Concurrency:
Multi-core Programming & Data Processing

Barrier Synchronization

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*Based on slides by **Maurice Herlihy** and **Nir Shavit***

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();
}
```

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

Two-Phase Rendering

1st thread

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

Even phases

Odd phases

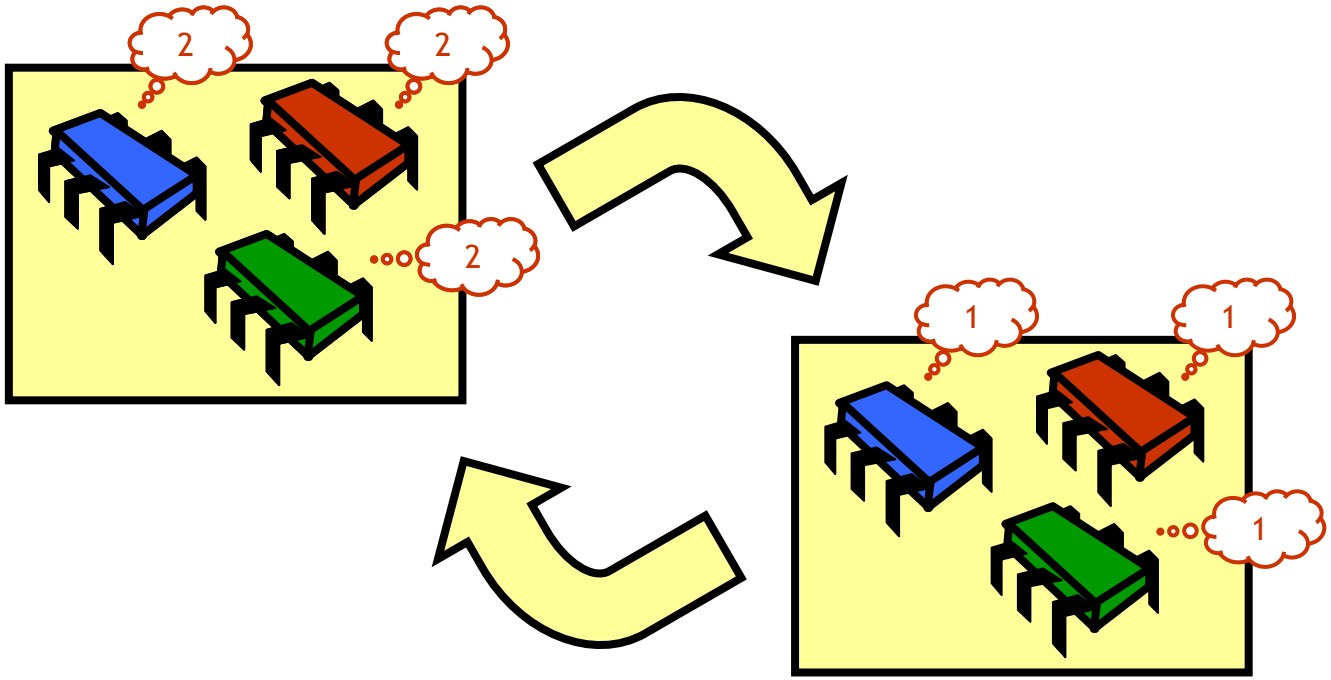
2nd thread

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

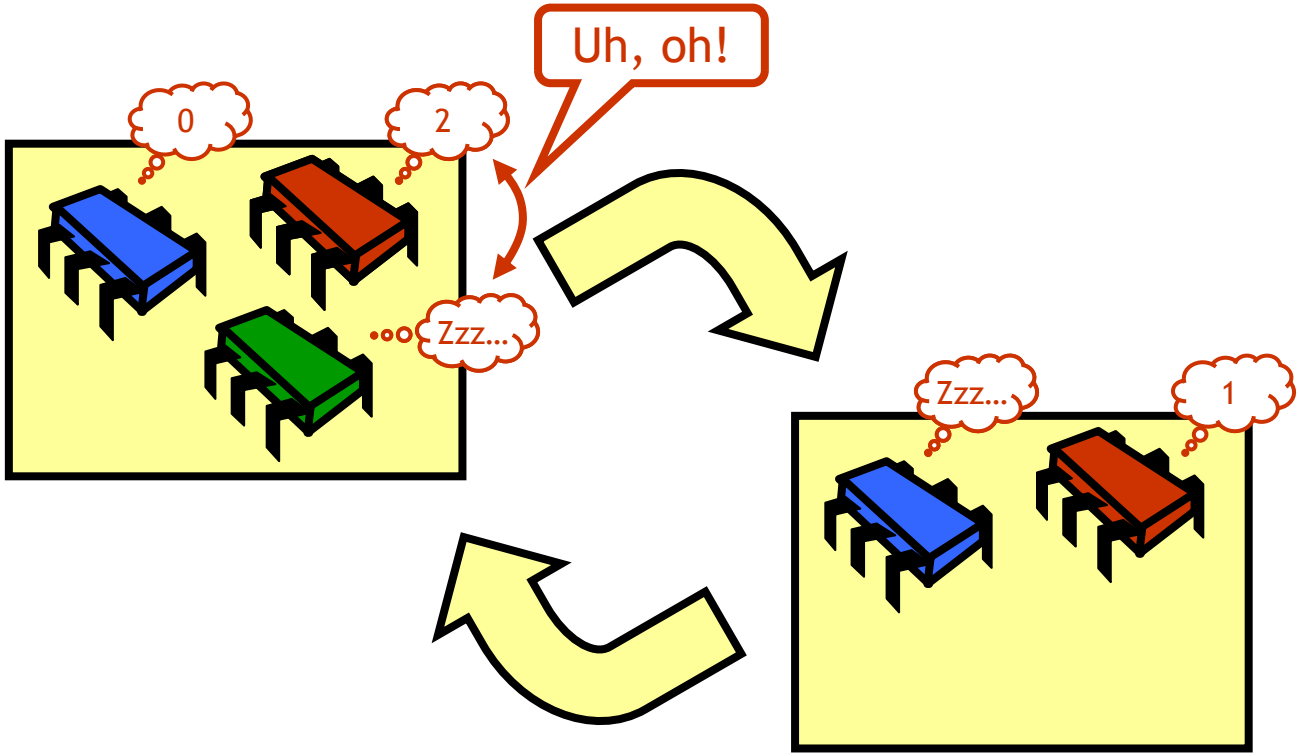
Synchronization Problems

- How do threads stay in phase?
- Too early?
