Practical Multi-Threading

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Overview

- threading basics:
  - thread objects: thread start, termination
  - synchronization, mutex, condition variable
- outlook: threading building blocks
- NOT: lock-free programming!

Quick Survey

- who uses STL algorithms?
- ... algorithms like sort(), lower_bound(), etc.?
- ... algorithms like copy(), find(), etc.?
- ... for_each()

Multi-Threading Problems

- dead-lock/live-lock
- race condition
- serial execution == no better performance

Thread Objects

- create a new thread: ctor + function object
- thread identity: the thread's ID
- join with a thread
- detach a thread: explicit or by destructor

Creating Threads I

- ctor of std::thread kicks off a new thread
- joinable until detached or moved
- from a function (note: no extern “C”):
  void work() { ... }
  std::thread(work);

Creating Threads II

- from function passing arguments:
  void work(int a1, int a2);
  std::thread(work, 1, 2);
- from a bound function:
  std::thread(std::bind(work, 1, 2));
- from a function object:
  struct work { void operator()() { ... } };
  std::thread(work());

Getting Rid Of Threads

- no cancellation support
  - use implicit termination at end of work
  - use explicit thread communication
- join() a joinable thread object
- detach for implicit clean-up: detach() or dtor

Complete Example

```
bool flag(true);
void work() {
  while (flag) { std::this_thread::sleep(t); }
}
int main() {
  std::thread worker(work);
  std::cin.ignore();
  flag = false;
  worker.join();
}
```

Race Conditions

```
> valgrind -q --tool=helgrind example1
...
Possible data race during write of size 1 at 0xaddr1
    at 0xaddr2: main (example1.cpp:31)
  Old state: owned exclusively by thread #2
  New state: shared-modified by threads #1, #2
  Reason:    this thread, #1, holds no locks at all
```

