CSEP 524: Parallel Computation
(week 3)

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Tuesdays 6:30 – 9:20

MGH 231

Shameless Plug

- The Chapel team is looking to fill two internship positions this summer if someone you know is interested.

What We've Discussed

- Why parallelism matters
- A bunch of terminology
- Ways of measuring parallel performance
- How to create/join tasks in C+Pthreads and Chapel
- Block and Cyclic work distributions
- Hopefully you've seen speedup firsthand by now

What’s Next?

- At a high level:
  - Discussion/Diagnosis of behavior in Assignment #1
  - Having tasks coordinate with one another

Discussion of Assignment #1

Assignment #1 Discussion

Q1: What kinds of parallel resources did you find?

- who has highest-core count desktop?
- what larger-scale systems are available to you?
- what parallel programming models did you identify?

We should soon have access to a UW CSE 8x4-core VM-based platform for the class to share

Assignment #1 Discussion

Q4: What block distribution strategy did you use?

- e.g., when dividing 10 items by 4 tasks, did you use:
  - 3 3 2 2
  - 3 2 3 2
  - 2 3 2 3
  - 3 3 3 1
  - other?

Assignment #1 Discussion

Q5: What were your predictions?

- random vs. ramp
- negation vs. factorial
- block vs. cyclic
- number of tasks

- What were the biggest surprises?

- Did you see linear speedup?

Summary of Observations

Block Distribution

	random	ramp
negation *should be faster than factorial*		
factorial	should be faster than ramp because	

Cyclic Distribution

	random	ramp
negation		
factorial		

Parallel Programming is Hard

(you may or may not agree with this sentiment yet, but it’s true)

Keep track of your war stories this quarter

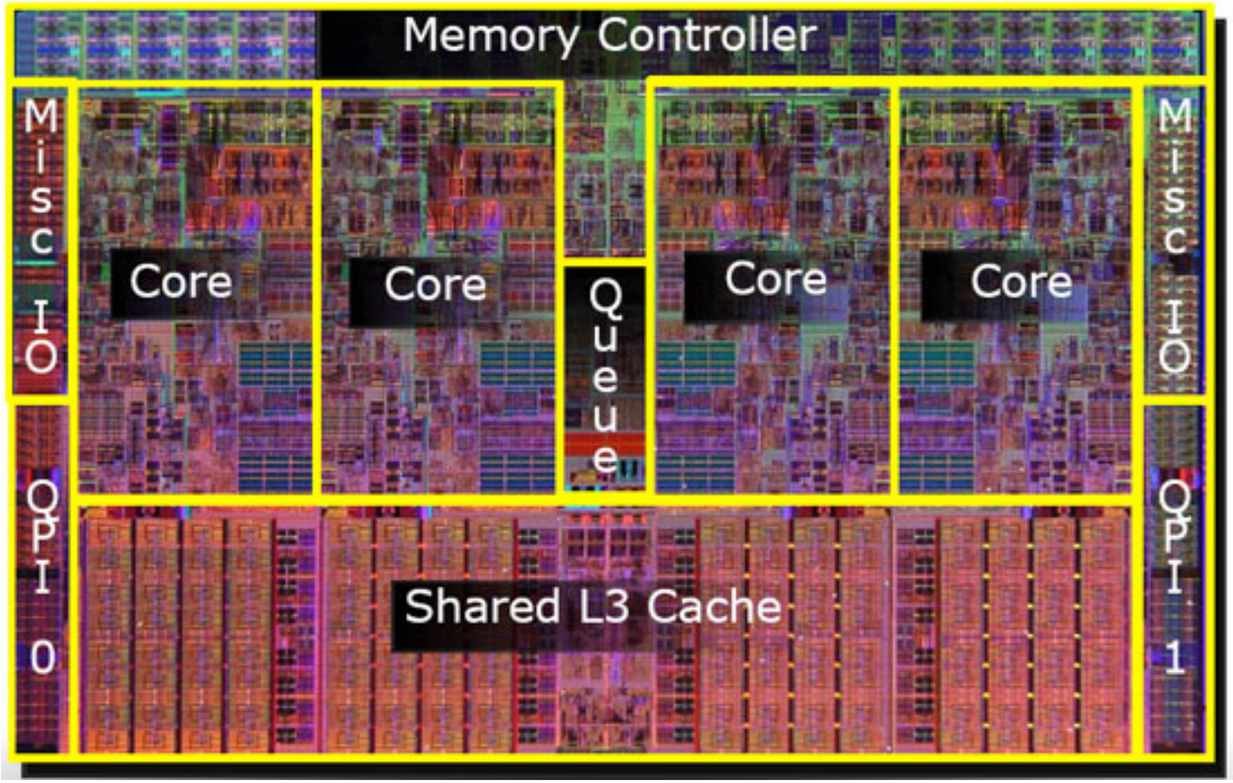
- for the purposes of classroom discussion
- because misery loves company

Two Performance Gotchas

Performance Gotcha #1: Memory

Issue #1: *Competition for Memory Locations*

- any time processors have non-shared caches there is the potential for them to compete for memory locations

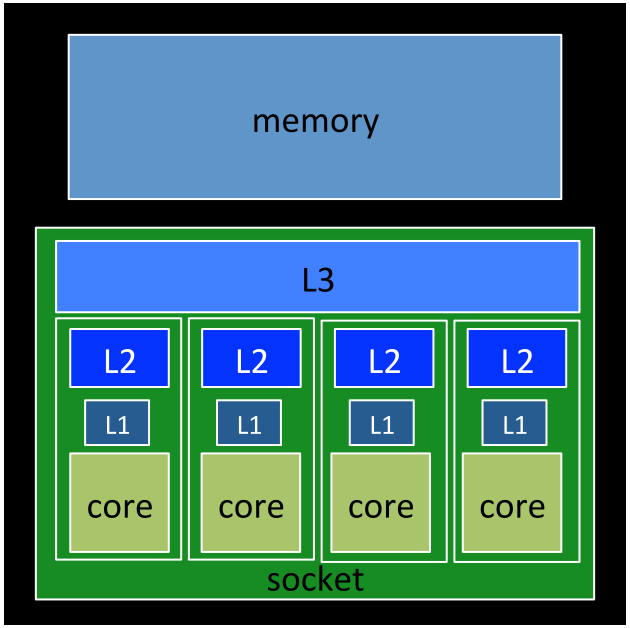


Source: http://www.legitreviews.com/article/1484/1/

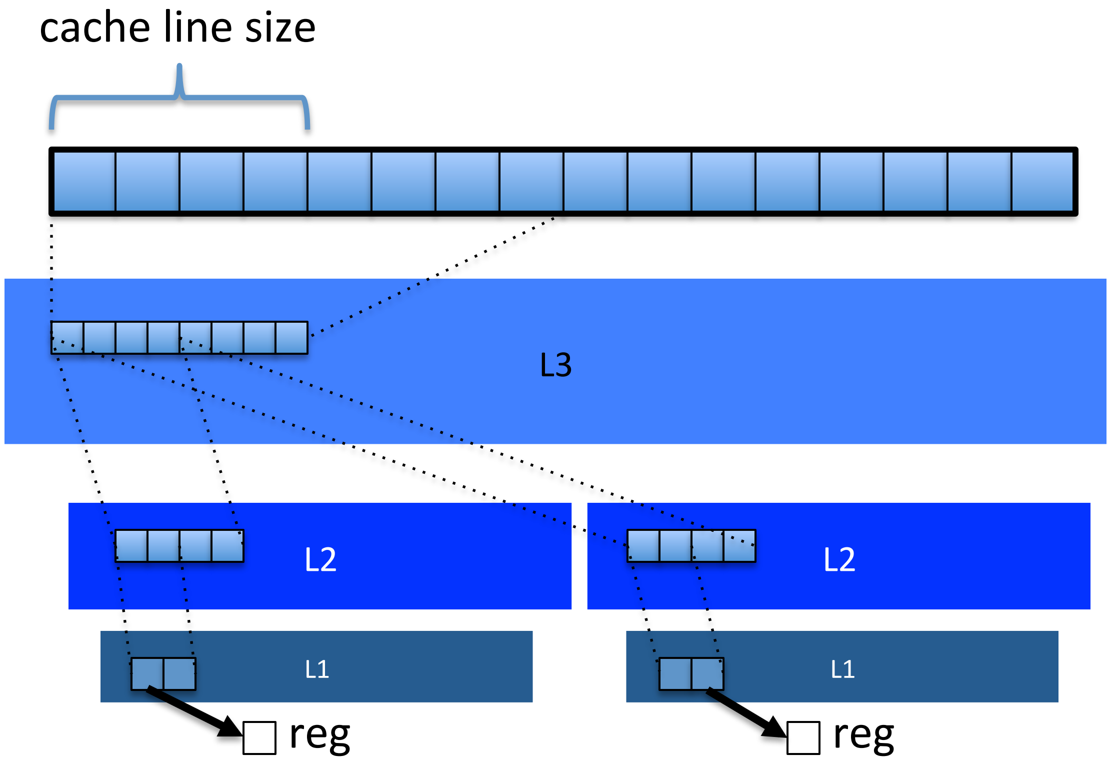
Performance Gotcha #1: Memory

Issue #1: *Competition for Memory Locations*

- any time processors have non-shared caches there is the potential for them to compete for memory locations
  - read-only accesses should not be an issue
  - once a task/core starts writing to a location, competition may ensue



Example: Competition For Memory



array negation using cyclic distribution:

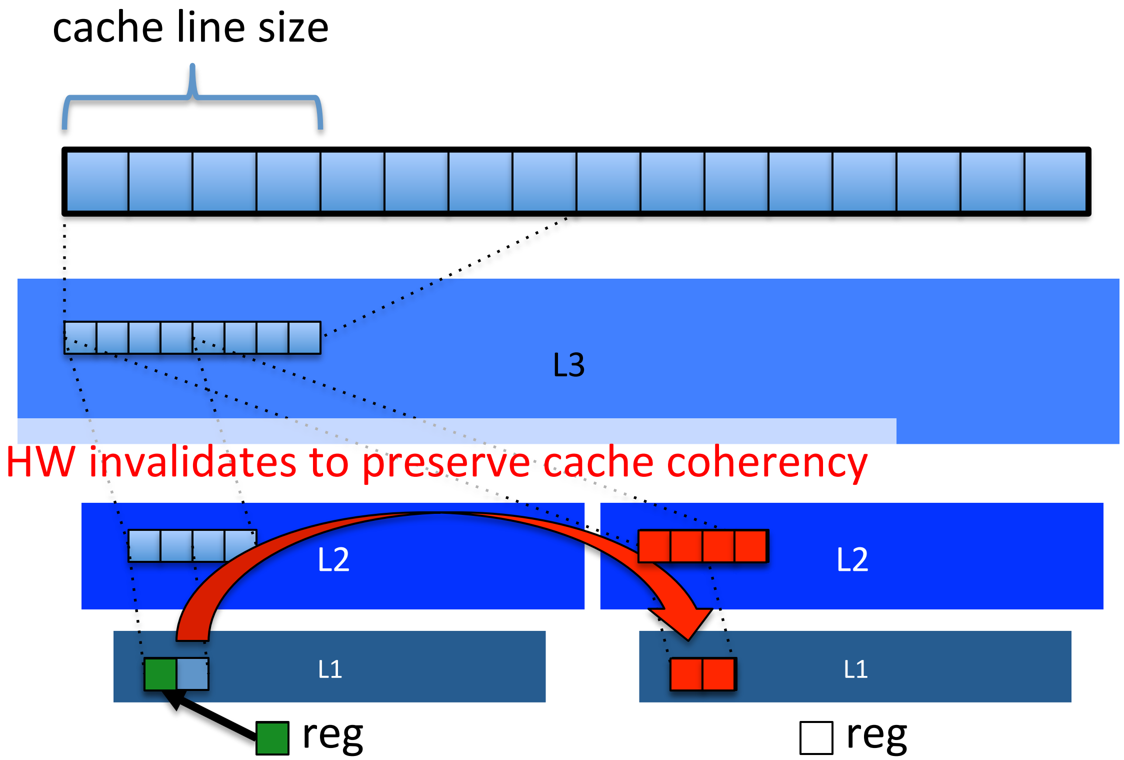
<u>Task 1</u>

```
→ reg = read A[0]
  reg = -reg
  A[0] = write reg
```

<u>Task 2</u>

```
→ reg = read A[1]
  reg = -reg
  A[1] = write reg
```

Example: Competition For Memory



HW invalidates to preserve cache coherency

array negation using cyclic distribution:

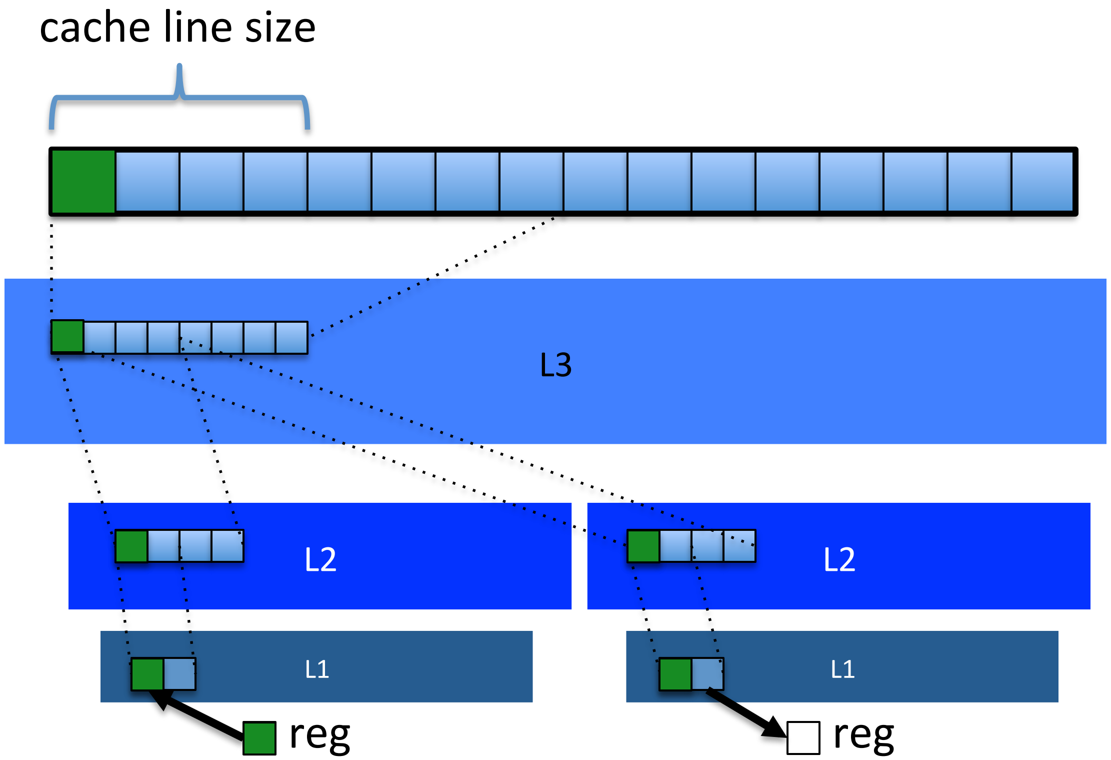
Task 1

```
   reg = read A[0]
➡  reg = -reg
➡  A[0] = write reg
```

