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Lecture 5: Languages and Locks

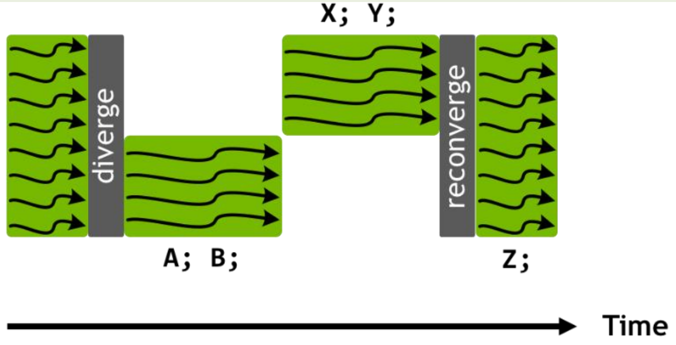
SPCL

GPUs: Recap

- **Massively parallel**
  - 84x256 ALUs
- **Composed of SMs**
  - Separate L1/scratch-pad caches
- **CUDA programming model**
  - Create as many threads as there are data
- **Execution follows SIMT**
  - 32-thread lock-step

```
__global__ void MatMulKernel(Matrix A, Matrix B, Matrix C) {
    // Each thread computes one element of C
    // by accumulating results into Cvalue
    float Cvalue = 0;
    int row = blockIdx.y * blockDim.y + threadIdx.y;
    int col = blockIdx.x * blockDim.x + threadIdx.x;

    for (int e = 0; e < A.width; ++e)
        Cvalue += A.data[row * A.width + e] * B.data[e * B.width + col];

    C.data[row * C.width + col] = Cvalue;
}
```

```
if (threadIdx.x < 4) {
    A;
    B;
} else {
    X;
    Y;
}
Z;
```



High-Level Languages: OpenMP and OpenACC

- **Directive-based programming**
- **Implicitly wrap for loops**
  - Advantages:

    Code can run without #pragmas

    Loop construct clearer than kernel
- **Portable across platforms**
  - …but has to be tuned for each platform separately
- **Directives nest into each other for increased control**
  - Disadvantage: It’s possible to have more #pragmas than code

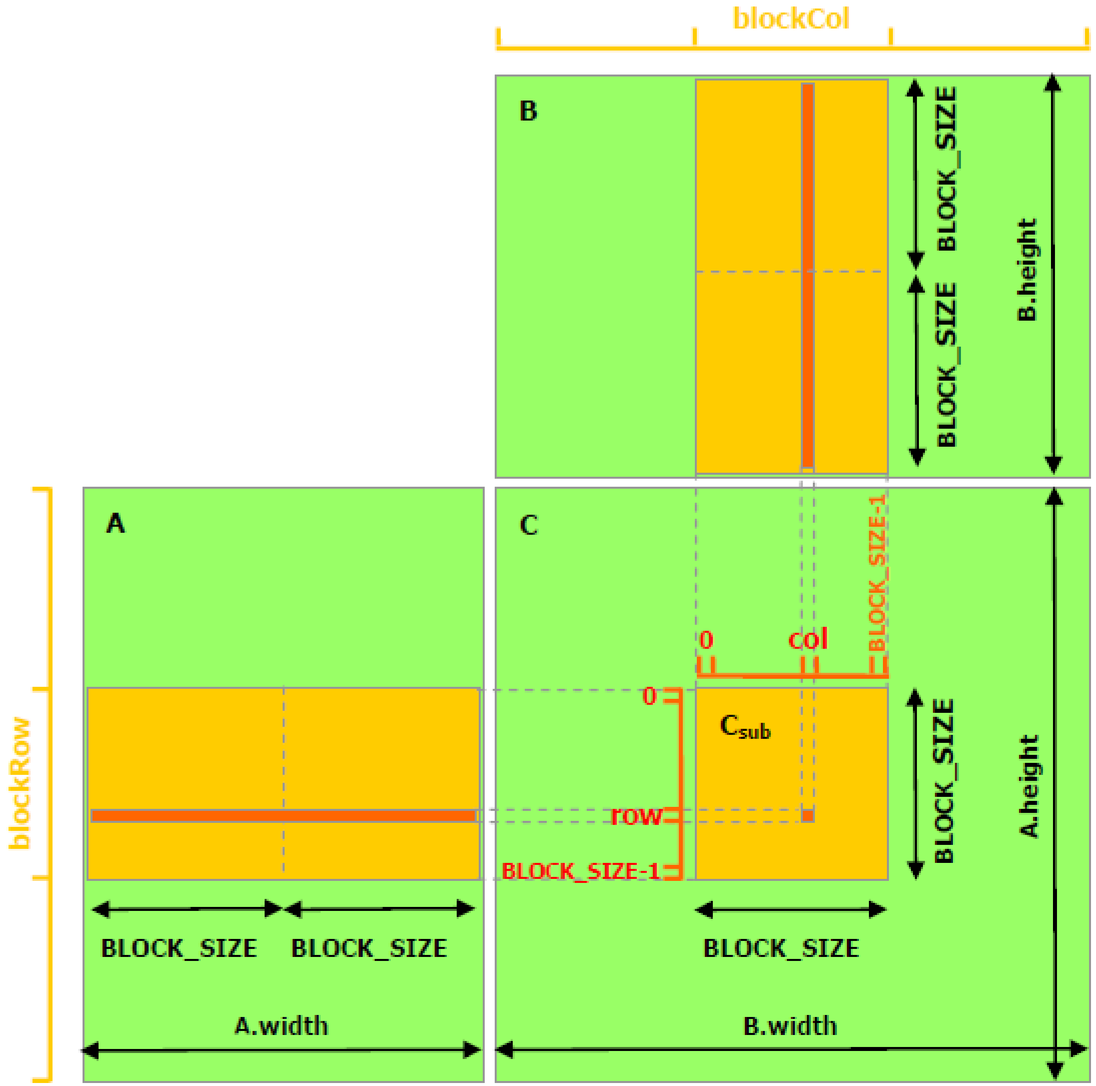
```
#pragma acc enter data create
  copyin(input[0:X])
#pragma acc enter data update
  device(input[0:X]

#pragma acc parallel loop gang collapse(2)
  present(input) \
  reduction(+:output_re(0,1,2), output_im(0,1,2))
for(X){
  for(N){
#pragma acc loop vector\
  reduction(+:output_re(0,1,2), output_im(0,1,2))
    for(M){
      for(int iw = 0; iw < 3; ++iw){
        //Store local
      }
    }
    output_re{0,1,2} += ...
    output_im{0,1,2} += ...
  }
}
```

Source: Gayatri and Yang, Optimizing Large Reductions in BerkeleyGW on GPUs Using OpenMP and OpenACC

Scratch-pad (shared) memory

Matrix Multiplication with Shared Memory

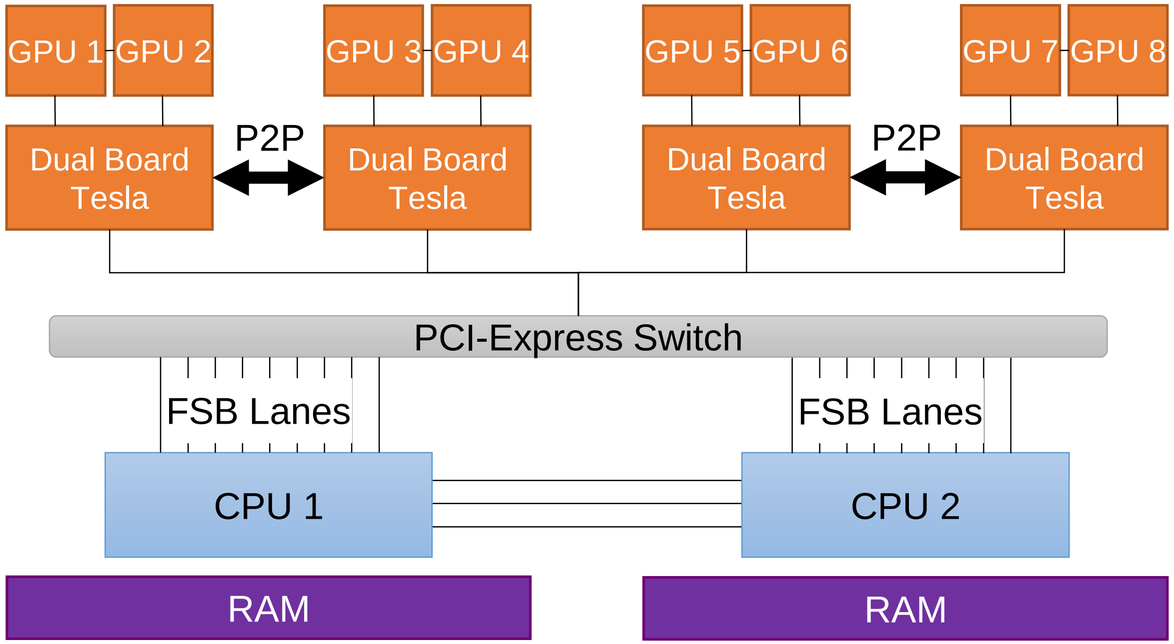
```
__global__ void MatMulKernel(Matrix A, Matrix B, Matrix C) {
    int blockRow = blockIdx.y; int blockCol = blockIdx.x;
    Matrix Csub = GetSubMatrix(C, blockRow, blockCol);
    float Cvalue = 0;
    int row = threadIdx.y; int col = threadIdx.x;

    for (int m = 0; m < (A.width / BLOCK_SIZE); ++m) {
        Matrix Asub = GetSubMatrix(A, blockRow, m);
        Matrix Bsub = GetSubMatrix(B, m, blockCol);
        __shared__ float As[BLOCK_SIZE][BLOCK_SIZE];
        __shared__ float Bs[BLOCK_SIZE][BLOCK_SIZE];
        As[row][col] = Asub.data[row][col];
        Bs[row][col] = Bsub.data[row][col];

        __syncthreads();

        for (int e = 0; e < BLOCK_SIZE; ++e)
            Cvalue += As[row][e] * Bs[e][col];

        __syncthreads();
    }
    Csub.data[row][col] = Cvalue;
}
```



Figures and code courtesy of nvidia.com

GPU Synchronization

- **Across warps –** No need
- **Across thread-blocks –** `__syncthreads()`
- **Across grid**
  - Simplest solution: Queue another kernel
  - Less simple: Grid barriers
- **Across GPU (multiple streams), multiple GPUs**
  - Paired synchronization (event + stream-wait-event)
- **Between host and GPU**
  - `cuda{Stream,Event,Device}Synchronize()`
  - `cudaMemcpy()` – Not async (also not recommended).



