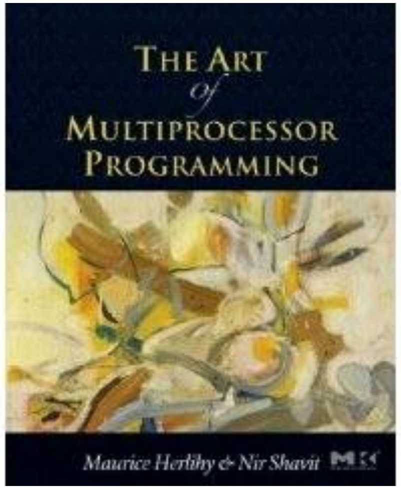
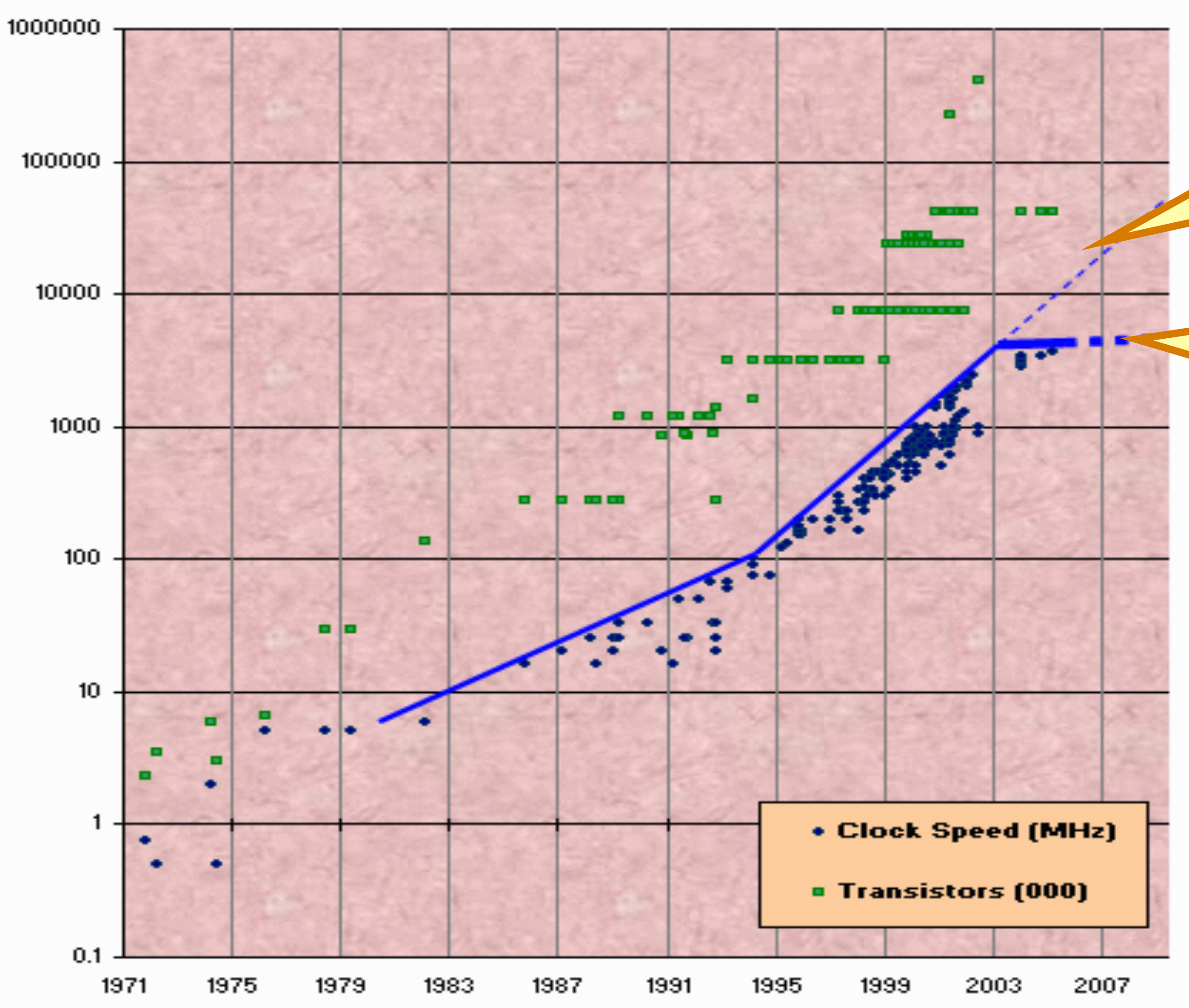
Introduction


THE ART of MULTIPROCESSOR PROGRAMMING
Maurice Herlihy & Nir Shavit
MK

Companion slides for
The Art of Multiprocessor Programming
by Maurice Herlihy & Nir Shavit

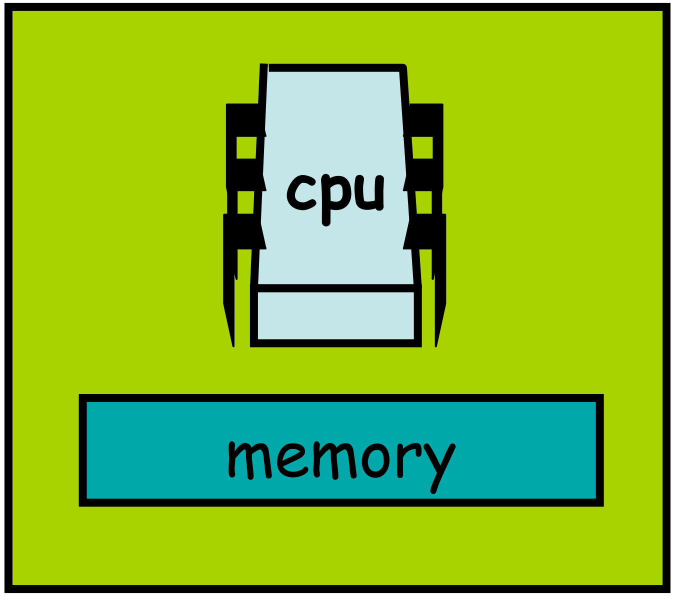
Moore's Law



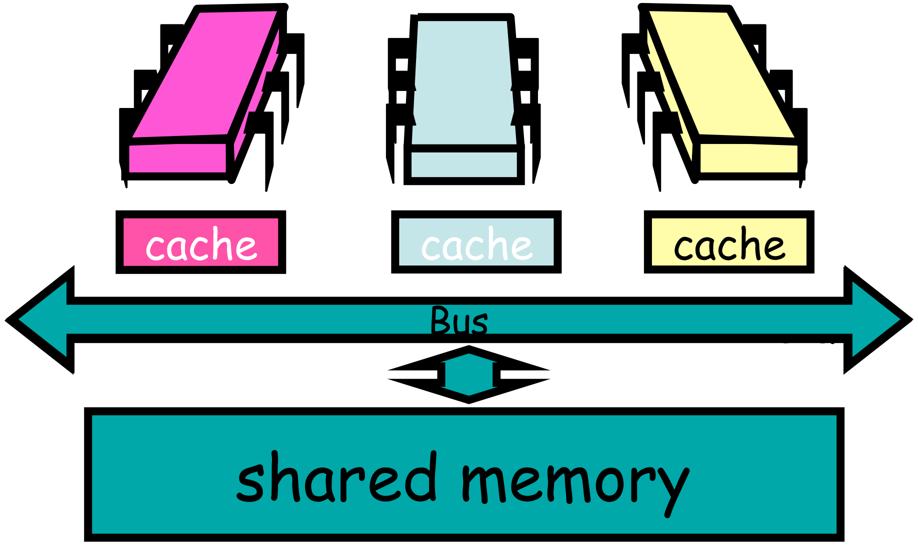
Transistor count still rising

Clock speed flattening sharply

Vanishing from your Desktops: The Uniprocesor

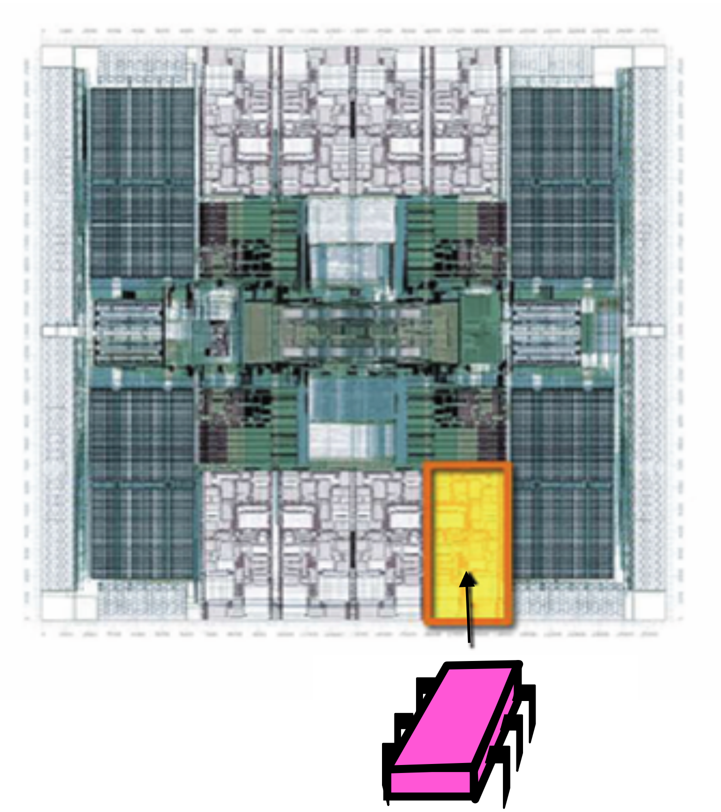


Your Server: The Shared Memory Multiprocessor (SMP)



Your New Server or Desktop: The Multicore Processor (CMP)

All on the same chip

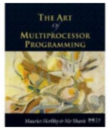


Sun T2000 Niagara

From the 2008 press…

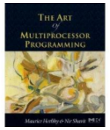
…*Intel* has announced a press conference in San Francisco on November 17th, where it will officially launch the Core *i7* Nehalem processor…

…Sun's next generation Enterprise T5140 and T5240 servers, based on the 3rd Generation UltraSPARC T2 Plus processor, were released two days ago…

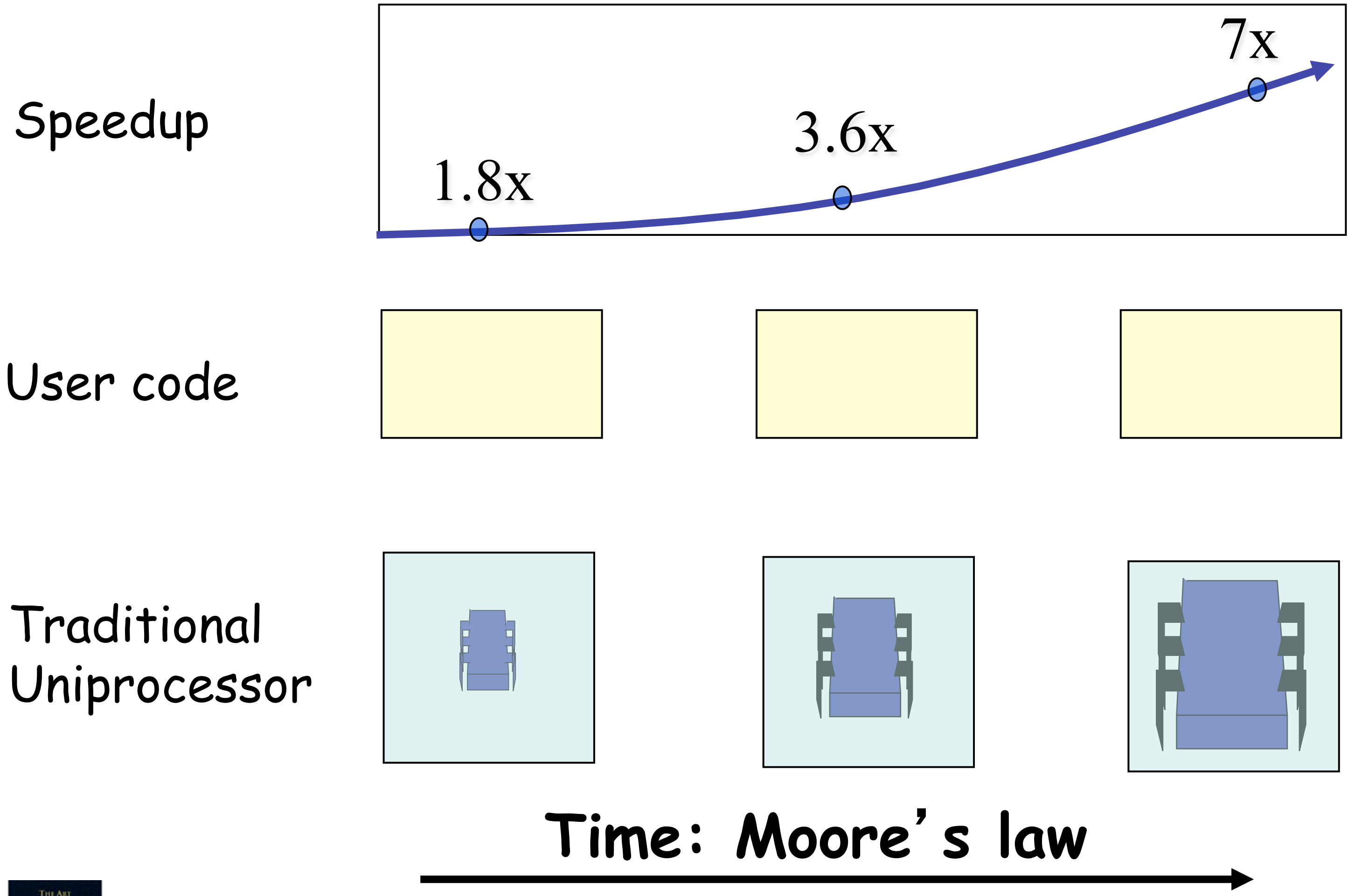


Why do we care?

- Time no longer cures software bloat
  - The “free ride” is over
- When you double your program’s path length
  - You can’t just wait 6 months
  - Your software must somehow exploit twice as much concurrency