Task 2

```
➡  reg = read A[1]
   reg = -reg
   A[1] = write reg
```

Example: Competition For Memory



array negation using cyclic distribution:

Task 1

```
reg = read A[0]
reg = -reg
A[0] = write reg
```

Task 2

```
reg = read A[1]
reg = -reg
A[1] = write reg
```

Definition: False Sharing

False Sharing: When cache lines must be invalidated not because two tasks are accessing the same data, but because they're accessing data on the same cache line

- in reality, the data is truly independent, hence "false"
- the details of the granularity at which data is stored within HW is what causes the interdependence ("sharing")
- NOTE: On cache coherent architectures, this is a performance issue, not a correctness issue
- ("true sharing" might be considered when two tasks actually access the same shared variable/data)

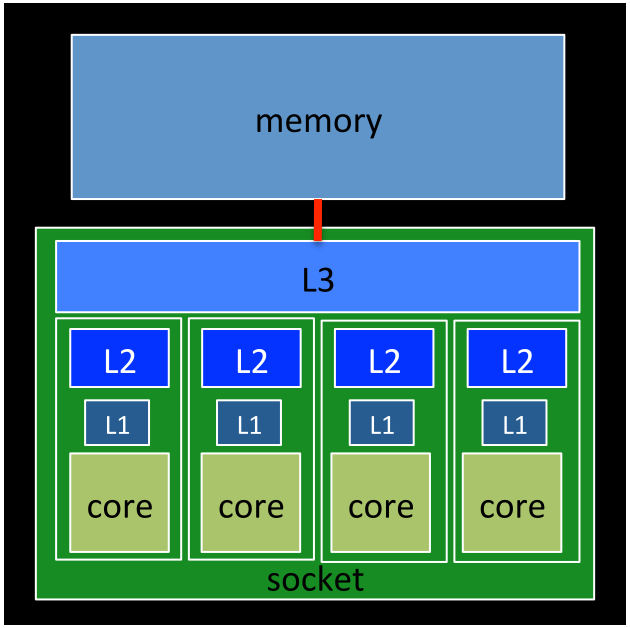
False Sharing Implications for Assignment #1

- Writing to an array using a cyclic distribution can result in performance impacts due to false sharing
  - possible fixes:
    - have each task 0 start its cyclic iteration from a skewed position
      - e.g., have task *t* starts from element *t* + *t***n/p*
      - but, results in more complex loop idioms due to need to wrap around
    - use padding/alignment pragmas to spread out array data
      - but, results in wasted space

Performance Gotcha #1: Memory

Issue #2: *Memory is a bottleneck*

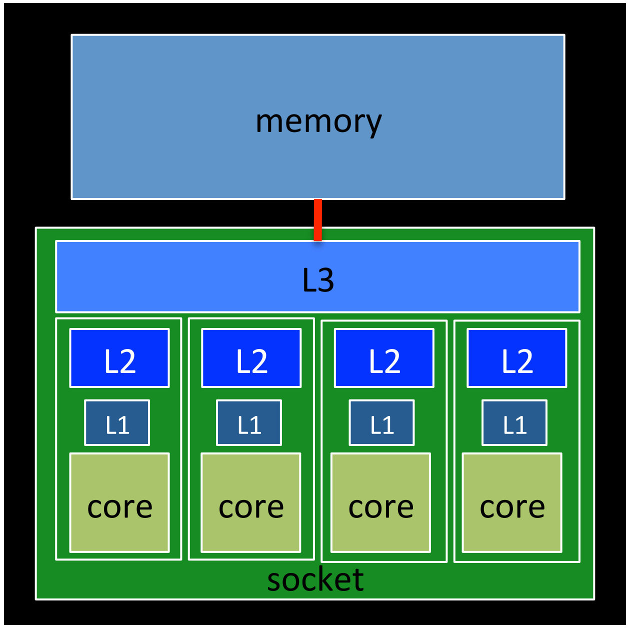
- typically, processors increase in speed faster than memory
- having multiple processors share memory doesn't help
  - there are only so many wires to access memory
  - cache coherence protocols also add overhead/complexity



Performance Gotcha #1: Memory

Issue #2: *Memory is a bottleneck*

- algorithms with more *computational intensity* can better amortize these memory overheads



Definition: Computational Intensity

Computational Intensity:

Definition: Computational Intensity

Computational Intensity: How much computation is performed per memory access

- high computational intensity: lots of OPS per load/store

  => memory performance is less of an issue

- low computational intensity: few OPS per load/store

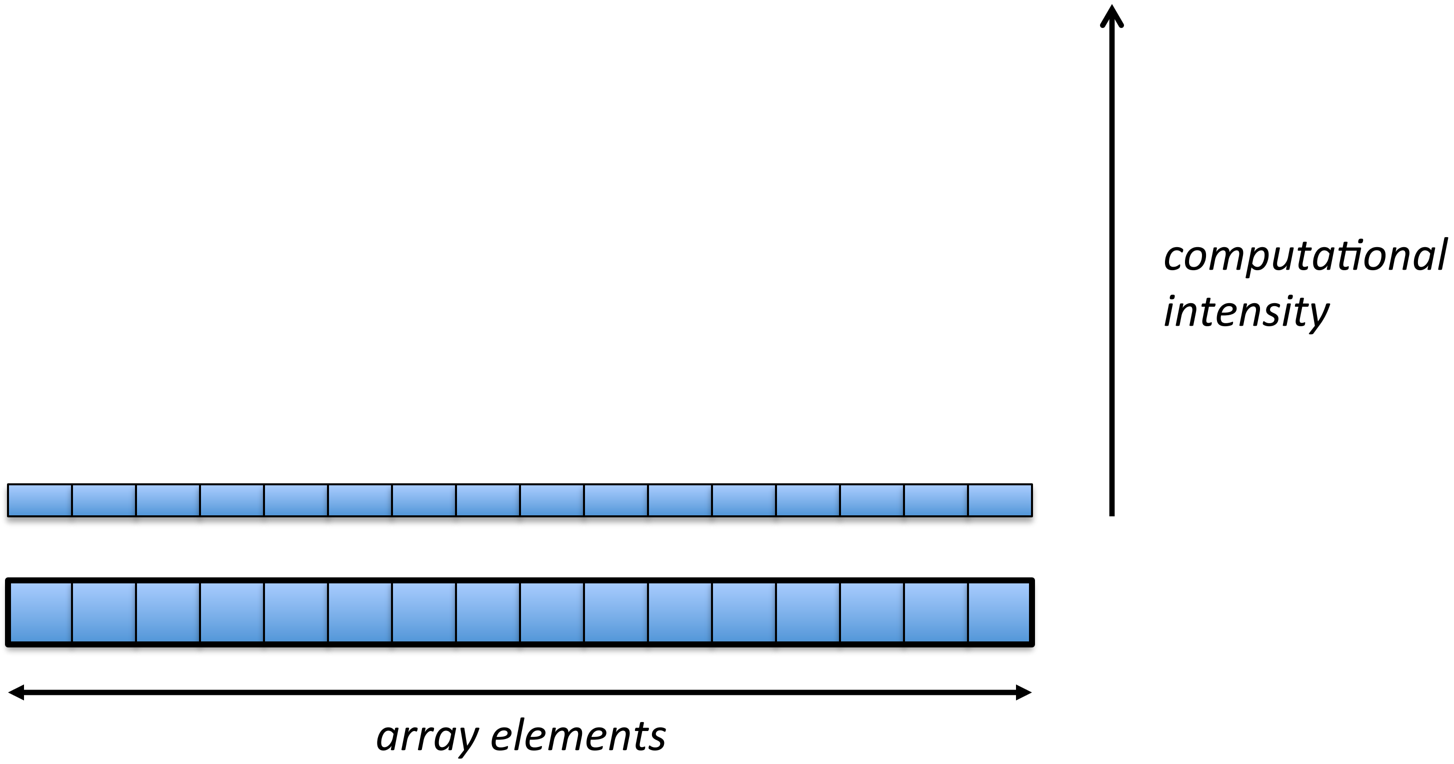
  => memory performance is more of an issue

Mem. Performance Implications for Assignment #1

- Computations with greater computational intensity should result in better speedup
  - e.g., factorial should speed up better than negation

Performance Gotcha #2: Load Balance

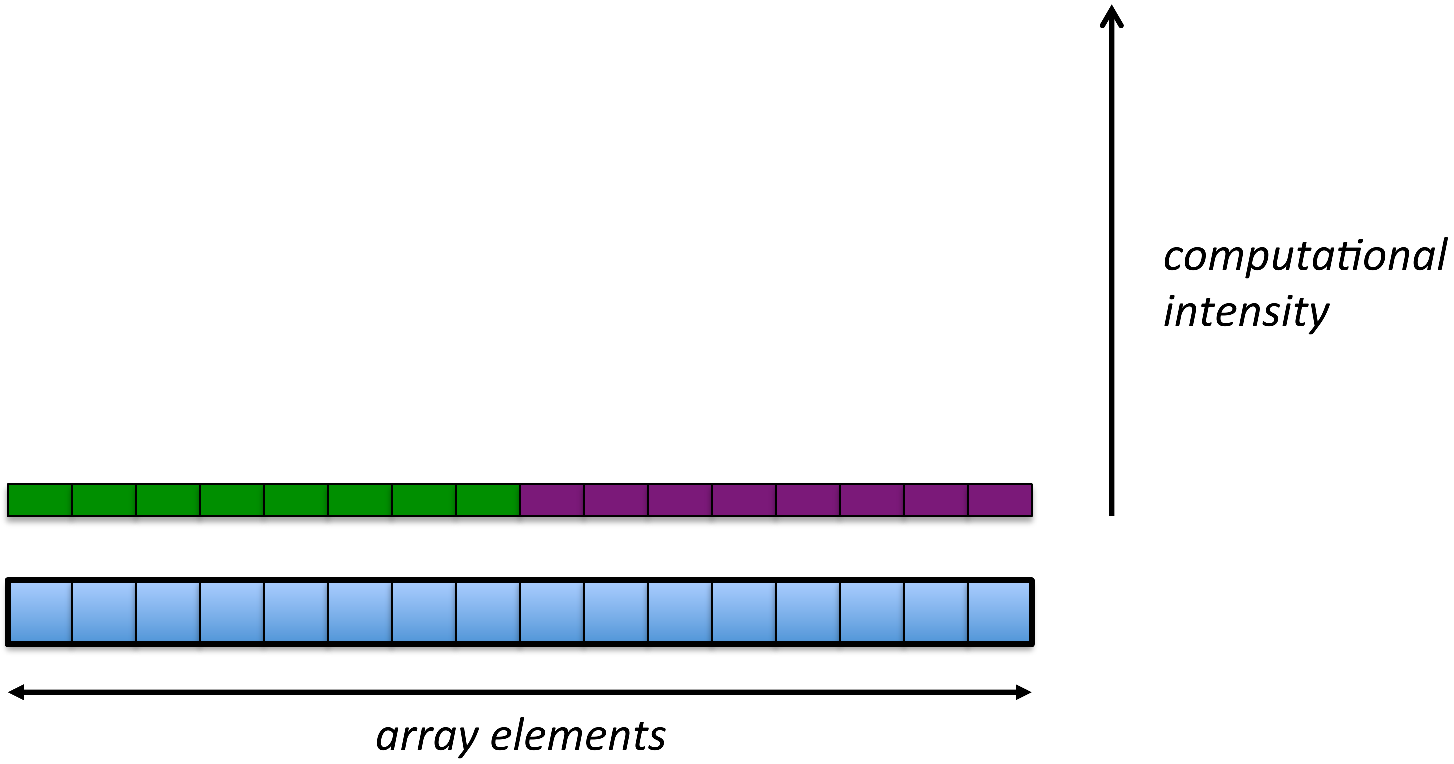
Negation + Ramp: Computational Intensity per Element



Performance Gotcha #2: Load Balance

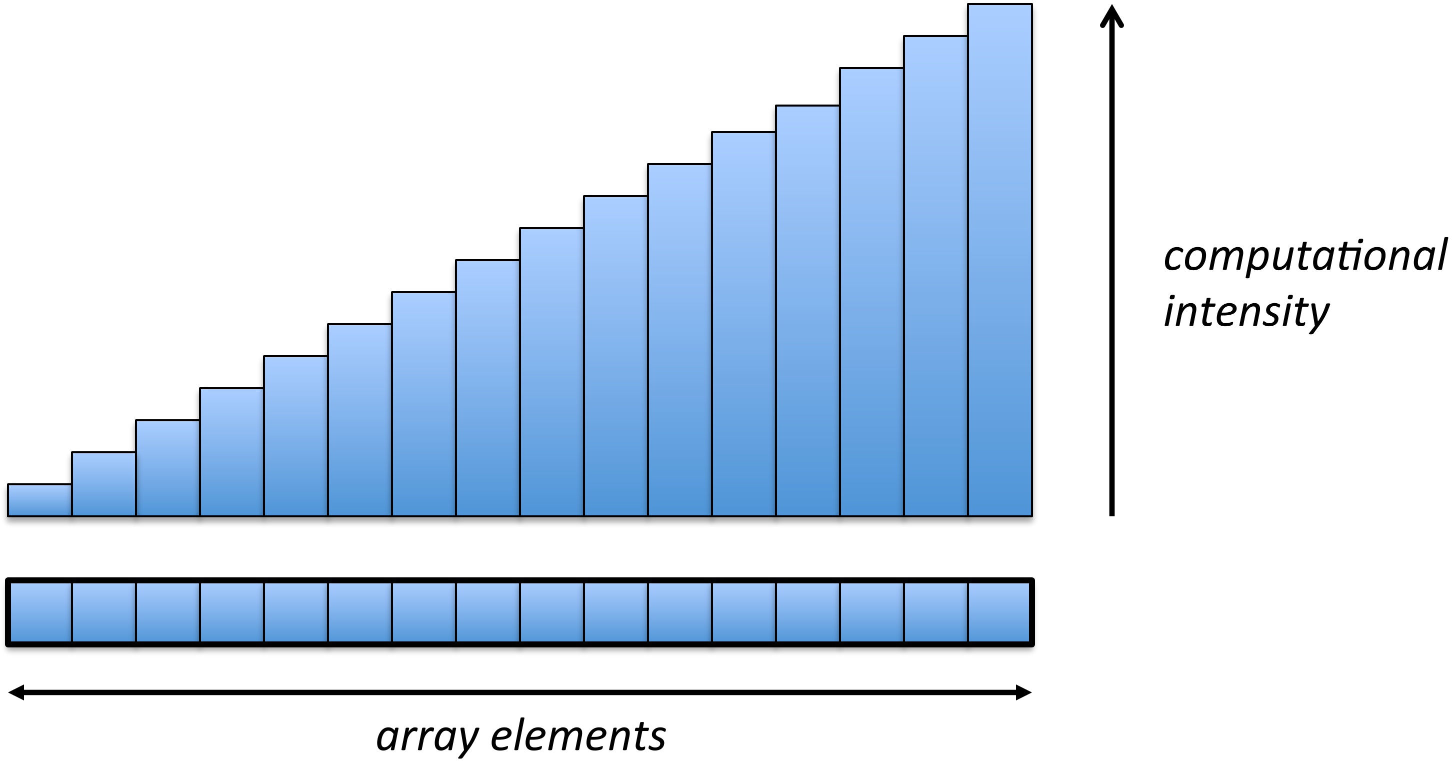
Negation + Ramp: Computational Intensity per Element