Class Discussion

- **How do we define a memory model for GPUs?**
  - Things to remember: Different memory spaces, logical thread hierarchy, SMs, cache model
- **Can GPUs guarantee SC? Should they?**
- **Open research question: Can we port the benefits of GPU fast thread-switching to CPUs?**

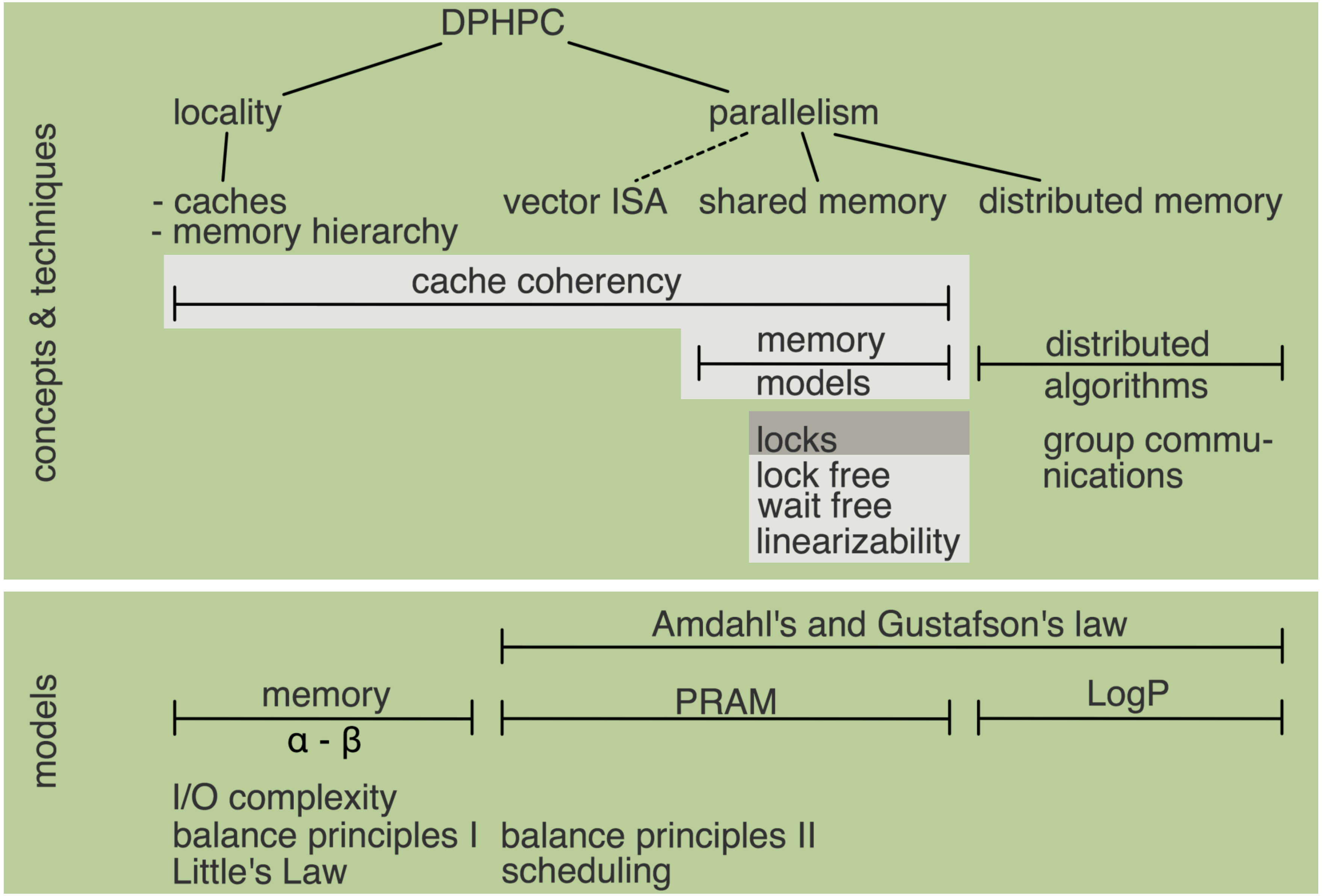
Review of last lecture

- **Memory models**
  - Ordering between accesses to different variables
  - Sequential consistency – nice but unrealistic

    Demonstrate how it prevents compiler and architectural optimizations

- **Practical memory models**
  - Overview of various models (TSO, PSO, RMO, … existing CPUs)
  - Case study of x86 (8 principles, TLO + CC)
  - Case study of NVIDIA GPUs (continuing today)

DPHPC Overview



Goals of this lecture

- **Recap: Correctness in parallel programs**
  - Covered in PP, here a slimmed down version to make the DPHPC lecture self-contained
    Watch for the green bar on the right side
- **Languages and Memory Models**
  - Java/C++ definition
  - Races (now in practice)
  - Synchronization variables (now in practice)
- **Mutual exclusion**
  - Recap – simple lock properties
  - Proving correctness in SC and memory models (x86)
  - Locks in practice – performance overhead of memory models!

Notions of Correctness

- **We discussed so far:**
  - Read/write of the same location
    Cache coherence (write serialization and atomicity)
  - Read/write of multiple locations
    Memory models (visibility order of updates by cores)

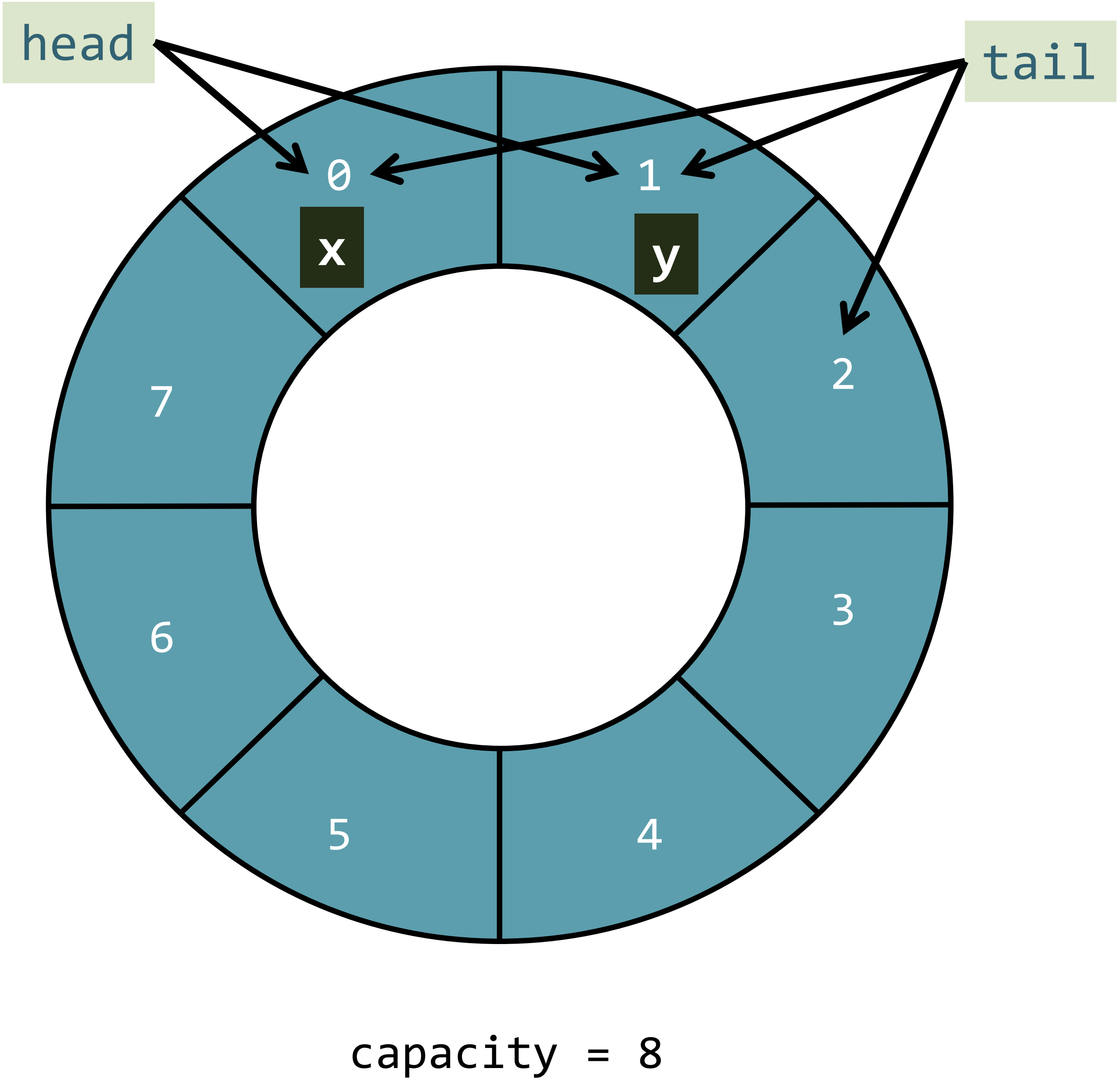
- **Now one level up: objects (variables/fields with invariants defined on them)**
  - Invariants “tie” variables together
  - Sequential objects
  - Concurrent objects

Sequential Objects

- **Each object has a type**
- **A type is defined by a class**
  - Set of fields forms the state of an object
  - Set of methods (or free functions) to manipulate the state
- **Remark**
  - An Interface is an abstract type that defines behavior
    A class implementing an interface defines several types