Traditional Scaling Process



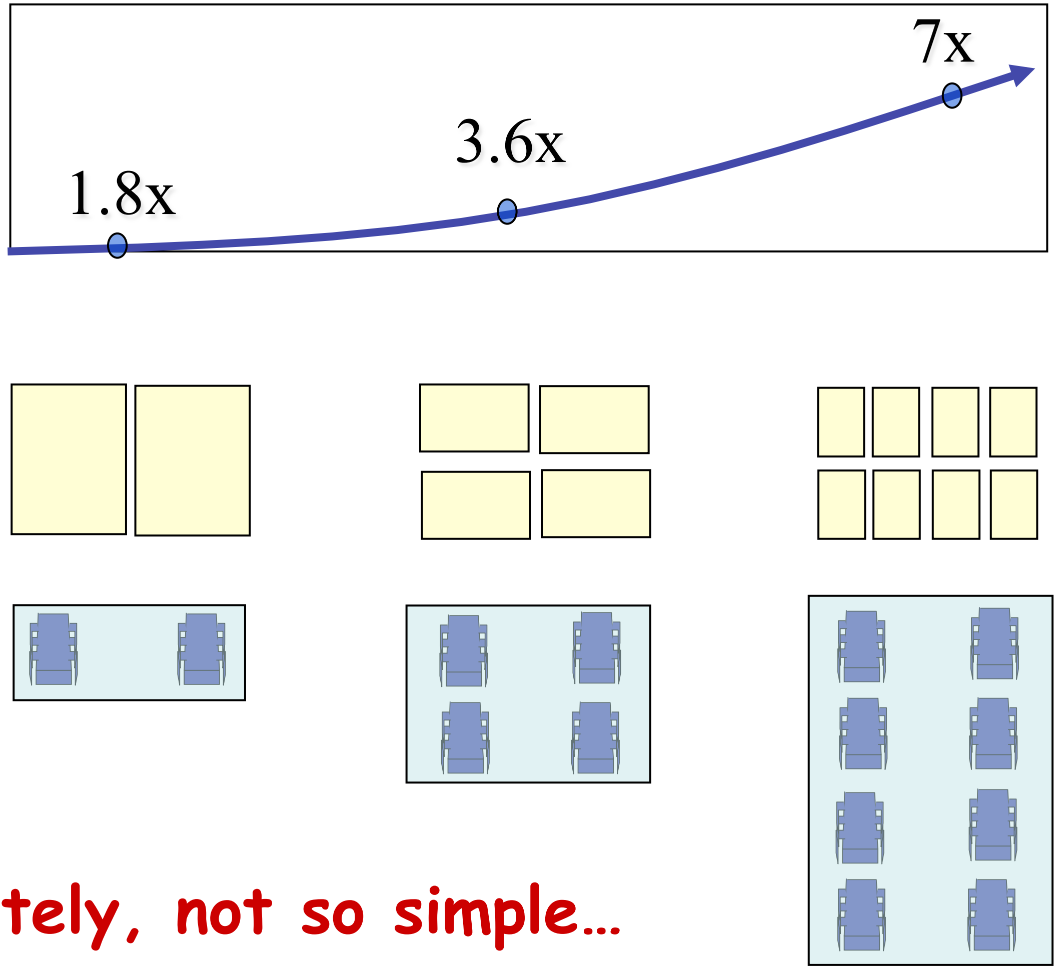
Speedup

User code

Traditional Uniprocessor

Time: Moore's law

Multicore Scaling Process



Speedup

User code

Multicore

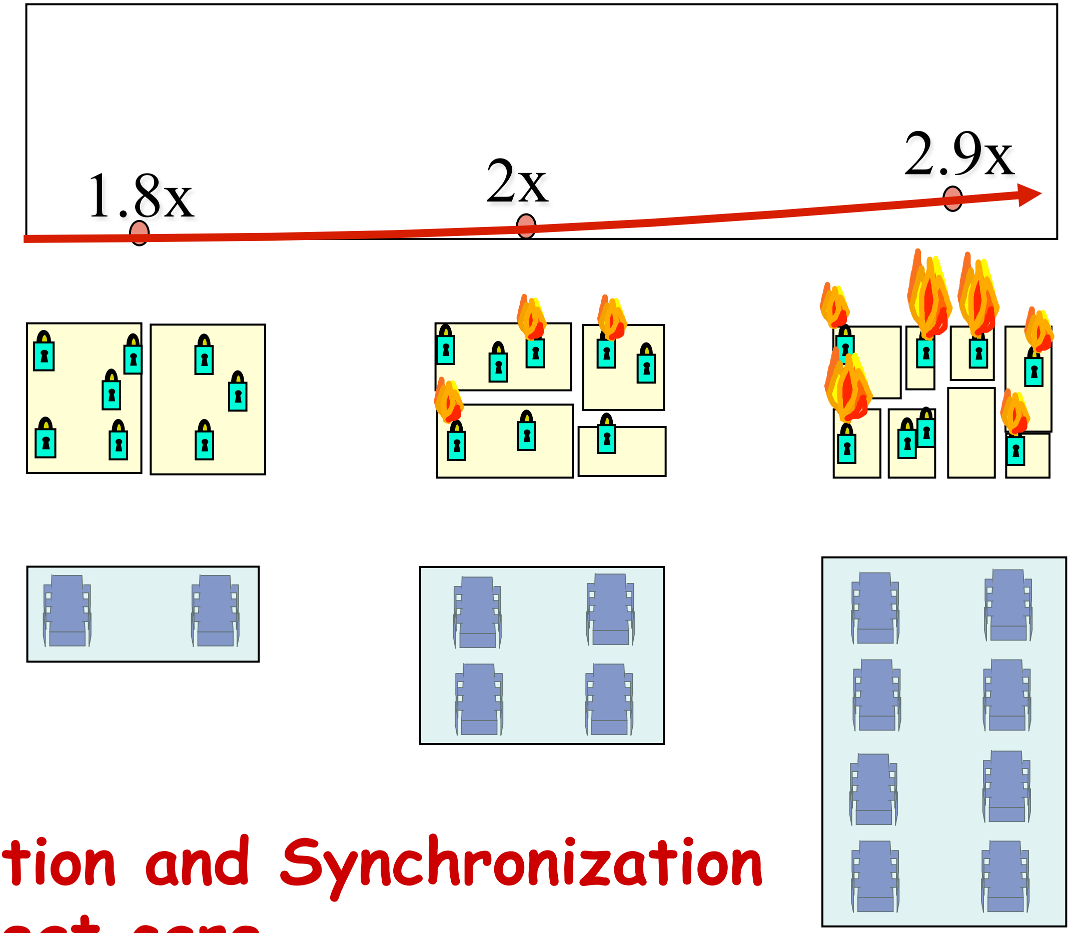
Unfortunately, not so simple…

Real-World Scaling Process

Speedup

User code

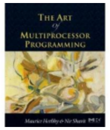
Multicore



Parallelization and Synchronization require great care…

Multicore Programming: Course Overview

- Fundamentals
  - Models, algorithms, impossibility
- Real-World programming
  - Architectures
  - Techniques

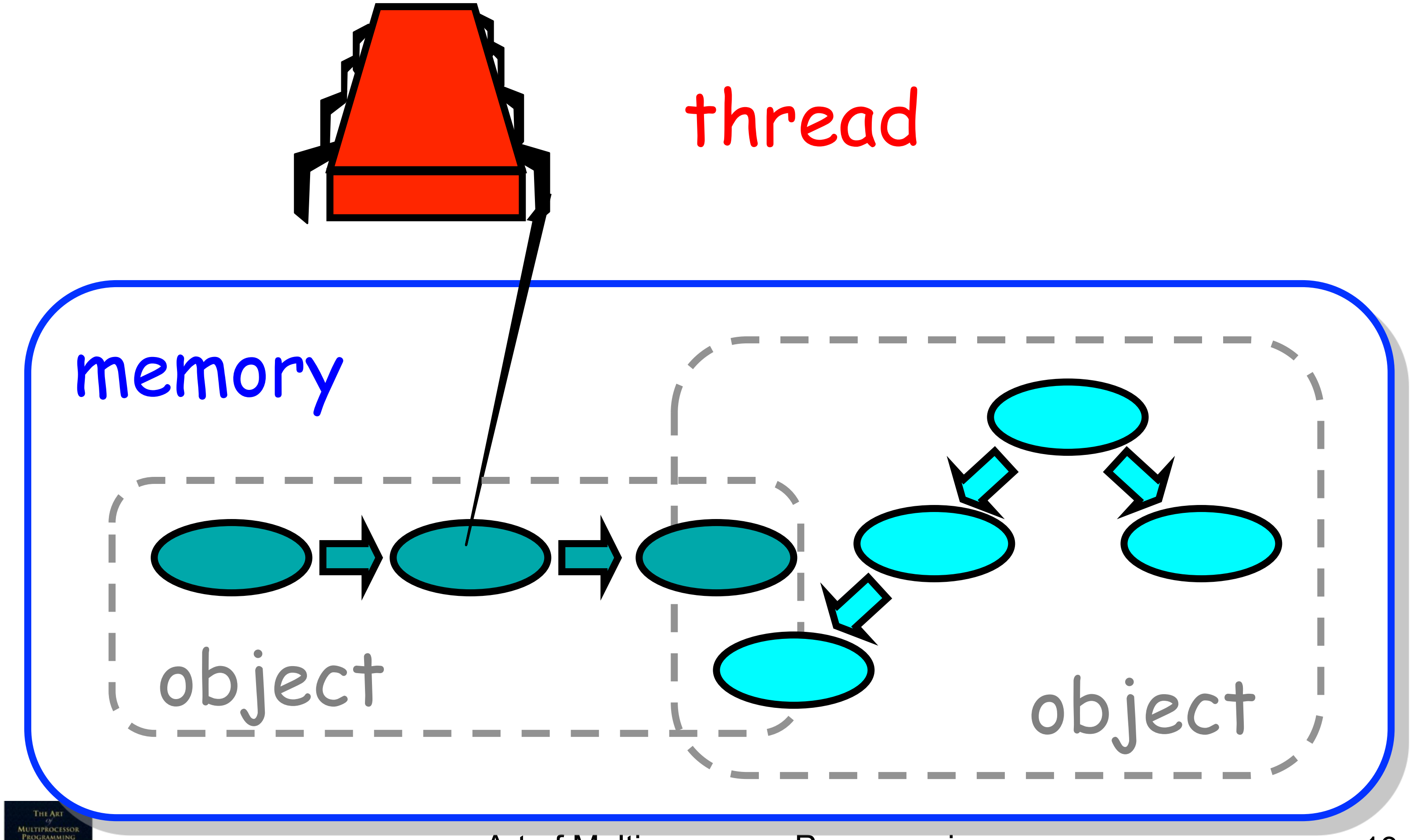


Multicore Programming: Course Overview

- Fundamentals
  - Models, algorithms, i
- Real-World pro
  - Architect
  - Techniques

We don’t necessarily want to make you experts…

Sequential Computation



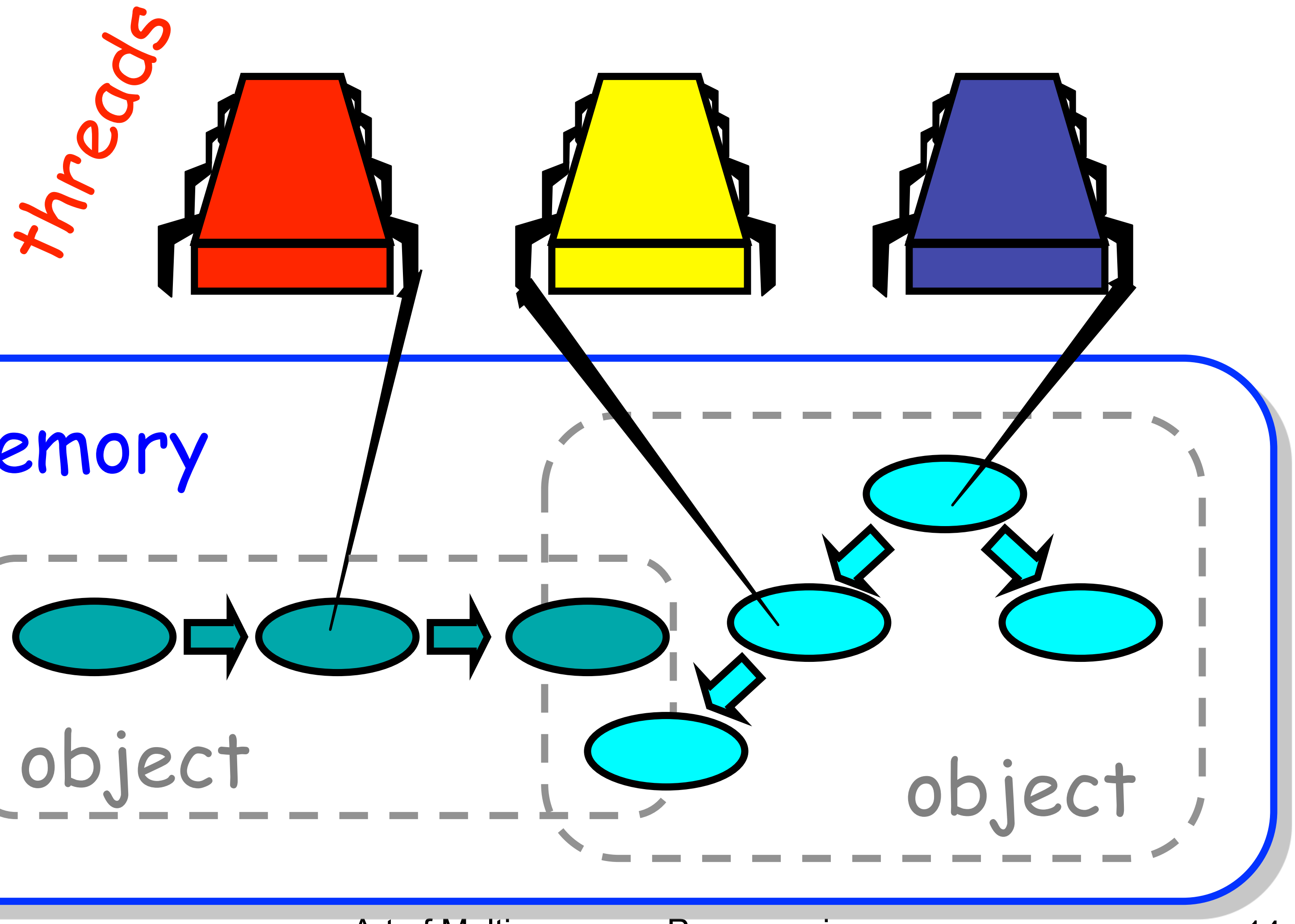
thread

memory

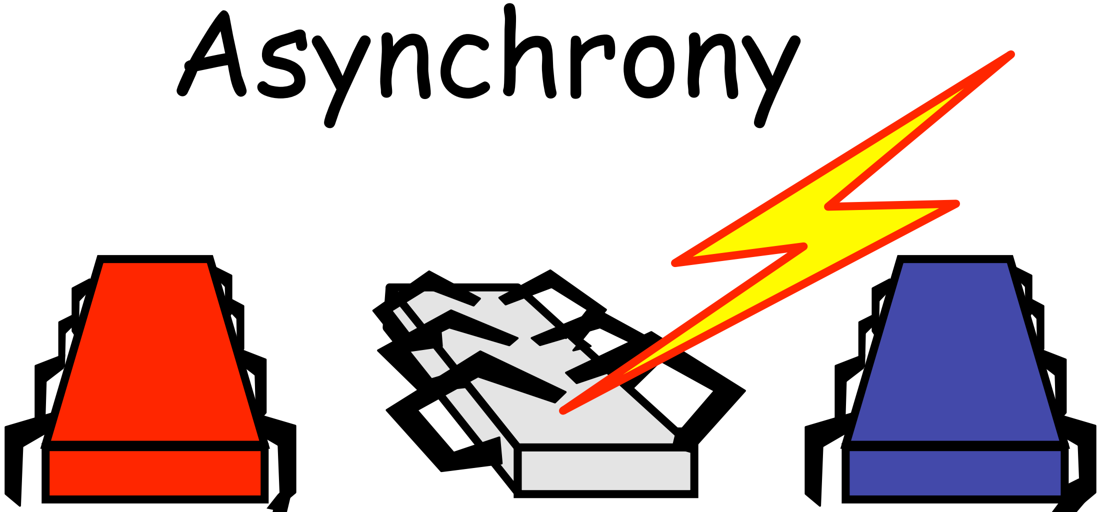
object

object

Concurrent Computation



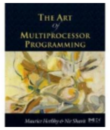
Asynchrony



- Sudden unpredictable delays
  - Cache misses (*short*)
  - Page faults (*long*)
  - Scheduling quantum used up (*really long*)

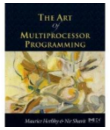
Model Summary

- Multiple *threads*
  - Sometimes called *processes*
- Single shared *memory*
- *Objects* live in memory
- Unpredictable asynchronous delays



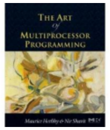
Road Map

- We are going to focus on principles first, then practice
  - Start with idealized models
  - Look at simplistic problems
  - Emphasize correctness over pragmatism
  - "Correctness may be theoretical, but incorrectness has practical impact"



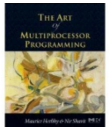
Concurrency Jargon

- Hardware
  - Processors
- Software
  - Threads, processes
- Sometimes OK to confuse them, sometimes not.

