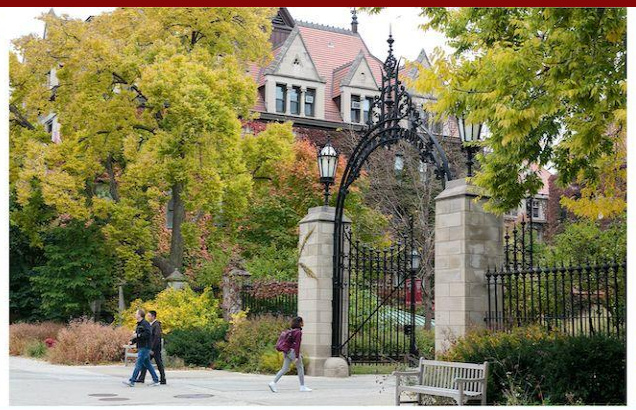
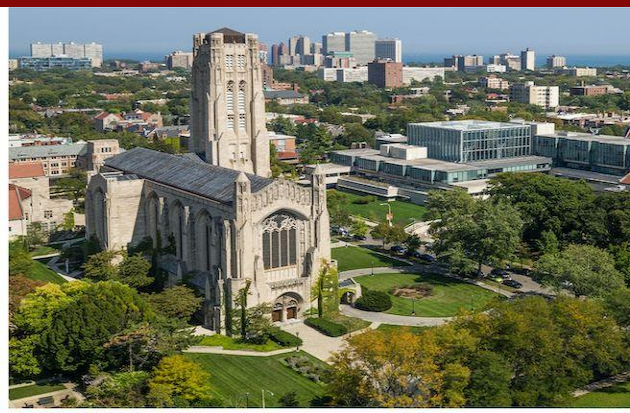
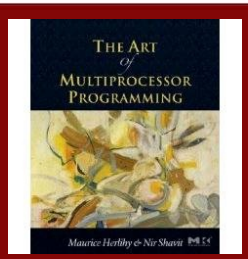
MPCS 52060 - Parallel Programming
M6: Advanced Parallel Patterns and Techniques (Part 2)



Original slides from "The Art of Multiprocessor Programming" by Maurice Herlihy & Nir Shavit with modifications by Lamont Samuels

Data Parallelism

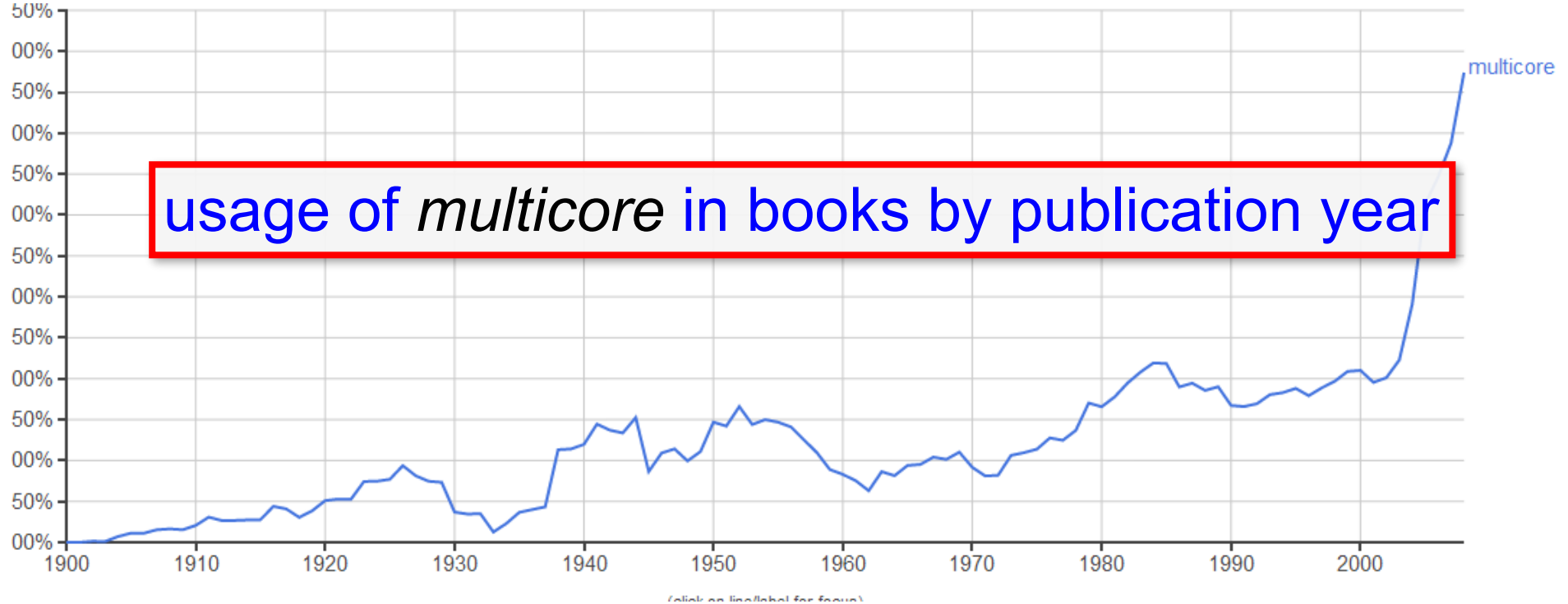
Ever Wonder …

When did the term *multicore* become popular?

A multi-core processor is a single computing component with two or more independent actual central processing units, which are the units that read and execute program instructions.)

wikipedia

Let's Ask Google Ngram!



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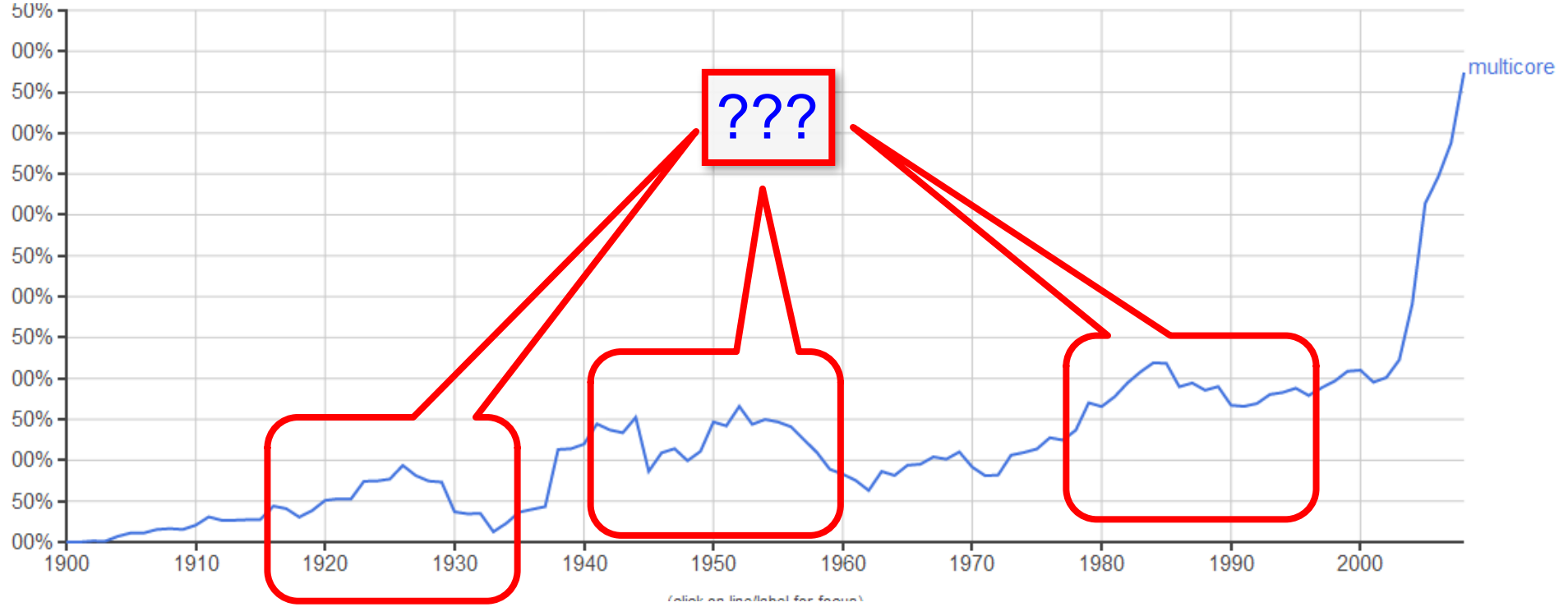

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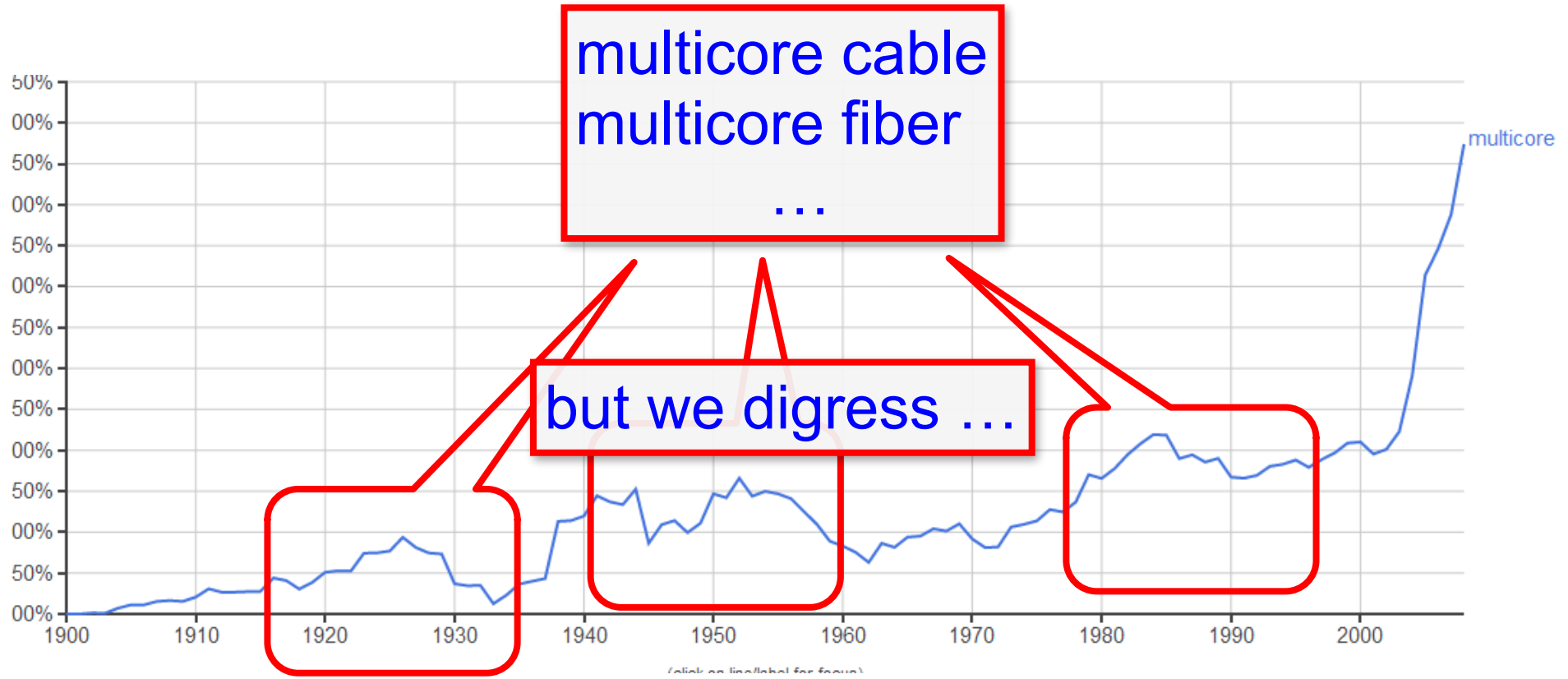
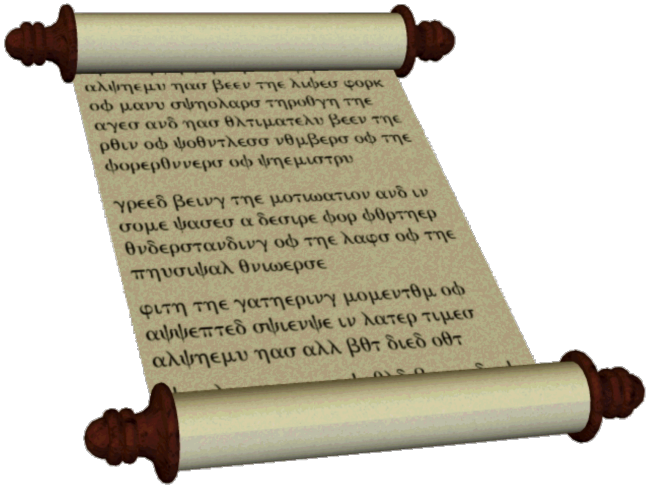
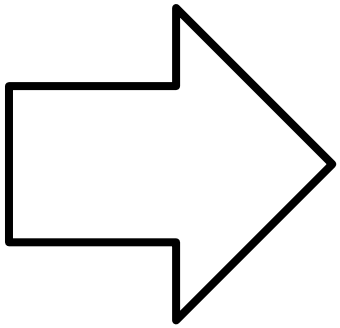