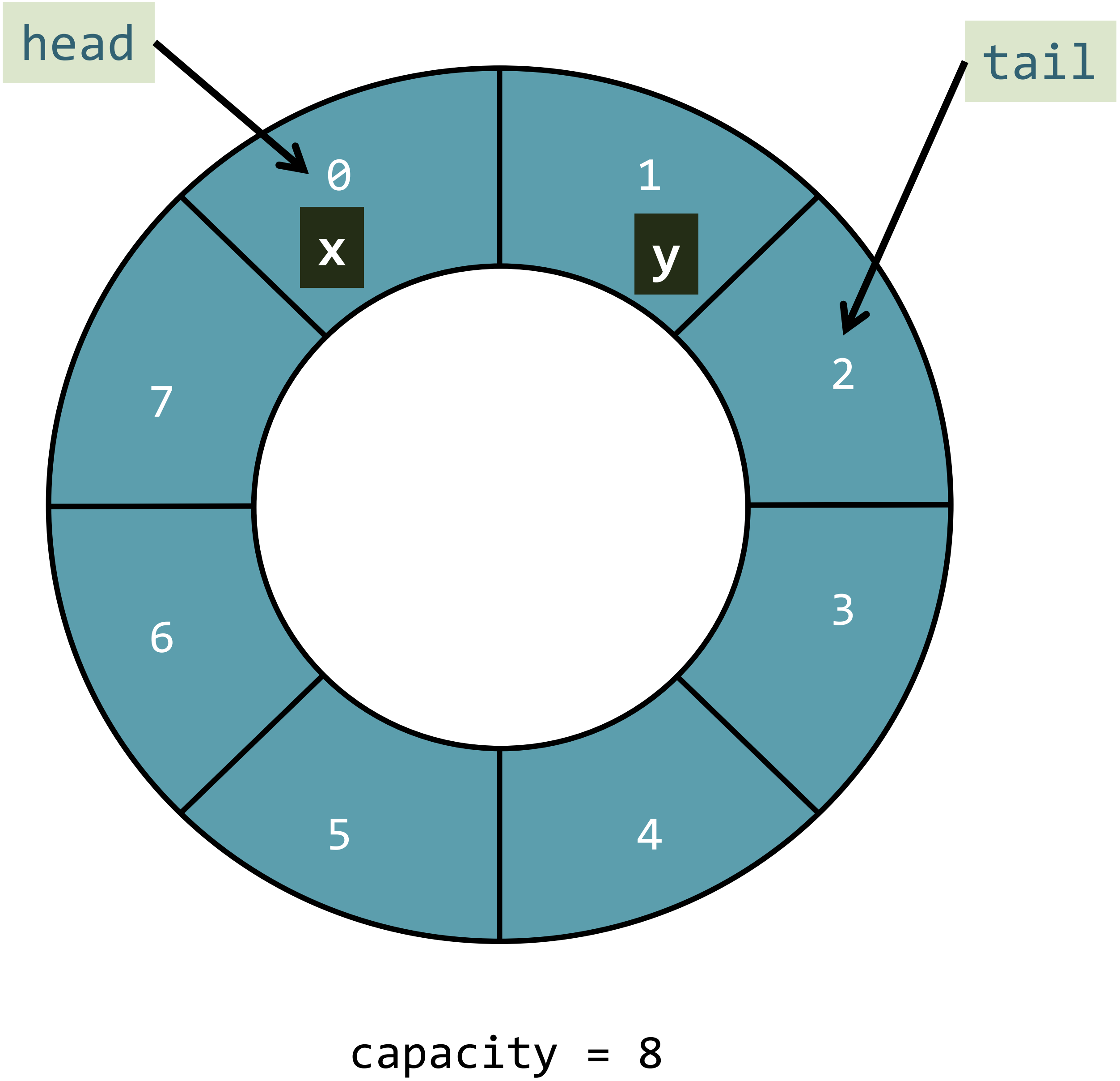
Running Example: FIFO Queue

- **Insert elements at tail**
- **Remove elements from head**
  - Initial: `head = tail = 0`
  - `enq(x)`
  - `enq(y)`
  - `deq() [x]`
  - …



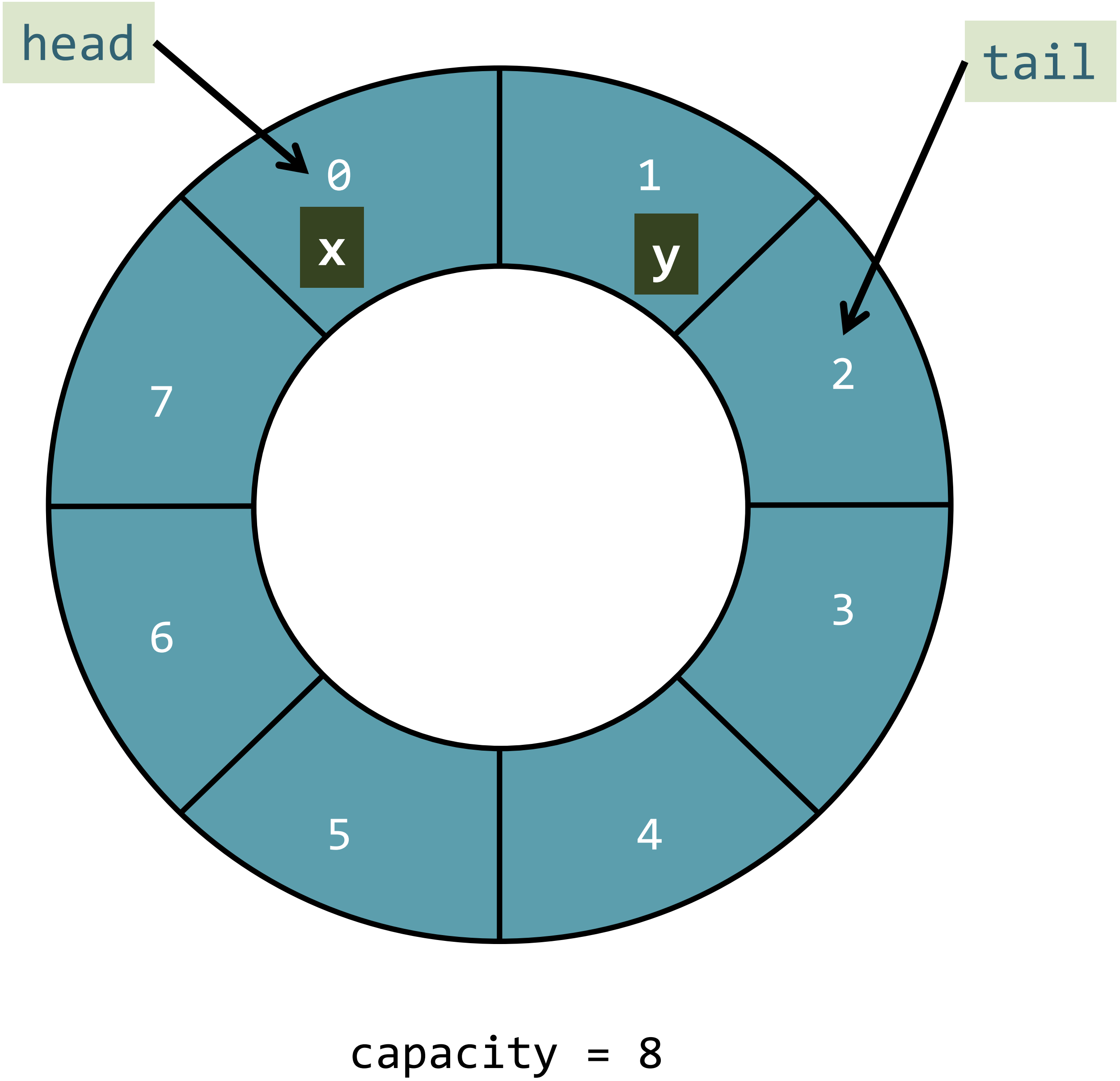
Sequential Queue

```
class Queue {
private:
  int head, tail;
  std::vector<Item> items;

public:
  Queue(int capacity) {
    head = tail = 0;
    items.resize(capacity);
  }

  // ...

};
```



Sequential Queue

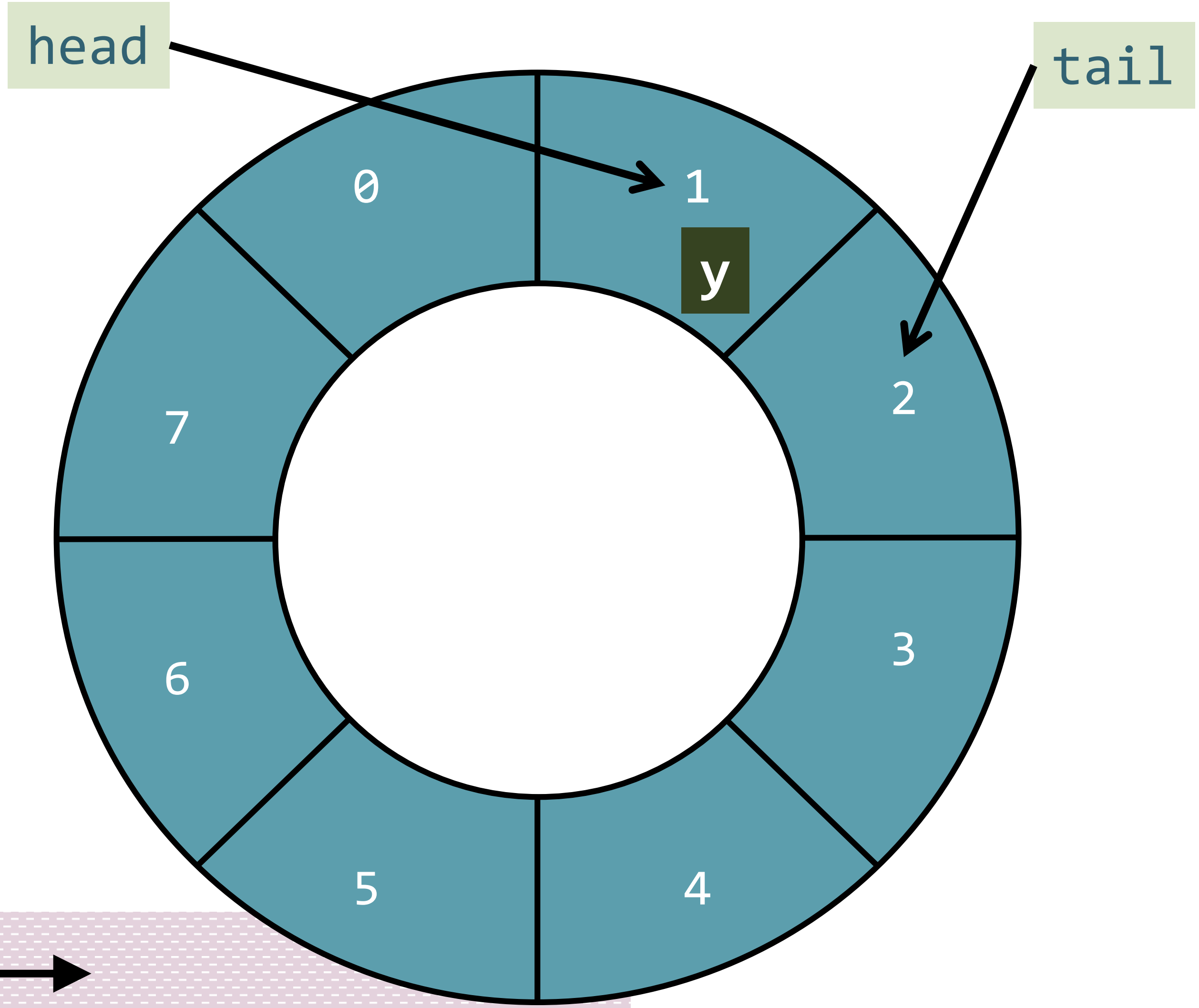
```
class Queue {
  // ...

public:
  void enq(Item x) {
    if((tail+1)%items.size() == head) {
      throw FullException;
    }
    items[tail] = x;
    tail = (tail+1)%items.size();
  }

  Item deq() {
    if(tail == head) {
      throw EmptyException;
    }
    Item item = items[head];
    head = (head+1)%items.size();
    return item;
  }
};
```

