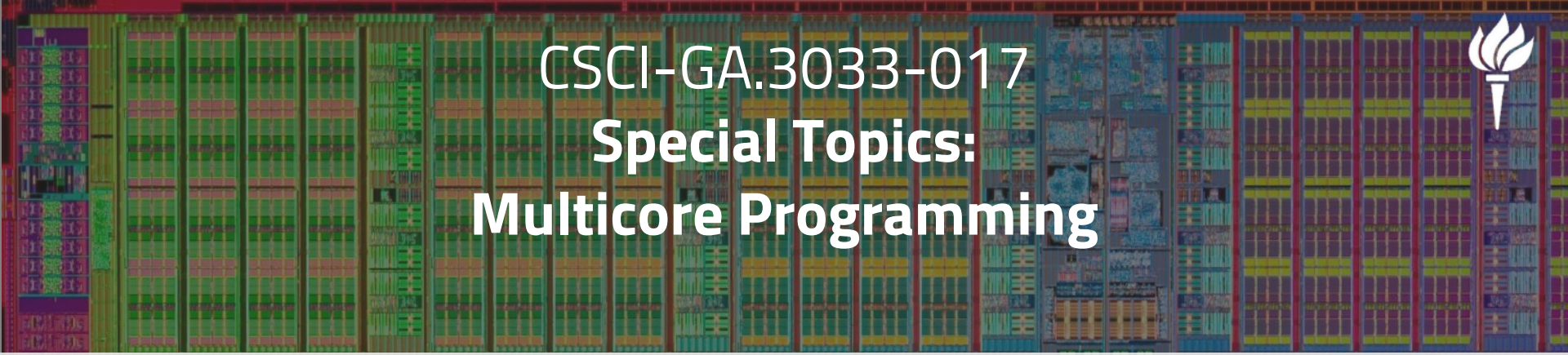


CSCI-GA.3033-017

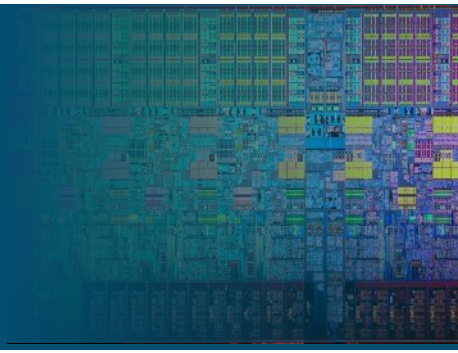
Special Topics:
Multicore Programming

Lecture 4
Concurrent Programming

Christopher Mitchell, Ph.D.

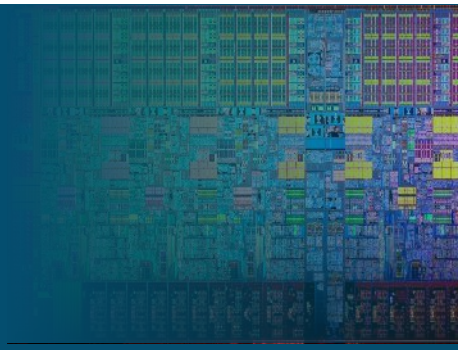
cmitchell@cs.nyu.edu || http://z80.me

Lecture 4 Outline



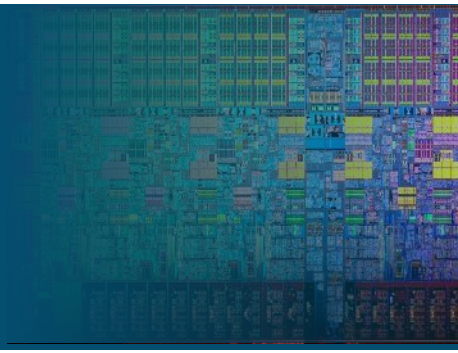
- Programming models for multicore systems
- Thread execution model
- A simple concurrent queue
- At last: Lab 1

Explicit Parallelism Review



- MIMD: Multiple Instruction, Multiple Data (Flynn's taxonomy)
- Pipelining parallelism on the granularity of instructions, even in sequential code
- Programmers' responsibility: task/thread/process parallelism

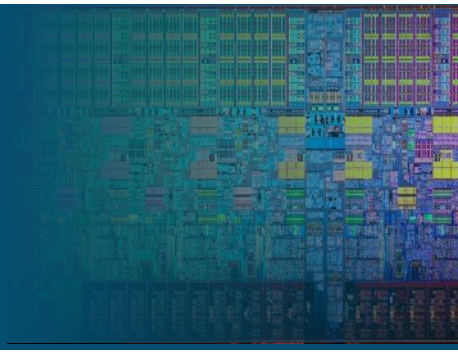
Review: Multicore Programming Tenets



- Keep all the cores busy
  - Break down a problem in smaller tasks
  - Perform tasks as independently as possible or with little synchronization
  - Always try to reduce the number and duration of sequential (non-parallelizable) tasks
- Your code would only go as fast as the duration of your sequential tasks
- Your code would scale with the number of cores to the proportion of its parallelizable tasks (Amdhal's law)

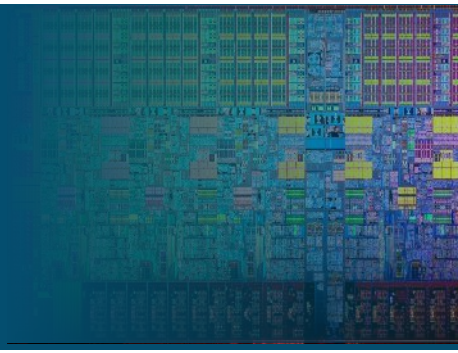
Easier said than done… Let's try it.

