Synchronization

Barriers

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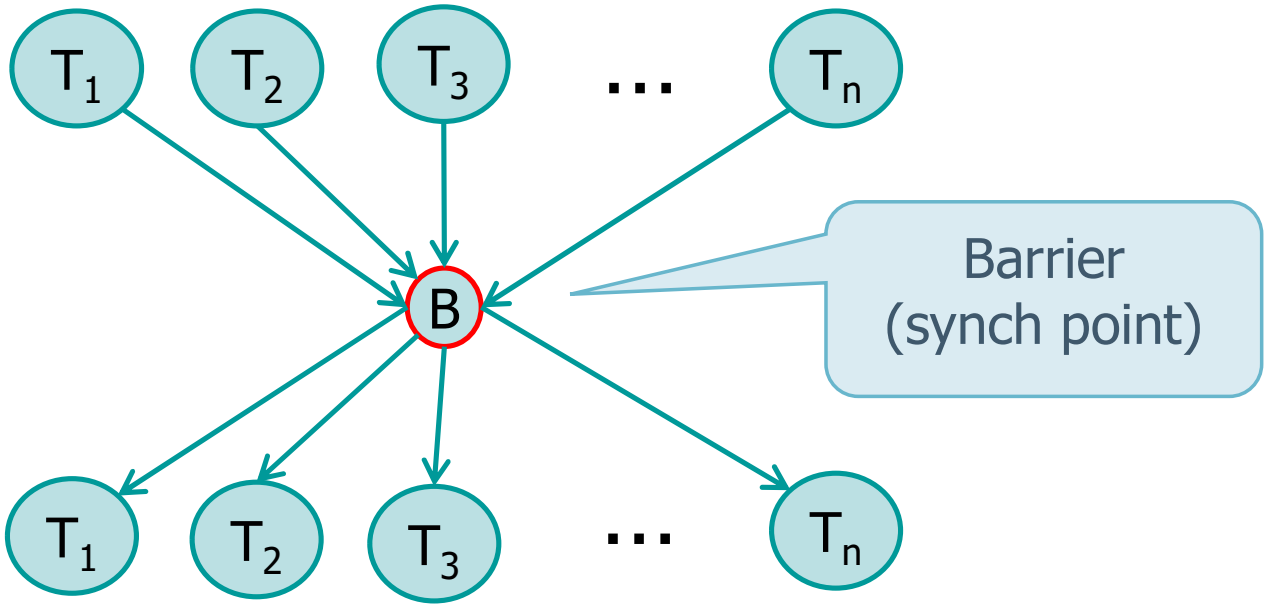
Barriers

- Barriers can be used to coordinate multiple threads working in parallel
  - A barrier allows each thread to wait until all cooperating threads have reached the same point, and then continue executing from there



Barriers

- Barriers generalize the pthread_join function
  - The function **pthread_join** acts as a barrier to allow **one** thread to wait until another thread completed their processing
  - Barriers allow **an arbitrary number** of threads to wait until all of the threads have completed their processing
  - The threads don't have to exit, as they can continue working after all threads have reached the barrier

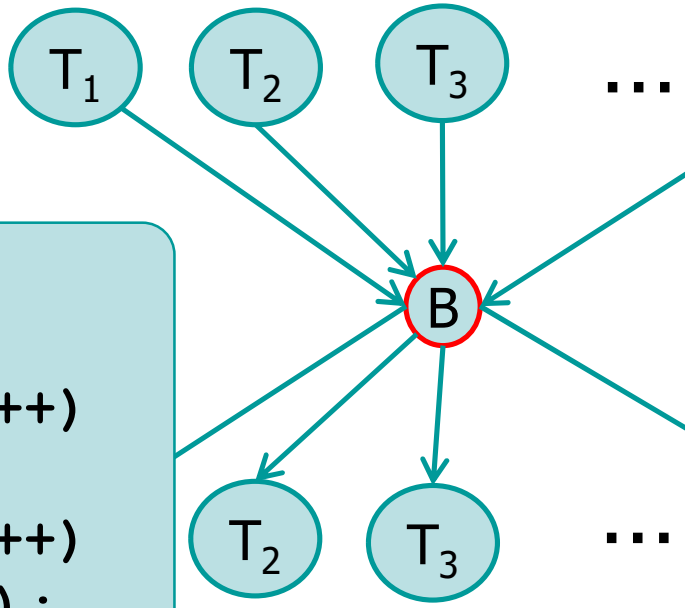
Trivial solution

- A possible trivial solution
  - Use one semaphore for each thread T_i
  - It implement one for the extra process B (for the barrier) using one more semaphore

