Concurrent Systems

Exercise 03 – Memory, Atomicity, Consistency

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Agenda

Memory Models

Sequential Consistency

C11/C++11 Atomic Types

C/C++ Memory Consistency Models

Thread Fences

Assignment 3

What is a memory model?

- Formal definition of memory behavior
  - More or less trivial for sequential programs
  - Complex for parallel programs
- Crucial for application correctness
  - Particularly for parallel programs
- Memory models are created by ...
  - Language designers
  - Hardware developers
  - Service providers

Sequential Consistency

Def. *Sequential Consistency* — Lamport, 1979

"[...] the result of any execution is the same as if the operations of all the processors were executed in some sequential order, and the operations of each individual processor appear in this sequence in the order specified by its program."

- Benefits of SC
  - Result is equivalent to a sequential execution
    → Pseudo-parallelism?
  - Global order of actions
  - Analysability
- Problems of SC
  - Even simple compiler optimisations violate SC
  - Strictly sequential memory becomes the system bottleneck

Why don't we always want SC?

- Modern Platforms are not WYSIWYG[1]
  - Optimizing Compiler, Assembler, Linker, Hardware
  - Every link in the tool-chain can reorder operations
    - We nearly always want that ...
    - ... but it can break parallel code
    - It does not matter which tool breaks our code
- SC makes optimisations hard

More Reordering

SC $\longrightarrow$?

$\rightarrow$ Analysability	$\rightarrow$ Bugs?
$\rightarrow$ Correctness	$\rightarrow$ Performance?

[1] What You See Is What You Get

Sequential Consistency – Data Race Free

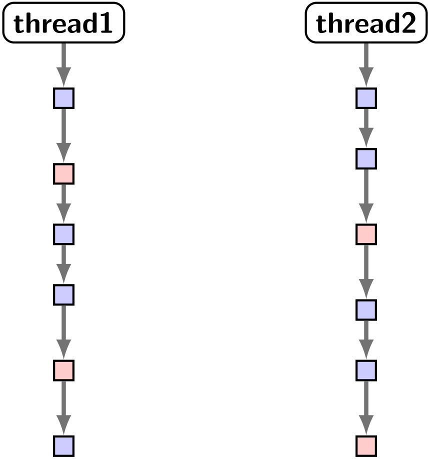
- SC-DRF
  - Distinguish *synchronising* actions from *non-synchronising* actions
    - Guarantee SC for programs without data races
    - Undefined behavior in case of data race
    - Most code parts allow optimisation
  - Synchronising actions provide SC
    - e.g. `mutex_lock`, `atomic_fetch_add`, ...
  - Non-synchronising actions can cause data races

Def. ***Data Race*** **C11 Standard (Draft)**

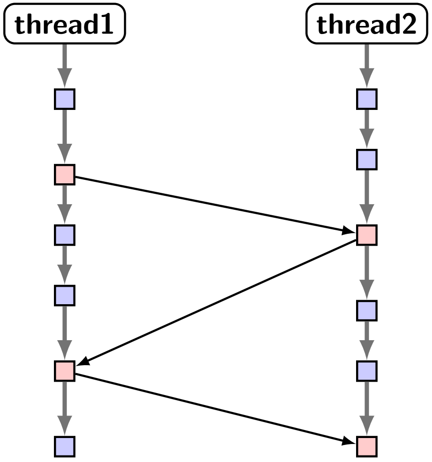
"Two expression evaluations **conflict** if one of them modifies a memory location and the other one reads or modifies the same memory location."

"The execution of a program contains a **data race** if it contains two conflicting actions in different threads, at least one of which is not atomic, and neither happens before the other."

Sequential Consistency – Data Race Free (2)



Sequential Consistency – Data Race Free (2)



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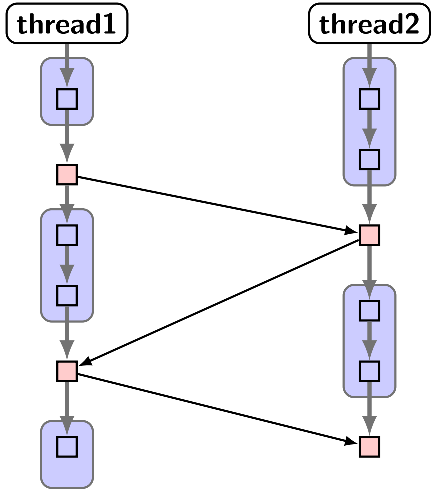

