Synchronization

Exercises on semaphores and mutexes

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Exercise 01

- Implement a C or C++ program that
  - Runs 1 thread TA and 1 thread TB
  - TA and TB include an infinite cycle in which they display one single character 'A' or 'B', respectively
  - Synchronize threads such that for each set of 3 characters there is 1 character A and 2 characters B in any position
  - Execution example

```
pgrm
     ABB
     BBA
     BAB
     etc.
```

Solution

```
#include <iostream>
#include <semaphore>
#include <thread>
#include <unistd.h>

using std::cout;
using std::endl;

std::counting_semaphore sa{1}, sb{2}, me{1};
int n;

static void TA (int);
static void TB (int);
```

To “sleep” for a random time

Mutexes cannot be used because they must be locked and unlocked by the same thread

Counter

2 Threads
2 semaphores
1 mutex (semaphore)
TA (sa) is the one to start

Solution

```
int main (int argc, char **argv) {
  int n1, n2;

  if (argc != 2) {
    fprintf (stderr, "Syntax: %s num_threads\n", argv[0]);
    return (1);
  }
  n1 = atoi(argv[1]);
  n2 = 2 * n1;
  n = 0;

  std::thread ta (TA, n1);
  std::thread tb (TB, n2);

  ta.join();
  tb.join();

  return (0);
}
```

To avoid running for ever we generate
n1 threads TA
n2 threads TB

Solution

```
static void TA (int nc) {
  for (int i=0; i<nc; i++) {
    sleep (rand()%2);
    sa.acquire();
    me.acquire();
    cout << "A";
    n++;
    if (n>=3) {
      cout << endl;
      n = 0; sa.release(); sb.release(); sb.release();
    }
    me.release();
  }
  return;
}
```

Wait for a random time

If TA starts

It must not start with TB

The last thread wakes-up one A and two B threads

Solution

```
static void TB (int nc) {
  for (int i=0; i<nc; i++) {
    sleep (rand()%2);
    sb.acquire();
    me.acquire();
    cout << "B";
    n++;
    if (n>=3) {
      cout << endl;
      n = 0;
      sa.release(); sb.release(); sb.release();
    }
    me.release();
  }
  return;
}
```

Wait for a random time

If TB starts

It must not start with TA

The last thread wakes-up one A and two B threads

Exercise 02

Exam of September 08, 2023

- A C program can execute four different threads
  - TP (thread plus), TM (thread minus), TS (thread star), and TNL (thread newline)
- Each thread is organized through an infinite cycle containing synchronization instructions but a single IO instruction
  - Thread TP displays a "+"
  - Thread TM displays a "-"
  - Thread TS displays a "*"
  - Thread TNL displays a "\n" (endln)

Exercise 02

- Synchronize the four threads to print the following sequence of lines

```
++++++++++
----------
**********
++++++++++
----------
**********
   etc.
```

  - Where the number of characters on each row is given as a parameter to the main program (e.g., 10)

Solution

```
#include <iostream>
#include <semaphore>
#include <thread>
#include <unistd.h>

using std::cout;
using std::endl;

std::counting_semaphore sp{1}, sm{0}, ss{0}, snl{0};

static void TP (int);
static void TM (int);
static void TS (int);
static void TNL ();
```

4 Threads
4 Semaphores
SP (+) is the one to start

Solution

```
int main (int argc, char **argv) {
  int n;
  if (argc != 2) {
    ... error ...
  }
  n = atoi(argv[1]);
  std::thread tp (TP, n);
  std::thread tm (TM, n);
  std::thread ts (TS, n);
  std::thread tnl (TNL);
  tp.join();
  tm.join();
  ts.join();
  tnl.join();
  return (0);
}
```

Threads never stop; but if we do not wait, we return and we stop all threads (there is no pthread_exit)

Solution

```
static void TP (int n) {
  int np = 0;
  while (1) {
    sp.acquire();
    cout << "+";
    np++;
    if (np<n) {
      sp.release();
    } else {
      np = 0;
      snl.release();
    }
  }
  return;
}
```

Re-wake up TP

Reset the number of calls for TP and call TNL

Solution

```
static void TM (int n) {
  int nm = 0;
  while (1) {
    sm.acquire();
    cout << "-";
    nm++;
    if (nm<n) {
      sm.release();
    } else {
      nm = 0;
      snl.release();
    }
  }
  return;
}
```