It uses too many semaphores

The barrier process waits n times on its semaphores and then wakes-up all threads T_i

```
B

for (i=0; i<n; i++)
  wait (semB);
for (i=0; i<n; i++)
  signal (sem[i]);
```



T_i

```
signal (semB);
wait (sem[i]);

Waiting ...
```

Each T_i wakes-up the barrier process and wait on its own semaphore

POSIX versus C++

- In the POSIX standard barriers are implemented using the primitives
  - pthread_barrier_init, pthread_barrier_wait
- In C++ standard barriers are implemented by the class template std::barrier
  - Unlike **std::latch**, barriers are reusable
    - Once a group of arriving threads are unblocked, the barrier can be reused
- We will use the POSIX implementation
  - See the documentation for the C++ version

POSIX barries

For more details see the reference documentation

- In the POSIX standard barriers are implemented in phtread.h

Type	Meaning
int pthread_barrier_init (...);	The count argument specifies the number of threads that must reach the barrier before all of the threads will be allowed to continue. The same barrier can be initialized more than once (but pay attention to the current value of the counter).
int pthread_barrier_wait (...);	Indicate that a thread is done with its work and it is ready to wait for all the other threads to catch up.
int pthread_barrier_destroy (...);	De-initialize a barrier. Any resource allocated for the barrier will be freed.

Example

```
#include <stdio.h>
#include <unistd.h>
#include <pthread.h>
#define N 4
#define C 5
...
pthread_barrier_t bar;
...
pthread_barrier_init (&bar, NULL, N);
for (i=0; i<N; i++) {
  v[i] = i;
  pthread_create (&th[i], NULL, f, (void *) &v[i]);
}
for (i=0; i<N; i++) {
  pthread_join (th[i], NULL);
}
pthread_barrier_destroy(&bar);
```

Main program calling the threas

Define the barrier

Init the barrier with a NULL attribute and a counter equal to N

Destroy the barrier

Example

Use the barrier to synchronize N threads **once**

```
void *f (void *par) {
  int *np, n;

  np = (int *) par;
  n = *np;

  fprintf (stdout, "T%d-In\n", n);
  pthread_barrier_wait(&bar);
  fprintf (stdout, "  T%d-Out\n", n);

  pthread_exit (NULL);
}
```

Example

```
void *f (void *par) {
  int i, *np, n;

  np = (int *) par;
  n = *np;
  for (i=0; i<C; i++) {
    fprintf (stdout, "T%d-In%d\n", n, i);
    pthread_barrier_wait(&bar);
    fprintf (stdout, "  T%d-Out%d\n", n, i);
  }

  pthread_exit (NULL);
}
```

Use the barrier to synchronize N threads **C times**

The barrier does not have to be re-initialized

Conclusions

- Barriers are used to coordinate multiple threads working in parallel
  - You want all threads to wait until everyone has arrived at a certain point
  - A simple semaphore would do the exact opposite, i.e., each thread would keep running and the last one will go to sleep

Exercise

- Suppose barrier constructs do not exist
  - Re-implement them using only **one** semaphore **and** one mutex

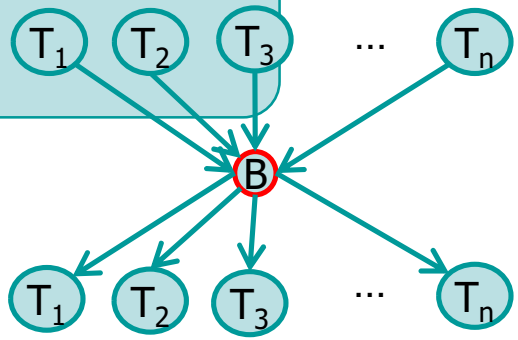
```
pthread_barrier_t b;
...
pthread_barrier_init (&b, NULL, N_THREAD);
for (i=0; i<N_THREAD; i++) {
  err = pthread_create (&tid[i], NULL, thr_fn, NULL);
}
...
```

Main

```
void *thr_fn () {
  ...
  pthread_barrier_wait (&b);
}
```

Threads (acyclic behavior)

Synchronization point among all threads



Solution

Initializazion

Barrier structure
sem to enqueue threads
mutex to protect counter
counter to count threads up

```
typedef struct barrier_s {
  sem_t sem;
  pthread_mutex_t mutex;
  int count;
} barrier_t;
```

