CS3211

AY22/23 Sem 2

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Lectures

L1: Introduction to Concurrency

Concurrency
- Concurency is pervasive when modern computers have several cores and types of memory
- $\geq$ 2 activities making progress at the same time (overlaping time periods)
- Involves interleaving of instructions from different activities

Parallelism
- $\geq$ 2 processes executing and making progress *simultaneously*
- Hardware dependent: requires hyperthreading (SMT), or multi-core and hardware threads

Processes Vs threads
- Independent Vs Shared memory (address) space
- Both use independet stack
- Expensive Vs Cheap context switch
- OS facilitated vs Non OS facilitated inter-process/thread Communication
- Expensive (copy on write mediates this somewhat) Vs Cheap creation

Interrupts
- Asynchronous (independent to program execution)
- Used by OS to interact with the programme
- Triggered by external events (e.g. I/O, timer, hardware failure)

Exceptions
- Synchronous (dependent on program execution)
- Used by process to interact with the OS
- Triggered by process error (e.g. underflow, overflow)

User thread
- Library created, linked to one kernel thread

Race condition
- Outcome depends on reltive ordering of operations on ge 2 Threads
- a flaw that occurs when the timing or ordering of events affects a program's correctness

Data Race
1. $\geq$ 2 concurrent threads concurrently access a shared resource without Synchronisation / fixed ordering
2. At least one modifies shared resource
3. Causes undefined behaviour

Mutex
- Creates critical section can be treated as a large atomic blocks
- Only one thread at a a time
- Supported by a hardware instruction (CAS, test and set etc)
- **Properties:** Mutex, progres, bounded wait, performance
- Provides **serialisation** (less concurrency)

Critical section
- Safety: nothing bad happens
- Liveness: Something good (progress) happens
- Performance: depends on aggregate performance of all threads

Locks
- Primitive that is provided b the hardware, minimal semantic
- E.g. Test and set

Deadlock iff
1. Mutex: One resource held in a non-shareable state
2. Hold and wait: One proces holding one resource and waiting for another resource
3. No-preemption: Resource and critical section cannot be aborted externally
4. Circular wait
5. Note: Lock free can deadlock

Dealing with deadlock
- Prevention: Eliminate one of the above conditions (E.g. hold all locks at the start)
- Detection and recovery: Look for cycles in dependencies (E.g. wait for graph)
- Avoidance: Control allocation of resources

Starvation
- One process cannot progress becausee another process is holding on a resource it needs
- Side effect of scheduling algorithm
- Wait-die and wound-wait are possible solutions, if priority of processes is preserved

Advantages of concurrency
- Performance
- Separation of concerns

Disadvanageous of concurrency
- Maintenance and debugging

Task parallelism
1. Do the **same type of** work faster
2. Task dependency graph can be parallel
3. Make tasks specialists: Same type of tasks are assigned to the same thread
4. Divide a sequence of tasks among threads to solve complexed task
5. **Pipeline:** 1 type of thread for one phase of execution

Data parallelism
1. Do **more work** in the same amount of time
2. Divide data to chunks and execute by different threads
3. Embarasingly parallel tasks

Challenges of concurrency
1. Finding enough parallelism: Amadahl's law
2. Granularity of tasks
3. Locality
4. Coordination and Synchronisation
5. debugging
6. Performance and monitroring

L2: Tasks, threads, synchronisation in modern C++

History of CPP
- 1998: No support for multithreading
  1. Effects of language model are assumed to be sequential and there are no established memory model
  2. Different libraries used different memory models
  3. Execution threads were not acknowledged
- 2011: C++11
  1. Standard threads are implemented
  2. Thread aware memory model.Do not rely on platform specific extensions to guarantee behaviour
  3. Atomic operations library, class to manage threads, protected shared data etc.

Four ways to manage threads

1. Declare a function that returns a thread

```
void hello() {
    std::cout << "Hello Concurrent
        World\n";
}
int main() {
    std::thread t(hello);
    t.join();// existing thread waits for
        t to finish
}
```

2. Thread with a function object

```
class background_task {
public:
    void operator()() const {
        do_something();
        do_something_else();
    }
};
/* Calleable object */
background_task f;
std::thread my_thread(f);
```

- $std :: my\_thread(background\_task())$ declares a function that takes a single parameter (type *f() $\rightarrow$ object)
- This is not the same as using a function object!

