CSE 410
Computer Systems

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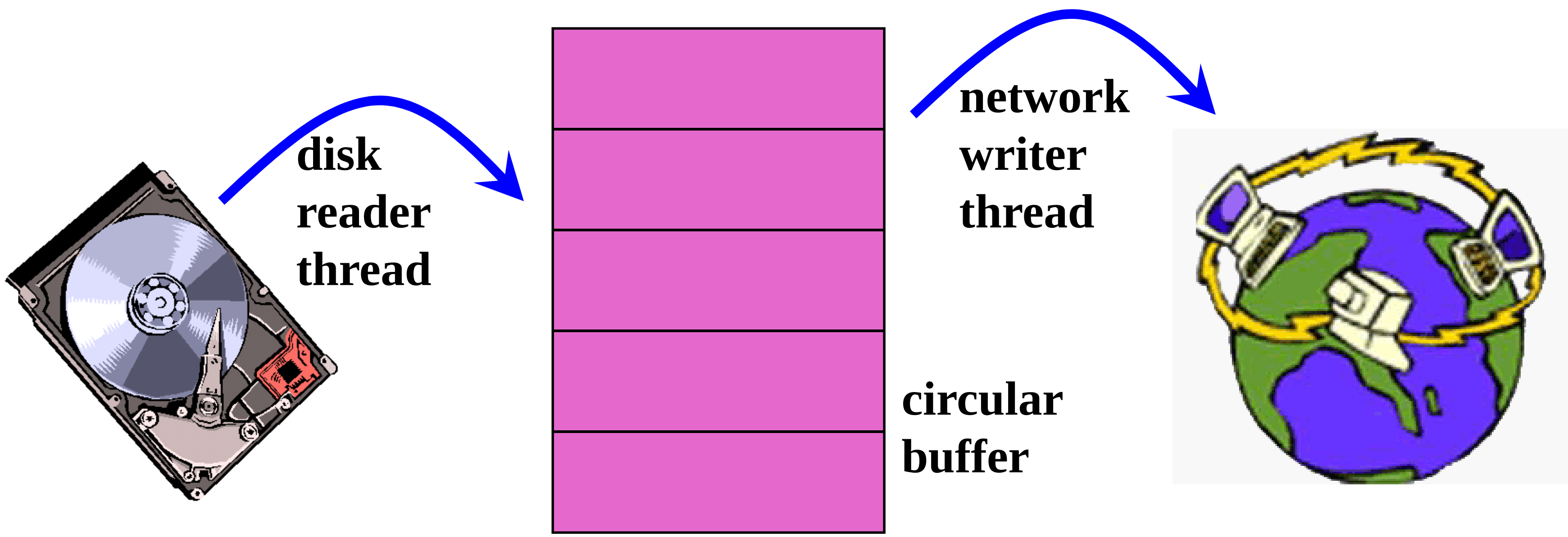
Lecture 18 – Synchronization

Readings and References

- Reading
  - Chapter 6, Operating System Concepts, Silberschatz, Galvin, and Gagne. Read 6.1, 6.2, 6.3 (skim), 6.4-6.5, 6.6 (skim), 6.7

Synchronization

- Threads cooperate in multithreaded programs
  - to share resources, access shared data structures
    - e.g., threads accessing a memory cache in a web server
  - also, to coordinate their execution
    - e.g., a disk reader thread hands off blocks to a network writer thread through a circular buffer



Synchronization

- For correctness, we have to control this cooperation
  - must assume threads interleave executions arbitrarily and at different rates
    - Modern OS's are preemptive
    - scheduling is not under application writers' control (except for real-time, but that's not of interest here).
- We control cooperation using synchronization
  - enables us to restrict the interleaving of executions
- Note: this also applies to processes, not just threads
  - (I may never say "process" again! Then again, I might say it a lot.)
- It also applies across machines in a distributed system

Shared resources

- We'll focus on coordinating access to shared resources
  - basic problem:
    - two concurrent threads are accessing a shared variable
    - if the variable is read/modified/written by both threads, then access to the variable must be controlled
    - otherwise, unexpected results may occur

The classic example

- Suppose we have to implement a function to withdraw money from a bank account:

```
int withdraw(account, amount) {
  int balance = get_balance(account);
  balance -= amount;
  put_balance(account, balance);
  return balance;
}
```

- Now suppose that you and your S.O. share a bank account with a balance of $100.00
  - what happens if you both go to separate ATM machines, and simultaneously withdraw $10.00 from the account?