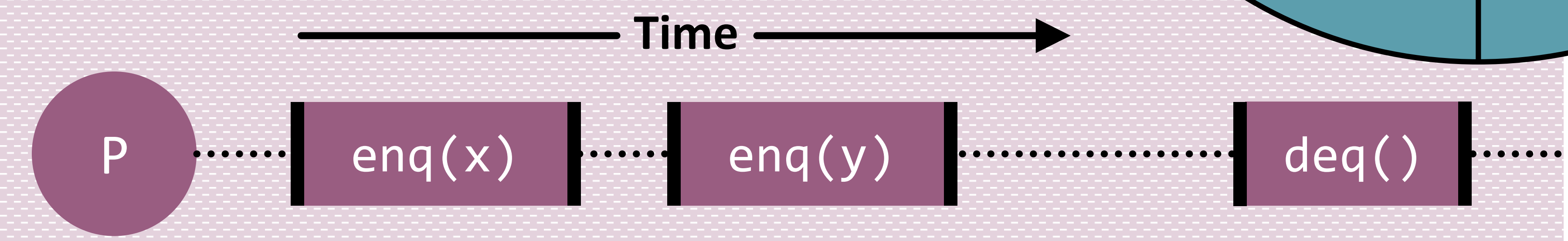


Sequential Execution

- **(The) one process executes operations one at a time**
  - Sequential ☺

- **Semantics of operation defined by specification of the class**
  - Preconditions and postconditions
    e.g., Hoare logic

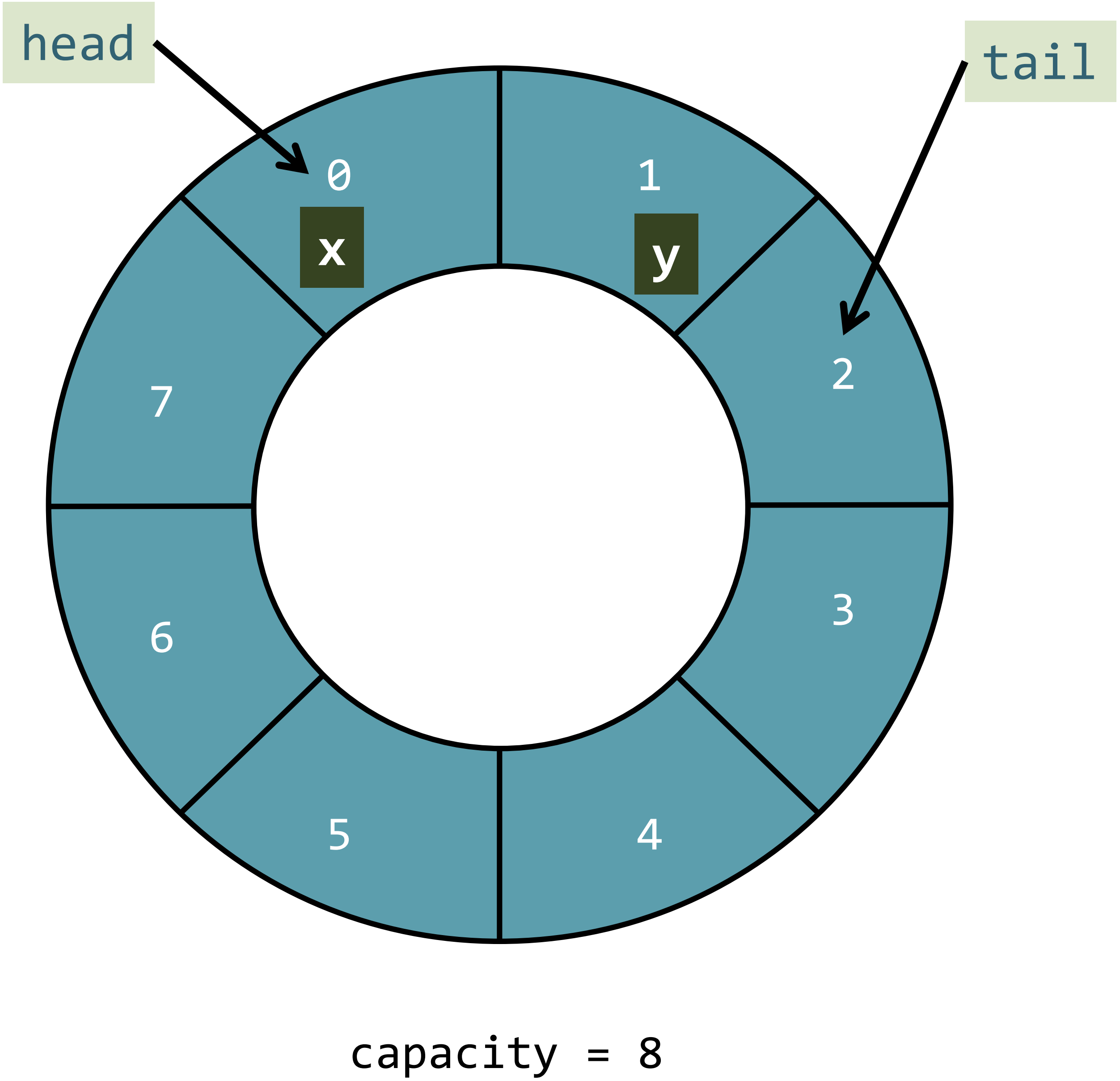




Design by Contract!

- **Preconditions:**
  - Specify conditions that must hold before method executes
  - Involve state and arguments passed
  - Specify obligations a client must meet before calling a method
- **Example: enq()**
  - Queue must not be full!

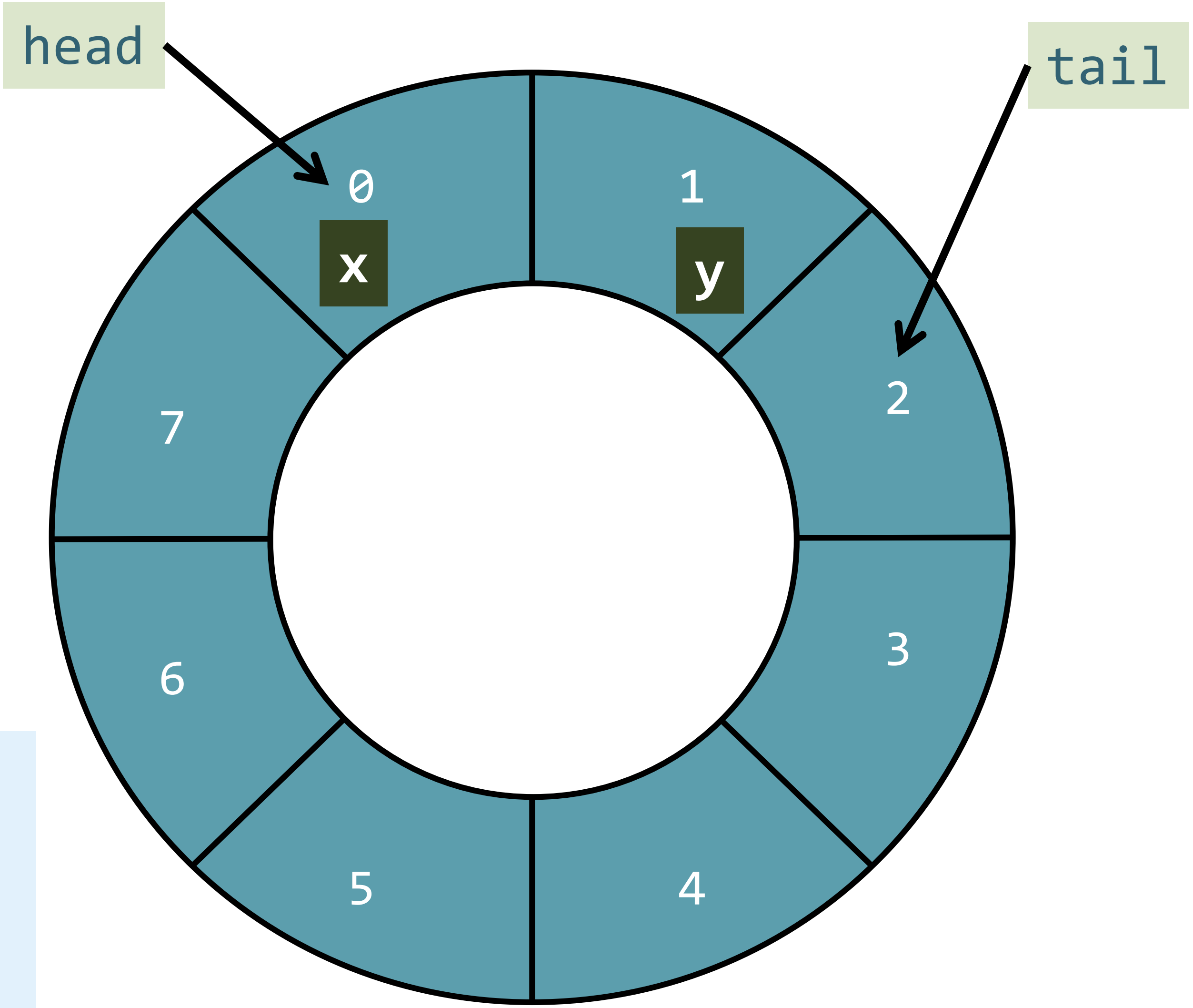
```
class Queue {
  // ...
  void enq(Item x) {
    assert((tail+1)%items.size() != head);
    // ...
  }
};
```



Design by Contract!

- **Postconditions:**
  - Specify conditions that must hold after method executed
  - Involve previous state, state, and arguments passed
- **Example: enq()**
  - Queue must contain element!

```
class Queue {
  // ...
  void enq(Item x) {
    // ...
    assert(
      (tail == (old_tail + 1)%items.size()) &&
      (items[old_tail] == x) );
  }
};
```



capacity = 8

Sequential specification

- **if(precondition)**
  - Object is in a **specified state**
- **then(postcondition)**
  - The method returns a particular value or
  - Throws a particular exception **and**
  - Leaves the object in a **specified state**

- **Invariants**
  - Specified conditions (e.g., object state) must hold **anytime** a client could invoke an object's method!