Making Programming Models Concrete



- Programming models should
  1. Start/stop tasks
  2. Allow tasks to communicate
  3. Synchronize tasks
  4. Schedule tasks

Starting/Stopping Tasks



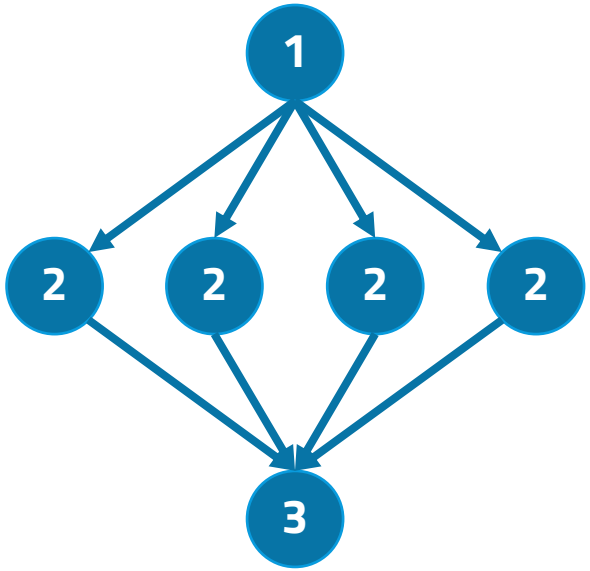
- Language support to identify concurrent tasks
  - Processes
  - Fork/Join
  - Co-routines
  - *(Others too numerous to mention)*

Cobegin/Coend

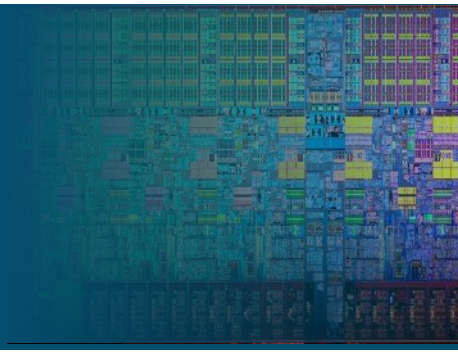
- Marks a portion of where several “threads” of execution are allowed

- Example: OpenMP

```
#pragma omp parallel for
for(int i = 0; i < n; i++) {
    c[i] = a[i] + b[i];
}
```



Coroutines



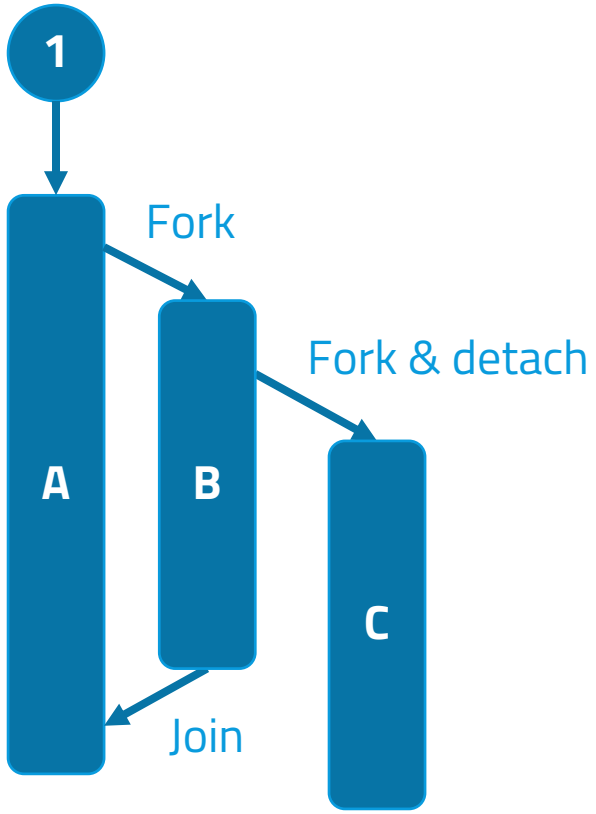
- For concurrency (and possibly parallelism)
- Execute part of a task
  - Control transfer granularity

C++ (Boost) Example:

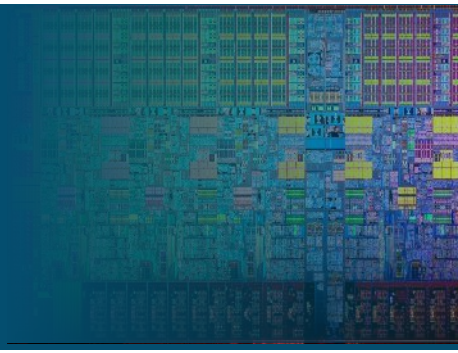
```
#include <boost/coroutine/all.hpp>
using namespace boost::coroutines;

coro(coroutine<void>::yield_type &yield) {
  printf("Exec 1\n");
  yield();
  printf("Exec 3\n");
}

int main(int argc, char* argv[]) {
  coroutine<void>::yield_type routine{coro};
  printf("Exec 2\n");
  routine();
  printf("Exec 4\n");
}
```

