Synchronization

Thread Throttles and Pools

Stefano Quer
Dipartimento di Automatica e Informatica
Politecnico di Torino

License Information

Introduction

Multi-threading: Designed to improve performance by allowing multiple threads to run concurrently.

Thread Creation and Destruction: Creating and destroying threads can be time-consuming and resource-intensive.
Number of Software Threads: The number of software threads is often limited by the number of hardware threads (CPU cores) available.

- Multi-threading is designed to improve performance, but it has overheads
  - Create and destroy a thread can be time-consuming
  - The number of software threads is a functions of the number of hardware threads
    - The **global load** has to be managed manually
    - **Over-subscription** occurs every time the number of software threads ready to start is higher than the number of hardware threads available in the system
    - Even without over-subscription, the running threads can exceed the system resources (e.g., memory-related ones) in **some code section**

Over-subscription: Occurs when the number of software threads ready to start is higher than the number of hardware threads available. This can lead to performance degradation due to excessive context switching.

Problem 1

Problem 2

Even without over-subscription, running too many threads can exceed system resources (e.g., memory) in certain code sections, leading to performance issues.

Introduction

Manual and Automatic Strategies: Various strategies can be employed to control overhead and prevent over-subscription.

- There are several manual and automatic strategies to keep overhead under control and avoid over-subscription
- In this section, we present
  - Semaphore Throttles
    - A strategy to manually reduce the number of workers in critical situations
  - Thread Pools
    - A design pattern for achieving concurrency but reducing overheads
    - Thread pools are also called the **replicated worker model** or the **worker-crew model**

Semaphore Throttles

Performance Degradation: Severe performance issues occur in specific "expensive" code sections where threads use too many resources, leading to high contention.

- Scenario
  - The user activate **N** worker threads
  - Unfortunately, performance degradation is severe in specific "expensive" code section
    - Ts use too much resources and contention is **high**
- "Semaphore throttles"

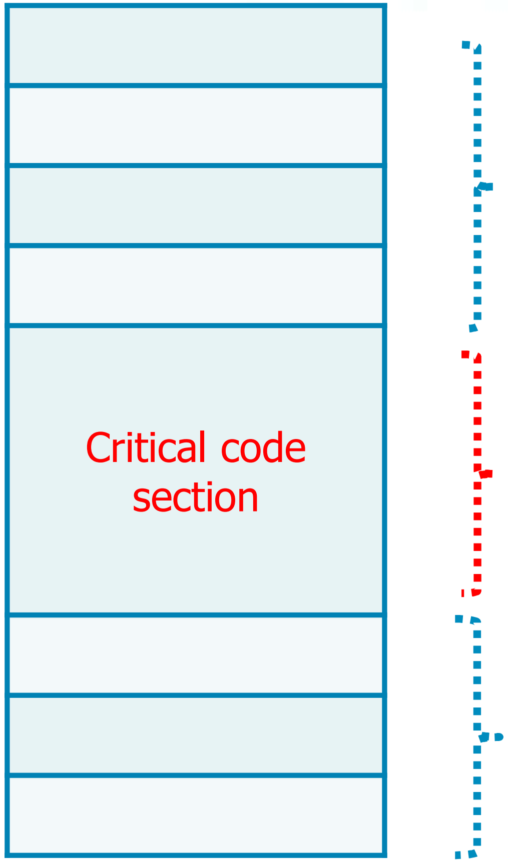
  Use a Semaphore: To limit the maximum number of threads running in specific (critical) sections of the code.

  - Use a semaphore to **reduce/fix** the **maximum** amount of running Ts in specific (**critical**) sections of the code
    - The boss T creates a **new** semaphore and sets the maximum number of Ts in the CS to a "reasonable value", depending on the number of cores, processors, etc.