3. Threads with a lambda expression (local fn instead of a calleable object)

```
std::thread my_thread([]{
    do_something();
    do_something_else();
});
```

Wait
- Uses join() on the thread instance exactly once
- Use joinable to check
- Local variables do not go out of scope
- Blocking

Detach()
- Local variable passed might go out of scope and 'disappear' during runtime, causing invalid access for the detached thread
- Example

```
void oops(){
    int local_state = 0;
    /* Reference passed might become
        invalid */
    func my_func(local_state);
    std::thread my_thread(my_func);
    my_thread.detach();
} /*oops ends here and local_state will
    be destroyed */
```

- Not blocking

Passing arguments
1. by value $std :: threadt(f, 3, "hello")$
2. by reference $std :: threadt(f, 3, buffer)$
   - Buffer is a charbuffer that only gets converted to str when we call f
   - Hence it is possible for buffer to go out of scope
   - Fix: Use explicit cast $std :: thread(f, 3, std :: string(buffer))$
   - **Major issue** with passing by reference is that threads outside of the scope can use it in **unsafe** ways. E.g. Not using mutex on shared data, deletion etc
3. by copy

```
void update_data_for_widget(widget_id w,
    widget_data& data);
void oops_again(widget_id w) {
    widget_data data;
    /* a copy of data is passed */
    std::thread t(update_data_for_widget,
        w, data);
    display_status();
    t.join();
    /* changes made to the copy is not
        reflected to other threads */
    process_widget_data(data);
}
```

- Fix: use reference $std :: threadt(update_data for_widget, w, std :: ref(data))$

Ownership in C++
- Owner is an object containing a pointer to an object allocated by new for which the owner is responsible for deleting
- Every object on free store (heap, dynamic store) must have **exactly one** owner

C++ Resource Management
- For scoped objects, desctructor is implicit at scope exit
- Free store objects (created using new) requires explicit delete

RAII
- Binds the lifetime of a resource that must be acquired before use to the lifetime of an object

```
/* Handle interrupts using RAII */
void enqueue(Job job) {
    std::unique_lock lock{mut}; //
        constructor locks mutex
    jobs.push(job);// destructor unlocks
        mutex
}
```

Lifetime
- Lifetime begins when storage is obtained and its initialization is complete (except std::allocator::allocate)
- Lifetime ends when :
  - Non-class type (int): destroyed
  - Class type: When destructor is called
  - Reference: begins with initialisation and ends when destroyed. A dangling reference is possible.

Ownership of thread
- Moveable but not copyable

```
void some_function();
void some_other_function();
std::thread t1(some_function);
/* t1 no longer references the thread */
std::thread t2 = std::move(t1);
/* t1 now owns a new thread */
t1 = std::thread(some_other_function);
std::thread t3;
/* t3 owns the thread running some
    function */
t3 = std::move(t2);
/* t1 already owns a thread, this will
    trigger a runtime error */
t1 = std::move(t3);
```

- C++ compiler cannot catch this

- Ownerhship can be moved out of a function and moved into another function

```
/* Transferrring out of a function */
std::thread g() {
    void some_function();
    std::thread t(some_function);
    return t; // ownership transferred
        out of g()
}

/* Transferring into a function */
void f(std::thread t);
void g() {
    void some_other_function();
    std::thread t(some_other_function);
    f(std::move(t)); // ownership
        transferred into f()
}
```

Mutex in C++

- $std::lock_guard$ locks the mutex upon initialisation, unlocks upon destruction
- $std::lock_guard < std::mutex > some_mutex;$
- Group mutex and protected data together in a class rather than use global variables
- Never pass data or pointers (via returns, sotring in externally visible memory, as input to functions etc) when their usage is not guaranteed to be safe

Types of lock guards

- **lock guard** no manual lock, can lock many or one mutex at once without deadlock
- **Scoped lock** accepts and locks a list of mutexes. Can be unintentionally initialized without a mutex
- **unique lock** manual unlock, defers locking using $std::defer_lock$, only single mutex.