Your Bank's Computer

- Represent the situation by creating a separate thread for each person to do the withdrawals
  - have both threads run on the same bank mainframe:

```
int withdraw(account, amount) {
  int balance = get_balance(account);
  balance -= amount;
  put_balance(account, balance);
  return balance;
}
```

```
int withdraw(account, amount) {
  int balance = get_balance(account);
  balance -= amount;
  put_balance(account, balance);
  return balance;
}
```

Interleaved schedules

- The problem is that the execution of the two threads can be interleaved, assuming preemptive scheduling:

Execution sequence as seen by CPU

```
balance = get_balance(account);
balance -= amount;
```

context switch

```
balance = get_balance(account);
balance -= amount;
put_balance(account, balance);
```

context switch

```
put_balance(account, balance);
```

- What’s the account balance after this sequence?
  – who’s happy, the bank or you?
- How often is this unfortunate sequence likely to occur?

The crux of the matter

- The problem is that two concurrent threads (or processes) access a shared resource (account) without any synchronization
  - creates a **race condition**
    - output is non-deterministic, depends on timing
- We need mechanisms for controlling access to shared resources in the face of concurrency
  - so we can reason about the operation of programs
    - essentially, re-introducing determinism
- Synchronization is necessary for any shared data structure
  - buffers, queues, lists, hash tables, scalars, …

What resources are shared?

- Local variables are *not* shared
  - refer to data on the stack, each thread has its own stack
  - *never* pass/share/store a pointer to a local variable on another thread's stack!
- Global variables are shared
  - stored in the static data segment, accessible by any thread
- Dynamic objects are shared
  - stored in the heap, shared if you can name it

Mutual exclusion

- We want to use mutual exclusion to synchronize access to shared resources
- Mutual exclusion makes reasoning about program behavior easier
  - making reasoning easier leads to fewer bugs
- Code that uses mutual exclusion to synchronize its execution is called a critical section
  - only one thread at a time can execute in the critical section
  - all other threads are forced to wait on entry
  - when a thread leaves a critical section, another can enter

Critical section requirements

- Critical sections have the following requirements
  - mutual exclusion
    - at most one thread is in the critical section
  - progress
    - if thread T is outside the critical section, then T cannot prevent thread S from entering the critical section
  - bounded waiting (no starvation)
    - if thread T is waiting on the critical section, then T will eventually enter the critical section
      - assumes threads eventually leave critical sections
    - vs. fairness?
  - performance
    - the overhead of entering and exiting the critical section is small with respect to the work being done within it

Mechanisms for building critical sections

- Locks
  - very primitive, minimal semantics; used to build others
- Semaphores
  - basic, easy to get the hang of, hard to program with
- Monitors
  - high level, requires language support, implicit operations
  - easy (easier) to program with; Java synchronized() as an example
- Messages
  - simple model of communication and synchronization based on (atomic) transfer of data across a channel
  - direct application to distributed systems

- We will survey the first three

Locks

- A lock is an object (in memory) that provides the following two operations:
  - `acquire()`: a thread calls this before entering a critical section
  - `release()`: a thread calls this after leaving a critical section
- Threads pair up calls to `acquire()` and `release()`
  - between `acquire()`and `release()`, the thread holds the lock
  - `acquire()` does not return until the caller holds the lock
    - at most one thread can hold a lock at a time (usually)
  - so: what can happen if the calls aren't paired?
- Two basic flavors of locks
  - spinlock
  - blocking (a.k.a. "mutex")

Using locks

```
int withdraw(account, amount) {
  acquire(lock);
  balance = get_balance(account);
  balance -= amount;
  put_balance(account, balance);
  release(lock);
  return balance;
}
```

critical section

```
acquire(lock)
balance = get_balance(account);
balance -= amount;
```

```
acquire(lock)
```

```
put_balance(account, balance);
release(lock);
```

```
balance = get_balance(account);
balance -= amount;
put_balance(account, balance);
release(lock);
```

- What happens when green tries to acquire the lock?
- Why is the “return” outside the critical section?
  - is this ok?