Semaphore Throttles

Pseudo-code

Task



N threads may run

Less than **N** threads may run

N threads may run

n<<N

Initializes the semaphore sem with a maximum count of n. This means up to n threads can enter the critical section simultaneously.

```
sem_init (sem, n)
```

Before Critical Section:

```
...
```

Each thread calls sem_wait(&sem) before entering the critical section. If the semaphore count is greater than zero, it decrements the count and allows the thread to proceed. If the count is zero, the thread is blocked until the count becomes positive.

```
sem_wait (sem);
```

The thread executes the critical section code.

```
... CS ...
```

The critical section is a part of the code where shared resources are accessed or modified. It is critical because improper access can lead to data corruption or inconsistent results.
In this context, the critical section is where resource contention is high, and we want to limit the number of threads accessing it simultaneously to avoid performance degradation

```
sem_post (sem);
```

After exiting the critical section, the thread calls sem_post(&sem), which increments the semaphore count, potentially unblocking a waiting thread.

```
...
```

Semaphore Throttles
Limiting the number of threads working in the hyper-critical SC section

Task: Represents the overall task being executed by multiple threads.
Critical Code Section: A specific part of the code where resource contention is high.
Semaphore Throttles: Limits the number of threads that can enter the critical section simultaneously, reducing contention and improving performance.

Semaphore Throttles

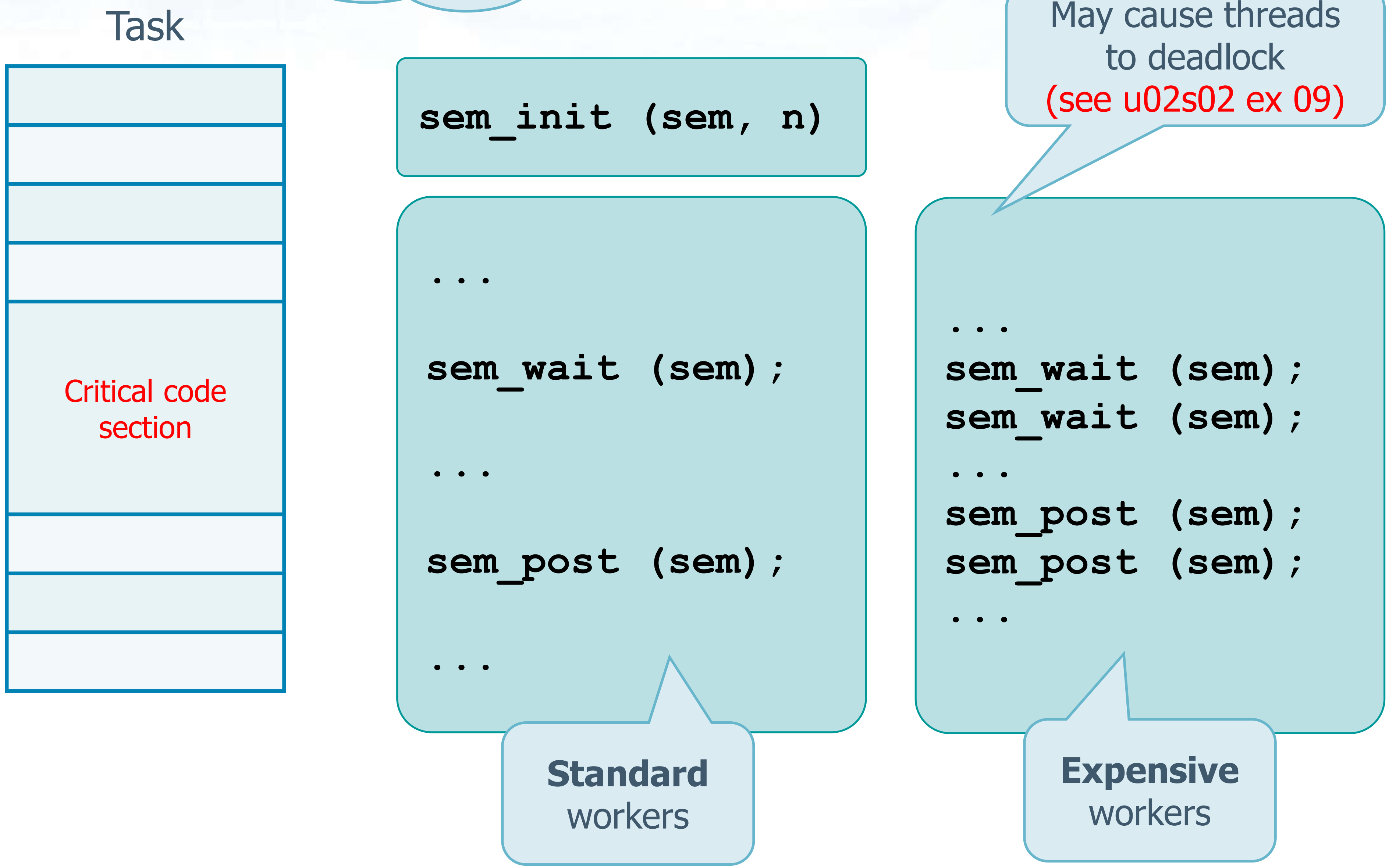
- The number of worker is tunable
  - The boss T may dynamically decrease or increase the number of active workers by waiting or releasing semaphore units
    - Notice that the maximum number of Ts allowed is set once and only once at initialization

