Department I - C Plus Plus

Modern and Lucid C++ Advanced for Professional Programmers

Week 11 – Memory Model

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Rapperswil, 02.05.2019
FS2019

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Recap Week 10

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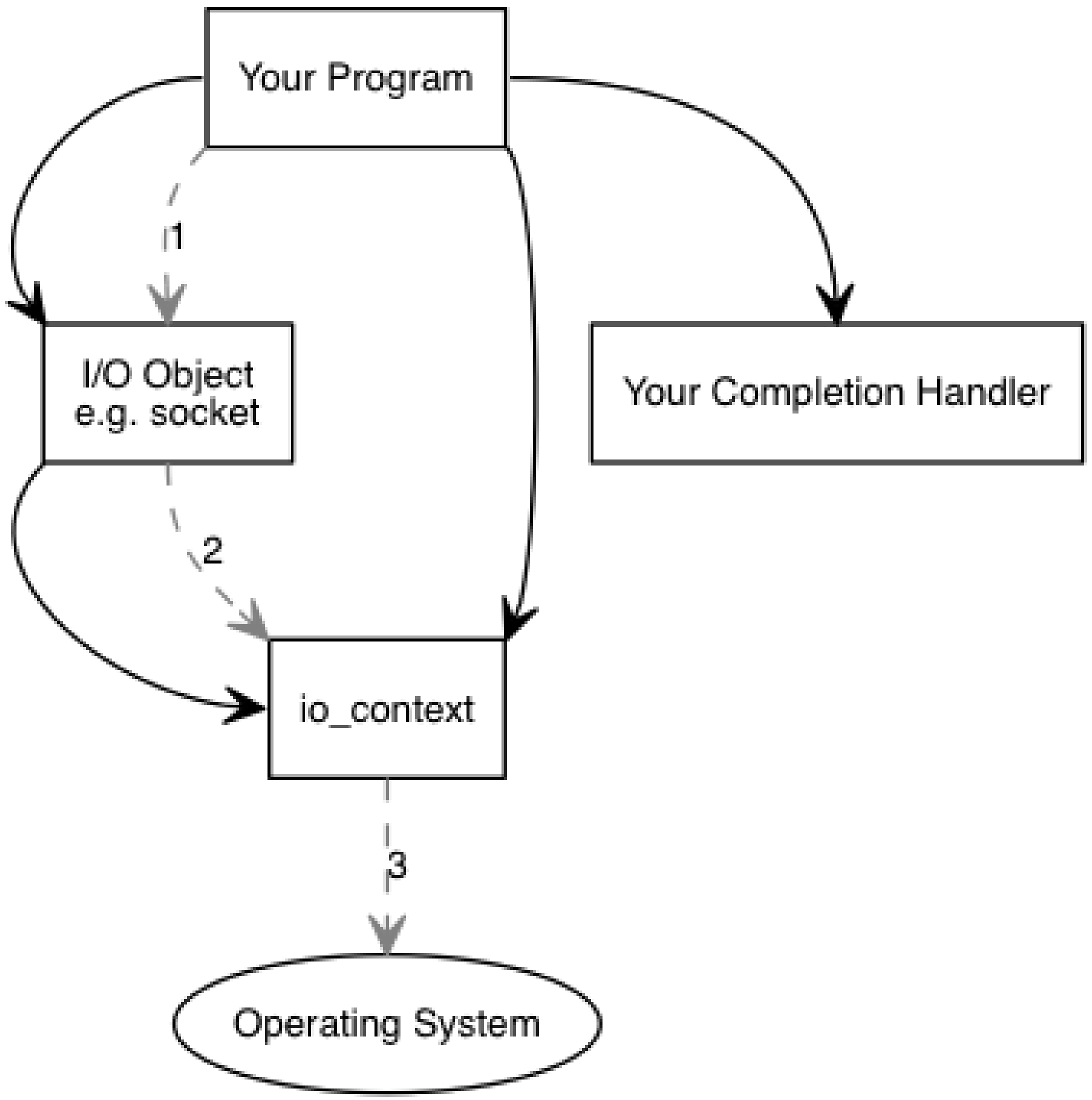
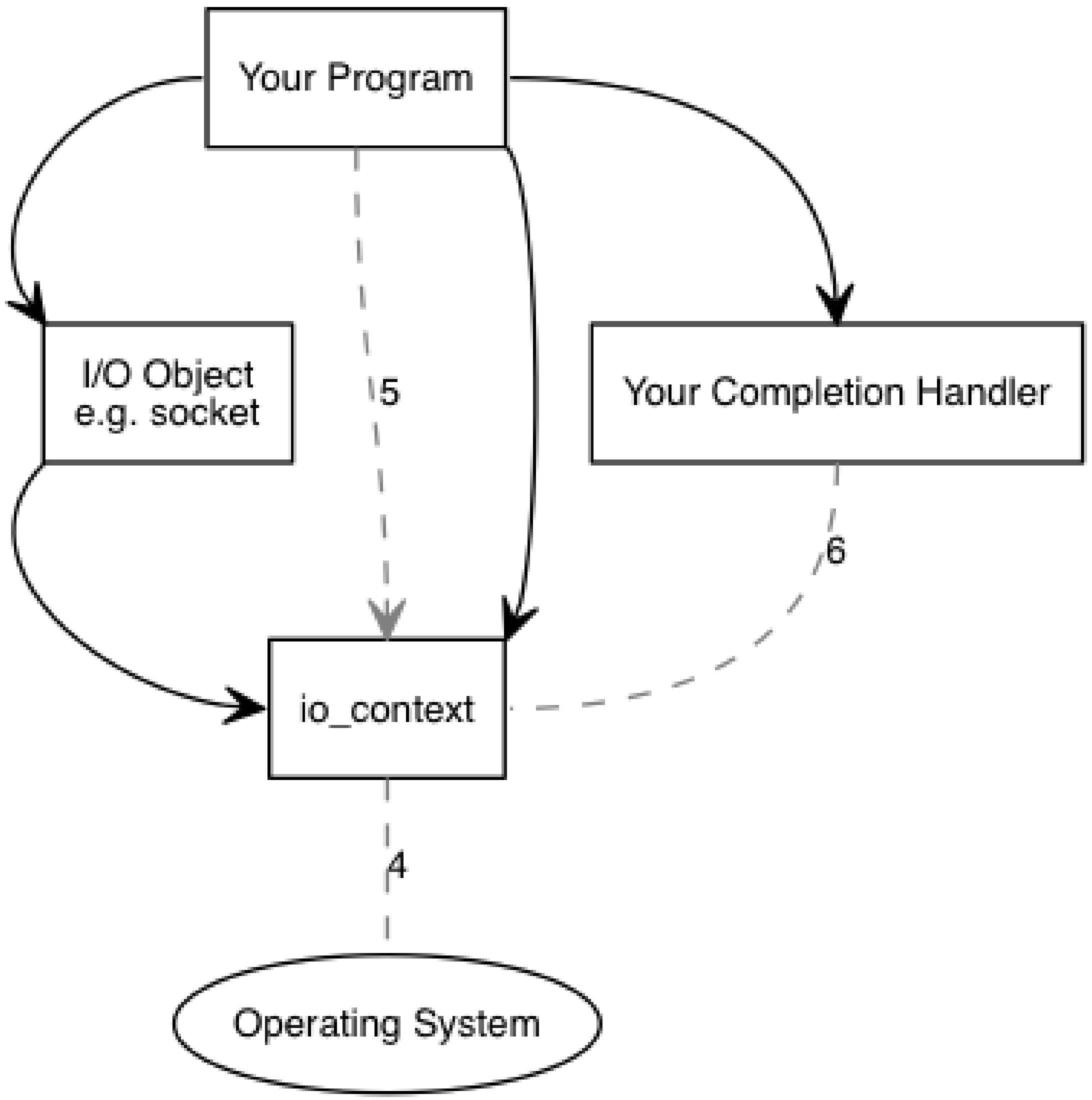
ASIO Basics of Asynchronous Operations