- Block distribution: green and purple have ~the same work



Performance Gotcha #2: Load Balance

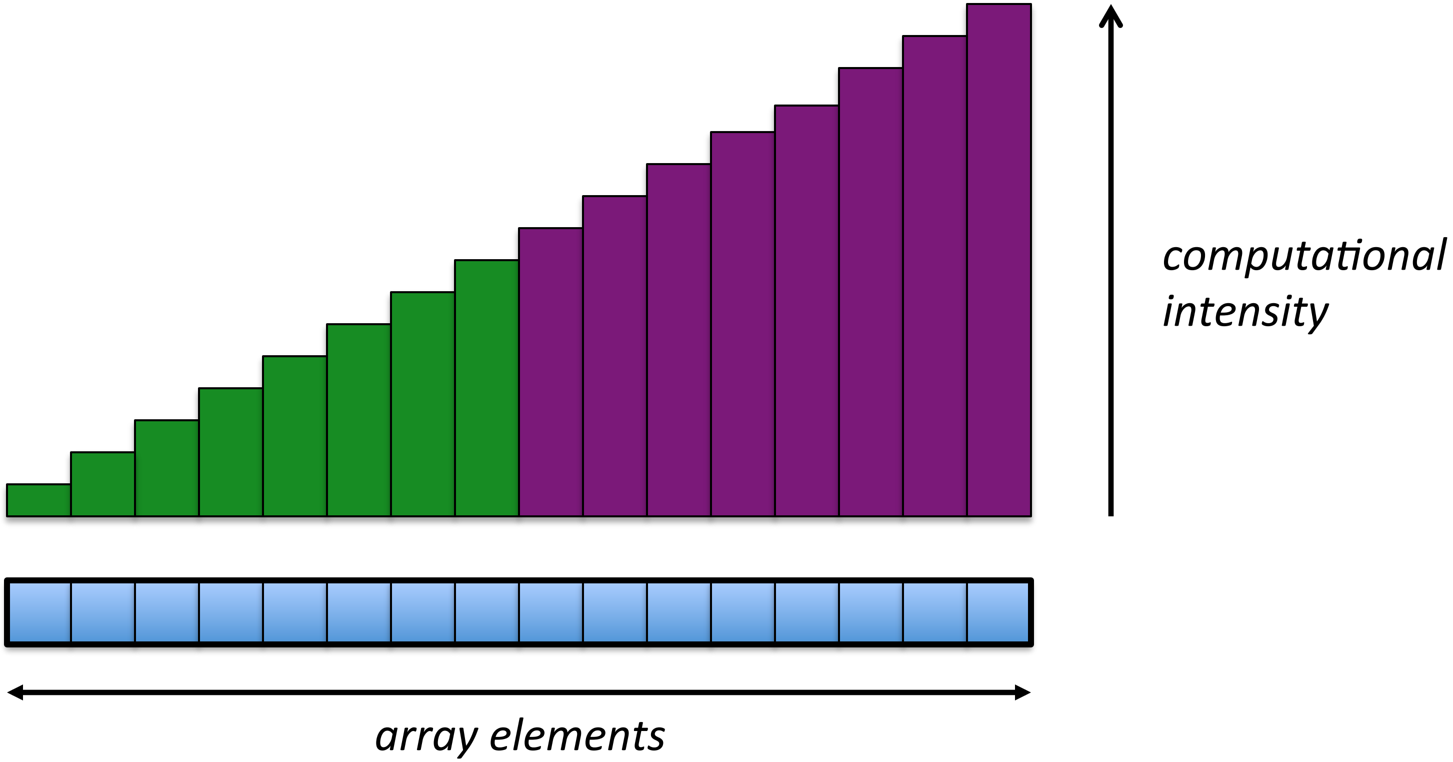
Factorial + Ramp: Computational Intensity per Element



Performance Gotcha #2: Load Balance

Factorial + Ramp: Computational Intensity per Element

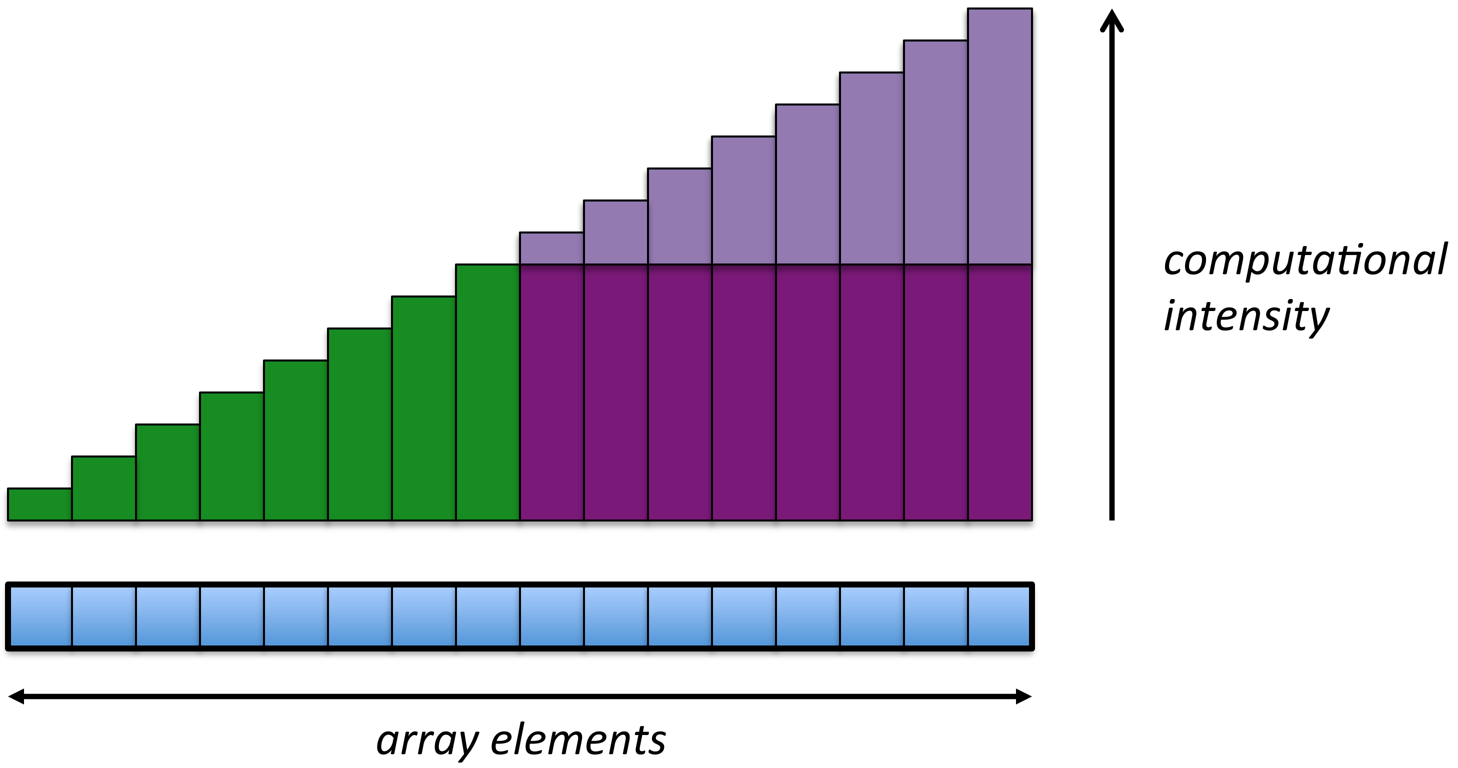
- Block Distribution



Performance Gotcha #2: Load Balance

Factorial + Ramp: Computational Intensity per Element

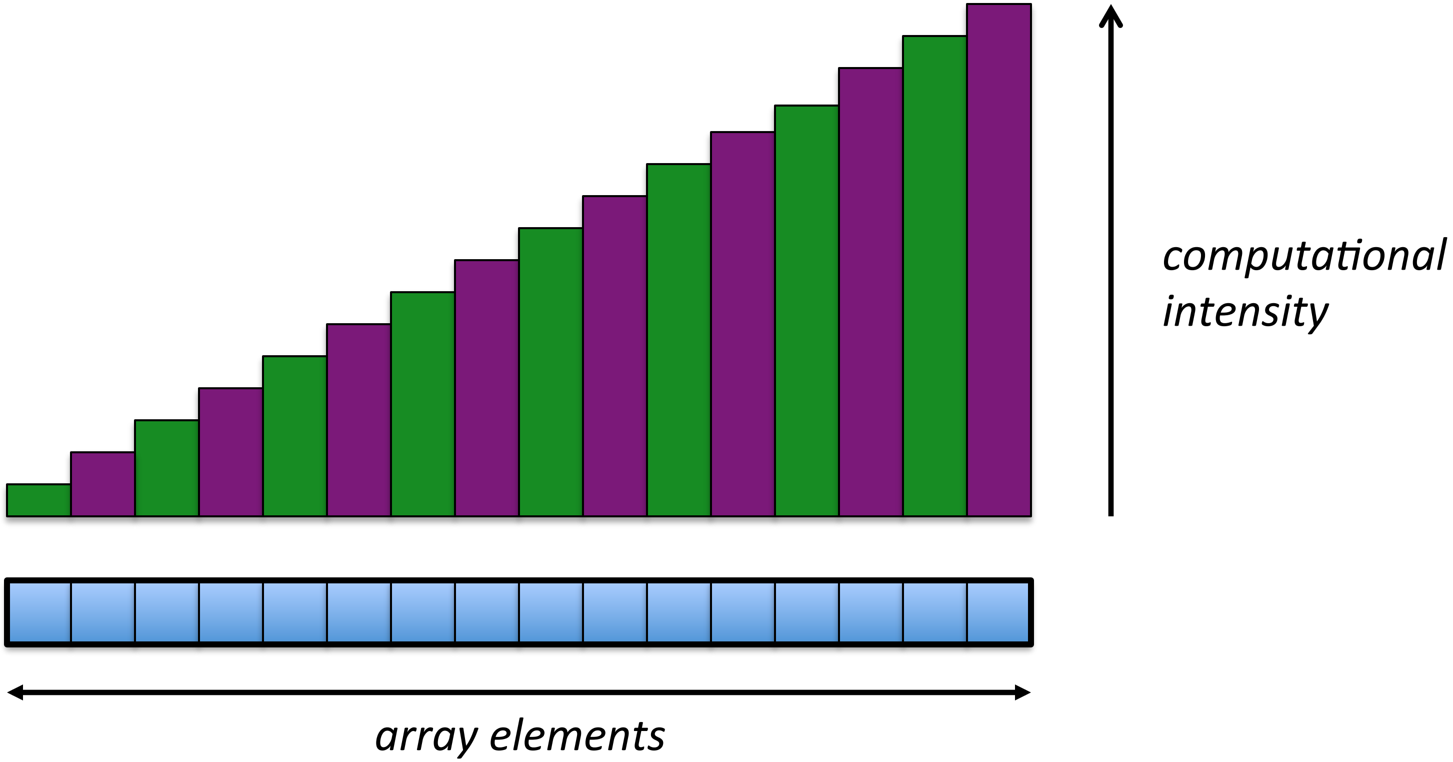
- Block Distribution: Purple has ~3x as much work as green



