CS 4414: Recitation 10

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Today: Multithreading and Functional Programming in C++

Multithreading Part III (BS Chapter 15)

- std::condition_variable
- Asynchronous computation in C++: std::future<>, std::promise<>, std::packaged_task, std::async
- Code walkthrough of third-party thread pooling libraries

Lazy Evaluation in C++ (From the book Functional Programming in C++)

- Implementation of lazy_val
- Lazy evaluation as an optimization technique
- Generalized memoization
- Expression templates

Synchronization in C++: std::condition_variable

- Pattern: A thread waits for a condition to be true. Another thread updates the condition and notifies the first thread.
- Updating thread
  - acquire a std::mutex (using a std::scoped_lock)
  - perform the update
  - call notify_one or notify_all ()
- Waiting thread
  - acquire the same std::mutex (using a std::unique_lock)
  - call wait, wait_for or wait_until supplying the condition as a predicate

std::condition_variable: wait and notify

```cpp
template< class Predicate >
void wait( std::unique_lock<std::mutex>& lock, Predicate pred );
```

- atomically unlocks lock
- reacquires it after waking up
- continues if the condition is true
- goes back to wait (unlocking again) if the condition is false

```cpp
void notify_one() noexcept;
```

- unblocks one of the waiting threads
- notify_all unblocks all of the waiting threads

Notes about std::condition_variable

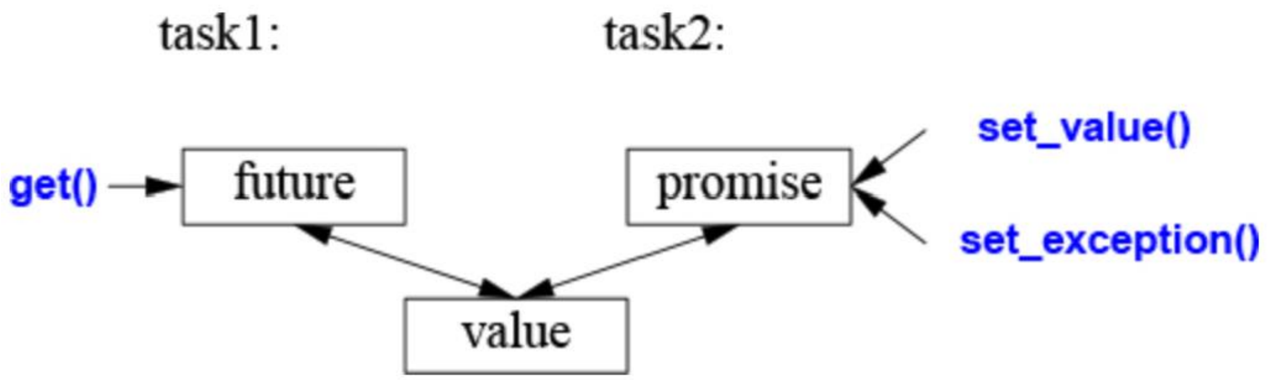
- Beware of spurious wake-ups! Always check the condition in wait.
- Why use a std::unique_lock<std::mutex> in wait? Because std::scoped_lock<std::mutex> does not offer the lock and unlock operations required in wait.
- std::condition_variable only works with std::mutex. Use std::condition_variable_any to work with other mutex types, for e.g. std::shared_mutex
- A writer can notify all readers waiting using std::condition_variable_any::notify_all. All readers can now work simultaneously holding the std::shared_mutex.

Thinking in terms of tasks

- In many cases, we don’t need to think at the lower level of threads and locks
- Task – work that needs to be done, potentially concurrently
- C++ provides std::future and std::promise, std::packaged_task and std::async
- Defined in #include<future>

Communicating tasks: std::future<> and std::promise<>

- Enable transfer of value between threads (or tasks) without explicit use of a lock
- std::promise<> is used by the producer task to supply the value
- std::future<> is used by the thread that needs the value



Using std::future<T>

```
T get();
```

- Blocks the thread until the result is available
- If the producer thread sets an exception, throws that same exception

```
template< class Rep, class Period >
std::future_status wait_for( const std::chrono::duration<Rep,Period>& timeout_duration ) const;
```