WordCount





alpha → 8

bravo → 3

charlie → 9

…

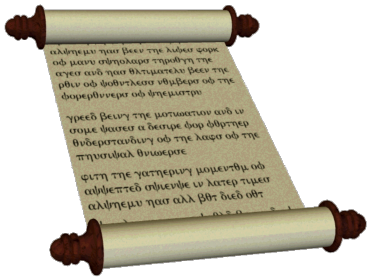
zulu → 1

easy to do sequentially …

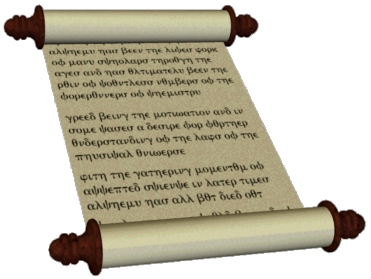
what about in parallel?

MapReduce

split text among *mapping* threads

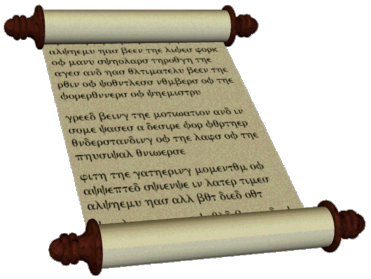


chapter 1



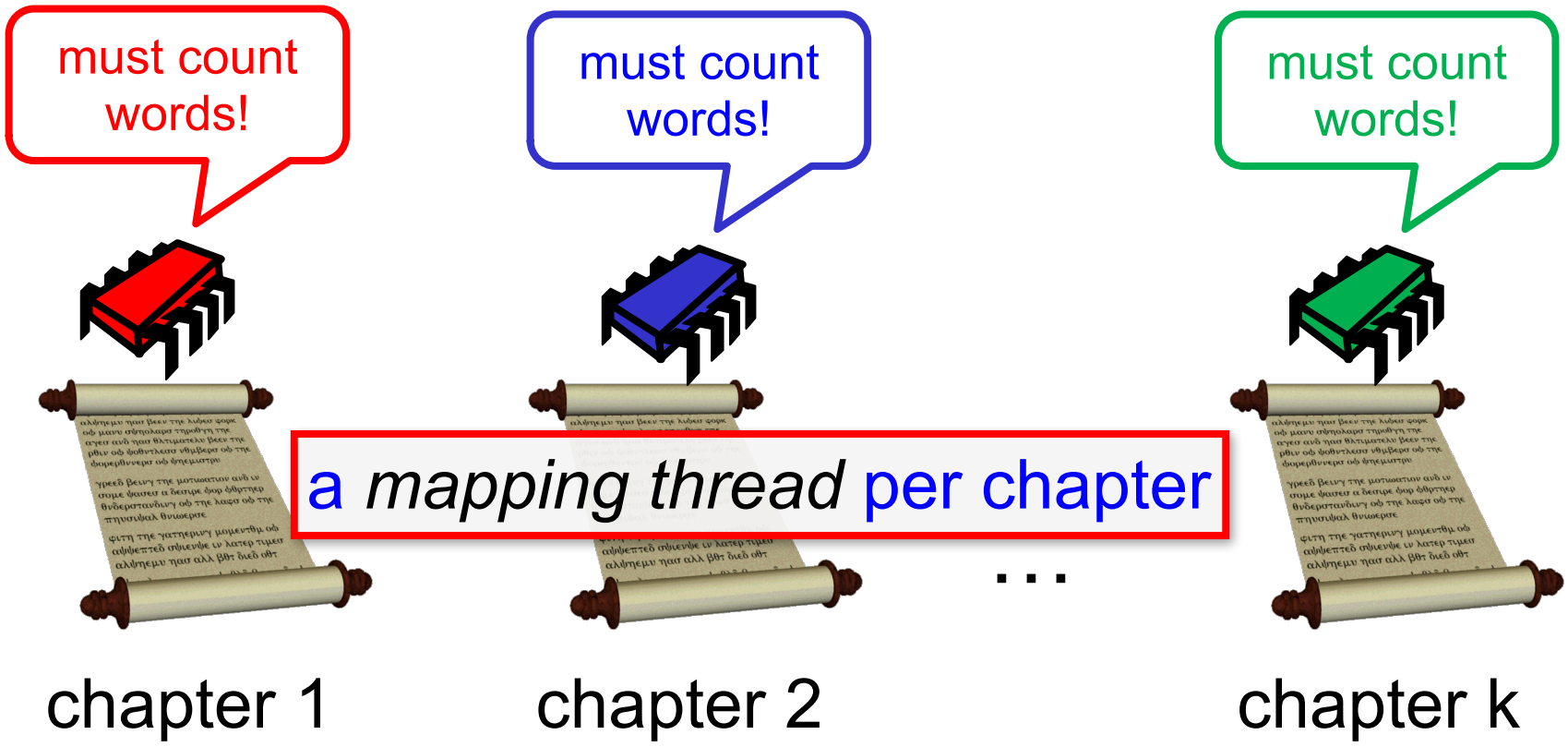
chapter 2

...



chapter k

Map Phase


must count words!
must count words!
must count words!
a *mapping thread* per chapter
...
chapter 1
chapter 2
chapter k

Map Phase

chapter 1

alpha → 9
juliet → 2,
alpha → 1
tango → 4

each mapper thread produces a *stream* …

of *key-value* pairs …

key: word

value: local count

Mapper Class

```
abstract class Mapper<IN, K, V>
    extends RecursiveTask<Map<K, V>> {
  IN input;
  public void setInput(IN anInput) {
    input = anInput;
  }
}
```

Mapper Class

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abstract class Mapper<IN, K, V>
    extends RecursiveTask<Map<K, V>> {
  IN input;
  public void setInput(IN anInput) {
    input = anInput;
  }
}
```

input: document fragment

Mapper Class

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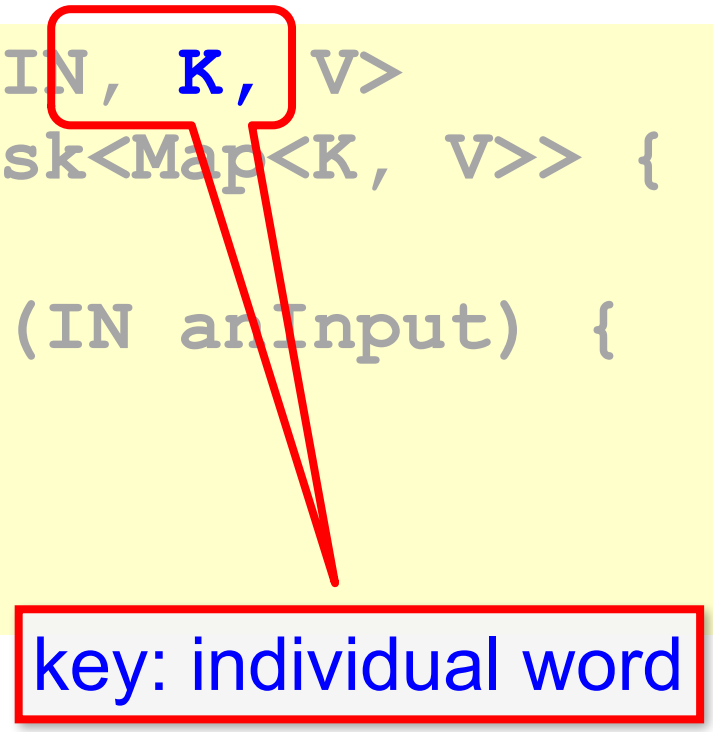
  }
}
```



Mapper Class

```
abstract class Mapper<IN, K, V>
    extends RecursiveTask<Map<K, V>> {
   IN input;
   public void setInput(IN anInput) {
      input = anInput;
   }
}
```

value: local count

Mapper Class

```
abstract class Mapper<IN, K, V>
    extends RecursiveTask<Map<K, V>> {
  IN input;
  public void setInput(IN anInput) {
    input = anInput;
  }
}
```

a task that runs in parallel with other tasks

Mapper Class

```
abstract class Mapper<IN, K, V>
    extends RecursiveTask<Map<K, V>> {
  IN input;
  public void setInput(IN anInput) {
    input = anInput;
  }
}
```

produces a map: word → count

Mapper Class

```
abstract class Mapper<IN, K, V>
    extends RecursiveTask<Map<K, V>> {
  IN input;
  public void setInput(IN anInput) {
    input = anInput;
  }
}
```

initialize input: which document fragment?

WordCount Mapper

```
class WordCountMapper extends
  mapreduce.Mapper<
      List<String>, String, Long
    > {
  …
  }
```

WordCount Mapper

```
class WordCountMapper extends
   mapreduce.Mapper<
        List<String>, String, Long
     > {
   …
```

document fragment is list of words

WordCount Mapper

```
class WordCountMapper extends
   mapreduce.Mapper<
        List<String>, String, Long
      > {
   …
```

document fragment is list of words

map each word …

WordCount Mapper

```
class WordCountMapper extends
   mapreduce.Mapper<
        List<String>, String, Long
     > {
   …
```

document fragment is list of words

map each word …

to its count in the fragment

WordCount Mapper

```
Map<String,Long> compute() {
  Map<String,Long> map = new HashMap<>();
      for (String word : input) {
        map.merge(word,
                  1L,
                  (x, y) -> x + y);
      }
      return map;
    }
  }
```

WordCount Mapper

```
Map<String,Long> compute() {
  Map<String,Long> map = new HashMap<>();
    for (String word : input) {
      map.merge(word,
                1L,
                (x, y) -> x + y);
    return map;
  }
}
```

the `compute()` method constructs the local word count

WordCount Mapper

```
Map<String,Long> compute() {
  Map<String,Long> map = new HashMap<>();
    for (String word : input) {
      map.merge(word,
                1L,
                (x, y) -> x + y);
    }
    return map;
  }
}
```

create a map to hold the output

WordCount Mapper

```
Map<String,Long> compute() {
  Map<String,Long> map = new HashMap<>();
    for (String word : input) {
      map.merge(word,
                1L,
                (x, y) -> x + y);
    }
    return map;
  }
}
```

examine each word in the document fragment

WordCount Mapper

```
Map<String,Long> compute() {
  Map<String,Long> map = new HashMap<>();
      for (String word : input) {
        map.merge(word,
                  1L,
                  (x, y) -> x + y);
      }
      return map;
    }
  }
```