Init barrier

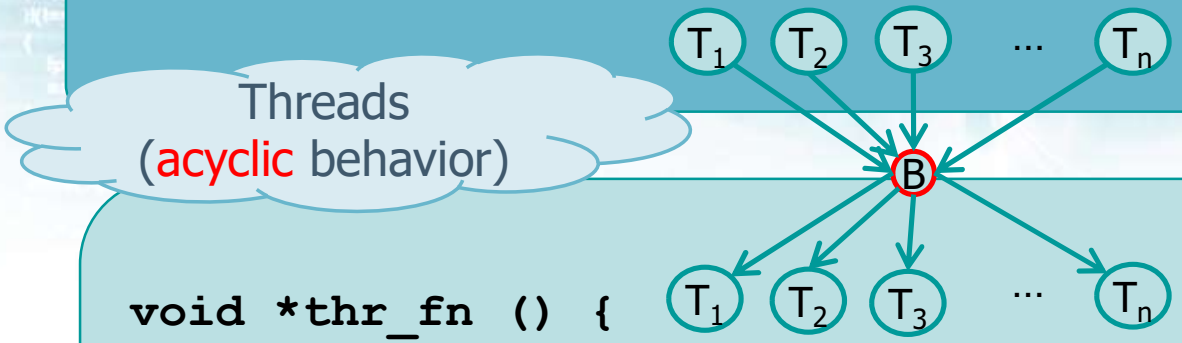
```
barrier_d = (barrier_t *) malloc (1 * sizeof(barrier_t));
sem_init (&barrier_d->sem, 0, 0);
pthread_mutex_init (&barrier_d->mutex, NULL);
barrier_d->count = 0;
```

Main

Run threads

```
for (i=0; i<N_THREAD; i++) {
  err = pthread_create (&tid[i], NULL, thr_fn, NULL);
}
```

Solution 1




```
void *thr_fn () {
  ...
  pthread_mutex_lock (&barrier->mutex);
  barrier->count++;
  if (barrier->count == N_THREAD) {
    for (j=0; j<N_THREAD; j++) {
      sem_post (&barrier_d->sem);
    }
  }
  pthread_mutex_unlock (&barrier->mutex);
  sem_wait (&barrier_d->sem);

  pthread_exit ();
}
```

Protect counter

Last thread awakes all

Un-protect counter

Waiting point for all threads

Solution 2

Solution with **turnstile**

```
void *thr_fn () {
  ...
  pthread_mutex_lock (&barrier->mutex);
  barrier->count++;
  if (barrier->count == N_THREAD) {
      sem_post (&barrier_d->sem);
    }
  }
  pthread_mutex_unlock (&barrier->mutex);
  sem_wait (&barrier_d->sem);
  sem_post (&barrier_d->sem);

  pthread_exit ();
}
```

Protect counter

Un-protect counter

Turnstile

One **extra** sem_post is done (pay attention to cycling threads)

Exercise

- Re-implement the following (cyclic) piece of code using only one semaphore and one mutex

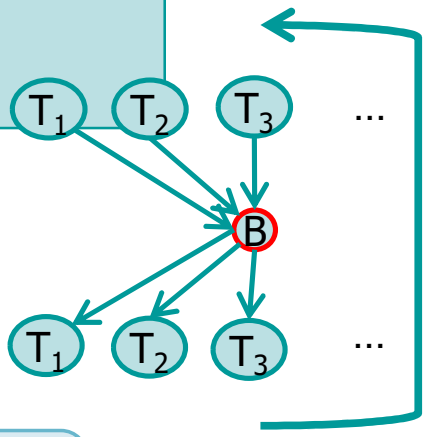
```
pthread_barrier_t b;
...
pthread_barrier_init (&b, NULL, N_THREAD);
for (i=0; i<N_THREAD; i++) {
  err = pthread_create (&tid[i], NULL, thr_fn, NULL);
}
...
```

Main

```
void *thr_fn () {
  while (1)
    ...
    pthread_barrier_wait (&b);
  }
}
```

Threads (**cyclic** behavior)