Fork/Join

- Any task can start another task at any point
- Parent and child execute concurrently (and possibly in parallel)
- Parent may or may not wait for child to finish
- Examples
  - Unix processes
  - POSIX threads

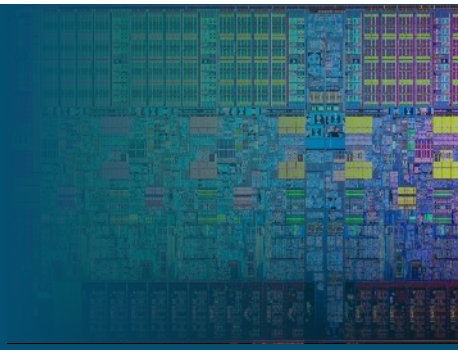


Communication and Synchronization



- Synchronization goals
  - To delay processing until certain conditions hold
  - To guarantee that a block of code behaves as if it were executed atomically
- Message passing
  - Asynchronous communication
- Shared memory
  - Coordinating access…

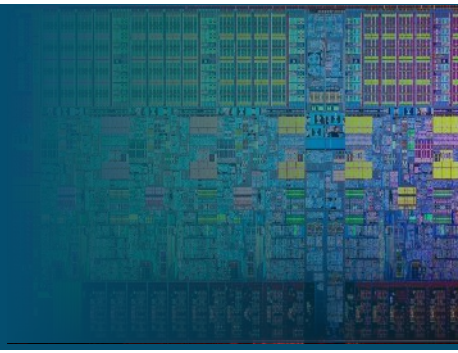
Message Passing



- Asynchronous inter-task communication
- Channels: Go example (thanks to Prof. Lerner)

```
func pump(ch chan int)
  for i:=0; ; i++ { ch <- i }

ch1 := make(chan int)
go pump(ch1)
fmt.Println(<- ch1)  # prints 0

func sink(ch chan int)
  for{ fmt.Println(<- ch) }
go sink(ch1) # prints continuosly
```

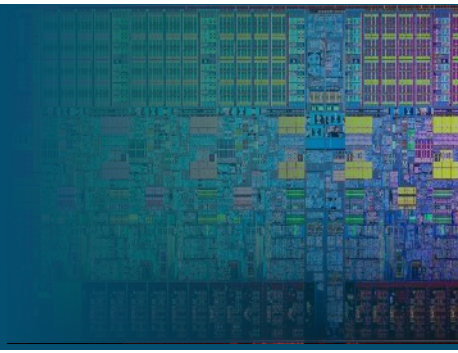
Shared Memory



- Communication via shared state
  - Same effective coordination as message passing, achieved differently
  - Main difference: multiple tasks can manipulate same state
- Sychronization primitives (coming momentarily)

Threads

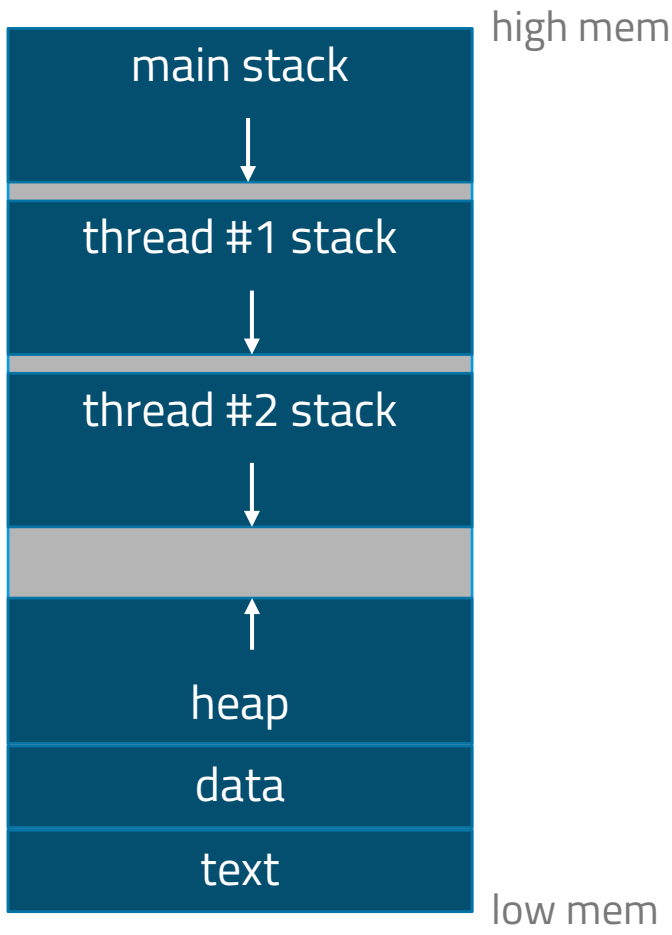
Threads



- Fork/join, shared memory model
- No consensus on whether this is optimal abstraction
  - Writing correct threaded programs is hard
  - Current hardware actually “understands” threads
  - Arguably, this model is where other higher level abstractions would be layered
- This has been ongoing research (for a while) and we’ll have a chance to explore other models later in the course