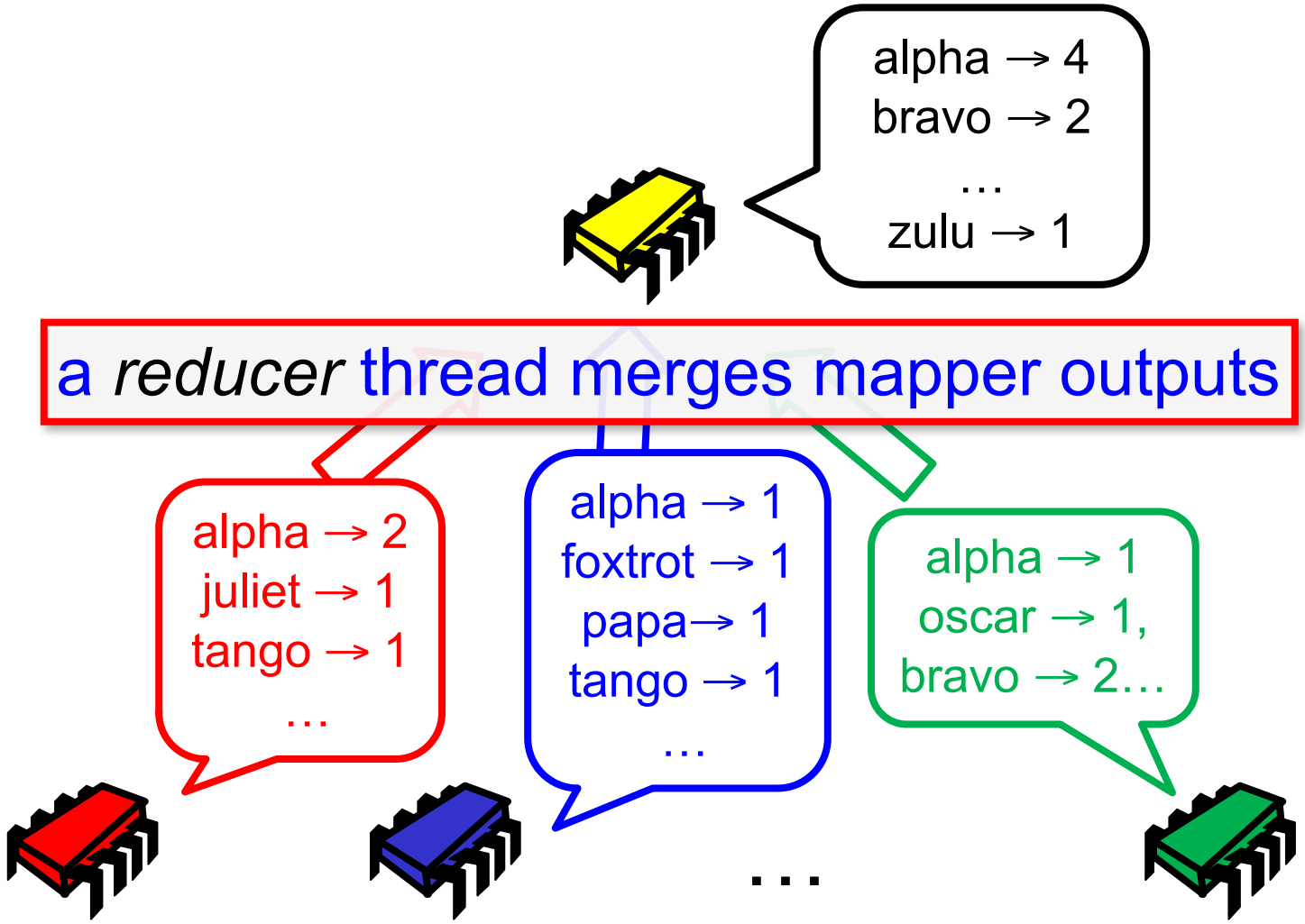
increment that word's count in the map

WordCount Mapper

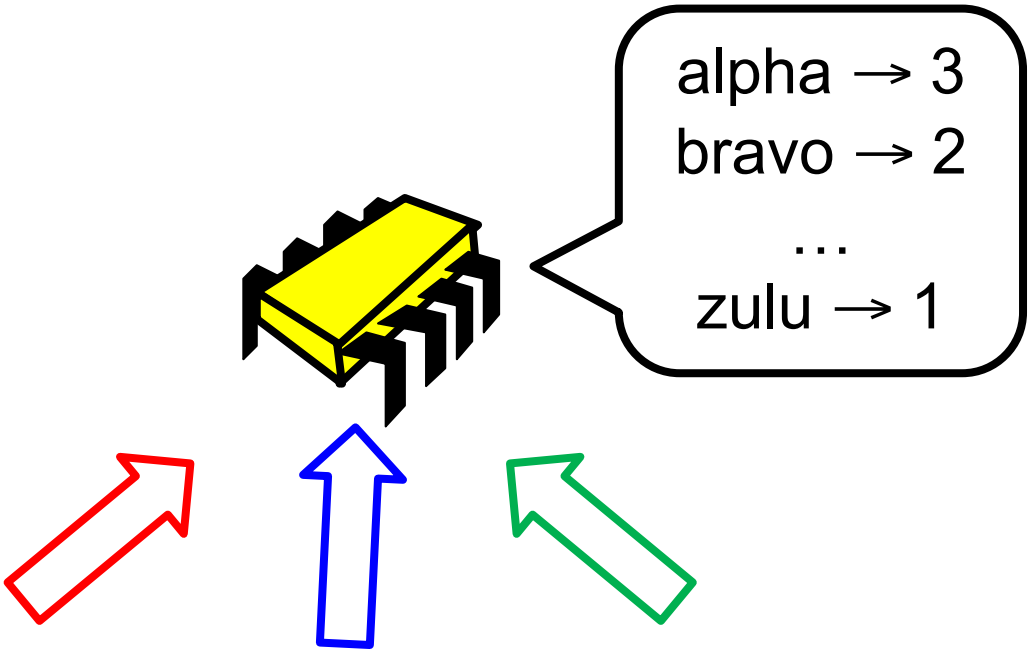
```
Map<String,Long> compute() {
  Map<String,Long> map = new HashMap<>();
      for (String word : input) {
        map.merge(word,
                  1L,
                  (x, y) -> x + y);
      }
      return map;
    }
  }
```

when the local count is complete, return the map

Reduce Phase



Reduce Phase



the reducer task produces a *stream* …

of *key-value* pairs …

key: word

value: word count

Reducer Class

```
abstract class Reducer<K, V, OUT>
    extends RecursiveTask<OUT> {
  K key;
  List<V> valueList;
  public void setInput(
    K aKey,
    List<V> aList) {
    key = aKey;
    valueList = aList;
  }
}
```

Reducer Class

```
abstract class Reducer<K, V, OUT>
    extends RecursiveTask<OUT> {
  K key;
  List<V> valueList;
  public void setInput(
    K aKey,
    List<V> aList) {
    key = aKey;
    valueList = aList;
  }
}
```

each reducer is given a single key (word)

Reducer Class

```
abstract class Reducer<K, V, OUT>
    extends RecursiveTask<OUT> {
  K key;
  List<V> valueList;
  public void setInput(
    K aKey,
    List<V> aList) {
    key = aKey;
    valueList = aList;
  }
}
```

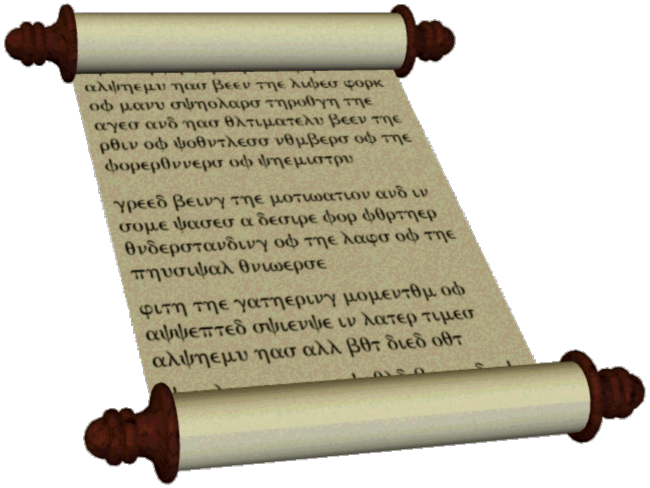
and a list of associated values (word count per fragment)

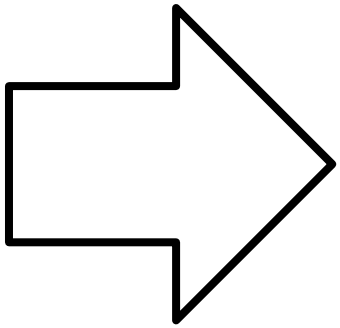
Reducer Class

```
abstract class Reducer<K, V, OUT>
    extends RecursiveTask<OUT> {
  K key;
  List<V> valueList;
  public void setInput(
    K aKey,
    List<V> aList) {
    key = aKey;
    valu
  }
}
```

It produces a single summary value (the total count for that word)

WordCount





$$\begin{pmatrix} 0.037 \\ 0.002 \\ 0.045 \\ \dots \\ 0.000 \end{pmatrix}$$

normalizing document wordcount

gives a *fingerprint* vector

Pseudocode Implementations

- See m6/concurrent/mapreduce/MapReduce.java
- See m6/concurrent/mapreduce/WordCount.java

Barriers

Simple Video Game

- Prepare frame for display
  - By graphics coprocessor
- “soft real-time” application
  - Need at least 35 frames/second
  - OK to mess up rarely

Simple Video Game

```
while (true) {
  frame.prepare();
  frame.display();
  }
```

Simple Video Game

```
while (true) {
  frame.prepare();
  frame.display();
  }
```

- What about overlapping work?
  - 1st thread displays frame
  - 2nd prepares next frame

Two-Phase Rendering

```
while (true) {
  if (phase) {
    frame[0].display();
  } else {
    frame[1].display();
  }
  phase = !phase;
}
```

```
while (true) {
  if (phase) {
    frame[1].prepare();
  } else {
    frame[0].prepare();
  }
  phase = !phase;
}
```

Two-Phase Rendering

```
while (true) {
  if (phase) {
    frame[0].display();
  } else {
    frame[1].display();
  }
  phase = !phase;
}
```

```
while (true) {
  if (phase) {
    frame[1].prepare();
  } else {
    frame[0].prepare();
  }
  phase = !phase;
}
```

even phases

Two-Phase Rendering

```
while (true) {
  if (phase) {
    frame[0].display();
  } else {
    frame[1].display();
  }
  phase = !phase;
}
```

