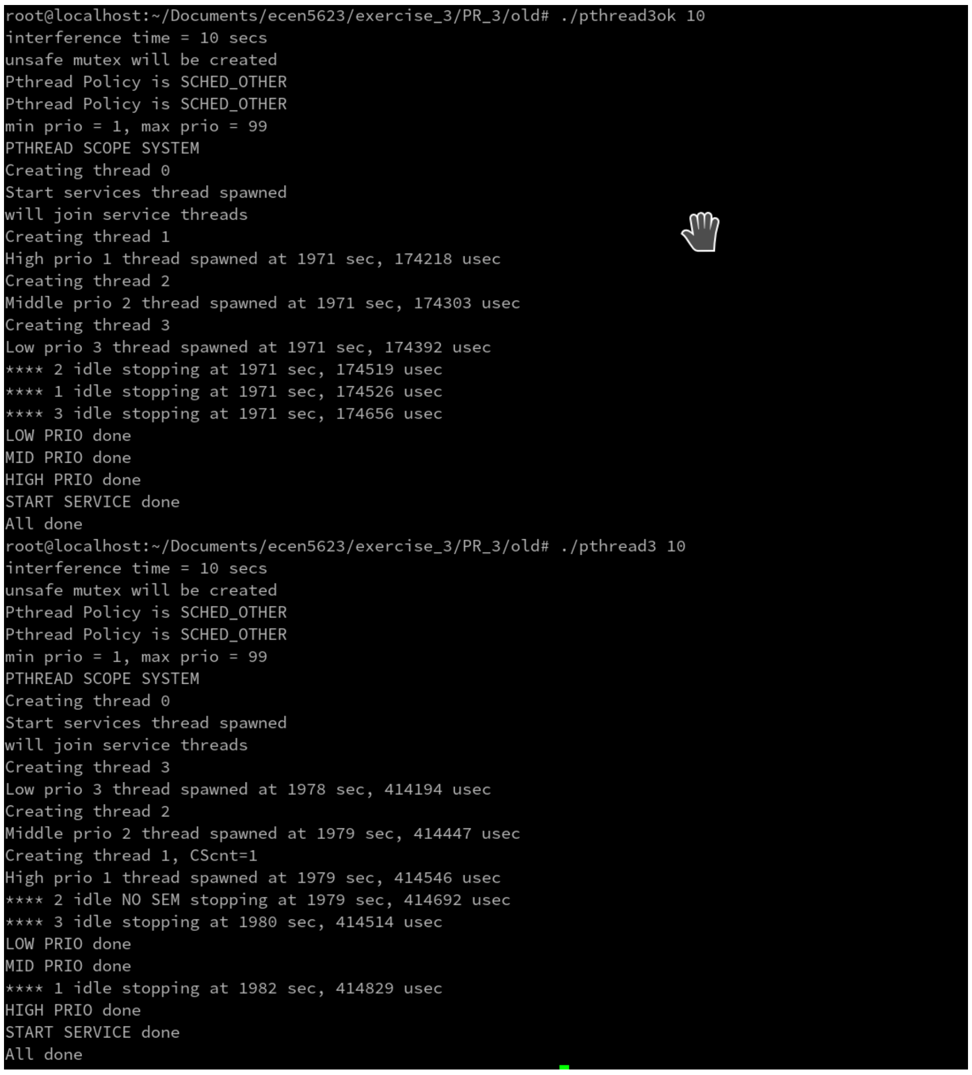
Figure 2: Here is the fixed deadlock code executing

Additionally, we built and ran the original code, located in PR_2/old. Here are screenshots of that running on the DE1.



```
root@localhost:~/Documents/ecen5623/exercise_3/PR_3/old# ./deadlock
Will set up unsafe deadlock scenario
Creating thread 1
Thread 1 spawned
Creating thread 2
THREAD 1 grabbing resources
Thread 2 spawned
rsrcACnt=1, rsrcBCnt=0
will try to join CS threads unless they deadlock
THREAD 2 grabbing resources
THREAD 1 got A, trying for B
THREAD 1 got B, trying for A
```