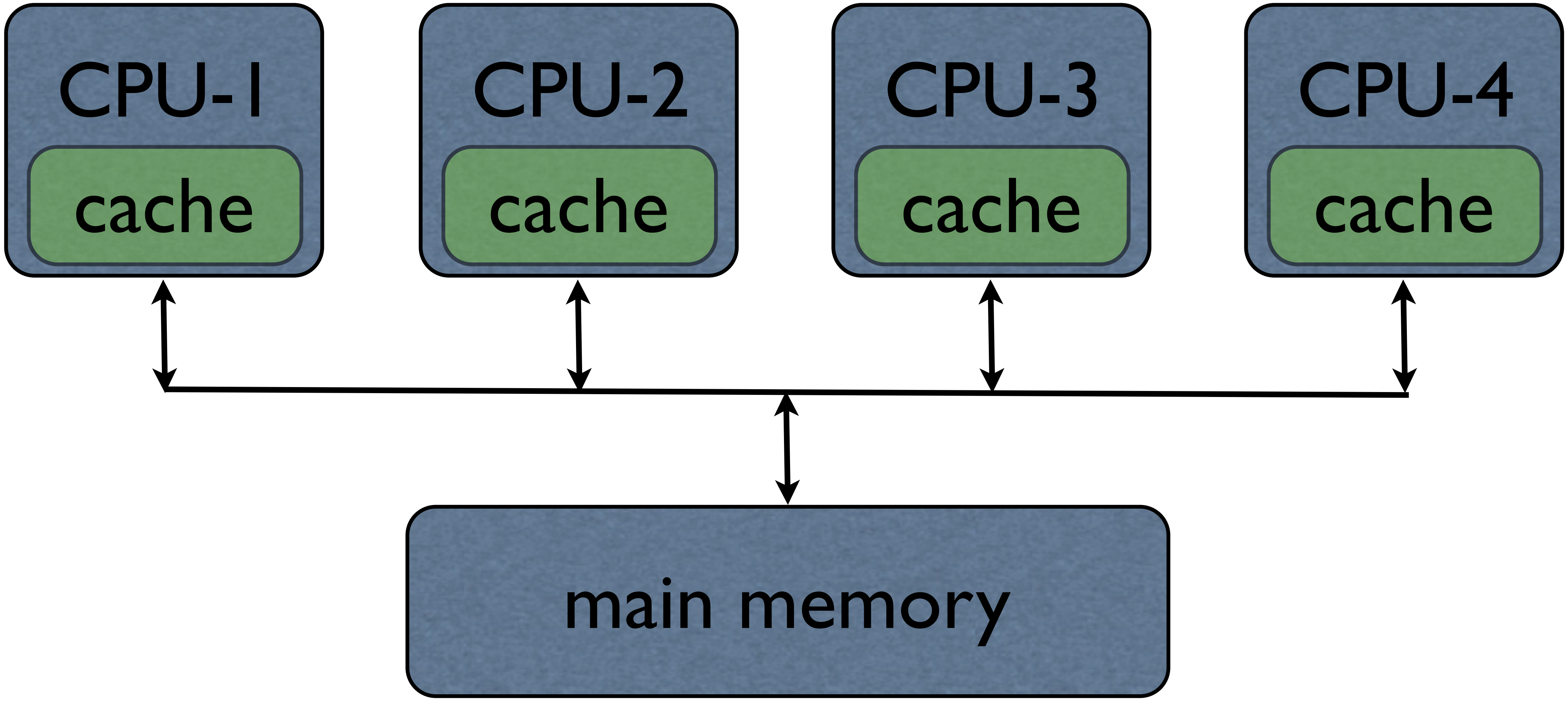
Valgrind/Helgrind

- emulates processors and observes programs behavior
- currently Linux only
- helgrind workable only with 3.3.0 and later
- can do other useful stuff e.g. leak detection

Errors in the Example

```
bool flag(true);
void work() {
  while (flag) { std::this_thread::sleep(t); }
}
int main() {
  std::thread worker(work);
  std::cin.ignore();
  flag = false;
  worker.join();
}
```

Why Is There A Problem?



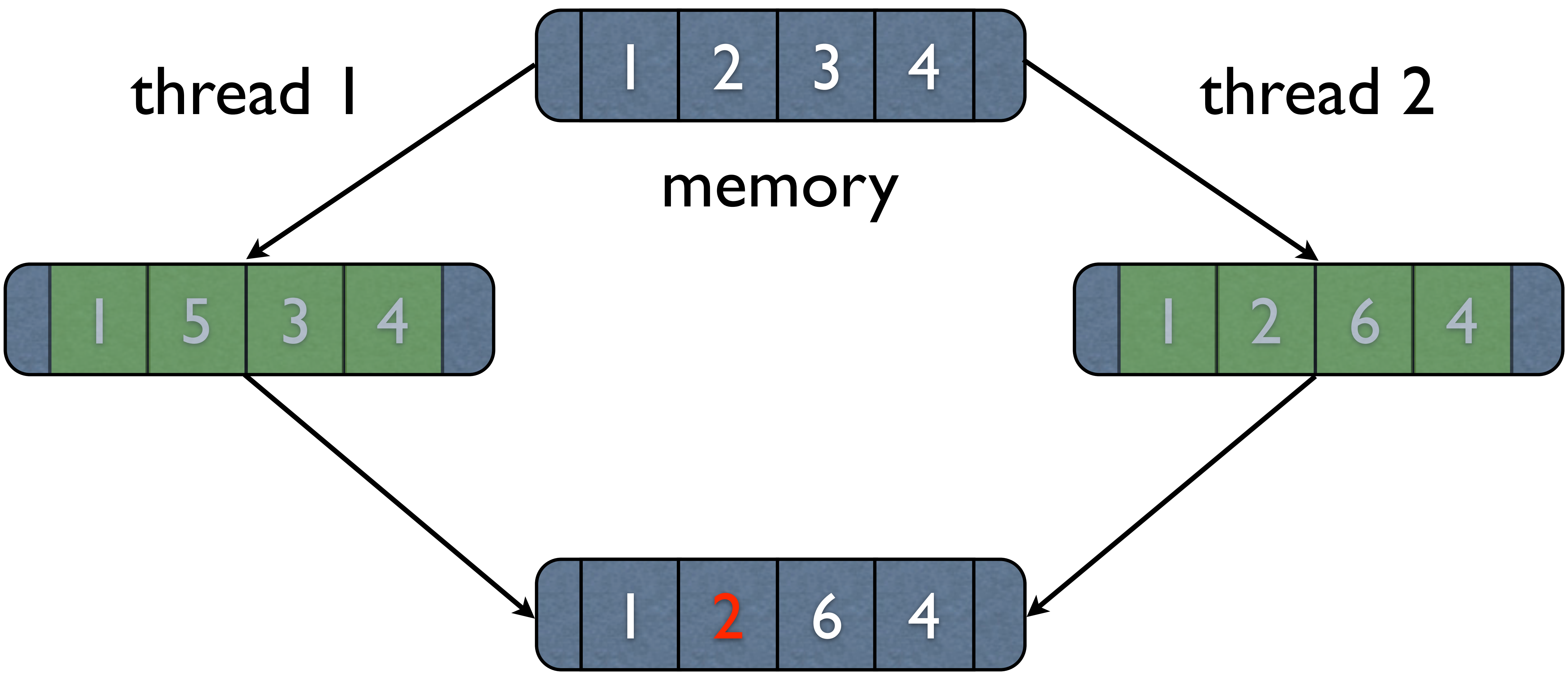
Problems Due To Caching

- reordered writes:

  initial state: bool flag(false); int value(0);
  thread 1: value = 42; flag = 1;
  thread 2: if (flag) std::cout << value << “\n”;
  output: ???