Performance Gotcha #2: Load Balance

Factorial + Ramp: Computational Intensity per Element

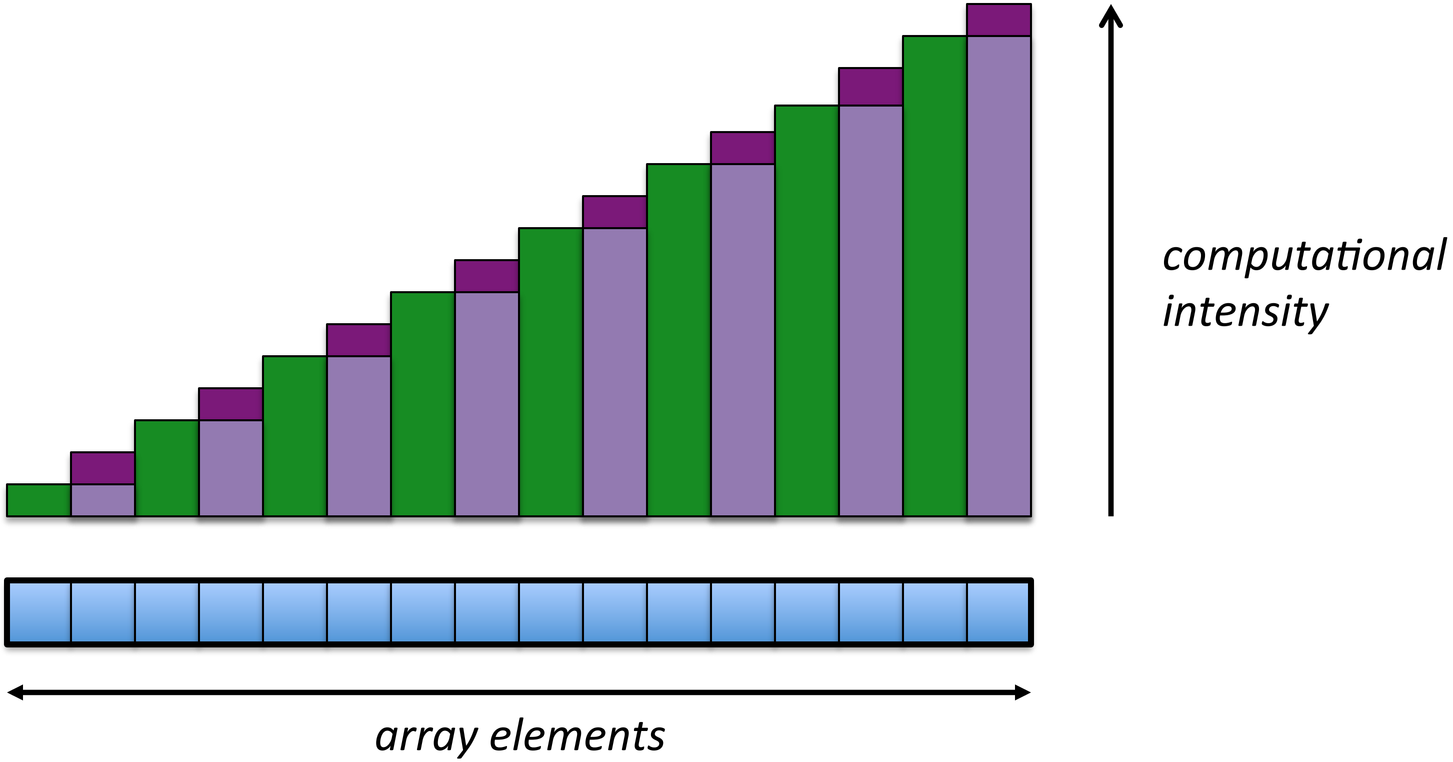
- Cyclic Distribution



Performance Gotcha #2: Load Balance

Factorial + Ramp: Computational Intensity per Element

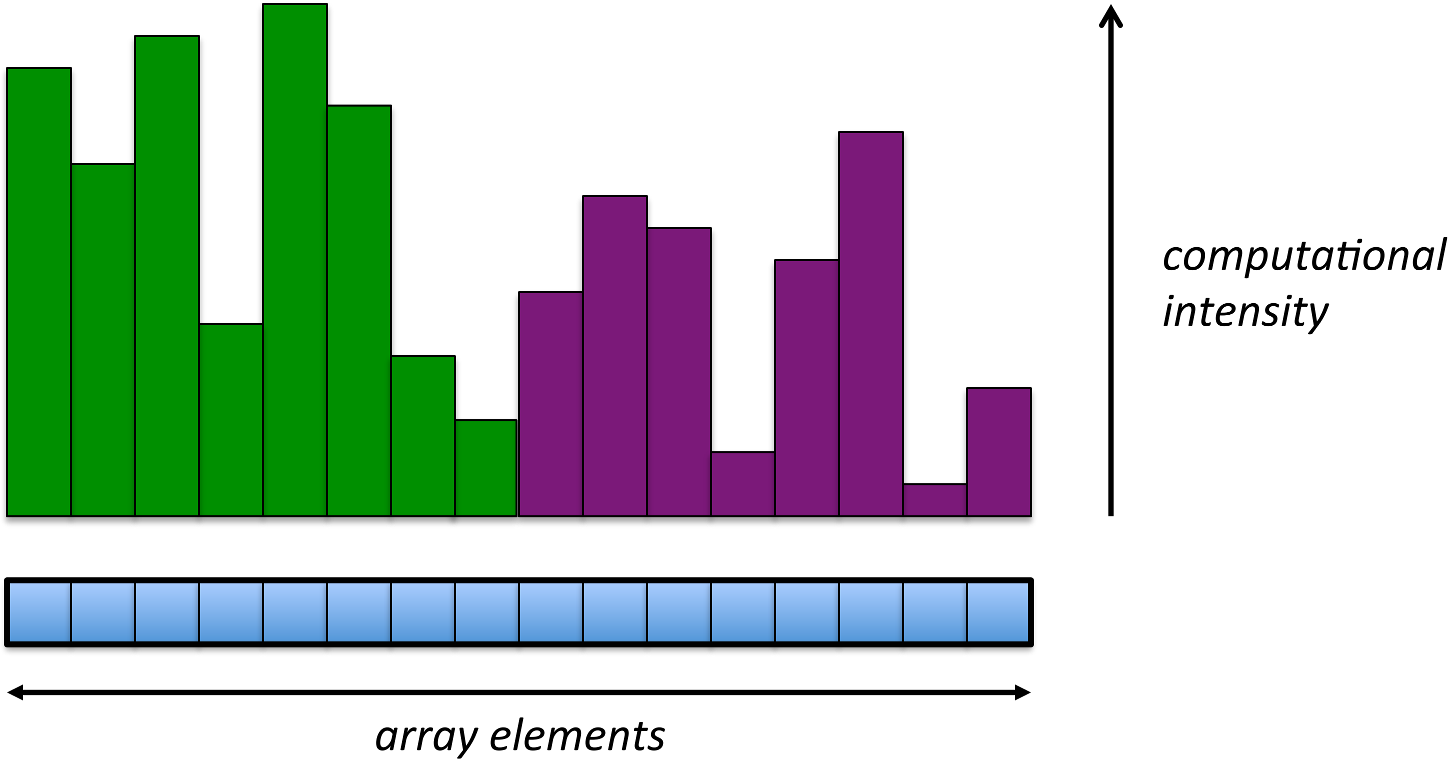
- Cyclic Distribution: Purple only has numItems/2 more work



Performance Gotcha #2: Load Balance

Factorial + Random:

- Block distribution: green has ~1.5x the work of purple
  - (for the data set shown)



Load Balance Implications for Assignment #1

- Block + factorial + ramp exhibits bad *load balance*
  - some tasks had significantly more work than others
  - cyclic/random input sets may result in better load balance

- Keep in mind that many algorithms must be written without knowing their input sets
  - i.e., can’t think “aha, my input will be a ramp so …”

Assignment #1 Debrief

- Who saw execution time behaviors similar to what I just described?
  - what kinds of things did you "do right" to get this result?
  - what kinds of issues did others do differently to not see it?
  - or perhaps, rather, what did you stumble across then fix?
    - measuring aggregate performance of all threads, not wallclock time

Assignment #1 Summary: Distributions

Block & Cyclic:

+ give each task a similar number of work items
+ reasonably easy to compute

Block:

+ results in good spatial locality (touches adjacent elements)
– can expose sensitivities to work distribution
  - as in ramp+factorial

Cyclic:

+ less likely to be sensitive to work distribution
– can result in false sharing issues

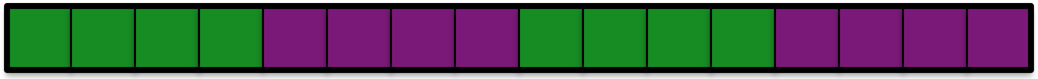
Time for a Break/Something Different?

Alternatives to Block and Cyclic

- Other distributions can help address the drawbacks of block and cyclic:
  - Block-Cyclic distribution
  - Dynamic distributions
  - Algorithmically-aware distributions

Distribution #3: Block-Cyclic Distribution

- As the name suggests, a hybrid of Block and Cyclic
  - deals blocks of items out cyclically
    - parameterized by block size, *b*
    - ideally, *b* should match or exceed cache line size
    - optimal choice of *b* often depends on algorithm, working set size, …



  - tradeoffs:
    - + gives tasks chunks of work (good spatial locality; less false sharing)
    - + like cyclic, results in probabilistically-oriented load balancing
    - – results in slightly more complicated loop nests

Dynamic Distributions

Concept:

- don't deal work out according to a fixed, *a priori* schedule
- instead, deal work out to tasks (or have them grab it) as they become idle

Goal:

- no task gets stuck with more work than it can handle

Challenge:

- what granularity (granularities?) to deal out work?
  - *if too large:* tasks may get unlucky and stuck with too much work
  - *if too small:* too much effort coordinating, not enough computing

Algorithmically-Aware Distributions

Concept:

- For some algorithms, there may be a way to scan the input data in order to compute a good distribution
  - e.g., dynamically sample the input data set to try and predict trends?
  - e.g., examine the placement of zeroes and non-zeroes in a sparse matrix?
  - e.g., compute a dependence graph for the computation and distribute it using a graph partitioning algorithm

Goal:

- use algorithmic-centric knowledge to improve load balance

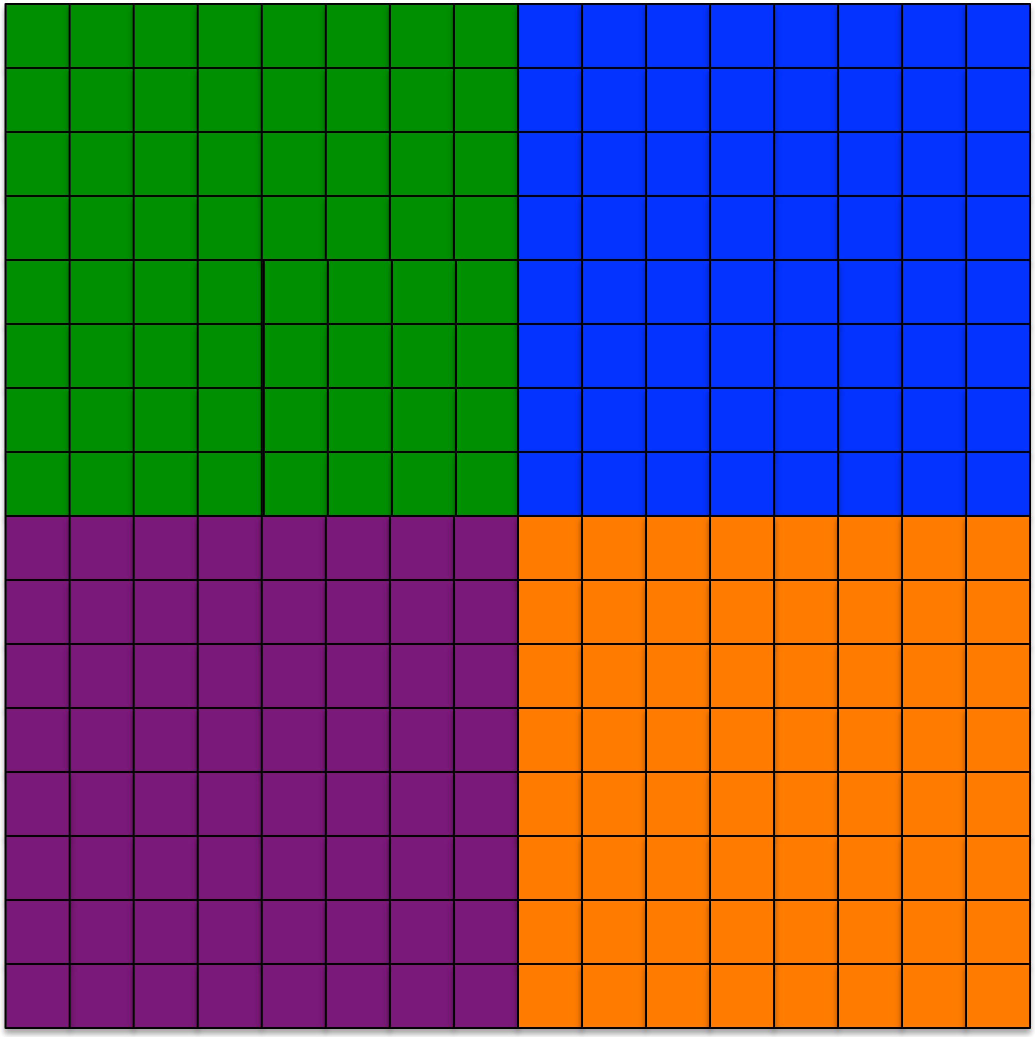
Challenge:

- Cost:Benefit ratio needs to be taken into account
  - since any overhead in computing a distribution is new work that wouldn't have been required in a serial version

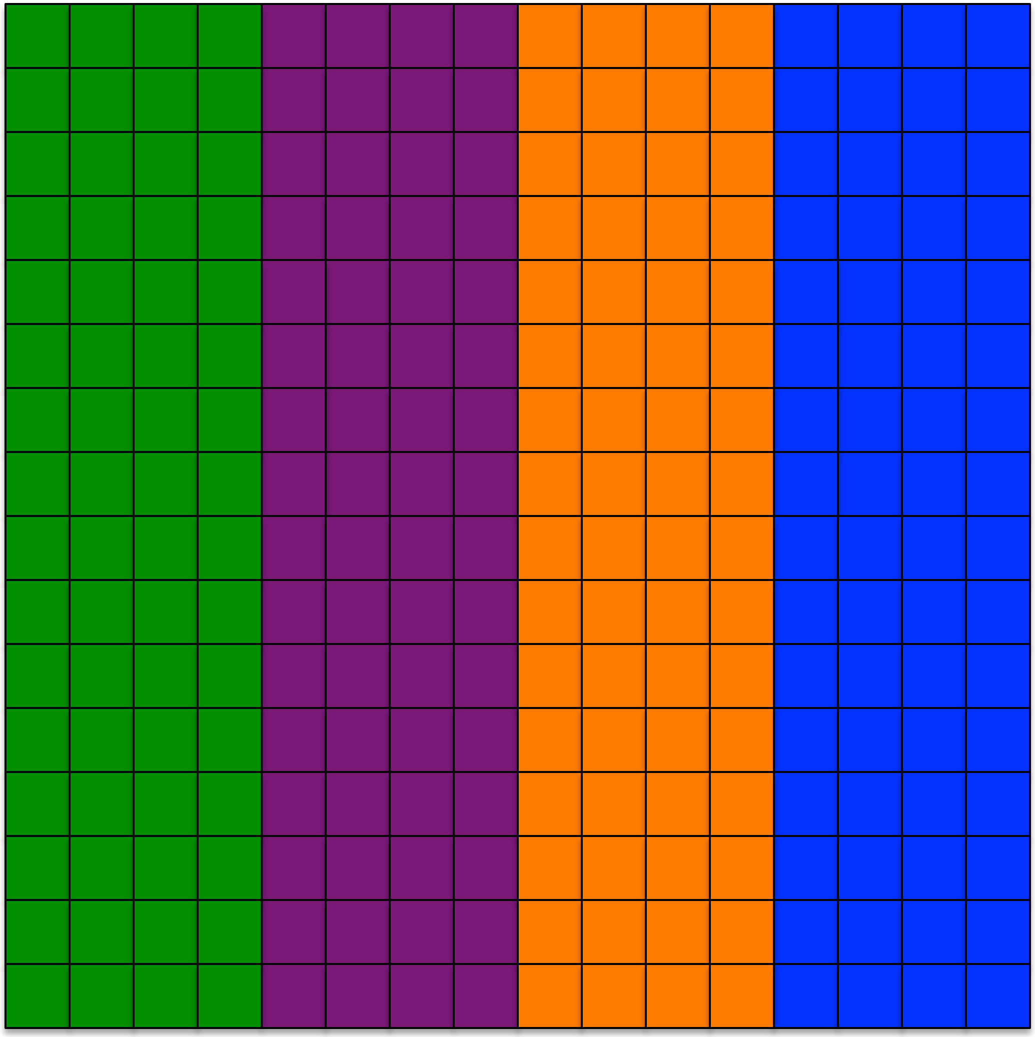
Multidimensional Distributions

- So far, we've looked solely at 1D distributions
- Distributions can also be multidimensional
  - one option is to apply a 1D distribution per dimension