  - Display frame before it is fully rendered
- Too late?
  - Recycle memory before frame is displayed

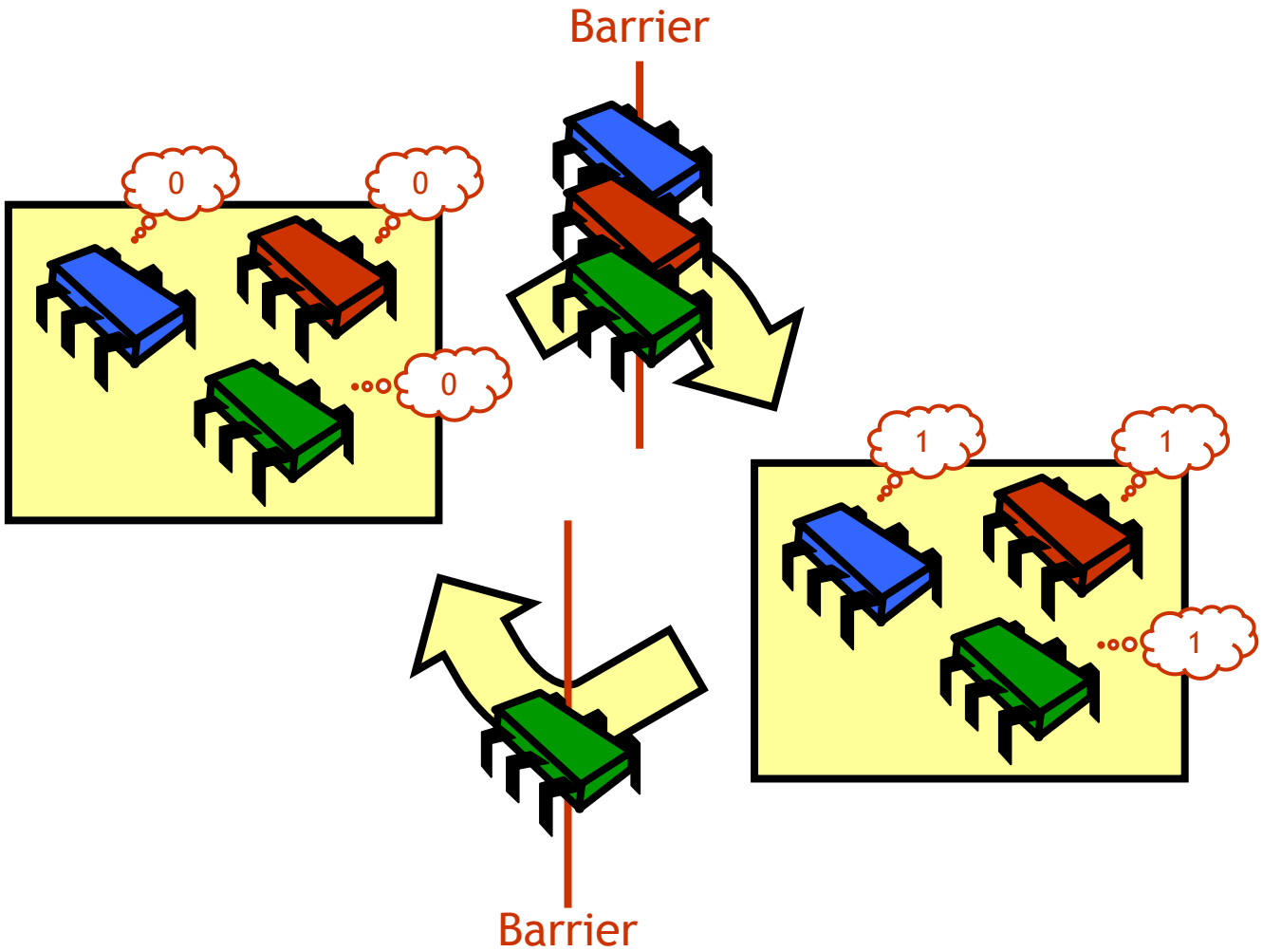
Ideal Parallel Computation



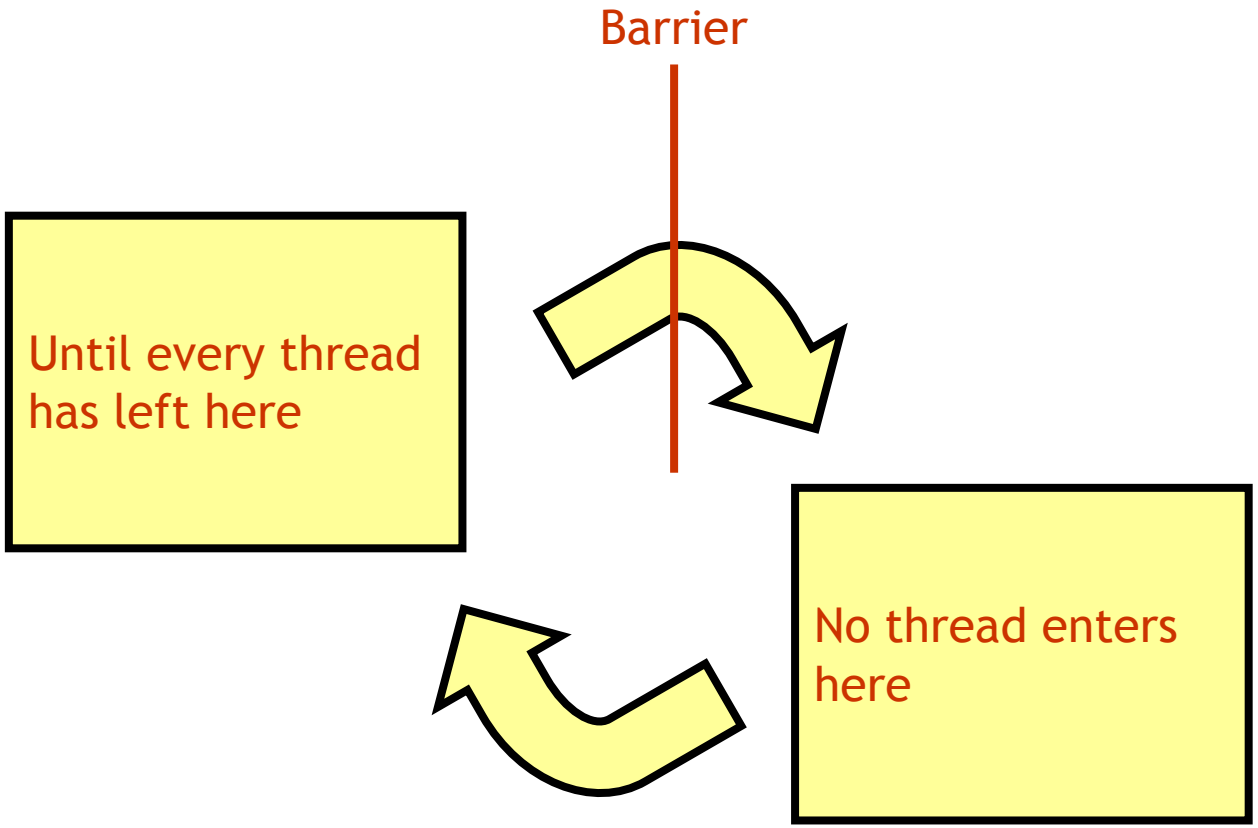
Real-Life Parallel Computation



Barrier Synchronization



Barrier Synchronization



Why Do We Care?