- Waits for a value until the provided timeout
- If you only want to check if the result is available without waiting, pass a duration of 0
- returns one of future_status::deferred, future_status::ready or future_status::timeout. If ready, call get to obtain the value

Using std::promise<R>

```
std::future<R> get_future();
```

- Returns the associated future object
- Can only call this once

```
void set_value( const R& value );
```

- Atomically stores the value into the shared state
- Now get on the associated future will unblock

```
void set_exception( std::exception_ptr p );
```

- Indicate that there won’t be any value, but an exception instead

Communicating tasks: std::packaged_task<R(Args...)>

- Solves the problem of managing futures and promises

Important functions

- template <class F> explicit packaged_task(F&& f);
- std::future<R> get_future();
- void operator()(ArgTypes... args);

std::packaged_task<R(Args...)> code example

```
double accum(double* beg, double* end, double init)
    // compute the sum of [beg:end) starting with the initial value init
{
    return accumulate(beg,end,init);
}

double comp2(vector<double>& v)
{
    using Task_type = double(double*,double*,double);          // type of task

    packaged_task<Task_type> pt0 {accum};                       // package the task (i.e., accum)
    packaged_task<Task_type> pt1 {accum};

    future<double> f0 {pt0.get_future()};                       // get hold of pt0's future
    future<double> f1 {pt1.get_future()};                       // get hold of pt1's future

    double* first = &v[0];
    thread t1 {move(pt0),first,first+v.size()/2,0};             // start a thread for pt0
    thread t2 {move(pt1),first+v.size()/2,first+v.size(),0};    // start a thread for pt1

    // ...

    return f0.get()+f1.get();                                   // get the results
}
```

Communicating tasks: std::async

- Async is used to specify tasks that run asynchronously, potentially in other threads
- No need to even think about threads, C++ manages them possibly as part of a thread pool
- There is no synchronization between the async tasks. Don't use it if you need synchronization!
- For specialized parallel executions, C++'s algorithm library offers execution policies such as std::execution::seq, std::execution::par, std::execution::par_unseq, and std::execution::unseq

std::async code example

```
double comp4(vector<double>& v)
    // spawn many tasks if v is large enough
{
    if (v.size()<10000)          // is it worth using concurrency?
        return accum(v.begin(),v.end(),0.0);

    auto v0 = &v[0];
    auto sz = v.size();

    auto f0 = async(accum,v0,v0+sz/4,0.0);              // first quarter
    auto f1 = async(accum,v0+sz/4,v0+sz/2,0.0);         // second quarter
    auto f2 = async(accum,v0+sz/2,v0+sz*3/4,0.0);       // third quarter
    auto f3 = async(accum,v0+sz*3/4,v0+sz,0.0);         // fourth quarter

    return f0.get()+f1.get()+f2.get()+f3.get();  // collect and combine the results
}
```

Multithreading in action: Implementing a thread pool

- C++ does not offer a native thread pool library
- We will review the implementation of two third-party libraries:
  - ThreadPool: https://github.com/progschj/ThreadPool
  - C++ Thread Pool Library: https://github.com/vit-vit/CTPL (referred only for function resize)

ThreadPool: Public functions

- ThreadPool::ThreadPool(size_t threads);
  - Create a thread pool with *threads* number of threads

- template<class F, class... Args>
  auto ThreadPool::enqueue(F&& f, Args&&... args)
  -> std::future<typename std::result_of<F(Args...)>::type>
  - Add a new task to the pool

- ThreadPool::~ThreadPool()
  - Non-trivial destructor since we are working with threads

ThreadPool: Data members

- std::vector< std::thread > workers;
  - collection of threads in the pool

- std::queue< std::function<void()> > tasks;
  - collection of tasks that need to be completed

- std::mutex queue_mutex;
  std::condition_variable condition;
  bool stop;
  - For synchronization

