Programming RT systems with pthreads

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Outline

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Timing handling in POSIX

- A time value is handled with different data structures and variable times, depending on the use and scope.
- The “most standard” way to store time values for real-time processing is through the timespec structure.

```c
// defined in <time.h>

struct timespec {
    time_t tv_sec;  // seconds
    long tv_nsec;   // nanoseconds
}
```

- `time_t` is usually an integer (32 bits) that stores the time in seconds.
- This data type can store both absolute and relative time values.

Operations with timespec

- It is very common to perform operation on timespec values. Unfortunately, the standard library does not provide any helper function to do such kind of operations.
- An example of two common operation follows (see file time_utils.h and time_utils.c)
**Example**

```c
void timespec_add_us(struct timespec *t, long us)
{
    t->tv_nsec += us * 1000;
    if (t->tv_nsec > 1000000000) {
        t->tv_nsec = t->tv_nsec - 1000000000; // + ms * 1000000;
        t->tv_sec += 1;
    }
}

int timespec_cmp(struct timespec *a, struct timespec *b)
{
    if (a->tv_sec > b->tv_sec) return 1;
    else if (a->tv_sec < b->tv_sec) return -1;
    else if (a->tv_sec == b->tv_sec) {
        if (a->tv_nsec > b->tv_nsec) return 1;
        else if (a->tv_nsec == b->tv_nsec) return 0;
        else return -1;
    }
}
```

**Getting the time**

- To get/set the current time, the following functions are available:

  ```c
  #include <time.h>

  int clock_getres(clockid_t clock_id, struct timespec *res);
  int clock_gettime(clockid_t clock_id, struct timespec *tp);
  int clock_settime(clockid_t clock_id, const struct timespec *tp);
  ```

- These functions are part of the Real-Time profile of the standard
- (in Linux these functions are part of a separate RT library)
- clockid_t is a data type that represents the type of real-time clock that we want to use
Clocks

- `clock_id` can be:
  - `CLOCK_REALTIME` represents the system real-time clock, it is supported by all implementations. The value of this clock can be changed with a call to `clock_settime()`
  - `CLOCK_MONOTONIC` represents the system real-time since startup, but cannot be changed. Not supported in all implementations
  - if `_POSIX_THREAD_CPUTIME` is defined, then `clock_id` can have a value of `CLOCK_THREAD_CPUTIME_ID`, which represents a special clock that measures execution time of the calling thread (i.e. it is increased only when a thread executes)
  - if `_POSIX_THREAD_CPUTIME` it is possible to get a special `clock_id` for a specific thread by calling `pthread_getcpuclockid()`

```c
#include <pthread.h>
#include <time.h>

int pthread_getcpuclockid(pthread_t thread_id, clockid_t *clock_id);
```

sleep functions

- To suspend a thread, we can call the following functions

```c
#include <unistd.h>

unsigned sleep(unsigned seconds);
```

```c
#include <time.h>

int nanosleep(const struct timespec *rqtp, struct timespec *rmtp);
```

- The first one only accepts seconds;
- The second one is part of the POSIX real-time profile and has a high precision (depends on the OS)
- `rqtp` represents the **interval of time** during which the thread is suspended
- if the thread is woke up before the interval has elapsed (for example, because of the reception of a signal), the `clock_nanosleep` will return -1 and the second parameter will contain the remaining time
Example of usage - I

Example of usage - II

The previous example does not work!
Problems

- Once again, it does not work!
  - It could happen that the thread is preempted between calls to clock_gettime and nanosleep!, in this case the interval is not correctly computed
  - The only “clean” solution is to use a system call that performs the above operations atomically

Correct implementation

```c
#include <time.h>

int clock_nanosleep(clockid_t clock_id, int flags,
                     const struct timespec *rqtp,
                     struct timespec *rmtp);
```