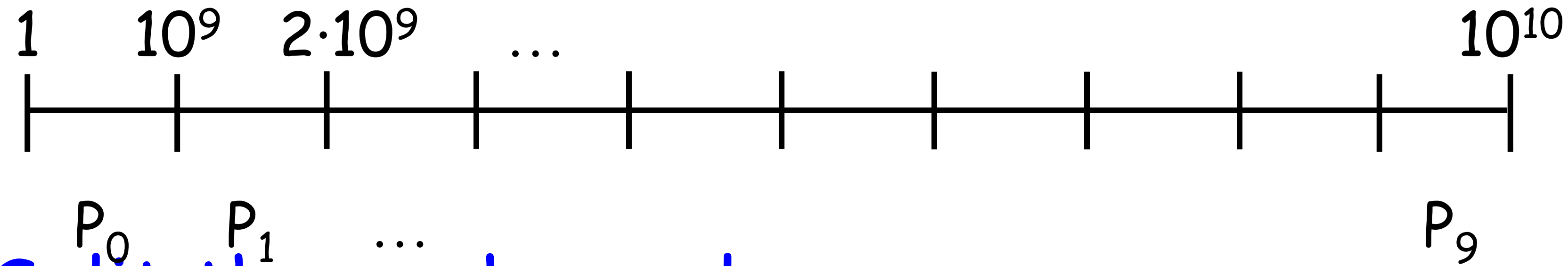


Parallel Primality Testing

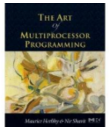
- Challenge
  - Print primes from 1 to 10^{10}
- Given
  - Ten-processor multiprocessor
  - One thread per processor
- Goal
  - Get ten-fold speedup (or close)



Load Balancing

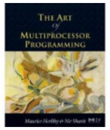


- Split the work evenly
- Each thread tests range of 10^9



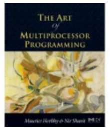
Procedure for Thread *i*

```
void primePrint {
  int i = ThreadID.get(); // IDs in {0..9}
  for (j = i*10^9+1, j<(i+1)*10^9; j++) {
    if (isPrime(j))
      print(j);
  }
}
```



Issues

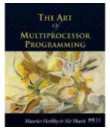
- Higher ranges have fewer primes
- Yet larger numbers harder to test
- Thread workloads
  - Uneven
  - Hard to predict



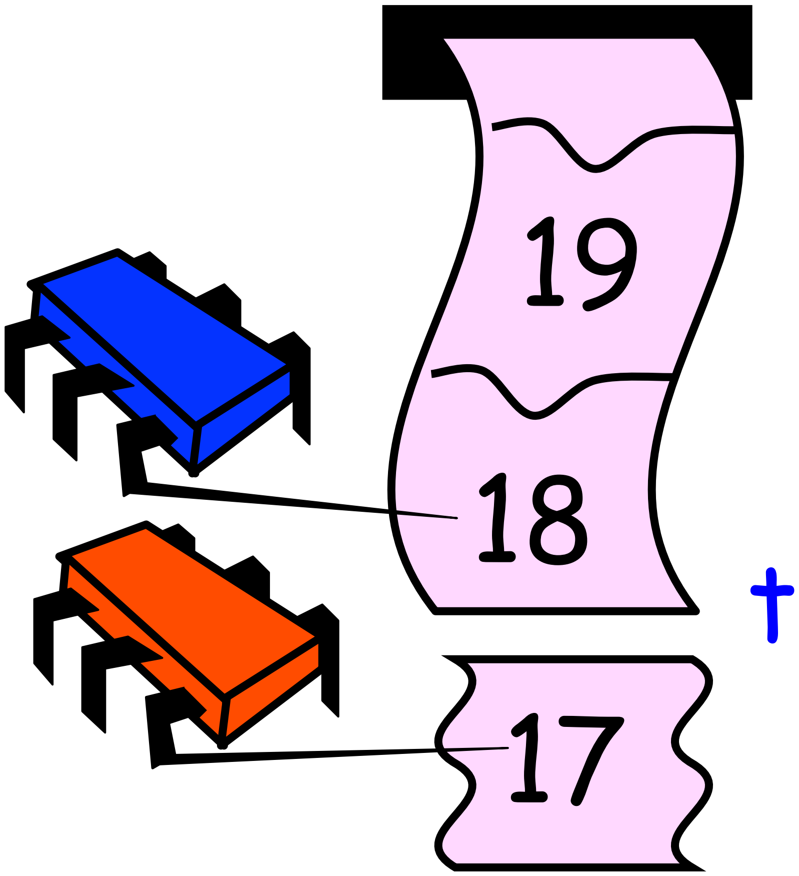
Issues

- Higher ranges have fewer primes
- Yet larger numbers harder to test
- Thread workloads
  - Uneven
  - Hard to predict
- Need *dynamic* load balancing

rejected



Shared Counter

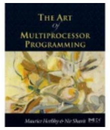


each thread takes a number

Procedure for Thread *i*

```
int counter = new Counter(1);

void primePrint {
  long j = 0;
  while (j < 10^10) {
    j = counter.getAndIncrement();
    if (isPrime(j))
      print(j);
  }
}
```



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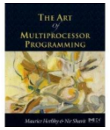
  }
}
```

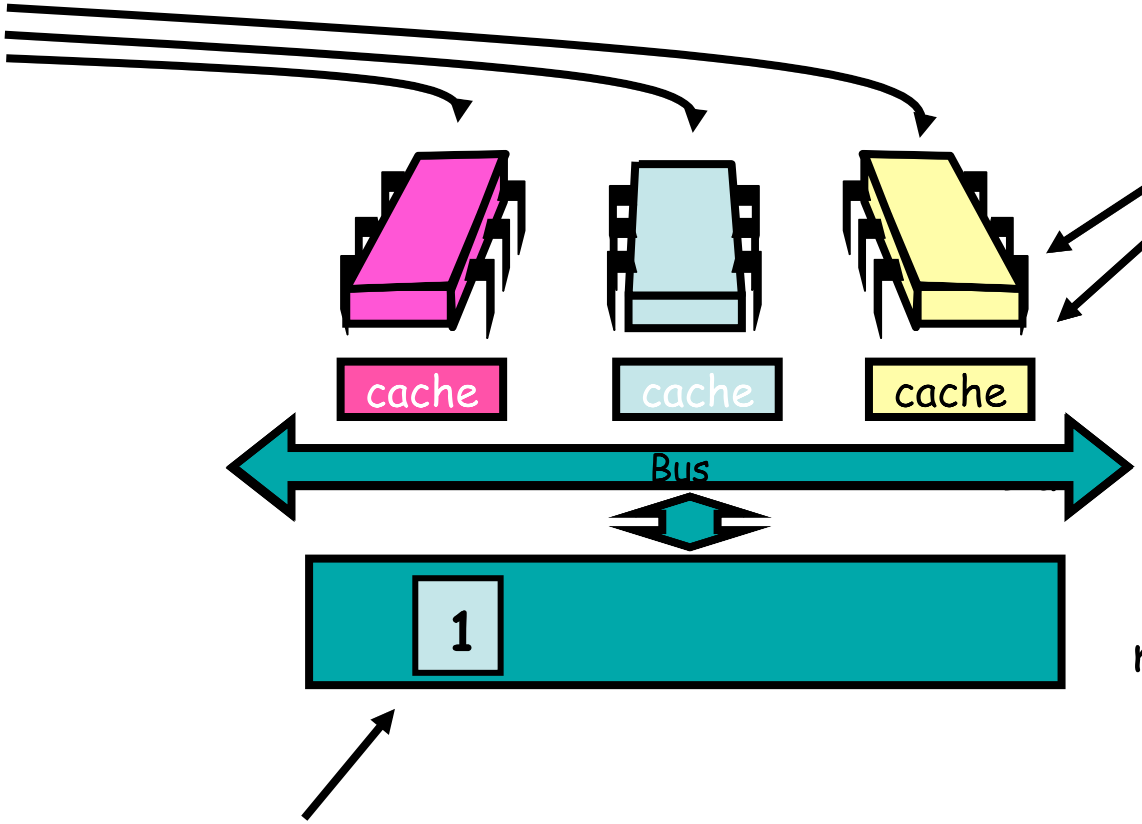
Shared counter object



Where Things Reside

```
void primePrint {
  int i =
ThreadID.get(); // IDs
in {0..9}
  for (j = i*10^9+1, j<(i
+1)*10^9; j++) {
    if (isPrime(j))
      print(j);
  }
}
```

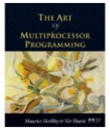
code



Local variables

shared memory

shared counter



Procedure for Thread *i*

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void primePrint {
  long j = 0;
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    j = counter.getAndIncrement();
    if (isPrime(j))
      print(j);
  }
}
```
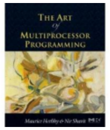
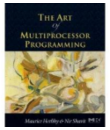

Stop when every value taken



Procedure for Thread *i*

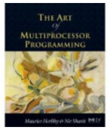
```
Counter counter = new Counter(1);

void primePrint {
  long j = 0;
  while (j < $10^{10}$) {
    j = counter.getAndIncrement();
    if (isPrime(j))
      print(j);
  }
}
```

Increment & return each new value



Counter Implementation

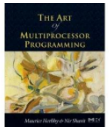
```
public class Counter {
  private long value;

  public long getAndIncrement() {
    return value++;
  }
}
```



Counter Implementation

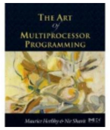
```
public class Counter {
  private long value;

  public long getAndIncrement() {
    return value++;
  }
}
```

OK for single thread, not for concurrent threads



What It Means

```
public class Counter {
  private long value;

  public long getAndIncrement() {
    return value++;
  }
}
```

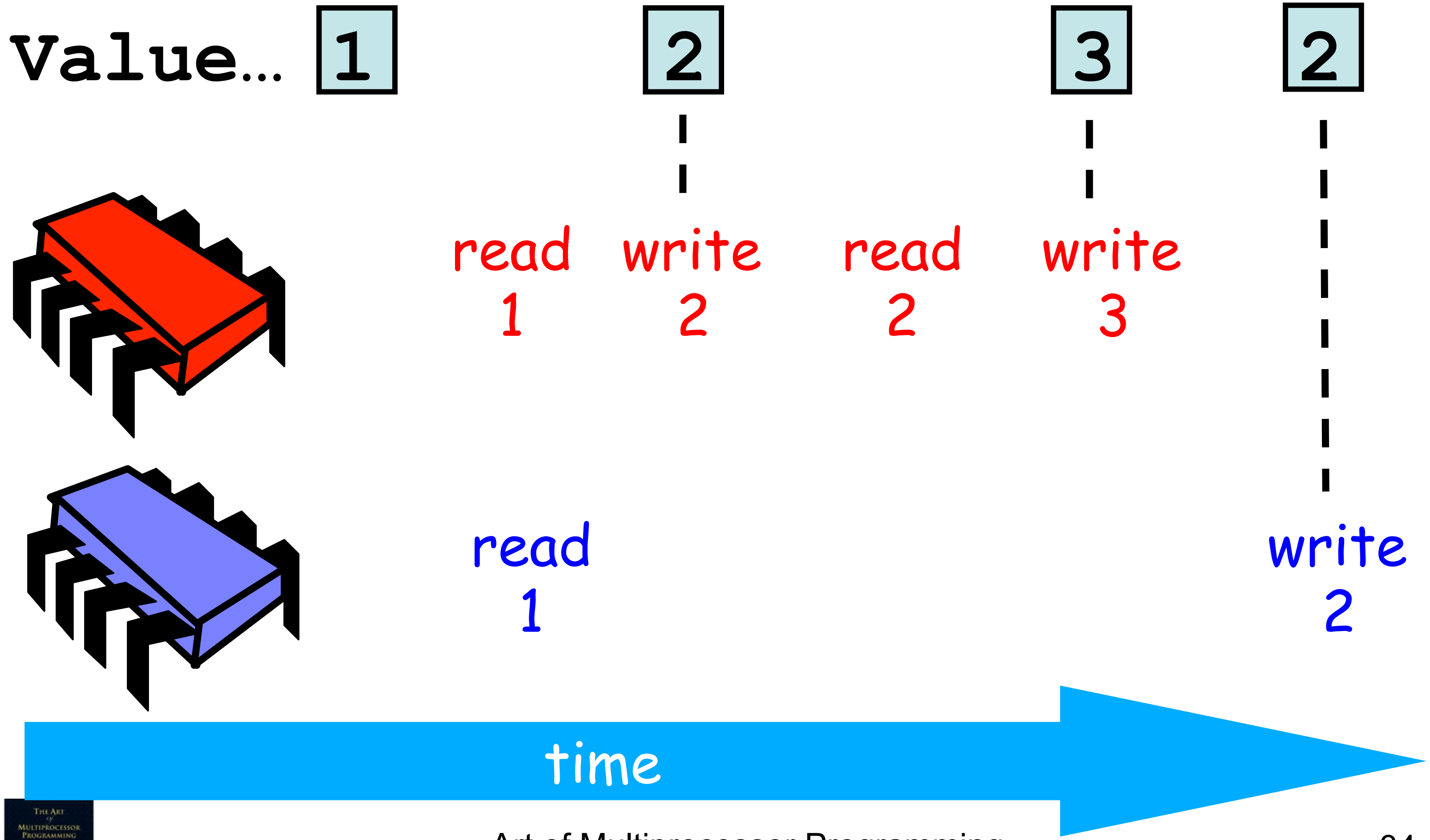


What It Means

```
public class Counter {
  private long value;

  public long getAndIncrement() {
    return value++;
  }
}
```

```
temp  = value;
value = temp + 1;
return temp;
```

Not so good…



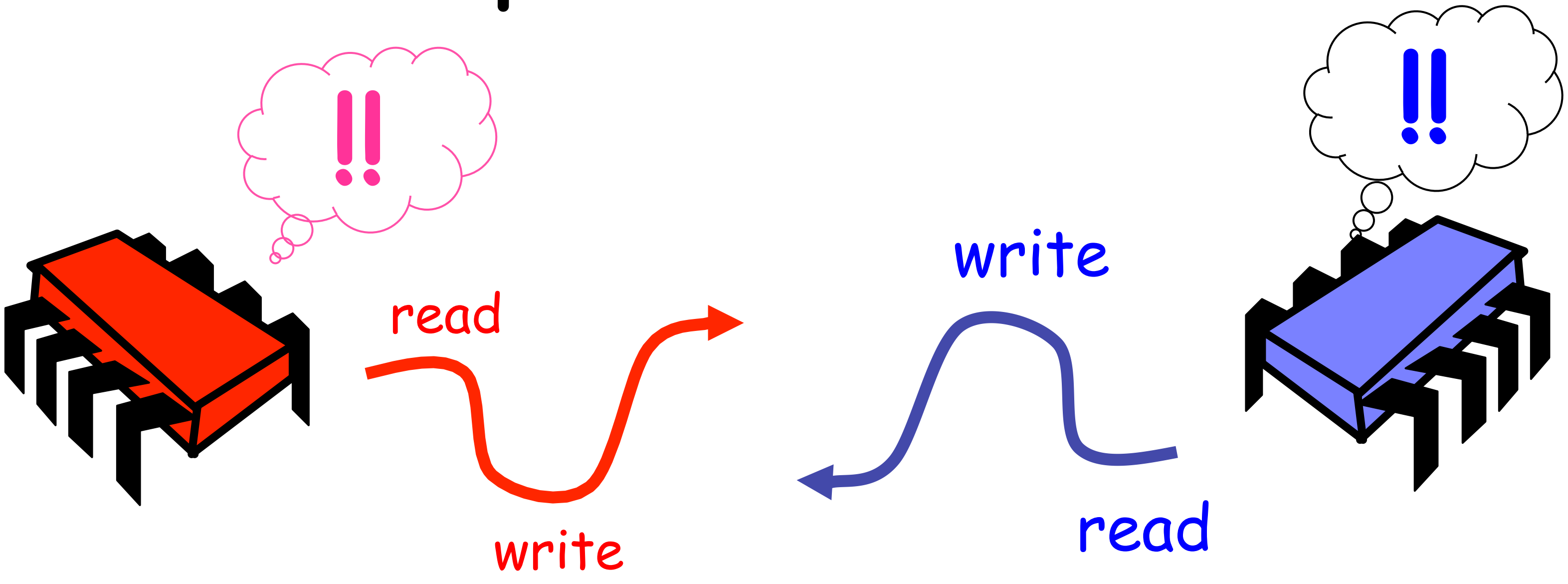
Value… 1 2 3 2

read 1 write 2 read 2 write 3

read 1 write 2

time

Is this problem inherent?