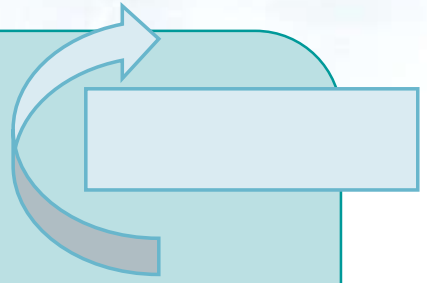
Synchronization point among all threads



Buggy Solution

Buggy attempt

```
void *thr_fn () {
  while (1) {
    ..
    pthread_mutex_lock (&barrier->mutex);
    barrier->count++;
    if (barrier->count == N_THREAD) {
      for (j=0; j<N_THREAD; j++) {
       sem_post (&barrier_d->sem);
      }
    }
    pthread_mutex_unlock (&barrier->mutex);
    sem_wait (&barrier_d->sem);
  }
  pthread_exit ();
}
```



Last threads awakes all

Waiting point for all threads

A fast threads can cycle more than once !

Solution

Initializazion

```
typedef struct barrier_s {
  sem_t sem1, sem2;
  pthread_mutex_t mutex;
  int count;
} barrier_t;
```

Barrier structure
2 sems to enqueue threads
mutex to protect counter
counter to count threads up

Init barrier

```
barrier_d = (barrier_t *) malloc (1 * sizeof(barrier_t));
sem_init (&barrier_d->sem1, 0, 0);
sem_init (&barrier_d->sem2, 0, 0);
pthread_mutex_init (&barrier_d->mutex, NULL);
barrier_d->count = 0;
```

Main

Run threads

```
for (i=0; i<N_THREAD; i++) {
  err = pthread_create (&tid[i], NULL, thr_fn, NULL);
}
```

Threads (cyclic behavior)

Barrier #1

```
...
pthread_mutex_lock (&barrier->mutex);
barrier->count++;
if (barrier->count == N_THREAD) {
  for (j=0; j<N_THREAD; j++) sem_post (&barrier_d->sem1);
}
pthread_mutex_unlock (&barrier->mutex);
sem_wait (&barrier_d->sem1);
```

Barrier #2

```
pthread_mutex_lock (&barrier->mutex);
barrier->count--;
if (barrier->count == 0) {
  for (j=0; j<N_THREAD; j++) sem_post (&barrier_d->sem2);
}
pthread_mutex_unlock (&barrier->mutex);
sem_wait (&barrier_d->sem2);
...
```

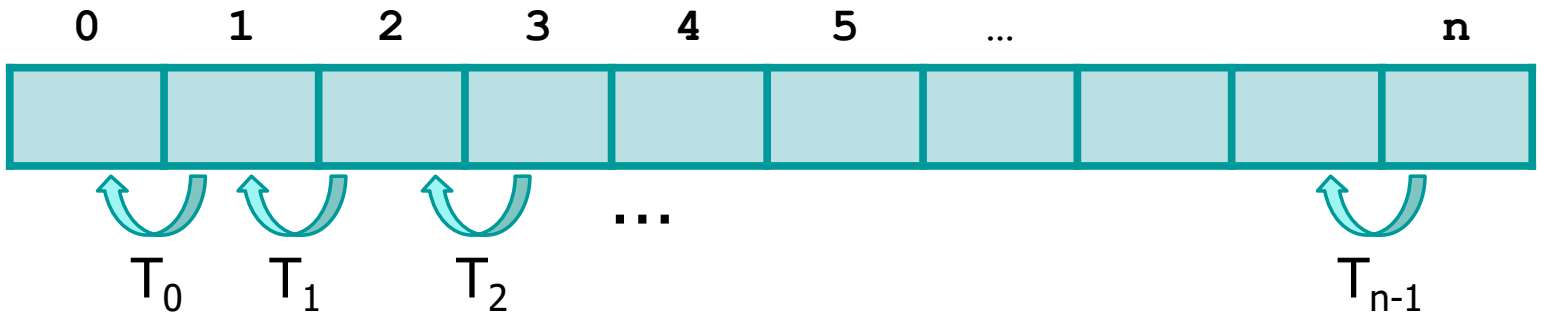
Exercise

Concurrent Bubble-sort

- Write a version of the exchange (bubblesort) sorting algorithm) as follows
  - A static array include n integer values
  - We want to ort it using n identical threads
  - Each thread is in charge of sorting two adjacent elements
    - Thread 0 sort elements 0 and 1
    - Thread 1 sort elements 1 and 2
    - …
    - Thread n-1 sort elements n-1 and n

Exercise

- Each thread
  - Compare the two elements it deals with, and exchange them if they are not in the correct order
  - Once their work is finished, all the threads wait for each-other, and if
    - All the elements are correctly ordered, the program terminates
    - Otherwise, all threads are run again to make a new series of exchanges