Condition Variable

- Use condition variables to wait for a an event to be triggered by another thread
- Avoids busy waiting

```
std::condition_variable.wait(lock,
    []{return predicate});
```

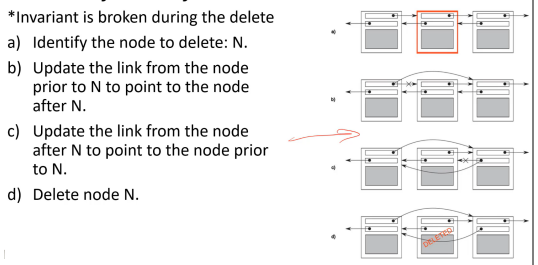
- if condition is satisfied, returns
- unlocks the mutex and places the thread in block state if condition is not satisfied
- $std::condition_variable.nofiy_one();$ to notify one thread waiting on the cond

Spurious Wake

- Thread wakes up from waiting, but is blocked again as the resource required is not available
- Leads to unnecessary context switching
- Use conditionals to prevent spurious wake

Shared DS - Invariants

- Often broken during an update
- **Case study: Doubly LL**



- invariant is temporarily broken during an update, and we need to prevent objects from accessing the DS during this time

L3: Atomics and Memory Model in C++

Reordering of operations

- Compiler may reorder (potentially conflicting) actions for performance
- Not visible to programmers

As-if rule

- Reordering is allowed as long as:

1. At termination, data written to files is exactly as if the program was executed as written (same final state)
2. Prompting text that is sent to interactive devices will be shown before the program waits for input
3. Programs with undefined behaviour is exempted from these rules.

Multi-threading aware memory model

- Using synchronisation constructs (mutexes, barriers etc) should preclude the need for a memory model since they serialise threads
- Memory model gives us more flexibility and speed by getting us closer to the machine

Stucture of memory model

- Every object has a memory location, some occupy exactly one, some occupy many
- The changes in memory location / what is stored there affects other threads

Modification Order

- Compose of all writes to an object from all threads in the program
- MO varies between runs, each object has their own MO
- The programmer is responsible that threads agree on the MO (if not, race condition happens)

MO - Requirements

- The MO of each object is monotonic within a thread
- But the relative ordering of MO of different objects is not guaranteed

MO - Building Blocks

- **Sequenced-before (SB)**
  - Each lines of code in a thread is sequenced before the next line
  - There is **NO** sequenced before in a statement with many function calls
- **Synchronises-with (SW)**
  - Established by a $load$ from T_i reading T_j's $store$
  - Both T_i and T_j are synced with respect to the common value in the MO
- **Happens-before (HB)** When an operation happens before another operation due to SW or SB
- **Interthread Happens Before (IHB)**
  - When a $store$ in T_i established a sequenced before a $load$ in T_j, $sotre_i$ happens before $load_j$
  - IHB $\subseteq$ HB
- **Visible Side effects**
  - Side effect of write A on O is visible to a read B on O if:
    1. A HB B
    2. There is no other side effects to O that happens between A and B
  - If the side effect of A is visible to B then the longest contiguous subset of the side-effects to O (that B does not HB) is known as the visible sequence of side effects
  - Do not think of ordering, think in terms of side effects that are visible
- **Modification Order**

MO - Seq Const

- The default
- All threads must see the same ordering of operation
- Synchronises with a sequentially consistent load of the same variable that reads the value loaded
- Does not apply to atomic operations with relaxed ordering
- Performance penalty when working with weakly ordered machine instructions (common)
- Essentially a serailised monoversion - global total order enforced
- Only guaranteed for data-race free programs (which is difficult since C++ is not as safe as Rust)

MO - Relaxed

- Atomic operations don't conform with SW relationships
- Happens before still applies within the thread $\rightarrow$ monotonicity and SB within the thread is preserved
- No HB between load and store, different store operations from T1 can be viewed out of order by reads in T2
- T1: $x = 1, y = 0$. T2 can see y=0 without seeing x=1 since there is no SW between the two threads even though x=1 HB y=1 in T1.