If we could only glue reads and writes together…

Challenge

```
public class Counter {
  private long value;

  public long getAndIncrement() {
    temp  = value;
    value = temp + 1;
    return temp;
  }
}
```

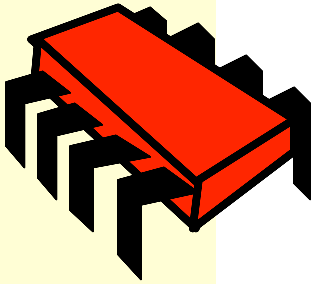
Challenge

```
public class Counter {
  private long value;

  public long getAndIncrement() {
    temp  = value;
    value = temp + 1;
    return temp;
  }
}
```

Make these steps *atomic* (indivisible)

Hardware Solution

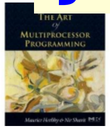
```
public class Counter {
  private long value;

  public long getAndIncrement() {
    temp  = value;
    value = temp + 1;
    return temp;
  }
}
```



ReadModifyWrite() instruction

An Aside: Java™

```
public class Counter {
  private long value;

  public long getAndIncrement() {
    synchronized {
      temp  = value;
      value = temp + 1;
      }
    return temp;
  }
}
```



An Aside: Java™

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  public long getAndIncrement() {
    synchronized {
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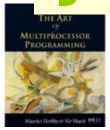
      }
    return temp;
  }
}
```

Synchronized block



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  private long value;

  public long getAndIncrement() {
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  }
}
```
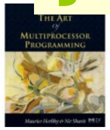
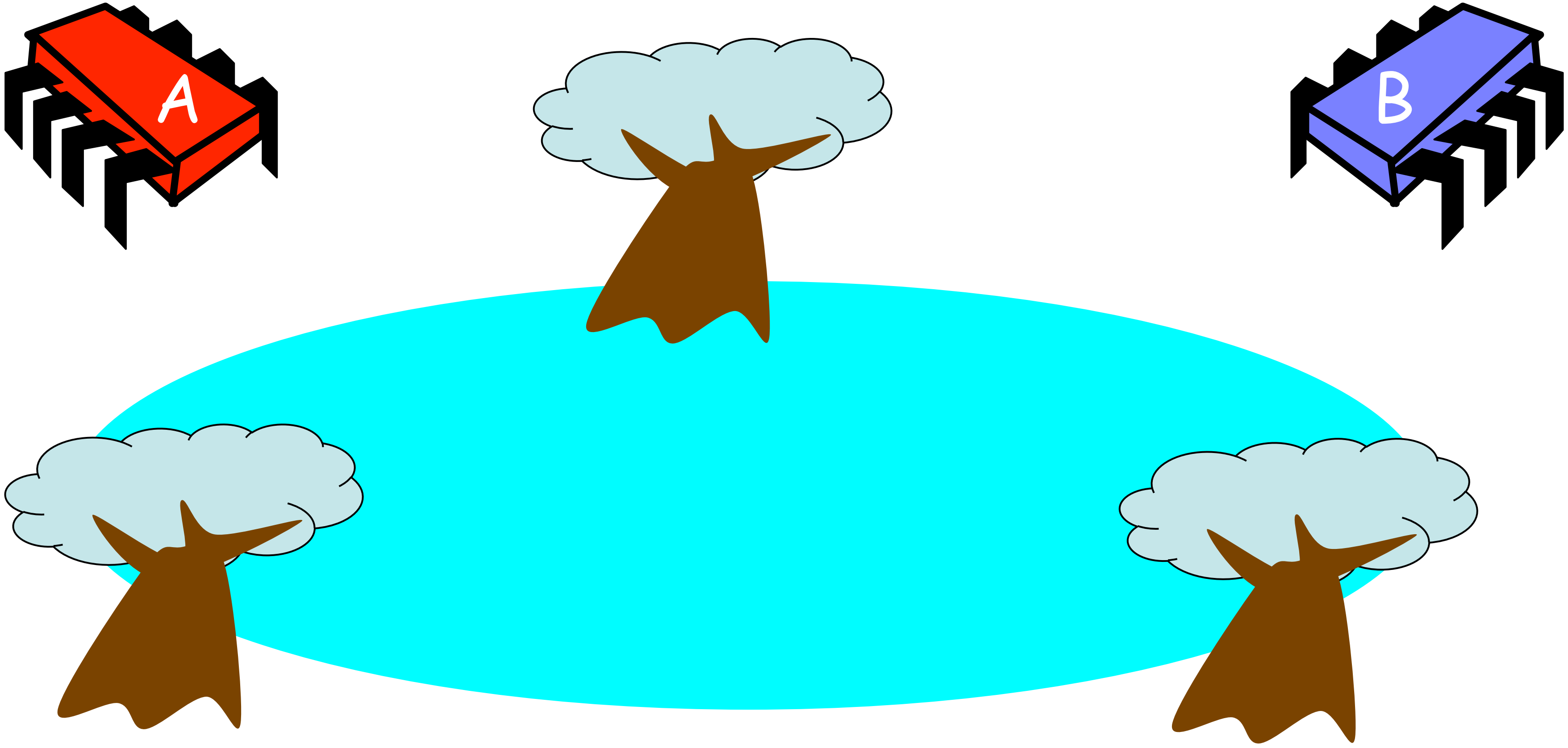
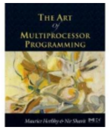

Mutual Exclusion



Mutual Exclusion or "Alice & Bob share a pond"





Alice has a pet

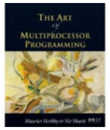
Bob has a pet

The Problem

The pets don’t get along

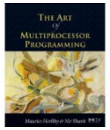
Formalizing the Problem

- Two types of formal properties in asynchronous computation:
- Safety Properties
  - Nothing bad happens ever
- Liveness Properties
  - Something good happens eventually



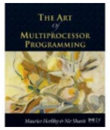
Formalizing our Problem

- Mutual Exclusion
  - Both pets never in pond simultaneously
  - This is a ***safety*** property
- No Deadlock
  - if only one wants in, it gets in
  - if both want in, one gets in.
  - This is a ***liveness*** property



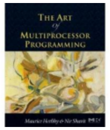
Simple Protocol

- Idea
  - Just look at the pond
- Gotcha
  - Not atomic
  - Trees obscure the view



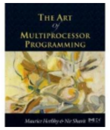
Interpretation

- Threads can’t “see” what other threads are doing
- Explicit communication required for coordination



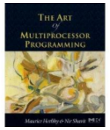
Cell Phone Protocol

- Idea
  - Bob calls Alice (or vice-versa)
- Gotcha
  - Bob takes shower
  - Alice recharges battery
  - Bob out shopping for pet food …

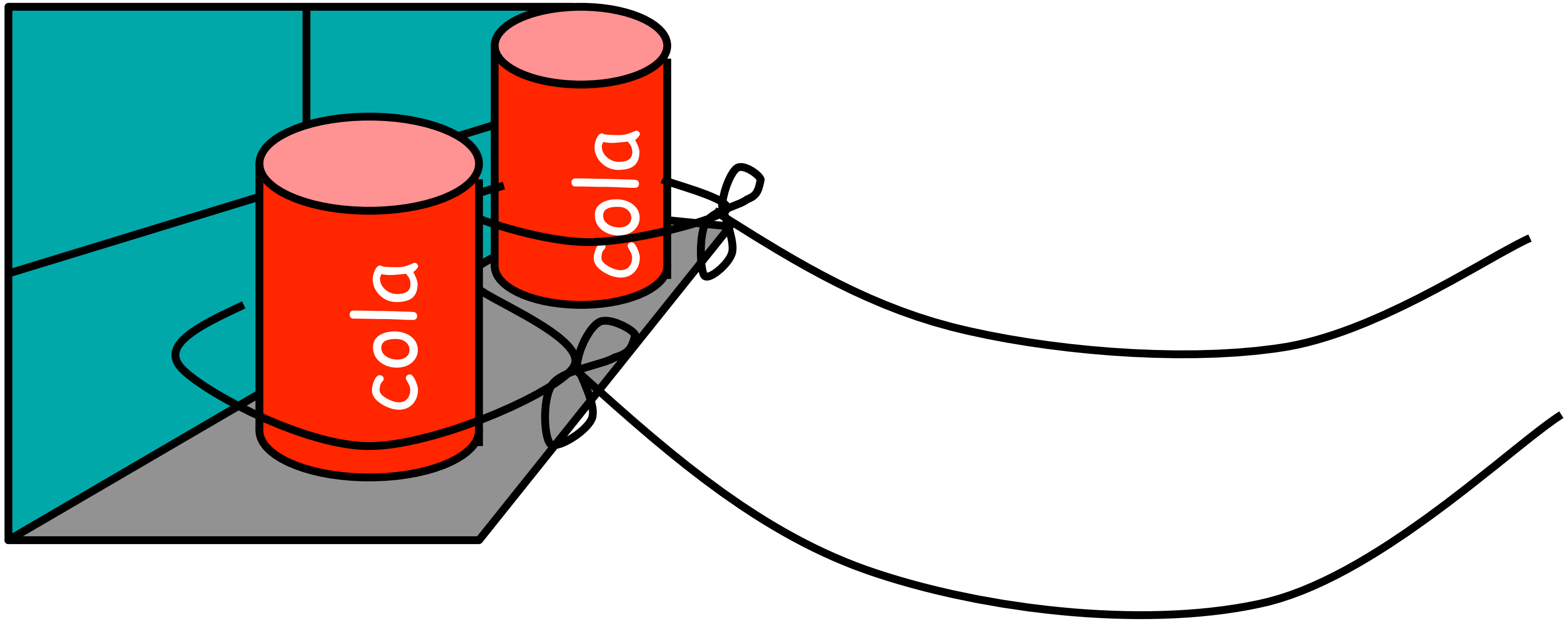


Interpretation

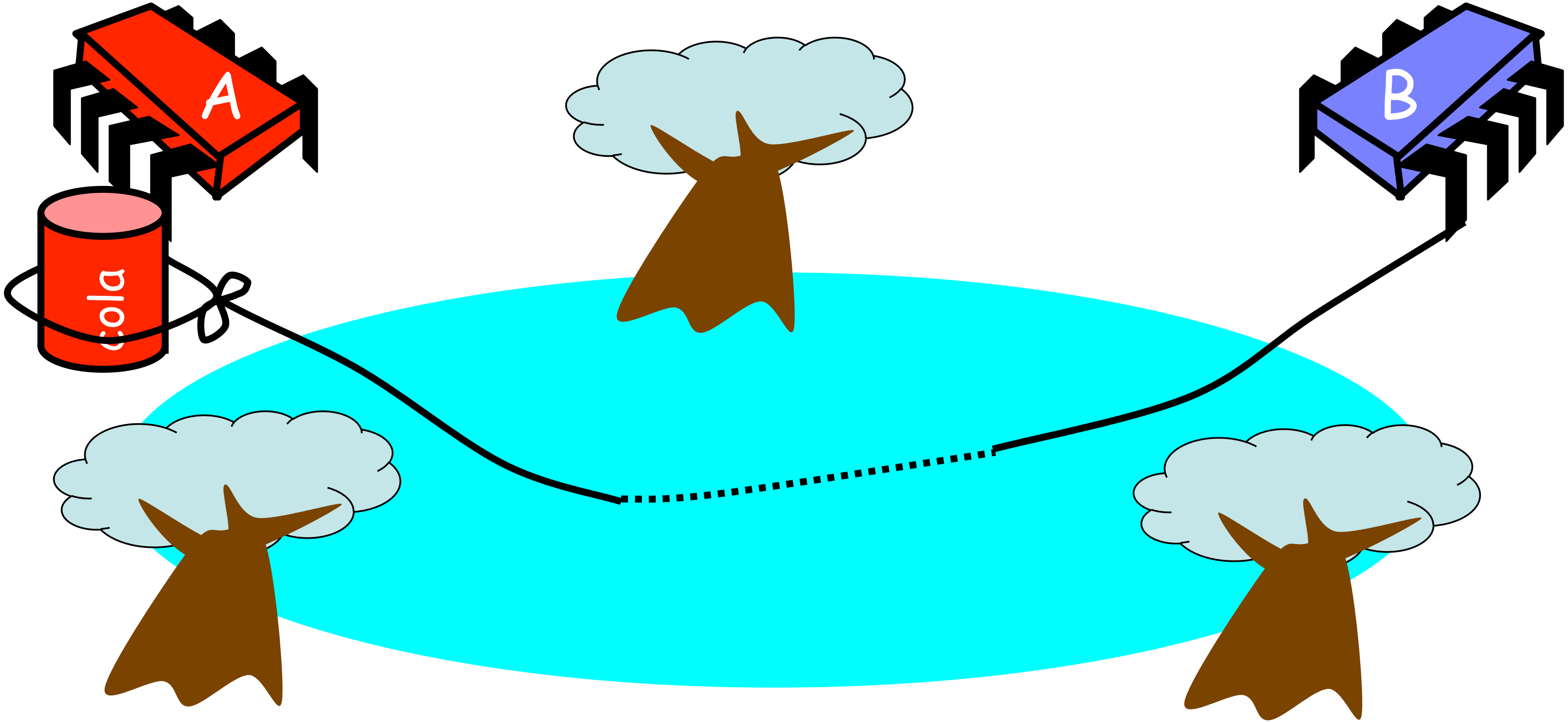
- Message-passing doesn’ t work
- Recipient might not be
  - Listening
  - There at all
- Communication must be
  - Persistent (like writing)
  - Not transient (like speaking)



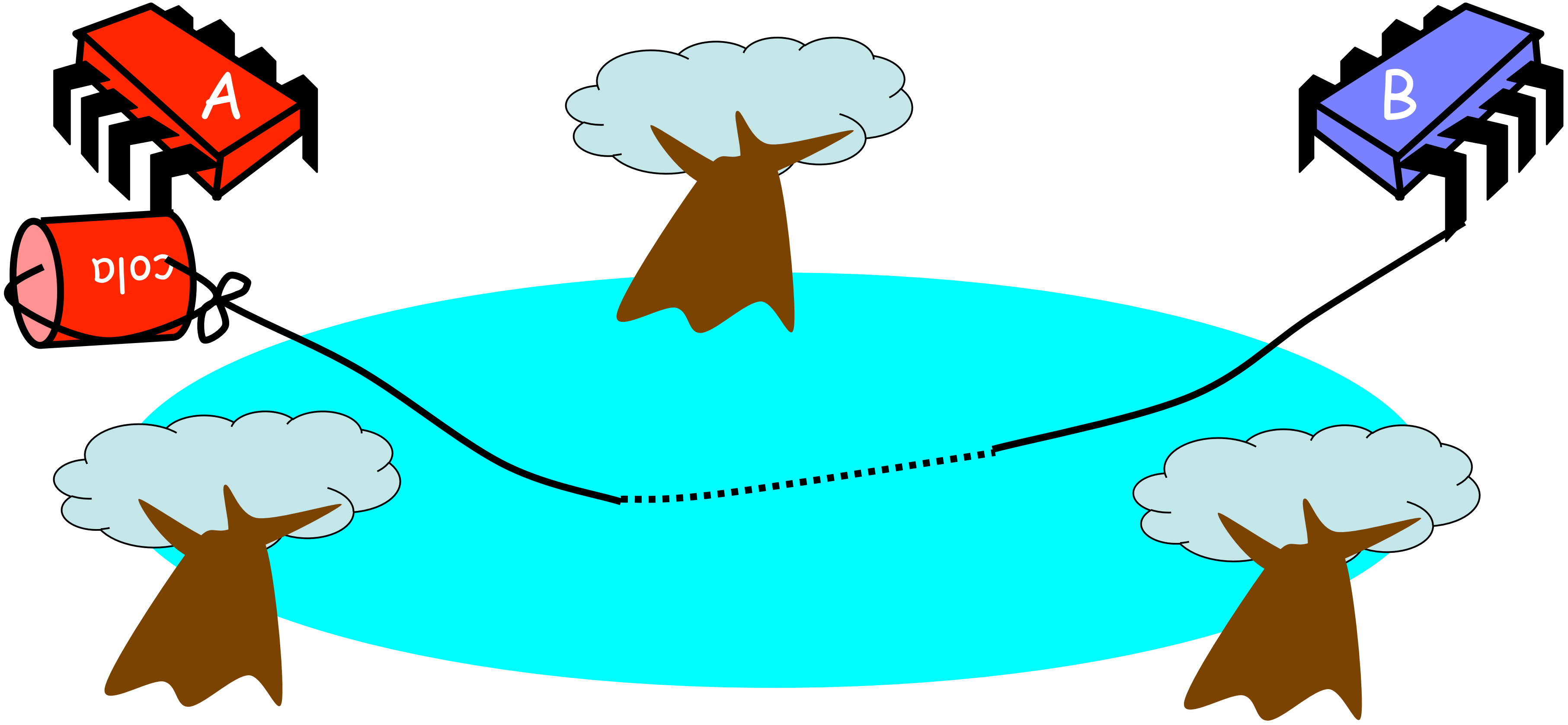
Can Protocol



Bob conveys a bit

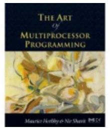


Bob conveys a bit



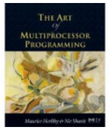
Can Protocol

- Idea
  - Cans on Alice’s windowsill
  - Strings lead to Bob’s house
  - Bob pulls strings, knocks over cans
- Gotcha
  - Cans cannot be reused
  - Bob runs out of cans

