Multi-Threading in C++

Multi-Threading in C++

In C++ it is allowed to run multiple threads simultaneously that use the same memory.

- Multiple threads may *read* from the same memory location
- All other accesses (i.e. read-write, write-read, write-write) are called *conflicts*
- Conflicting operations are only allowed when threads are *synchronized*
- This can be done with *mutexes* or *atomic operations*
- Unsynchronized accesses (also called *data races*), deadlocks, and other potential issues when using threads are undefined behavior!

All conflicting operations must be synchronized in some way!

Threads Library (1)

The header `<thread>` defines the class `std::thread`

- Using this class is the best way to use threads platform-independently
- May require additional compiler flags depending on the actual underlying implementation
- Use CMake to determine these flags in a platform-independent way
- For `gcc` and `clang` on Linux this will usually be `-pthread`

```
cmake_minimum_required(VERSION 3.21)
project(sample)

find_package(Threads REQUIRED)
add_executable(sample main.cpp)
target_link_libraries(sample PUBLIC Threads::Threads)
```

Threads Library (2)

The constructor of `std::thread` can be used to start a new thread

- Syntax: `thread(Function&& f, Args&&... args)`
- The function `f` will be invoked in a new thread with the arguments `args`
- The thread will terminate once `f` returns
- The default constructor can be used to create an empty thread object

The member function `join()` must be used to wait for a thread to finish

- `join()` must be called exactly once for each thread
- `join()` must be called *before* an `std::thread` object is destroyed
- When the destructor of an `std::thread` is called, the program is terminated if the associated thread was not joined

Threads Library (3)

Example

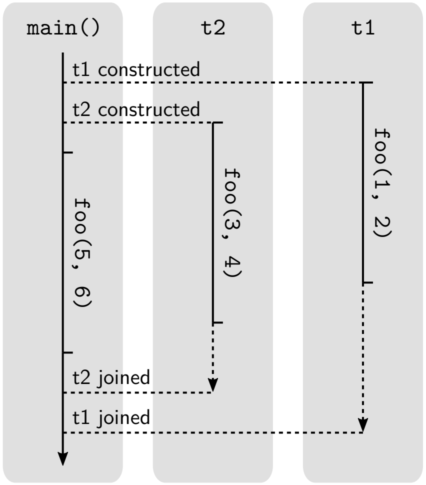
```cpp
#include <thread>

void foo(int a, int b);

int main() {
    // Pass a function and args
    std::thread t1(foo, 1, 2);
    // Pass a lambda
    std::thread t2([]() {
        foo(3, 4);
    });

    foo(5, 6);

    t2.join();
    t1.join();
}
```



Threads Library (4)

Example

```
#include <iostream>
#include <string_view>
#include <thread>

void safe_print(std::string_view s);

int main() {
    {
        std::thread t1([]() { safe_print("Hi\n"); });
        t1.join();
    }
    // Everything is fine, we called t1.join()
    {
        std::thread t2([]() {});
    }
    // Program terminated because t2.join() was not called
}
```

Threads Library (5)

`std::thread` is movable but not copyable

- Moving transfers all resources associated with the running thread
- Only the moved-to thread can be joined
- The moved-from thread object is empty (not associated with any thread)

Example

```cpp
#include <iostream>
#include <string_view>
#include <thread>

void safe_print(std::string_view s);

int main() {
    std::thread t1([]() { safe_print("Hi\n"); });
    std::thread t2 = std::move(t1); // t1 is now empty
    t2.join(); // OK, thread originally started in t1 is joined
}
```

Threads Library (6)

std::thread can be used in standard library containers

```
#include <thread>
#include <vector>

void safe_print(int i);

int main() {
    std::vector<std::thread> threadPool;
    for (int i = 1; i <= 9; ++i) {
        threadPool.emplace_back([i]() { safe_print(i); });
    }
    // Digits 1 to 9 are printed (unordered)
    for (auto& t : threadPool) {
        t.join();
    }
}
```

Other Functions of the Thread Library

The thread library also contains other useful functions that are closely related to starting and stopping threads:

- `std::this_thread::sleep_for()`: Stop the current thread for a given amount of time
- `std::this_thread::sleep_until()`: Stop the current thread until a given point in time
- `std::this_thread::yield()`: Let the operating system schedule another thread
- `std::this_thread::get_id()`: Get the (operating-system-specific) id of the current thread