https://think-async.com/Asio/asio-1.12.2/doc/asio/overview/core/basics.html

Asynchronous Acceptor (Overview)

```
struct Server {
  using tcp = asio::ip::tcp;
  Server(asio::io_context & context, unsigned short port)
      : acceptor{context, tcp::endpoint{tcp::v4(), port}}{
    accept();
  }

private:
  void accept() {
    auto acceptHandler = [this] (asio::error_code ec, tcp::socket peer) {
      if (!ec) {
        auto session = std::make_shared<Session>(std::move(peer));
        session->start();
      }
      accept();
    };
    acceptor.async_accept(acceptHandler);
  }
  tcp::acceptor acceptor;
};
```

```
class std::thread
```

```
int main() {
  std::thread greeter {
    [] { std::cout << "Hello, I'm thread!" << std::endl; }
  };
  greeter.join();
}
```

- **A new thread is created and started automatically**
- **Creates a new execution context (thread)**
- **`join()` waits for the thread to finish**

Goals

- **You know how threads safely communicate with each other**
- **You are aware of the pitfalls of synchronization**
- **You can use atomics**
- **You can implement thread-safe data structures**

Communication Between Threads

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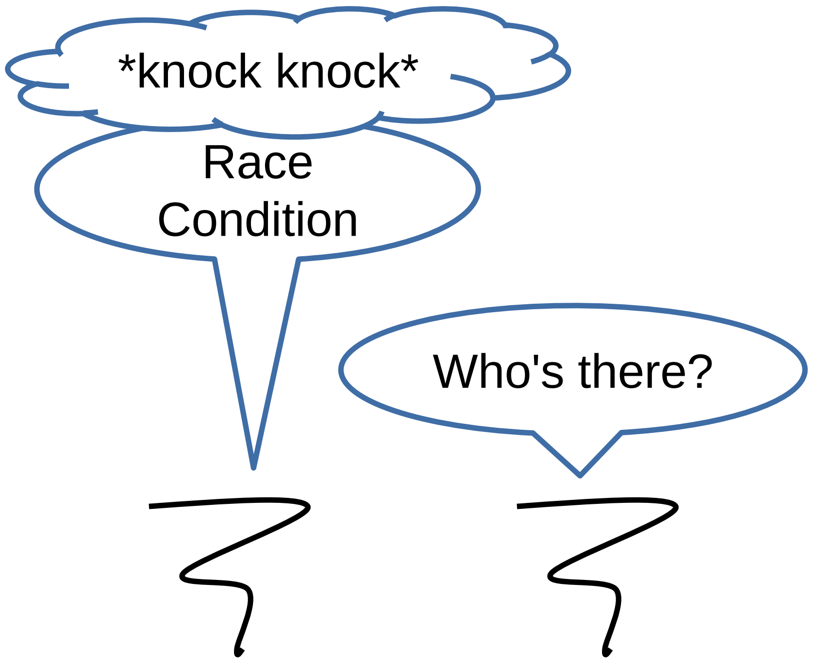
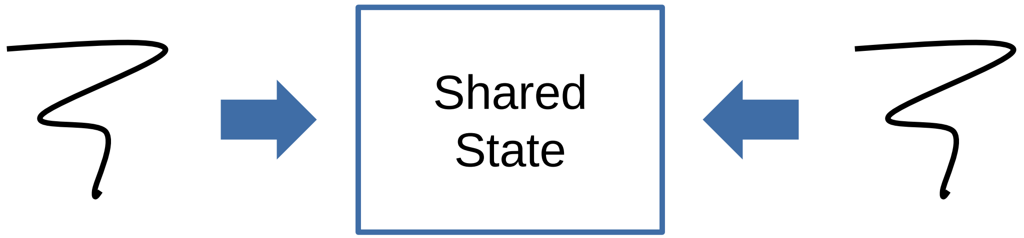


- **Mutable Shared State**
- **Problem: Data Race**
  - Two operations on the same memory location (In different threads)
  - At least one is not atomic (at the same time)
  - At least one is a modifying operation



Data Race Example

DANGER

Data Race

```cpp
int main () {
  UnsynchronizedCounter counter{};
  auto run = [&counter] {
    for (int i = 0; i < 100'000'000; ++i) {
      counter.increment();
    }
  };
  std::thread t1{run}, t2{run};
  t1.join();
  t2.join();
  std::cout << counter.current();
}
```

```cpp
struct UnsynchronizedCounter {
  void increment() {
    ++value;
  }

  int current() const {
    return value;
  }

private:
  int value{};
};
```