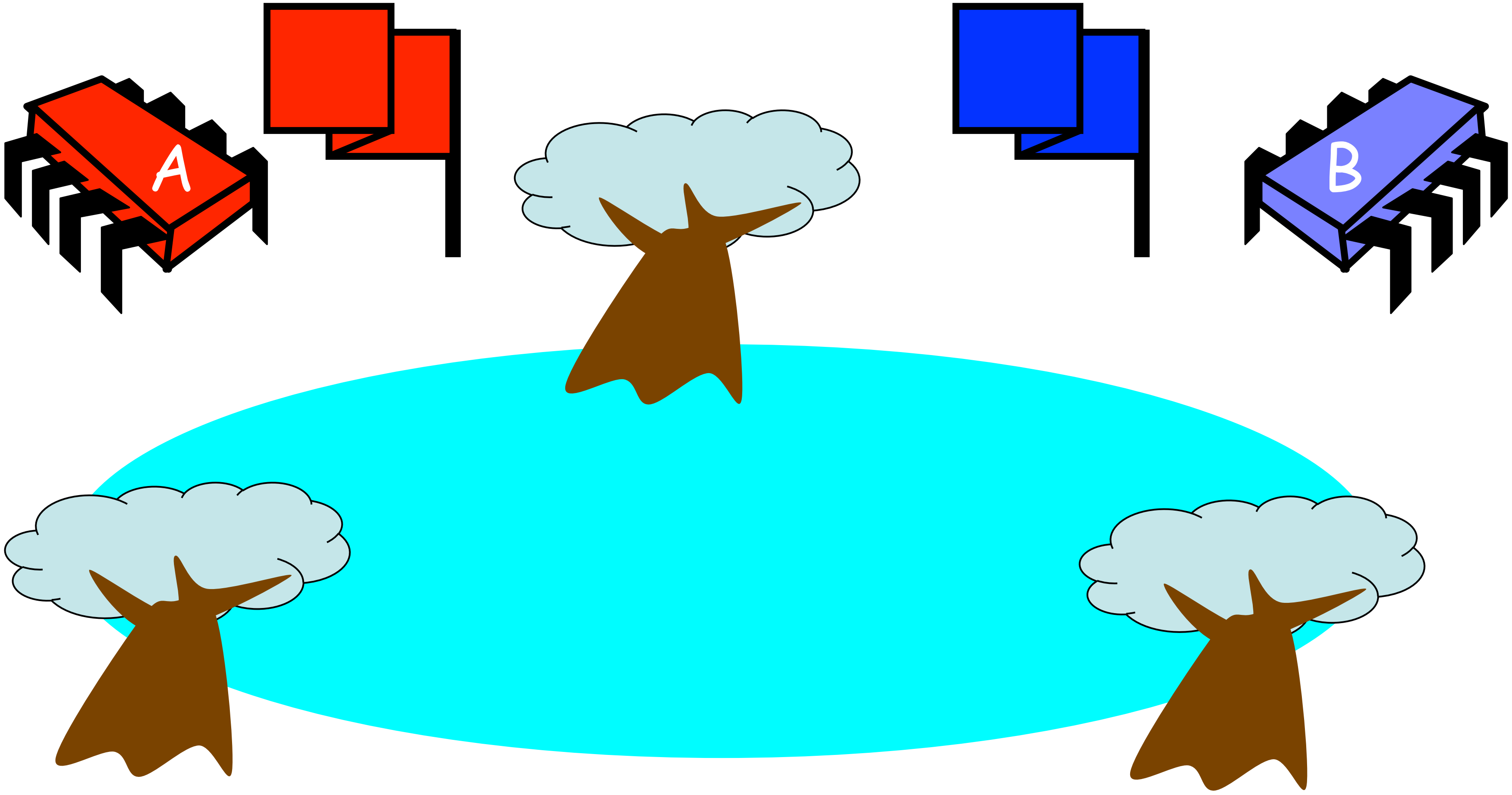


Interpretation

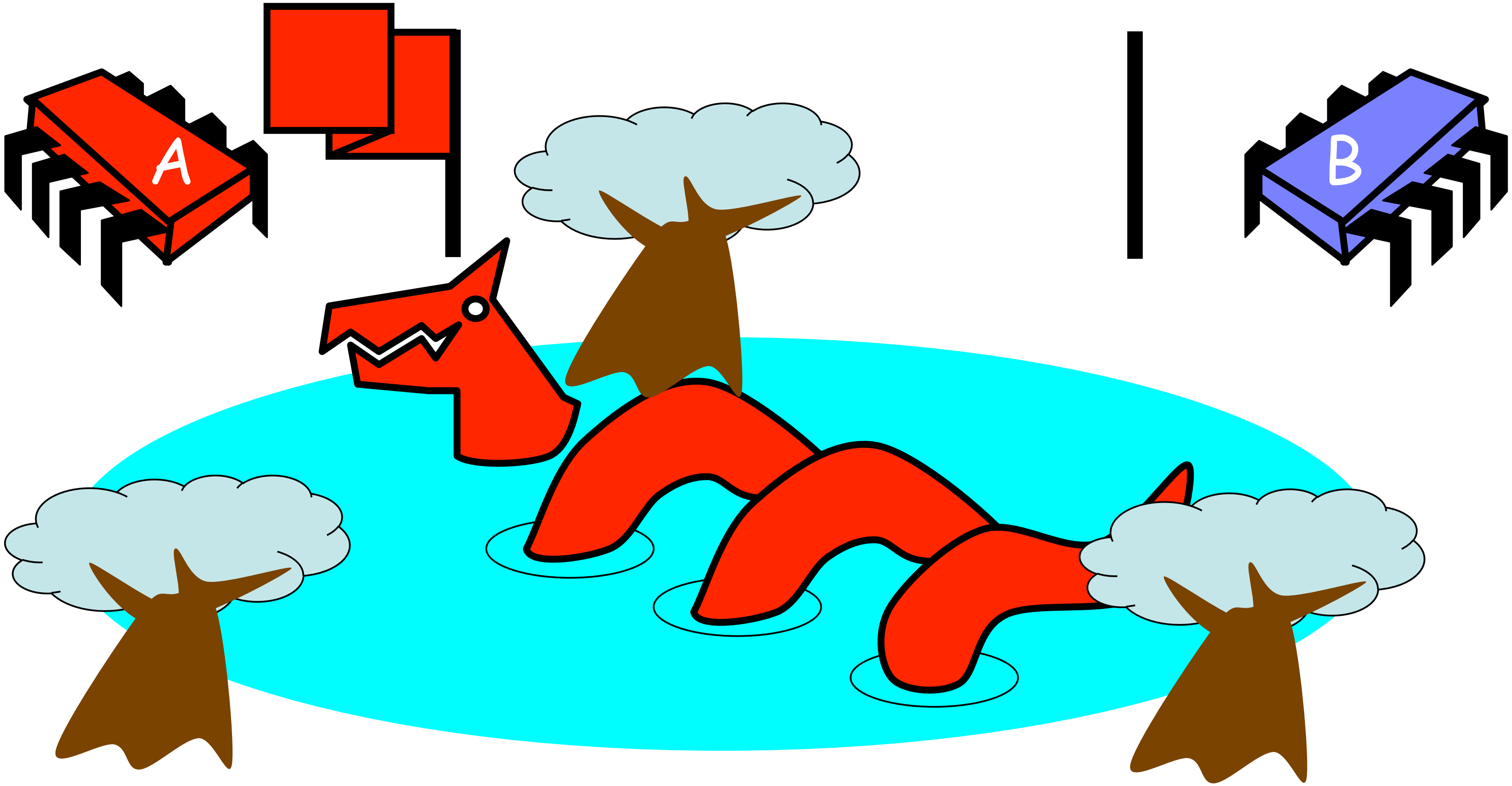
- Cannot solve mutual exclusion with interrupts
  - Sender sets fixed bit in receiver's space
  - Receiver resets bit when ready
  - Requires unbounded number of interrupt bits



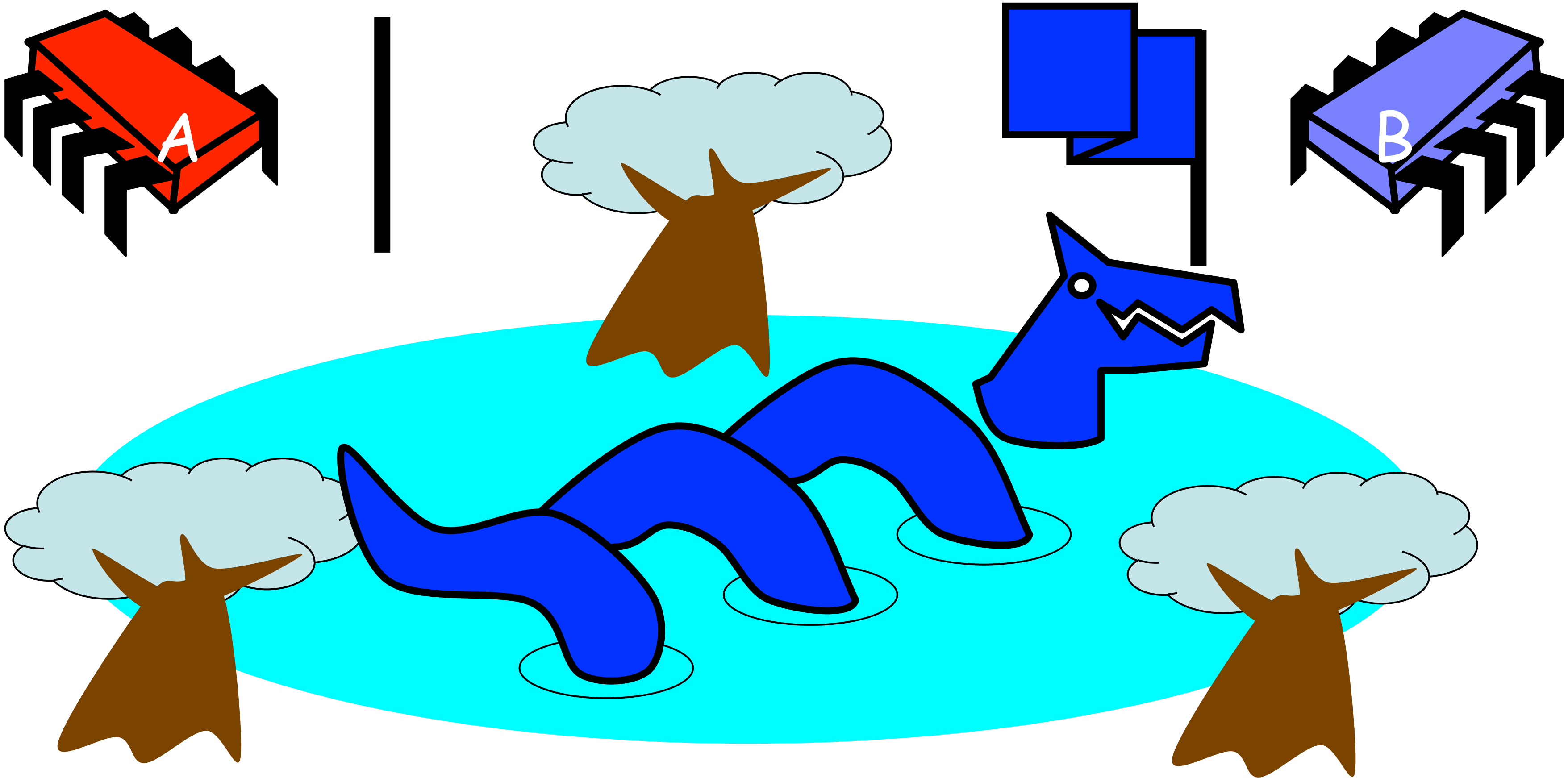
Flag Protocol



Alice's Protocol (sort of)

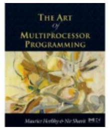


Bob’s Protocol (sort of)



Alice’s Protocol

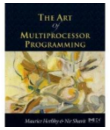
- Raise flag
- Wait until Bob’s flag is down
- Unleash pet
- Lower flag when pet returns



Bob’s Protocol

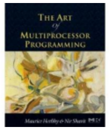
- Raise flag
- Wait until Alice’s flag is down
- Unleash pet
- Lower flag when pet returns

danger!



Bob's Protocol (2nd try)

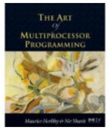
- Raise flag
- While Alice's flag is up
  - Lower flag
  - Wait for Alice's flag to go down
  - Raise flag
- Unleash pet
- Lower flag when pet returns



Bob's Protocol

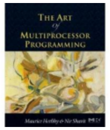
- Raise flag
- While Alice's flag is up
  - Lower flag
  - Wait for Alice's flag to go down
  - Raise flag
- Unleash pet
- Lower flag when pet returns

Bob defers to Alice



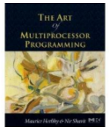
The Flag Principle

- Raise the flag
- Look at other’s flag
- Flag Principle:
  - If each raises and looks, then
  - Last to look must see both flags up

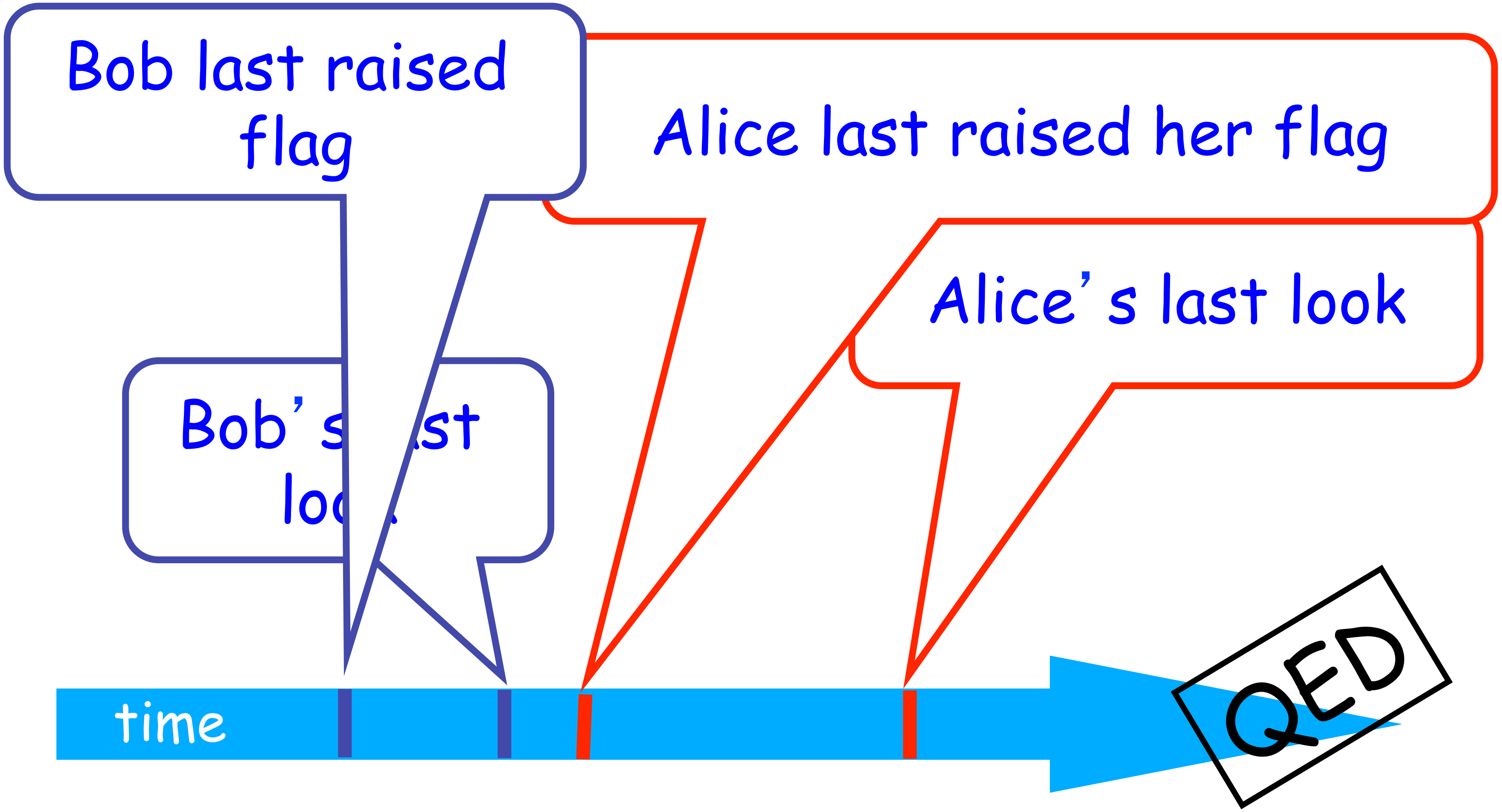


Proof of Mutual Exclusion

- Assume both pets in pond
  - Derive a contradiction
  - By reasoning **backwards**
- Consider the last time Alice and Bob each looked before letting the pets in
- Without loss of generality assume Alice was the last to look…



Proof



Bob last raised flag

Bob's last look

Alice last raised her flag

Alice's last look

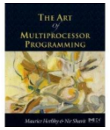
time

QED

Alice must have seen Bob's Flag. A Contradiction

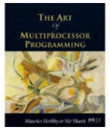
Proof of No Deadlock

- If only one pet wants in, it gets in.



Proof of No Deadlock

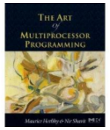
- If only one pet wants in, it gets in.
- Deadlock requires both continually trying to get in.