- Mostly of interest to
  - Scientific and numeric computation

- Elsewhere
  - Garbage collection
  - Less common in systems programming
  - Still important topic

Duality

- Dual to mutual exclusion
  - Include others, not exclude them
  - Same implementation issues

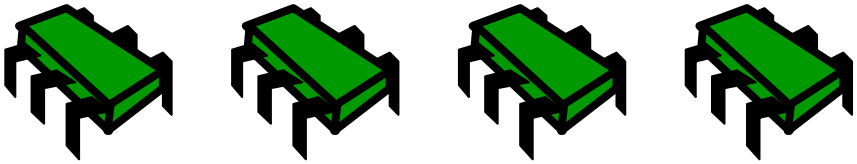
- Interaction with caches
  - Invalidation?
  - Local spinning?

Example: Parallel Prefix

Before

a	b	c	d

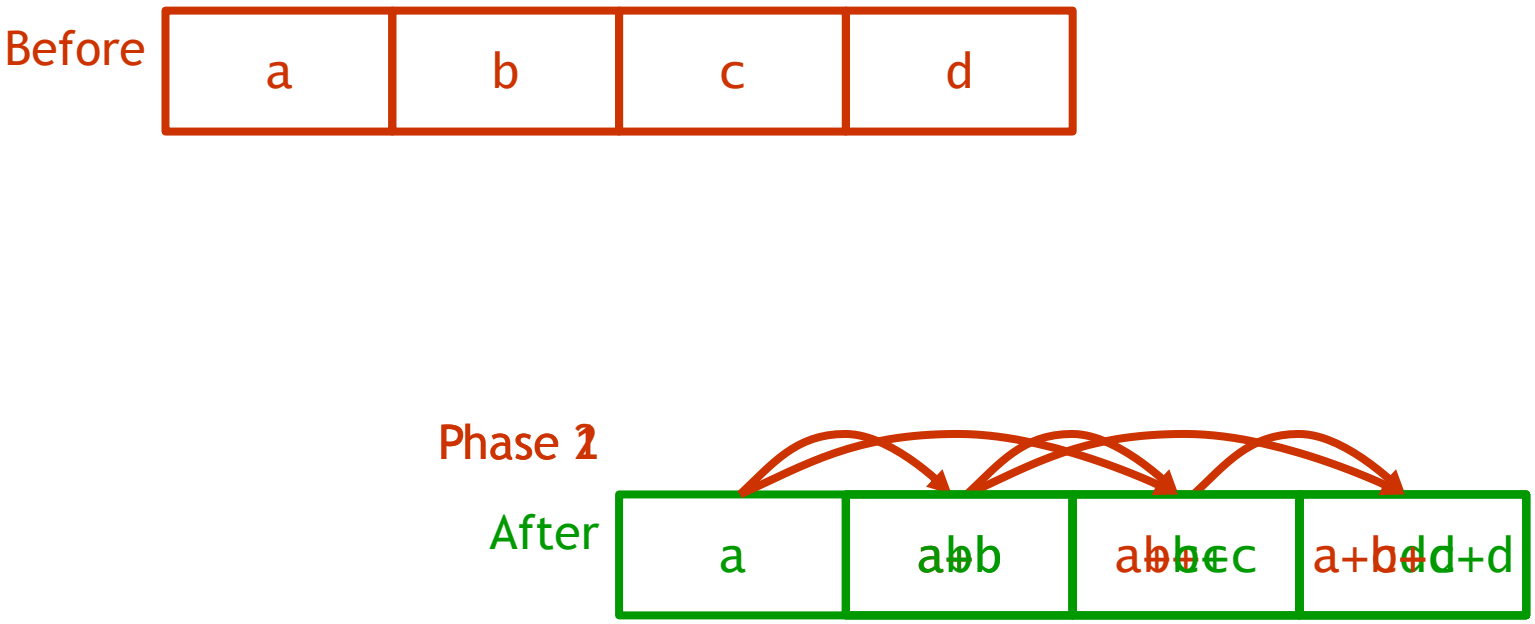
One thread per entry



After

a	a+b	a+b+c	a+b+c+d

Parallel Prefix: Phases



Parallel Prefix

- N threads can compute
  - Parallel prefix
  - Of N entries
  - In $\log_2$ N rounds

- What if system is asynchronous?