- **What is the expected output?**
- **Solutions**
  - Locking the shared access
  - Make all accesses atomic

Mutexes for Exclusive Access

#include <mutex>

- **Acquire:**
  - `lock()` – blocking
  - `try_lock()` – non-blocking
- **Release:**
  - `unlock()` – non-blocking


```cpp
struct ConcurrentCounter {
  void increment() {
    m.lock();
    ++value;
    m.unlock();
  }

  int current() const {
    m.lock();
    int const current = value;
    m.unlock();
    return current;
  }

private:
  mutable std::mutex m{};
  int value{};
};
```

Capabilities of Mutexes

`#include <mutex>`

- **Recursive – Allow multiple nested acquire operations of the same thread**
  - Prevents self-deadlock

- **Timed - Also provide timed acquire operations:**
  - `try_lock_for(<duration>)`
  - `try_lock_until(<time>)`

		Recursive	
		No	Yes
Timed	No	`std::mutex`	`std::recursive_mutex`
	Yes	`std::timed_mutex`	`std::recursive_timed_mutex`

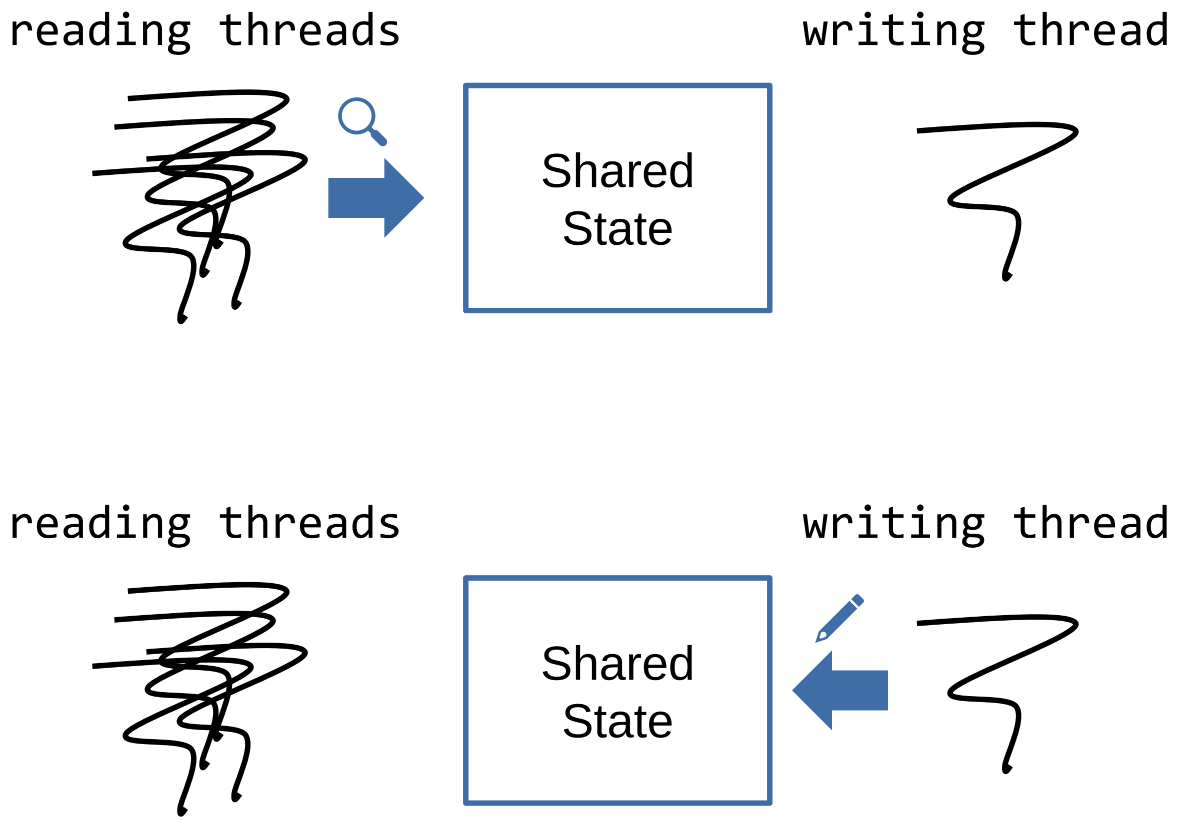
`#include <shared_mutex>`

- **Reading operations don't need exclusive access**
  - Only concurrent writes need exclusive locking
- **`std::shared_mutex` and `std::shared_timed_mutex` provide exclusive and shared locking**
  - `lock_shared()`
  - `try_lock_shared()`
  - `try_lock_shared_for(<duration>)`
  - `try_lock_shared_until(<time>)`
  - `unlock_shared()`

```
struct ConcurrentCounter {
  void increment() {
    m.lock();
    ++value;
    m.unlock();
  }

  int current() const {
    m.lock_shared();
    int const current = value;
    m.unlock_shared();
    return current;
  }

private:
  mutable std::shared_mutex m{};
  int value{};
};
```



- **Beware: a `std::shared_mutex` might be slower due to more overhead**
  - Use only if writes are scarce and reads very common

- **Usually you will not acquire and release mutexes directly through the supplied member functions**
- **Instead you use a lock that manages the mutex (RAII wrappers)**

`std::lock_guard`	RAII wrapper for a single mutex: • Locks immediately when constructed • Unlocks when destructed
`std::scoped_lock`	RAII wrapper for mutliple mutexes • Locks immediately when constructed • Unlocks when destructed
`std::unique_lock`	Mutex wrapper that allows defered and timed locking: • Similar interface to timed mutex • Allows explicit locking/unlocking • Unlocks when destructed (if still locked)
`std::shared_lock`	Wrapper for shared mutexes • Allows explicit locking/unlocking • Unlocks when destructed (if still locked)

Counter with Scoped Lock

- **Scoped Locking Pattern**
  - Create a lock guard that locks and unlocks the mutex automatically
- **Code is shorter**
- **Code is safer**
  - In case of an exception the mutex is released

```
struct ConcurrentCounter {
  void increment() {
    std::scoped_lock lock{m};
    ++value;
  }

  int current() const {
    std::scoped_lock lock{m};
    return value;
  }

private:
  mutable std::mutex m{};
  int value{};
};
```

Why `mutable`?