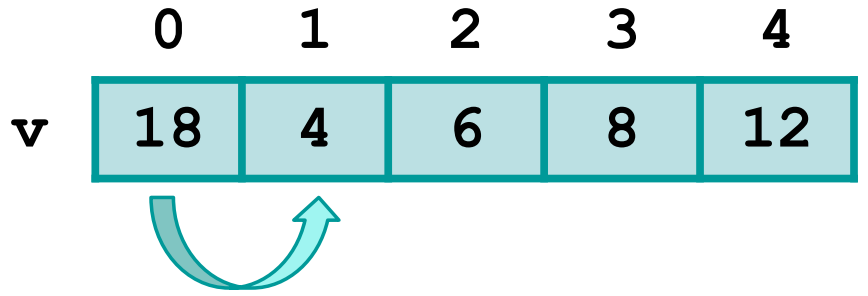


Exercise

- Each thread
  - Compare the two elements it deals with, and exchange them if they are not in the correct order
  - Once their work is finished, all the threads wait for each-other, and if
    - All the elements are correctly ordered, the program terminates
    - Otherwise, all threads are run again to make a new series of exchanges

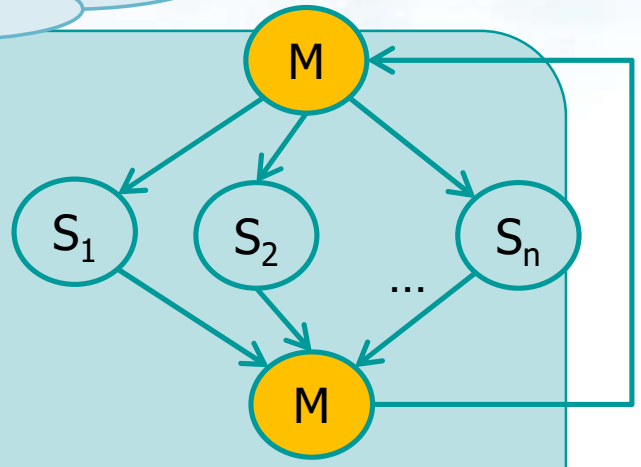
As the order in which all swaps are performed is not defined (inner iteration) the number of necessary outer iterations is upper bounded by n

```
for (i=0; i<n-1; i++)
  for (j=0; j<n-i-1; j++)
    if (v[j] > v[j+1])
      swap (v, i, j+1);
```



Solution 1

Solution in C with semaphores (no barriers)

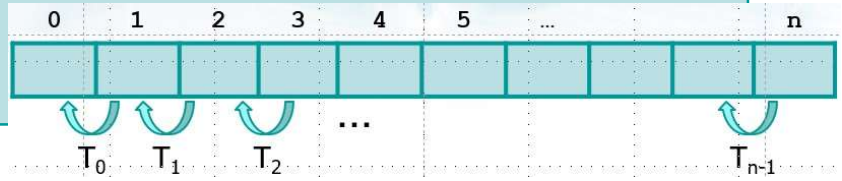



```
#include <stdio.h>

typedef enum {false, true} boolean;

int num_threads;
int vet_size;
int *vet;
boolean sorted = false;
boolean all_ok = false;
sem_t semMaster;
sem_t *semSlave;
pthread_mutex_t *me;

static int max_random (int);
void *master (void *);
void *slave (void *);
```

Boolean type (implicit in C++)

Global variables:
1 semaphore for the master thread
1 semaphore for each slave thread
1 mutex for each element of the vector

Prototypes



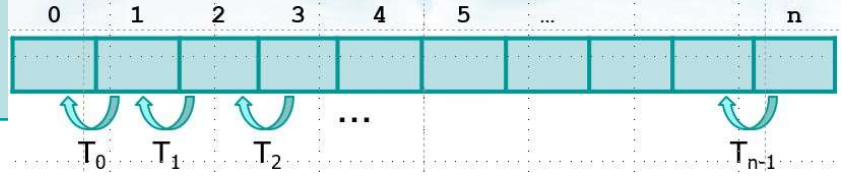
Solution 1

Main (Estract)
Part 1

```
int main (int argc, char **argv) {

  ... Definitions ...

  vet_size = atoi (argv[1]);
  num_threads = vet_size - 1;

  ... Allocations ...

  for (i=0; i<vet_size; i++) {
    vet[i] = max_random (1000);
  }
  for (i=0; i<vet_size; i++) {
    pthread_mutex_init (&me[i], NULL);
  }
```