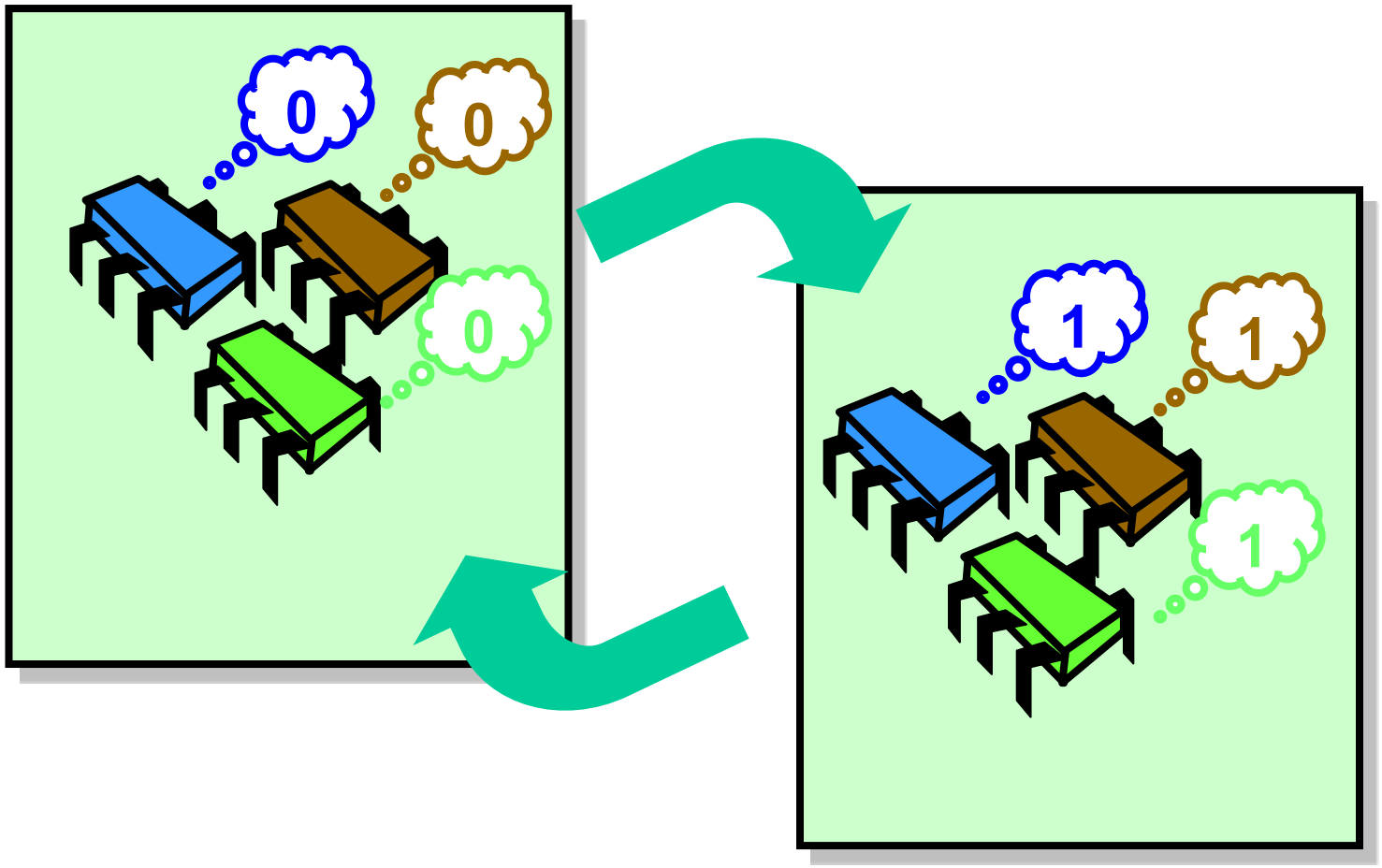
```
while (true) {
  if (phase) {
    frame[1].prepare();
  } else {
    frame[0].prepare();
  }
  phase = !phase;
}
```

odd phases

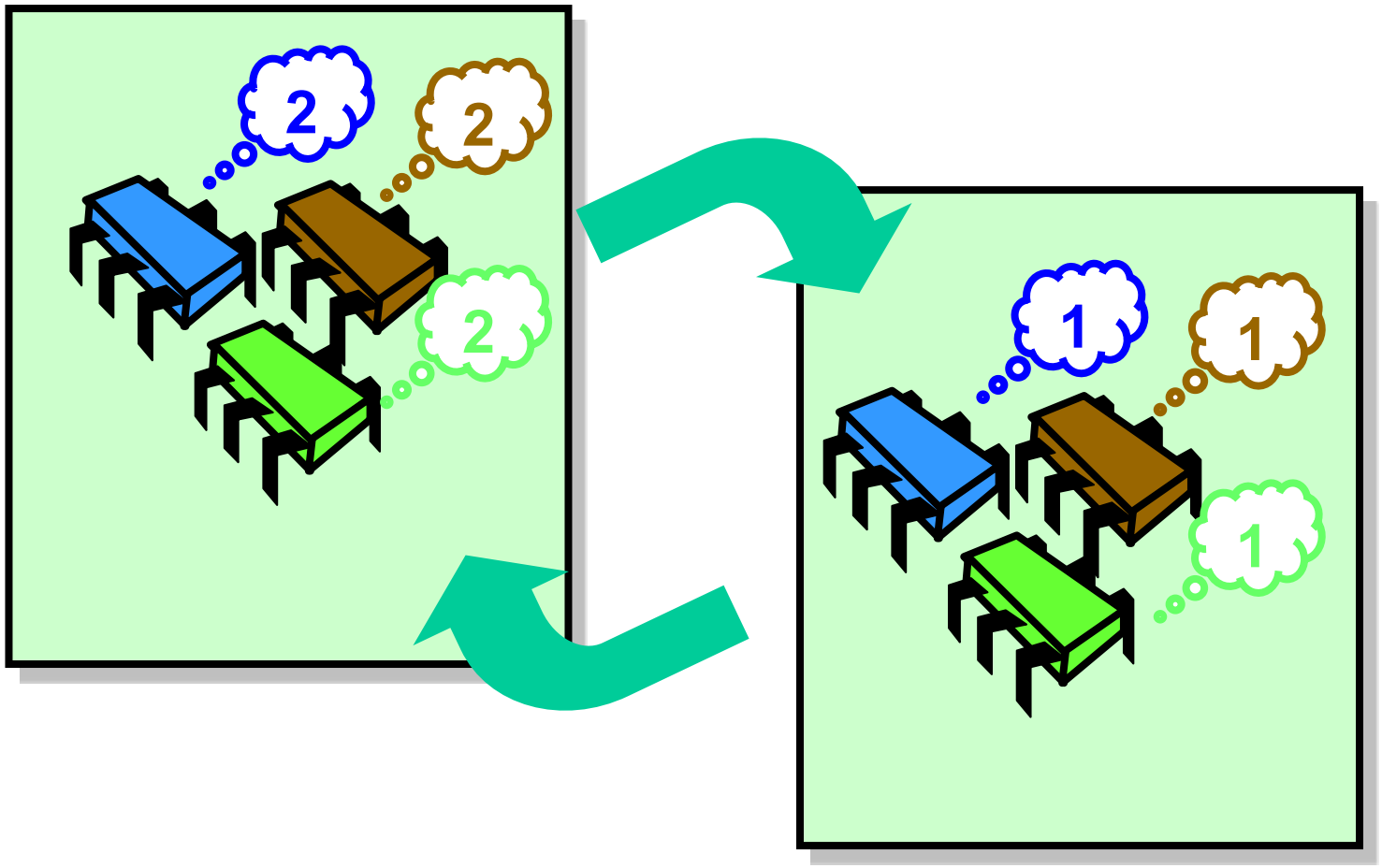
Synchronization Problems

- How do threads stay in phase?
- Too early?
  - "we render no frame before its time"
- Too late?
  - Recycle memory before frame is displayed