- lost updates

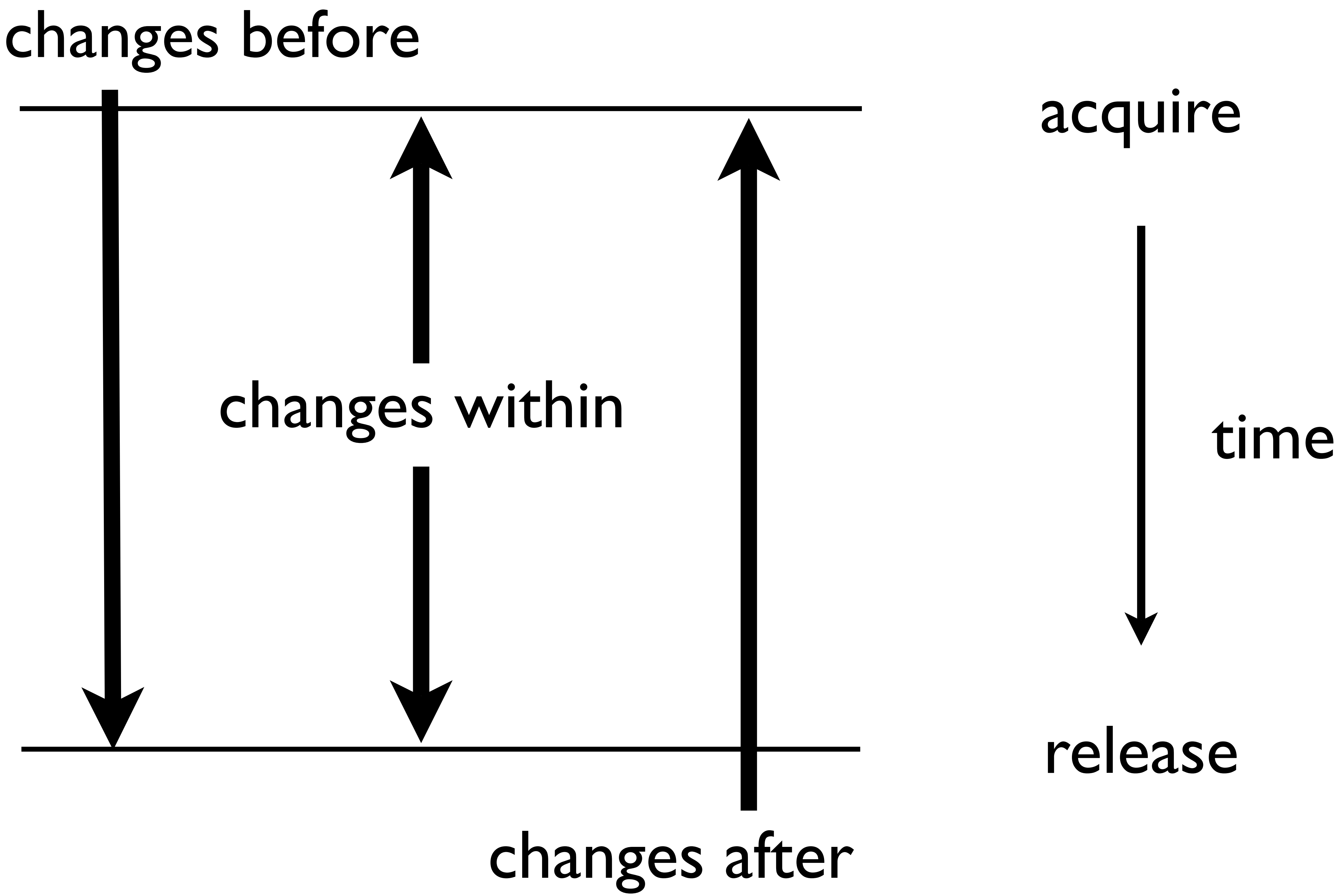
Disappearing Writes



Critical Sections

- any code accessing mutable, shared resources
- always requires some form of synchronization
- has to start with acquisition
- has to end with release
- different models on how this can be done