C11 / C++11 Atomic Types

Modern C/C++ offers atomic types

- C ⇒ `_Atomic` qualifier
- C++ ⇒ `std::atomic<type>` template
- Intentionally compatible:

```
#ifdef __cplusplus
#define _Atomic(type) std::atomic<type>
#endif
```

Well-defined semantics

- Compiler guarantees atomicity
- *unlike volatile ...*

Portable

- Actual run-time properties still depend on the hardware
- Lock-freedom is not guaranteed

C11 Atomic Operations

- Atomic operations

```
#include <stdatomic.h>
atomic_store(AT*, T);
atomic_load(AT*);
atomic_exchange(AT*, T);
atomic_compare_exchange_strong(AT*, T*, T);
atomic_compare_exchange_weak(AT*, T*, T);
atomic_fetch_add(AT*, T);
atomic_fetch_sub(AT*, T);
atomic_fetch_or(AT*, T);
atomic_fetch_xor(AT*, T);
atomic_fetch_and(AT*, T);
```

C11 Atomic Operations (2)

- Atomic operations with explicit memory order parameter

```
#include <stdatomic.h>
atomic_store_explicit(AT*,T, MO);
atomic_load_explicit(AT*,MO);
atomic_exchange_explicit(AT*, T, MO);
atomic_compare_exchange_strong_explicit(AT*,
    T*,T,MO,MO);
atomic_compare_exchange_weak_explicit(AT*,
    T*,T,MO,MO);
atomic_fetch_add_explicit(AT*, T, MO);
atomic_fetch_sub_explicit(AT*, T, MO);
atomic_fetch_or_explicit(AT*, T, MO);
atomic_fetch_xor_explicit(AT*, T, MO);
atomic_fetch_and_explicit(AT*, T, MO);
```

C/C++ Memory Order Parameters

1. sequential-consistent
   - `memory_order_seq_cst`
2. acquire-release
   - `memory_order_acquire`
   - `memory_order_release`
   - `memory_order_acq_rel`
3. consume-release
   - `memory_order_consume`
   - `memory_order_release`
4. relaxed
   - `memory_order_relaxed`

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   - `memory_order_relaxed`

Performance?

`memory_order_seq_cst`

- Strongest consistency model available
- Implicit consistency model
  - All operations without `_explicit`
- Semantics: SC-DRF
  - All operations with `memory_order_seq_cst` are sequentially consistent
  - Non-atomic variables can cause data races

memory_order_{acquire,release,acq_rel}

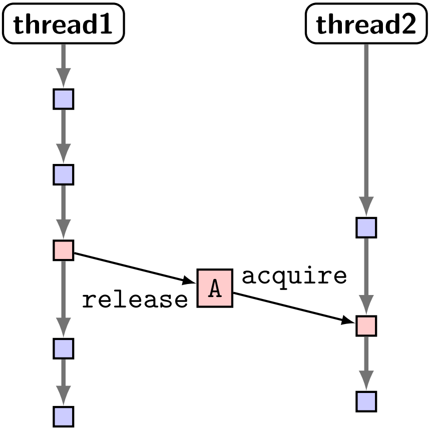
- Happens-before relation
  - Intra-thread: trivial
  - Inter-thread: If S_A release-stores a value v in A and L_A acquire-loads that value, then S_A **happens before** L_A.
  - S_A also happens before L_A if L_A reads a **later** value v' of A

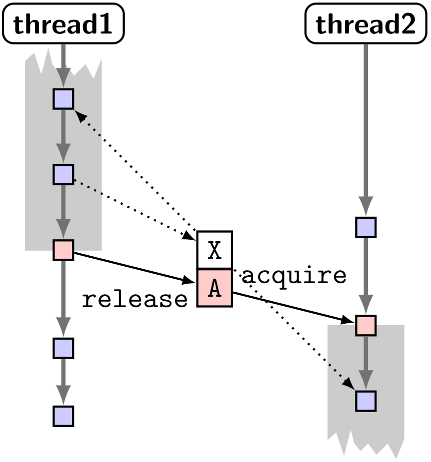
  → modification order
  - Transitive relation
- Acquire/Release consistency
  - Each operation sees side effects of all operations that happened before
- Partial Ordering
  - No global sequence of operations
  - Synchronisation per variable
  - Concurrent operations are possible

`memory_order_{acquire,release,acq_rel}` (2)