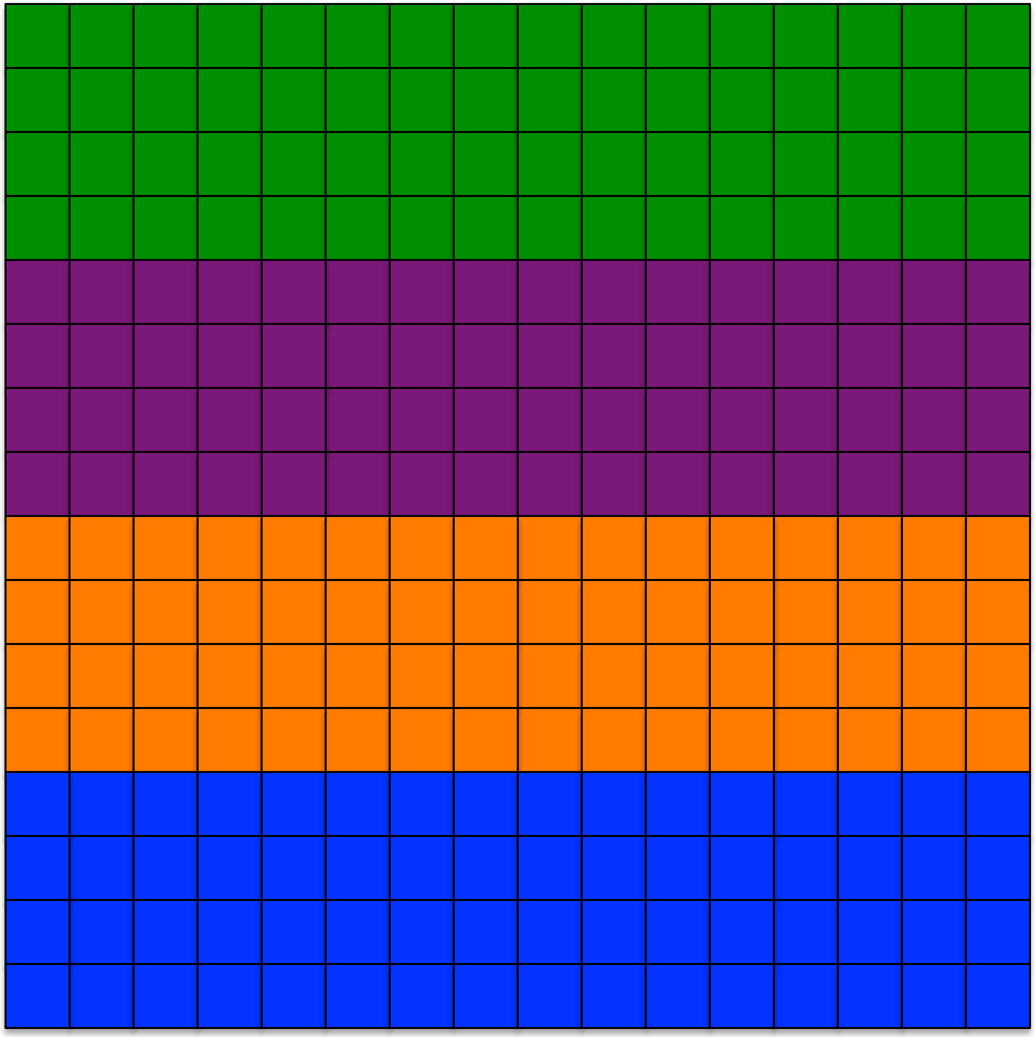
2D Block x Block (distributed to 2x2 tasks)



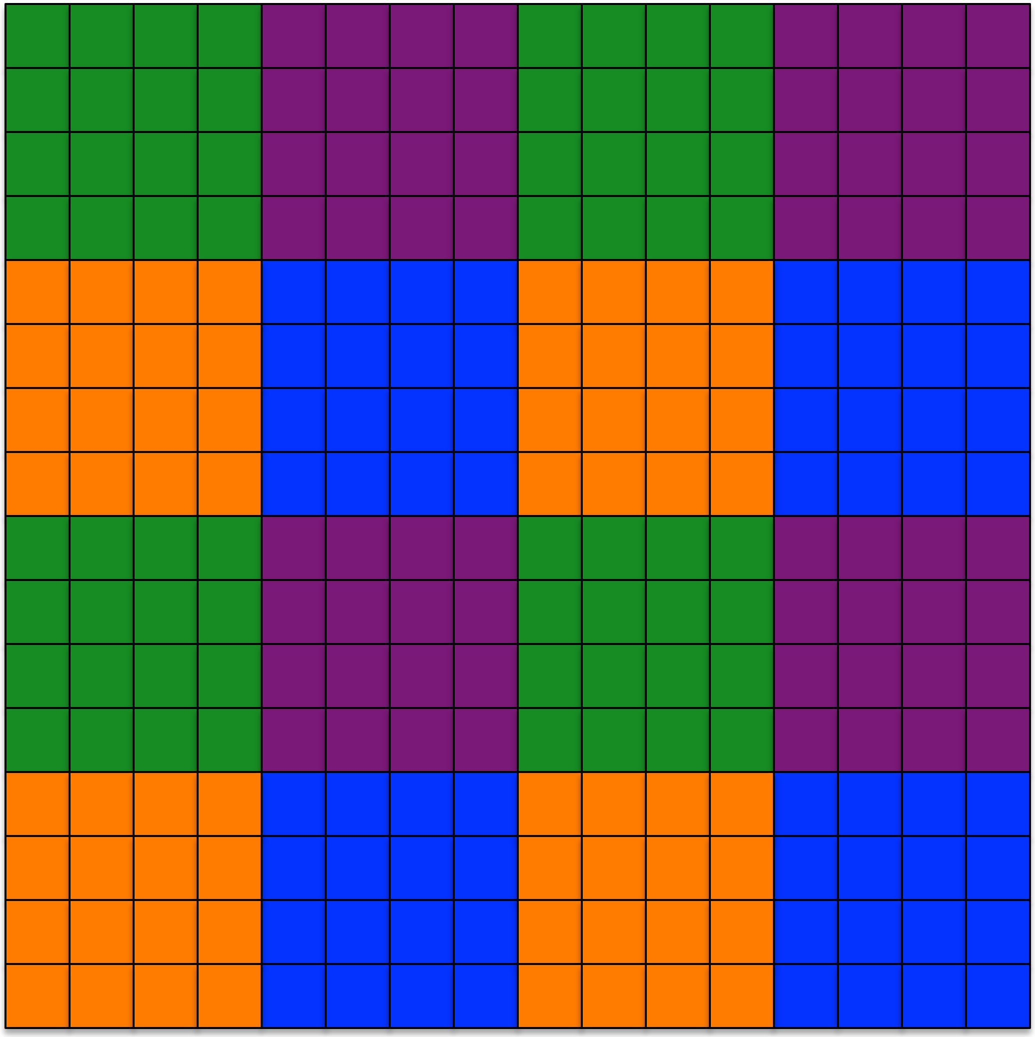
2D Block x Block (distributed to 1x4 tasks)



2D Block x Block (distributed to 4x1 tasks)



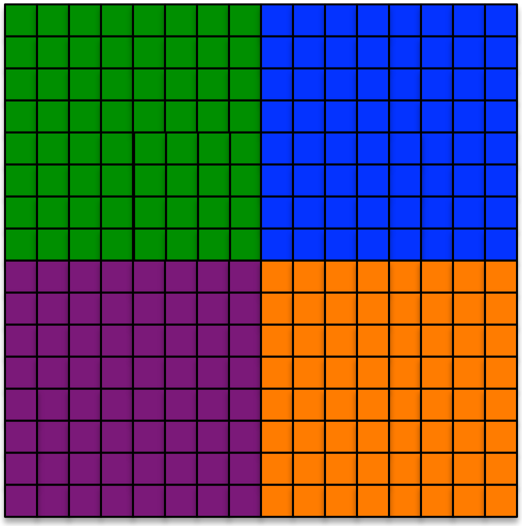
2D Block-Cyclic x Block-Cyclic (distributed to 2x2 tasks)

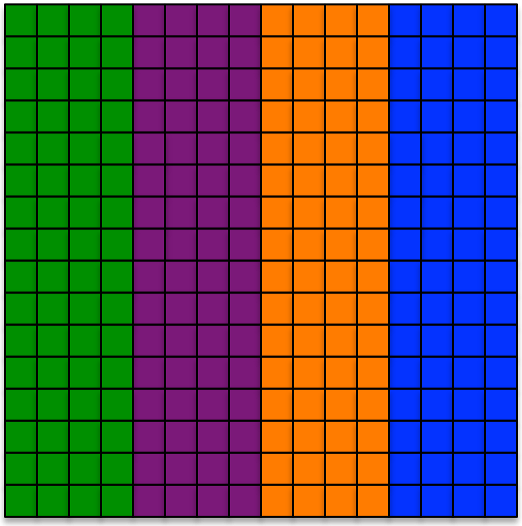


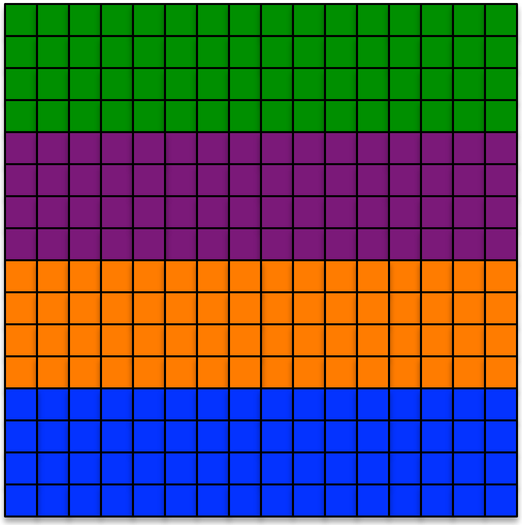
…and so on and so forth

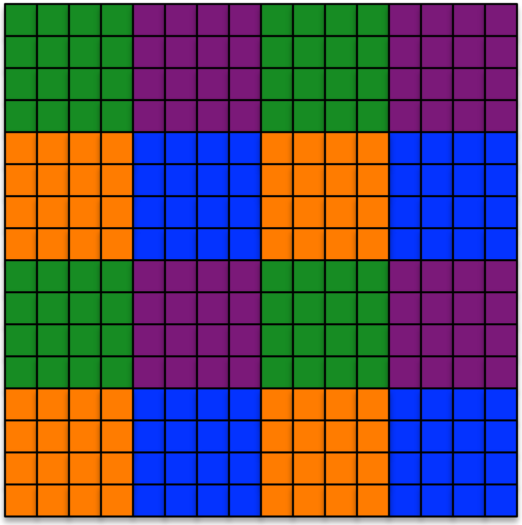
- Cyclic x Cyclic
- Block x Cyclic
- Cyclic x Block
- Block-Cyclic x Block-Cyclic with different block sizes
- Block-Cyclic x Block
- Block x Block-Cyclic
- etc.

Q: In a Shared-Memory setting, which would you use from the perspective of memory?





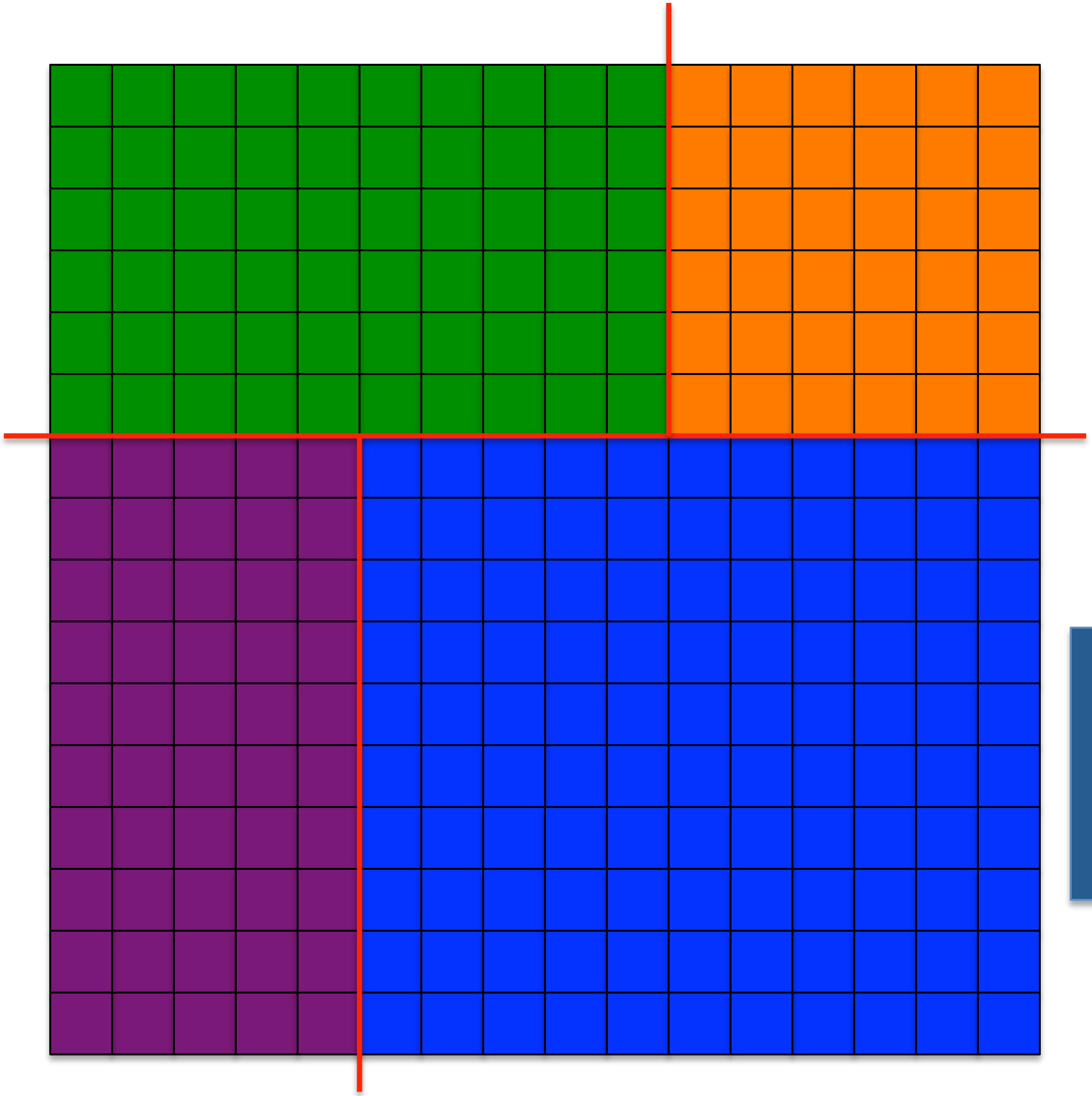




Multidimensional Distributions

- So far, we've primarily looked at 1D distributions
- Distributions can also be multidimensional
  - one option is to apply a 1D distribution per dimension
  - another is to distribute the items holistically