Set it to be "large enough"

- Workers using more resources
  - Should acquire multiple semaphore units
    - The idea is that with expensive threads we may be forced to reduce the level of parallelism
  - Caution
    - Heavy threads can wait **more** on the throttles
    - We can generate deadlocks

Example (part A)

Pseudo-code



Example (part B)

Pseudo-code

Task

Critical code section

```
sem_init (sem, n)
mutex_init (m, 1)
```

```
...
mutex_lock (m);
sem_wait (sem);
mutex_unlock (m);
...
mutex_lock (m);
sem_post (sem);
mutex_unlock (m);
...
```

Standard workers

We need to see «waits» as part of a CS and protect them with a mutex

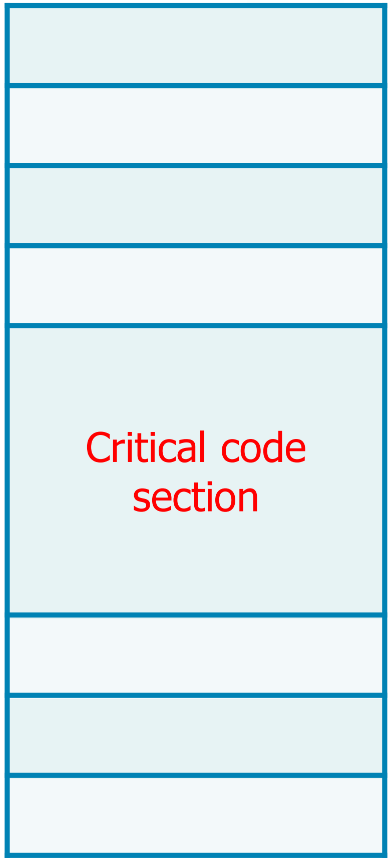
```
...
mutex_lock (m);
sem_wait (sem);
sem_wait (sem);
mutex_unlock (m);
...
mutex_lock (m);
sem_post (sem);
sem_post (sem);
mutex_unlock (m);
...
```

Expensive workers

Example (part C)

Pseudo-code

Task




```
sem_init (sem, n)
mutex_init (m, 1)
```

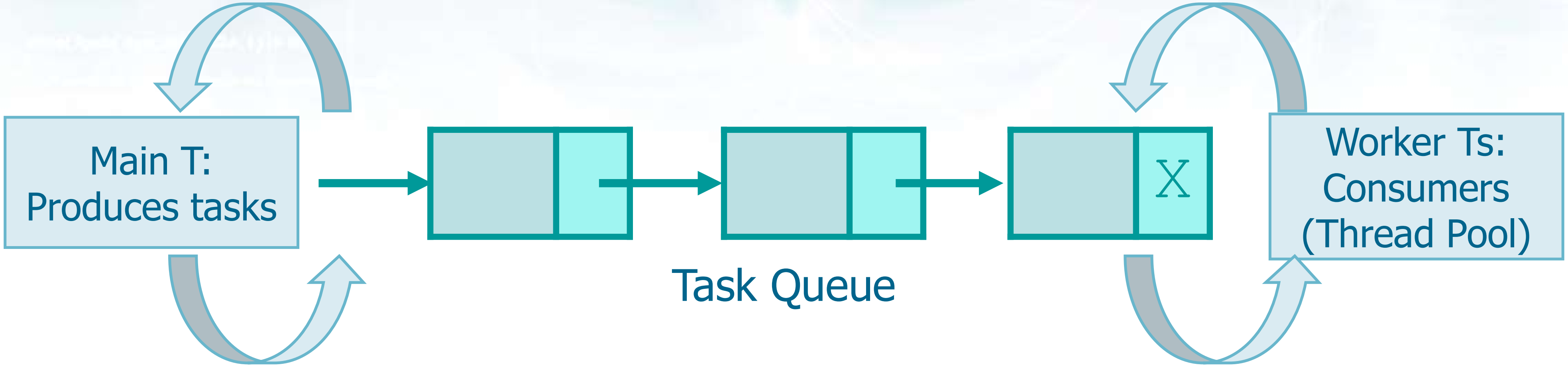
We need to see «waits» as part of a CS and protect them with a mutex

```
...
mutex_lock (m);
sem_wait (sem);
sem_wait (sem);
mutex_unlock (m);
...
mutex_lock (m);
sem_post (sem);
sem_post (sem);
mutex_unlock (m);
...
```