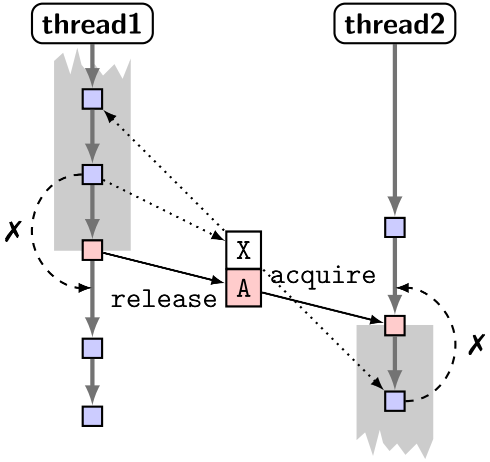
- `acquire` → load
  - *fetch-all-data*
  - Side effects after `load-acquire` remain afterwards
  - Implicit in `thrd_join`, `mtx_lock`
- `release` → store
  - *push-all-data*
  - Side effects before `store-release` remain before
  - Implicit in `thrd_exit`, `mtx_unlock`
- `acq_rel` → load/store
  - e.g. `atomic_fetch_and_*`, `atomic_compare_exchange_*`

memory_order_{acquire,release,acq_rel} (3)

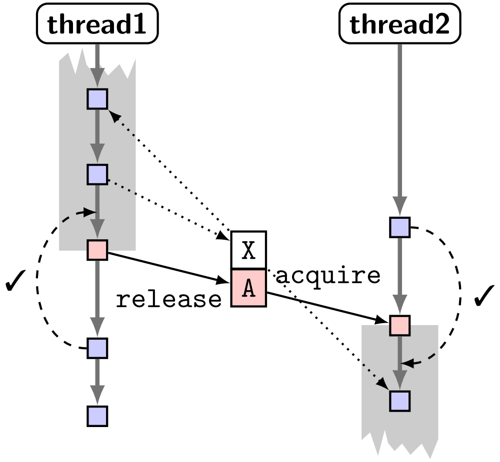



thread1
thread2
X
A
release
acquire

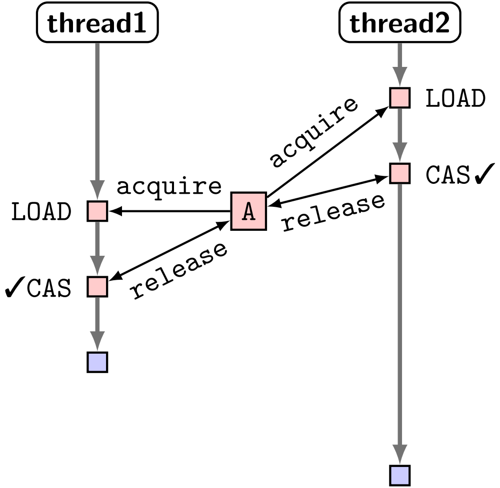
memory_order_{acquire,release,acq_rel} (3)



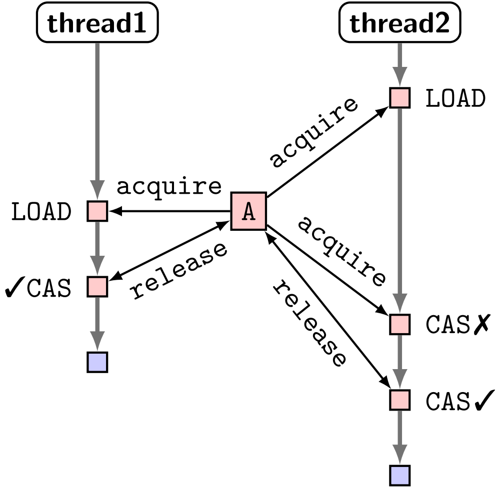
memory_order_{acquire,release,acq_rel} (3)



memory_order_{acquire,release,acq_rel} (4)



memory_order_{acquire,release,acq_rel} (4)



- Example:

```
int data; _Atomic(bool) avail;
thread1() {
  data = createdata(); // not atomic
  atomic_store_explicit(&avail, 1,
      memory_order_release);
}
thread2() {
  if (atomic_load_explicit(&avail,
      memory_order_acquire)) {
    int mycopy = data; use(mycopy);
  }
}
```

memory_order_{acquire,release,acq_rel} (5)