  - That is why we need barriers!

Parallel Prefix

```
class Prefix extends Thread {
  private int[] a;
  private int i;
  private Barrier b;
  public Prefix(int[] a, int i, Barrier b) {
   this.a = a;
   this.i = i;
   this.b = b;
  }
  …
}
```

Array of input values

Thread index

Shared barrier

Initialize fields

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

Number of threads not yet arrived

Number of threads participating

Initialization

Wait on barrier

If I am last, reset fields for next time

Otherwise, wait for everyone else

What's wrong with this protocol?

Reuse

```
{
  …
  Barrier b = new Barrier(n);
  while (mumble()) {

    work();
    b.await();

  }
}
```

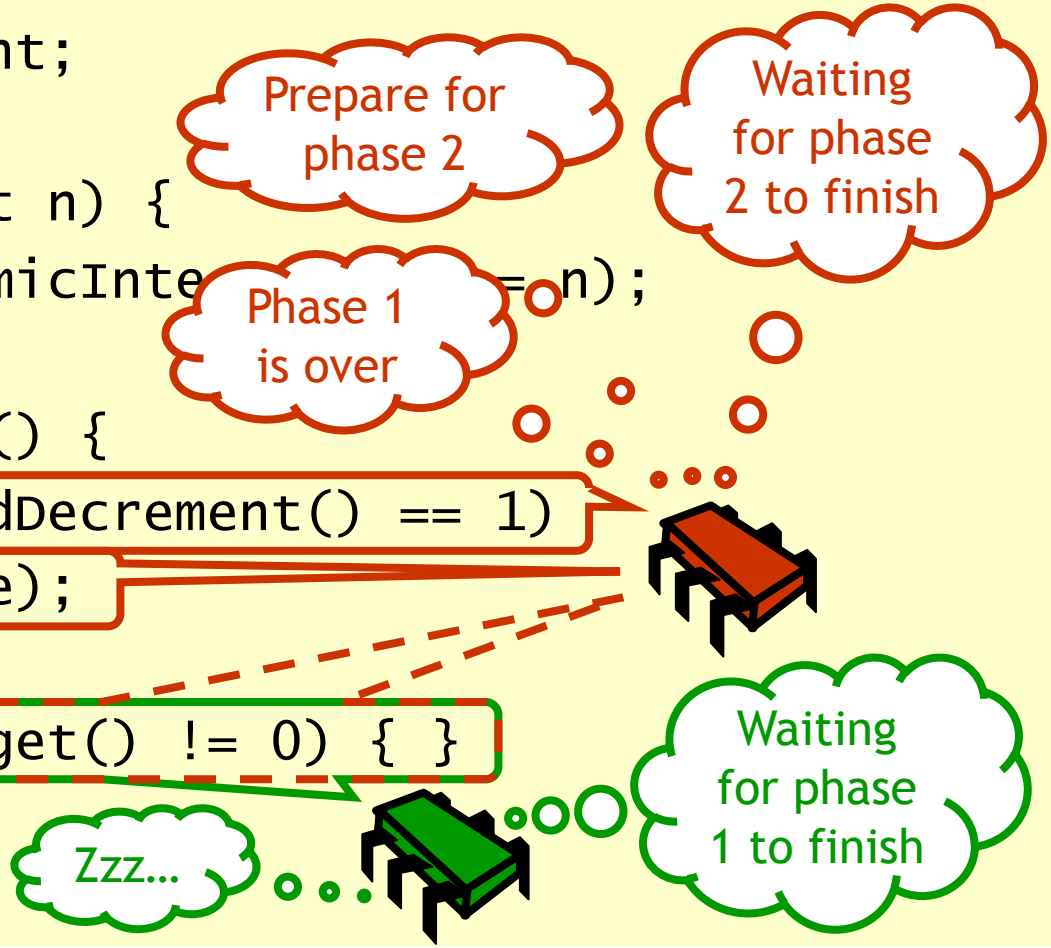
Do work

Synchronize

Repeat

Barriers

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



Basic Problem

- One thread “wraps around” to start phase 2…

  …while another thread is still waiting for phase 1

- Solutions
  - Always use two barriers
  - Sense-reversing barrier

Sense-Reversing Barriers

```
public class SenseBarrier {
  AtomicInteger count;
  int size;
  volatile boolean sense = true;
  public void await(boolean mySense) {
    if (count.getAndDecrement() == 1) {
      count.set(size);
      sense = mySense
    } else
      while (sense != mySense) { }
  }
}
```

Completed odd or even phase?