ThreadPool: Implementation of the constructor

```
// the constructor just launches some amount of workers
inline ThreadPool::ThreadPool(size_t threads)
    :   stop(false)
{
    for(size_t i = 0;i<threads;++i)
        workers.emplace_back(
            [this]
            {
                for(;;)
                {
                    std::function<void()> task;

                    {
                        std::unique_lock<std::mutex> lock(this->queue_mutex);
                        this->condition.wait(lock,
                            [this]{ return this->stop || !this->tasks.empty(); });
                        if(this->stop && this->tasks.empty())
                            return;
                        task = std::move(this->tasks.front());
                        this->tasks.pop();
                    }

                    task();
                }
            }
        );
}
```

ThreadPool: Implementation of enqueue

```cpp
// add new work item to the pool
template<class F, class... Args>
auto ThreadPool::enqueue(F&& f, Args&&... args)
    -> std::future<typename std::result_of<F(Args...)>::type>
{
    using return_type = typename std::result_of<F(Args...)>::type;

    auto task = std::make_shared< std::packaged_task<return_type()> >(
            std::bind(std::forward<F>(f), std::forward<Args>(args)...)
        );

    std::future<return_type> res = task->get_future();
    {
        std::unique_lock<std::mutex> lock(queue_mutex);

        // don't allow enqueueing after stopping the pool
        if(stop)
            throw std::runtime_error("enqueue on stopped ThreadPool");

        tasks.emplace([task](){ (*task)(); });
    }
    condition.notify_one();
    return res;
}
```

ThreadPool: Implementation of the destructor

```
// the destructor joins all threads
inline ThreadPool::~ThreadPool()
{
    {
        std::unique_lock<std::mutex> lock(queue_mutex);
        stop = true;
    }
    condition.notify_all();
    for(std::thread &worker: workers)
        worker.join();
}
```

CTPL: Implementation of resize

```
void resize(int nThreads) {
    if (!this->isStop && !this->isDone) {
        int oldNThreads = static_cast<int>(this->threads.size());
        if (oldNThreads <= nThreads) {  // if the number of threads is increased
            this->threads.resize(nThreads);
            this->flags.resize(nThreads);

            for (int i = oldNThreads; i < nThreads; ++i) {
                this->flags[i] = std::make_shared<std::atomic<bool>>(false);
                this->set_thread(i);
            }
        }
        else {  // the number of threads is decreased
            for (int i = oldNThreads - 1; i >= nThreads; --i) {
                *this->flags[i] = true;  // this thread will finish
                this->threads[i]->detach();
            }
            {
                // stop the detached threads that were waiting
                std::unique_lock<std::mutex> lock(this->mutex);
                this->cv.notify_all();
            }
            this->threads.resize(nThreads);  // safe to delete because the threads are detached
            this->flags.resize(nThreads);  // safe to delete because the threads have copies of shared_ptr of the flags, not originals
        }
    }
}
```

Part II: Lazy Evaluation in C++

- Chapter 6 of *Functional Programming in C++* by Ivan Čukić
- C++ does not provide lazy evaluation like Haskell does
  - auto P = A * B; for matrices A and B will be evaluated immediately
- But we can use C++'s functional programming features for lazy eval.
- For example, one can define

```
auto P = [A, B] { return A * B; };
```

- Now, P can be called when the value is needed
- What if the value is needed multiple times?

Laziness in C++

- Define a class lazy_val with the following data members

```
template <typename F>
class lazy_val {
private:
       F m_computation;
       mutable bool m_cache_initialized;
       mutable decltype(m_computation()) m_cache;
       mutable std::mutex m_cache_mutex;

public:
       ...
};
```

- Declaring cache-related members as mutable means that the member functions can be declared const

Implementation of implicit cast of lazy_val

```
operator const decltype(m_computation())& () const
{
      std::unique_lock<std::mutex> lock{m_cache_mutex};
      if (!m_cache_initialized) {
            m_cache = m_computation();
            m_cache_initialized = true;
      }

      return m_cache;
}
```