- Example:

```
_Atomic(foo *) data;
thread1() {
  foo *d = createdata(); // not atomic
  atomic_store_explicit(&data, d,
    memory_order_release);
}
thread2() {
  foo *d = atomic_load_explicit(&data,
    memory_order_acquire);
  if (d)
    use(d);
}
```

memory_order_relaxed

- Weakest memory order parameter
  - Meaningful when additional mechanisms synchronise
- Ensures atomicity
  - No synchronisation
  - Lock-freedom not guaranteed
- No reordering constraints
  - Except for thread fences ...
  - Dangerous to use
- Performance improvement?

memory_order_relaxed (2)

```
_Atomic(unsigned int) counter;
search() {
  while (...) {
    if (...)
      atomic_fetch_add_explicit(&counter, 1,
          memory_order_relaxed);
  }
  thrd_exit(...);
}
main() {
  for (...) thrd_create(..., search, ...);
  for (...) thrd_join(...);
  unsigned int total = atomic_load_explicit(&counter,
      memory_order_relaxed);
}
```

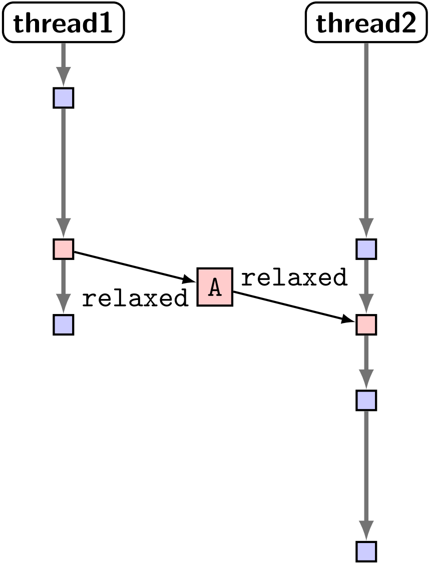
memory_order_relaxed (2)

```
_Atomic(unsigned int) counter;
search() {
  while (...) {
    if (...)
      atomic_fetch_add_explicit(&counter, 1,
          memory_order_relaxed);
  }
  thrd_exit(...);
}
main() {
  for (...) thrd_create(..., search, ...);
  for (...) thrd_join(...);
  unsigned int total = atomic_load_explicit(&counter,
      memory_order_relaxed);
}
```

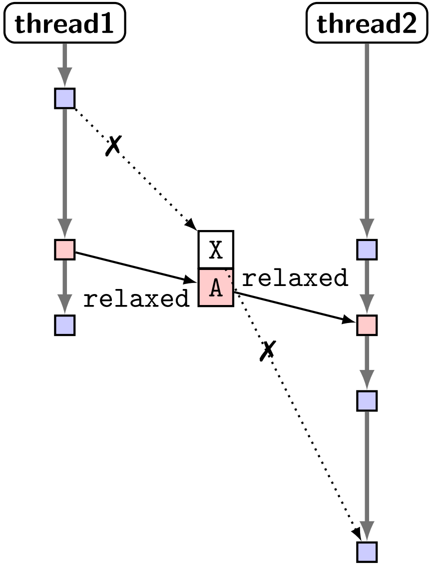
`atomic_thread_fence` (1)

- Enforces additional memory ordering guarantees
  - Often better: use stronger memory order parameter at critical operation
- Parameter: memory order
  - `memory_order_acquire`
  - `memory_order_release`
  - `memory_order_acq_rel`
  - `memory_order_seq_cst`
- Improves consistency of `relaxed-atomic` operations
  - Useful for library functions

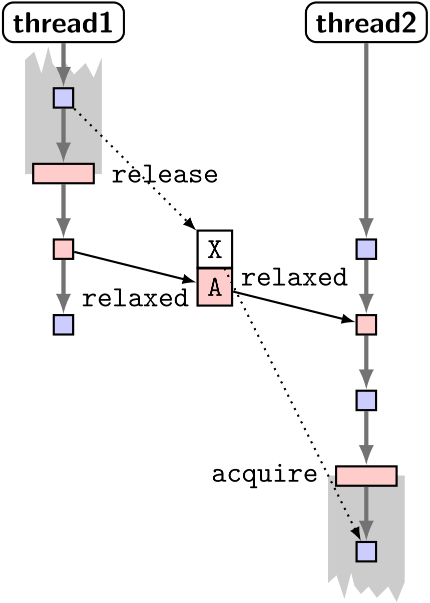
atomic_thread_fence (2)