Figure 3: original deadlock code deadlocking



```
root@localhost:~/Documents/ecen5623/exercise_3/PR_3/old# ./pthread3ok 10
interference time = 10 secs
unsafe mutex will be created
Pthread Policy is SCHED_OTHER
Pthread Policy is SCHED_OTHER
min prio = 1, max prio = 99
PTHREAD SCOPE SYSTEM
Creating thread 0
Start services thread spawned
will join service threads
Creating thread 1
High prio 1 thread spawned at 1971 sec, 174218 usec
Creating thread 2
Middle prio 2 thread spawned at 1971 sec, 174303 usec
Creating thread 3
Low prio 3 thread spawned at 1971 sec, 174392 usec
**** 2 idle stopping at 1971 sec, 174519 usec
**** 1 idle stopping at 1971 sec, 174526 usec
**** 3 idle stopping at 1971 sec, 174656 usec
LOW PRIO done
MID PRIO done
HIGH PRIO done
START SERVICE done
All done
root@localhost:~/Documents/ecen5623/exercise_3/PR_3/old# ./pthread3 10
interference time = 10 secs
unsafe mutex will be created
Pthread Policy is SCHED_OTHER
Pthread Policy is SCHED_OTHER
min prio = 1, max prio = 99
PTHREAD SCOPE SYSTEM
Creating thread 0
Start services thread spawned
will join service threads
Creating thread 3
Low prio 3 thread spawned at 1978 sec, 414194 usec
Creating thread 2
Middle prio 2 thread spawned at 1979 sec, 414447 usec
Creating thread 1, CScnt=1
High prio 1 thread spawned at 1979 sec, 414546 usec
**** 2 idle NO SEM stopping at 1979 sec, 414692 usec
**** 3 idle stopping at 1980 sec, 414514 usec
LOW PRIO done
MID PRIO done
**** 1 idle stopping at 1982 sec, 414829 usec
HIGH PRIO done
START SERVICE done
All done
```

Figure 4: Both sets of pthread code executing

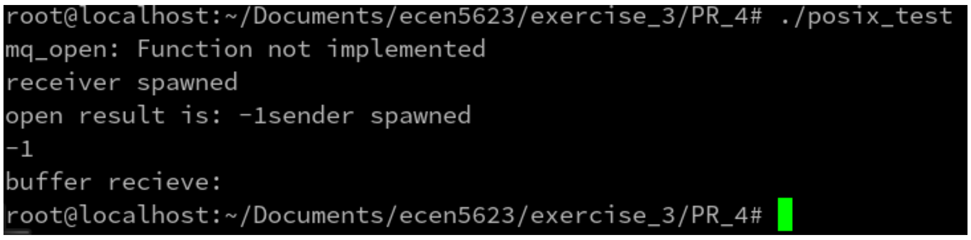
Problem 4

Message Queues and Global Memory Sharing

Message queues prevent the problem of unbounded priority inversion as the enqueue and dequeue operations are thread safe. It services messages in the order of priority and guarantees message delivery in a timely fashion. Therefore a low priority task cannot be preempted by a medium priority task. So the higher priority task waiting on the lower priority task waits for deterministic amount of time thus avoiding unbounded priority inversion.