- **Strategized Locking Pattern**
  - Template parameter for mutex type
  - Could also be `null_mutex` (boost)

```
template <typename Mutex = std::mutex>
struct ConcurrentCounter {
  using Lock = std::scoped_lock<Mutex>;
  void increment() {
    Lock lock{m};
    ++value;
  }

  int current() const {
    Lock lock{m};
    return value;
  }

private:
  mutable Mutex m{};
  int value{};
};
```

https://wiki.hsr.ch/PnProg/files/StrategizedLocking.pdf

- **`std::scoped_lock`**
  - Acquires multiple locks in the constructor
  - Avoids deadlocks, by relying on internal sequence
  - Blocks until all locks could be acquired
  - Class template argument deduction avoids the need for specifying the template arguments

```
struct ConcurrentCounter {
  // can't be noexcept, because locks might throw
  void swap(ConcurrentCounter & other) {
    if (this == &other) return;

    std::scoped_lock both{m, other.m};

    std::swap(value, other.value);
    // no need to swap mutex
  }
};
```

Multiple Locks (Before `std::scoped_lock`)

- **`std::lock`**
  - Acquires multiple locks in a single call
  - Avoids deadlocks
  - Blocks until all locks could be acquired
- **`std::try_lock`**
  - Tries to acquire multiple locks in a single call
  - Does not block
  - When it returns...
    - `true`, all locks have been acquired
    - `false`, no lock has been acquired

```cpp
struct ConcurrentCounter {
  // can't be noexcept, because locks might throw
  void swap(ConcurrentCounter & other) {
    if (this == &other) return;

    // std::defer_lock prevents immediate locking
    lock my_lock{m, std::defer_lock};
    lock other_lock{other.m, std::defer_lock};

    // blocks until all locks are acquired
    std::lock(my_lock, other_lock);

    std::swap(value, other.value);
    // no need to swap
  }
};
```

`std::condition_variable`

- **Similar to Java Condition**
  - But is not bound to a lock at construction
- **Waiting for the condition**
  - `wait(<mutex>)` – requires surrounding loop
  - `wait(<mutex>, <predicate>)` – loops internally
  - Timed waits `wait_for` and `wait_until`
- **Notifying a (potential) change**
  - `notify_one()`
  - `notify_all()`
- **`std::unique_lock` is required as condition might release lock (`wait`)**

`#include <condition_variable>`


```
template <typename T, typename MUTEX = std::mutex>
struct ThreadsafeQueue {
  using guard = std::lock_guard<MUTEX>;
  using lock = std::unique_lock<MUTEX>;
  void push(T const & t) {
    guard lk{mx};
    q.push(t);
    notEmpty.notify_one();
  }
  T pop() {
    lock lk{mx};
    notEmpty.wait(lk, [this] { return !q.empty(); });
    T t = q.front();
    q.pop();
    return t;
  }
private:
  mutable MUTEX mx{};
  std::condition_variable notEmpty{};
  std::queue<T> q{};
};
```

```cpp
struct ConcurrentCounter {
  void incrementAndGet() {
    std::scoped_lock{m};
    return ++value;
  }
  mutable std::mutex m{};
  int value{};
};
```

```cpp
template<typename T>
struct ThreadsafeQueue {
  std::optional<T> tryPop() {
    guard lk{mx};
    if (empty()) { return std::nullopt; }
    return pop();
  }
  bool empty() const {
    std:: scoped_lock lk{mx};
    return q.empty();
  }
private:
  mutable std::mutex mx{};
  std::queue<T> q{};
};
```

<pre>struct ConcurrentCounter {
  void incrementAndGet() {
    std::scoped_lock{m};
    return ++value;
  }
  mutable std::mutex m{};
  int value{};
};</pre>
	Incorrect
	
	`std::scoped_lock` creates a temporary variable. It is immediately destroyed at the end of the statement and the rest of the function is not locked.

<pre>template<typename T>
struct ThreadsafeQueue {
  std::optional<T> tryPop() {
    guard lk{ mx };
    if (empty()) { return std::nullopt; }
    return pop();
  }
  bool empty() const {
    std:: scoped_lock lk { mx };
    return q.empty();
  }
private:
  mutable std::mutex mx { };
  std::queue<T> q{};
};</pre>
	Incorrect
	
	An std::mutex is not recursive. If `empty()` or `pop()` are called in `tryPop()` it self deadlocks. A private non-locking helper function is required that can be called.

- **There is no thread-safety wrapper for standard containers! (yet)**
- **Access to different individual elements from different threads is not a data race**
  - Container must not change during the concurrent access to elements!
  - Using different elements of a `std::vector` from different threads is OK!
- **Almost all other concurrent uses of containers is dangerous**
- **`std::shared_ptr` copies to the same object can be used from different threads, but accessing the object itself can race if non-const**
  - Reference counter is an atomic

Async, Future and Promise

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```
template <class Function, class...Args>
std::future<std::result_of_t<std::decay_t<Function>(std::decay_t<Args>...)>>
async(std::launch policy, Function && f, Args &&... args );
```

- **std::async provides a simple interface for**
  - Background tasks (in separate threads)
  - Postponed computation
- **Launch policies (arguments)**
  - `std::launch::async` – actual asynchronous computation
  - `std::launch::deferred` – lazy evaluation
- **Executes a function `f` with the given arguments `args` and returns an `std::future` of the return type of the called function `f`**

```
int main() {
  httplib::Client cli("www.w3.org", 80);
  auto fetchUrl = [&] (std::string_view url) {
    return cli.Get(url.data());
  };
  auto future =
      std::async(std::launch::async, fetchUrl, "/");
  std::cout << "Do something else...\n";
  auto result = future.get();
  if (result) {
    printHeaders(std::cout, result->headers);
  }
}
```