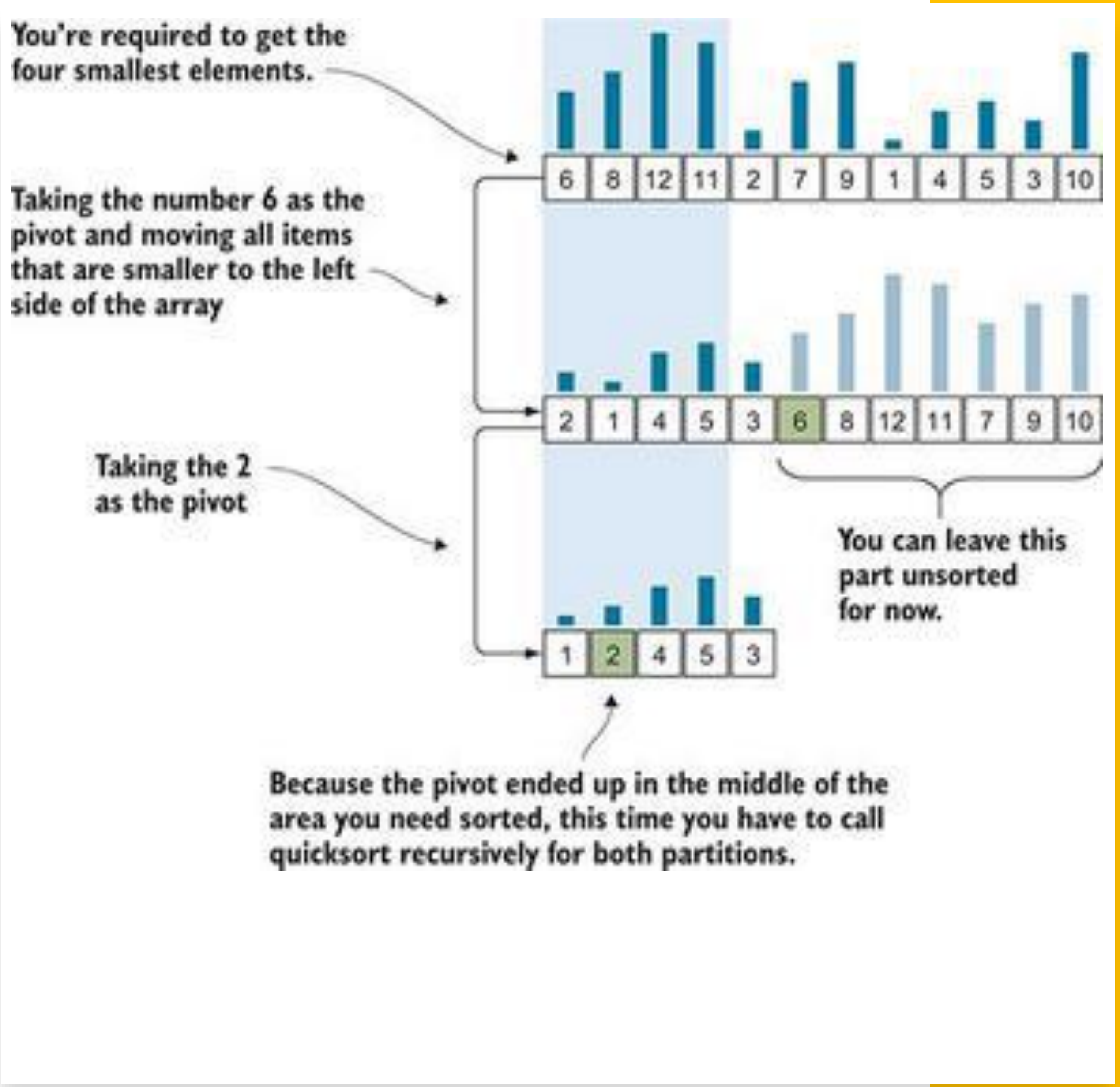
We don't even need the mutex with std::call_once!

```
template <typename F> class lazy_val {
private:
      F m_computation;
      mutable decltype(m_computation()) m_cache;
      mutable std::once_flag m_value_flag;

public:
      ...
      operator const decltype(m_computation())& () const {
            std::call_once(m_value_flag, [this] {
                  m_cache = m_computation();
            });
            return m_cache;
      }
};
```