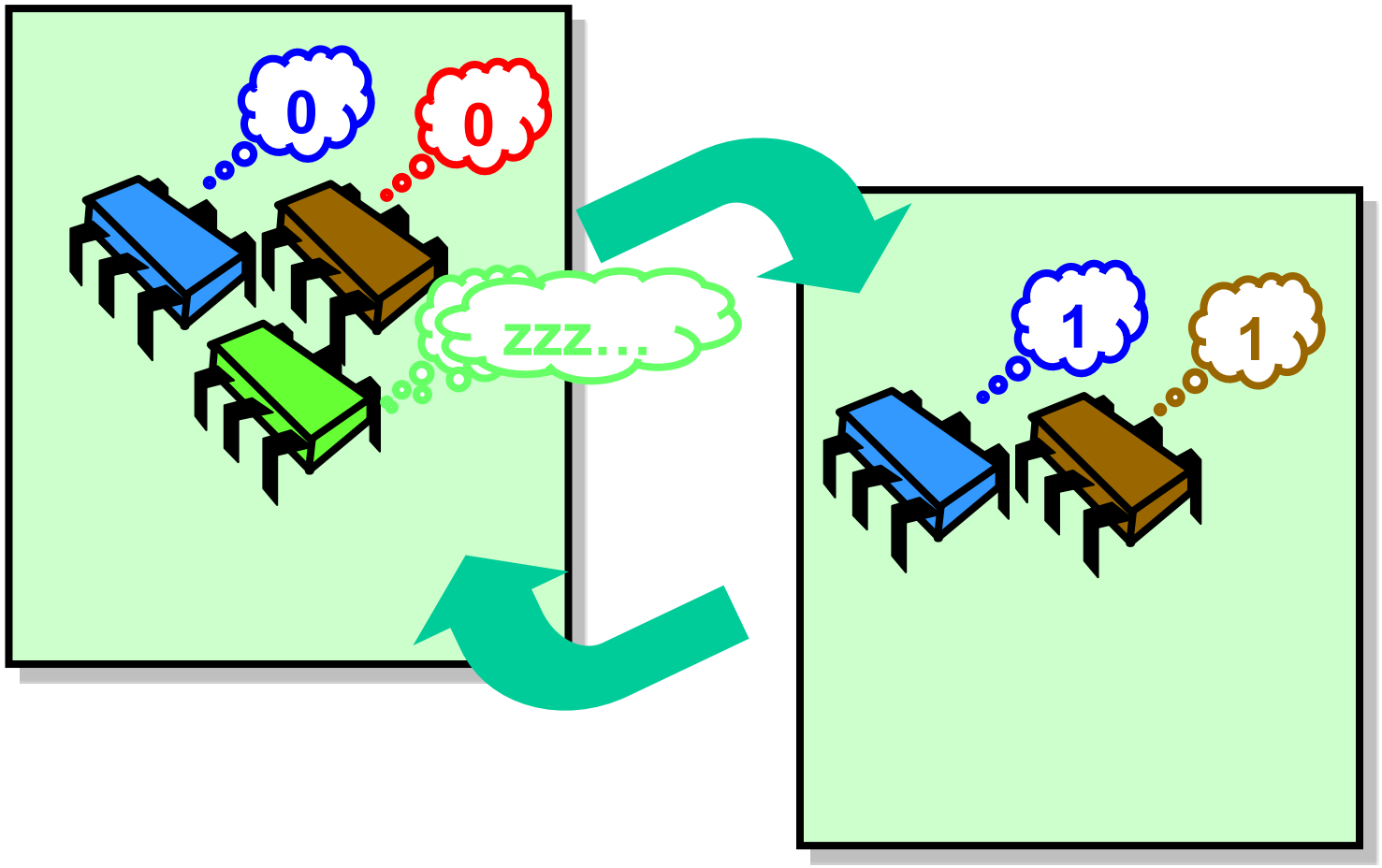
Ideal Parallel Computation



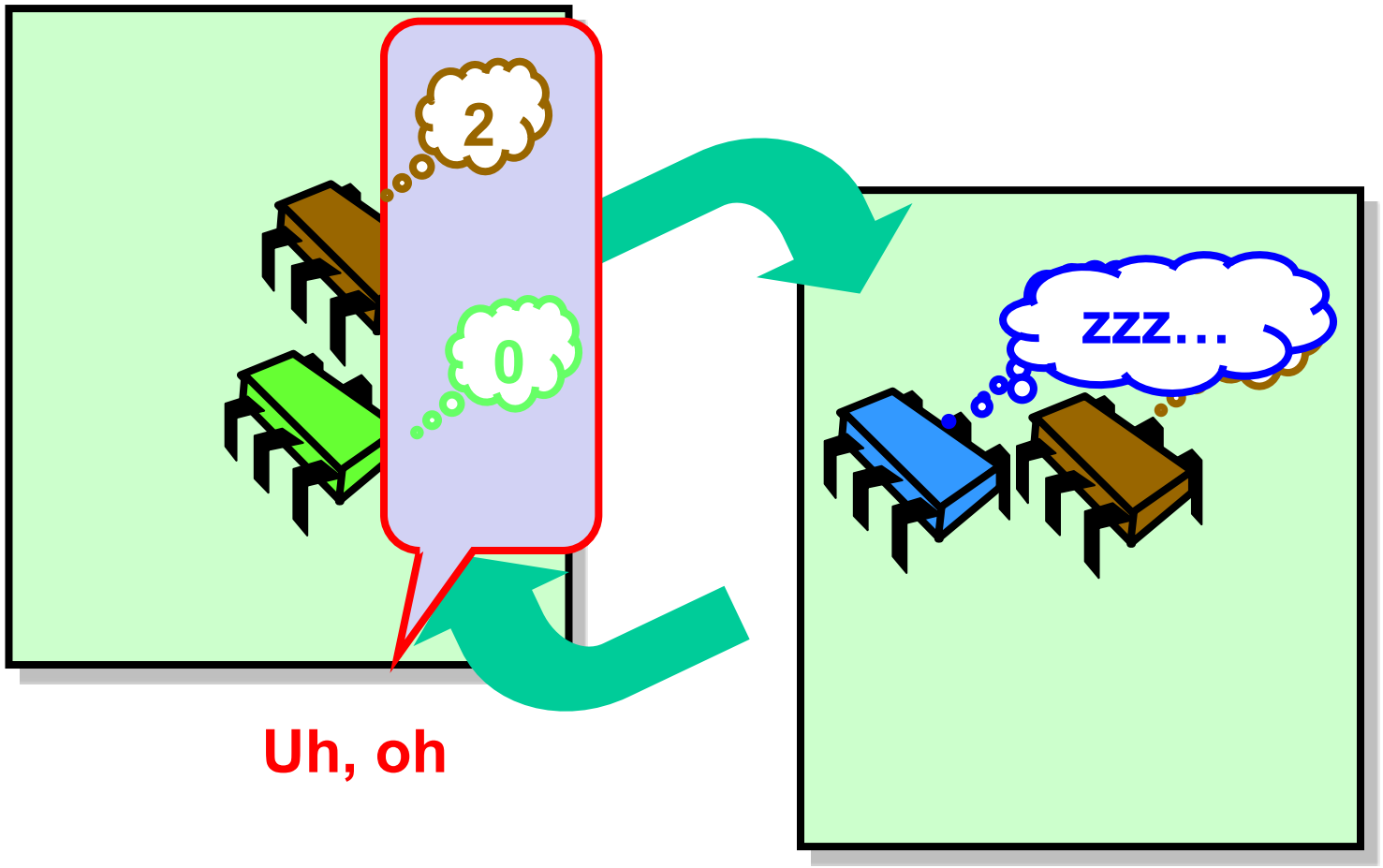
Ideal Parallel Computation



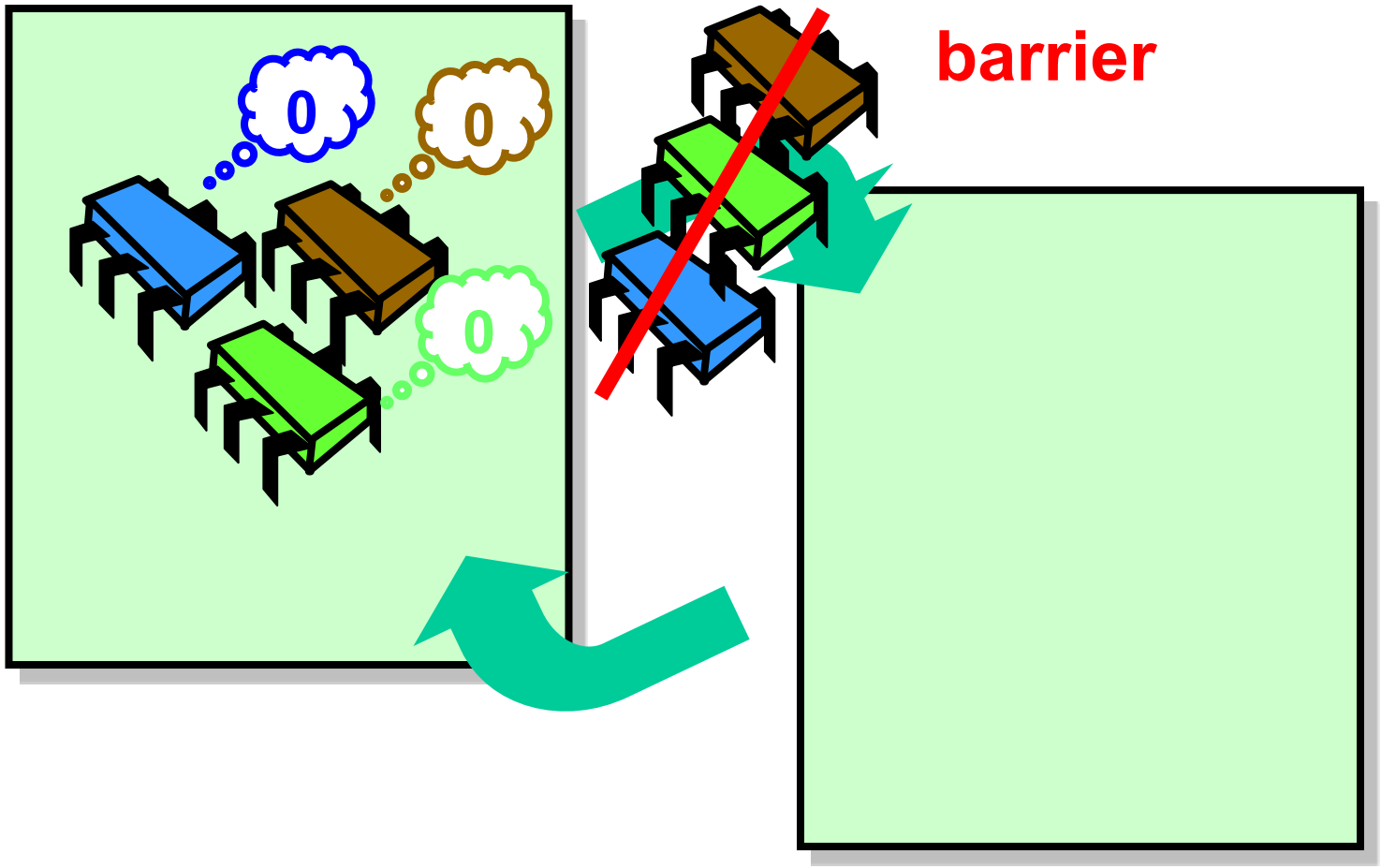
Real-Life Parallel Computation



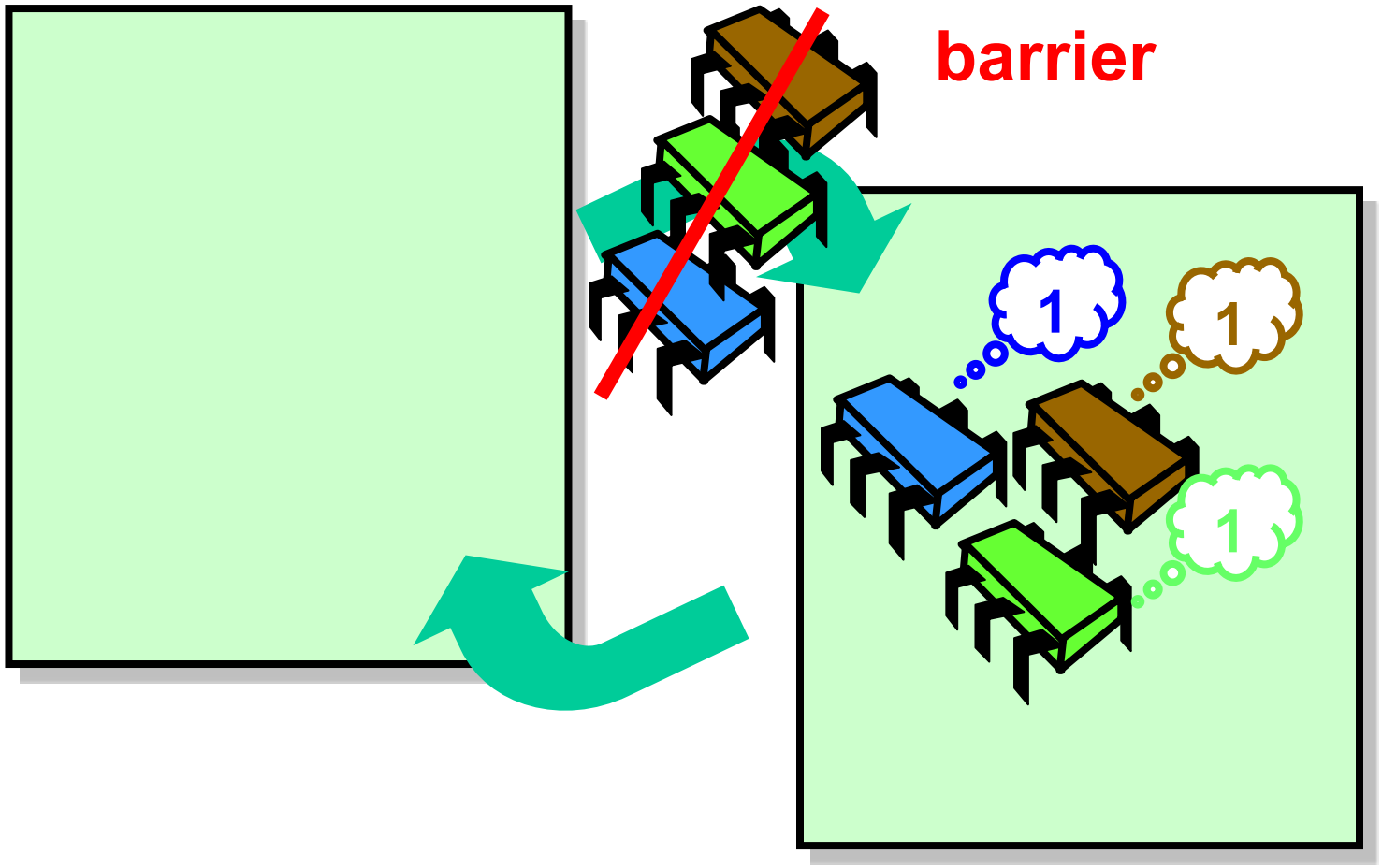
Real-Life Parallel Computation



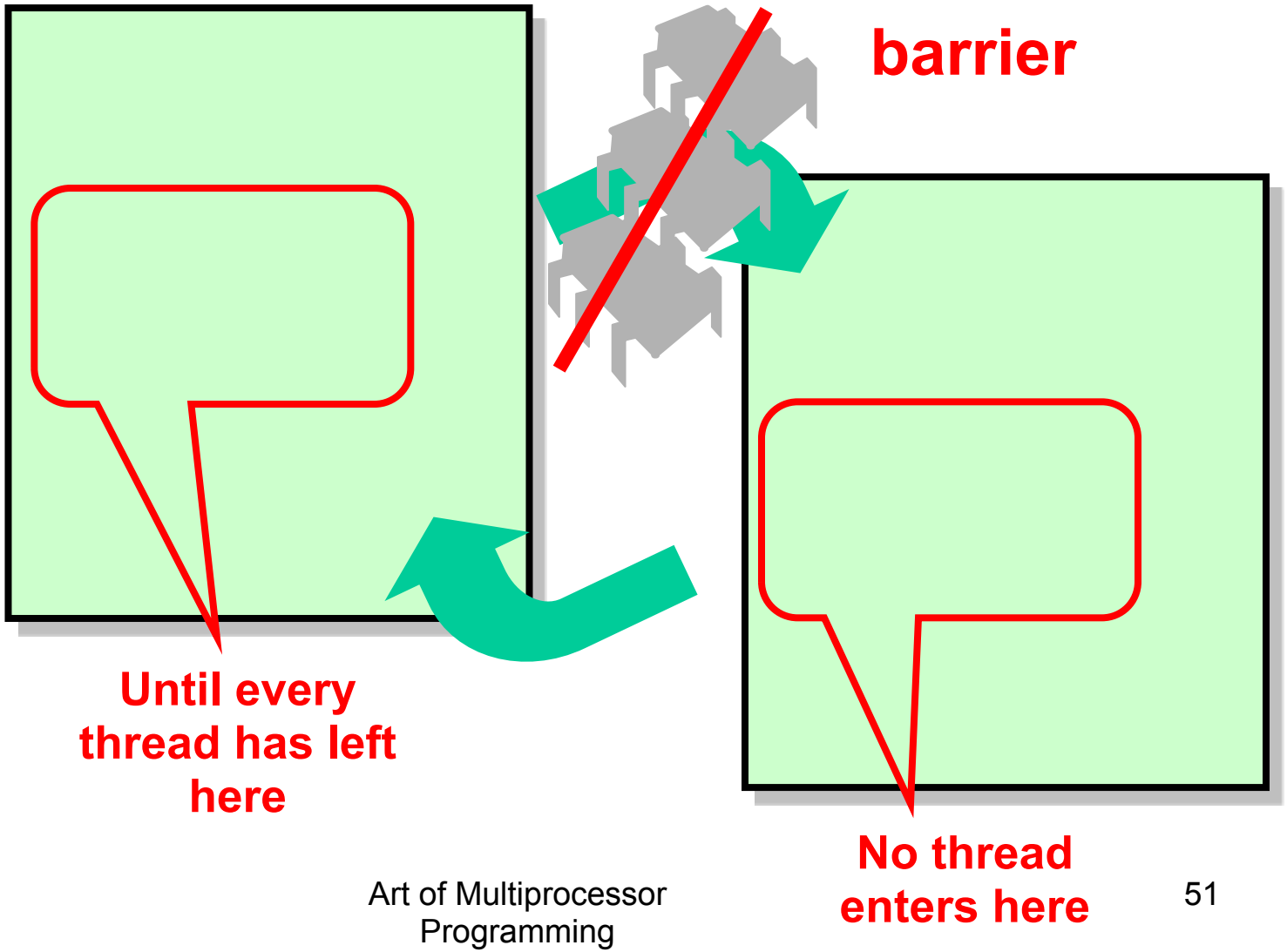
Barrier Synchronization



Barrier Synchronization



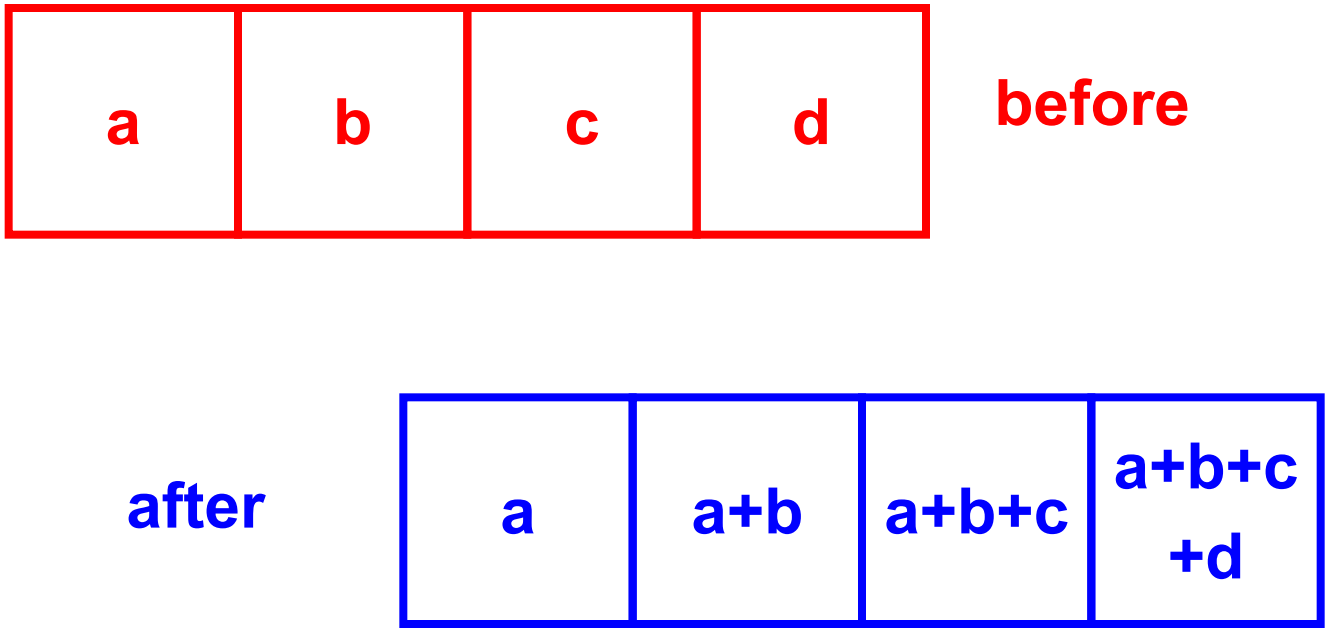
Barrier Synchronization



Why Do We Care?

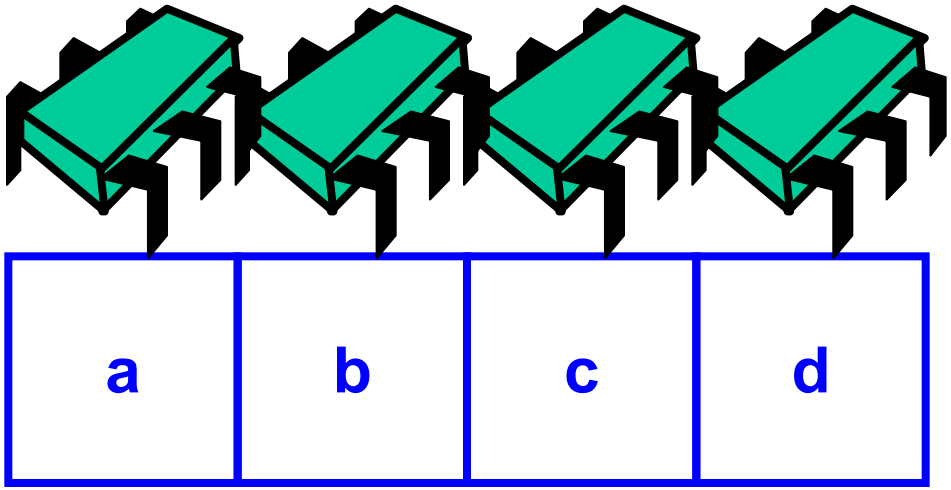