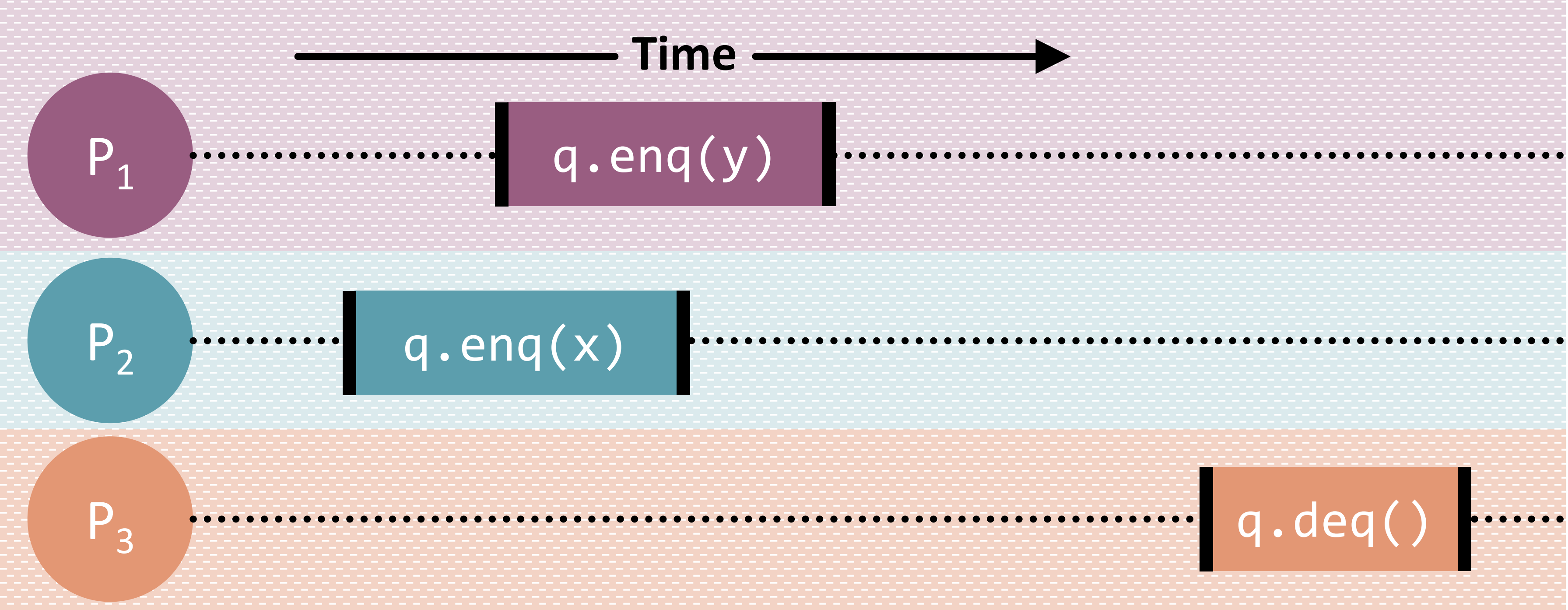
Advantages of sequential specification

- **State between method calls is defined**
  - Enables reasoning about objects
  - Interactions between methods captured by side effects on object state
- **Enables reasoning about each method in isolation**
  - Contracts for each method
  - Local state changes global state
- **Adding new methods**
  - Only reason about state changes that the new method causes
  - If invariants are kept: **no need to check old methods**
  - **Modularity!**

Concurrent execution - State

- **Concurrent threads invoke methods on possibly shared objects**
  - At overlapping time intervals!

Property	Sequential	Concurrent
State	Meaningful only between method executions	Overlapping method executions → object may never be "between method executions"



Each method execution takes some non-zero amount of time!

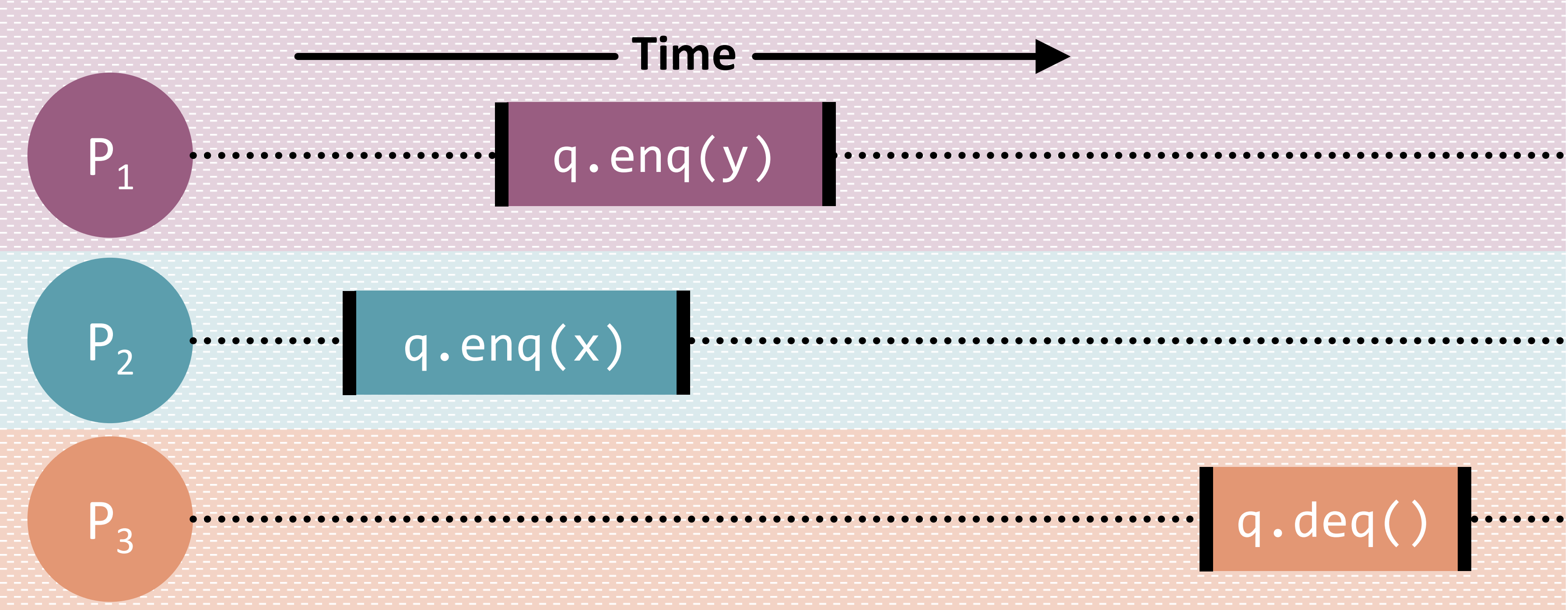
Concurrent execution - Reasoning

- **Reasoning must now include all possible interleavings**
  - Of changes caused by methods themselves

Property	Sequential	Concurrent
Reasoning	Consider each method in isolation; invariants on state before/after execution.	Need to consider all possible interactions; all intermediate states during execution

That is, now we have to consider what will happen if we execute:

- **enq()** concurrently with **enq()**
- **deq()** concurrently with **deq()**
- **deq()** concurrently with **enq()**



Each method execution takes some non-zero amount of time!

Concurrent execution - Method addition

- **Reasoning must now include all possible interleavings**
  - Of changes caused by and methods themselves

Property	Sequential	Concurrent
Add Method	Without affecting other methods; invariants on state before/after execution.	Everything can potentially interact with everything else

- **Consider adding a method that returns the last item enqueued**

```
Item peek() {
  if(tail == head) throw EmptyException;
  return items[head];
}
```

```
void enq(Item x) {
  items[tail] = x;
  tail = (tail+1) % items.size();
}
```

```
Item deq() {
  Item item = items[head];
  head = (head+1) % items.size();
}
```

  - If **peek()** and **enq()** run concurrently: what if tail has not yet been incremented?
  - If **peek()** and **deq()** run concurrently: what if last item is being dequeued?

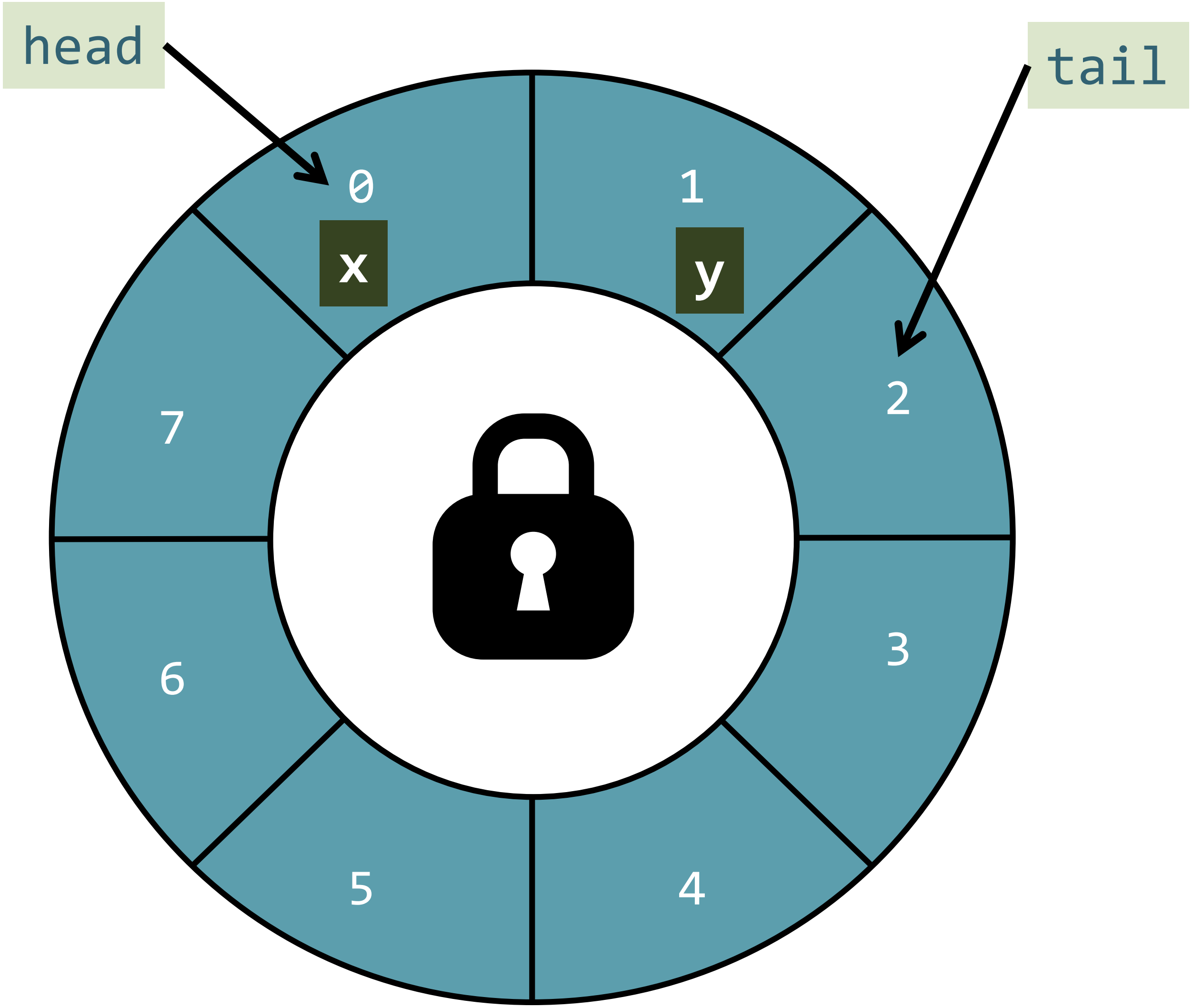
Concurrent objects

- **How do we describe one?**
  - No pre-/postconditions ☹
- **How do we implement one?**
  - Plan for quadratic or exponential number of interactions and states
- **How do we tell if an object is correct?**
  - Analyze all quadratic or exponential interactions and states

Is it time to panic for (parallel) software engineers?
Who has a solution?