```
template<typename T>
class future;
```

- **An `std::future` instance is a surrogate object for retrieving a value**
- **`get()` retrieves the value**
  - Or throws the exception that occured while computing its value
  - Blocks until the value is available (possibly forever)
  - Releases the shared state `->` must only be called once!
- **`wait()`, `wait_for()`, `wait_until()`**
  - Waits until the value is available or the time expires
- **An `std::future` is an exclusive handle for the value and cannot be copied (only moved)**
  - `share()` creates an `std::shared_future` that can be copied – required when multiple threads wait for the same value (multiple `get()` calls allowed – even to the same `std::shared_future` object)

Destruction of `std::future` From `std::async`

- **Beware: If you get an `std::future` through a call to `std::async` the destructor of the `std::future` may block until the `std::async` execution is completed**

- **This might sound innocent, but has significant consequences**

```
void someAsyncStuff();

void startAsyncStuff() {
  std::async(std::launch::async, someAsyncStuff);
  std::async(std::launch::async, someAsyncStuff);
  std::async(std::launch::async, someAsyncStuff);
}
```

- **Each call of `std::async` will block because the `std::future` return value will be destroyed immediately**

std::promise

#include <future>

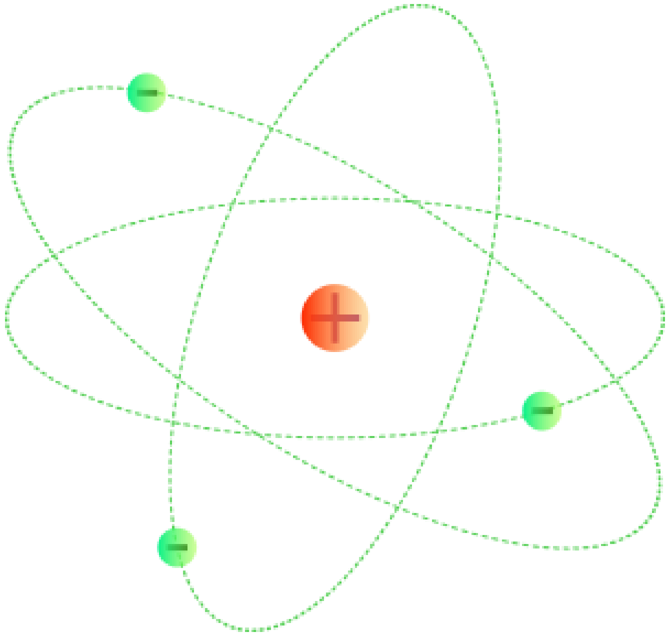

```
template<typename T>
class promise;
```

- **std::promise is the other end of the std::future, which allows setting the value (or exception)**
  - set_value(T const &) – makes the value available
  - set_exception(std::exception_ptr) – the exception will be thrown in the get() call
- **get_future() – gets the corresponding std::future object**
  - Must not be called more than once

```
void compute(int num, int den, std::promise<int> p) {
  if (den == 0) {
    std::logic_error e{"must not divide by 0"};
    auto e_ptr = std::make_exception_ptr(e);
    p.set_exception(e_ptr);
  }
  auto result = num / den;
  p.set_value(result);
}

std::future<int> compute_in_thread(int n, int d) {
  std::promise<int> res_promise{};
  std::future<int> res_future{res_promise.get_future()};
  std::thread t{compute, n, d, std::move(res_promise)};
  t.detach();
  return res_future;
}
```

Atomics and the Memory Model



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```
#include <atomic>
```



```
template<typename T>
struct atomic;
```

```
class atomic_flag;
```

- **Atomics are guaranteed to be data race free!**
- **Most primitive atomic: `std::atomic_flag`**
  - Lock-free
  - `clear()` – sets flag to false
  - `test_and_set()` – sets flag to true and returns previous value
- **Other atomic types might require using locks**
  - `std::atomic<bool>` and `std::atomic<int>` usually can be implemented without relying on mutexes/locks
  - Can be checked with `is_lock_free()`

```
void outputWhenReady(std::atomic_flag & flag,
                     std::ostream & out) {
  while (flag.test_and_set())
    yield();
  out << "Here is thread: "
      << get_id()
      << std::endl;
  flag.clear();
}

int main() {
  std::atomic_flag flag { };
  std::thread t { [&flag] {
    outputWhenReady(flag, std::cout);}
  };
  outputWhenReady(flag, std::cout);
  t.join();
}
```

- **Can everything be used as template argument for `std::atomic<T>`?**
  - T must be trivially copyable
- **Member Operations (all atomic)**

`void store(T)` set the new value	`T load()` get the current value	`T exchange(T)` set a new value and get the previous
`bool compare_exchange_weak(T & expected, T desired)` compare `expected` with current value, if equal replace the current value with `desired`, otherwise replace `expected` with current value. May spuriously fail (even when current value == `expected`). **`compare_exchange_strong`** cannot fail spuriously, but might be slower		

- **Specializations like `std::atomic<int>` also provide atomic operators like ++, --, +=, etc.**

- **The C++ memory model specifies**
  - When the effect of an operation is visible to other threads (storing and writing)
  - The possibility of reordering instructions
- **Different relations about visibility of effects**
  - sequenced-before: within a single thread
  - happens-before: sequenced-before or inter-thread happens-before
  - synchronizes-with: cross-thread sync.
- **Note: Read/writes in a single statement are "unsequenced"**

```
std::cout << ++i << ++i; //don't know output
```

- **Atomic operations have an optional parameter for memory order**
  - `std::memory_order_seq_cst` (default)
  - `std::memory_order_acquire`
  - `std::memory_order_release`
  - `std::memory_order_acq_rel`
  - `std::memory_order_relaxed`
  - `std::memory_order_consume` (discouraged)

```
int main() {
  std::atomic<int> c{};
  c.fetch_add(1, std::memory_order_seq_cst);
  //...
}
```

- **Sequential consistency**
  - Global execution order of operations
  - Every thread observes the same order
- **Memory order flag**
  - `std::memory_order_seq_cst`
- **The latest modification (in the global execution order) will be available to a read**

```
std::atomic<bool> x, y;
std::atomic<int> z;
```

Each function is executed in its own thread:

```
void write_x() {
  x.store(true);
}
```

```
void read_x_then_y() {
  while (!x.load());
  if (y.load()) ++z;
}
```

```
void write_y() {
  y.store(true);
}
```

```
void read_y_then_x() {
  while (!y.load());
  if (x.load()) ++z;
}
```

What are possible values of z after the execution of all threads?