Mutual Exclusion (1)

Mutual exclusion is a straightforward way to synchronize multiple threads

- Threads acquire a lock on a mutex object before entering a critical section
- Threads release their lock on the mutex when leaving a critical section

High-level programming model

- The resource (usually a class) that requires protection from data races owns a mutex object of the appropriate type
- Threads that intend to access the resource acquire a suitable lock on the mutex *before* performing the actual access
- Threads release their lock on the mutex *after* completing the access
- Usually locks are simply acquired and released in the member functions of the class

Mutual Exclusion (2)

The standard library defines several useful classes that implement mutexes in the `<mutex>` and `<shared_mutex>` headers

- `std::mutex` – regular mutual exclusion
- `std::recursive_mutex` – recursive mutual exclusion
- `std::shared_mutex` – mutual exclusion with shared locks

The standard library provides RAII wrappers for locking and unlocking mutexes

- `std::unique_lock` – RAII wrapper for exclusive locking
- `std::shared_lock` – RAII wrapper for shared locking

The RAII wrappers should *always* be preferred for locking and unlocking mutexes

- Makes bugs due to inconsistent locking/unlocking much more unlikely
- Manual locking and unlocking may be required in some rare cases
- Should still be performed through the corresponding functions of the RAII wrappers

std::unique_lock (1)

std::unique_lock can be used to lock a mutex in exclusive mode

- The constructor acquires an exclusive lock on the mutex
- Constructor syntax: unique_lock(mutex_type& m)
- Blocks the calling thread until the mutex becomes available
- The destructor releases the lock automatically
- Can be used with any mutex type from the standard library

```
#include <mutex>
#include <iostream>

std::mutex printMutex;
void safe_print(int i) {
    std::unique_lock lock(printMutex); // lock is acquired
    std::cout << i;
} // lock is released
```

`std::unique_lock` (2)

`std::unique_lock` provides additional constructors

- `unique_lock(mutex_type& m, std::defer_lock_t t)` – Do not immediately lock the mutex
- `unique_lock(mutex_type& m, std::try_to_lock_t t)` – Do not block when the mutex cannot be locked

`std::unique_lock` provides additional member functions

- `lock()` – Manually lock the mutex
- `try_lock()` – Try to lock the mutex, return `true` if successful
- `operator bool()` – Check if the `std::unique_lock` holds a lock on the mutex

std::unique_lock (3)

Example

```cpp
#include <mutex>

std::mutex mutex;

void foo() {
    std::unique_lock lock(mutex, std::try_to_lock);
    if (!lock) {
        doUnsynchronizedWork();

        // block until we can get the lock
        lock.lock();
    }

    doSynchronizedWork();

    // release the lock early
    lock.unlock();

    doUnsynchronizedWork();
}
```

std::unique_lock (4)

std::unique_lock is movable to transfer ownership of a lock on a mutex

```
#include <mutex>

class MyContainer {
    private:
    std::mutex mutex;

    public:
    class iterator { /* ... */ };

    iterator begin() {
        std::unique_lock lock(mutex);

        // compute the begin iterator constructor args

        // keep the lock for iteration
        return iterator(std::move(lock), ...);
    }
};
```

Recursive Mutexes (1)

The following code will deadlock since `std::mutex` can be locked at most once

```
#include <mutex>

std::mutex mutex;

void bar() {
    std::unique_lock lock(mutex);

    // do some work...
}

void foo() {
    std::unique_lock lock(mutex);

    // do some work...

    bar(); // INTENTIONALLY BUGGY, will deadlock
}
```

Recursive Mutexes (2)

`std::recursive_mutex` implements recursive ownership semantics

- The same thread can lock an `std::recursive_mutex` multiple times without blocking
- Other threads will still block if an `std::recursive_mutex` is currently locked
- Can be used with `std::unique_lock` just like a regular `std::mutex`
- Useful for functions that call each other and use the same mutex

```
#include <mutex>

std::recursive_mutex mutex;
void bar() {
    std::unique_lock lock(mutex);
}
void foo() {
    std::unique_lock lock(mutex);
    bar(); // OK, will not deadlock
}
```

`std::shared_lock` (1)

`std::shared_lock` can be used to lock a mutex in shared mode

- Constructors and member functions analogous to `std::unique_lock`
- Multiple threads can acquire a shared lock on the same mutex
- Shared locking attempts block if the mutex is locked in exclusive mode
- Only usable in conjunction with `std::shared_mutex`