Spinlocks

- How do we implement locks? Here's one attempt:

```
struct lock {
  int held = 0;
}
void acquire(lock) {
   while (lock->held);
   lock->held = 1;
}
void release(lock) {
  lock->held = 0;
}
```

```
the caller “busy-waits”,
or spins, for lock to be
released ⇒ hence spinlock
```

- Why doesn't this work?
  – where is the race condition?

Implementing locks (cont.)

- Problem is that implementation of locks has critical sections, too!
  - the acquire/release must be **atomic**
    - atomic == executes as though it could not be interrupted
    - code that executes “all or nothing”
- Need help from the hardware
  - atomic instructions
    - test-and-set, compare-and-swap, …
    - see text for examples
  - disable/reenable interrupts
    - to prevent context switches
    - crude – and can only be done in the kernel

Summary so far

- Synchronization can be provided by locks, semaphores, monitors, messages …
- Locks are the lowest-level mechanism
  - very primitive in terms of semantics – error-prone
  - implemented by spin-waiting (crude) or by disabling interrupts (also crude, and can only be done in the kernel)
- In our next exciting episode …
  - semaphores are a slightly higher level abstraction
    - less crude implementation too
  - monitors are significantly higher level
    - utilize programming language support to reduce errors

Semaphores

- Semaphore = a synchronization primitive
  - higher level of abstraction than locks
  - invented by Dijkstra in 1968, as part of the THE operating system
- A semaphore is:
  - a variable that is manipulated through two operations, P and V (Dutch for “test” and “increment”)
    - **P(sem)** (wait)
      - block until sem > 0, then subtract 1 from sem and proceed
    - **V(sem)** (signal)
      - add 1 to sem
- Do these operations *atomically*

Blocking in semaphores

- Each semaphore has an associated queue of threads
  - when P(sem) is called by a thread,
    - if sem was “available” (>0), decrement sem and let thread continue
    - if sem was “unavailable” (<=0), place thread on associated queue; dispatch some other runnable thread
  - when V(sem) is called by a thread
    - if thread(s) are waiting on the associated queue, unblock one
      - place it on the ready queue
      - might as well let the “V-ing” thread continue execution
      - or not, depending on priority
    - otherwise (when no threads are waiting on the sem), increment sem
      - the signal is “remembered” for next time P(sem) is called
- Semaphores thus have history

Abstract implementation

- P/wait(sem)
  - acquire “real” mutual exclusion
    - if sem is “available” (>0), decrement sem; release “real” mutual exclusion; let thread continue
    - otherwise, place thread on associated queue; release “real” mutual exclusion; run some other thread
- V/signal(sem)
  - acquire “real” mutual exclusion
    - if thread(s) are waiting on the associated queue, unblock one (place it on the ready queue)
    - if no threads are on the queue, sem is incremented
      - » the signal is “remembered” for next time P(sem) is called
  - release “real” mutual exclusion
  - [the “V-ing” thread continues execution or is preempted]

Two types of semaphores

- Binary semaphore (aka mutex semaphore)
  - sem is initialized to 1
  - guarantees mutually exclusive access to resource (e.g., a critical section of code)
  - only one thread/process allowed entry at a time

- Counting semaphore
  - sem is initialized to N
    - N = number of units available
  - represents resources with many (identical) units available
  - allows threads to enter as long as more units are available

Usage

- From the programmer's perspective, P and V on a binary semaphore are just like Acquire and Release on a lock

```
P(sem)
   .
   .
   .
   do whatever stuff requires mutual exclusion; could conceivably
   be a lot of code
   .
   .
   .
V(sem)
```