Example taken from Anthony Williams: C++ Concurrency in Action

C++ Memory Model (Sequential Consistency)

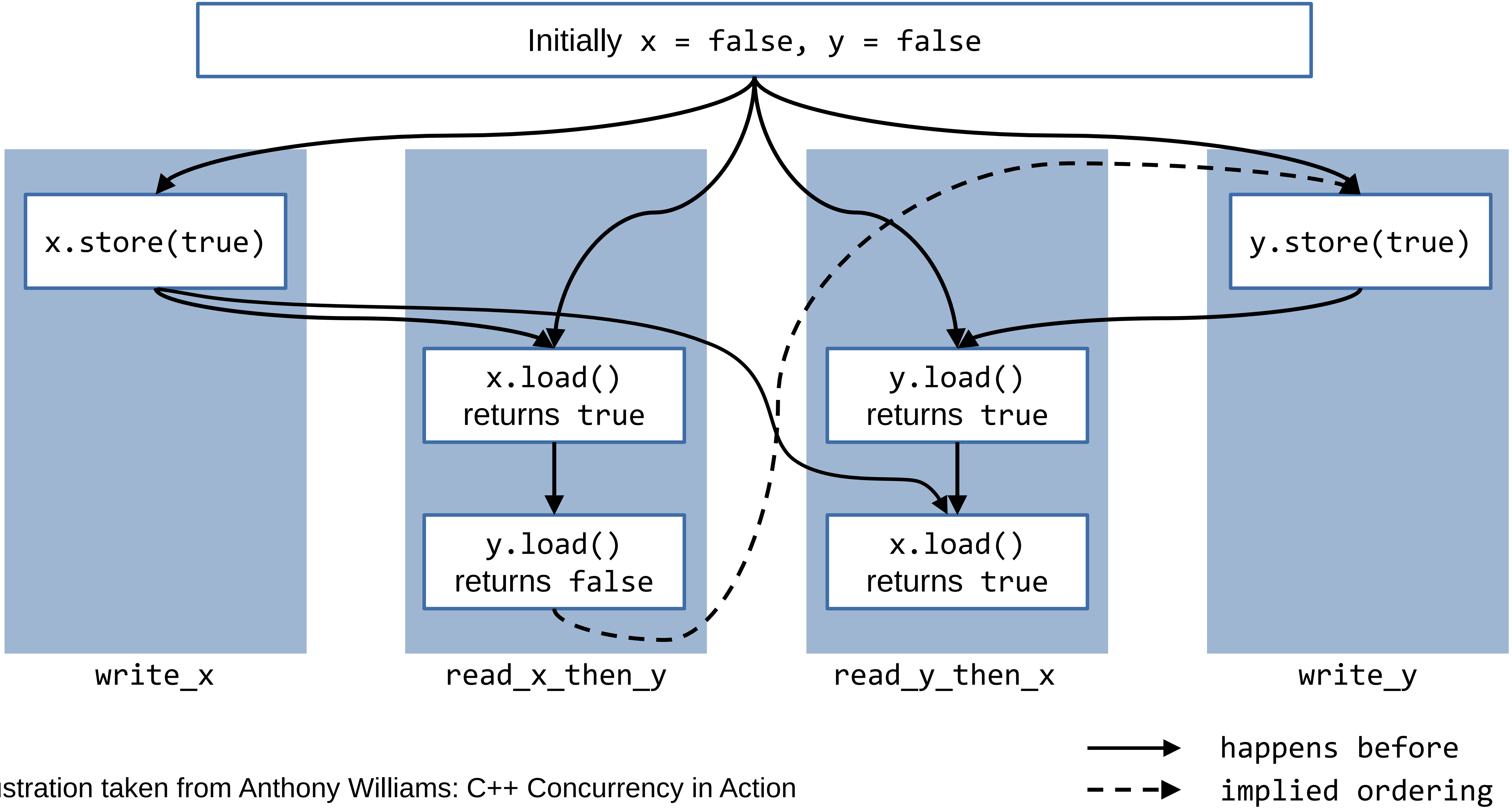


Illustration taken from Anthony Williams: C++ Concurrency in Action

- **Acquire (`std::memory_order_acquire`)**
  - No reads or writes in the current thread can be reordered before this load
  - All writes in other threads that release the same atomic are visible in the current thread

```
x.load(std::memory_order_acquire);
```

Note: It is not guaranteed that you always see the latest write in a read operation, but what you see is consistent according to the ordering above regarding the same atomic!

- **Release (`std::memory_order_release`)**
  - No reads or writes in the current thread can be reordered after this store
  - All writes in the current thread are visible in other threads that acquire the same atomic

```
x.store(std::memory_order_release);
```

- **Acquire/Release (`std::memory_order_acq_rel`)**
  - Works on the latest value

```
x.test_and_set(std::memory_order_acq_rel);
```

http://en.cppreference.com/w/cpp/atomic/memory_order

C++ Memory Model (Acquire/Release)