Critical Section Schema



Critical Sections: Mutexes

- preferred way for critical sections
- manually using lock()/unlock():
```
mutex.lock();
...
mutex.unlock();
```
- automatic using lock guard:
```
std::lock_guard<std::mutex> lock(mutex);
...
```

Critical Sections: Atomics

- limited use in general (best left to experts)
- form critical sections on their own
- critical section (may require memory barriers):

```
std::atomic<bool> flag(false);
while (!flag.load()) {} // acquire;
...                         // critical section
flag.store(false);     // release
```

Synchronization

- sharing mutable data requires synchronization
- ... but not required for immutable data
- synchronization can be provided by
  - ... using mutex, semaphore, etc. locks
  - ... using atomic types or memory barriers

Fixing the Write I

```
std::mutex flag_mutex; bool flag(true);

int main() {
  std::thread worker(work); std::cin.ignore();
  {
    std::lock_guard<std::mutex> lock(flag_mutex);
    flag = false;
  }
  worker.join();
}
```

Fixing the Write II

```
std::mutex flag_mutex; bool flag(true);
void set_flag(bool value) {
  std::lock_guard<std::mutex> lock(flag_mutex);
  flag = value;
}
int main() {
  std::thread worker(work); std::cin.ignore();
  set_flag(false);
  worker.join();
}
```

Fixing the Read

```
std::mutex flag_mutex; bool flag(true);

bool get_flag() {
  std::lock_guard<std::mutex> lock(flag_mutex);
  return flag;
}
void work() {
  while (get_flag()) { std::this_thread::sleep(t); }
}
```

Using Atomic Types

```
std::atomic<bool> flag(true);
void work() { while (flag.load()) { ... } }

int main() {
  std::thread worker(work);
  std::cin.ignore();
  flag.store(false);
  worker.join();
}
```

Mutexes

- THE general purpose synchronization device
- not very expensive but not free either: ~7.5 M/s (uncontended) locks on this machine
- essentially: one mutex for each unit of shared data

Mutex Granularity

- few mutexes => a lot of contention
- each mutex should protect a complete entity:
  - a simple variable: counter, flag
  - communication device: queue
  - a shared data structure

Thread-Safe Interfaces

- internal locking (monitor objects):
  - pros: user doesn't need to know or care
  - cons: useful only for "fire & forget"
  - e.g.: atomics, (non-STL) queue, allocator
- external locking:
  - pros: more flexible
  - cons: more error prone

STL Thread Safety

- user is responsible for proper access
- one container can be ...
  - ... read by multiple threads simultaneously
  - ... written by only one thread and may not be accessed by another thread
- restrictions are per object

Dead-Lock

- threads mutually awaiting release of locks

thread 1		thread 2
M1.lock(); ... M2.lock();		M2.lock(); ... M1.lock();

time

Mutex Hierarchies

- dead-lock prevention: lock in the same order
- sort mutexes into numbered levels (essentially according to abstraction levels)
- after locking a mutex at level n, only acquire locks for mutexes at lower levels, i.e. < n
- locks at the same level must be acquired

Recursive Mutexes

- obviously not allowed under hierarchy regime
- questionable anyway:
  - critical sections represent transaction
  - within inconsistencies are allowed and likely
  - why use a nested transaction?

Refactoring for Locking

```
void foo() {
  guard l(mutex);
  ...
  bar();
}
void bar() {
  guard l(mutex);
  ...
}
```

```
void foo() {
  guard l(mutex);
  ...
  intern_bar();
}
void bar() {
  guard l(mutex);
  intern_bar();
}
```

Locking and Generic Code

- don’t call unknown code from critical sections
- any such code may lock at the wrong level
- what is generic/unknown code?
  - callback: function pointer, function object
  - virtual function

Try-Lock

- alternate dead-lock prevention: only try-lock
- when locking fails, bail-out of all locks
- ... undoing all work as necessary, of course
- danger: live-lock, i.e two threads starting at the opposite ends continuously failing
- may still cut necessary leeway for calling

Try-Lock Example

```
std::mutex mutex;

std::unique_lock<std::mutex> lock(mutex,
                                  std::try_to_lock);

if (!lock)
  throw std::runtime_error(“already
locked”);

...
```

Condition Variables

- synchronizing actions of threads
  - have multiple threads wait for an event
  - producer/consumer relationship
- event indicator is protected by a mutex
- threads waiting for the event are asleep