  - same lack of programming language support for correct usage

- Important differences in the underlying implementation, however

Semaphores vs. Locks

- Threads that are blocked by the semaphore P operation are placed on queues, rather than busy-waiting
- Busy-waiting may be used for the “real” mutual exclusion required to implement P and V
  - but these are very short critical sections – totally independent of program logic

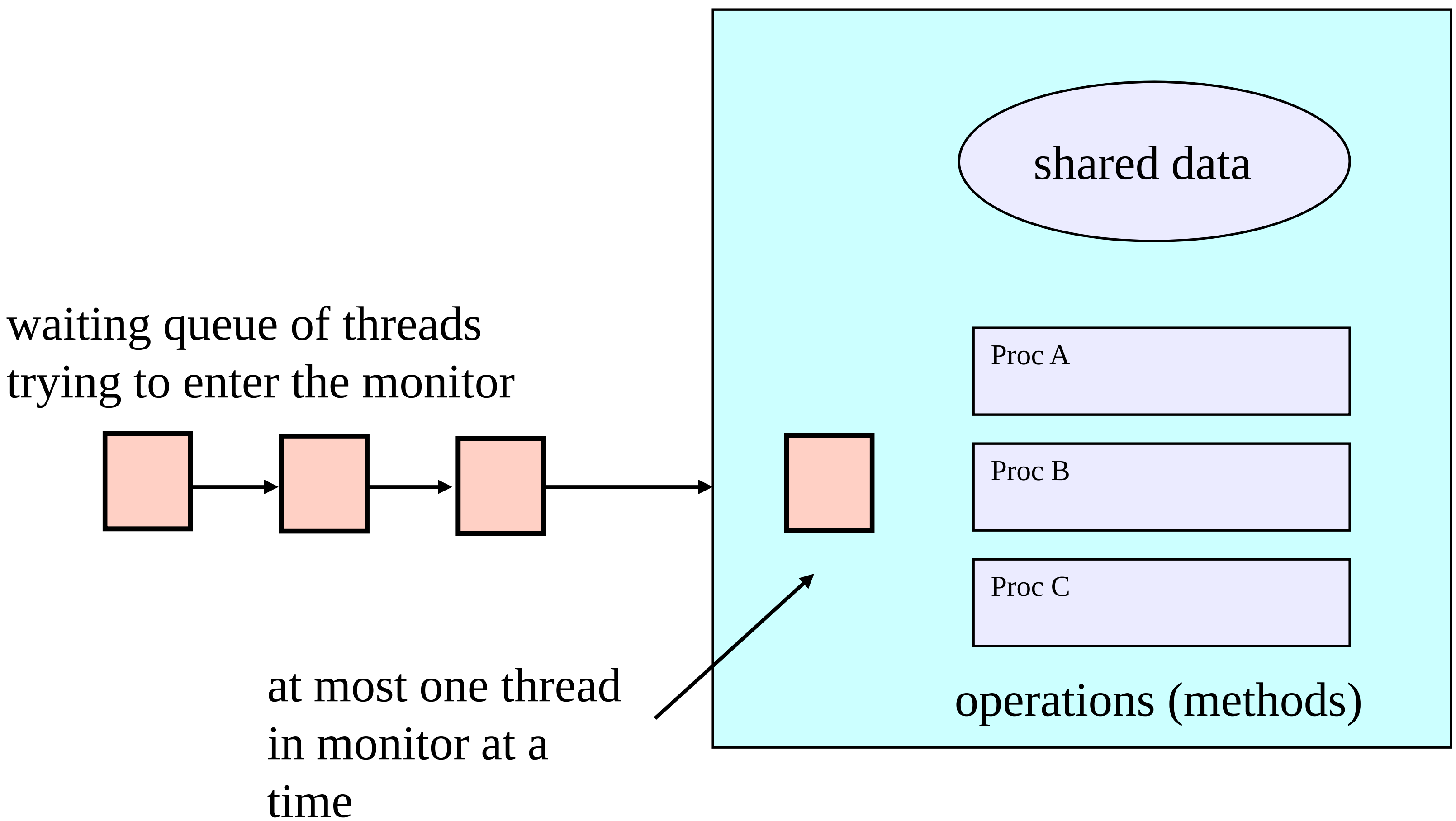
Problems with semaphores (and locks)

