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

```
// 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

```
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:

```
#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 represent 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 every implementation supports it
  - 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()

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

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

Outline

Sleep functions

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

```
#include <unistd.h>

unsigned sleep(unsigned seconds);
```

```
#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 remaing time

Example of usage - I

examples/nanosleepexample.c

```
void *thread(void *arg)
{
  struct timespec interval;

  interval.tv_sec = 0;
  interval.tv_nsec = 500 * 1000000; // 500 msec
  while(1) {
    // perform computation
    nanosleep(&interval, 0);
  }
}
```

Example of usage - II

- The previous example does not work!

examples/nanosleepexample2.c

```
void *thread(void *arg)
{
  struct timespec interval;
  struct timespec next;
  struct timespec rem;
  struct timespec now;

  interval.tv_sec = 0;
  interval.tv_nsec = 500 * 1000000;  // 500 msec
  clock_gettime(&next);
  while(1) {
    // perform computation
    timespec_add(&next, &interval);  // compute next arrival
    clock_gettime(&now);             // get time
    timespec_sub(&rem, &next, &now); // compute sleep interval
    nanosleep(&rem, 0);              // sleep
  }
}
```

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

```
#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 specify 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. If the function is interrupted by a signal, this parameter will contain the remaining interval of sleeping time

Example

examples/periodicslides.c

```
struct periodic_data {
  int index;
  long period_us;
  int wcet_sim;
};

void *thread_code(void *arg) {
  struct periodic_data *ps = (struct periodic_data *) arg;
  int j; int a = 13, b = 17;
  struct timespec next;
  struct timespec now;

  clock_gettime(CLOCK_REALTIME, &next);
  while (1) {
    timespec_add_us(&next, ps->period_us);

    clock_nanosleep(CLOCK_REALTIME, TIMER_ABSTIME,
                    &next, NULL);

    for (j=0; j<ps->wcet_sim; j++) a *= b;
  }
  return NULL;
}
```

Deadline miss detection

- The following code is used to detect a deadline miss (in this case, the behaviour is to abort the thread)

examples/periodicslides2.c

```
void *thread_code(void *arg) {
  struct periodic_data *ps = (struct periodic_data *) arg;
  int j;
  int a = 13, b = 17;
  struct timespec next, now;

  clock_gettime(CLOCK_REALTIME, &next);
  while (1) {
    clock_gettime(CLOCK_REALTIME, &now);
    timespec_add_us(&next, ps->period_us);

    if (timespec_cmp(&now, &next) > 0) {
      fprintf(stderr, "Deadline miss for thread %d\n", ps->index);
      fprintf(stderr, "now: %d sec %ld nsec     next: %d sec %ldnsec \n",
              now.tv_sec, now.tv_nsec, next.tv_sec, next.tv_nsec);
      exit(-1);
    }

    clock_nanosleep(CLOCK_REALTIME, TIMER_ABSTIME,
                    &next, NULL);

    for (j=0; j<ps->wcet_sim; j++) a *= b;
  }
  return NULL;
}
```

Outline

Scheduling policy

- 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:

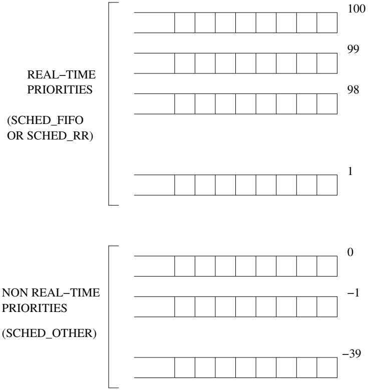
a
: attributes

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.

Scheduling in POSIX

- The scheduling policies in POSIX:



Example

```
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 paramters 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 on the same processor

Setting scheduling priority

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

```
#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)

Outline

Resources

- A resource can be
  - A HW resource like a I/O device
  - A SW resource, i.e. a data structure
  - In both cases, access to a resource must be regulated to avoid interference
- example 1
  - If two processes want to print on the same printer, their access must be sequentialised, otherwise the two printing could be intermingled!
- example 2
  - If two threads access the same data structure, the operation on the data must be sequentialized otherwise the data could be inconsistent!

Mutual Exclusion Problem

- We do not know in advance the relative speed of the processes
  - hence, we do not know the order of execution of the hardware instructions
- Recall the example of incrementing variable x
  - incrementing x is not an atomic operation
  - atomic behaviour can be obtained using interrupt disabling or special atomic instructions

Example 1

```
/* Shared memory */
int x;
```

```
void *threadA(void *)
{
  ...;
  x = x + 1;
  ...;
}
```

```
void *threadB(void *)
{
  ...;
  x = x + 1;
  ...;
}
```

- Bad Interleaving:

```
...
LD    R0, x     (TA)   x = 0
LD    R0, x     (TB)   x = 0
INC   R0        (TB)   x = 0
ST    x, R0     (TB)   x = 1
INC   R0        (TA)   x = 1
ST    x, R0     (TA)   x = 1
...
```

Example 2

```
// Shared object (sw resource)
class A {
    int a;
    int b;
public:
    A() : a(1), b(1) {};
    void inc() {
      a = a + 1; b = b +1;
    }
    void mult() {
      b = b * 2; a = a * 2;
    }
} obj;
```

```
void * threadA(void *)
{
     ...
     obj.inc();
     ...
}
```

```
void * threadB(void *)
{
    ...
    obj.mult();
    ...
}
```

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void * threadA(void *)
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Consistency:
After each operation, a == b

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```

Consistency:
After each operation, a == b