Expensive workers

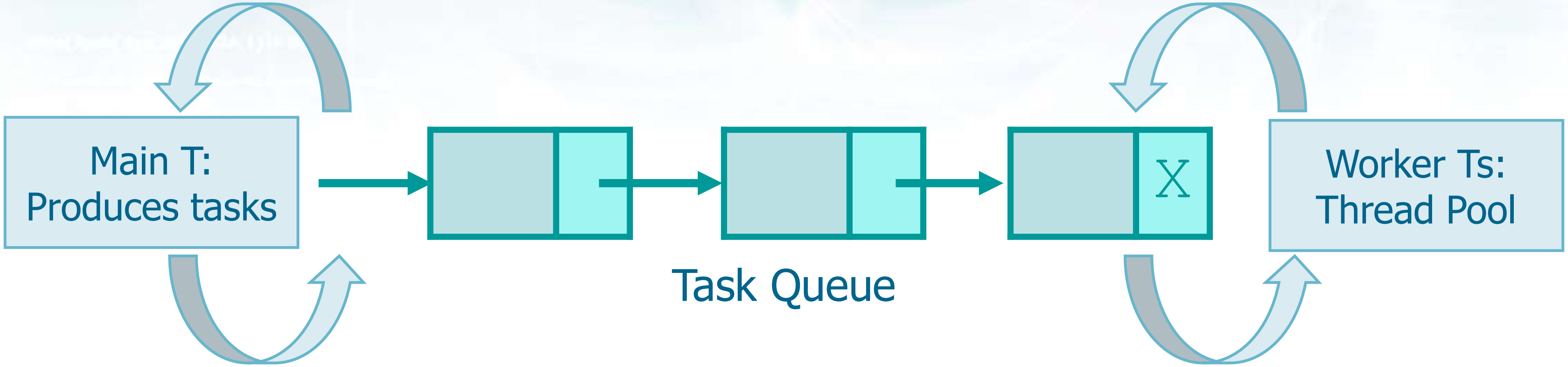
Even this scheme has limited applications and it can create a deadlock. For example, with n=3 the first expensive worker passes. but the second blocks everybody else because it stops on the second wait and it does not release the mutex.

Thread Pools



- A thread pool maintains multiple threads waiting for tasks to be allocated for concurrent execution
  - One main thread generates the tasks
    - Tasks are enqueued in a (FIFO) queue
      - Dynamic list, circular array, etc.
  - The thread pool organizes the working threads manipulating the tasks

Thread Pools



- More specifically
  - The Main thread
    - Initializes the "task queue" and the "working theads"
    - Creates "work objects" (or "tasks")
    - Inserts tasks into the queue
  - Worker threads in the pool
    - Get tasks from the queue

Thread Pools

- The size of a thread pool is the number of threads ready to execute tasks
  - It is a tunable parameter
  - It is crucial to optimize performance
    - Instead of a new thread for each task, thread **creation** (**destruction)** is restricted to the **initial** (**final)** generation of the pool
    - This often results in better performance and better system stability
    - An excessive number of threads may waste memory and increase context-switching incurring in performance penalties