Holistic Distribution: Recursive Bisection



Note: Can't be expressed as the conflation of two 1D distributions

Multidimensional Distributions

- So far, we've primarily looked at 1D distributions
- Distributions can also be multidimensional
  - one option is to apply a 1D distribution per dimension
  - another is to distribute the items holistically

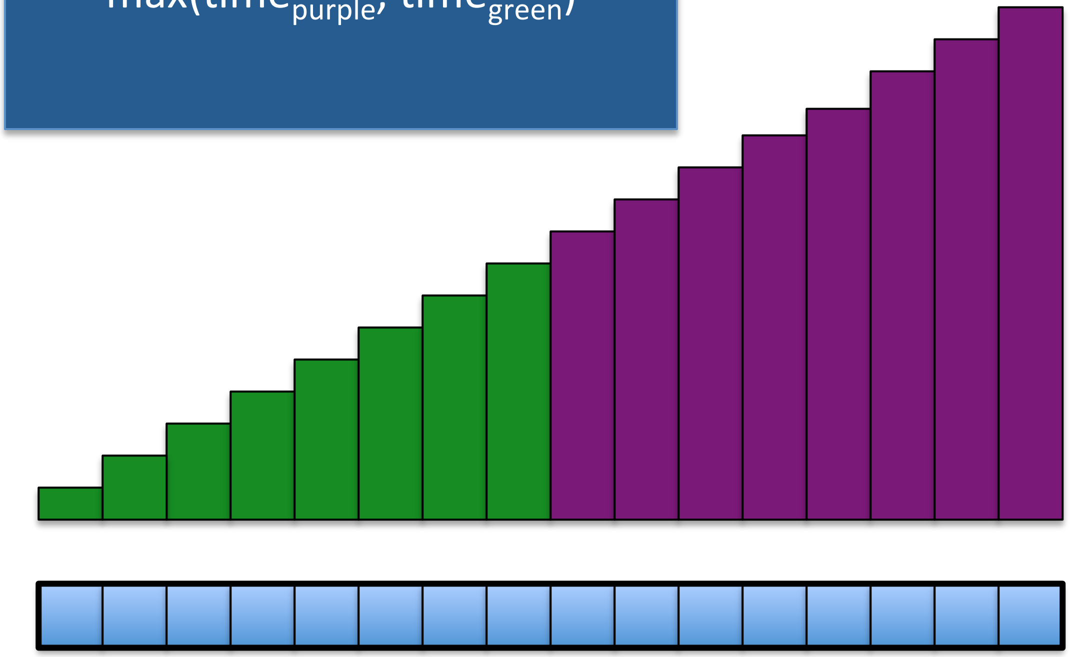
- Or, even unstructured (e.g., distribute a graph)
  - a topic for another day

Measuring Load Imbalance

- In assignment #1, we used the following pattern to measure the overall execution time of the code:

```
start timer
   create tasks
      do work
   join tasks
check timer
```

This essentially measured max($\text{time}_{\text{purple}}$, $\text{time}_{\text{green}}$)

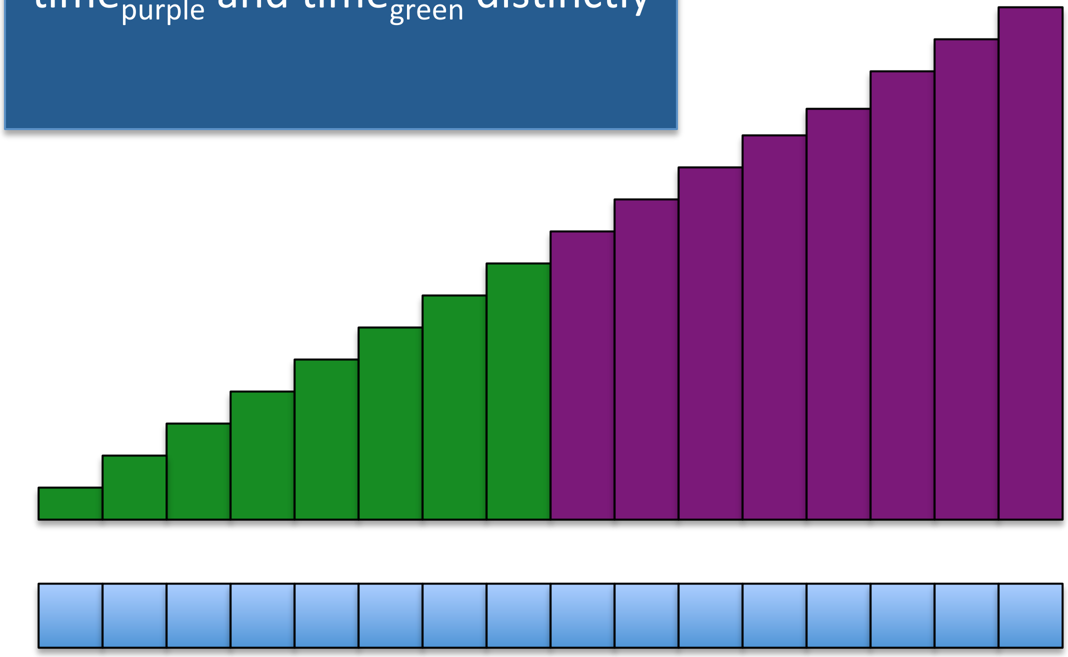


Measuring Load Imbalance

- Imagine instead, pushing the timing into the loop:

```
create tasks
  start timer
    do work
  check timer
join tasks
```

This permits us to measure $\text{time}_{\text{purple}}$ and $\text{time}_{\text{green}}$ distinctly



Measuring Load Imbalance

- Now, we can compute statistics on a task-by-task basis:

```
var totTime, maxTime = 0.0;
var minTime = max(real);
coforall tid in 0..#numTasks {
  start timer
    do work
  const myTime = check timer
  totTime += myTime;
  if myTime < minTime then minTime = myTime;
  if myTime > maxTime then maxTime = myTime;
}
const avgTime = totTime / numTasks;
```

What’s the bug in this code?

Bug of the week

- The previous slide contains a classic bug
  - Code that looks innocuous is actually problematic
  - Cause: reading parallel code as though it were sequential

```
coforall tid in 0..#numTasks {
  …
  totTime += myTime;
  …
}
```

Task 1

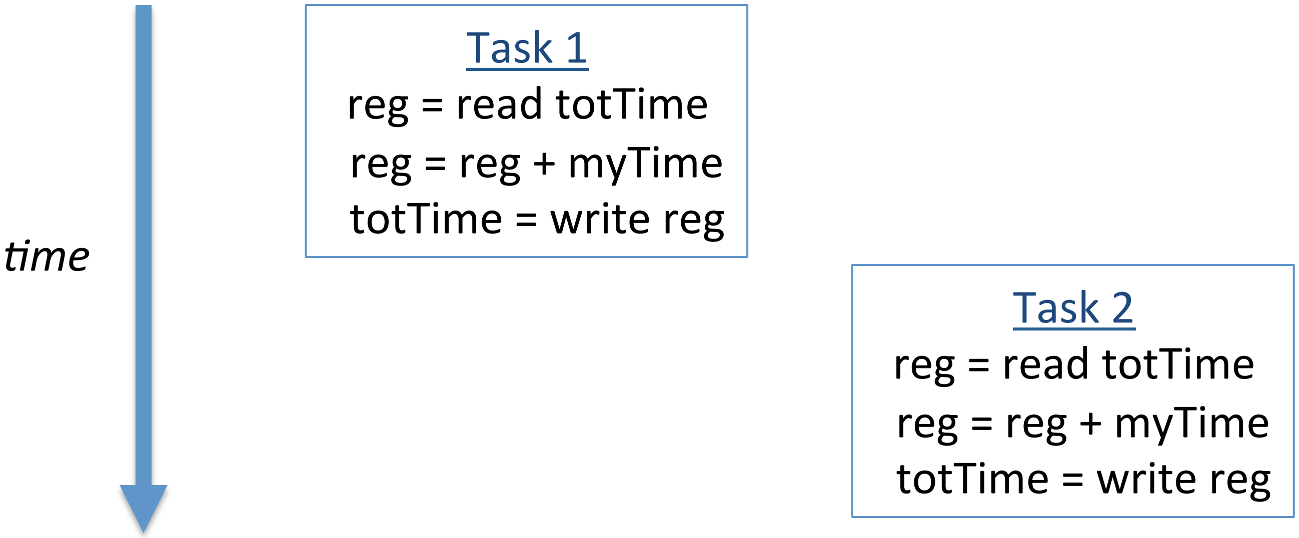
reg = read totTime
reg = reg + myTime
totTime = write reg

Task 2

reg = read totTime
reg = reg + myTime
totTime = write reg

Bug of the week

- Whether or not this bug exhibits itself depends on the scheduling of the tasks
  - the following schedule would be fine:



time

Task 1

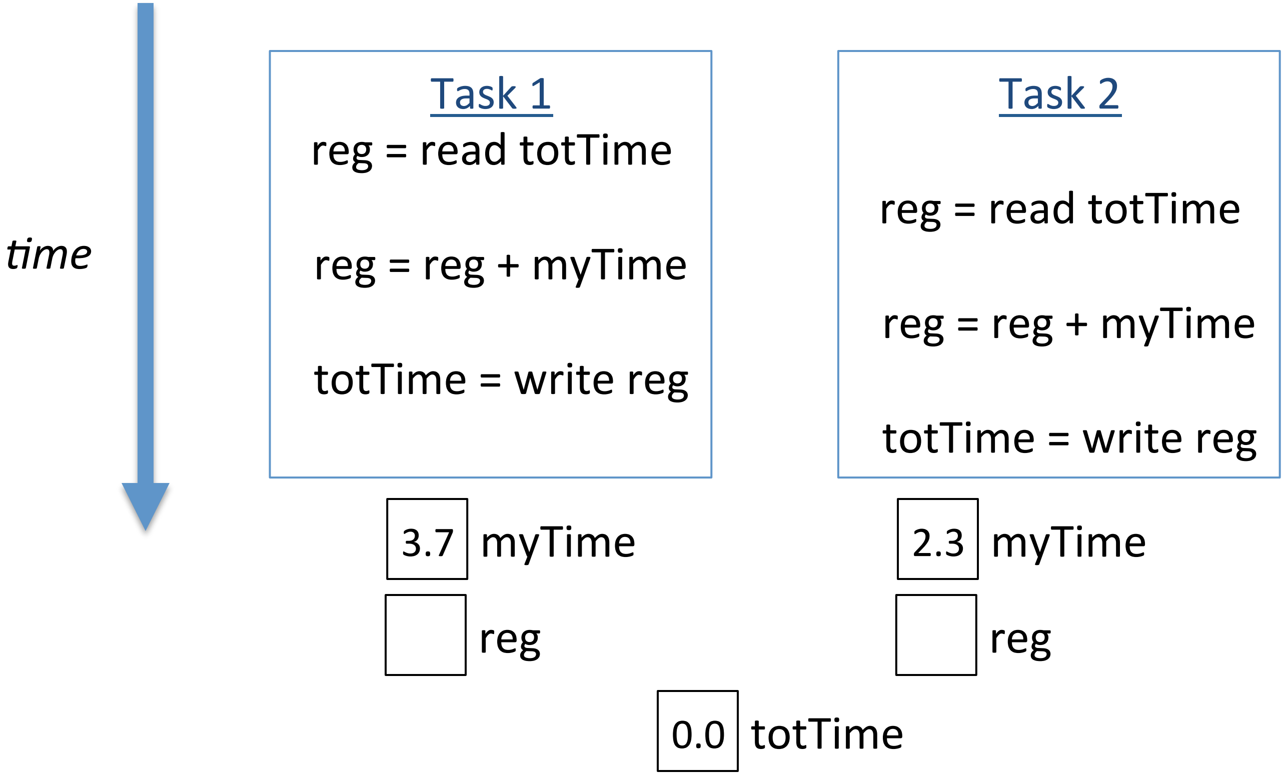
```
reg = read totTime
reg = reg + myTime
totTime = write reg
```