- Mostly of interest to
  - Scientific & numeric computation
- Elsewhere
  - Less common in systems programming
  - Still important topic

Example: Parallel Prefix

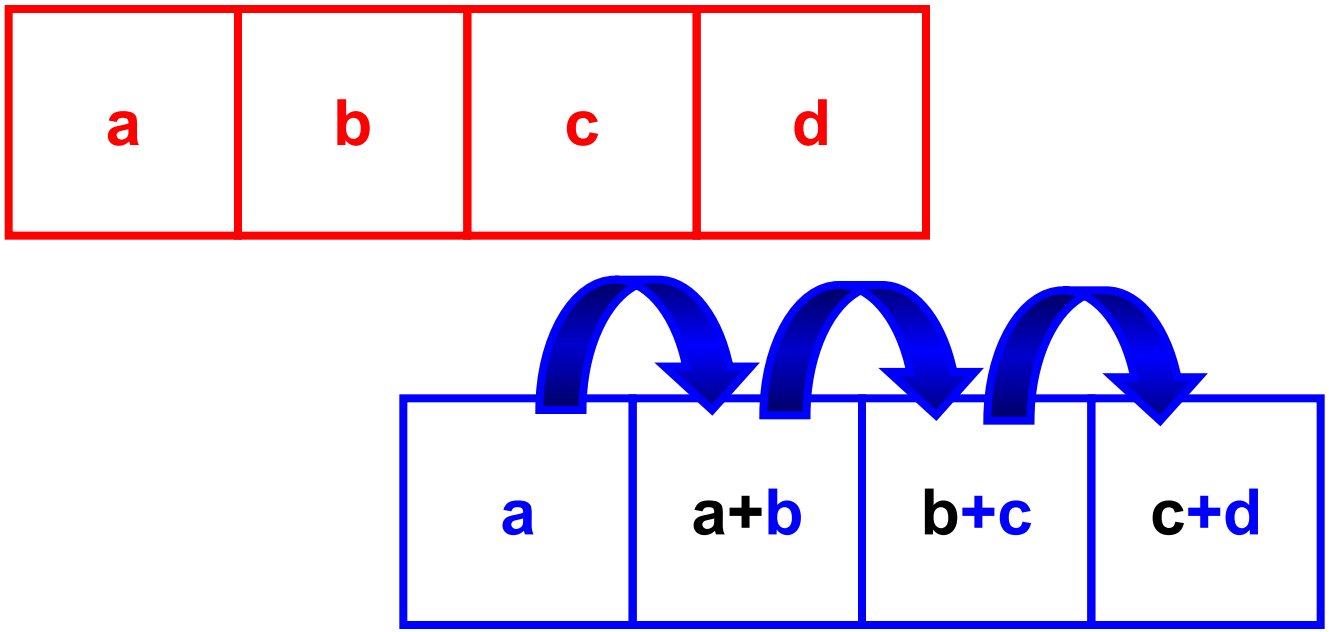


Parallel Prefix

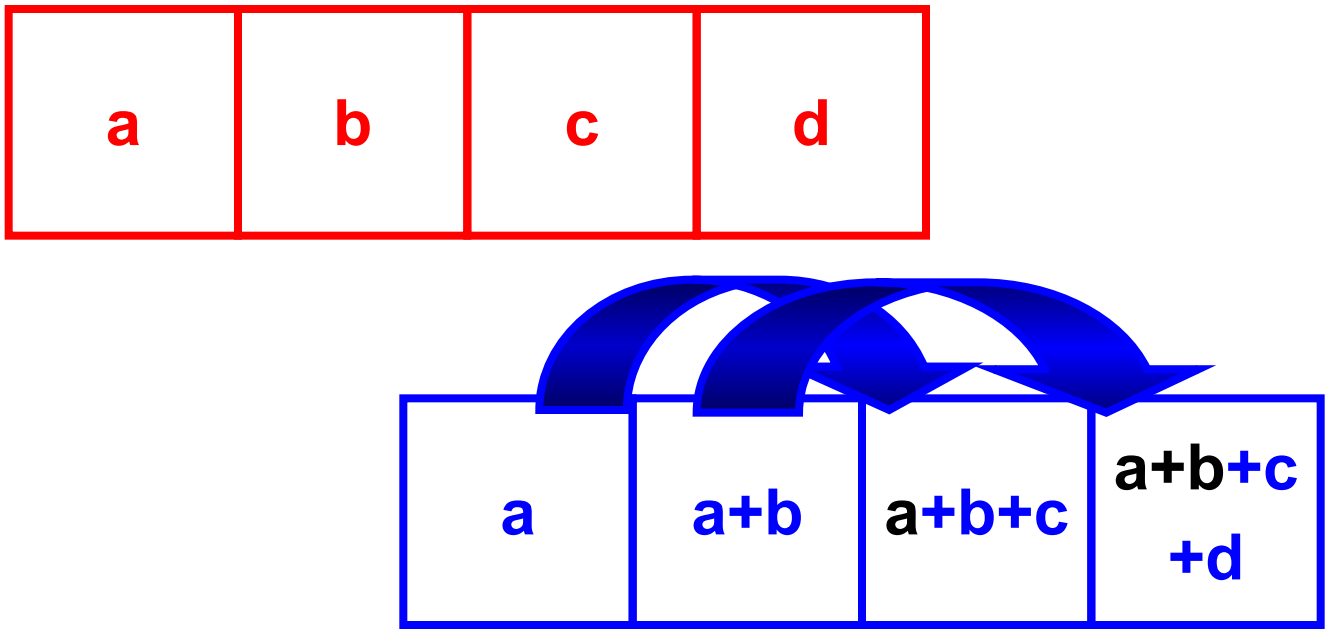
One thread
Per entry



Parallel Prefix: Phase 1



Parallel Prefix: Phase 2



Parallel Prefix

- N threads can compute
  - Parallel prefix
  - Of N entries
  - In $\log_2 N$ rounds
- What if system is asynchronous?
  - Why we need barriers