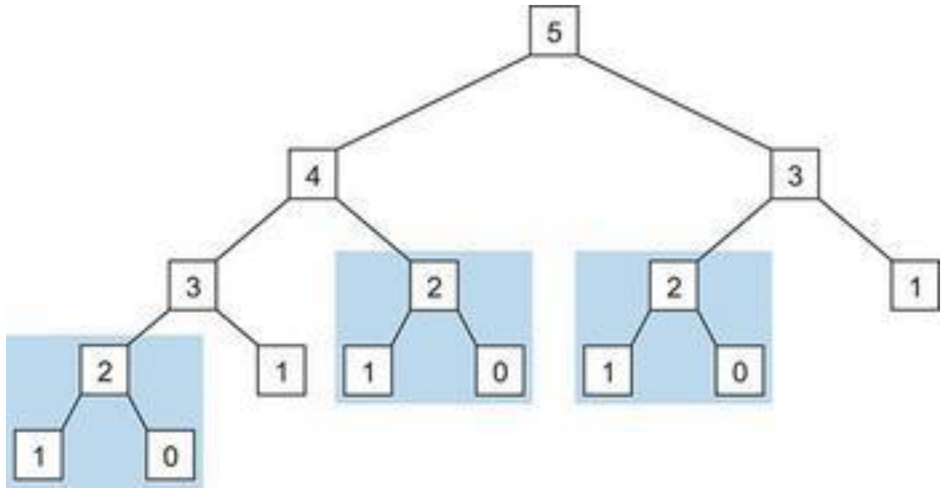
Laziness as an optimization technique

- Sorting collections lazily
  - What if you only need the top k elements?
  - For example, displaying results page by page for a web query
  - Lazy quicksort: Don't sort the partitions that are not part of the result



Laziness as an optimization technique

- Pruning recursion trees by caching function results
  - Fibonacci is a classic example
  - Also applicable to dynamic programming through memoization




```
std::vector<unsigned int> cache{0, 1};

unsigned int fib(unsigned int n) {
        if (cache.size() > n) {
                return cache[n];
        } else {
                const auto result =
                        fib(n - 1)
                        + fib(n - 2);
                cache.push_back(result);
                return result;
        }
}
```

Generalized memoization

- Question: Can we write a generalized function wrapper that can provide caching? We don’t need to be smart about what to cache.

```
template <typename Result, typename... Args>
auto make_memoized(Result (*f)(Args...)) {
        std::map<std::tuple<Args...>, Result> cache;

        return [f, cache](Args... args) mutable -> Result {
                const auto args_tuple = std::make_tuple(args...);
                const auto cached = cache.find(args_tuple);

                if (cached == cache.end()) {
                        auto result = f(args...);
                        cache[args_tuple] = result;
                        return result;
                } else {
                        return cached->second; }
         };
}
```

What about recursive functions?

- Refer to the book for an implementation
- Makes the following possible with automatic memoization:

```
auto fibmemo = make_memoized_r<
            unsigned int(unsigned int)>(
      [](auto& fib, unsigned int n) {
            std::cout << "Calculating " << n << "!\n";
            return n == 0 ? 0
                  : n == 1 ? 1
                  : fib(n - 1) + fib(n - 2);
});
```

Expression templates and lazy string concat.

- Consider the following expressions:

```
std::string fullname = title + " " + surname + ", " + name;
```

- + is a left-associative binary operator, so it's evaluated as

```
std::string fullname = (((title + " ") + surname) + ", ") + name;
```

- This generates and destroys strings that are not needed. This is not efficient.

Solution: Define a class that can hold multiple strings together using variadic templates

```
template <typename... Strings> class lazy_string_concat_helper;
template <typename LastString, typename... Strings>
class lazy_string_concat_helper<LastString, Strings...> {

private:
      LastString data;
      lazy_string_concat_helper<Strings...> tail;

public:
      ...
}


template <> class lazy_string_concat_helper<> {...}
```

Definition of operator +

```
lazy_string_concat_helper<std::string,
                               LastString,
                               Strings...>
operator+(const std::string& other) const {
    return lazy_string_concat_helper
              <std::string, LastString, Strings...>(
                  other,
                  *this);
}
```

Final remarks about template expressions

- We can hold the operands (strings in case of string concatenation) by references to avoid copying
- But we need to make sure that we only access the expression as long as the strings are in scope