Re-wake up TM

Reset the number of calls for TM and call TNL

Solution

```
static void TS (int n) {
  int ns = 0;
   while (1) {
    ss.acquire();
    cout << "*";
    ns++;
    if (ns<n) {
      ss.release();
    } else {
      ns = 0;
      snl.release();
    }
  }
  return;
}
```

Re-wake up TS

Reset the number of calls for TS and call TNL

Solution

```
static void TNL () {
  int nnl = 0;
  while (1) {
    snl.acquire(); nnl++; cout << endl;
    sleep (rand()%2);
    if (nnl==1) {
      sm.release();
    } else {
      if (nnl==2) {
        ss.release();
      } else {
        sp.release(); nnl = 0;
      }
    }
  }
  return;
}
```

POSIX
(we can use C++ to sleep)

Wake up TM

Wake up TS

Wake up TP
and restart

Exercise 03

- Fairness consideration on synchronization primitives
  - C++ synchronization primitives are unfair
    - Some threads can lock a mutex more often than others
      - A simple experiment on Linux shows that if threads repeatedly try to lock the same mutex, some threads lock the mutex 1.13x more often than others
    - Some threads can lock a semaphore or a spinlock 3.91x more often than others

Exercise 03

- Implement a **priority semaphore**, i.e., a semaphore in which
  - Each thread has an intrinsic priority
    - The priority is an integer value
    - The **higher** priority corresponds to the **lower** value
  - Unlocking is done in order following the threads priority

Solution

- Core idea
  - The semaphore must have a **priority queue** associated with it, where threads await to be signalled
  - When a call to the signal function wakes-up a thread, threads must be woken-up following their priority
    - We have to awake the threads with the higher priority among the ones waiting on that semaphore

In C++ lock and unlock must be called by the same thread.
We should use C++ semaphores but semaphores are not copyble

Solution

```
#include <iostream>
#include <algorithm>
#include <vector>
#include <map>
#include <thread>
#include <semaphore>

using std::cout;
using std::endl;
...

const int TIME = 3;

map<int,std::unique_ptr<std::binary_semaphore>> my_sem;
std::mutex m;
```

C++20 semaphore are neither copyble nor movable.
We need to carefully use dynamic memory allocation

Solution

Worker running threads

```
static void worker (int i, int priority) {
  m.lock();
  cout << "Locking thread " << i <<
          " with priority " << priority << endl;
  m.unlock();
  my_sem.insert
    ({priority,std::make_unique<std::binary_semaphore>(0)});
  (*my_sem[priority]).acquire();
  m.lock();
  cout << "          Unlocked thread " << i <<
          " with priority " << priority << endl;
  m.unlock();
  return;
}
```

Solution

Main: Part 1

```
int main (int argc, char *argv[]) {
  int i, priority;
  if (argc != 2) {
    cout << "Syntax: " << argv[0] << " num_threads\n";
    return (1);
  }
  int n = atoi (argv[1]);
  vector<thread> pool;
  for (i=0; i<n; i++) {
    priority = (i+1) * 10;
    pool.emplace_back([i, priority] { worker (i, priority); });
  }
  std::this_thread::sleep_for
    (std::chrono::seconds(rand()%TIME));
```

Running workers

From POSIX sleep to C++

Put the thread in a sleep status for rand()%TIME seconds

Solution

Main: Part 2

```
  i = 0;
  for (const auto &t : my_sem) {
    m.lock();
    cout << "      Unlocking thread " << i++ <<
                " with priority " << t.first << endl;
    m.unlock();
    (*(t.second)).release();
  }
  for (i=0; i<n; i++) {
    pool[i].join();
  }
  cout << "Main exits." << endl;
  return (1);
}
```

Wait workers

Solution

Output

```
Locking thread 0 with priority 10
Locking thread 6 with priority 70
Locking thread 2 with priority 30
Locking thread 1 with priority 20
Locking thread 9 with priority 100
...
     Unlocking thread 0 with priority 10
     Unlocking thread 1 with priority 20
     ...
          Unlocked thread 0 with priority 10
          Unlocked thread 1 with priority 20
     Unlocking thread 5 with priority 60
     ...
          Unlocked thread 5 with priority 60
          Unlocked thread 9 with priority 100
          Unlocked thread 4 with priority 50
          Unlocked thread 3 with priority 40
          ...
Main exits.
```

Locking the threads

Unlocking them …

… which then start

Exercise 04

- Write a program to implement an election algorithm that elects a leader thread
  - The system has N threads
  - Each thread has its
    - Thread identifier
    - Rank, i.e., and integer value randomly generated
  - To elect the leader each thread must
    - Compare its own rank value with the current value in **best_rank** to decide if it is the leader or not
      - To do that, it synchronizes with all the other threads
      - It re-start when the election process is completed (i.e., all other threads have updated the value of **best_rank**)