```
a = a + 1;    TA   a = 2
b = b * 2;    TB   b = 2
b = b + 1;    TA   b = 3
a = a * 2;    TB   a = 4
```

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    }
    void mult() {
      b = b * 2; a = a * 2;
    }
} obj;
```

```
void * threadA(void *)
{
     ...
     obj.inc();
     ...
}
```

```
void * threadB(void *)
{
    ...
    obj.mult();
    ...
}
```

Consistency:
After each operation, a == b

Resource in a non-consistent state!!

```
a = a + 1;    TA    a = 2
b = b * 2;    TB    b = 2
b = b + 1;    TA    b = 3
a = a * 2;    TB    a = 4
```

Consistency

- For any resource, we can state a set of consistency properties
  - A consistency property C_i is a boolean expression on the values of the internal variables
  - A consistency property must hold before and after each operation
  - It does not need to hold during an operation
  - If the operations are properly sequentialized, the consistency properties will always hold
- Formal verification
  - Let R be a resource, and let $C(R)$ be a set of consistency properties on the resource
  - $C(R) = \{C_i\}$
  - A concurrent program is correct if, for every possible interleaving of the operations on the resource, $\forall C_i \in C(R)$, C_i holds.

Outline

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  - disabling the preemption (system-wide)

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- we say that two critical sections on the same resource must execute in MUTUAL EXCLUSION
- there are three ways to obtain mutual exclusion
    - implementing the critical section as an atomic operation
    - disabling the preemption (system-wide)
    - selectively disabling the preemption (using semaphores and mutex)

Implementing atomic operations

- In single processor systems
  - disable interrupts during a critical section
  - non-voluntary context switch is disabled!

```
CLI;
<critical section>
STI;
```

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```
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```

- Limitations:
  - if the critical section is long, no interrupt can arrive during the critical section
    - consider a timer interrupt that arrives every 1 msec.
    - if a critical section lasts for more than 1 msec, a timer interrupt could be lost
    - It must be done only for very short critical section;
  - Non voluntary context switch is disabled during the critical section
    - Disabling interrupts is a very low level solution: it is not possible in user space.

Atomic operations on multiprocessors

- Disabling interrupts is not sufficient
  - disabling interrupts on one processor lets a thread on another processor free to access the resource
- Solution: use lock() and unlock() operations
  - define a flag s for each resource, and then surround a critical section with lock(s) and unlock(s);

```
int s;
...
lock(s);
<critical section>
unlock(s);
...
```

Disabling preemption

- On single processor systems
  - in some scheduler, it is possible to disable preemption for a limited interval of time
- problems:
  - if a high priority critical thread needs to execute, it cannot make preemption and it is delayed
  - even if the high priority task does not access the resource!

```
disable_preemption();
<critical section>
enable_preemption();
```

no context switch may happen during the critical section, but interrupts are enabled

Producer / Consumer model

- Mutual exclusion is not the only problem
  - we need a way of synchronise two or more threads
- example: producer/consumer
  - suppose we have two threads,
  - one produces some integers and sends them to another thread (PRODUCER)
  - another one takes the integer and elaborates it (CONSUMER)

A more general approach

- We need to provide a general mechanism for synchonisation and mutual exclusion
- Requirements
  - Provide mutual exclusion between critical sections
    - Avoid two interleaved insert operations
    - (semaphores, mutexes)
  - Synchronise two threads on one condition
    - for example, block the producer when the queue is full
    - (semaphores, condition variables)

Outline

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

```
#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 binay semaphore
- a mutex can be initialized with attributes regarding the resource access protocol

Example with mutexes

examples/mutex.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,"%s",(char *)arg);
    pthread_mutex_unlock(&mymutex);

  }

  return NULL;
}
```

Example continued

examples/mutex.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

```
#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 sempahore
  - 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

Example with conditions

- 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

Example with conditions

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

examples/synch.cpp

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

  nblocked++;

  if (nblocked < nthreads)
    pthread_cond_wait(&c, &m);
  else {
    nblocked = 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

examples/synchperiodic.h

```
#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

examples/synchperiodic.cpp

```
#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);
}
```

Thread code

examples/exsynchper.cpp

```
PeriodicBarrier pb(NTHREADS);

void *thread_code(void *arg) {
  struct periodic_data *ps = (struct periodic_data *) arg;
  struct timespec next;

  fprintf(stdout, "TH %d waiting for start\n", ps->index);

  pb.wait(&next);

  while (1) {
    fprintf(stdout, "TH %d activated at time %ld\n", ps->index,
            next.tv_nsec/1000);

    waste(ps->wcet_sim);

    timespec_add_us(&next, ps->period_us);
    clock_nanosleep(CLOCK_REALTIME, TIMER_ABSTIME,
                    &next, NULL);
  }
  return NULL;
```

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

Outline

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

```
int pthread_mutexattr_getprotocol(const pthread_mutexattr_t *
              restrict 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 specigy the priority ceiling of the mutex with the following function

```
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

```
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

```
pthread_mutexattr_t mymutexattr;

pthread_mutexattr_init(&mymutexattr);
pthread_mutexattr_setprotocol(&mymutexattr, PTHREAD_PRIO_PROTECT);
pthread_mutexattr_setprioceiling(&mymutexattr, 10);
pthread_mutex_init(&mymutex1, &mymutexattr);
pthread_mutexattr_setprioceiling(&mymutexattr, 15);
pthread_mutex_init(&mymutex(2, &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

Outline

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?