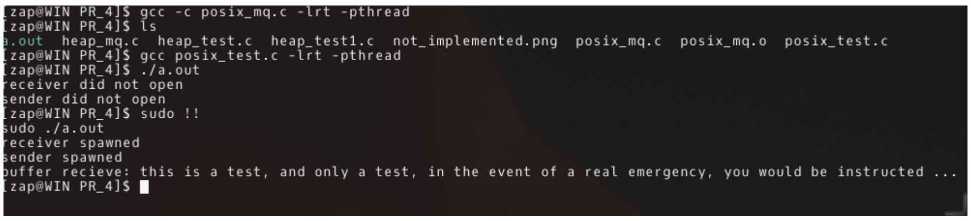
Fixing and Running Old Code

We never ended up having time to fix the heap_mq.c implementation properly as can be seen by trying to compile and run it. It works kind of, but ends up crashing. Additionally, neither of these sets of code ran on the DE1 board because the mqueue library was not implemented as can be seen in figure 5. A makefile is included which will build this code properly on both a normal linux install and the DE1, but mqueue functions aren't actually implemented on Lubuntu for the DE1. This was checked using the perror, error message.



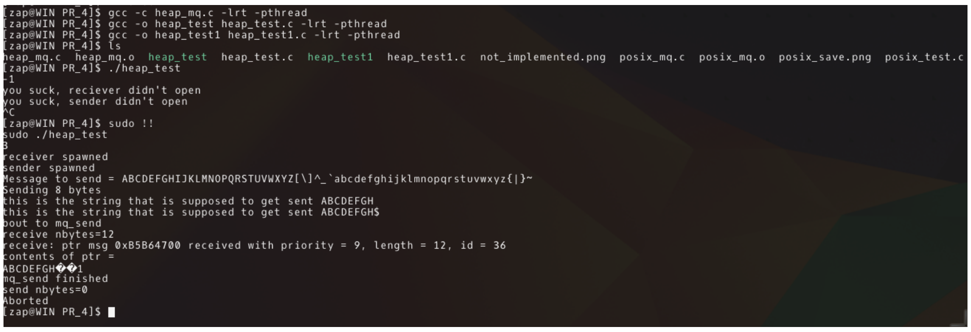
```
root@localhost:~/Documents/ecen5623/exercise_3/PR_4# ./posix_test
mq_open: Function not implemented
receiver spawned
open result is: -1sender spawned
-1
buffer recieve:
root@localhost:~/Documents/ecen5623/exercise_3/PR_4#
```

Figure 5: Functions are declared but not implemented on DE1



```
[zap@WIN PR_4]$ gcc -c posix_mq.c -lrt -pthread
[zap@WIN PR_4]$ ls
a.out  heap_mq.c  heap_test.c  heap_test1.c  not_implemented.png  posix_mq.c  posix_mq.o  posix_test.c
[zap@WIN PR_4]$ gcc posix_test.c -lrt -pthread
[zap@WIN PR_4]$ ./a.out
receiver did not open
sender did not open
[zap@WIN PR_4]$ sudo !!
sudo ./a.out
receiver spawned
sender spawned
buffer recieve: this is a test, and only a test, in the event of a real emergency, you would be instructed ...
[zap@WIN PR_4]$
```

Figure 6: The posix message queue compiling and running on a Linux install



```
[zap@WIN PR_4]$ gcc -c heap_mq.c -lrt -pthread
[zap@WIN PR_4]$ gcc -o heap_test heap_test.c -lrt -pthread
[zap@WIN PR_4]$ gcc -o heap_test1 heap_test1.c -lrt -pthread
[zap@WIN PR_4]$ ls
heap_mq.c  heap_mq.o  heap_test  heap_test.c  heap_test1  heap_test1.c  not_implemented.png  posix_mq.c  posix_mq.o  posix_save.png  posix_test.c
[zap@WIN PR_4]$ ./heap_test
-1
you suck, reciever didn't open
you suck, sender didn't open
^C
[zap@WIN PR_4]$ sudo !!
sudo ./heap_test
3
receiver spawned
sender spawned
Message to send = ABCDEFGHIJKLMNOPQRSTUVWXYZ[\]^_`abcdefghijklmnopqrstuvwxyz{|}~
Sending 8 bytes
this is the string that is supposed to get sent ABCDEFGH
this is the string that is supposed to get sent ABCDEFGH$
bout to mq_send
receive nbytes=12
receive: ptr msg 0xB5B64700 received with priority = 9, length = 12, id = 36
contents of ptr =
ABCDEFGH��1
mq_send finished
send nbytes=0
Aborted
[zap@WIN PR_4]$
```