MO - Acquire Release

- No total modification order, but there is a partial order
- Read - acquire updates about the memory order, load - release updates about the memory order
- A link between acquire and release acts like a barrier

MO - Mixing Models

- Seq const and Release Acquire: load and store of seq const behaves similar to release acquite
- any MO and relaxed: Relaxed behaves like relaxed but is bounded by the other more limiting MO

```
// T1
x.store(true, std::memory_order_relaxed);
y.store(true, std::memory_order_release);
// T2
while (!y.load(std::memory_order_acquire) );
/* Never fires because acquire and release */
/* x.store HB y.store  & y.store SW y.load */
assert(x.load(std::memory_order_relaxed));
```

Atomic Operations

- Compiler ensures necesary synchronisation is in place and enforces MO
- Atomic ops are indivisible
- Atomic load loads either the initial value or the value stored by one of the modifications (cannot be half-done)
- Can be lock free or be implemented using mutex (which wipes off performance gains)
- Not necessarily race free

L4: Testing and debugging in C++

Concurrency related bugs

- Unwanted blocking: Deadlock, livelock, blocking while waiting on I/O
- Race conditions:

1. Data races: Undefined behaviour due to unsynchronised access to a shared memory locaiton. Obseravable.
2. Broken Invariants:
   - Dangling pointers: another thread deleted the data being accessed
   - Random memory corruption: Inconsitent values being read due to partial updates
   - Double free: Two threads pop the same value from a queue / deleting the same memory address twice - causes possible memory leak
   - Use After Free - Reading or writing after a memory has been freed
   - Uinitialised variables - Reading from a variable that has not been initialised
3. Lifetime issues:
   - Thread outlives data
   - Call to join skipped doe to an exception thrown

Techniques to locate concurrency bugs

- Look at the code
- Testing: Difficult to reproduce, Tests do not always fail (Heisenbug)

Guidelines for testing

- Run the smallest amount of code that could potentially demonstrate the bug to locate faulty code
- Do single threaded tests to verify the bug is concurrency related
- Run on sinlge core system to identify issues with interleavings

Test environment

- Number of threads: More threads increases the chance of deadlock (at least 2), contention (blocking while contending for shared resources, degrades performance), overhead
- Architecture
- Number of cores
- Having memory fences and barriers to sync threads

Designs for testability

- Responsiblity for each function and thread should be clear

- Check that library calls are thread safe (e.g. do they use internal states to ensure correctness?)

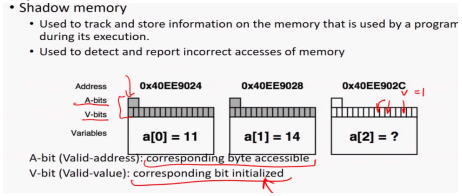
Techniques for testing

1. Stress testing
2. Use special implementation of synchronisation primitives (e.g. log when mutexes are locked, unlocked)
3. **Scalability** does the speedup scale when the number of threads increase? Contention to

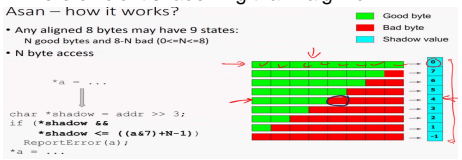
Debugging Tools

- Identify bugs:

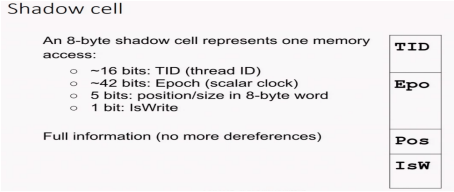
1. Valgrind (dynamic instrumentation)
   - Shadow memory: track and store information on the memory that is used by a program during its execution. A bits and V bits must match for valid.
   - 20x slowdown
   - Provides more details than sanitizers despite its performance overhead