Proof of No Deadlock

- If only one pet wants in, it gets in.
- Deadlock requires both continually trying to get in.
- If Bob sees Alice's flag, he gives her priority (a gentleman…)

QED

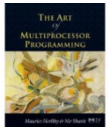


Remarks

- Protocol is *unfair*
  - Bob's pet might never get in
- Protocol uses *waiting*
  - If Bob is eaten by his pet, Alice's pet might never get in

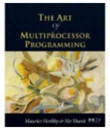
starvation

espera X tol falhas



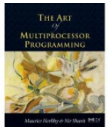
Moral of Story

- Mutual Exclusion cannot be solved by
  - transient communication (cell phones)
  - interrupts (cans)
- It can be solved by
  - one-bit shared variables
  - that can be read or written



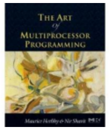
The Fable Continues

- Alice and Bob fall in love & marry
- Then they fall out of love & divorce
  - She gets the pets
  - He has to feed them

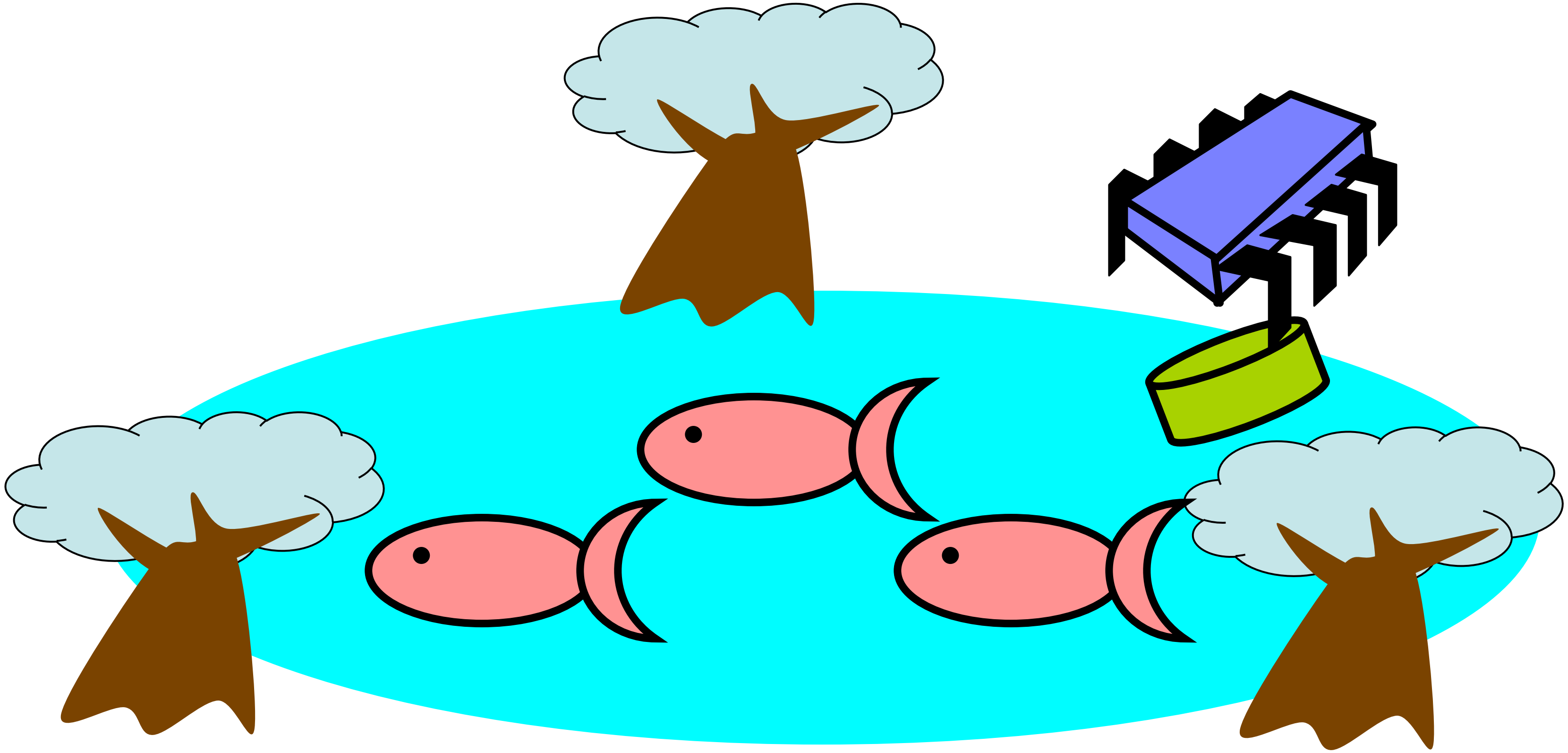


The Fable Continues

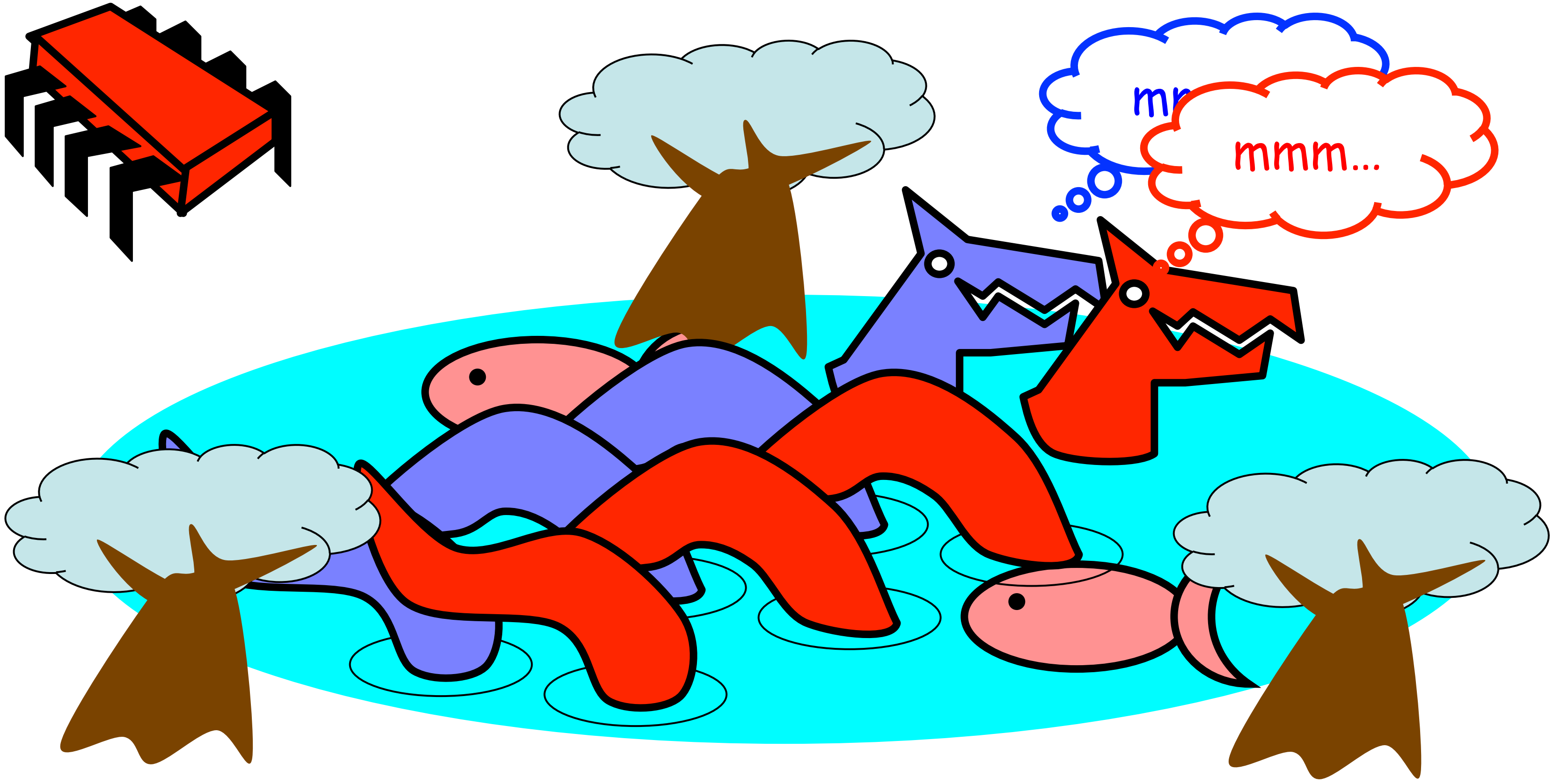
- Alice and Bob fall in love & marry
- Then they fall out of love & divorce
  - She gets the pets
  - He has to feed them
- Leading to a new coordination problem: Producer-Consumer



Bob Puts Food in the Pond

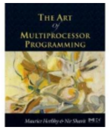


Alice releases her pets to Feed



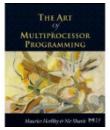
Producer/Consumer

- Alice and Bob can’t meet
  - Each has restraining order on other
  - So he puts food in the pond
  - And later, she releases the pets
- Avoid
  - Releasing pets when there’s no food
  - Putting out food if uneaten food remains

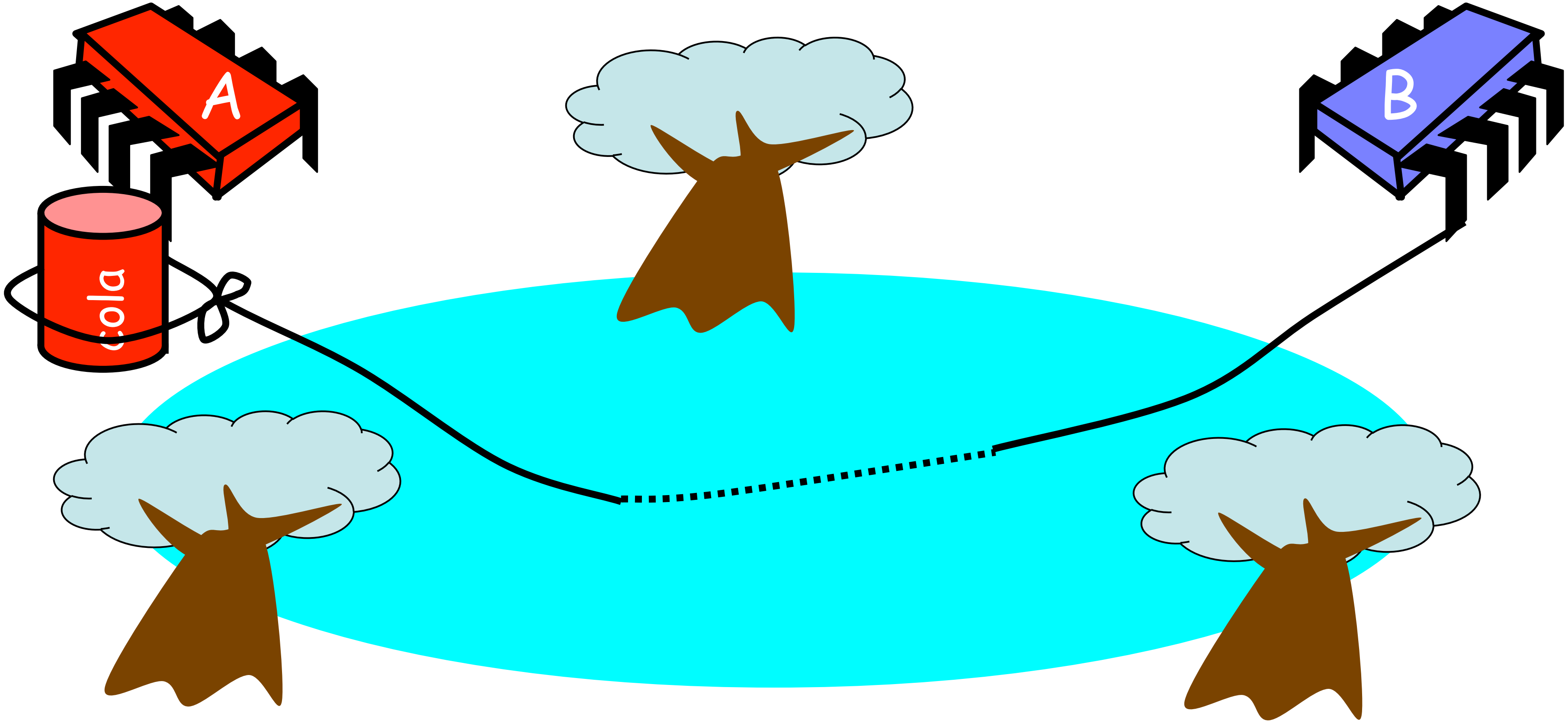


Producer/Consumer

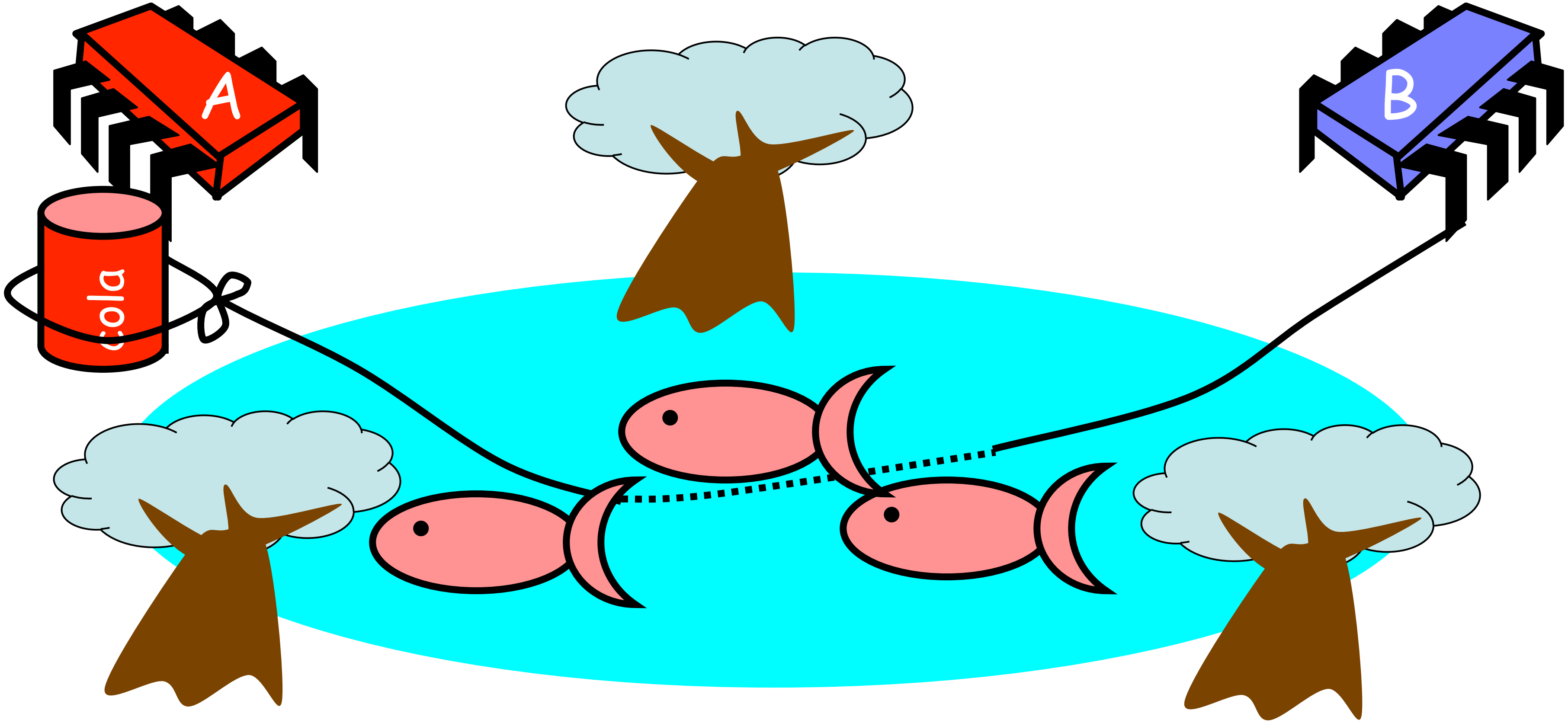
- Need a mechanism so that
  - Bob lets Alice know when food has been put out
  - Alice lets Bob know when to put out more food