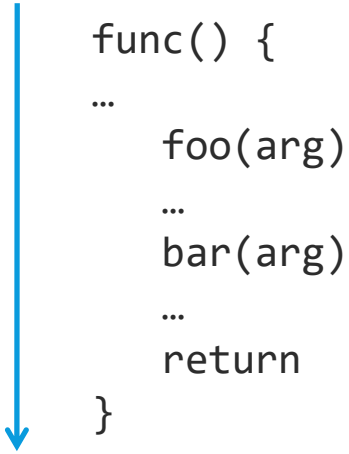
Background: Hardware "Contexts"

- Context: thread's current state
  - PC
  - Stack
  - Registers/flags
  - Memory map
- Threads share address space, but have local context

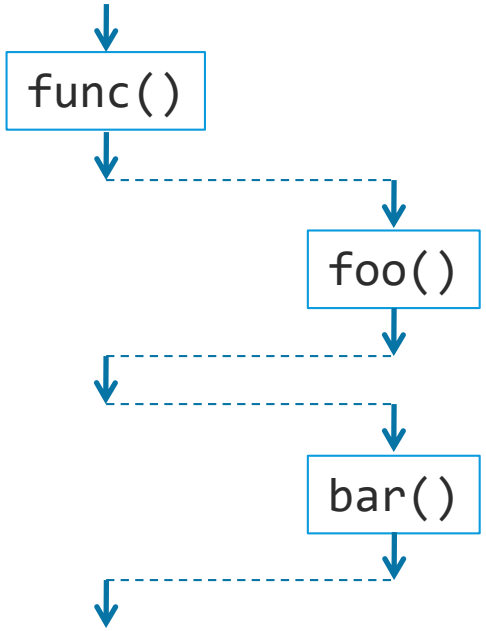


Sequential Execution Model

A single flow of instructions at any point in time. (This was not exactly always true, e.g., signals…)

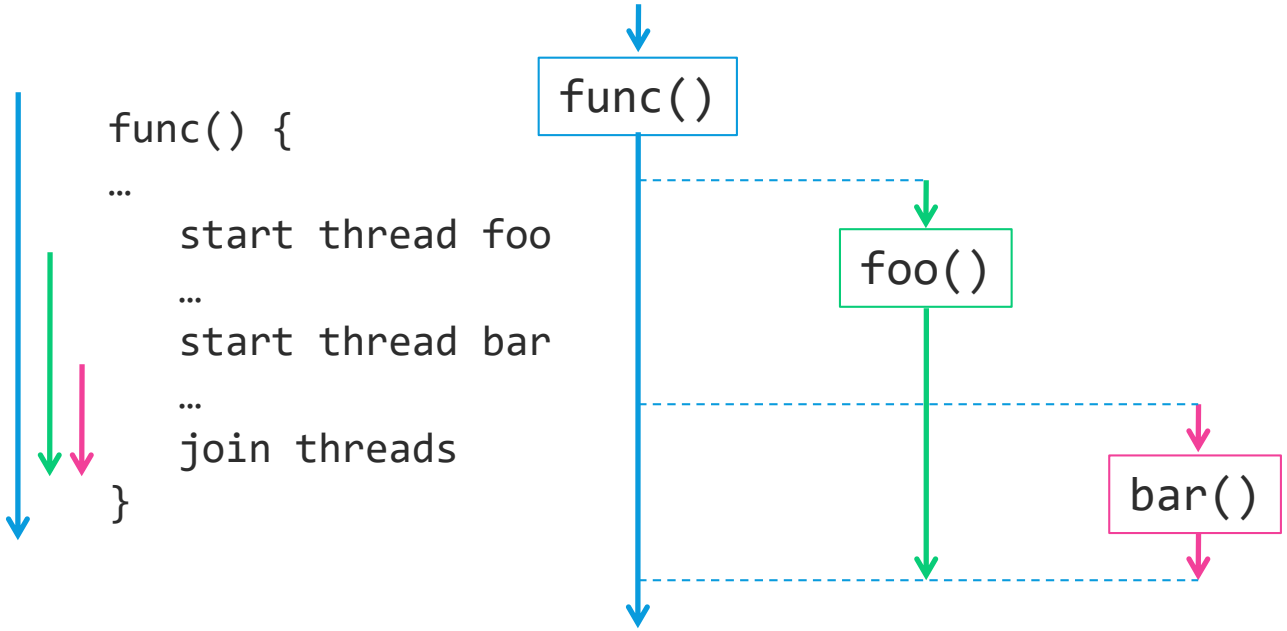


```
func() {
…
    foo(arg)
    …
    bar(arg)
    …
    return
}
```



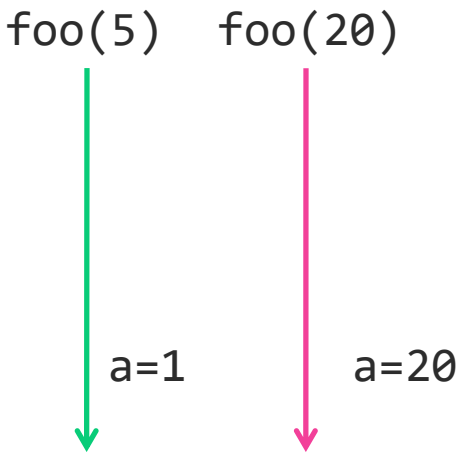
Thread Execution Model

Several flow of instructions at any point in time. How independent are they?