2. Helgrind (dynamic instrumentation)
   - 100x slow down
   - intercepts function calls to functions and instruments
   - Detects: misuses of POSIX threads API, potential deadlocks (checking cyclic lock acquisition), data races (checks existence of HB between memory accesses)
3. Sanitizers (compilation-based approach)
   - 5-10x overhead (lmao just use rust)
   - $-fsanitize = address$ or $-fsanitize = thread$ or $-fsanitize = memory$ (to catch unitialised memory)
   - Output is verbose (unlike rust compiler)
4. Adress Sanitizers (compilation-based approach)
   - 2x slowdown, 3x overhead
   - More efficient shadowing than valgrind



5. Thread Sanitizer
   - 5-10x slow down, 5-15x overhead
   - Function entry/exit and memory access are logged
   - An 8-byte shadow cell represents one memory access
   - Epoch: time of access
   - Pos: location accessed
   - If there is an overlap in Pos, we check epoch for evidence of HB. If no HB, then there might be a data race
   - Use graph-based deadlock detection



L5: Concurrent DS in modern C++

Goal

- Multiple threads can access the same DS concurrently
- The scope of concurrency (all operations, some operations, one operation) depends
- Each thread has a self-consistent view of the DS
- **Broken invariants** should not be visible E.g. delete() of DLL
- Avoid race conditions
- Handle exceptions, prevent exceptions from exposing broken invariants. E.g. UAF when a thread aborts after freeing
- **Thread safe**
  - No data is lost or corrupted
  - All invariants are kept
  - No problematic race conditions

Problems with mutex

- Prevents true concurrent access to DS - Serialisation
- Possible for deadlocks (well, same for lock-free but harder)

Concurrency while calling functions

- Constructors and destructors require exclusive access to the DS - users should not access DS before construction is complete and after desctruction
- Swap(), assignment, copy(): Can they be used concurrently with other operations in the DS?

Design Principles

- Smaller the protected region, the better - fewer serialised region
- Provide opportunities for concurrency to threads accessing a thread safe DS - what can be called concurrently?
- One type of operation can be performing one type of operation exclusively from another type of operation (reader writer) - consider shared mutex
- Or allow different types of operations to happen concurrently but disallow the same type to be used by concurrent threads

Maximising concurrency

- Use different mutexes to protect different parts
- Give more concurrency to more frequent operations

Example: threadsafe stack

1. Exception Safety - safe!

```
std::shared_ptr<T> pop() {
    std::lock_guard<std::mutex> lock(m);
    /* This is safe */
    if (data.empty()) throw empty_stack();
    /* Potential out of memory error */
    /* This is fine since the mutex will
       be unlocked during exception */
    std::shared_ptr<T> const res(
std::make_shared<T>(std::move(data.top())));
    value = std::move(data.top());
    data.pop();
    return res;
}
```

2. Work is serialized for the DS - low concurrency
3. Should use a monitor to allow waiting for an item to be added

Example: threadsafe Queue

1. Exception Safety: Suppose a thread is woken up by the monitor and that an exception occuring after this point will cause nothing to be popped from the queue.
2. And other threads waiting on the condition variable is not able to be notified of the non-empty queue

```
void wait_and_pop(T & value) {
    std::unique_lock<std::mutex> lock(m);
    data_cond.wait(lock, [this]{return
        !data.empty();});
    std::shared_ptr<T> res(
/* Exception here is problematic */
std::make_shared<T>(std::move(data.top())));
    value = std::move(data.top());
    /* Important to pop after moving */
    data.pop();
    return res;
}
```

3. Fix 1 Notify All: Works ... but cause spurious wakes
4. Fix 2: Put the shared pointer in the queue directly, so we can obtain a shared pointer directly by popping from the queue
5. Shared pointer helps us to handle deallocation

```
class threadsafe_queue {
    private:
    std::mutex m;
    std::queue<std::shared_ptr<T>>
        data_queue;
    std::condition_variable data_cond;
    public:
    ...
void push(T new_value) {
    /* Creation of new data takes place
       outside mutex */
    /* This is exception safe */
    std::shared_ptr<T> data(
std::make_shared<T>(std::move(new_value)));
    std::lock_guard<std::mutex> lock(m);
    data_queue.push(data);
    data_cond.notify_one();
}
}
```