- They can be used to solve any of the traditional synchronization problems, but:
  - semaphores are essentially shared global variables
    - can be accessed from anywhere (bad software engineering)
  - there is no connection between the semaphore and the data being controlled by it
  - used for both critical sections (mutual exclusion) and for coordination (scheduling)
  - no control over their use, no guarantee of proper usage
- Thus, they are prone to bugs
  - another (better?) approach: use programming language support

One More Approach: Monitors

- A *monitor* is a programming language construct that supports controlled access to shared data
  - synchronization code is added by the compiler
- A monitor encapsulates:
  - shared data structures
  - procedures that operate on the shared data
  - synchronization between concurrent threads that invoke those procedures
- Data can only be accessed from within the monitor, using the provided procedures
  - protects the data from unstructured access
- Addresses the key usability issues that arise with semaphores

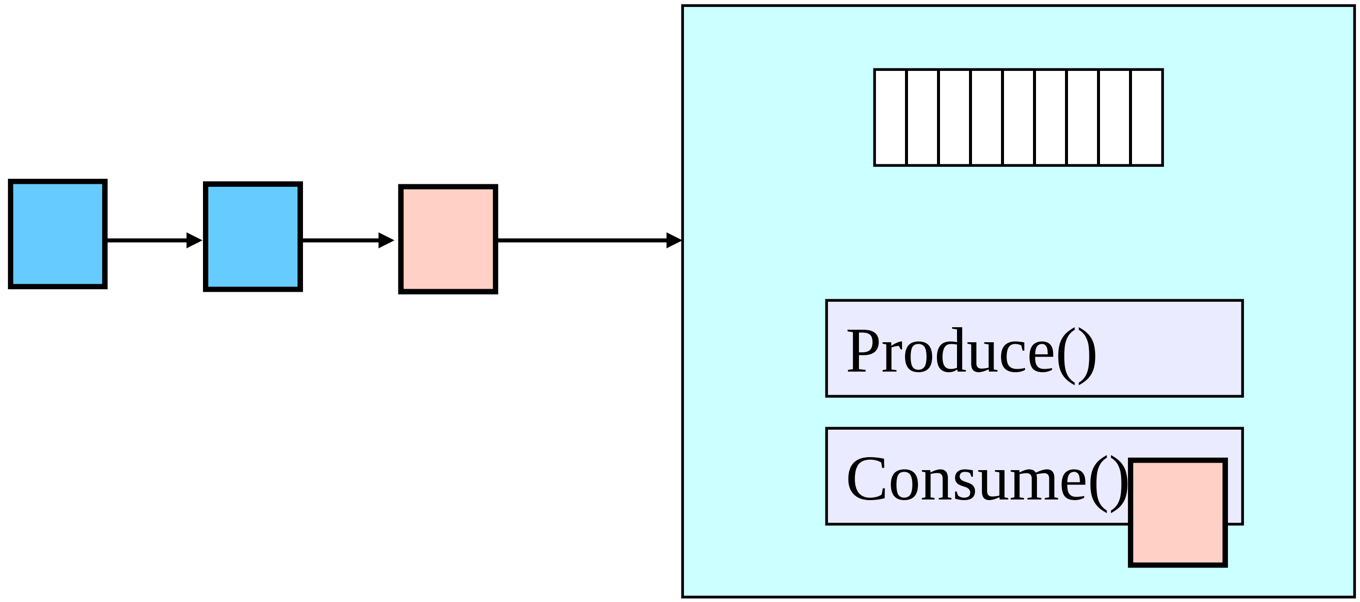
A monitor


shared data
waiting queue of threads
trying to enter the monitor
Proc A
Proc B
Proc C
at most one thread
in monitor at a
time
operations (methods)