Fill the vector with random numbers

Create a mutex for each element of the vector



Solution 1

Main (Estract) Part 2

MT starts

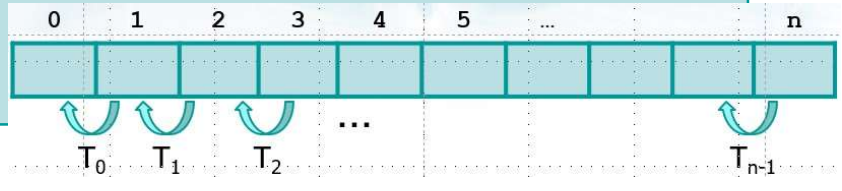
```
sem_init (&semMaster, 0, num_threads);
pthread_create (&thMaster, NULL, master, &num_threads);

for (i=0; i<num_threads; i++) {
  id[i] = i;
  sem_init (&semSlave[i], 0, 0);
  pthread_create (&thSlave[i], NULL, slave, &id[i]);
}

for (i=0; i<num_threads; i++) {
  pthread_join (thSlave[i], NULL);
}
pthread_join (thMaster, NULL);

... Free memory and semaphores ...
```

Creates 1 master thread

STs wait

Creates num_threads slave threads

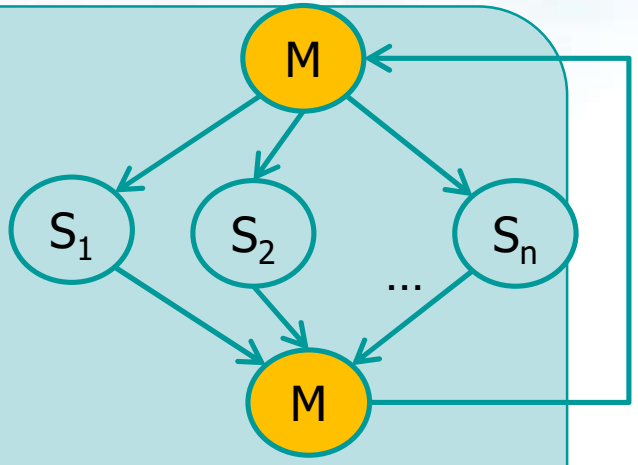
Wait all



Solution 1

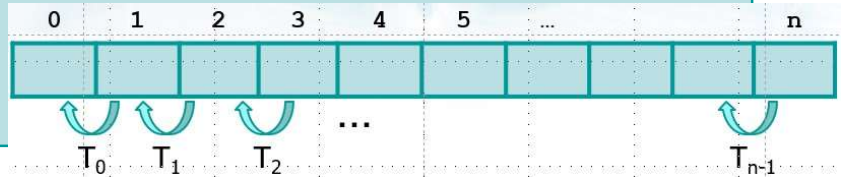
```
void *master (void *arg) {
  int *ntp, nt, i;
  ntp = (int *) arg;
  nt = *ntp;
  while (!sorted) {
    for (i=0; i<nt; i++)
      sem_wait (&semMaster);
    if (all_ok) {
      sorted = true;
    } else {
      all_ok = true;
    }
    for (i=0; i<nt; i++)
      sem_post (&semSlave[i]);
  }
  pthread_exit (0);
}
```

Wait for slave threads



If a worker performs a swap, it sets all_ok to false and here we set if back to true.
If no worker performs a swap, all_ok remais true, we set sorted to true, and slaves will stop at the next iteration

Wake up slave threads



Solution 1

```
void *slave (void *arg) {
  int i = *((int *) arg);
  while (1) {
    sem_wait (&semSlave[i]);
    if (sorted) break;
    pthread_mutex_lock(&me[i]);
    pthread_mutex_lock(&me[i+1]);
    if (vet[i] > vet[i + 1]) {
      swap (vet[i], vet[i + 1]);
      all_ok = false;
    }
    pthread_mutex_unlock(&me[i+1]);
    pthread_mutex_unlock(&me[i]);
    sem_post (&semMaster);
  }
  pthread_exit (0);
}
```

