Systems Programming

Lecture 8 | 18th of November 2018

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Level 3 Student Survey

http://bit.do/lv3survey

Recap of last week

- **C++** provides **thread** facilities similar to Pthread, but easier to use:

```
auto t = std::thread([](){ printf("Hello World from a thread!\n"); }); t.join();
```

- For this we learned two useful features of C++: type inference with **`auto`** and **lambda expressions**
- We use the idea of temporary **ownership** of a **`std::mutex`** to provide mutual exclusion without the possibility to forget to unlock
- To make data structures thread safe we can **encapsulate** an unsafe version and provide a thread safe interface to them
- A **task** is an abstraction of a thread, where we no longer think about low level synchronisation mechanisms, but instead about **communication** between tasks
- **`std::async`** launches a task and communicates its result back via a **`std::future`**
- A **`std::future`** is the reading end of a communication channel. The writing end is called a **`std::promise`**

Thread safe interfaces

- We discussed last week the encapsulation of a non-thread-safe data structure to make it thread-safe
- This might involve changing the interface of the data structure! Let's have a look at `std::list`:

```
while ( list.size() > 0 ) {
  auto item = list.front();
  list.pop_front();
  // ...
}
```

- In the code snippet we want to remove elements until the list is empty
- The interface of `std::list` splits this into three functions: `size`, `front` and `pop_front`
- Even if we assume that each individual function is protected with a mutex, there are problems
- For example could two threads simultaneously execute `list.front();`
  both access the first element of the list; and then
  both threads call `pop_front()`, resulting in the second element to be removed but never accessed

A thread-safe interface for `std::list` - Take 1

- To address this we can change the interface into a single function:

```
struct maybe_safe_list {
private: std::list<int> list; std::mutex m;
public:
  void push_back(int i) { ...  }
  int size() { ... }
  int ts_pop_front() {
    std::unique_lock<std::mutex> l(m); // protect the function body
    auto item = list.front(); list.pop_front();
    return item;
  } };
```

- We have to adapt the client code as well:

```
  while ( list.size() > 0 ) { auto item = list.ts_pop_front(); /* ... */ }
```

- This resolves the issue, as now `front()` and `pop_front()` have to be executed together
- Is the implementation now thread-safe?

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```
  while ( list.size() > 0 ) { auto item = list.ts_pop_front(); /* ... */ }
```

- This resolves the issue, as now `front()` and `pop_front()` have to be executed together
- Is the implementation now thread-safe?
- No! Two threads could execute `size()` simultaneously for a list with 1 element;

A thread-safe interface for `std::list` - Take 2

- So we have to combine the `size` check into the same function:

```
// The function might now return no value when the list is empty
std::optional<int> ts_pop_front() {
  std::unique_lock<std::mutex> l(m); // enter critical section
  if (list.size() > 0) { // check if there is an element to remove
    auto item = list.front();
    list.pop_front();
    return item; // return item after it has been removed
  } else {
    return {};    // nothing to remove; return empty optional
  }
} // exit critical section
```

- This function can now be used in a thread safe way:

```
auto item = list.pop_front();
while ( item.has_value() ) { printf("%d\n", item.value()); item = list.pop_front(); }
```

- We have seen, that it is sometimes required to change the interface design to make an interface thread-safe!

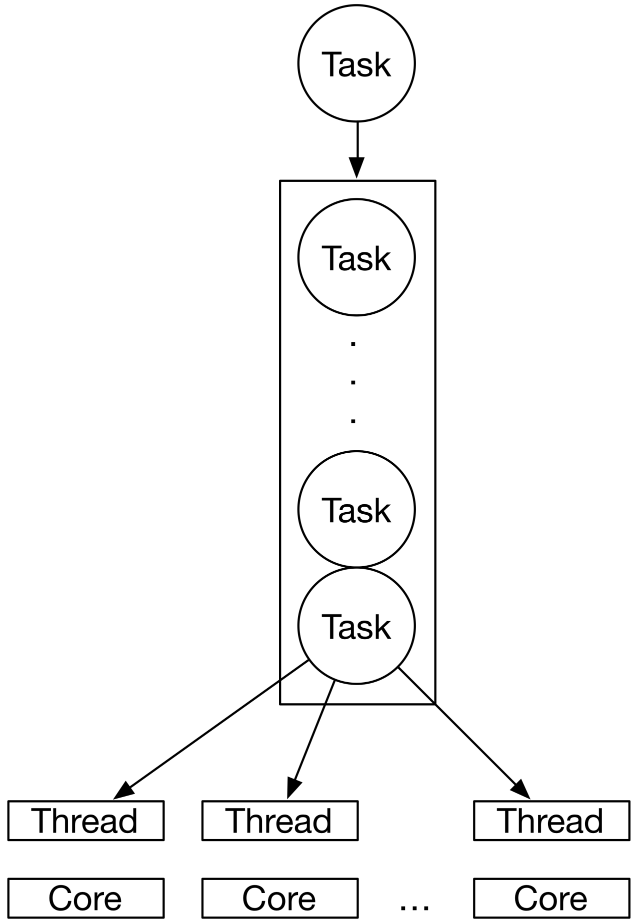
Task management

- Last week we have seen `std::async` as a way to launch *tasks* that communicate their computed results back via an `std::future`
- This way we can write applications without caring about low level synchronisation issues
- In the rest of the lecture we will investigate a task management system
- This is based on the excellent talk *"Better Code: Concurrency"* by Sean Parent
  http://sean-parent.stlab.cc/papers-and-presentations/#better-code-concurrency
- Sean Parent has more excellent tasks about modern `C++` on his website

A basic task system

- We start by building a task system that operates with a single queue to manage the incoming tasks
- Multiple threads will take tasks out of the queue and execute them concurrently
- This follows the guidelines of an multi-threaded programming guide published in 2010 by Oracle

  (https://docs.oracle.com/cd/E19253-01/816-5137/ggedn/index.html)



`std::function` for passing functions as arguments

- Each task is defined by the function it executes
- To add a task into our task system we provide a function as argument
- In `C` we have used function pointers for this:

```
void foo() { ... }

void async( void(*f)() ) { ...}
int main() { async(foo); }
```

- In `C++` we use `std::function`:

```
void foo() { ... }

void async( std::function<void()> f ) { ... }
int main() { async(foo); }
```

- We specify the type signature of the function in the < angle brackets >: `std::function<void()>`

The basic queue implementation

```
struct notification_queue {
private:
  std::list<std::function<void()>> q;     // this is our list of tasks; each task is a function
  std::mutex                       m;     // a mutex to protect the queue
  std::condition_variable          ready; // a condition variable indicating available tasks
public:
  std::function<void()> pop() {           // pop removes a task from the queue
    std::unique_lock<std::mutex> lock(m); // enter a critical section to protect the std::list
    ready.wait(lock, [this]{ return !q.empty(); }); // it waits until a task is in the queue
    auto f = q.front(); // access the first task ...
    q.pop_front();      // ... remove it from the queue
    return f;           // ... and return it
  } // exit critical section

  void push(std::function<void()> f) {    // push adds a task to the queue
    {
      std::unique_lock<std::mutex> lock(m); // enter critical section to protect the std::list
      q.push_back(f);                       // add task f to the queue
    } // exit critical section
    ready.notify_one();   // notify a waiting thread that a task is in the queue
  }
};
```

The basic task system implementation

```
struct task_system {
private:
  const int count = std::thread::hardware_concurrency(); // init with number of cores
  std::vector<std::thread> threads;   // a vector to store all the worker threads
  notification_queue q;               // the queue to store the tasks

  void run(int i) {  // function executed by each worker thread
    while (true) { auto f = q.pop(); f(); } // forever, we remove a task and execute it
  }
public:
  task_system() { // This is the constructor
    printf("Start task system with %d threads\n", count);
    for (auto n = 0; n != count; n++) { // for each hardware core ...
      threads.emplace_back([this, n](){ run(n); }); } // ... we create a thread executing run
  }

  ~task_system() { // This is the destructor
    for (auto n = 0; n != count; n++) { threads[n].join(); } // we ensure to wait for all threads
  }

  void async(std::function<void()> f) { // This is the interface to add tasks to the system
    q.push(f);  // we simply push the task into the queue, which will notify a waiting thread
  }
};
```

Stopping Tasks