Lock-based queue

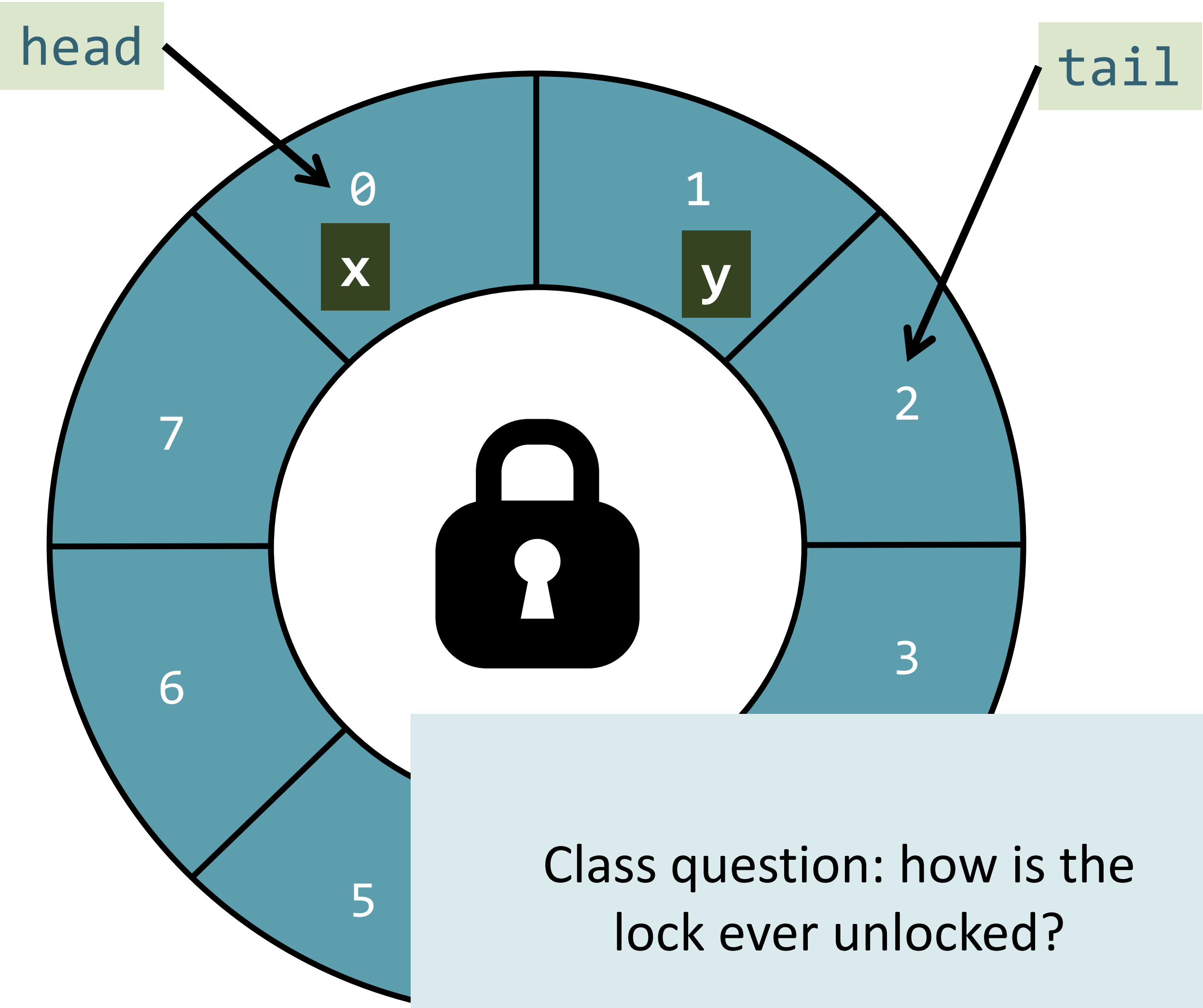
```cpp
class Queue {
private:
  int head, tail;
  std::vector<Item> items;
  std::mutex lock;

public:
  Queue(int capacity) {
    head = tail = 0;
    items.resize(capacity);
  }
  // ...
};
```



We can use the lock to protect Queue's fields.

Lock-based queue

```
class Queue {
  // ...
public:
  void enq(Item x) {
    std::lock_guard<std::mutex> l(lock);
    if((tail+1)%items.size()==head) {
      throw FullException;
    }
    items[tail] = x;
    tail = (tail+1)%items.size();
  }

  Item deq() {
    std::lock_guard<std::mutex> l(lock);
    if(tail == head) {
      throw EmptyException;
    }
    Item item = items[head];
    head = (head+1)%items.size();
    return item;
  }
};
```



Class question: how is the lock ever unlocked?

One of C++'s ways of implementing a **critical section**

C++ Resource Acquisition is Initialization

- **RAII – suboptimal name**
- **Can be used for locks (or any other resource acquisition)**
  - Constructor grabs resource
  - Destructor frees resource
- **Behaves as if**
  - Implicit unlock at end of block!
- **Main advantages**
  - Always unlock/free lock at exit
  - No “lost” locks due to exceptions or strange control flow (goto ☺)
  - Very easy to use

```
template <typename mutex_impl>
class lock_guard {
  mutex_impl& _mtx; // ref to the mutex

public:
  lock_guard(mutex_impl& mtx ) : _mtx(mtx) {
    _mtx.lock(); // lock mutex in constructor
  }

  ~lock_guard() {
    _mtx.unlock(); // unlock mutex in destructor
  }
};
```

Example execution

and proceeds.

```
void enq(Item x) {
  std::lock_guard<std::mutex> l(lock);
  if((tail+1)%items.size()==head) {
    throw FullException;
  }
  items[tail] = x;
  tail = (tail+1)%items.size();
}
```

```
Item deq() {
  std::lock_guard<std::mutex> l(lock);

  if(tail == head) {
    throw EmptyException;
  }
  Item item = items[head];
  head = (head+1)%items.size();
  return item;
}
```

enq(x)

deq()

Methods effectively execute one after another, sequentially.

Correctness – end of interlude

- **Is the locked queue correct?**
  - Yes, only one thread has access if locked correctly
  - Allows us again to reason about pre- and postconditions
  - Smells a bit like sequential consistency, no?
- **Class question: What is the problem with this approach?**
  - Same as for SC ☺

It does not scale!
What is the solution here?

Back to memory models: Language Memory Models

- **Which transformations/reorderings can be applied to a program**
- **Affects platform/system**
  - Compiler, (VM), hardware
- **Affects programmer**
  - What are possible semantics/output
  - Which communication between threads is legal?
- **Without memory model**
  - Impossible to even define “legal” or “semantics” when data is accessed concurrently
- **A memory model is a contract**
  - Between platform and programmer

History of Memory Models

- **Java's original memory model was broken [1]**
  - Difficult to understand => widely violated
  - Did not allow reorderings as implemented in standard VMs
  - Final fields could appear to change value without synchronization
  - Volatile writes could be reordered with normal reads and writes

    => counter-intuitive for most developers
- **Java memory model was revised [2]**
  - Java 1.5 (JSR-133)
  - Still some issues (operational semantics definition [3])
- **C/C++ didn't even have a memory model until much later**
  - Not able to make any statement about threaded semantics!
  - Introduced in C++11 and C11
  - Based on experience from Java, much more conservative

[1] Pugh: "The Java Memory Model is Fatally Flawed", CCPE 2000
[2] Manson, Pugh, Adve: "The Java memory model", POPL'05
[3] Aspinall, Sevcik: "Java memory model examples: Good, bad and ugly", VAMP'07

Everybody wants to optimize

- **Language constructs for synchronization**
  - Java: volatile, synchronized, …
  - C++: atomic, (**NOT volatile**!), mutex, …

- **Without synchronization (defined language-specific)**
  - Compiler, (VM), architecture
  - Reorder and appear to reorder memory operations
  - Maintain sequential semantics per thread
  - Other threads may observe any order (have seen examples before)

Java and C++ High-level overview

- **Relaxed memory model**
  - No global visibility ordering of operations
  - Allows for standard compiler optimizations
- **But**
  - Program order for each thread (sequential semantics)
  - Partial order on memory operations (with respect to synchronizations)
  - Visibility function defined
- **Correctly synchronized programs**
  - Guarantee sequential consistency
- **Incorrectly synchronized programs**
  - Java: maintain safety and security guarantees
    Type safety etc. (require behavior bounded by causality)
  - C++: undefined behavior
    No safety (anything can happen/change)

Communication between threads: Intuition

- **Not guaranteed unless by:**
  - Synchronization
  - Volatile/atomic variables
  - Specialized functions/classes (e.g., java.util.concurrent, …)