Monitor facilities

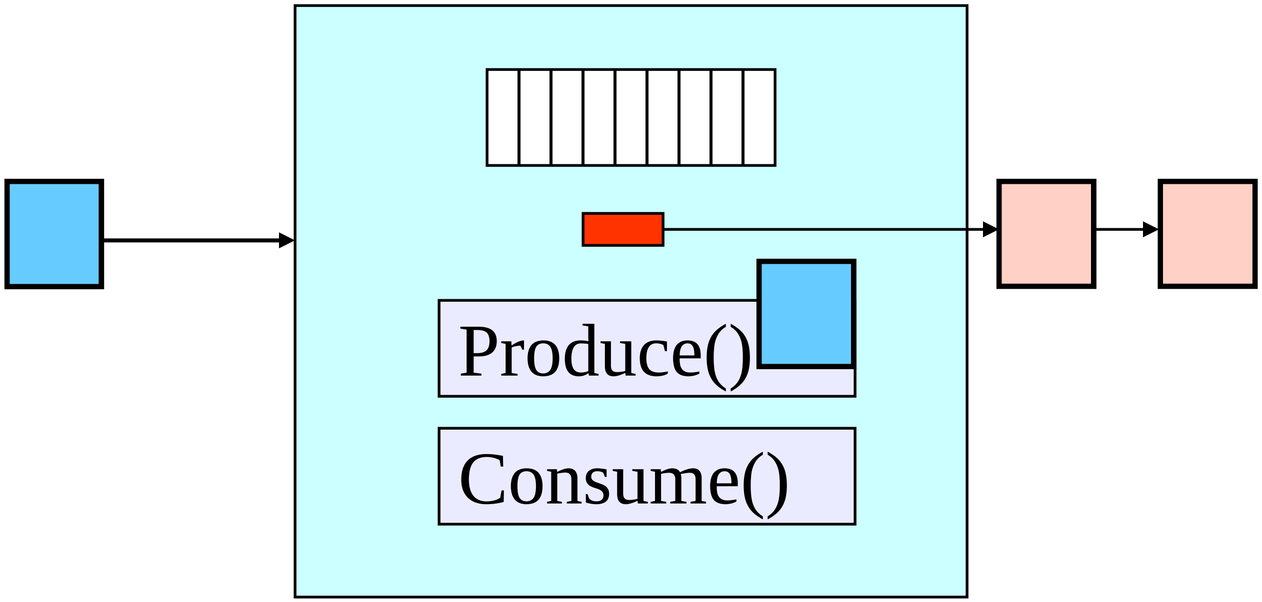
- “Automatic” mutual exclusion
  - only one thread can be executing inside at any time
    - thus, synchronization is implicitly associated with the monitor – it “comes for free”
  - if a second thread tries to execute a monitor procedure, it blocks until the first has left the monitor
    - more restrictive than semaphores
    - but easier to use (most of the time)
- But, there’s a problem…

Example: Bounded Buffer Scenario



- Buffer is empty
- Now what?