Thread Pools

- Smart implementations of a thread pool may use specific tasks and specific functions
  - The queue stores the tasks to solve but also the functions to solve it
    - Tasks and functions **may vary** for each run
  - Functions are usually called **callback** functions

Exercise

- Implement a thread pool
  - In C
    - Use the producer-and-consumer paradigm
    - Producers create tasks and insert them into the queue
    - Consumers get tasks from the queue and manage them
    - Task can be a randomly **generated strings** to be **capitalized** and display on standard output
  - In C++
    - Use generic tasks and thread (callback) functions

C Solution I

(Trivial) C Version

- Logic behavior of a producer-consumer scheme

Initialization

```
init (full, 0);
init (empty, SIZE);
init (MEp, 1);
init (MEc, 1);
```

Producer

```
Producer () {
  int val;
  while (TRUE) {
    produce (&val);
    wait (empty);
    wait (MEp);
    enqueue (val);
    signal (MEp);
    signal (full);
  }
}
```

Consumer

```
Consumer () {
  int val;
  while (TRUE) {
    wait (full);
    wait (MEc);
    dequeue (&val);
    signal (MEc);
    signal (empty);
    consume (val);
  }
}
```

C Solution II

```c
typedef struct thread_s {
    int n, nP, nC;
    char **v;
    int size;
    int head;
    int tail;
    pthread_mutex_t meP;
    pthread_mutex_t meC;
    sem_t empty;
    sem_t full;
} thread_t;
```

n = Number of (total) tasks
nP = Number of tasks produced
nC = Number of tasks consumed

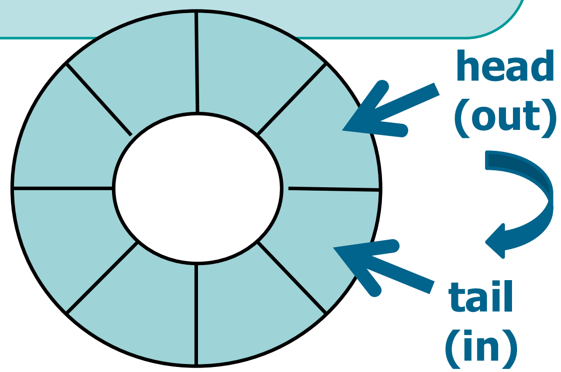
Task array (pointer to strings)

Size, head and tail index of the queue (for in and out)

Mutual exclusion for producers and consumers

Empty and full task queue

Circular buffer



C Solution III

```
tp = my_malloc (P, sizeof (pthread_t));
tc = my_malloc (C, sizeof (pthread_t));
thread_d.n = N;
thread_d.nP = thread_d.nC = 0;
thread_d.size = SIZE;
thread_d.v = my_malloc (thread_d.size, sizeof (char *));
thread_d.head = thread_d.tail = 0;
pthread_mutex_init (&thread_d.meP, NULL);
pthread_mutex_init (&thread_d.meC, NULL);
sem_init (&thread_d.empty, 0, SIZE);
sem_init (&thread_d.full, 0, 0);

for (i=0; i<P; i++)
    pthread_create(&tp[i], NULL, producer, (void *) &thread_d);
for (i=0; i<C; i++)
    pthread_create(&tc[i], NULL, consumer, (void *) &thread_d);

for (i=0; i<P; i++)
    pthread_join (tp[i], NULL);
for (i=0; i<C; i++)
    pthread_join (tc[i], NULL);
```

Initialization

Stop the pool after N tasks

Create the worker threads

Wait all threads

C Solution IV

Producer

```
static void *producer (void *arg) {
  thread_t *p; int goon = 1;
  p = (thread_t *) arg;
  while (goon == 1) {
    waitRandomTime (...);
    sem_wait (&p->empty);
    pthread_mutex_lock (&p->meP);
    if (p->nP > p->n) {
       goon = 0;
    } else {
       p->nP = p->nP + 1; p->v[p->tail] = generate();
       printf ("Producing %d: %s\n", p->nP, p->v[p->tail]);
       p->tail = (p->tail+1) % SIZE;
    }
    pthread_mutex_unlock (&p->meP);
    sem_post (&p->full);
  }
  pthread_exit ((void *) 1);
}
```