Thread 1

```
x = 10
y = 5
flag = true
```

synchronization

Thread 2

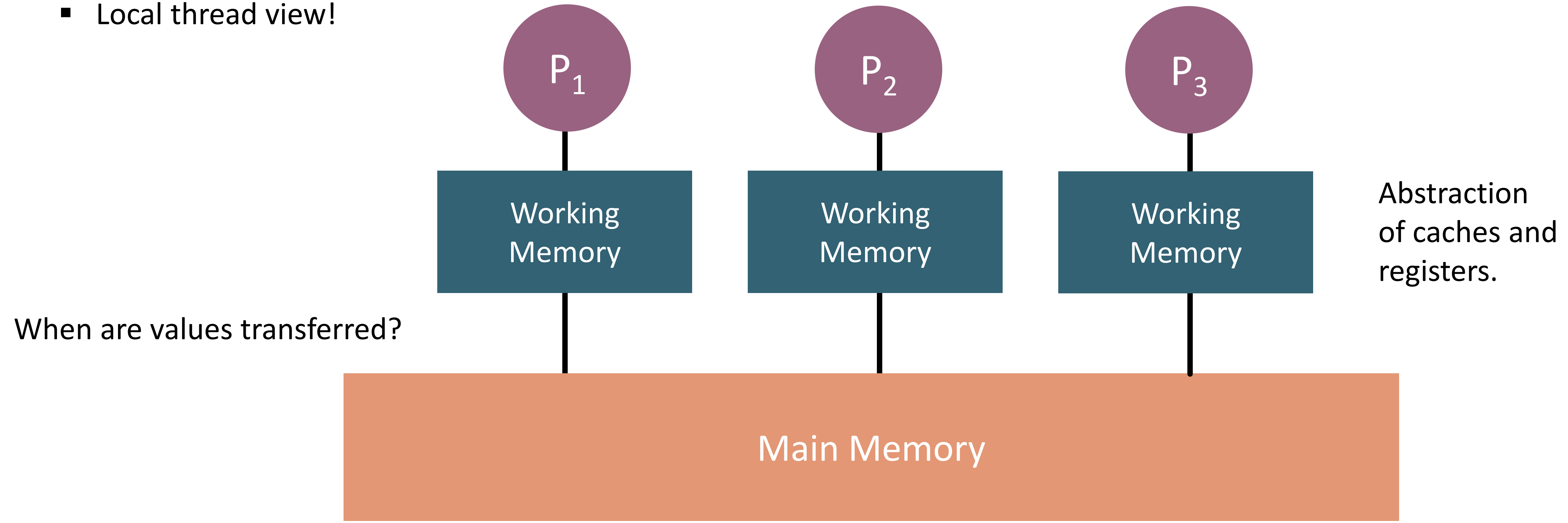
```
if(flag)
 print(x+y)
```

Flag is a synchronization variable (`atomic` in C++, `volatile` in Java),

i.e., all memory written by T1 must be visible to T2 after it reads the value true for `flag`!

Recap: Memory Model (Intuition)

- **Abstract relation between threads and memory**
  - Local thread view!



- **Does not talk about classes, objects, methods, …**
  - Linearizability is a higher-level concept!

Locks synchronize threads *and* memory!

- **Java**

```
synchronized (lock) {
   // critical region
}
```

  - Synchronized methods as syntactic sugar

- **C++ (RAII)**

```
{
  unique_lock<mutex> l(lock);
  // critical region
}
```

  - Many flexible variants

- Semantics:
  - mutual exclusion
  - at most one thread may hold a lock at a time
  - a thread B trying to acquire a lock held by thread A blocks until thread A releases the lock
  - note: threads may wait forever (no progress guarantee!)

Memory model semantics of locks

- **Similar to synchronization variables**

Thread 1

```
x = 10
…
y = 5
…
unlock(m)
```

Thread 2

```
lock(m)
  print(x+y)
```

  - All memory accesses before an unlock …
  - are ordered before and are visible to …
  - any memory access after a matching lock!

Memory model semantics of synchronization variables

- **Variables can be declared volatile (Java) or atomic (C++)**

- **Reads and writes to synchronization variables**
  - Are totally ordered with respect to all threads
  - Must not be reordered with normal reads and writes

- **Compiler**
  - Must not allocate synchronization variables in registers
  - Must not swap variables with synchronization variables
  - May need to issue memory fences/barriers
  - …

Memory model semantics of synchronization variables

- **Write to a synchronization variable**
  - Similar memory semantics as unlock (no process synchronization!)
- **Read from a synchronization variable**
  - Similar memory semantics as lock (no process synchronization!)

```
class example {
  int x = 0;
  atomic<bool> v = false;

  public void writer() {
    x = 42;
    v = true;
  }

  public void reader() {
    if(v) {
      print(x);
    }
  }
```

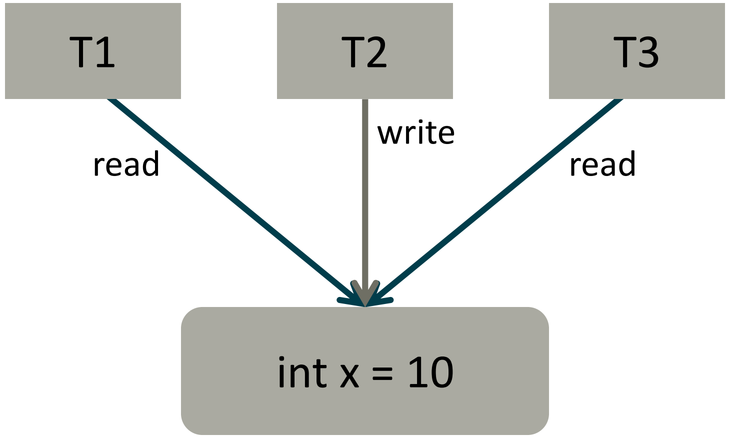
Thread 1

Thread 2

Without atomic or volatile, a platform may reorder these accesses!

Intuitive memory model rules

- **Java/C++: Correctly synchronized programs will execute sequentially consistent**
- **Correctly synchronized = data-race free**
  - iff all sequentially consistent executions are free of data races
- **Two accesses to a shared memory location form a data race in the execution of a program if**
  - The two accesses are from different threads
  - At least one access is a write and
  - The accesses are not synchronized

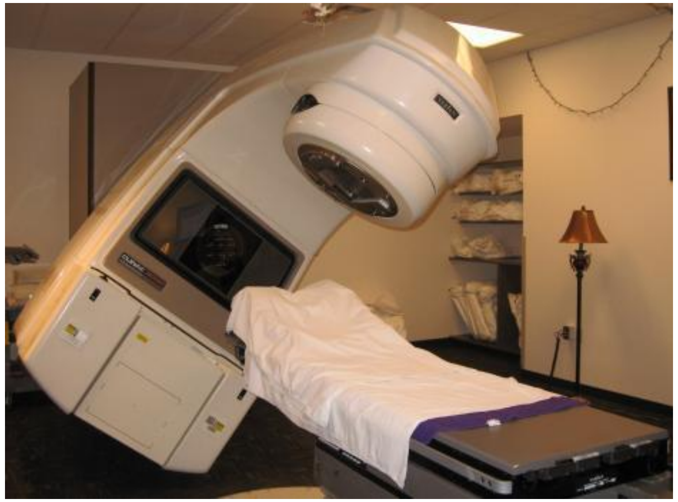


Conflicting Accesses

- **(recap) two memory accesses conflict if they can happen at *the same time* (in happens-before) and one of them is a write (store)**
- **Such a code is said to have a "race condition"**
  - Also data-race
  - Trivia around races:

    The Therac-25 killed three people
    due to a race

    A data-race lead to a large blackout
    in 2003, leaving 55 million people
    without power causing $1bn damage
- **Can be avoided by critical regions**
  - Mutually exclusive access to a set of operations



Case Study: Implementing locks - lecture goals

- **Among the simplest concurrency constructs**
  - Yet, complex enough to illustrate many optimization principles
- **Goal 1: You understand locks in detail**
  - Requirements / guarantees
  - Correctness / validation
  - Performance / scalability

    Why you do not want to use them in many cases!
- **Goal 2: Acquire the ability to design your own locks (and other constructs)**
  - Understand techniques and weaknesses/traps
  - Extend to other concurrent algorithms

    Issues are very much the same
- **Goal 3: Understand the complexity of shared memory!**
  - Memory models in realistic settings

Preliminary Comments

- **All code examples are in C/C++ style**
  - Neither C (<11) nor C++ (<11) had a clear memory model
  - C++ is one of the languages of choice in HPC
  - Consider source as exemplary (and pay attention to the memory model)!

    In fact, many/most textbook examples are incorrect in anything but sequential consistency!

    In fact, you'll most likely not need those algorithms, but the principles will be useful!
- **x86 is really only used because it is common**
  - This does not mean that we consider the ISA or memory model elegant!
  - We assume atomic memory (or registers)!

    Usually given on x86 (easy to enforce)
- **Number of threads/processes is p, tid is the thread id**

Recap Concurrent Updates

```
const int n=1000;
volatile int a=0;
for (int i=0; i<n; ++i)
  a++;
```

gcc -O3

```
      movl  $1000, %eax     // i=n=1000
.L2:
      movl  (%rdx), %ecx    // ecx = *a
      addl  $1, %ecx        // ecx++
      subl  $1, %eax        // i--
      movl  %ecx, (%rdx)    // *a = ecx
      jne   .L2             // loop if i>0
```

- **Multi-threaded execution!**
  - Demo: value of a for p=1?
  - Demo: value of a for p>1?

    Why? Isn't it a single instruction?

```
const int n=1000;
std::atomic<int> a;
a=0;
for (int i=0; i<n; ++i)
  a++;
```

g++ -O3

```
      movl  $1000, %eax     // i=n=1000
      movl  $0, -24(%rsp)   // a = 0
      mfence                // a is visible!
.L2:
      lock addl $1 , -24(%rsp)  // (*a)++
      subl  $1, %eax        // i--
      jne   .L2             // loop if i>0
```

One instruction less! Performance!?

- **Run with larger n (10^8)**
- **Compiler: gcc version 7.3.0 (enabled c++11 support, -O3)**
- **Single-threaded execution only!**

```
const int n = 1e8;
volatile int a=0;
for (int i=0; i<n; ++i)
  a++;
```

Demo: 0.17s

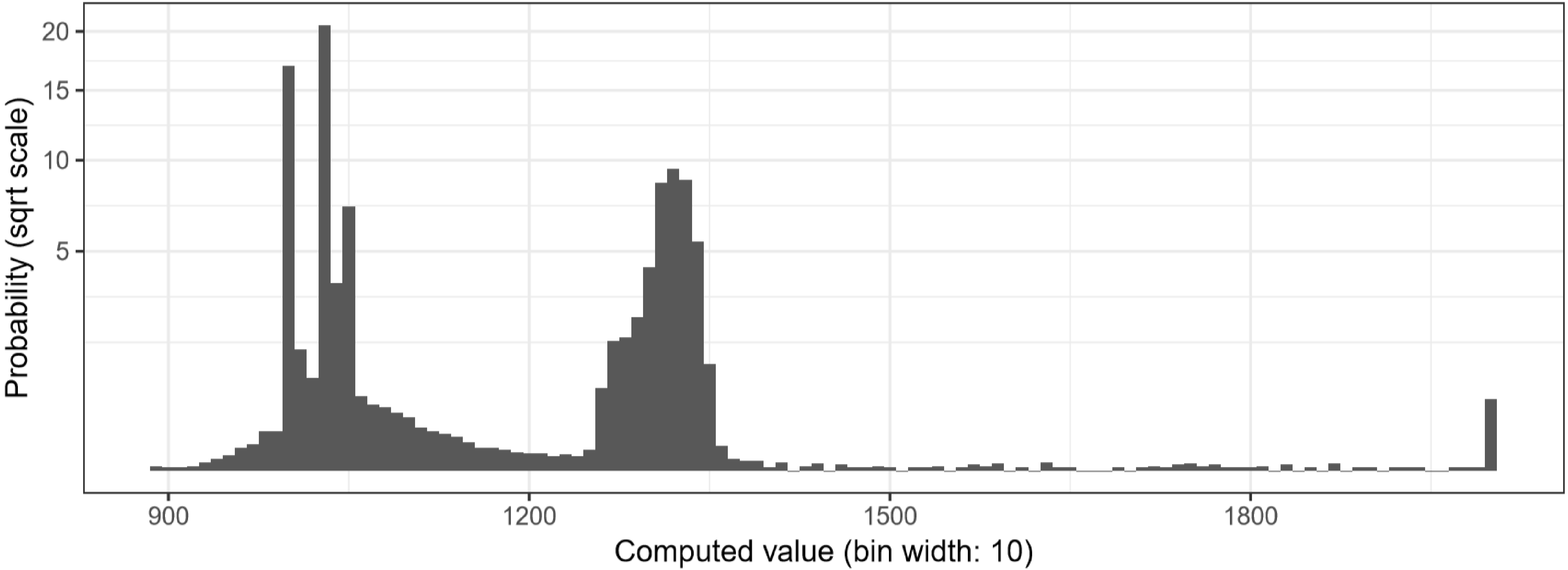
```
const int n = 1e8;
std::atomic<int> a;
a=0;
for (int i=0; i<n; ++i)
  a++;
```

Guess!