We have to adhere to some contract to write well-behaved programs

- Shared mutexes are mostly used to implement read/write-locks
- Only read accesses are allowed when holding a shared lock
- Write accesses are only allowed when holding an exclusive lock

std::shared_lock (2)

Example

```
#include <shared_mutex>

class SafeCounter {
    private:
    mutable std::shared_mutex mutex;
    size_t value = 0;

    public:
    size_t getValue() const {
        std::shared_lock lock(mutex);
        return value; // read access
    }

    void incrementValue() {
        std::unique_lock lock(mutex);
        ++value; // write access
    }
};
```

Working with Mutexes

We usually have to make mutexes `mutable` within our data structures

- The RAII wrappers require mutable references to the mutex
- `const` member functions of our data structure usually also need to use the mutex

Using mutexes without care can easily lead to deadlocks within the system

- Usually occurs when a thread tries to lock another mutex when it already holds a lock on some mutex
- Can in some cases be avoided by using `std::recursive_mutex` (if we are locking the same mutex multiple times)
- Requires dedicated programming techniques when multiple mutexes are involved

Avoiding Deadlocks (1)

The following example will lead to deadlocks

```
std::mutex m1, m2, m3;
void threadA() {
    // INTENTIONALLY BUGGY
    std::unique_lock l1{m1}, l2{m2}, l3{m3};
}
void threadB() {
    // INTENTIONALLY BUGGY
    std::unique_lock l3{m3}, l2{m2}, l1{m1};
}
```

Possible deadlock scenario

- `threadA()` acquires locks on `m1` and `m2`
- `threadB()` acquires lock on `m3`
- `threadA()` waits for `threadB()` to release `m3`
- `threadB()` waits for `threadA()` to release `m2`

Avoiding Deadlocks (2)

Deadlocks can be avoided by always locking mutexes in a *globally* consistent order

- Ensures that one thread always "wins"
- Maintaining a globally consistent locking order requires considerable developer discipline
- Maintaining a globally consistent locking order may not be possible at all

```
std::mutex m1, m2, m3;
void threadA() {
    // OK, will not deadlock
    std::unique_lock l1{m1}, l2{m2}, l3{m3};
}
void threadB() {
    // OK, will not deadlock
    std::unique_lock l1{m1}, l2{m2}, l3{m3};
}
```

Avoiding Deadlocks (3)

Sometimes it is not possible to guarantee a globally consistent order

- The `std::scoped_lock` RAII wrapper can be used to safely lock any number of mutexes
- Employs a deadlock-avoidance algorithm if required
- Generally quite inefficient in comparison to `std::unique_lock`
- Should only be used as a last resort!

```
std::mutex m1, m2, m3;
void threadA() {
    // OK, will not deadlock
    std::scoped_lock l{m1, m2, m3};
}
void threadB() {
    // OK, will not deadlock
    std::scoped_lock l{m3, m2, m1};
}
```

Condition Variables (1)

A condition variable is a synchronization primitive that allows multiple threads to wait until an (arbitrary) condition becomes true.

- A condition variable uses a mutex to synchronize threads
- Threads can *wait* on or *notify* the condition variable
- When a thread waits on the condition variable, it blocks until another thread notifies it
- If a thread waited on the condition variable and is notified, it holds the mutex
- A notified thread must check the condition explicitly because *spurious wake-ups* can occur

Condition Variables (2)

The standard library defines the class `std::condition_variable` in the header `<condition_variable>` which has the following member functions:

- `wait()`: Takes a reference to a `std::unique_lock` that must be locked by the caller as an argument, unlocks the mutex and waits for the condition variable
- `notify_one()`: Notify a single waiting thread, mutex does not need to be held by the caller
- `notify_all()`: Notify all waiting threads, mutex does not need to be held by the caller

Condition Variables Example

One use case for condition variables are worker queues: Tasks are inserted into a queue and then worker threads are notified to do the task.

```
std::mutex m;
std::condition_variable cv;
std::vector<int> taskQueue;

void pushWork(int task) {
  {
    std::unique_lock l{m};
    taskQueue.push_back(task);
  }
  cv.notify_one();
}
```

```
void workerThread() {
  std::unique_lock l{m};
  while (true) {
    while (!taskQueue.empty()) {
      int task = taskQueue.back();
      taskQueue.pop_back();
      l.unlock();
      // [...] do actual work here
      l.lock();
    }
    cv.wait(l);
  }
}
```

Atomic Operations

Mutual exclusion may be inefficient for synchronization

- Very coarse-grained synchronization
- May require communication with the operating system

Modern hardware also supports *atomic operations* for synchronization.