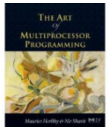


Surprise Solution

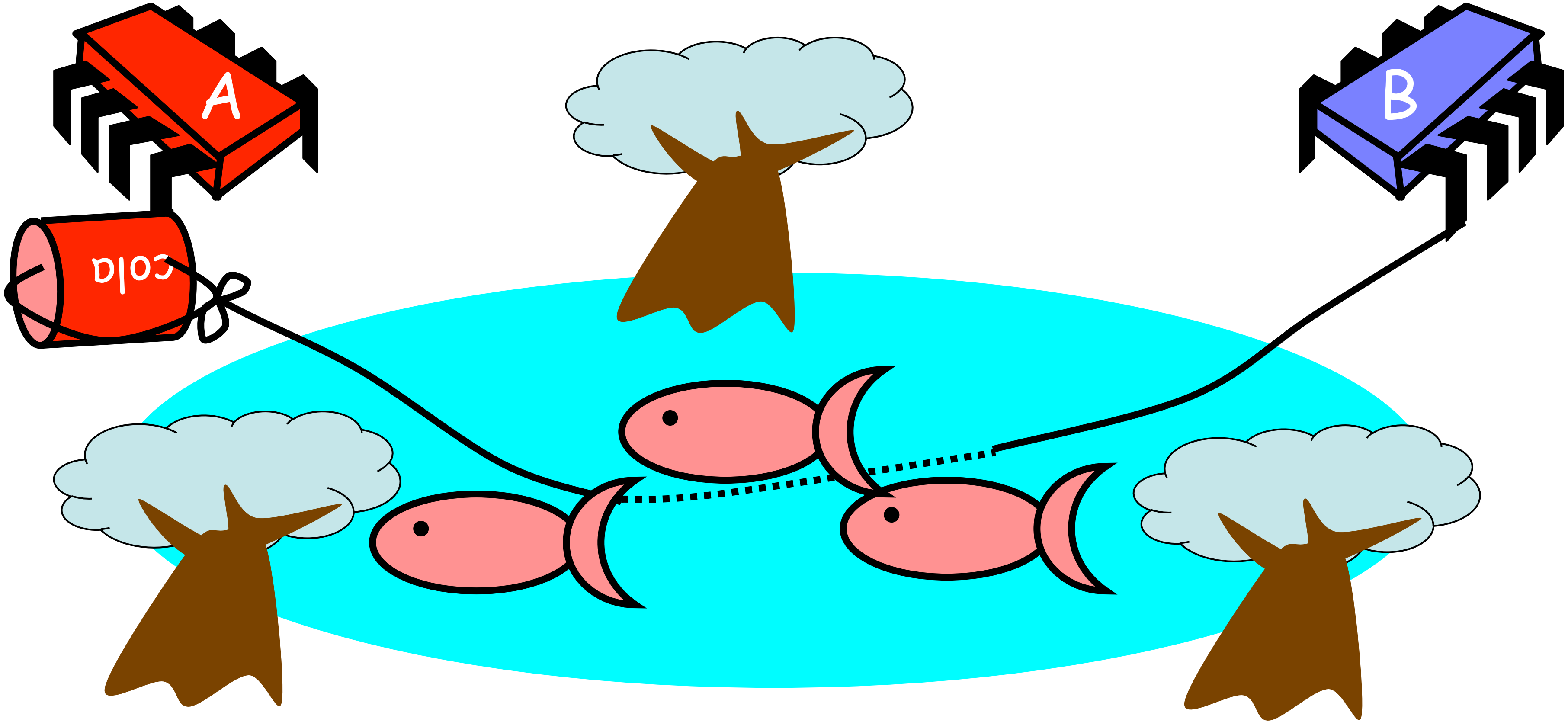


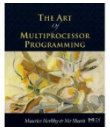
Bob puts food in Pond



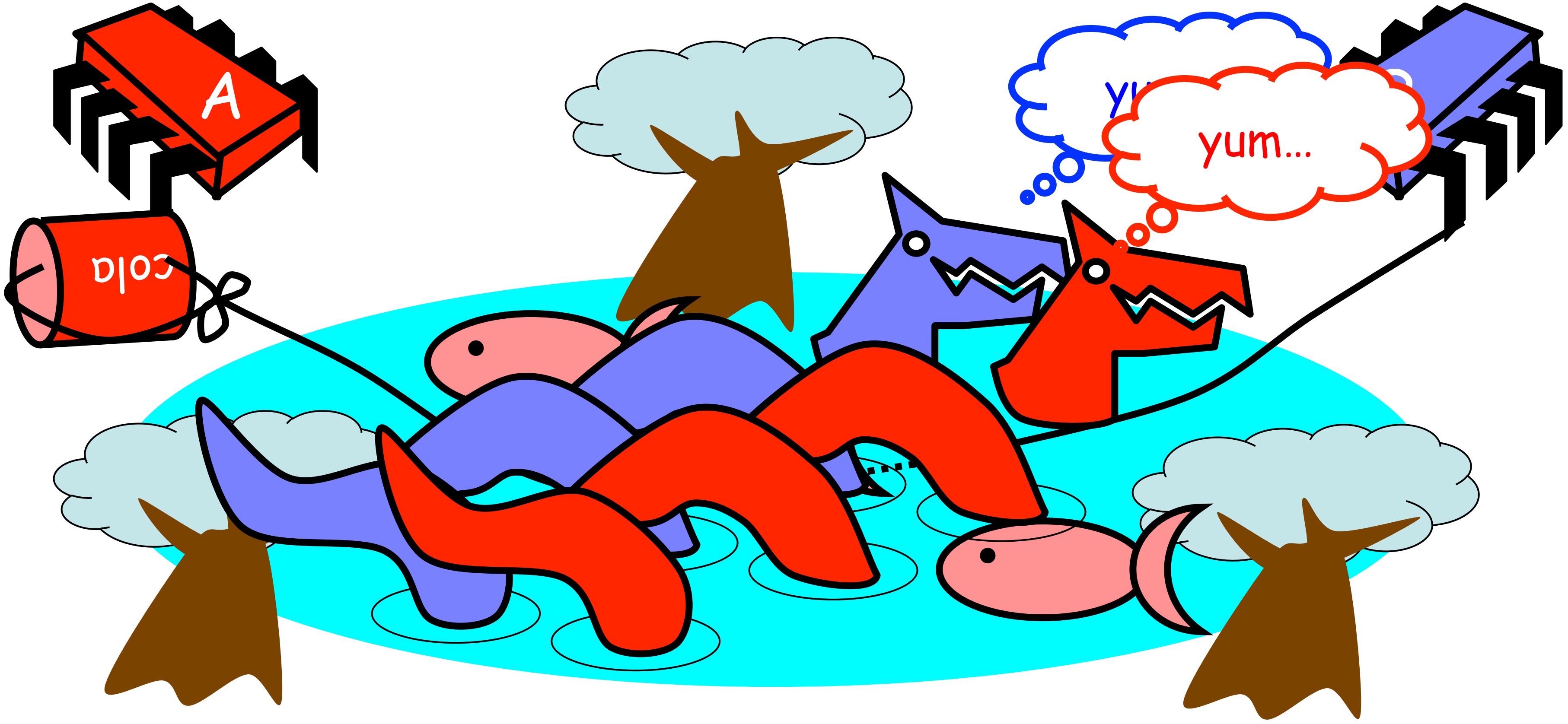


Bob knocks over Can

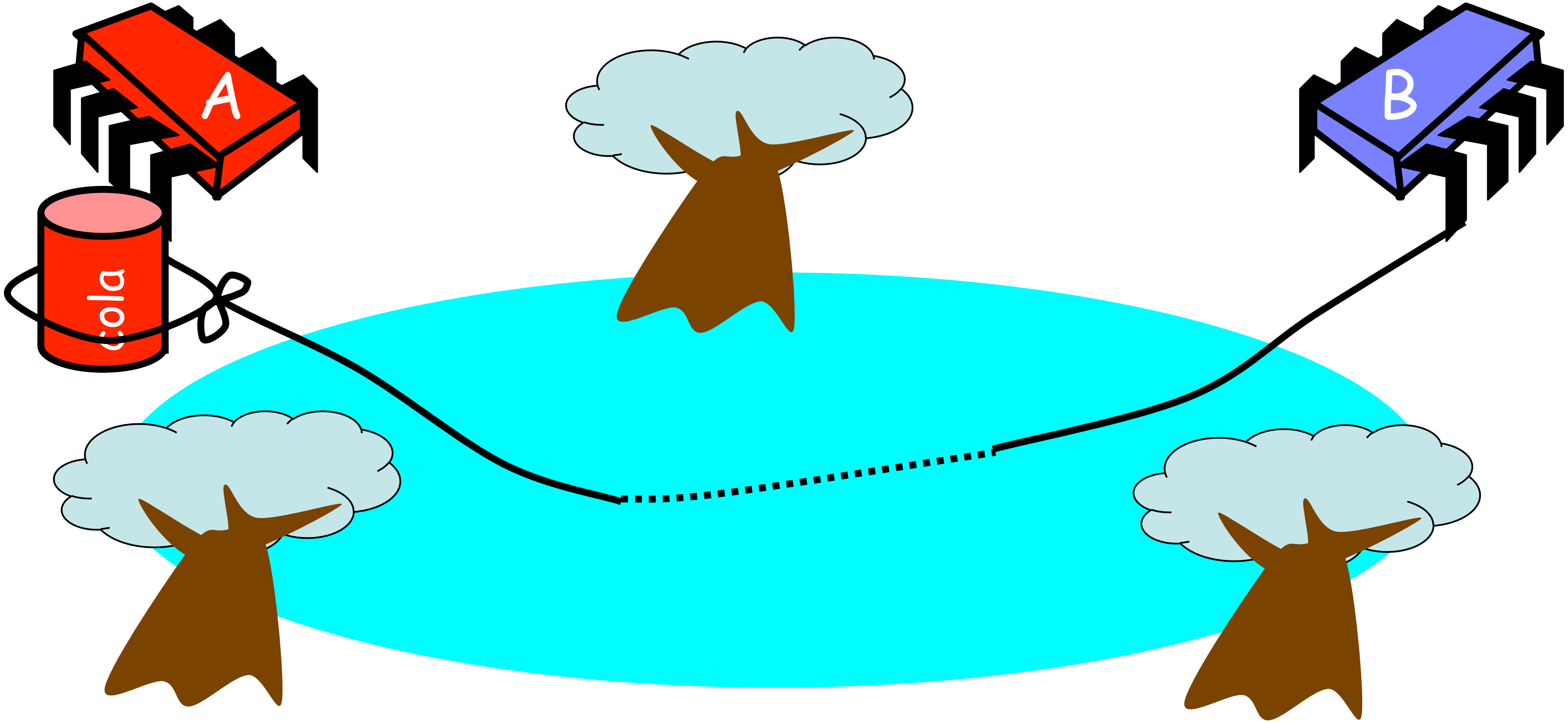




Alice Releases Pets



Alice Resets Can when Pets are Fed



Pseudocode

```
while (true) {
  while (can.isUp()){};
  pet.release();
  pet.recapture();
  can.reset();
}
```

Alice’s code

Pseudocode

```
while (true) {
   while (can.isUp()){};
   pet.release();
   pet.recapture();
   can.reset();
}
```

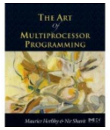
Alice’s code

Bob’s code

```
while (true) {
   while (can.isDown()){};
   pond.stockWithFood();
   leaveYard()
   can.knockOver();
}
```

Correctness

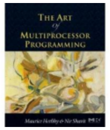
- Mutual Exclusion
  - Pets and Bob never together in pond



Correctness

- Mutual Exclusion
  - Pets and Bob never together in pond
- No Starvation

  if Bob always willing to feed, and pets always famished, then pets eat infinitely often.



Correctness

- Mutual Exclusion

  safety

  - Pets and Bob never together in pond

- No Starvation

  liveness

  if Bob always willing to feed, and pets always famished, then pets eat infinitely often.

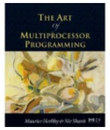
- Producer/Consumer

  safety

  The pets never enter pond unless there is food, and Bob never provides food if there is unconsumed food.

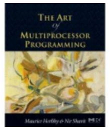
Waiting

- Both solutions use waiting
  - `while(mumble){}`
- In some cases waiting is ***problematic***
  - If one participant is delayed
  - So is everyone else
  - But delays are common & unpredictable



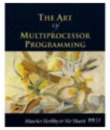
The Fable drags on …

- Bob and Alice still have issues



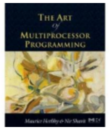
The Fable drags on …

- Bob and Alice still have issues
- So they need to communicate

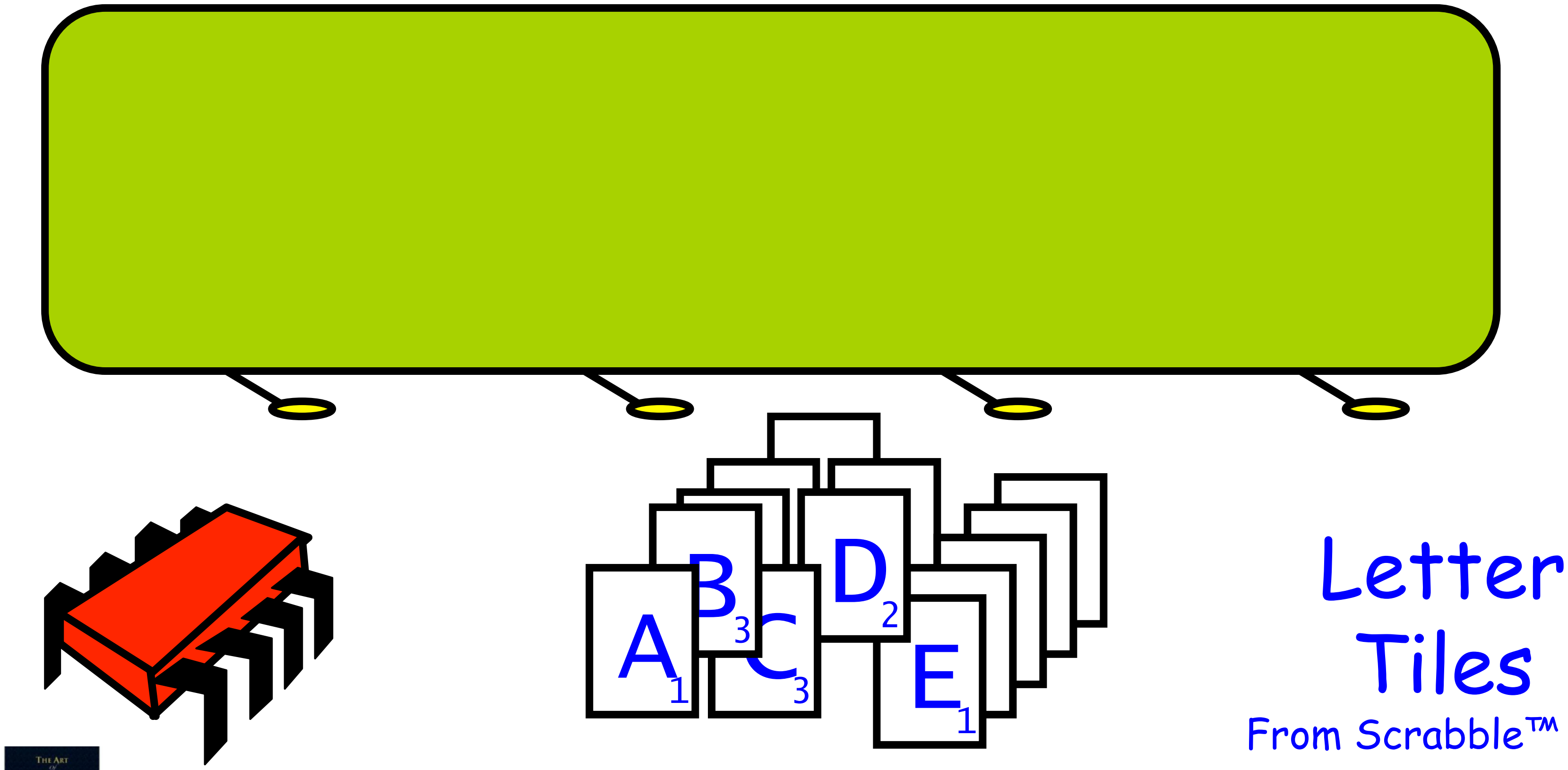


The Fable drags on …

- Bob and Alice still have issues
- So they need to communicate
- They agree to use billboards …