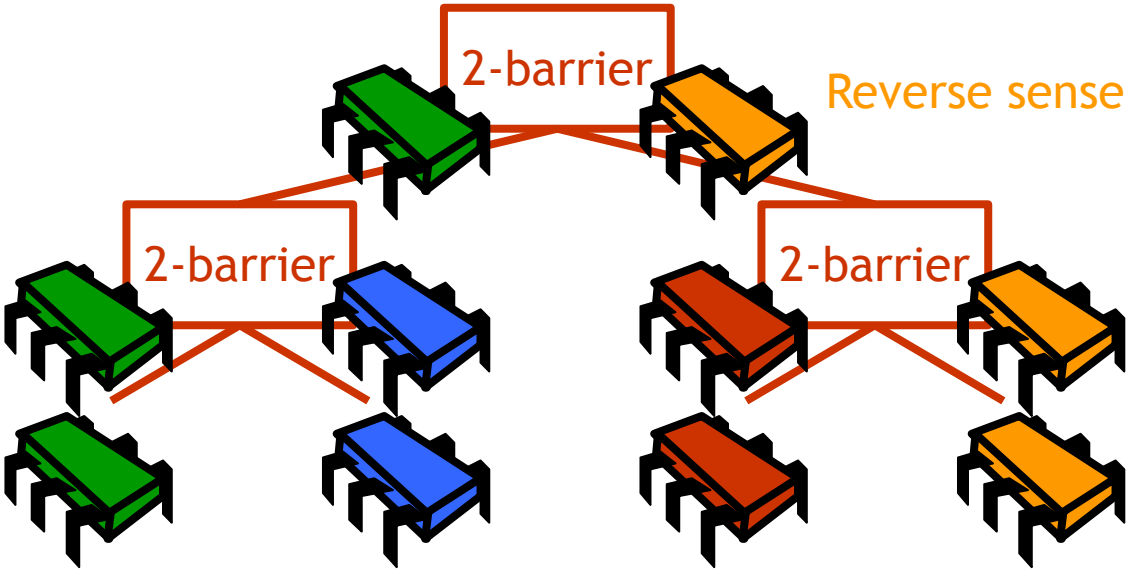
Thread working on odd or even phase?

If last, reverse sense for next time

Otherwise, wait for sense to flip

Combining Tree Barriers

- Goal: decrease contention
  - Processors at leaves
  - Node are *n*-way barriers (in different cache lines)



Combining Tree Barriers

```
public class TreeBarrier {
  AtomicInteger count;
  int size;
  TreeBarrier parent;
  public void await(boolean mySense) {
    if (count.getAndDecrement() == 1) {
      if (parent != null)
        parent.await(mySense);
      count.set(size);
      sense = mySense;
    } else while (sense != mySense) { }
  }
}
```

Parent barrier in tree

Thread working on odd or even phase?

Am I last?

Proceed to parent barrier

Reset barrier and notify others at this node

I am not last, so wait for notification

Combining Tree Barriers

- No sequential bottleneck
  - Parallel `getAndDecrement()` calls
- Low memory contention
  - Same reason
- Cache behavior
  - Everyone spins on `sense` field
  - Local spinning on bus-based architecture
  - Not so good for NUMA

Summary

- Basic barrier must be used carefully
- Sense-reversing
  - Reuse without reinitializing
- Combining tree
  - Less contention, more scalable
- Other barriers
  - Tournament tree
  - Dissemination barrier…