Thread Execution Model

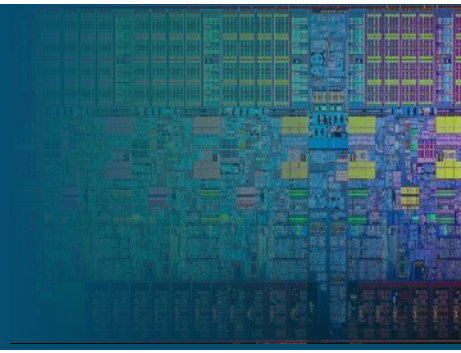
- Each thread executes independently of the others
- Therefore, several threads could be executing the very same instruction of the code
- But each thread has its own stack (remember how functions calls work?)



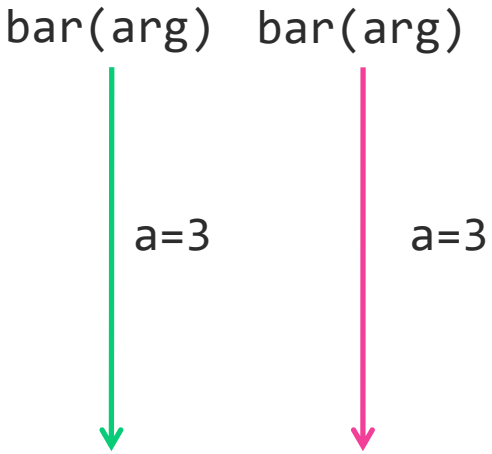
local variables

```
foo(arg) {
   int a;
   if (arg < 10)
      a = 1;
   else
      a = arg;
   …
   … access a …
   return
}
```

Thread Execution Model



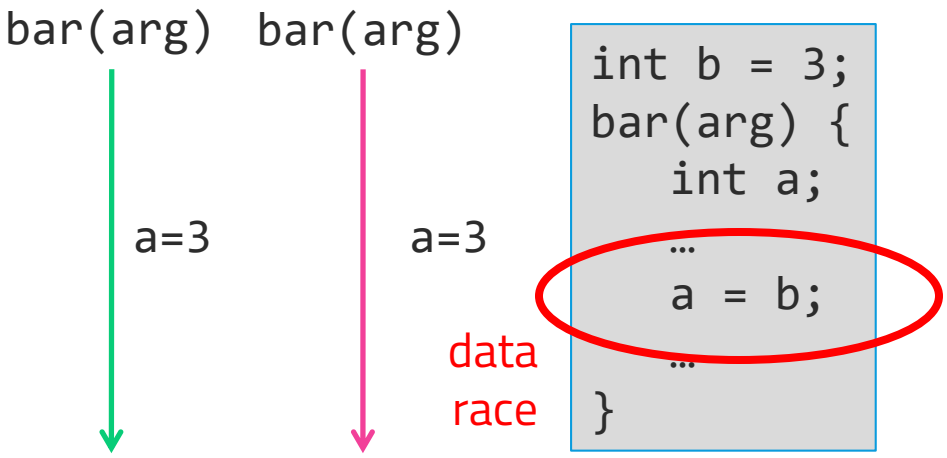
But all threads share the same address space.




```
int b = 3;
bar(arg) {
    int a;
    …
    a = b;
    …
}
```

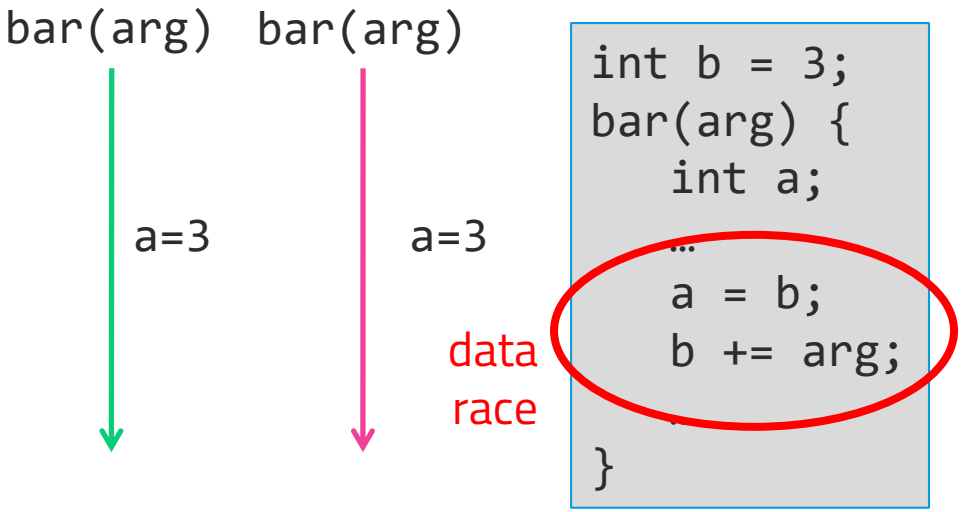
Thread Execution Model

But all threads share the same address space.