Figure 7: The heap message queue compiling and failing to run properly on a Linux install

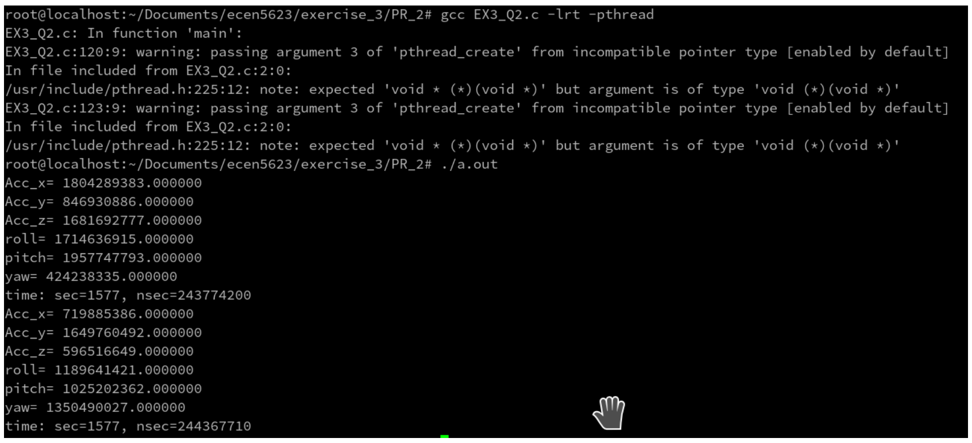
Problem 5

Linux Watchdog Timer

The Linux Watchdog Timer is used by the Linux Watchdog Daemon to act as stand-alone system monitor. The watchdog daemon for Linux can be configured to periodically run several basic tests to verify that the system is functioning properly.It opens /dev/watchdog, and keeps writing to it every minute or so to keep the kernel from resetting.When a deadlock occurs, then the watchdog will not be serviced and the system will be reset, thus coming out of deadlock situation. But the system might get into a live lock, a situation where the system gets into a deadlock after coming out of reset.

Problem 2 Code Adaptation

Here is the adaption showing a mutex_timedlock for sharing data. It prints that no new data is ready after 10 seconds of waiting and exits when it finally does get the data.



```
root@localhost:~/Documents/ecen5623/exercise_3/PR_2# gcc EX3_Q2.c -lrt -pthread
EX3_Q2.c: In function 'main':
EX3_Q2.c:120:9: warning: passing argument 3 of 'pthread_create' from incompatible pointer type [enabled by default]
In file included from EX3_Q2.c:2:0:
/usr/include/pthread.h:225:12: note: expected 'void * (*)(void *)' but argument is of type 'void (*)(void *)'
EX3_Q2.c:123:9: warning: passing argument 3 of 'pthread_create' from incompatible pointer type [enabled by default]
In file included from EX3_Q2.c:2:0:
/usr/include/pthread.h:225:12: note: expected 'void * (*)(void *)' but argument is of type 'void (*)(void *)'
root@localhost:~/Documents/ecen5623/exercise_3/PR_2# ./a.out
Acc_x= 1804289383.000000
Acc_y= 846930886.000000
Acc_z= 1681692777.000000
roll= 1714636915.000000
pitch= 1957747793.000000
yaw= 424238335.000000
time: sec=1577, nsec=243774200
Acc_x= 719885386.000000
Acc_y= 1649760492.000000
Acc_z= 596516649.000000
roll= 1189641421.000000
pitch= 1025202362.000000
yaw= 1350490027.000000
time: sec=1577, nsec=244367710
```

Figure 8: Code for problem 5 running on the DE1