Prefix

```
class Prefix extends Thread {
 int[] a;
 int i;
 Barrier b;
 void Prefix(int[] a,
             Barrier b, int i) {
  a = a;
  b = b;
  i = i;
 }
```

Prefix

```
class Prefix extends Thread {
 int[] a;
 int i;
 Barrier b;
 void Prefix(int[] a,
             Barrier b, int i) {
  a = a;
  b = b;
  i = i;
 }
```

Array of input values

Prefix

```
class Prefix extends Thread {
 int[] a;
 int i;
 Barrier b;
 void Prefix(int[] a,
             Barrier b, int i) {
  a = a;
  b = b;
  i = i;
 }
```

Thread index

Prefix

```
class Prefix extends Thread {
 int[] a;
 int i;
 Barrier b;
 void Prefix(int[] a,
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  a = a;
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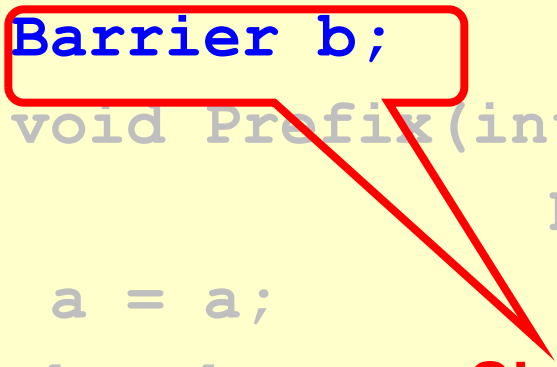
  i = i;
 }
```



Prefix

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class Prefix extends Thread {
 int[] a;
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 void Prefix(int[] a,
             Barrier b, int i) {
  a = a;
  b = b;
  i = i;
 }
```

Initialize fields

Where Do the Barriers Go?

```
public void run() {
 int d = 1, sum = 0;
 while (d < N) {
  if (i >= d)
    sum = a[i-d];
  if (i >= d)
   a[i] += sum;
  d = d * 2;
}}}
```

Where Do the Barriers Go?

```
public void run() {
 int d = 1, sum = 0;
 while (d < N) {
  if (i >= d)
    sum = a[i-d];
  b.await();
  if (i >= d)
   a[i] += sum;
  d = d * 2;
}}}
```

Make sure everyone reads before anyone writes

Where Do the Barriers Go?

```
public void run() {
 int d = 1, sum = 0;
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  if (i >= d)
   a[i] += sum;
  b.await();
  d = d * 2;
}}}
```

Make sure everyone reads before anyone writes

Make sure everyone writes before anyone reads

Barrier Implementations

- Cache coherence
  - Spin on locally-cached locations?
  - Spin on statically-defined locations?
- Latency
  - How many steps?
- Symmetry
  - Do all threads do the same thing?

Barriers

```
public class Barrier {
 AtomicInteger count;
 int size;
 public Barrier(int n){
  count = AtomicInteger(n);
  size = n;
 }
 public void await() {
  if (count.getAndDecrement()==1) {
   count.set(size);
  } else {
   while (count.get() != 0);
 }}}}
```

Barriers

```
public class Barrier {
 AtomicInteger count;
 int size;
 public Barrier(int n){
  count = AtomicInteger(n);
  size = n;
 }
 public void await() {
  if (count.getAndDecrement()==1) {
   count.set(size);
  } else {
   while (count.get() != 0);
 }}}}
```

Number of threads not yet arrived

Barriers

```
public class Barrier {
 AtomicInteger count;
 int size;
 public Barrier(int n){
  count = AtomicInteger(n);
  size = n;
 }
 public void await() {
  if (count.getAndDecrement()==1) {
   count.set(size);
  } else {
   while (count.get() != 0);
 }}}}
```

Number of threads participating

Barriers

```
public class Barrier {
 AtomicInteger count;
 int size;
 public Barrier(int n){
  count = AtomicInteger(n);
  size = n;
 }
 public void await() {
  if (count.getAndDecrement()==1) {
   count.set(size);
  } else {
   while (count.get() != 0);
 }}}}
```

Initialization

Barriers

```
public class Barrier {
 AtomicInteger count;
 int size;
 public Barrier(int n){
  count = AtomicInteger(n);
  size = n;
 }
 public void await() {
  if (count.getAndDecrement()==1) {
   count.set(size);
  } else {
   while (count.get() != 0);
 }}}}
```

Principal method

Barriers

```
public class Barrier {
 AtomicInteger count;
 int size;
 public Barrier(int n){
  count = AtomicInteger(n);
  size = n;
 }
 public void await() {
  if (count.getAndDecrement()==1) {
   count.set(size);
  } else {
   while (count.get() != 0);
 }}}}
```

If I'm last, reset fields for next time

Barriers

```
public class Barrier {
 AtomicInteger count;
 int size;
 public Barrier(int n){
  count = AtomicInteger(n);
  size = n;
 }
 public void await() {
  if (count.getAndDecrement()==1) {
   count.set(size);
  } else {
   while (count.get() != 0);
}}}}
```

Otherwise, wait for everyone else

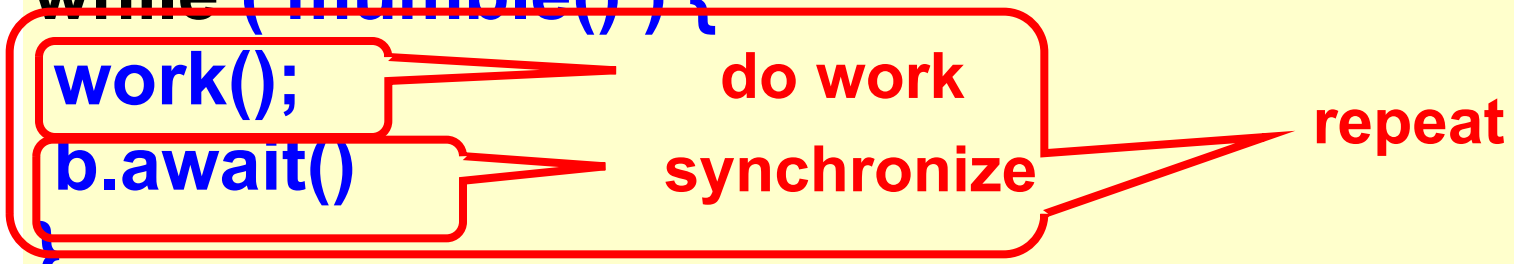
Barriers

```
public class Barrier {
 AtomicInteger count;
 int size;
 public Barrier(int n){
  count = AtomicInteger(n);
  size = n;
 }
 public void await() {
  if (count.getAndDecrement()==1) {
   count.set(size);
  } else {
   while (count.get() != 0);
 }}}}
```

What's wrong with this protocol?

Reuse