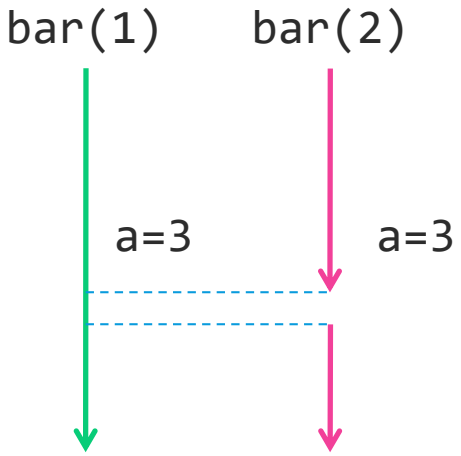
Thread Execution Model: Data Races

- What if two threads want to change a process variable?
- Rule of thumb: if it is not a local variable, do assume others may change it
- Simultaneous accesses may occur and have unpredictable results



Critical Sections

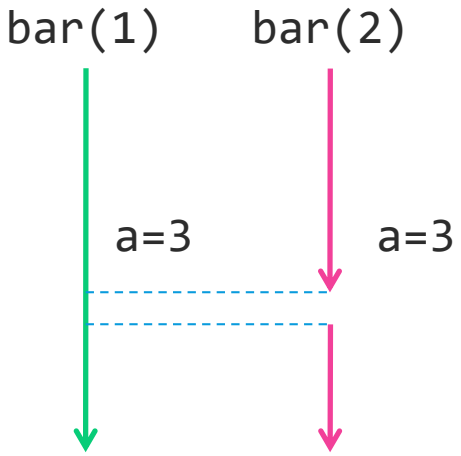
- We need a mutual exclusion mechanism.
- At most one thread can execute inside each critical section at any point in time.




```
int b = 3;
bar(arg) {
    int a;
    …
    enter crit section
    a = b;
    b += arg
    leave crit section
}
```

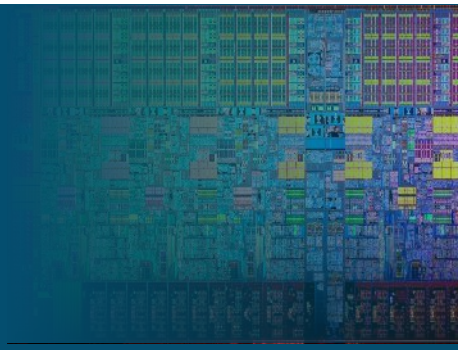
Locks

- Used to implement critical sections
- Lock
  - If no other thread is in the critical section, proceed
  - Otherwise, wait
- Unlock
  - Leave critical section
  - Allow another thread to enter, if one is waiting.




```
int b = 3;
bar(arg) {
    int a;
    …
    lock
    a = b;
    b += arg
    unlock
}
```

Threading and Synchronization Gotchas



- Simultaneous access & data races
  - Guard with locks if shared
- Single-instruction atomicity
  - `x += 1;`
  - Lock around anything that must look atomic
- Data atomicity
  - `struct Foo a = struct Foo b;`
- Data-race-free programs ONLY!

Pthreads Concepts: Threads

- In this course: Pthreads (POSIX Threads)
  - Shared memory, shared file pointers: need explicit synchronization
- Create: `pthread_create()`
- Join or detach: `pthread_join()`, `pthread_detach()`
- Exit: `pthread_exit()`

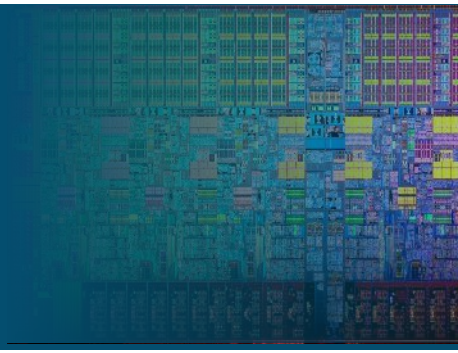
Pthreads Concepts: Mutices

- Mutex ("Mutual Exclusion"): `pthread_mutex()`
- Lock that can be used for exclusive access to any shared resource(s)
- Programmer defines what is protected
  - Programmer responsible for locking/unlocking around access to protected resource

Pthreads Concepts: Mutices

- Using a mutex
  - `pthread_mutex_lock(mutex)`
  - Use shared resources
  - `pthread_mutex_unlock(mutex)`
  - *Do not* use shared resource until lock is re-acquired

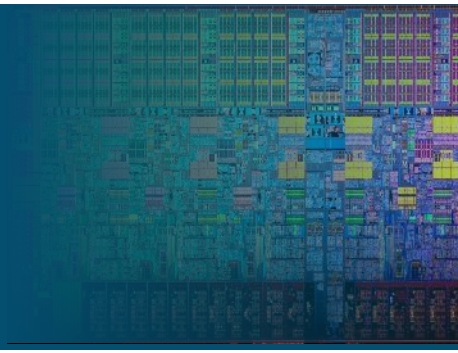
Pthread Concepts: Condition Variables



Threads	Mutices	Condition Variables	Semaphores

- `pthread_cond()`
- Synchronization based on data values
- Always used with mutex
- Replaces:
  1. Lock mutex
  2. Check value of data
  3. Unlock mutex, repeat.