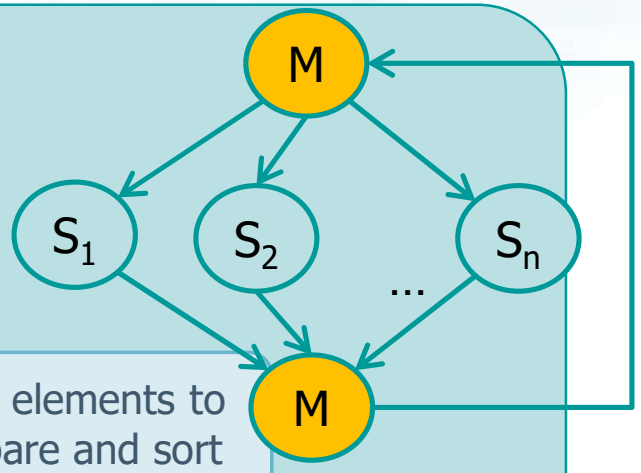
Wait the master thread

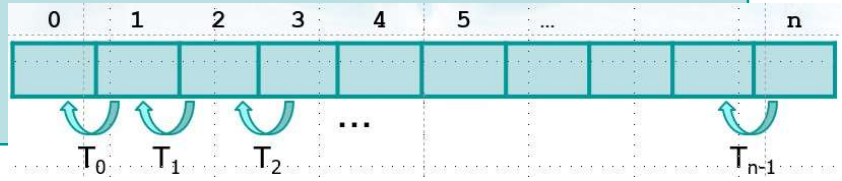
Get 2 elements to compare and sort

Sort them: If we do, set all_ok to false (cycle again)

Release elements

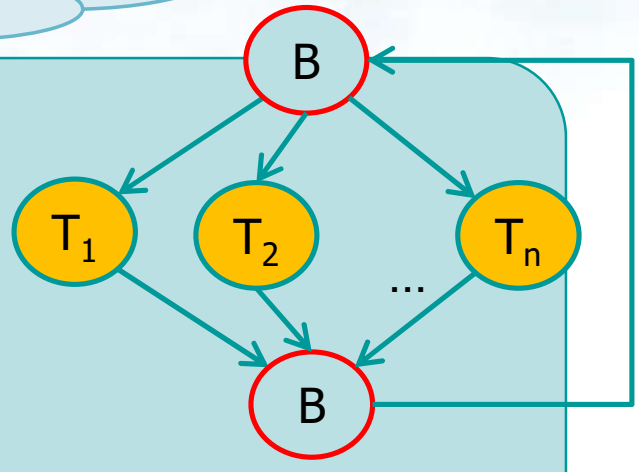
Wake up master thread





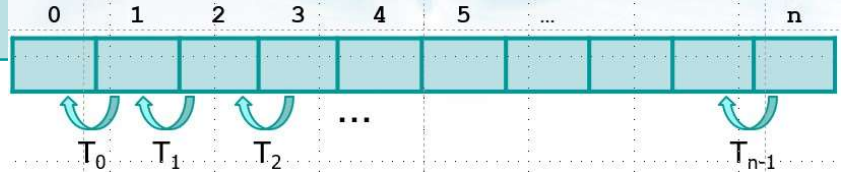
Solution 2

Solution in C with barriers




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

#define N 10

int count, vet[N];
int sorted = 0;
int all_ok = 1;
sem_t me[N];
sem_t mutex, barrier1, barrier2;
```

Instead of using one semaphore for each slave, why do not use barriers?



Solution 2

read_array read or generate the array

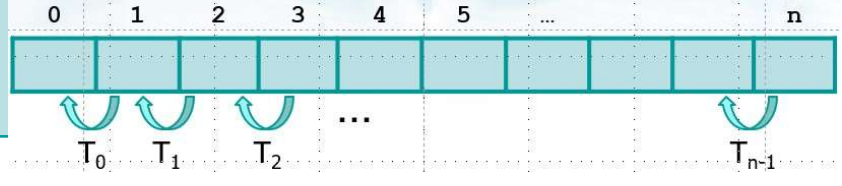
```
int main (int argc, char * argv[]) {
  ...
  count = 0;
  sem_init (&mutex, 0, 1);
  sem_init (&barrier1, 0, 0);
  sem_init (&barrier2, 0, 0);

  for (i=0; i<N; i++)
    sem_init (&me[i], 0, 1);

  for (i=0; i<N-1; i++) {
    id[i] = i;
    pthread_create (&th[i], NULL, sorter, &id[i]);
  }

  pthread_exit (0);
}
```

Create a mutex to protect the counter, and 2 barriers based on semaphores

Create a semaphore for each element of the vector

No joins (threads are detached)

Create N threads



Solution 2