```
struct notification_queue {
private:
  std::list<std::function<void()>> q; std::mutex m; std::condition_variable ready;
  bool done = false; // this flag indicates the end of executing tasks
public:
  // We change the return type, as pop might now return 'nothing' when done is set
  std::optional<std::function<void()>> pop() {
    std::unique_lock<std::mutex> lock(m);
    ready.wait(lock, [this]{ return (!q.empty()) || done; }); // if done is set we will not wait
    if (q.empty()) return {}; // if the queue is empty (because done was set) we return 'nothing'
    auto f = q.front();
    q.pop_front();
    return f;
  }
  void push(std::function<void()> f) { ... }
  void setDone() {
    {
      std::unique_lock<std::mutex> lock(m); // enter critical region to protect 'done'
      done = true;                          // set done
    }
    ready.notify_all();                     // Notify all threads that they should finish
  }
};
```

Stopping Tasks

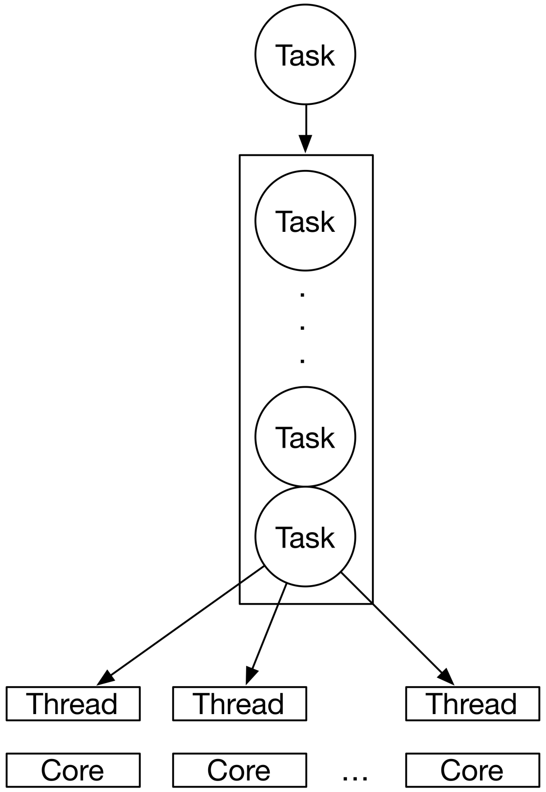
```
struct task_system {
private:
  const int count = ... ; std::vector<std::thread> threads; notification_queue q;
  void run(int i) {
    while (true) {
      auto optional_f = q.pop();             // we now return an optional
      if (!optional_f.has_value()) return;   // if 'nothing' was returned we exit the function
      auto f = optional_f.value();           // if something was returned we get the task out ...
      f();                                   // ... and execute it
    }
  }

public:
  task_system() { ... }

  ~task_system() {
    q.setDone(); // when we destroy the task system, let all threads now they should finish ...
    for (auto n = 0; n != count; n++) { threads[n].join(); } // ... and then wait for them
  }

  void async(std::function<void()> f) { ... }
};
```

Performance of the simple task system



Pretty bad performance, as all threads access the same queue there is a lot of blocking an waiting

Take 2: Improved task system - Multiple Queues

- **Idea**: to reduce blocking and waiting time use multiple queues
- A scheduling policy will decide in which queue to enter the task
- Each thread will exclusively access tasks from their own queue
- Different scheduling policies could be implemented, we pick a very simple, but widely used one: *round robin*
    - Every time a task has been added to a queue we add the next task to the next queue
    - Once we arrive at the last queue, we start again with the first queue
- For this implementation we use the exact same queue implementation as before , we only change the task system

The multi-queue task system implementation

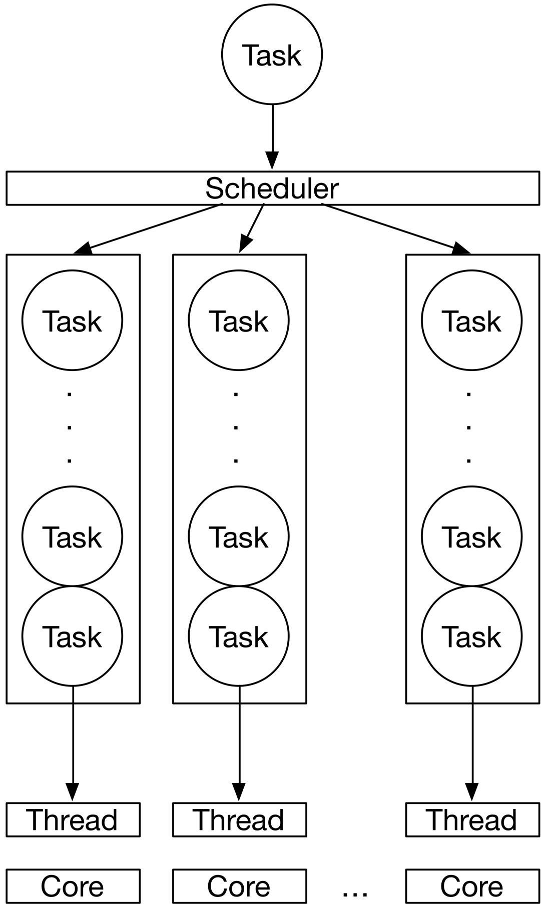
```
struct task_system {
private: const int  count = ...; std::vector<std::thread> threads;
  // we now have one queue per thread
  std::vector<notification_queue> q = std::vector<notification_queue>(count);
  // this 'atomic' int can be incremented thread-safely without requiring a lock
  std::atomic<int> index = 0;

  void run(int i) {
    while (true) {
      auto optional_f = q[i].pop(); // now every thread pops the tasks from their queue
      if (!optional_f.has_value()) return;
      auto f = optional_f.value(); f(); } }
public:
  task_system() { ... }