Protect queue

Protect producers

Stop after N tasks

See complete solution for details

Insert the task in the queue

C Solution V

Consumer

```
static void *consumer (void *arg) {
  thread_t *p; int goon = 1; char *str;
  p = (thread_t *) arg;
  while (goon == 1) {
    pthread_mutex_lock (&p->meC);
    if (p->nC > p->n) {
      goon = 0;
    } else {
      p->nC = p->nC + 1;
      sem_wait (&p->full);
      str = p->v[p->head]; convert (str);
      printf ("--- CONSUMING %d: %s\n", p->nC, str);
      free (str); p->head = (p->head+1) % SIZE;
      sem_post (&p->empty);
    }
    pthread_mutex_unlock (&p->meC);
  }
  pthread_exit ((void *) 1);
}
```

Protect consumers

Protect queue

See complete solution for details

C++ Solution I

(Complex) C++ Version (Partial)

In the general case, tasks are call-back functions that must be run by the working thread

```
class ThreadPool {
public:
  void Start();
  void QueueJob(const std::function<void()>& job);
  void Stop();
  void busy();

private:
  void ThreadLoop();

  // Tells threads to stop looking for jobs
  bool should_terminate = false;
  // Prevents data races to the job queue
  std::mutex queue_mutex;
  // Allows threads to wait on new jobs or termination
  std::condition_variable mutex_condition;
  std::vector<std::thread> threads;
  std::queue<std::function<void()>> jobs;
};
```

C++ Solution II

- Running threads in the pool
  - Each thread should run its own infinite loop, constantly waiting for new tasks to grab and execute

```
void ThreadPool::Start() {
  // Max # of threads the system supports
  const uint32_t num_threads =
    std::thread::hardware_concurrency();

  threads.resize(num_threads);
  for (uint32_t i = 0; i < num_threads; i++) {
    threads.at(i) = std::thread(ThreadLoop);
  }

  return;
}
```

Define pool size

Run worker threads

C++ Solution III

- The infinite loop function
  - A loop waiting for the task queue to open up

```
void ThreadPool::ThreadLoop() {
  while (true) {
    std::function<void()> job;
    {
      std::unique_lock<std::mutex> lock(queue_mutex);
      mutex_condition.wait(lock, [this] {
        return !jobs.empty() || should_terminate;
      });
      if (should_terminate) {
        return;
      }
      job = jobs.front();
      jobs.pop();
    }
    job();
  }
}
```

Workers wait on a condition variable

Terminate worker thread

Get a task from a queue (and erase it in the queue)

C++ Solution IV

- Add a new job to the pool
  - Use a lock so that there is not a data race
  - Once the job is there, signal a condition variable to wake-up one worker

```
void ThreadPool::QueueJob(const std::function<void()>& job) {
  {
  std::unique_lock<std::mutex> lock(queue_mutex);
  jobs.push(job);
  }
  mutex_condition.notify_one();
}
```

Insert a tack in the queue

Protect the task queue

Notify one working tread

C++ Solution V

- Use the thread pool
  - The function **busy** can be used in a while loop, such that the main thread can wait the thread pool to complete all the tasks before calling the thread pool destructor

```
thread_pool->QueueJob([] { /* ... */ });


void ThreadPool::busy() {
  bool poolbusy;
  {
    std::unique_lock<std::mutex> lock(queue_mutex);
    poolbusy = jobs.empty();
  }
  return poolbusy;
}
```

Polling to know whether all job have been done

C++ Solution VI

- Stop the pool

```
void ThreadPool::Stop() {
  {
    std::unique_lock<std::mutex> lock(queue_mutex);
    should_terminate = true;
  }
  mutex_condition.notify_all();
  for (std::thread& active_thread : threads) {
    active_thread.join();
  }
  threads.clear();
}
```

Notify all threads

Join all working threads

Conclusions

- Thread pools are used to limit the cost of re-creating threads over and over again
  - There are languages / environments in which thread pools have an explicit support
    - Windows API, C++
  - Smart implementations may use a **callback** function
    - The queue stores the tasks to solve and the functions to solve them
      - Functions and task can differ
      - Functions are usually called callback function