Task 2

```
reg = read totTime
reg = reg + myTime
totTime = write reg
```

Bug of the week

- Whether or not this bug exhibits itself depends on the scheduling of the tasks
  - the following schedule is problematic:



time

Task 1

reg = read totTime

reg = reg + myTime

totTime = write reg

Task 2

reg = read totTime

reg = reg + myTime

totTime = write reg

3.7 myTime

reg

2.3 myTime

reg

0.0 totTime

Bug of the week

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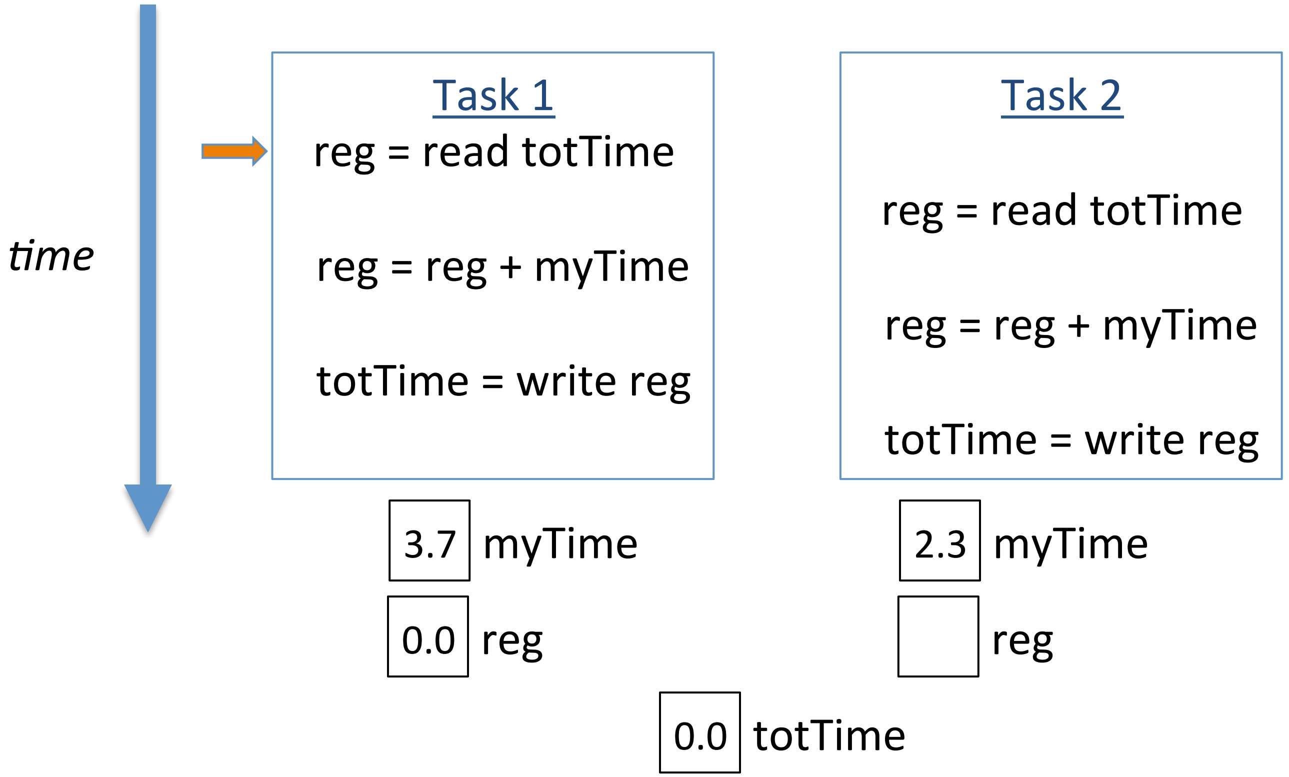
  - the following schedule is problematic:



time

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totTime = write reg

Task 2

reg = read totTime

reg = reg + myTime

totTime = write reg

Task 1		Task 2	
3.7	myTime	2.3	myTime
0.0	reg		reg

0.0 totTime

Bug of the week

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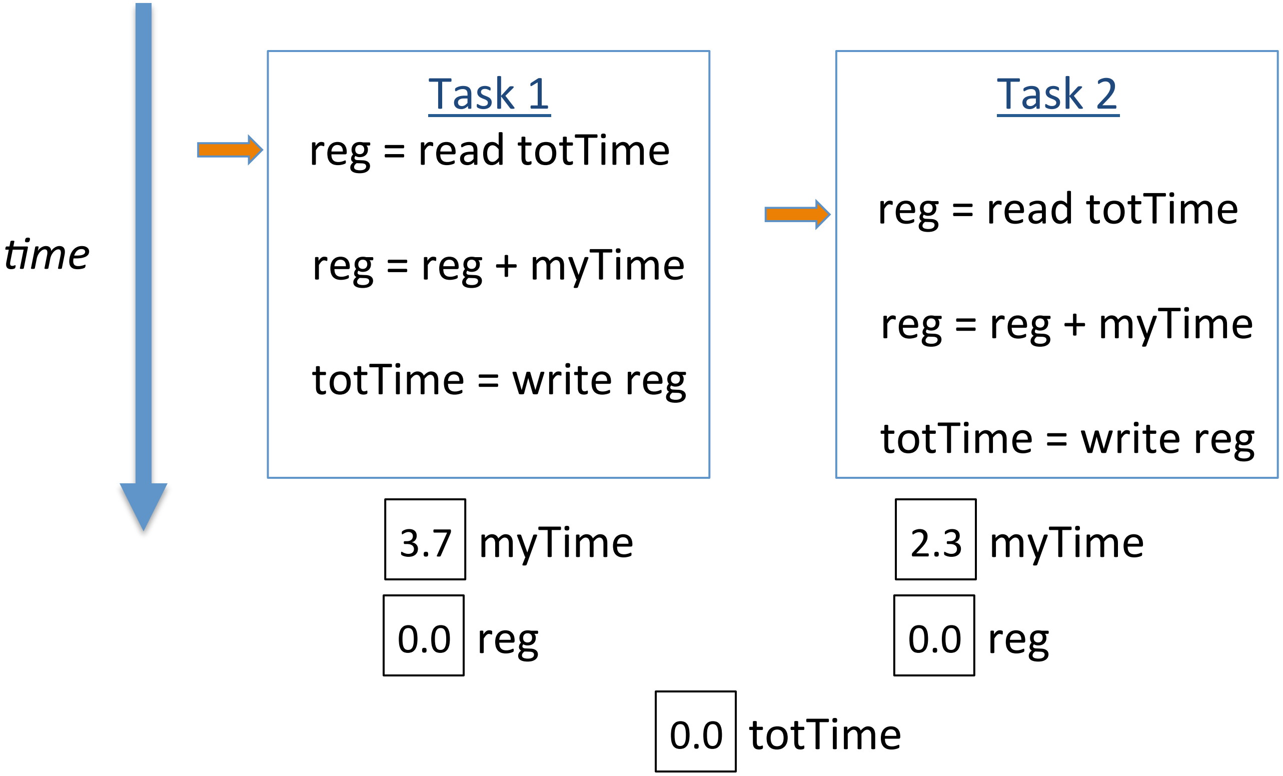
  - the following schedule is problematic:



time

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totTime = write reg
```

Task 2

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reg = read totTime
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```

3.7	myTime
0.0	reg

2.3	myTime
0.0	reg

0.0	totTime

Bug of the week

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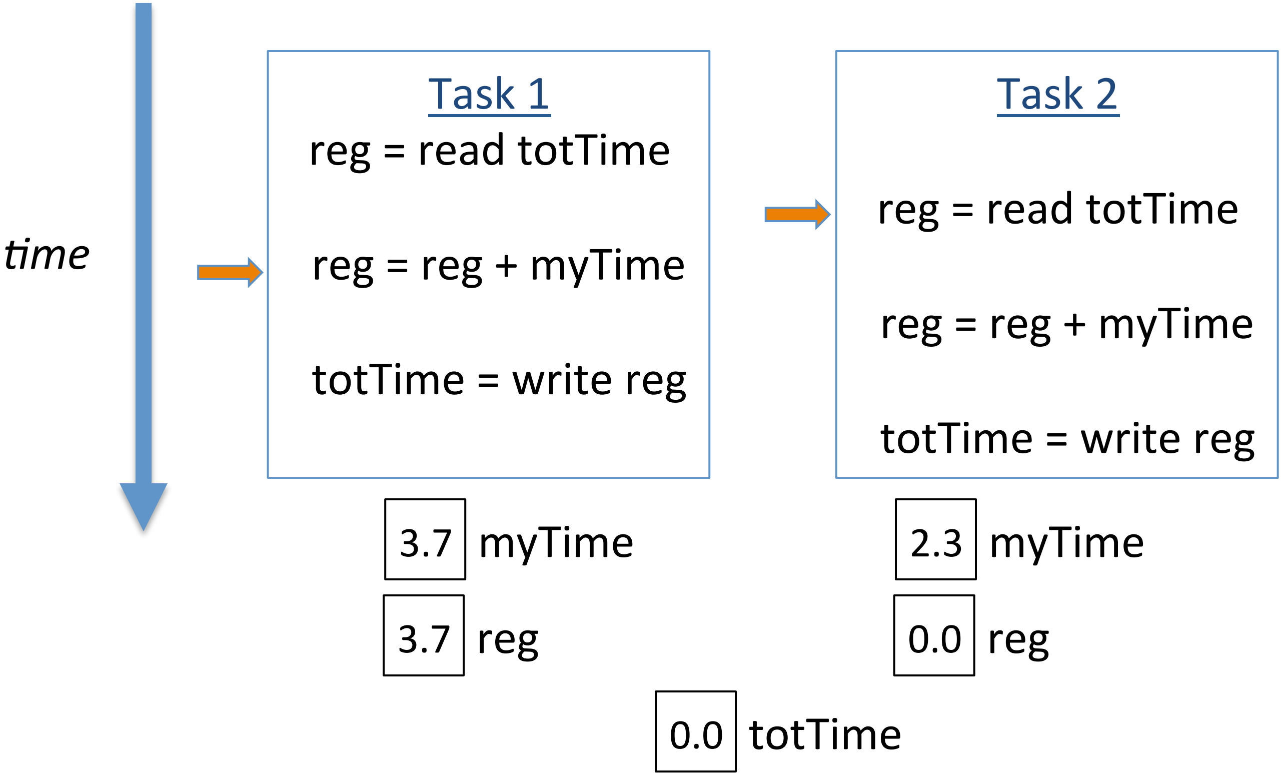

time

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Task 2

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reg = read totTime
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```

3.7	myTime
3.7	reg
2.3	myTime
0.0	reg
0.0	totTime

Bug of the week

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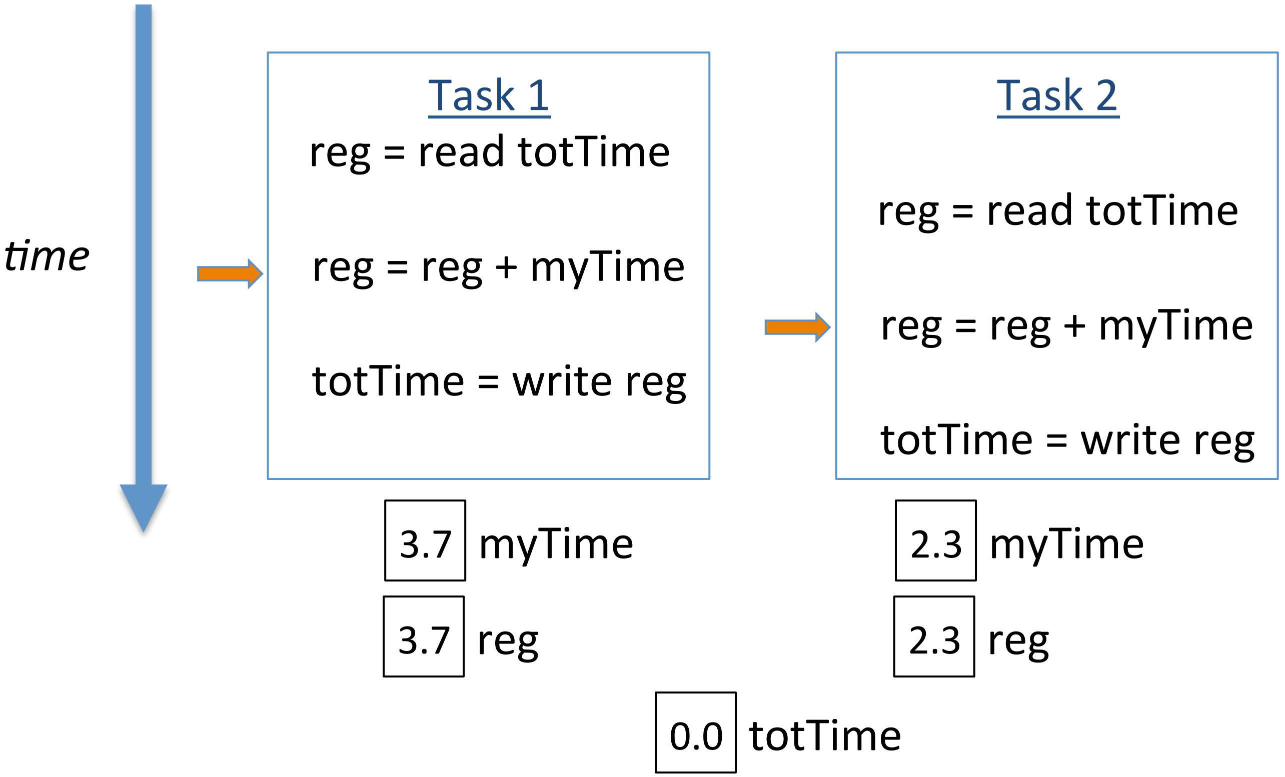

time

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totTime = write reg

3.7 myTime

3.7 reg

2.3 myTime

2.3 reg

0.0 totTime

Bug of the week

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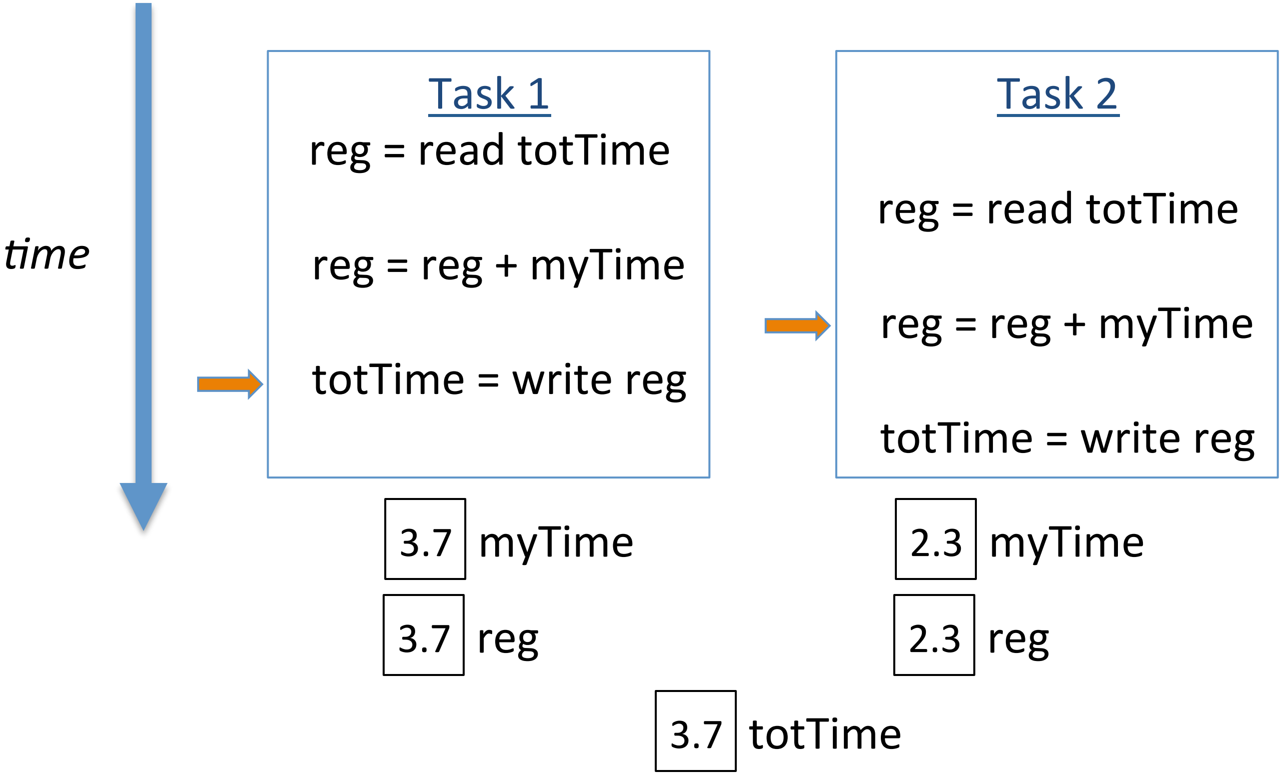

time

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totTime = write reg

3.7	myTime
3.7	reg

2.3	myTime
2.3	reg

3.7	totTime

Bug of the week

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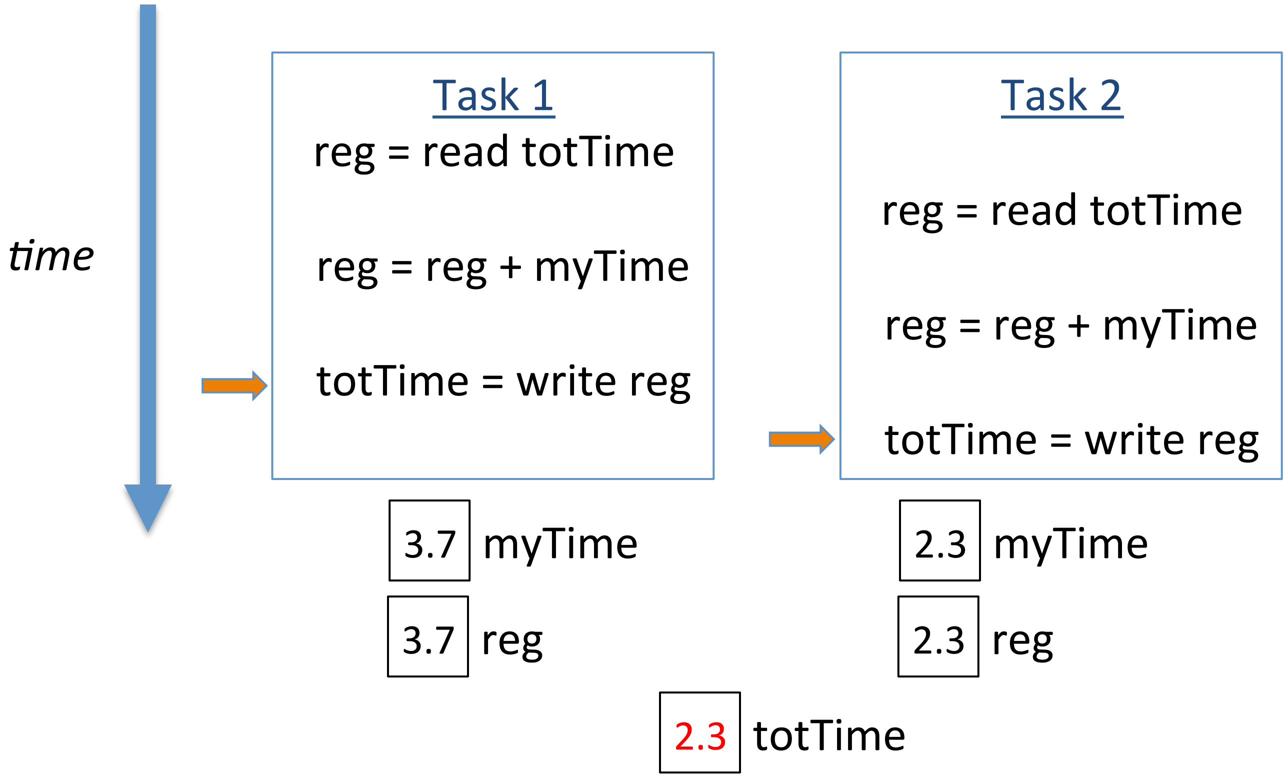

time

Task 1

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Task 2

reg = read totTime

reg = reg + myTime

totTime = write reg

3.7	myTime
3.7	reg

2.3	myTime
2.3	reg

2.3	totTime

Bug of the week: RRWW (Read-Read-Write-Write)

- Due to interleaving, uncoordinated reads and writes to shared state may cause values to be lost
- The fix is to coordinate such accesses to shared state
  - in this case, totTime, minTime, maxTime
  - e.g., could protect each/all of them by a lock