Example: Bounded Buffer Scenario

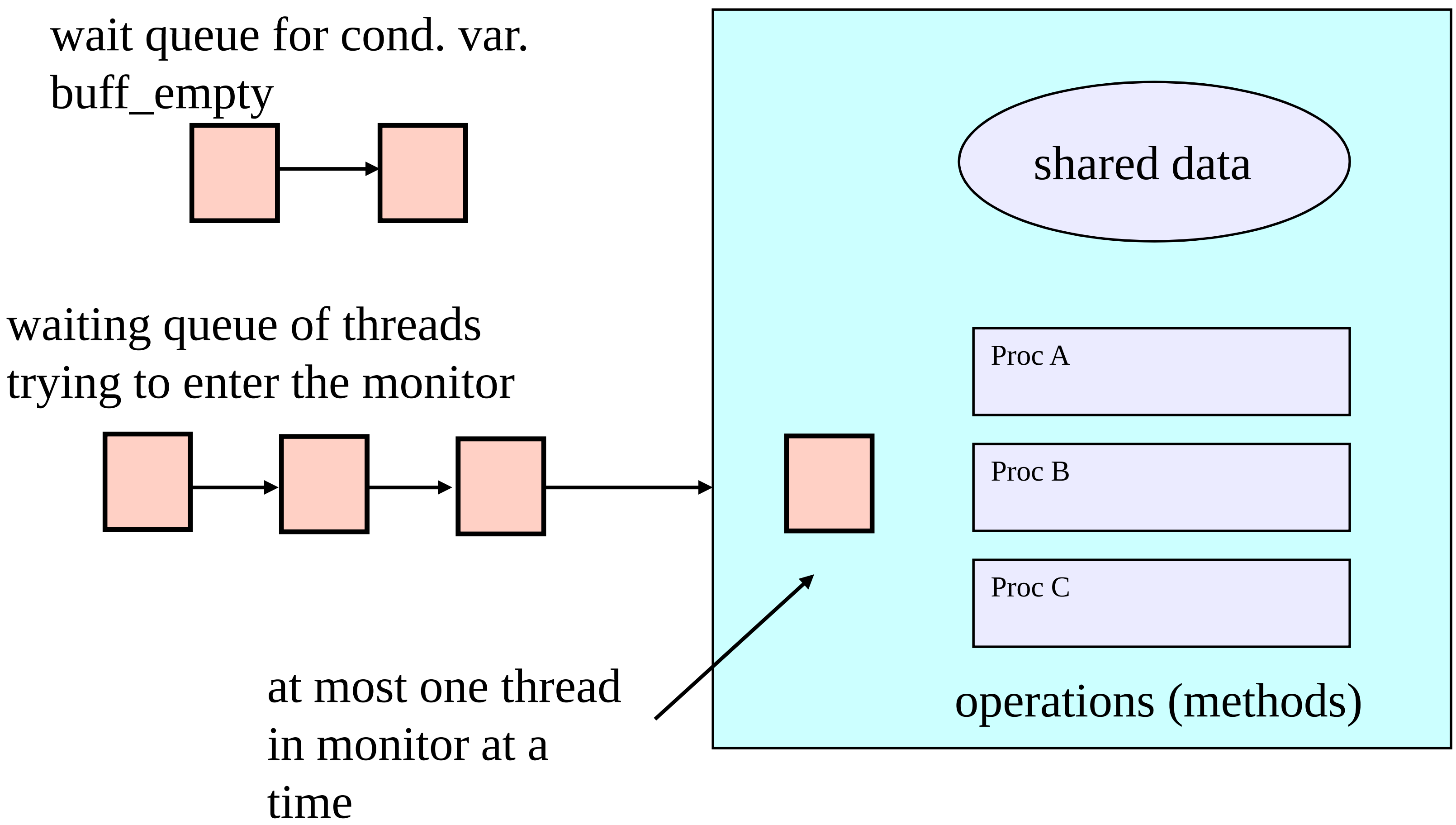


- Buffer is full
- Now what?

Condition variables

- A place to wait; sometimes called a rendezvous point
- “Required” for monitors
  - So useful they’re often provided even when monitors aren’t available
- Three operations on condition variables
  - wait(c)
    - release monitor lock, so somebody else can get in
    - wait for somebody else to signal condition
    - thus, condition variables have associated wait queues
  - signal(c)
    - wake up at most one waiting thread
    - if no waiting threads, signal is lost
      - this is different than semaphores: no history!
  - broadcast(c)
    - wake up all waiting threads

A monitor (including CVs)



Bounded buffer using (Hoare) monitors

```
Monitor bounded_buffer {
  buffer resources[N];
  condition not_full, not_empty;

produce(resource x) {
    if (array “resources” is full)
          wait(not_full);
    insert “x” in array “resources”
    signal(not_empty);
  }

 consume(resource *x) {
    if (array “resources” is empty)
           wait(not_empty);
    *x = get resource from array “resources”
    signal(not_full);
  }
```

Monitor Summary

- Language supports monitors
- Compiler understands them
  - compiler inserts calls to runtime routines for
    - monitor entry
    - monitor exit
    - signal
    - Wait
  - Language/object encapsulation ensures correctness
    - Sometimes! With conditions you STILL need to think about synchronization and state of monitor invariants on wait/signal
- Runtime system implements these routines
  - moves threads on and off queues
  - ensures mutual exclusion!