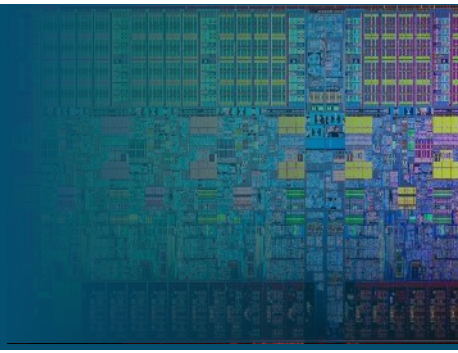
Pthread Concepts: Semaphores



- Counting mutex: `sem_init()`
- Atomically increase or decrease
- Sample use: communication management
  - `sem_post()` (atomically increment) when sending new message to receiver
  - `sem_wait()` (atomically decrement) to receive (or wait for) new message from sender

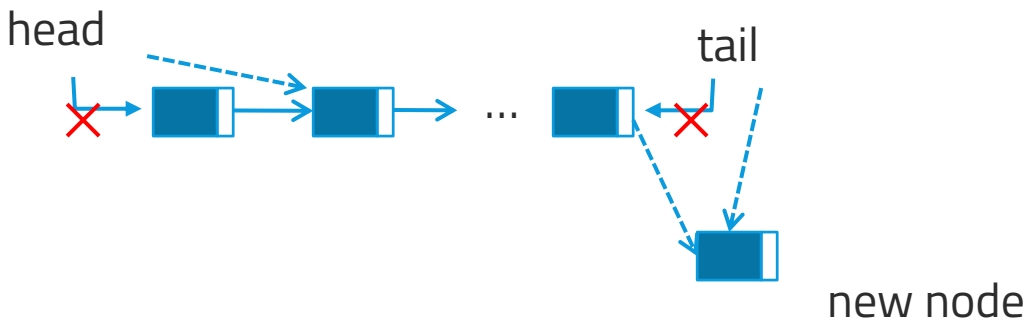
Building a Concurrent Queue

Building a ~~Concurrent~~ Queue



```
element dequeue():
  element = head.data
  head = head.next
  return element
```

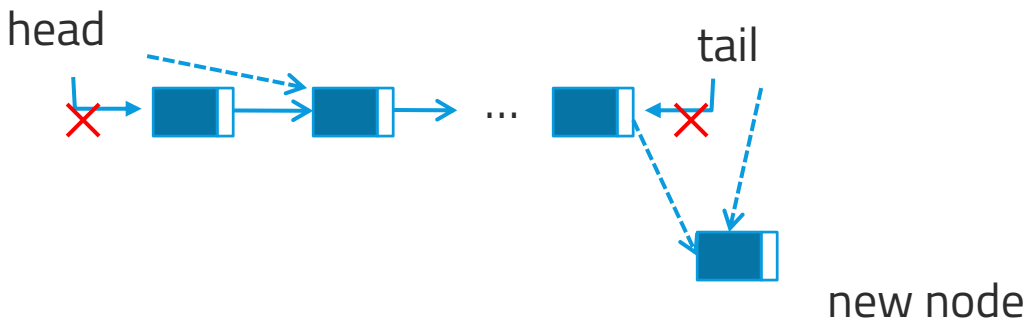
```
enqueue(element)
  n = new node(element)
  tail.next = n
  tail = n
```



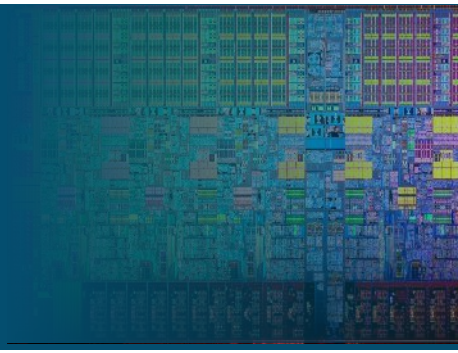
Building a Concurrent Queue

```
element dequeue():
  pthread_lock(queue_lock)
  element = head.data
  head = head.next
  pthread_unlock(queue_lock)
  return element
```

```
enqueue(element)
  pthread_lock(queue_lock)
  n = new node(element)
  tail.next = n
  tail = n
  pthread_unlock(queue_lock)
```

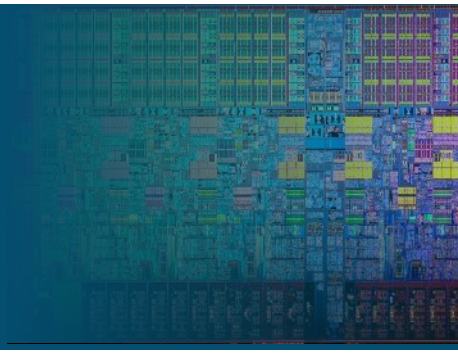


Invariants



- A way to reason about correctness.
- Queue consistency
  - To be consistent, a queue has to maintain certain properties throughout its lifetime
  - If the properties hold during the queue operations, then the queue is consistent
- What are the invariants that guarantee our queue consistency?