- This is the most flexible and complete function for suspending a thread (only available in the POSIX RT profile)
- clock_id is the clock id, usually CLOCK_REALTIME
- flags is used to decide if we want to suspend for a relative amount of time, or until an absolute point in time. It can be TIMER_ABSTIME or 0 to mean relative interval
- rqtp is a pointer to a timespec value that contains either the interval of time or the absolute point in time until which the thread is suspended (depending on the flag value)
- rmtp only makes sense if the flag is 0, in which case if the function is interrupted by a signal it contains the remaining interval of sleeping time
Deadline miss detection

The following code is used to detect a deadline miss (in this case, the behaviour is to abort the thread)
It is possible to specify the policy and the parameters by using the thread attributes before creating the thread.

```
#include <pthread.h>
int pthread_attr_setschedpolicy(pthread_attr_t *a, int policy);
```

**Input arguments:**
- `a`: attributes
- `policy`: can be SCHED_RR, SCHED_FIFO (fixed priority scheduling with or without round-robin) or SCHED_OTHER (standard Linux scheduler).

**IMPORTANT:** to use the real-time scheduling policies, the user id of the process must be root.

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The scheduling policies in POSIX:

- **REAL-TIME PRIORITIES**:
  - SCHED_FIFO or SCHED_RR
  - 100
  - 99
  - 98
  - 97

- **NON REAL-TIME PRIORITIES**:
  - SCHED_OTHER
  - 0
  - -1
  - -39
Example

```c
pthread_t th1, th2, th3;
pthread_attr_t my_attr;
struct sched_param param1, param2, param3;

pthread_attr_init(&my_attr);
pthread_attr_setschedpolicy(&my_attr, SCHED_FIFO);

param1.sched_priority = 1;
param1.sched_priority = 2;
param1.sched_priority = 3;

pthread_attr_setschedparam(&my_attr, &param1);
pthread_create(&th1, &my_attr, body1, 0);

pthread_attr_setschedparam(&my_attr, &param2);
pthread_create(&th2, &my_attr, body2, 0);

pthread_attr_setschedparam(&my_attr, &param3);
pthread_create(&th3, &my_attr, body3, 0);

pthread_attr_destroy(&my_attr);
```

Warning

- It is important to underline that only the superuser (root) can assign real-time scheduling parameters to a thread, for security reasons.
- if a thread with SCHED_FIFO policy executes forever in a loop, no other thread with lower priority can execute.
- All other thread will starve.
Other API

To dynamically thread scheduling and priority, use the following functions:

```c
#include <sched.h>

int sched_setscheduler(pid_t pid, int policy,
                        const struct sched_param *param);
int sched_setparam(pid_t pid, const struct sched_param *param);
```

Input arguments:
- `pid` id of the process (or thread) on which we want to act
- `policy` the new scheduling policy
- `param` the new scheduling parameters (priority)

Mutex generalities

A mutex is a special kind of binary semaphore, with several restrictions:
- It can only be used for mutual exclusion (and not for synchronization)
- If a thread locks the mutex, only the same thread can unlock it!

Advantages:
- It is possible to define RT protocols for scheduling, priority inheritance, and blocking time reduction
- Less possibility for errors
Mutex creation and usage

```c
#include <pthread.h>

pthread_mutex_t m;

int pthread_mutex_init(pthread_mutex_t * m,
                        const pthread_mutex_attr_t * attr);

int pthread_mutex_lock (pthread_mutex_t * mutex);
int pthread_mutex_trylock (pthread_mutex_t * mutex);
int pthread_mutex_unlock (pthread_mutex_t * mutex);
```

- lock corresponds to a wait on a binary semaphore
- unlock corresponds to a post on a binary semaphore
- a mutex can be initialized with attributes regarding the resource access protocol