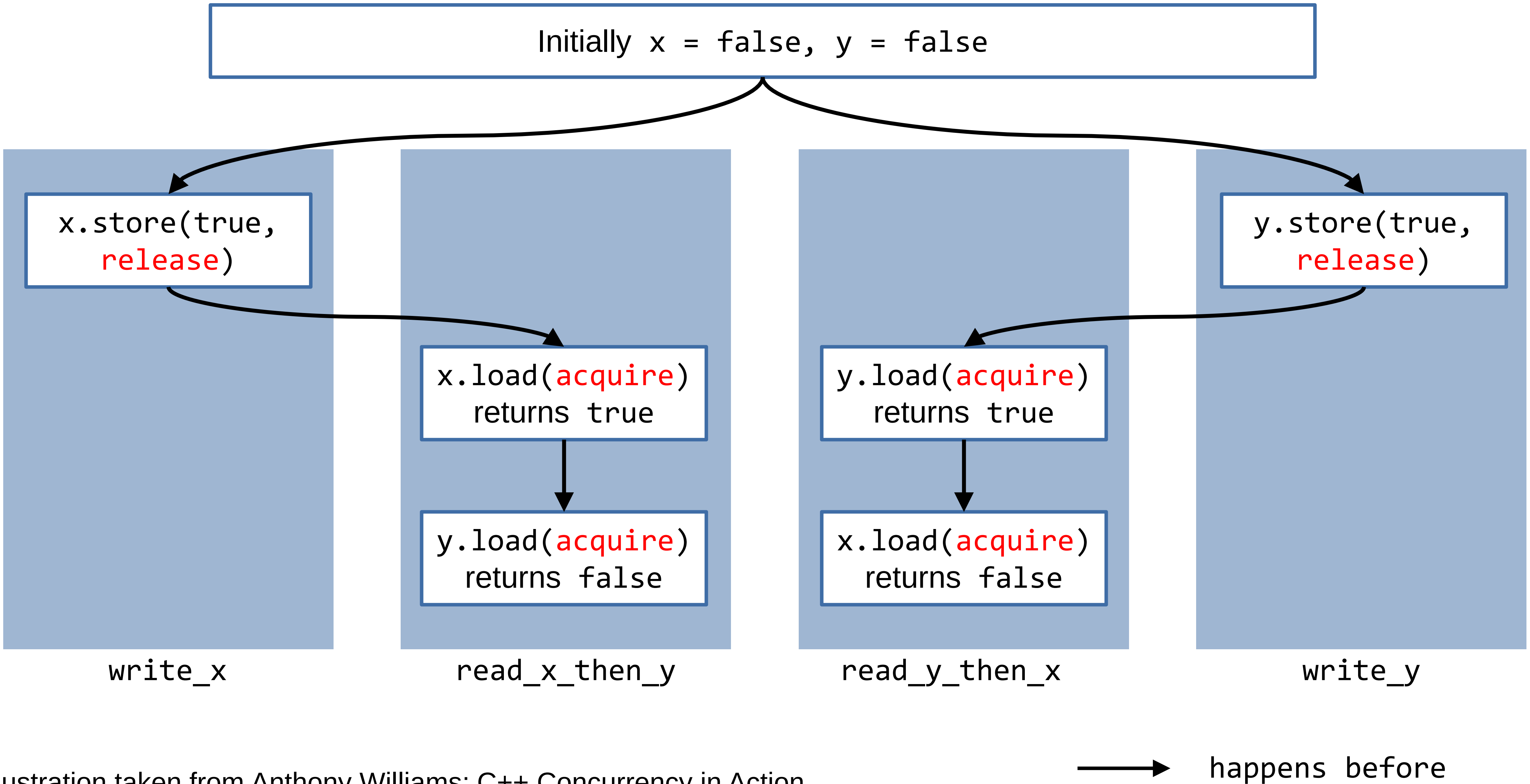


Illustration taken from Anthony Williams: C++ Concurrency in Action

Memory Order Relaxed

- **Relaxed memory order**
  - Does not give promises about sequencing
  - No data race for atomic variables
- **Order of observable effects can be inconsistent (in different threads)**
  - load() and store() operations happen in parallel
- **Depends on processor hardware if more "efficient" or not (and compiler support)**
  - Less synchronization effort means less processor pipeline stalling or needing to wait for memory loads
- **Using non sequentially consistent operations correctly is an art and requires proving correctness! (beyond this course)**

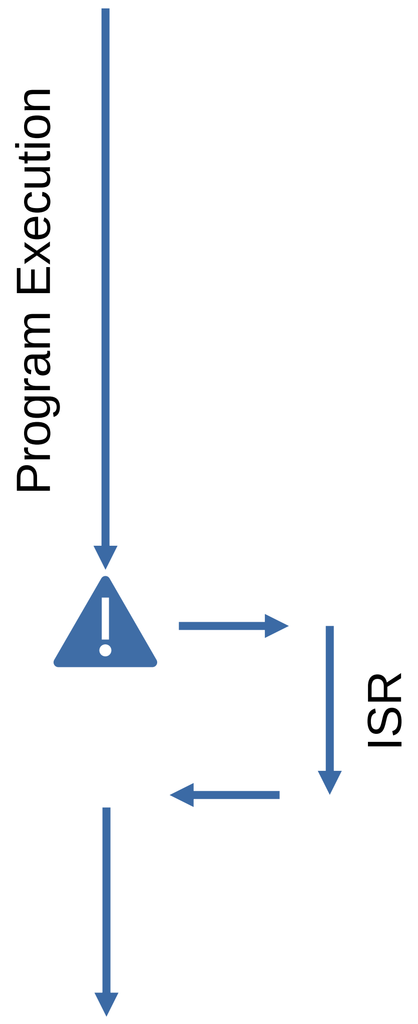
```
size_t max_count{ 10 };
size_t max_threads{ 5 };
std::memory_order order = std::memory_order_relaxed;

void increment(std::atomic<int> & x_or_y,
               std::array<values_read, max_count> & val) {
  waitForStartFlag();
  for (size_t i = 0; i < max_count; ++i) {
    val[i].x = x.load(order);
    val[i].y = y.load(order);
    val[i].z = z.load(order);
    x_or_y.store(i + 1, order);
    yield();
  }
}

void read(std::array<values_read, max_count> &val) {
  waitForStartFlag();
  for (size_t i = 0; i < max_count; ++i) {
    val[i].x = x.load(order);
    val[i].y = y.load(order);
    val[i].z = z.load(order);
    yield();
  }
}
// see github repo, adapted from C++ Concurrency in Action
// DEMO!
```