  ~task_system() {
    for (auto n = 0; n != count; n++) { q[n].setDone();} // indicate each queue to finish
    for (auto n = 0; n != count; n++) { threads[n].join(); }
  }

  void async(std::function<void()> f) {
    // This implements the round robin scheduling
    auto i = index++;      // every time increment the index by one
    q[i % count].push(f); // the modulo makes sure that we are staying in bound
```

Performance of multi-queue task system



Better performance, but still not great. Some threads might have more work than others.

Take 3: Improved task system - Work stealing

- **Idea**: Let a thread try to help others by stealing a task - if one is available - from the other threads queues. If no task can be stolen, wait on your own queue for a task to arrive.

- Work stealing only works efficiently if we can avoid blocking (i.e. waiting for a task to arrive) when we steal

- In `C++` we can *try to acquire* a `mutex`.
  If the mutex is locked we do not block:

```
void try_lock() {
  std::unique_lock<std::mutex> lock(m, std::try_to_lock);
  if (!lock) { // if not locked successfully
    return; }  // do not enter critical section
  // otherwise enter critical section
  // ...
}
```

Updated Queue - `try_push`, `try_pop`

```
struct notification_queue {
private:
 std::list<std::function<void()>> q; bool done=false; std::mutex m; std::condition_variable ready;
public:
  // new function: tries to pop, if queue is locked it will return 'nothing'
  std::optional<std::function<void()>> try_pop() {
    std::unique_lock<std::mutex> lock(m, std::try_to_lock); // do not wait if the mutex is locked
    if (!lock || q.empty()) return {}; // we have to(!) check if the lock was acquired
    auto f = q.front(); q.pop_front(); return f;
  }
  // new function: tries to push, if queue is locked it will return false
  bool try_push(std::function<void()> f) {
    { std::unique_lock<std::mutex> lock(m, std::try_to_lock);
      if (!lock) return false; // return false to indicate that the push has not been successful
      q.push_back(f);
    }
    ready.notify_one();
    return true; // return true if the task was successfully added to the queue
  }

  std::optional<std::function<void()>> pop() { ... }
  void push(std::function<void()> f) { ... }
  void setDone() { ... }
```

Updated task system - run

```
struct task_system { private: // ...

void run(int i) { while (true) {
  std::optional<std::function<void()>> optional_f;
  // first try to steal from all other queues
  for (auto n = 0; n != count; n++) {
    optional_f = q[ (i + n) % count ].try_pop();
    if (optional_f.has_value()) break; // once a steal was successful -> stop looking
  }
  // if we have not stole successfully, we are accessing our own queue ...
  if (!optional_f.has_value()) {
    // ... and potentially block and wait
    optional_f = q[i].pop();
    if (!optional_f.has_value()) return; // if our queue returns no task, we are done
  }
  // if we (somehow) got a task ...
  auto f = optional_f.value(); // ... access ...
  f();                         // ... and execute it
} }

public:
  task_system()  { ... }    ~task_system() { ... }
  void async(std::function<void()> f) { ... } // see next slide
};
```

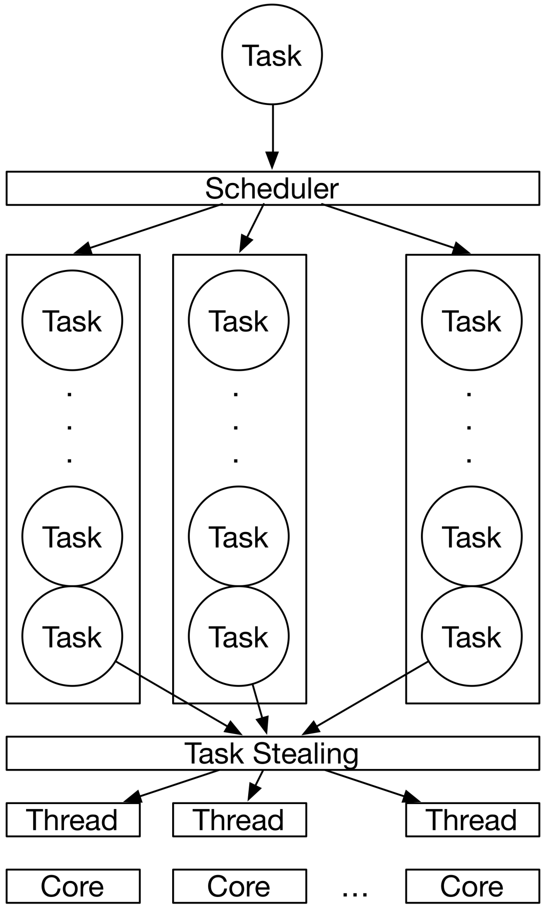
Updated task system - async