6. Share-pointers are exception safe
7. The creation now takes place outside the mutex - improves performance
8. However, using the standard container and mutex limits concurrency as the queue is either protected or not
9. For a more fine-grained locking, we need to write a customised DS

Example: threadsafe stack with fine-grained locks

- **Node**

1. Data is not meant to be shared, so shared ptr is not used
2. Pointers to nodes should only be modified by one thread, so we use an unique poitner

```
struct node {
    T data;
    /* Only one copy of next */
    std::unique_ptr<node> next;
    node(T data_):
            data(std::move(data_))
    {}
};
```

- **Push - attempt 1**

1. Modify the front of the queue if it is empty
2. Else we modify the back
3. Using a lock for checking front and back is problematic as we need to lock both mutexes if the queue is initially empty (front=back, potential for deadlock if two threads tries to push concurrently). This also serialises the queue

```
void push(T new_value) {
    std::unique_ptr<node> p(new
        node(std::move(new_value)));
    node* const new_back = p.get();
    std::lock_guard<std::mutex>
        lock(tail_mutex);
    if (back) {
        back->next = std::move(p);
    } else {
        front = std::move(p);
    }
    back = new_back;
}
```

- **Push - attempt 2**

1. Ensure that there's always $ge1$ node in the queue to separate the node being accessed at the front from the node being accessed at the back
2. Empty queue: front and back point at a dummy node
3. No race on front.next and back.next (additional layer of indirection)

Tutorials

T1: Threads and Synchronisation

Why mutexes work - standard argument

- Define a critical section that contains all acesses to the shared resource
- Argue that mutex guarantees mutual exclusivity of threads - removes interleaving, data race precluded

Why mutexes work - theoretical argument

- Lock and unlock appears in a single total order
- Only one thread owns the lock at any pointer
- Unlock happens after lock, creating a synchronises with relationship between processes and **serialises the interleaving** - no concurrent access

Monitor

- Allows us to block until a condition becomes true
- The monitor has:

1. A mutex on the critical section
2. A condition variable
3. A condition to wait for

```
std::condition_variable cond;

Job dequeue() {
    std::unique_lock lock{mut};
    /* wait until there is a job */
    cond.wait(lock, [this]() { return
        !jobs.empty(); });
    Job job = jobs.front();
    jobs.pop();
    return job;
    }

void enqueue(Job job) {
    {
        std::unique_lock lock{mut};
        jobs.push(job);
    }
    /* notify one thread waiting on the
        condition variable */
    cond.notify_one();
    }
```

T2: Atomics in C++

Data races and undefined behaviour

- For undefined behaviour, the C++ compiler **will allow it to be compiled**
- Compilers are free to do any reordering and the answer cannot be predicted.
- E.g. GCC and Clang will return different runtime outputs as they compile it differently
- See snipet 1

Mutexes Vs Atomics

- Consider the following implementation of a counter

```
int counter = 0
std::mutex m;
void t1 {
    for (int i = 0; i < 1000000; i++) {
        std::lock_guard lock{mut};
        counter++;
    }
}

std::atomic<int> atomic_counter = 0
void t2 {
    for (int i = 0; i < 1000000; i++) {
        atomic_counter.fetch_add(1,
            std::memory_order_seq_cst);
    }
}
```

- The atomic version is much faser than the mutex version
- Mutex calls lock and unlock multiple times around the add operation, which compiles to more instructions and may cause the threads to sleep / fight for access
- The atomic version is a single instruction $lock\ addl\ \$1$, which is much faster

Memory order and performance

- Seq cst $\geq$ Acquire-Release $\geq$ Relaxed
- Seq cst's store uses $xchg$ (requires the processor to have exclusive access to shared mem) while the other orders allows x86 to use a simple mov instruction

Forcing ordering with $std :: atomic < int >$

- Compiler reorders instructions to preserve visible side effects and optimise
- We can use atomics to force the compiler to preserve ordering
- But this also forces the compiler to use the more expensive $xchg$ instruction, since atomics use seq cst by default