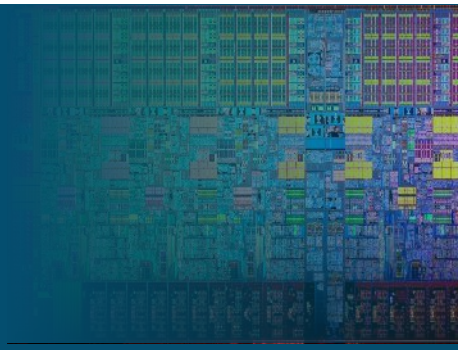
Handling the Empty Queue Case: Invariants



```
element dequeue():
  pthread_lock(queue_lock)
  while (empty):
    pthread_cond_wait(cond, queue_lock)

  // Inv: queue is not empty
  element = head.data
  head = head.next

  // Inv: either head=tail=NULL or !empty
  if head is NULL:
     tail = NULL
     empty = true

  pthread_unlock(queue_lock)
  return element
```

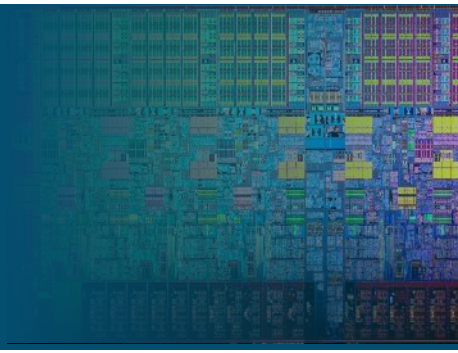
```
enqueue(element)
  pthread_lock(queue_lock)
  n = new node(element)
  if tail != NULL:
    tail.next = n
  tail = n

  // Inv: either !empty or head=tail=NULL
  empty = false
  pthread_cond_signal(cond)
  pthread_unlock(queue_lock)
```

Concurrent Queue Design Details



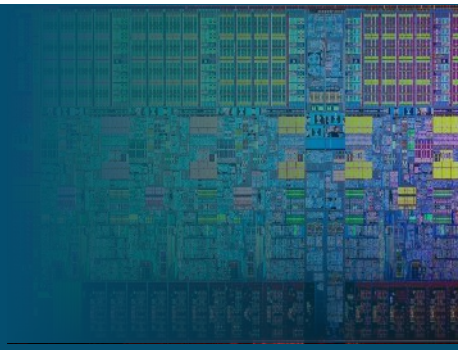
- Why do we wait with the lock taken? How can the signal code execute if signal is inside the lock?
  -
  -
- Why do we signal inside the lock?
  -
  -

Concurrent Queue Design Details



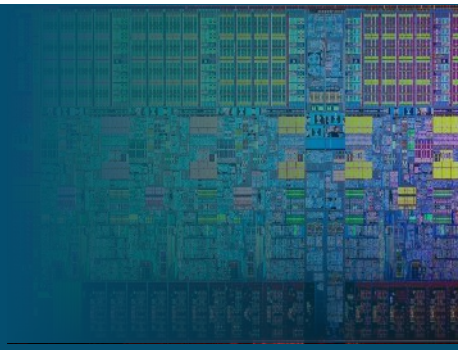
- Why do we wait with the lock taken? How can the signal code execute if signal is inside the lock?
  - The wait code releases the lock if the thread goes to sleep and the wakeup only proceeds if it manages to reacquire the lock.
  - If the lock was not taken, by the time we got outside the while loop, the predicate the condition is on may not be true any more.
- Why do we signal inside the lock?
  - We don't have to but it's strongly suggested you do
  - What we must do is never to change the predicate outside the lock (data-race-free, right?)

Concurrent Queue Design Details



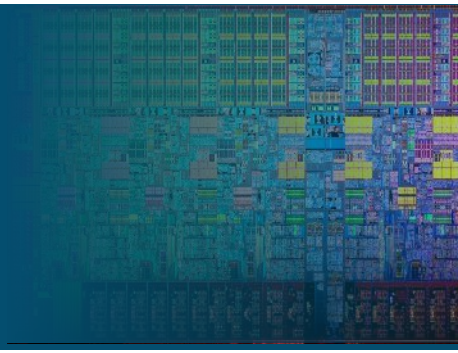
- Why did we signal at every enqueue? Isn't our condition based on the queue being non-empty?
  -
- Can we allow enqueue/dequeue in parallel (e.g., by using two locks instead of one)?
  -
  -

Concurrent Queue Design Details



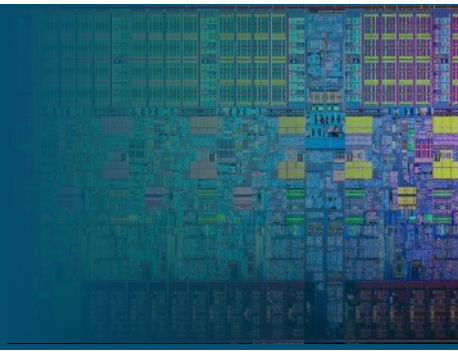
- Why did we signal at every enqueue? Isn't our condition based on the queue being non-empty?
  - We're waiting on every dequeue. Signal/wait here cannot "peek into" our predicate. Our code needs to make the checking of the predicate itself because of the semantics of cond vars.
- Can we allow enqueue/dequeue in parallel (e.g., by using two locks instead of one)?
  - No, enqueue and dequeue are sharing state
  - Yes, if we made them not share state (hint: use a sentinel)

Lab 1



- Semester-long (2.25-month) lab: building a threaded server
  - HTTP-like: GET and POST
- Will test your abilities with:
  - Sockets
  - Threads
  - Concurrent data structures

Lab 1



- Due: Thursday, October 13th
- Create a multithreaded O(1) key-value data structure
  1. Create the (thread-safe) data structure
  2. Create fixed number of workers to service requests
- Preview
  - Lab 2: Implement GET/POST frontend and thread pool
  - Lab 3: Add disk-based storage and cache
  - Lab 4: Implement a spinlock
  - Lab 5: Statistics