```
struct task_system {
private: // ...
  void run(int i) { ... }

public:
  task_system()  { ... }
  ~task_system() { ... }

  void async(std::function<void()> f) {
    auto i = index++;
    // first try to insert in all other queues
    for (auto n = 0; n != count; ++n) {
      // if an insertion is successful, return from the function
      if (q[ (i + n) % count ].try_push(f)) return;
    }
    // only if no other insertion was successful, add in our own queue
    // and potentially block
    q[i % count].push(f);
  }
};
```

Performance of work stealing task system



Very good performance.
Work stealing is a crucial technique for a high-performance task system

System Programming Recap - Part 1

- In this course we have studied systems programming. We have learned, that:
  - **data types** give bit representations in memory a meaning
  - **structs** allow us to implement custom data structures (like link lists or trees)
  - every variable is stored at a fix location **memory**
  - a **pointer** is a variable storing the address of a memory location
  - memory on the **stack** is automatically managed but memory on the **heap** must be managed manually
  - to organise resource and memory management we should think about **ownership**
  - in C++ ownership is implemented by tying the resource management to the **lifetime** of a stack variable
  - there exist a set of **smart pointers** and **containers** for easy and non-leaking memory management
  - **debuggers**, **static** and **dynamic analysis tools** help to detect and fix bugs

System Programming Recap - Part 2

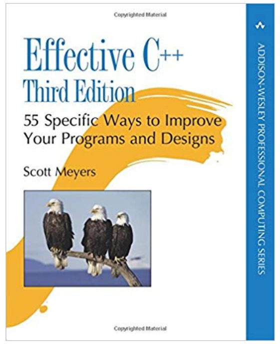
- In the second part of the course, we talked about programming concurrent systems. We learned, that:
  - **concurrency** is a programming paradigm to *deal with lots of things at once*
  - **parallelism** is about *doing lots of things at once* and this way making a program run faster
  - multiple **threads** share the same address space of a single **process**
  - `Pthreads` is a threading implementation in `C`, `C++` provides threads in its standard library
  - **mutual exclusion** ensures that two threads don't simultaneously enter their **critical section**
  - **condition variables** are a synchronisation mechanism to avoid busy waiting for a condition
  - the bounded buffer is an example of a **monitor**, an object that encapsulates low level synchronisation
  - **tasks** provide an abstraction over threads:
    we thing about communicating tasks rather than threads modifying shared state
  - a **task system** allows to efficiently use hardware threads using multiple queues and **work-stealing**

Where to go from here?

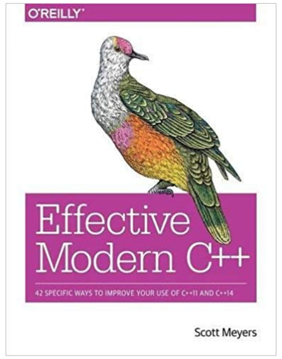
- There a multiple *systems* courses that build up on the ideas you have learned in this course:
  - *Operating Systems*
  - *Networked Systems*
  - *Distributed and Parallel Technologies*
  - *Advanced Systems Programming*
- For all of these it is important to have a good understanding of **memory** as discussed it in this course
- In *Advanced Systems Programming* you are going to learn *Rust* - a modern systems programming language - that enforces the idea of ownership to guarantee concurrent data race free programs

More Reading and Viewing Tips

- You have seen pretty much everything there is too see of `C` in this course
- You have pretty much seen only a very small fraction of `C++` in this course
- There is much more to discover in `C++`. These two books are good intermediate reading material:



Great best practice guide of C++



Great best practice guide of modern C++.
Complementary to the first book

- There are many great talks about `C++` on Youtube (and other video platforms):
  - *Sean Parents* series on *Better Code*: http://sean-parent.stlab.cc/papers-and-presentations/

Next week

- Guest lecture:
  Alastair Murray from **Codeplay** will be talking about his industry experience in systems programming
- Codeplay is a Edinburgh based company working on *compilers*, *debuggers*, *runtimes*, *testing systems*, and other software *development tools*.
- They have had (and currently have) Glasgow University students for placements and internships

Systems Programming

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