```
Barrier b = new Barrier(n);
while ( mumble() ) {
  work();
  b.await()
}
```

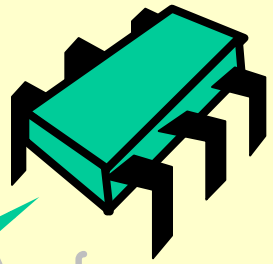


Barriers

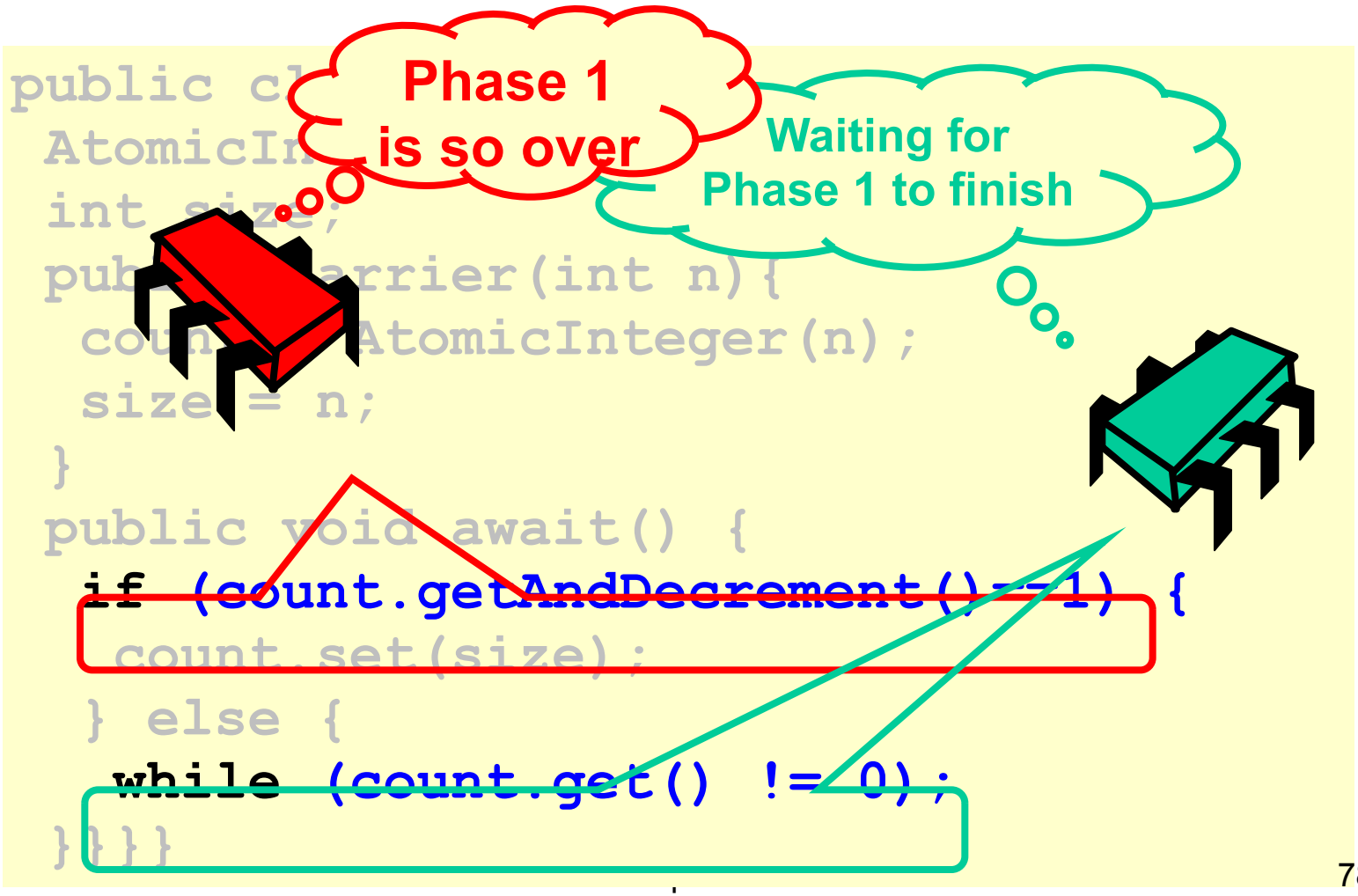
```
public class Barrier {
 AtomicInteger count;
 int size;
 public Barrier(int n){
  count = AtomicInteger(n);
  size = n;
 }
 public void await() {
  if (count.getAndDecrement()==1) {
   count.set(size);
  } else {
   while (count.get() != 0);
 }}}}
```

Barriers

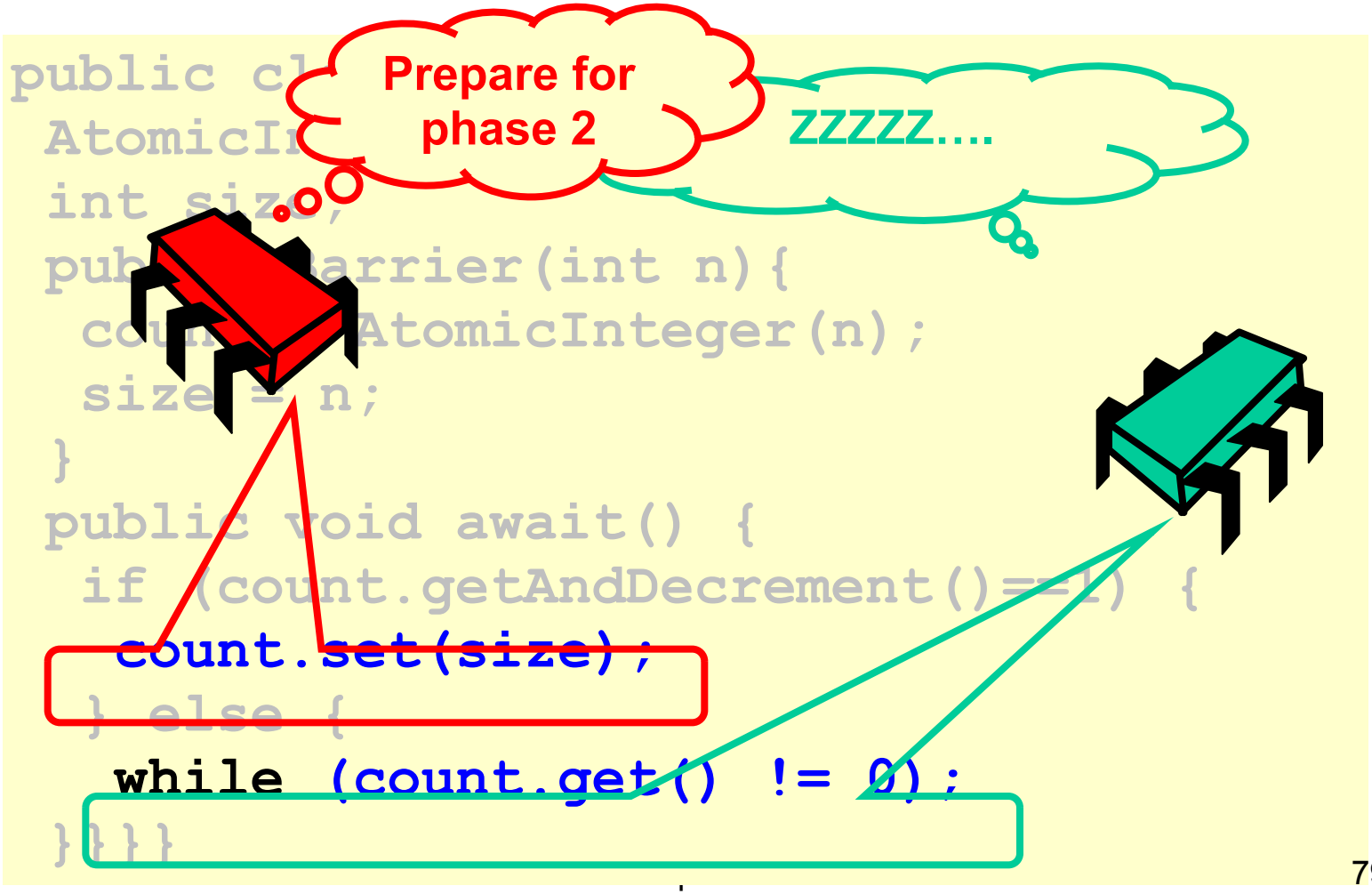
```
public class Barrier {
 AtomicInteger count
 int size;
 public Barrier(int n){
  count = AtomicInteger(n);
  size = n;
 }
 public void await() {
  if (count.getAndDecrement()==1) {
   count.set(size);
  } else {
   while (count.get() != 0);
 }}}}
```



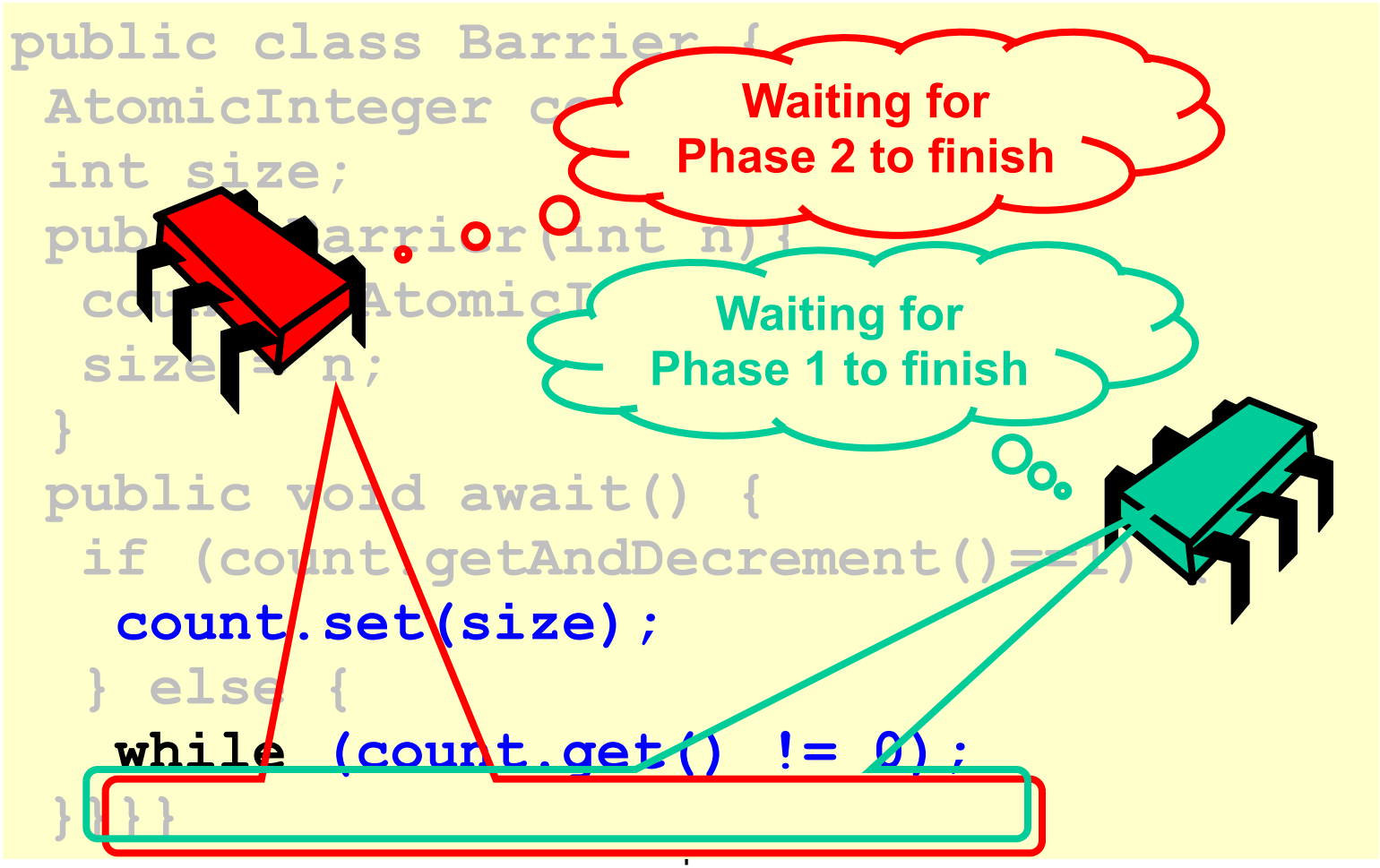
Barriers


Phase 1
is so over
Waiting for
Phase 1 to finish
public cl
AtomicIn
int size;
pub arrier(int n){
coun AtomicInteger(n);
size = n;
}
public void await() {
if (count.getAndDecrement()==1) {
count.set(size);
} else {
while (count.get() != 0);
}}}

Barriers


Prepare for phase 2
ZZZZZ….
public cl
AtomicIn
int size;
pub arrier(int n){
count AtomicInteger(n);
size = n;
}
public void await() {
if (count.getAndDecrement()==1) {
count.set(size);
} else {
while (count.get() != 0);
}}}

Uh-Oh


public class Barrier {
AtomicInteger co
int size;
pub Barrier(int n){
co AtomicI
size = n;
}
public void await() {
if (count.getAndDecrement()==1) {
count.set(size);
} else {
while (count.get() != 0);
}}}
Waiting for
Phase 2 to finish
Waiting for
Phase 1 to finish

Basic Problem

- One thread “wraps around” to start phase 2
- While another thread is still waiting for phase 1
- One solution:
  - Always use two barriers

Sense-Reversing Barriers

```
public class Barrier {
 AtomicInteger count;
 int size;
 volatile boolean sense = false;
 threadSense = new ThreadLocal<boolean>…

 public void await {
  boolean mySense = threadSense.get();
  if (count.getAndDecrement()==1) {
   count.set(size); sense = mySense
  } else {
   while (sense != mySense) {}
 }
 threadSense.set(!mySense)}}}
```

Sense-Reversing Barriers

Completed odd or even-numbered phase?

```
public class Barrier {
 AtomicInteger count;
 int size;
 volatile boolean sense = false;
 threadSense = new ThreadLocal<boolean>…

 public void await {
  boolean mySense = threadSense.get();
  if (count.getAndDecrement()==1) {
   count.set(size); sense = mySense
  } else {
   while (sense != mySense) {}
 }
 threadSense.set(!mySense)}}}
```

Sense-Reversing Barriers

```
public class Barrier {
 AtomicInteger count;
 int size;
 volatile boolean sense = false;
 threadSense = new ThreadLocal<boolean>…

 public void await {
  boolean mySense = threadSense.get();
  if (count.getAndDecrement()==1) {
   count.set(size); sense = mySense
  } else {
   while (sense != mySense) {}
 }
 threadSense.set(!mySense)}}}
```

Store sense for next phase

Sense-Reversing Barriers

```
public class Barrier {
 AtomicInteger count;
 int size;
 volatile boolean sense = false;
 threadSense = new ThreadLocal<boolean>…

 public void await {
  boolean mySense = threadSense.get();
  if (count.getAndDecrement()==1) {
    count.set(size); sense = mySense
   } else {
    while (sense != mySense) {}
 }
 threadSense.set(!mySense)}}}
```

Get new sense determined by last phase

Sense-Reversing Barriers

```
public class Barrier {
 AtomicInteger count;
 int size;
 volatile boolean sense = false;
 threadSense = new ThreadLocal<boolean>…

 public void await {
  boolean mySense = threadSense.get();
  if (count.getAndDecrement()==1) {
   count.set(size); sense = mySense
  } else {
   while (sense != mySense) {}
 }
 threadSense.set(!mySense)}}}
```

If I'm last, reverse sense for next time

Sense-Reversing Barriers

```
public class Barrier {
 AtomicInteger count;
 int size;
 volatile boolean sense = false;
 threadSense = new ThreadLocal<boolean>…

 public void await {
  boolean mySense = threadSense.get();
  if (count.getAndDecrement()==1) {
   count.set(size); sense = mySense
  } else {
   while (sense != mySense) {}
  }
 threadSense.set(!mySense)}}}
```

Otherwise, wait for sense to flip

Sense-Reversing Barriers

```
public class Barrier {
 AtomicInteger count;
 int size;
 volatile boolean sense = false;
 threadSense = new ThreadLocal<boolean>…

 public void await {
  boolean mySense = threadSense.get();
  if (count.getAndDecrement()==1) {
   count.set(size); sense = mySense
  } else {
   while (sense != mySense) {}
 }
 threadSense.set(!mySense)}}}
```

Prepare sense for next phase