Example with mutexes

```c
#include <stdio.h>
#include <pthread.h>
#include <semaphore.h>

pthread_mutex_t mymutex;

void *body(void *arg)
{
    int i, j;
    for (j=0; j<40; j++) {
        pthread_mutex_lock(&mymutex);
        for (i=0; i<1000000; i++);
        for (i=0; i<5; i++) fprintf(stderr,(char *)arg);
        pthread_mutex_unlock(&mymutex);
    }
    return NULL;
}
```
Example continued

```c
int main()
{
    pthread_t t1, t2, t3;
    pthread_attr_t myattr;
    int err;
    pthread_mutexattr_t mymutexattr;

    pthread_mutexattr_init(&mymutexattr);
    pthread_mutex_init(&mymutex, &mymutexattr);
    pthread_mutexattr_destroy(&mymutexattr);

    pthread_attr_init(&myattr);
    err = pthread_create(&t1, &myattr, body, (void *)(".");
    err = pthread_create(&t2, &myattr, body, (void *)("#");
    err = pthread_create(&t3, &myattr, body, (void *)("o");
    pthread_attr_destroy(&myattr);

    pthread_join(t1, NULL);
    pthread_join(t2, NULL);
    pthread_join(t3, NULL);

    printf("\n");
    return 0;
}
```

Condition variables

- To simplify the implementation of critical section with mutex, it is possible to use condition variables.
- A condition variable is a special kind of synchronization primitive that can only be used together with a mutex.

```
#include <pthread.h>

int pthread_cond_wait(pthread_cond_t *restrict cond, pthread_mutex_t *restrict mutex);
```

- A call to pthread_cond_wait() is equivalent to:
  - release the mutex
  - block on the condition
  - when unblock from condition, lock the mutex again
Condition variables

- To unblock a thread on a condition

```c
#include <pthread.h>

int pthread_cond_signal(pthread_cond_t *cond);
int pthread_cond_broadcast(pthread_cond_t *cond);
```

- The first one unblocks one thread blocked on the condition
- The second one unblocks all threads blocked in the conditions

More on conditions

- A condition variable is not a semaphore
  - internally, there is a queue of blocked threads
  - however, unlike the semaphore there is no counter
  - hence, if a thread calls pthread_cond_signal and there is no blocked thread on the condition, *nothing happens*
  - Vice-versa, a call to pthread_cond_wait is always a blocking call
Let’s implement a synchronization barrier with mutex and condition variables

- A synch barrier can synchronize up to N thread on one point
- it has only one method, synch()
- the first N-1 threads that call synch() will block, the N-th will unblock all previous threads

```cpp
examples/synch.cpp

class SynchObj {
    pthread_mutex_t m;
    pthread_cond_t c;
    int nblocked;
    int nthreads;
public:
    SynchObj(int n);

    void synch();
};

SynchObj::SynchObj(int n)
{
    nthreads = n;
    nblocked = 0;
    pthread_mutex_init(&m, 0);
    pthread_cond_init(&c, 0);
}
Example continued

```c
void SynchObj::synch()
{
    pthread_mutex_lock(&m);
    nblocked++;

    if (nbocked < nthreads)
        pthread_cond_wait(&c, &m);
    else
    {
        nbocked = 0;
        pthread_cond_broadcast(&c);
    }

    pthread_mutex_unlock(&m);
}
```

Exercise

- Suppose we want to guarantee that a set of N periodic threads are activated at the same time (i.e. their first instance all arrive at the same time)
- When calling pthread_create, the thread is immediately active, so we cannot guarantee synchronicity
- We must implement this behavior manually
  - Every thread, will initially block on a condition
  - when the manager (the main()) calls a function, all threads are waken up at the same time, and get the same value of the arrival time
# Design the data structure

```c
#ifndef __SYNCHPERIODIC_H__
#define __SYNCHPERIODIC_H__

#include <time.h>
#include <pthread.h>

class PeriodicBarrier {
  public:
    // constructor, initialize the object
    PeriodicBarrier(int n);

    // called by the threads for initial synch,
    // returns the same arrival time for all threads
    void wait(struct timespec *a);

    // called by the manager thread
    void start();

  private:
    struct timespec arrival;
    int nthreads;
    int blocked;
    pthread_mutex_t m;
    pthread_cond_t c_threads;
    pthread_cond_t c_manager;
};
#endif
```

# Implementation

```c
#include "synchperiodic.h"