```
static void *sorter (void *arg) {
  int *a = (int *) arg;
  int i, j, tmp;

  i = *a;

  pthread_detach (pthread_self ());

  while (!sorted) {
    sem_wait (&me[i]);
    sem_wait (&me[i+1]);
    if (vet[i] > vet[i+1]) {
      swap (vet[i], vet[i + 1]);
      all_ok = 0;
    }
    sem_post (&me[i + 1]);
    sem_post (&me[i]);
```

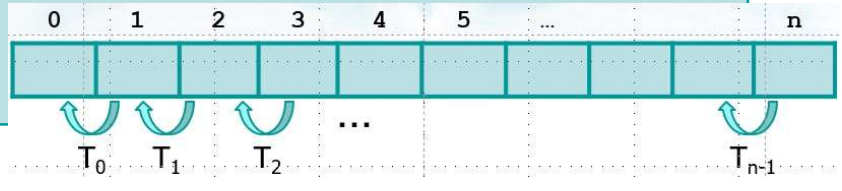
We do not need the master any more !!!

Acquires the 2 elements it has to manage

Sort them

all_ok remains 1 if no thread makes an exchange

Release the array elements



Solution 2

Barrier #1

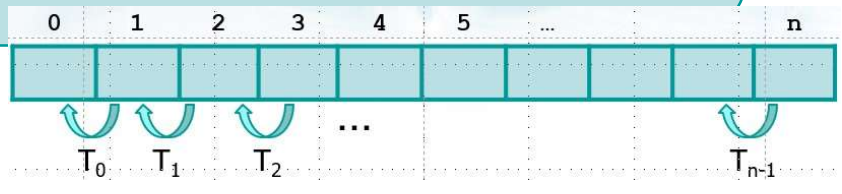
```
sem_wait (&mutex);
count++;
if (count == N-1) {
  for (j=0; j<N-1; j++)
    sem_post (&barrier1);
}
sem_post (&mutex);

sem_wait (&barrier1);
```

Before the iteration, you need to synchronize all the threads

The last thread to arrive unblock all threads

All the other threads wait on a barrier

The mutex protect the counter



Solution 2

```
    sem_wait (&mutex);
    count--;
    if (count == 0) {
      printf ("all_ok %d\n", all_ok);
      for (j=0; j<N; j++)
        printf ("%d ", vet[j]);
      printf ("\n");
      if (all_ok)
        sorted = 1;
      all_ok = 1;
      for (j=0; j<N-1; j++)
        sem_post (&barrier2);
    }
    sem_post (&mutex);
    sem_wait (&barrier2);
  }
  return 0;
}
```

Barrier #2

Only one barrier is not enough, because the last thread wake up all the threads, and a fast thread can iterate more times

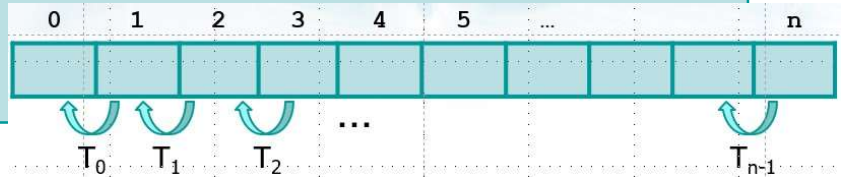
For this reason a second barrier is used

Restart (if necessary)

Block everything

The last thread to arrive unblock all

All the other threads wait on a barrier



Solution 3

- Can we use pthread_barrier_wait?
  - Yes, and one barrier should suffice for synchronization purposes
    - Unfortunately, we must also check if the array is sorted after the barrier
    - Thus, we need a second barrier anyway
  - In the second barrier, the last thread arriving checks the sorting and displays the array
    - It is convenient to implement it with a counter, a mutex, and a semaphore

Solution 3

Solution in C with one library barriers

```
pthread_barrier_wait (&barrier1);
sem_wait (&mutex);
count++;
if (count == N-1) {
  printf ("all_ok %d\n", all_ok);
  for (j=0; j<N; j++)
    printf ("%d ", vet[j]);
  fprintf (stdout, "\n");
  if (all_ok)
    sorted = 1;
  all_ok = 1;
  for (j=0; j<N-1; j++) {
    sem_post (&barrier2);
  }
  count = 0;
}
sem_post (&mutex);
sem_wait (&barrier2);
```

Barrier #1

Barrier #2

As Solution 2, but …

… we must reset the counter back to zero