- The memory order of a CPU determines how *non-atomic* memory operations are allowed to be reordered
- In C++ all non-atomic conflicting operations have undefined behavior even if the memory order of the CPU would allow it!
- There is one exception: Special atomic functions are allowed to have conflicts
- The compiler usually knows your CPU and generates “real” atomic instructions only if necessary

Atomic Operations Library (1)

C++ provides atomic operations in the atomic operations library

- Implemented in the `<atomic>` header
- `std::atomic<T>` is a class that represents an atomic version of the type `T`
- Can be used (almost) interchangeably with the original type `T`
- Has the same size and alignment as the original type `T`
- Conflicting operations are only allowed on `std::atomic<T>` objects

`std::atomic` on its own does not provide any synchronization at all

- Simply makes conflicting operations possible and defined behavior
- Exposes the guarantees of specific memory models to the programmer
- Suitable programming models must be used to achieve proper synchronization

Atomic Operations Library (2)

`std::atomic` has several member functions that implement atomic operations

- `T load()`: Loads the value
- `void store(T desired)`: Stores `desired` in the object
- `T exchange(T desired)`: Stores `desired` in the object and returns the old value

If `T` is a integral type, the following operations also exist:

- `T fetch_add(T arg)`: Adds `arg` to the value and returns the old value
- `T fetch_sub(T arg)`: Same for subtraction
- `T fetch_and(T arg)`: Same for bitwise and
- `T fetch_or(T arg)`: Same for bitwise or
- `T fetch_xor(T arg)`: Same for bitwise xor

Atomic Operations Library (3)

Example (without atomics)

```
#include <thread>

int main() {
    unsigned value = 0;
    thread t([]() {
        for (size_t i = 0; i < 10; ++i)
            ++value; // UNDEFINED BEHAVIOR, data race
    });

    for (size_t i = 0; i < 10; ++i)
        ++value; // UNDEFINED BEHAVIOR, data race

    t.join();

    // value will contain garbage
}
```

Atomic Operations Library (4)

Example (with atomics)

```cpp
#include <atomic>
#include <thread>

int main() {
    std::atomic<unsigned> value = 0;
    thread t([]() {
        for (size_t i = 0; i < 10; ++i)
            value.fetch_add(1); // OK, atomic increment
    });

    for (size_t i = 0; i < 10; ++i)
        value.fetch_add(1); // OK, atomic increment

    t.join();

    // value will contain 20
}
```

Semantics of Atomic Operations

C++ may support atomic operations that are not supported by the CPU

- `std::atomic<T>` can be used with any trivially copyable type
- In particular also for types that are much larger than one cache line
- To guarantee atomicity, compilers are allowed to fall back to mutexes

The C++ standard defines precise semantics for atomic operations

- Every atomic object has a totally ordered *modification order*
- There are several *memory orders* that define how operations on different atomic objects may be reordered
- The C++ memory orders do not necessarily map precisely to memory orders defined by a CPU

Modification Order (1)

All modifications of a *single* atomic object are totally ordered

- This is called the *modification order* of the object
- All threads are guaranteed to observe modifications of the object in this order

Modifications of *different* atomic objects may be unordered

- Different threads may observe modifications of multiple atomic objects in a different order
- The details depend on the *memory order* that is used for the atomic operations

Modification Order (2)

Example

```
std::atomic<int> i = 0, j = 0;
void workerThread() {
    i.fetch_add(1); // (A)
    i.fetch_sub(1); // (B)
    j.fetch_add(1); // (C)
}
void readerThread() {
    int iLocal = i.load(), jLocal = j.load();
    assert(iLocal != -1); // always true
}
```

Observations

- Reader threads will never see a modification order with `(B)` before `(A)`
- Depending on the memory order, multiple reader threads may see any of `(A),(B),(C)`, or `(A),(C),(B)`, or `(C),(A),(B)`

Memory Order (1)