Keyword `volatile`

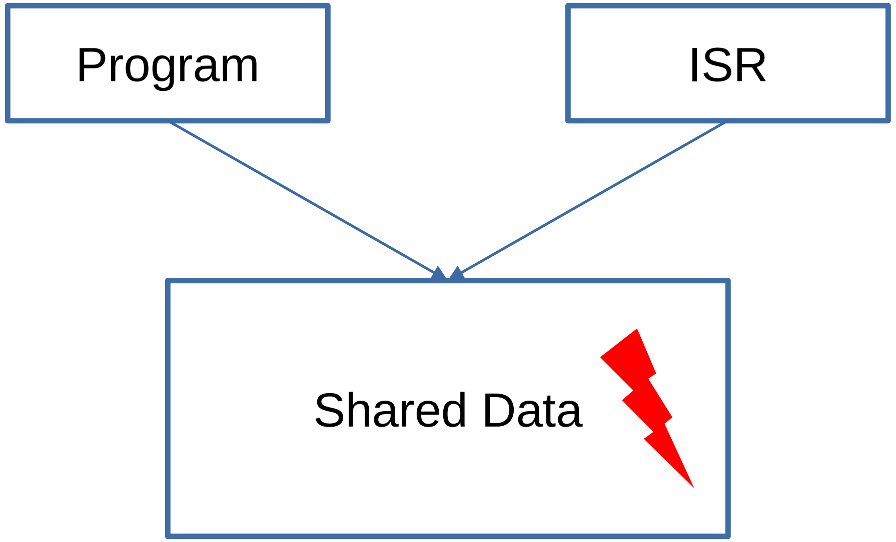

```cpp
volatile int mem{0};
```

- **The semantics of the `volatile` specifier for variables in C++ is different from the same specifier in Java and C#**
- **Load and store operations of volatile variables must not be removed, even if the compiler cannot recognize a visible effect within the same thread**
- **Prevents the reordering by the compiler within the same thread**
  - The hardware may still reorder it
- **Only useful when writing memory to access hardware directly**
  - Not for inter-thread communication!

- **An interrupt is a high priority event in a system that interrupts the normal program execution**
- **It invokes by a function that is registered to handle this event specifically**
  - Interrupt Service Routine
  - ISRs need to be short and must not block (run to completion)
- **After the interrupt has been handled, normal program execution is continued**



- **Data shared between an interrupt and the normal program execution needs to be protected**
  - Access needs to be atomic
  - Modifications have to become visible
- **volatile helps regarding visibility**
- **For atomicity interrupts might need to be disabled temporarily when accessing the data from the "normal" program execution**
- **Exact details about how to deal with interrupts depend on the specific microcontroller**



- **On Ardiuno interrupts cannot be interrupted**
- **Before accessing shared data interrupts need to be disabled**
- **Example**
  - Pin with ID 2 can be configured as interrupt pin.
- **`toggleLed()` is the ISR for the interrupt**
- **Every time before the `ledState` is read the interrupts are disabled. Afterwards they are reenabled again.**

```
constexpr byte ledPin = 13;
constexpr byte switchPin = 2;

volatile bool ledState = LOW;

void toggleLed() {
  ledState = !ledState;
}

void setup() {
  pinMode(ledPin, OUTPUT);
  pinMode(switchPin, INPUT_PULLUP);
  attachInterrupt(digitalPinToInterrupt(switchPin),
                  toggleLed,
                  CHANGE);
}

void loop() {
  noInterrupts();
  digitalWrite(ledPin, ledState);
  interrupts();
}
```

- **Getting programs working on shared mutable data correct is terribly difficult**
- **Use the appropriate kind of mutex and lock for protecting common data**
- **C++ has a memory model featuring very fine grained configuration possibilities, but unless you really know what you are doing and you inevitably need something else, stick with the defaults.**
- **Interrupts require special treatment of shared data, depending the actual platform**

What Else?

Cevelop
Your C++ deserves it

HSR
HOCHSCHULE FÜR TECHNIK
RAPPERSWIL
FHO Fachhochschule Ostschweiz

IFS INSTITUTE FOR SOFTWARE

- **Concurrency, Parallelism Technical Specification and Transactional Memory Support**
  - http://en.cppreference.com/w/cpp/experimental/concurrency (C++17)
  - http://en.cppreference.com/w/cpp/experimental/parallelism (C++17)
  - http://en.cppreference.com/w/cpp/language/transactional_memory
- **Continuations for futures (`std::future::then()`)**
- **Parallel versions of standard algorithms**
- **Latches and barriers**
- **Atomic smart pointers**
- **ACCU 2017 talk of Anthony Williams: https://www.youtube.com/watch?v=UhrIKqDADX8**
- **Still no thread pool and task abstraction**

```
template<typename R, typename...Args>
class packaged_task<R(Args...)>;
```

- **`std::packaged_task` wraps a function call with arguments**
  - The call is deferred until the task's call operator is called
- **Allows to obtain a future to the call's result**
  - Another thread can synchronize with the actual call through the future object
- **Call `operator()` of `std::packaged_task` makes the future ready when done**
  - Could be called from a thread
  - Need to pass by `std::move()` or `ref()` wrapper, can not be copied

```
std::string compute_the_answer(int i) {
  using namespace std::literals;
  std::this_thread::sleep_for(1s);
  return "the answer is "s + std::to_string(i);
}

using pt_fun = std::packaged_task<std::string(int)>;

int main() {
  std::cout << "computing" << std::endl;
  pt_fun task { compute_the_answer };
  auto future = task.get_future();
  std::thread compute { std::move(task), 42 };
  std::cout << future.get();
  compute.join();
}
```

- **For initialization code that might be needed by different threads, but called atomically only by one**
- **`std::once_flag` can be**
  - global (hard to test)
  - static local in a function (also hard to test)
  - or a class member
- **`std::call_once` takes the `std::once_flag`**
  - a callable
  - all arguments
  - need to wrap passed references with `std::ref` as with `std::thread`

```
void initfun(threadsafe_queue<int> & q){
  q.push(999);
}
//...
  std::once_flag init{};
  std::thread prod1{[&]{
    sleep_for(10ms);
    call_once(init, initfun, std::ref(queue));
    for(int i=0; i < 10; ++i) {
      queue.push(i);
      yield();
    }
  }};

  std::thread prod2{[&]{
    sleep_for(9ms);
    call_once(init, initfun, std::ref(queue));
    for(int i = 0; i < 10; ++i) {
      queue.push(i*10);
      yield();
    }
  }};
```

```
thread_local bool done{};
```

- **Thread-local variables are possible (global or static)**
  - Unfortunately not through a library type, but built-in prefix (storage class)
  - Compilers used to provide that through this mechanism
  - I (Peter Sommerlad) believe it is an error
- **No simple and easy examples**
  - One could implement recursive_mutex with a tread_local counter per mutex, but that requires a map of mutex to counter in a static thread_local member of the recursive_mutex class