Exercise 04

- When all threads have done their job, each thread displays
  - Its identifier and its rank value
  - The leader thread identifier and its rank value
- Restriction
  - Threads cannot access the rank value of other threads, only the current best thread rank value is available in a global variable **best_rank** together with the corresponding thread identifier
  - Hint: Referring to a voting algorithm, use a global variable to count the number of threads that completed their voting process

Solution

C Code
Write the corresponding C++

```
#include <sys/time.h>
#include <time.h>
#include <stdlib.h>

#define N 10

typedef struct best_s {
  int rank;
  long int id;
  int num_votes;
  pthread_mutex_t mutex;
} best_t;

best_t *best;
sem_t *sem;
int max_random (int max);
```

Thread structure

Semaphore to make threads wait

Solution

```
int main (int argc, char **argv){
  pthread_t th;
  int i, j, k, pi;
  best = (best_t *) malloc (sizeof (best_t));
  best->rank = best->num_votes = 0;
  pthread_mutex_init (&best->mutex, NULL);
  sem = (sem_t *) malloc (sizeof (sem_t));
  sem_init (sem, 0, 0);
  for (i = 0; i < N; i++) {
    // Assign a rank to pi
    ...
    pthread_create (&th, NULL, process, (void *) pi);
  }
  pthread_exit (0);
}
```

Must assign
different rank values

Solution

```
static void *process (void *arg){
  int rank = (int) arg;
  int i;
  long int id;
  id = pthread_self ();
  pthread_detach (pthread_self ());
```

Solution

```
  pthread_mutex_lock (&best->mutex);
  if (rank > best->rank) {
    best->rank = rank;
    best->id = id;
  }
  best->num_votes++;
  if (best->num_votes < N){
    pthread_mutex_unlock (&best->mutex);
    sem_wait (sem);             /* wait for all to vote */
  } else {
    pthread_mutex_unlock (&best->mutex);
    for (i = 0; i < N - 1; i++)
      sem_post (sem);           /* release all waiting */
  }
  printf ("my_id=%ld my_rank=%d leader_id=%ld leade_rank=%d\n",
   id, rank, best->id, best->rank);
}
```

Check personal rank with best global rank

Update best rank

If not the last one, wait the others

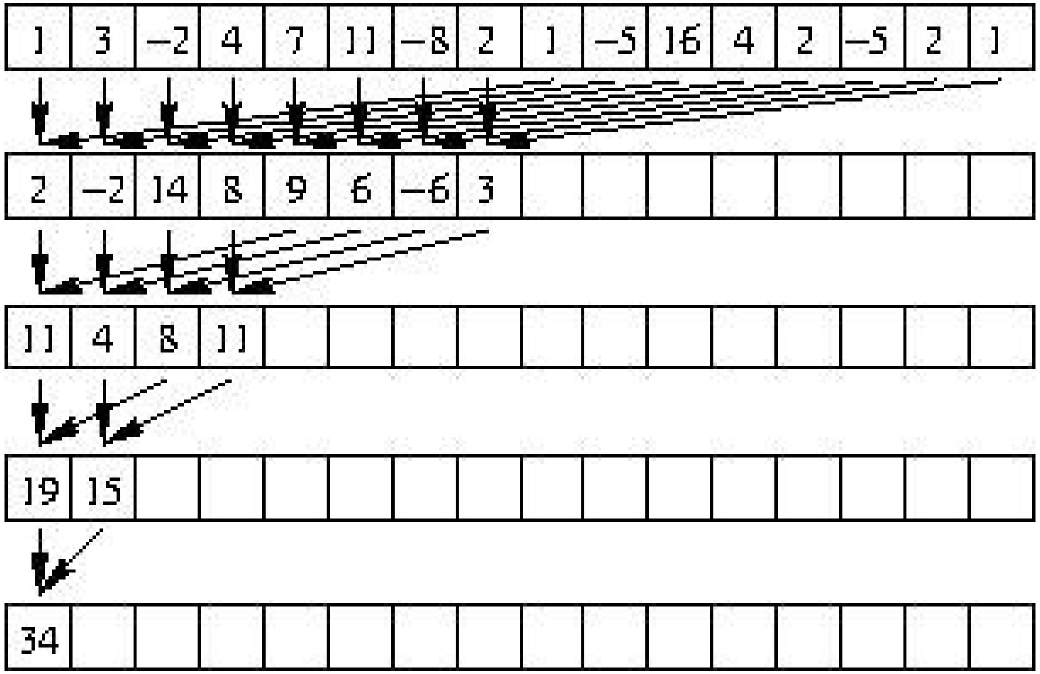
If the last one, release all

Exercise 05

- We are viven an array vet of size n
  - We supposed **n** is a **power of 2** (e.g., 16)
- Write the function

```
int array_sum (int *vet, int n);
```