Two Roles

- event consumer (while holding a mutex lock)
  - checks condition
  - wait()s if the condition is not met
- event producer
  - [possibly] changes the condition
  - either signals one thread: notify_one()
  - or broadcasts to all threads: notify_all()

The Producer

- may change condition (while holding a lock)
- sends notify, probably not holding the lock

```
std::queue<int> q; std::mutex mutex;
std::condition_variable condition;
void add_message(int message) {
  { std::lock_guard<std::mutex> lock(mutex);
    q.push(message); }
    condition.notify_one();
}
```

The Consumer

- gets lock, checks conditions, waits if not

```
std::queue<int> q; std::mutex mutex;
std::condition_variable condition;
int pop_message() {
  std::unique_lock<std::mutex> lock(mutex);
  while (q.empty()) condition.wait(lock);
  int rc = q.back(); q.pop_back(); return rc;
}
```

Notes on the Consumer

- holding the mutex lock
  - the lock is held when calling wait()!
  - it gets unlocked while waiting
  - it is locked again when wait() returns
- there may be spurious returns from wait()
  - the condition needs to be rechecked!

Spurious Wake-Ups

- producer notifies without meeting condition
- different thread may acquire the lock first
- signal may have been received by the thread
- rule avoids problems with implementations

Summary of Basics

- synchronize shared resources
  - mutexes, atomics, thread start/ termination
- try to avoid use of shared resources
  - stay within cache, don't risk contention
- synchronize threads: condition variables

Implicit Parallelism

- ideally parallel execution is automated
- to this end ...
  - represent program as independent tasks
  - give some indication on the costs of tasks
  - don't specify number of threads

Futures

- like a function call
- returns a handle for the result
- may compute the function call in a separate thread
- synchronization upon accessing the result
- not yet in C++Ox working paper (i.e. example below is made up)

Future Example

```
result function(int arg) { .... }
int main()
{
  std::future<result> f1(std::bind(&function, 1));
  std::future<result> f2(std::bind(&function, 2));
  ...
  result const& r1(f1.get_result());
}
```

Parallel Algorithms

- Threading Building Blocks offers:
  - parallel_for(range, function [, splitter])
  - parallel_reduce(range, function [, splitter])
  - parallel_scan(range, function [, splitter])
- other algorithms can be built on top of these

General TBB Approach

- ranges splitable into equal-sized subranges
- ranges have an optional grainsize
- function objects splitable into multiple instances
- function objects responsible to process subranges
- subranges processed by separate threads

TBB Precondition

- every thread needs to initialize a scheduler
- ideally, this should be done at start-up
  - tbb::task_scheduler_init init(...);
  - in main() and thread entry function
- termination is at corresponding scope
- future: integrated into program/thread

tbb::parallel_for()

```
struct function { ...
  template <typename Range>
  void operator()(Range const& r) const {
    std::for_each(r.begin(), r.end(), *this);
  }
};
tbb::parallel_for(
  tbb::blocked_range<Iterator>(begin, end),
  function(...),
  tbb::auto_partitioner());
```

TBB Ranges

- ranges have grainsize, indicating atomic sizes
- grainsize may be heuristically determined
  - it isn’t exact
  - rule of thumb: at least 10,000 instructions
- have “split constructor”
  - take a dummy argument of type tbb::split

More On TBB Ranges

- tbb::blocked_range<T> works for
  - integral types
  - random access iterators
- ranges can be user defined
  - have to follow some simple concept

tbb::parallel_reduce()

- similar use to tbb::parallel_for()
- function object non-constant
- the result is accumulate using join() function
  on the function object
- used e.g. for find(), min_element(), etc.

tbb::parallel_scan()

- computes a scan for some associative $\oplus$
  - $y[0] = id \oplus x[0]$
  - $y[i] = y[i-1] \oplus x[i] \; \forall \; i > 0$
- two passes over each range
- dummy argument indicating which pass

Other TBB Compoents

- usual mutex, lock, etc.
- atomic operations
- concurrent containers
  - concurrent_queue<T>
  - concurrent_vector<T>
  - concurrent_hash_map<Key, Value,

TBB Summary

- restores free lunch when using many tasks
- library on which to build parallel components
- it probably needs some baking to work smoothly
- ... but it is certainly an interesting approach

Detailed Information

- Herb Sutter's articles in Dr.Dobb's which hopefully becomes "Effective Threading"
- "Programming with POSIX Threads", David R. Butenhof, Addison-Wesley
- "Intel Threading Building Blocks", James Reinders, O'Reilly
- www.sgi.com/tech/stl/thread_safety.html