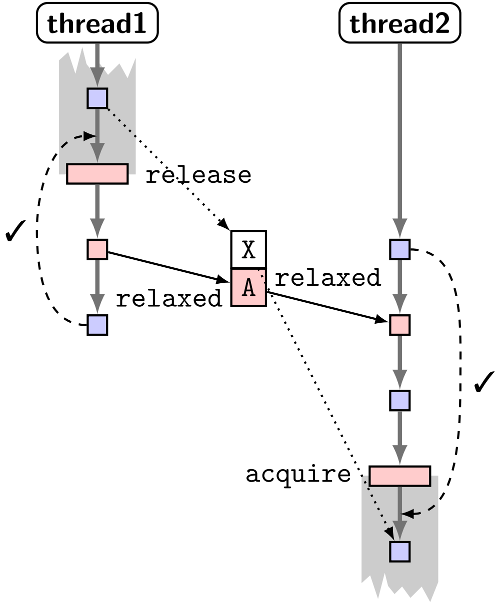
atomic_thread_fence (2)



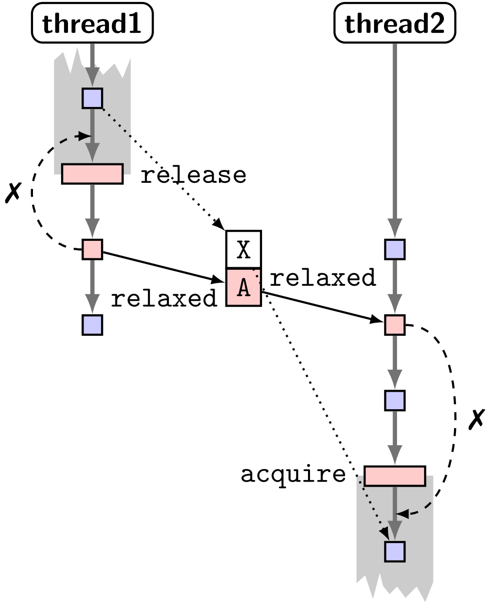
atomic_thread_fence



atomic_thread_fence



atomic_thread_fence (2)



```
int data; atomic_bool avail;
thread1() {
  data = createdata(); // not atomic

  atomic_store_explicit(&avail, 1,
      memory_order_relaxed);
}
thread2() {
  if (atomic_load_explicit(&avail,
         memory_order_relaxed)) {

    int mydata = data; use(mydata);
  }
}
```

atomic_thread_fence (3)

```c
int data; atomic_bool avail;
thread1() {
  data = createdata(); // not atomic
  atomic_thread_fence(memory_order_release);
  atomic_store_explicit(&avail, 1,
      memory_order_relaxed);
}
thread2() {
  if (atomic_load_explicit(&avail,
        memory_order_relaxed)) {
    atomic_thread_fence(memory_order_acquire);
    int mydata = data; use(mydata);
  }
}
```

Assignment 3

- Implement lock algorithms
  - Lock algorithms are discussed in the lecture
- Test all lock algorithms
- Evaluate all lock algorithms
  - Vary the degree of contention
  - Check multiple back-off algorithms
- Use a model checker for concurrent data structures
  - `CDSChecker` → dl.acm.org/doi/10.1145/2509136.2509514
  - Write a unit test for at least one lock algorithm

Assignment 3 (2)

- Implement a simple actor library
  - Actors send requests asynchronously
  - Each actor owns a worker thread
  - Requests are sequentialised implicitly
- Shortcommings
  - No actor states and mutation
  - No actor migration
  - ...
- Test your actor library
  - Write test cases for your actor
  - Can you re-use the lock test cases?
- Evaluate your actor library
  - Compare your actor implementation against lock-based synchronisation
  - Under which conditions are actors a better choice?

compare_exchange_weak

- *weak* ⇒ Operation may fail spuriously
- Efficient implementation with LL/SC possible
- maybe ABA-free
- Example:

```
int n, o = atomic_load(&shared);
do {
  n = compute(o);
  if (atomic_compare_exchange_weak(&shared,&o,n))
    break;

} while (1);
```

compare_exchange_weak

- *weak* ⇒ Operation may fail spuriously
- Efficient implementation with LL/SC possible
- maybe ABA-free
- Example:

```
int n, o = LL(&shared);
do {
  n = compute(o);
  if (SC(&shared, n))
    break;
  o = LL(&shared);
} while (1);
```