Demo: 0.55s

Schweizer, Besta, Hoefler: “Evaluating the Cost of Atomic Operations on Modern Architectures”, ACM PACT’15

Some Statistics



More formal: Mutual Exclusion

- **Control access to a critical region**
  - Memory accesses of all processes happen in program order (a partial order, many interleavings)

    An execution history defines a total order of memory accesses
  - Some subsets of memory accesses (issued by the same process) need to happen atomically (thread a's memory accesses may not be interleaved with other thread's accesses)

    To achieve linearizability!

    We need to restrict the valid executions
- **→ Requires synchronization of some sort**
  - Many possible techniques (e.g., TM, CAS, T&S, …)
  - We first discuss locks which have wait semantics

```
 movl     $1000, %eax    // i=1000
.L2:
     movl (%rdx), %ecx   // ecx = *a
     addl $1, %ecx       // ecx++
     subl $1, %eax       // i--
     movl %ecx, (%rdx)   // *a = ecx
     jne  .L2            // loop if i>0
```

Fixing it with locks

```
const int n=1000;
volatile int a=0;
omp_lock_t lck;
for (int i=0; i<n; ++i) {
  omp_set_lock(&lck);
  a++;
  omp_unset_lock(&lck);
}
```

gcc -O3

```
      movl  $1000, %ebx      // i=1000
.L2:
      movq  0(%rbp), %rdi    // (SystemV CC)
      call  omp_set_lock     // get lock
      movq  0(%rbp), %rdi    // (SystemV CC)
      movl  (%rax), %edx     // edx = *a
      addl  $1, %edx         // edx++
      movl  %edx, (%rax)     // *a = edx
      call  omp_unset_lock   // release lock
      subl  $1, %ebx         // i—
      jne   .L2              // repeat if i>0
```

- What must the functions lock and unlock guarantee?
  - #1: prevent two threads from simultaneously entering CR

    i.e., accesses to CR must be mutually exclusive!
  - #2: ensure consistent memory

    i.e., stores must be globally visible before new lock is granted!
- Any performance guesses (remember, 0.17s → 0.55s for atomics)
  - 2.26s

Lock Overview

- **Lock/unlock or acquire/release**
  - Lock/acquire: before entering CR
  - Unlock/release: after leaving CR
- **Semantics:**
  - Lock/unlock pairs must match
  - Between lock/unlock, a thread holds the lock

Desired Lock Properties

- **Mutual exclusion**
  - Only one thread is in the critical region
- **Consistency**
  - Memory operations are visible when critical region is left
- **Progress**
  - If any thread a is not in the critical region, it cannot prevent another thread b from entering
- **Starvation-freedom (implies deadlock-freedom)**
  - If a thread is requesting access to a critical region, then it will eventually be granted access
- **Fairness**
  - A thread a requested access to a critical region before thread b. Was it also granted access to this region before b?
- **Performance**
  - Scaling to large numbers of contending threads

?

Simplified Notation (cf. Histories)

- **Time defined by precedence (a total order on events)**
  - Events are instantaneous (linearizable)
  - Threads produce sequences of events $a_0, a_1, a_2, \ldots$
  - Program statements may be repeated, denote i-th instance of a as a^i
  - Event a occurs before event b: $a \rightarrow b$
  - An interval (a,b) is the duration between events $a \rightarrow b$
  - Interval $I_1=(a,b)$ precedes interval $I_2=(c,d)$ iff $b \rightarrow c$
- **Critical regions**
  - A critical region CR is an interval (a,b), where a is the first operation in the CR and b the last
- **Mutual exclusion**
  - Critical regions CR_A and CR_B are mutually exclusive if:
    Either $CR_A \rightarrow CR_B$ or $CR_B \rightarrow CR_A$ for all valid executions!
- **Assume atomic registers (for now)**

Simple Two-Thread Locks

- **A first simple spinlock**

```
volatile int flag=0;

void lock() {
  while(flag);
  flag = 1;
}

void unlock() {
  flag = 0;
}
```

Busy-wait to acquire lock (spinning)

Is this lock correct?

Why does this not guarantee mutual exclusion?

Simple Two-Thread Locks

- **Another two-thread spin-lock: LockOne**

```
volatile int flag[2];

void lock() {
  int j = 1 - tid;
  flag[tid] = true;
  while (flag[j]) {} // wait
}

void unlock() {
  flag[tid] = false;
}
```

When and why does this guarantee mutual exclusion?

Correctness Proof

- **In sequential consistency!**
- **Intuitions:**
  - Situation: both threads are ready to enter
  - Show that situation that allows both to enter leads to a schedule violating sequential consistency
    Using transitivity of program and synchronization orders

Simple Two-Thread Locks

- **Another two-thread spin-lock: LockOne**

```
volatile int flag[2];

void lock() {
  int j = 1 - tid;
  flag[tid] = true;
  while (flag[j]) {} // wait
}

void unlock() {
  flag[tid] = false;
}
```

When and why does this guarantee mutual exclusion?

Does it work in practice?

Simple Two-Thread Locks

- **A third attempt at two-thread locking: LockTwo**

```
volatile int victim;

void lock() {
  victim = tid; // grant access
  while (victim == tid) {} // wait
}

void unlock() {}
```

Does this guarantee mutual exclusion?

Correctness Proof

- **Intuition:**
  - Victim is only written once per lock()
  - A can only enter after B wrote
  - B cannot enter in any sequentially consistent schedule

Simple Two-Thread Locks

- **A third attempt at two-thread locking: LockTwo**

```
volatile int victim;

void lock() {
  victim = tid; // grant access
  while (victim == tid) {} // wait
}

void unlock() {}
```

Does this guarantee mutual exclusion?

Does it work in practice?

Simple Two-Thread Locks

- **The last two locks provide mutual exclusion**
  - LockOne succeeds iff lock attempts do not overlap
  - LockTwo succeeds iff lock attempts do overlap
- **Combine both into one locking strategy!**
  - Peterson’s lock (1981)

Peterson's Two-Thread Lock (1981)

- **Combines the first lock (request access) with the second lock (grant access)**

```
volatile int flag[2];
volatile int victim;

void lock() {
  int j = 1 - tid;
  flag[tid] = 1; // I'm interested
  victim = tid; // other goes first
  while (flag[j] && victim == tid) {}; // wait
}

void unlock() {
  flag[tid] = 0; // I'm not interested
}
```

Proof Correctness

- **Intuition:**
  - Victim is written once
  - Pick thread that wrote victim last
  - Show thread must have read flag==0
  - Show that no sequentially consistent schedule permits that

Starvation Freedom

- **(recap) definition: Every thread that calls lock() eventually gets the lock.**
  - Implies deadlock-freedom!
- **Is Peterson's lock starvation-free?**

```
volatile int flag[2];
volatile int victim;

void lock() {
  int j = 1 - tid;
  flag[tid] = 1; // I'm interested
  victim = tid; // other goes first
  while (flag[j] && victim == tid) {}; // wait
}

void unlock() {
  flag[tid] = 0; // I'm not interested
}
```

Proof Starvation Freedom

- **Intuition:**
  - Threads can only wait/starve in while()

    Until flag==0 or victim==other
  - Other thread enters lock() → sets victim to other

    Will definitely “unstuck” first thread
  - So other thread can only be stuck in lock()

    Will wait for victim==other, victim cannot block both threads → one must leave!

Lock Fairness

- **Starvation freedom provides no guarantee on how long a thread waits or if it is "passed"!**
- **To reason about fairness, we define two sections of each lock algorithm:**
  - Doorway D (bounded # of steps)
  - Waiting W (unbounded # of steps)

```
void lock() {
  int j = 1 - tid;
  flag[tid] = true; // I'm interested
  victim = tid;     // other goes first
  while (flag[j] && victim == tid) {};
}
```

- **FIFO locks:**
  - If T_A finishes its doorway before T_B then $CR_A \rightarrow CR_B$
  - Implies fairness

Lamport's Bakery Algorithm (1974)

- **Is a FIFO lock (and thus fair)**
- **Each thread takes a number in the doorway and threads enter in the order of their number!**

```
volatile int flag[n] = {0,0,…,0};
volatile int label[n] = {0,0,….,0};

void lock() {
  flag[tid] = 1; // request
  label[tid] = max(label[0], ...,label[n-1]) + 1; // take ticket
  while ((∃k != tid)(flag[k] && (label[k],k) <* (label[tid],tid))) {};
}
public void unlock() {
  flag[tid] = 0;
}
```

Lamport's Bakery Algorithm (1974)

- **Advantages:**
  - Elegant and correct solution
  - Starvation free, even FIFO fairness

- **Not used in practice!**
  - Why?
  - Needs to read/write N memory locations for synchronizing N threads
  - Can we do better?

    Using only atomic registers/memory

A Lower Bound to Memory Complexity

- **Theorem 5.1 in [1]: *"If S is a [atomic] read/write system with at least two processes and S solves mutual exclusion with global progress [deadlock-freedom], then S must have at least as many variables as processes"***

- **So we're doomed! Optimal locks are available and they're fundamentally non-scalable. Or not?**

[1] J. E. Burns and N. A. Lynch. Bounds on shared memory for mutual exclusion. Information and Computation, 107(2):171–184, December 1993