Memory order - atomics

- Note: data races **is not possible** when atomics are used. If load and store are not atomic, then the output can theoretically be anything (segfault, garbage value etc)

Thread 1

```
x.store(1, stdmo::relaxed);  // (a)
y.store(2, stdmo::release);  // (b)
x.store(3, stdmo::relaxed);  // (c)
z.store(4, stdmo::release);  // (d)
x.store(5, stdmo::relaxed);  // (e)
```

Thread 2

```
while (y.load(stdmo::acquire) != 2) { }  // (p)
cout << x.load(stdmo::relaxed);          // (q)
while (z.load(stdmo::acquire) != 4) { }  // (r)
cout << x.load(stdmo::relaxed);          // (s)
```

- The first cout can print 1,3,5. The secon cout can print 3,5. They will never print 0 due to the acquire release.

Fences

- Enforces memory order without modifying the data
- Can be used with Relaxed MO to enforce ordering while preserving concurrency
- **Memory Barrier** puts a line that certain operations cannot pass
- **Atomic fence** with acquire release MO prevents all preceding read and writes from moving past all subsequent stores

T3: Debugging Concurrent C++ Programs

Protecting shared resource with unique_ptr

- std::unique_ptr is a smart pointer that owns and manages another object through a pointer and disposes of that object when the unique_ptr goes out of scope.
- Destroys object with the provided $deleter$

```
{
std::unique_ptr<int> foo =
    std::make_unique<int>(5);
/* custom deleter for File */
auto deleter = [](FILE* f) { fclose(f); };
auto bar = std::unique_ptr<FILE,
    decltype(deleter)>(fopen("file.txt",
    "w"), deleter);
}
/* Foo and bar are destroyed here */
```

Protecting against shared lifetimes

- std::shared_ptr is a smart pointer that retains shared ownership of an object through a pointer.
- When shared ptr is copied, we increase the count by 1. When it is destroyed, we decrease the count by 1. When count is 0, we delete the object
- While deleting shared ptr is thread safe (since it just deceremnts the counter), the object wrapped by shared ptr may not be (data races can still happen)

Possible bugs with shared_ptr

- Unsynchronised access to managed object - WR, WW can still happen if exclusive lock is not used
- Data race on ptr (UAF): Overwrites to ptr deletes the old value and make a new one. But the reader may still be using the old ptr. Do not pass shared ptr by reference.
- Circular reference: A points to B, B points to A. Both will never be deleted since the reference count will be at least 1. E.g. A.prev = B, B.next = A.
  - Using DLLNode* prev and DLLNode next. Only the next pointer copies the shared pointer, so there is no cycle.

Implementing shared ptr

- The semantics of a shared ptr is that it manages when to destroy a shared resource.
- This means that we need to keep a shared count, that is stored as a reference
- Since this is shared, we need to use a mutex (see 3.4) or atomic operations (see 3.5) to protect it
- During deletion (count == 0), we cannot delete the mutex in the critical section since the std::unique lock will call unlock when exiting the CS
- So we store the decremented value of counter in a temp var and check $temp == 0$ outside of the critical section
- This is correct since $temp == 0$ implies no thread can modify the counter so no data race
- Note: Use an atomic int for the atomic implementation

Extra overhead of shared pointer

- Ambiguous ownership: Most resources should have a single owner using std::unique ptr and use a singleton pattern
- Memory leaks: Cyclic references, as shown above, can cause memory leaks. Std::unique ptr does not face this.
- Performance overhead: Maintaining reference counts result in unnecessary synchronisation. Initialising memory on the heap instead of the stack (since shared ptr is shared) may slow down the program and reduce cache locality

Classical Synchronisation Problems

Comparison between Rust, Go, C++

Ownership

- C++ has RAII to manage resources, moveable but not copyable reference

Testing and debugging

- C++ cannot catch many race conditions and concurrency bugs at compile time, and requires testing at run time
- Tsan and Asan has verbose output (unlike rust compiler)

- Catching concurrent bugs at run time runs into heisenbugs