PeriodicBarrier::PeriodicBarrier(int n) :
  nthreads(n), blocked(0)
{
  pthread_mutex_init(&m, 0);
  pthread_cond_init(&c_threads, 0);
  pthread_cond_init(&c_manager, 0);
}

void PeriodicBarrier::wait(struct timespec *a)
{
  pthread_mutex_lock(&m);
  blocked++;
  if (blocked == nthreads)
    pthread_cond_signal(&c_manager);
  pthread_cond_wait(&c_threads, &m);
  *a = arrival;
  pthread_mutex_unlock(&m);
}

void PeriodicBarrier::start()
{
  pthread_mutex_lock(&m);
  if (blocked < nthreads)
    pthread_cond_wait(&c_manager, &m);
  pthread_cond_broadcast(&c_threads);
  clock_gettime(CLOCK_REALTIME, &arrival);
  pthread_mutex_unlock(&m);
}
```
Exercise

- Modify the previous code to add an offset to the periodic threads
- Modify the previous code to add a “stop” mechanism (i.e. the manager thread can stop all periodic threads by pressing a key on the keyboard)
  - Hint: modify the data structure such that the wait() is called every instance, and add a stop() function
Setting protocol attributes

- With mutexes it is possible to set the priority inheritance or priority ceiling protocol
- This can be done on each semaphore separately by using the `pthread_mutexattr_t` attributes

```c
int pthread_mutexattr_getprotocol(const pthread_mutexattr_t * attr, int *restrict protocol);
int pthread_mutexattr_setprotocol(pthread_mutexattr_t *attr, int protocol);
```

- where the protocol can be `PTHREAD_PRIO_NONE`, `PTHREAD_PRIO_INHERIT` or `PTHREAD_PRIO_PROTECT`, for no protocol, priority inheritance or priority ceiling, respectively

Priority Ceiling

- when specifying `PTHREAD_PRIO_PROTECT`, it is necessary to specify the priority ceiling of the mutex with the following function

```c
int pthread_mutexattr_setprioceiling(pthread_mutexattr_t *attr, int prioceiling);
```

- where `prioceiling` is the ceiling of the semaphore
Example with priority inheritance

- In this example, we create 2 mutex semaphores with priority inheritance

```c
pthread_mutexattr_t mymutexattr;

pthread_mutexattr_init(&mymutexattr);
pthread_mutexattr_setprotocol(&mymutexattr, PTHREAD_PRIO_INHERIT);
pthread_mutex_init(&mymutex1, &mymutexattr);
pthread_mutex_init(&mymutex2, &mymutexattr);
pthread_mutexattr_destroy(&mymutexattr);
```

- Notice that we can reuse the same attributes for the 2 semaphores
- Of course, the usage of the mutex remains the same (i.e. `lock()` and `unlock()` where appropriate)

Example with priority ceiling

- In this example, we create 2 mutex semaphores with priority ceiling

```c
pthread_mutexattr_t mymutexattr;

pthread_mutexattr_init(&mymutexattr);
pthread_mutexattr_setprotocol(&mymutexattr, PTHREAD_PRIO_PROTECT);
pthread_mutexattr_setpriocelling(&mymutexattr, 10);
pthread_mutex_init(&mymutex1, &mymutexattr);
pthread_mutexattr_setpriocelling(&mymutexattr, 15);
pthread_mutex_init(&mymutex2, &mymutexattr);
pthread_mutexattr_destroy(&mymutexattr);
```

- In this case, the first mutex (mymutex1) has priority ceiling equal to 10 (i.e. the highest priority task that accesses this semaphore has priority 10)
- the second mutex (mymutex2) has priority 15
Some exercise

1. Modify the periodic thread example so that a periodic thread can tolerate up to N consecutive deadline misses. Write an example that demonstrate the functionality.

2. Modify the periodic thread example so that the period can be modified by an external manager thread. Write an example that demonstrates the functionality.

3. (Dual priority) Modify the periodic thread example so that each thread is assigned 2 priorities and:
   - The first part of the code runs at “low” priority
   - The last part of the code executes at “high” priority

4. Write a “chain” of threads, so that each thread can start executing only when the previous one has completed its job.

5. Which solution is better for the dual priority scheme? the chain of two tasks of modifying the priority on the fly?