- Which computes the sum of the elements of the array as represented in the picture



1	3	-2	4	7	11	-8	2	1	-5	16	4	2	-5	2	1
2	-2	14	8	9	6	-6	3								
11	4	8	11												
19	15														
34															

Exercise 05

- In particular
  - All sums must be executed in parallel by n/2 (at most) separate threads
  - Each thread is associated with one of the first n/2 cells of the array
- Note that the number of sums each thread will have to execute depends on the position of the cell
- Manage synchronization between threads with semaphores, so that all sums are made respecting precedence

Solution

C Code
Write the corresponding C++

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <pthread.h>
#include <semaphore.h>

typedef struct {
  int *vet;
  sem_t *sem;
  int n;
  int id;
} args_t;

... main ...
```

Array of n elements

Array of n/2 semaphores

User and thread identifier

Initialize variables and calls function array_sum

Solution

Call the thread functions

```
int array_sum (int *vet, int n) {
  int k=n/2; pthread_t *tids; args_t *args; sem_t *sem;
  tids = (pthread_t *) malloc (k*sizeof(pthread_t));
  sem = (sem_t *) malloc (k*sizeof(sem_t));
  for (int i=0; i<k; ++i) sem_init(&sem[i], 0, 0);
  args = (args_t *) malloc (k*sizeof(args_t));
  for (int i=0; i<k; ++i) {
    args[i].id = i; args[i].vet = vet;
    args[i].n = n; args[i].sem = sem;
  }
  for (int i=0; i<k; ++i)
    pthread_create (&tids[i], NULL, adder, &args[i]);
  pthread_join (tids[0], NULL);
  for (int i=0; i<k; ++i) sem_destroy(&sem[i]);
  free (tids);
  free (sem);
  free (args);
  return vet[0];
}
```

n/2 Ts and Sems

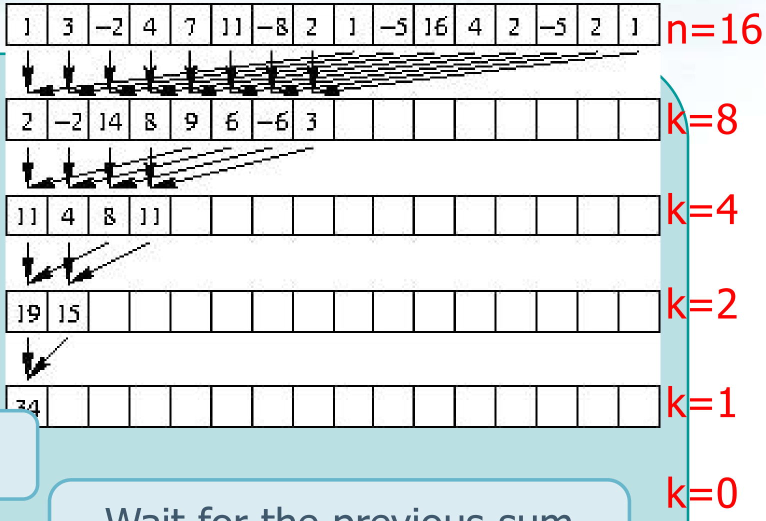
Initialize

Run threads

Wait for threads and free memory

Solution

Thread function



```
void *adder (void * arg) {
  sem_t *sem = ((args_t *) arg)->sem;
  int *vet = ((args_t *) arg)->vet;
  int id = ((args_t *) arg)->id;
  int n = ((args_t *) arg)->n;
  int k = n/2, i = 0;
  while (k != 0) {
    if (i!=0 && k<n/2)
      sem_wait (&sem[id + k]);
    else
      i++;
    vet[id] += vet[id + k];
    k = k/2;
    if (id >= k) {
      sem_post (&sem[id]);
      break;
    }
  }
  pthread_exit(0);
}
```

k = # iterations

Wait for the previous sum to be done id ∈ [0, n/2[

… but not during the fist cycle

Make the sum

My sum has been done

This thread must stop