The atomics library defines several memory orders

- All atomic functions take a memory order as their last parameter
- The two most important memory orders are `std::memory_order_relaxed` and `std::memory_order_seq_cst`
- `std::memory_order_seq_cst` is used by default if no memory order is explicitly supplied
- You should stick to this default unless you identified the atomic operation to be a performance bottleneck

```
std::atomic<int> i = 0;

i.fetch_add(1); // uses std::memory_order_seq_cst
i.fetch_add(1, std::memory_order_seq_cst);
i.fetch_add(1, std::memory_order_relaxed);
```

Memory Order (2)

`std::memory_order_relaxed`

- Roughly maps to a CPU with weak memory order
- Only consistent modification order is guaranteed
- Atomic operations of different objects may be reordered arbitrarily

```
std::atomic<int> i = 0, j = 0;
void threadA() {
    while (true) {
        i.fetch_add(1, std::memory_order_relaxed); // (A)
        i.fetch_sub(1, std::memory_order_relaxed); // (B)
        j.fetch_add(1, std::memory_order_relaxed); // (C)
    }
}
void threadB() { /* ... */ }
void threadC() { /* ... */ }
```

Observations

- `threadB()` may observe `(A),(B),(C)`
- `threadC()` may observe `(C),(A),(B)`

Memory Order (3)

`std::memory_order_seq_cst`

- Roughly maps to a CPU with strong memory order
- Guarantees that all threads see all atomic operations in one globally consistent order

```
std::atomic<int> i = 0, j = 0;
void threadA() {
    while (true) {
        i.fetch_add(1, std::memory_order_seq_cst); // (A)
        i.fetch_sub(1, std::memory_order_seq_cst); // (B)
        j.fetch_add(1, std::memory_order_seq_cst); // (C)
    }
}
void threadB() { /* ... */ }
void threadC() { /* ... */ }
```

Observations

- `threadB()` may observe `(C),(A),(B)`
- `threadC()` will then also observe `(C),(A),(B)`

Compare-And-Swap Operations (1)

Compare-and-swap operations are one of the most useful operations on atomics

- Signature: `bool compare_exchange_weak(T& expected, T desired)`
- Compares the current value of the atomic to `expected`
- Replaces the current value by `desired` if the atomic contained the expected value and returns `true`
- Updates expected to contain the current value of the atomic object and returns `false` otherwise

Often the main building block to synchronize data structures without mutexes

- Allows us to check that no modifications occurred to an atomic over some time period
- Can be used to implement “implicit” mutual exclusion
- Can suffer from subtle problems such as the A-B-A problem

Compare-And-Swap Operations (2)

Example: Insert into a lock-free singly linked list

```
#include <atomic>

class SafeList {
    private:
    struct Entry {
        T value;
        Entry* next;
    };

    std::atomic<Entry*> head;

    Entry* allocateEntry(const T& value);

    public:
    void insert(const T& value) {
        auto* entry = allocateEntry(value);
        auto* currentHead = head.load();
        do {
            entry->next = currentHead;
        } while (!head.compare_exchange_weak(currentHead, entry));
    }
};
```

Compare-And-Swap Operations (3)

`std::atomic` actually provides two CAS versions with the same signature

- `compare_exchange_weak` – weak CAS
- `compare_exchange_strong` – strong CAS

Semantics

- The weak version is allowed to return false, even when no other thread modified the value
- This is called “spurious failure”
- The strong version may use a loop internally to avoid this
- General rule: If you use a CAS operation in a loop, always use the weak version

`std::atomic_ref` (1)

`std::atomic` can be unwieldy

- `std::atomic` is neither movable nor copyable
- As a consequence it cannot easily be used in standard library containers

`std::atomic_ref` allows us to apply atomic operations to non-atomic objects

- The constructor takes a reference to an arbitrary object of type `T`
- The referenced object is treated as an atomic object during the lifetime of the `std::atomic_ref`
- `std::atomic_ref` defines similar member functions to `std::atomic`

Data races between accesses through `std::atomic_ref` and non-atomic accesses are still undefined behavior!

std::atomic_ref (2)

Example

```
#include <atomic>
#include <thread>
#include <vector>

int main() {
    std::vector<int> localCounters(4);
    std::vector<std::thread> threads;

    for (size_t i = 0; i < 16; ++i) {
        threads.emplace_back([]() {
            for (size_t j = 0; j < 100; ++j) {
                std::atomic_ref ref(localCounters[i % 4]);
                ref.fetch_add(1);
            }
        });
    }

    for (auto& thread : threads) {
        thread.join();
    }
}
```