```
coforall tid in 0..#numTasks
  …
  grab totTime lock
    totTime += myTime;
  release totTime lock
  …
```

Glossary: Synchronization

Synchronization:

Glossary: Synchronization

Synchronization: Coordination between tasks

Synchronization Mechanisms in Pthreads

1) mutex: "mutual exclusion" – essentially a lock

- operations:
  - **init, destroy:** create and destroy them
  - **lock, unlock:** grab and release the lock
  - **trylock:** attempt to grab the lock, but don't block if you can't

Synchronization Mechanisms in Pthreads

2) condition variables: a "waiting room" for some condition to become true

- operations:
  - **init, destroy:** create and destroy them
  - **wait:** wait for a condition to become true
  - **signal/broadcast:** signal to one/multiple thread(s) that it is
- rationale: avoid spinning on some test in user code
  - e.g., "wait for this variable to take on some nonzero value"
  - such spinning is typically not a wise use of resources
  - *instead:* let the thread library manage who should wake up when

Condition Variables: Fiddly Details

There are some details that complicate condition vars:

- **mutex argument:** must be managed properly
- **spurious wakeups:** verifying that the condition is still true once you've awoken from a wait()

See Ch. 6 of the text and/or this tutorial for details:

- https://computing.llnl.gov/tutorials/pthreads/#ConditionVariables

Using Mutexes to fix RRWW bugs

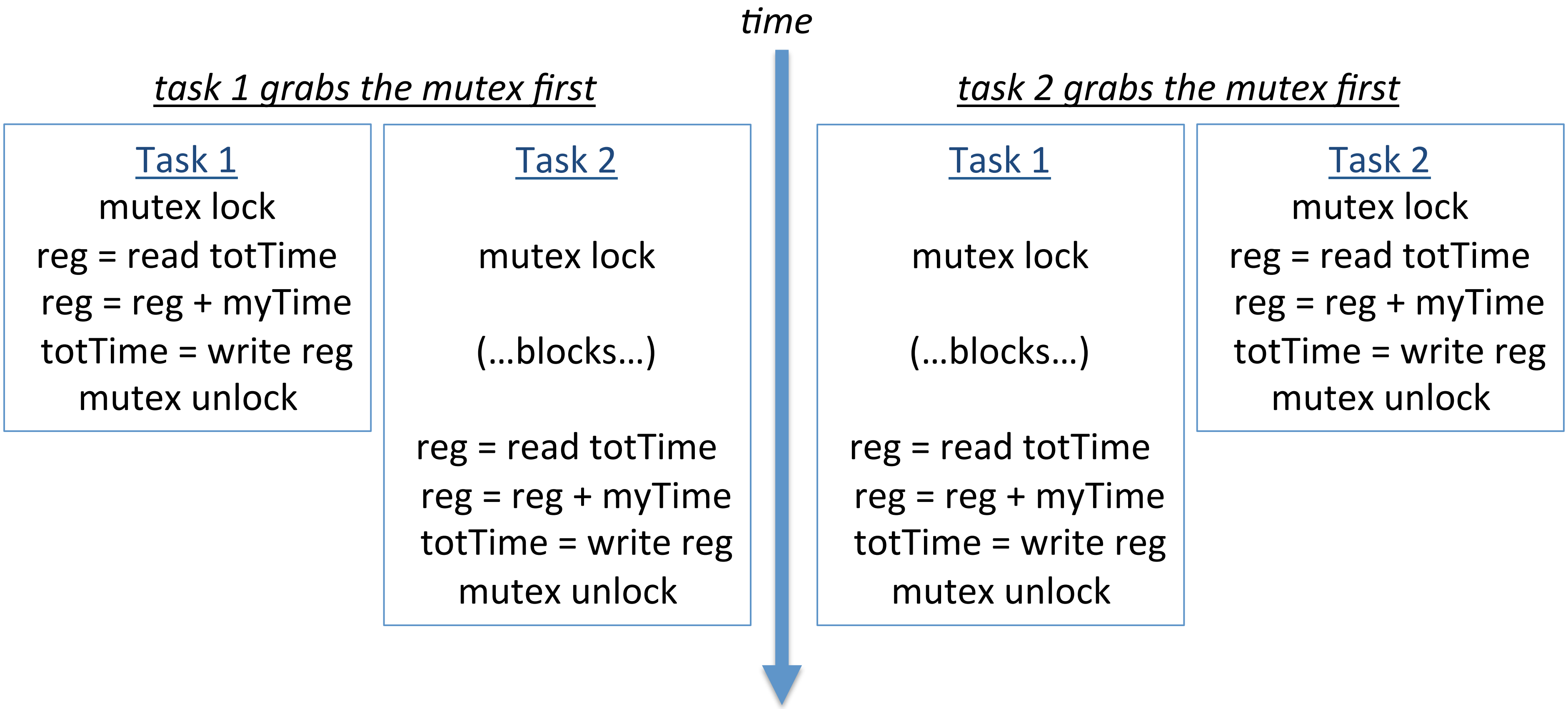
```
pthread_mutex_t totTimeMutex;
pthread_mutex_init(&totTimeMutex, NULL);

create tasks
  …
  pthread_mutex_lock(&totTimeMutex);
    totTime += myTime;
  pthread_mutex_unlock(&totTimeMutex);
  …
join tasks

pthread_mutex_destroy(&totTimeMutex);
```

Using Mutexes to fix RRWW bugs

The result is that there are only two legal orderings of the totTime updates:



time

task 1 grabs the mutex first

Task 1	Task 2
mutex lock	
reg = read totTime	mutex lock
reg = reg + myTime	
totTime = write reg	(…blocks…)
mutex unlock	
	reg = read totTime
	reg = reg + myTime
	totTime = write reg
	mutex unlock

task 2 grabs the mutex first

Task 1	Task 2
	mutex lock
mutex lock	reg = read totTime
	reg = reg + myTime
(…blocks…)	totTime = write reg
	mutex unlock
reg = read totTime	
reg = reg + myTime	
totTime = write reg	
mutex unlock	

Synchronization Mechanisms in Chapel

1) synchronization variables

2) single-assignment variables

Synchronization Variables

- Syntax

```
sync-type:
  sync type
```

- Semantics
  - Stores *full/empty* state along with normal value
  - Defaults to *full* if initialized, *empty* otherwise
  - Default read blocks until *full,* leaves *empty*
  - Default write blocks until *empty,* leaves *full*
- Examples: Critical sections and futures

```
var lock$: sync bool;

lock$ = true;
critical();
var lockval = lock$;
```

```
var future$: sync real;

begin future$ = compute();
computeSomethingElse();
useComputedResults(future$);
```

Example: Bounded Buffer Producer/Consumer

```
var buff$: [0..#buffersize] sync real;

cobegin {
  producer();
  consumer();
}

proc producer() {
  var i = 0;
  for … {
    i = (i+1) % buffersize;
    buff$[i] = …;      // blocks until empty, leaves full
  }
}

proc consumer() {
  var i = 0;
  while … {
    i= (i+1) % buffersize;
    …buff$[i]…;        // blocks until full, leaves empty
  }
}
```

Single-Assignment Variables

- Syntax

```
single-type:
  single type
```

- Semantics
  - Similar to sync variables, but stays *full* once written

- Example: Multiple Consumers of a future

```
var future$: single real;

begin future$ = compute();
computeSomethingElse(future$);
computeSomethingElse(future$);
```

Synchronization Type Methods

- **`readFE():t`** block until *full*, leave *empty*, return value
- **`readFF():t`** block until *full*, leave *full*, return value
- **`readXX():t`** return value (non-blocking)
- **`writeEF(v:t)`** block until *empty*, set value to `v`, leave *full*
- **`writeFF(v:t)`** wait until *full*, set value to `v`, leave *full*
- **`writeXF(v:t)`** set value to `v`, leave *full* (non-blocking)
- **`reset()`** reset value, leave *empty* (non-blocking)
- **`isFull: bool`** return *true* if full else *false* (non-blocking)

- **Defaults:** read: **`readFE`**, write: **`writeEF`**

Single Type Methods

- ~~`readFE():t` block until *full*, leave *empty*, return value~~
- `readFF():t` block until *full*, leave *full*, return value
- `readXX():t` return value (non-blocking)
- `writeEF(v:t)` block until *empty*, set value to `v`, leave *full*
- ~~`writeFF(v:t)` wait until *full*, set value to `v`, leave *full*~~
- ~~`writeXF(v:t)` set value to `v`, leave *full* (non-blocking)~~
- ~~`reset()` reset value, leave *empty* (non-blocking)~~
- `isFull: bool` return *true* if full else *false* (non-blocking)

- **Defaults:** read: **`readFF`**, write: **`writeEF`**

Using Sync vars to fix RRWW bugs

```
var totTime$: sync real = 0.0;  // starts full

coforall tid in 0..#numTasks {
  …
  totTime$ += myTime; // readFE followed by writeEF
  …
}
```

Summary: Pthreads vs. Chapel Synchronization

Pthreads mutex & condition variables:

+ arguably a reasonable backbone for synchronization
  - based on the endurance of Pthreads
  - use of these concepts in other languages/contexts

– arguably result in complex code for common patterns

Chapel sync/single variables:

+ *data-centric synchronization:* expressing synchronization in terms of the data being accessed

– arguably a little artificial/confusing when used as a mutex
  - e.g., see unused boolean value in previous critical section example

Both approaches also have some common liabilities (stay tuned)

Diagnosing Deadlock/Livelock in Chapel

- If you suspect you have a deadlock problem…
  - re-execute your program using –b/--blockreport
    - adds a certain amount of overhead, but beats deadlocking!
  - if deadlock is detected, the program will…
    - terminate
    - do its best to tell you where the tasks were

- If you suspect you have a livelock problem…
  - re-execute your program using –t/--taskreport
    - again, adds a certain amount of overhead
  - upon hitting Ctrl-C/sending SIGINT, the program will…
    - terminate and do its best to tell you where the tasks are

This week's assignment

- extend the single-producer/single-consumer bounded buffer pattern shown in lecture to support multiple producers and consumers
  - in Chapel (to get practice with sync/single variables)
  - in Pthreads (to get practice with mutex/condition variables)
- write a dynamic load balancing distribution in Chapel OR Pthreads
  - apply to ramp + factorial case
- some written questions