Billboards are Large

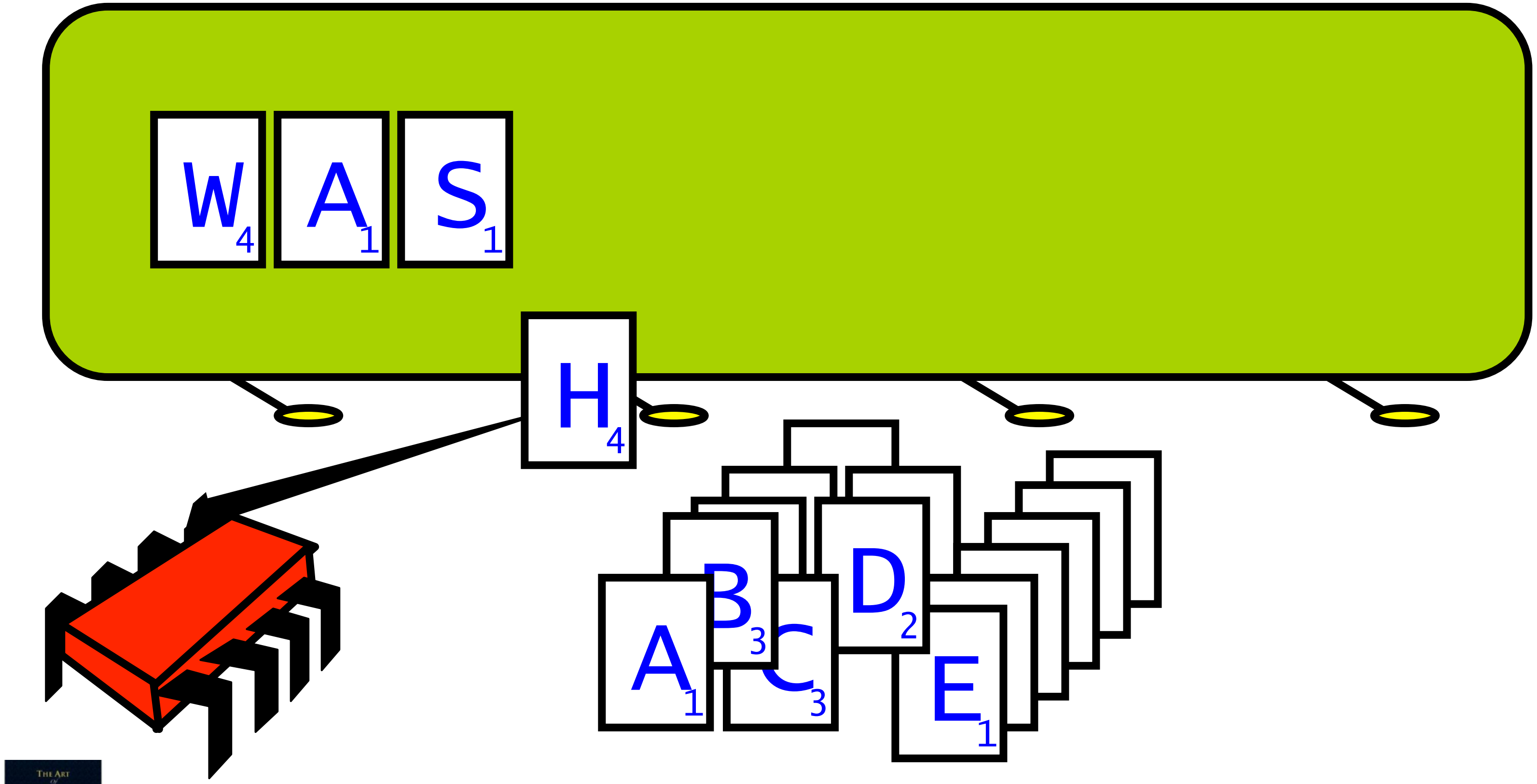


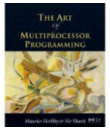
Letter Tiles

From Scrabble™ box

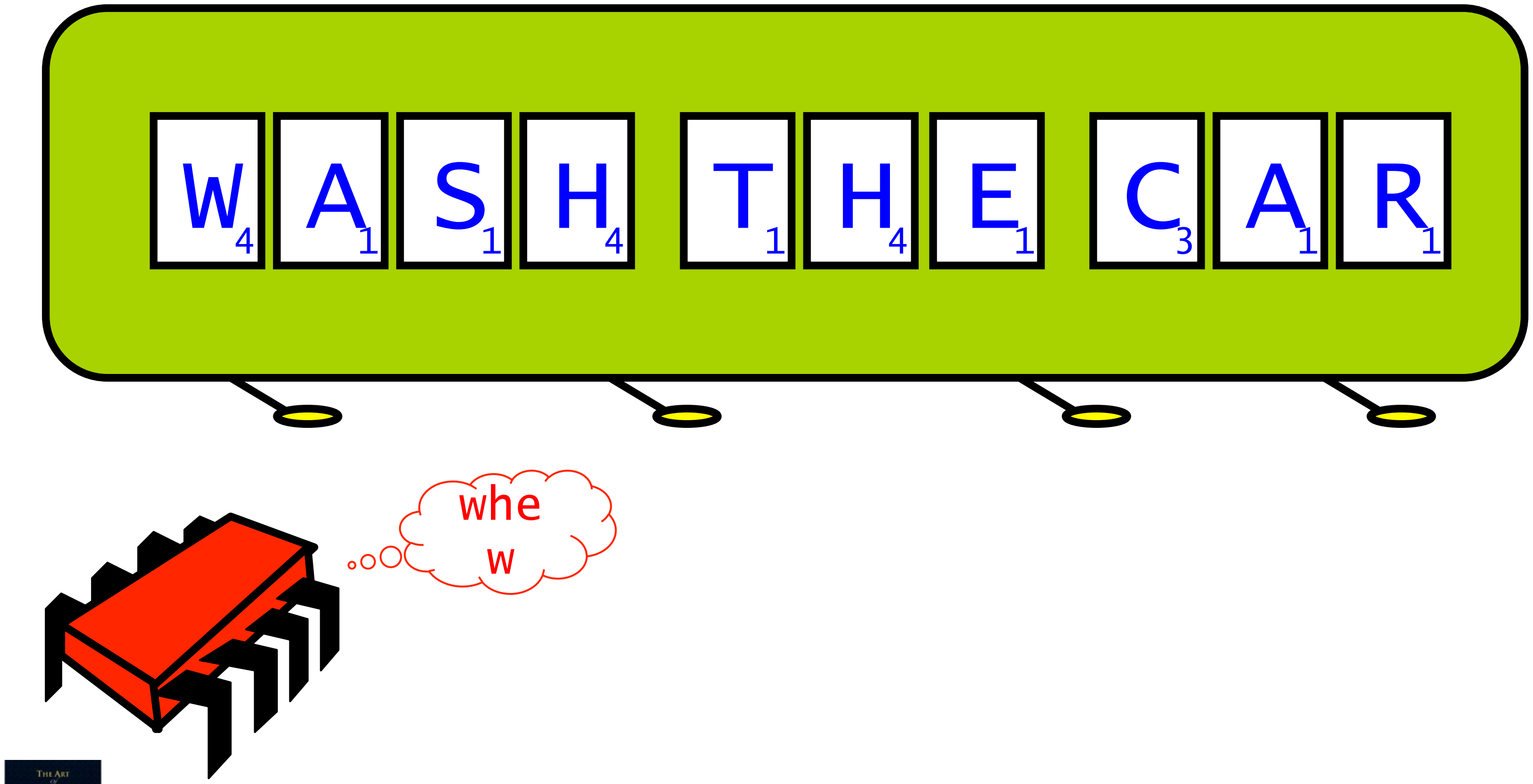
Art of Multiprocessor
Programming

Write One Letter at a Time …

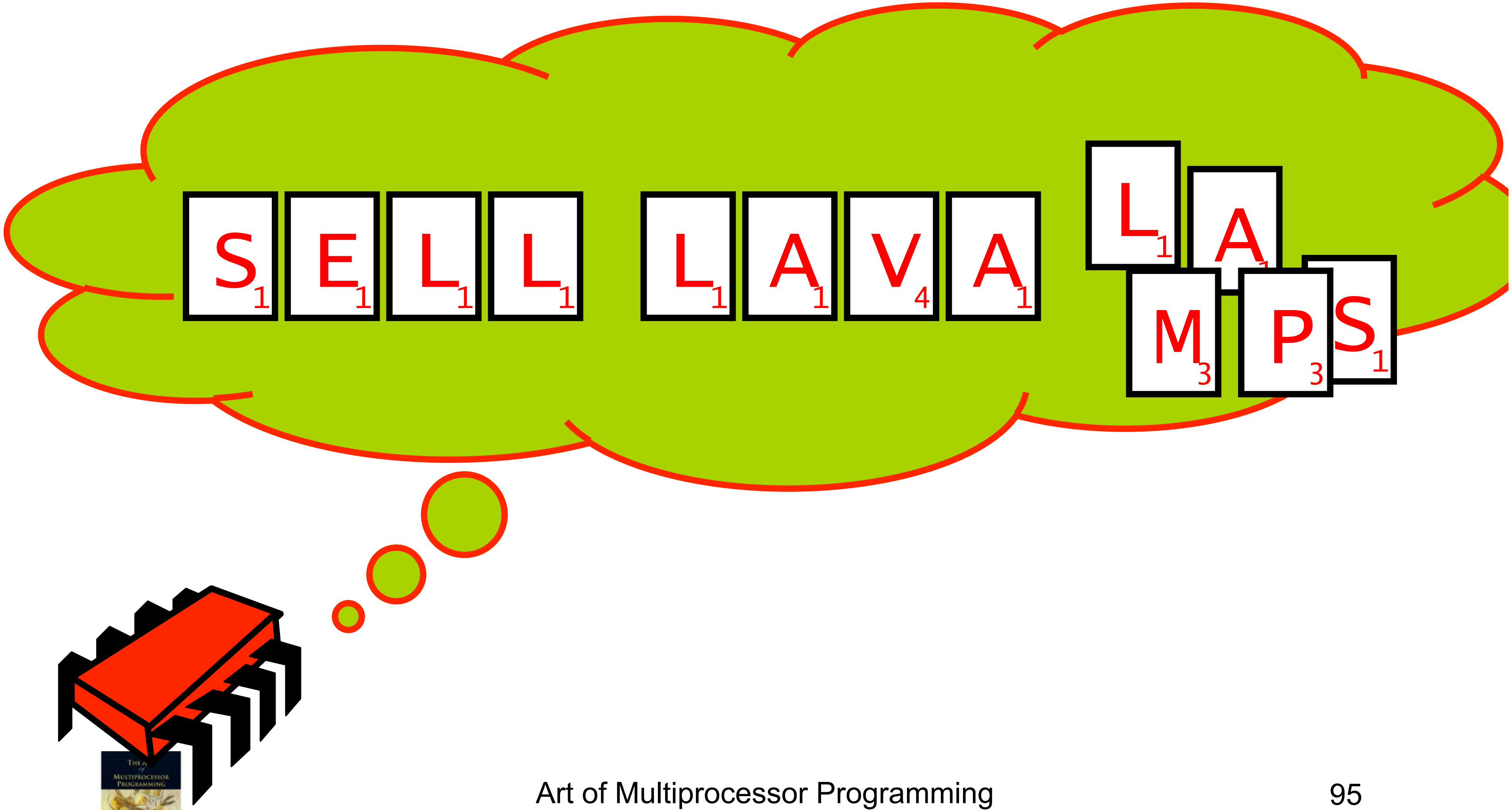




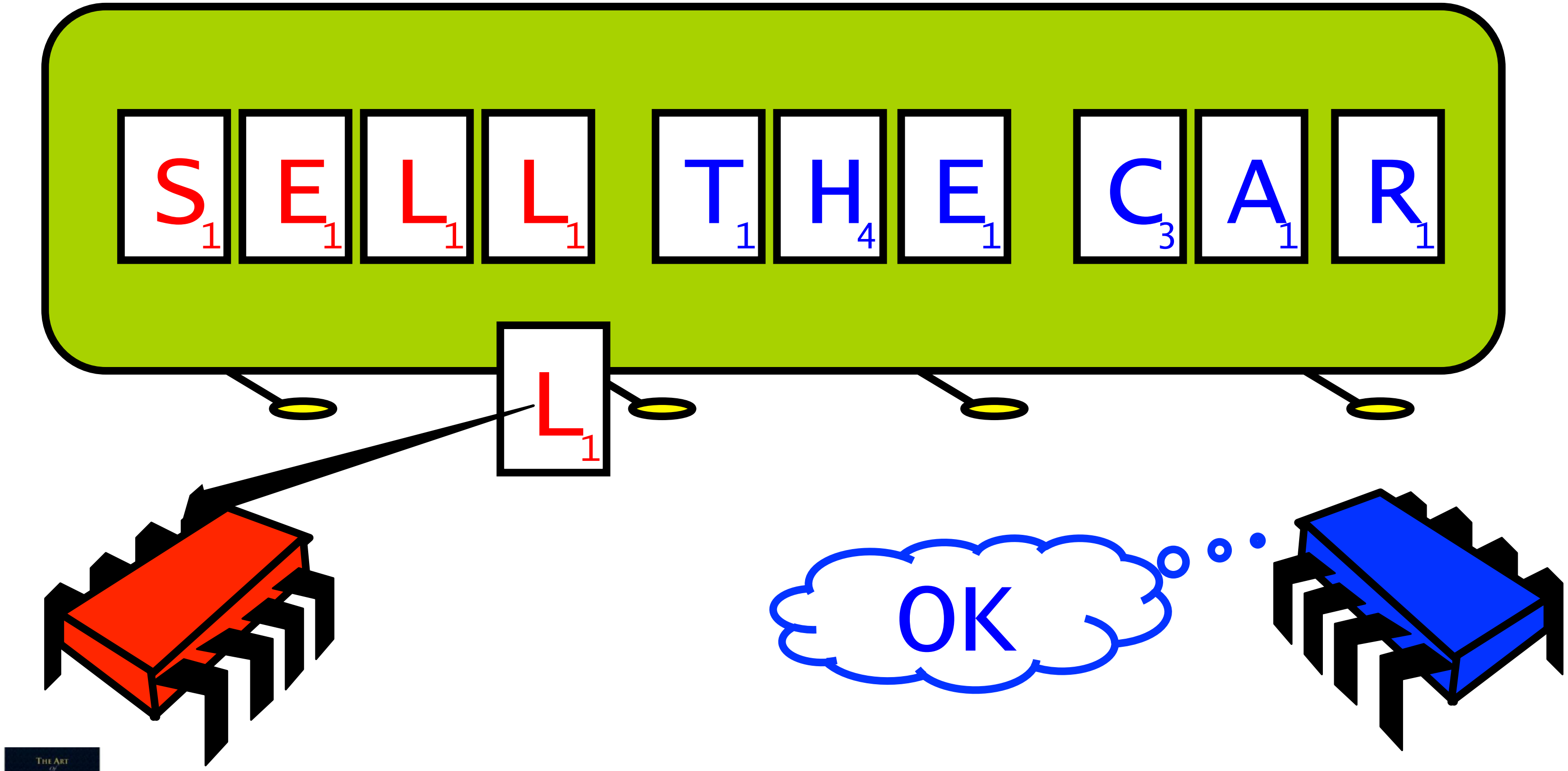
To post a message

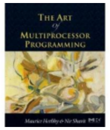


Let's send another message



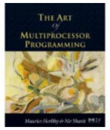
Uh-Oh





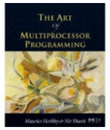
Readers/Writers

- Devise a protocol so that
  - Writer writes one letter at a time
  - Reader reads one letter at a time
  - Reader sees “snapshot”
    - Old message or new message
    - No mixed messages



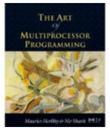
Readers/Writers (continued)

- Easy with mutual exclusion
- But mutual exclusion requires waiting
  - One waits for the other
  - Everyone executes sequentially
- Remarkably
  - We can solve R/W without mutual exclusion



Why do we care?

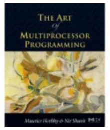
- We want as much of the code as possible to execute concurrently (in parallel)
- A larger sequential part implies reduced performance
- Amdahl's law: this relation is not linear…



Amdahl’ s Law

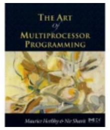
$$\text{Speedup}= \frac{\text{OldExecutionTime}}{\text{NewExecutionTime}}$$

…of computation given n CPUs instead of 1



Amdahl’s Law

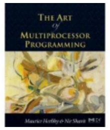
$$\textbf{Speedup=}\ \frac{1}{1-p+\frac{p}{n}}$$



Amdahl’s Law

$$\text{Speedup}=\frac{1}{1-p+\frac{\boxed{p}}{n}}$$

Parallel fraction

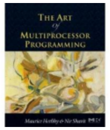


Amdahl’s Law

Sequential fraction

Parallel fraction

$$\text{Speedup}=\frac{1}{\boxed{1-p}+\frac{\boxed{p}}{n}}$$



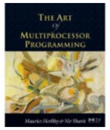
Amdahl's Law

Sequential fraction

Parallel fraction

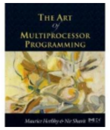
$$\text{Speedup}=\frac{1}{1-p+\frac{p}{n}}$$

Number of processors



Example

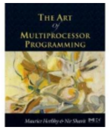
- Ten processors
- 60% concurrent, 40% sequential
- How close to 10-fold speedup?



Example

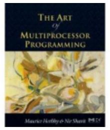
- Ten processors
- 60% concurrent, 40% sequential
- How close to 10-fold speedup?

$$\text{Speedup} = 2.17 = \frac{1}{1 - 0.6 + \frac{0.6}{10}}$$



Example

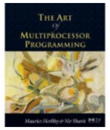
- Ten processors
- 80% concurrent, 20% sequential
- How close to 10-fold speedup?



Example

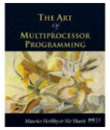
- Ten processors
- 80% concurrent, 20% sequential
- How close to 10-fold speedup?

$$\text{Speedup} = 3.57 = \frac{1}{1 - 0.8 + \frac{0.8}{10}}$$



Example

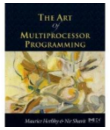
- Ten processors
- 90% concurrent, 10% sequential
- How close to 10-fold speedup?



Example

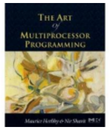
- Ten processors
- 90% concurrent, 10% sequential
- How close to 10-fold speedup?

$$\text{Speedup} = 5.26 = \frac{1}{1-0.9+\frac{0.9}{10}}$$



Example

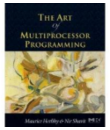
- Ten processors
- 99% concurrent, 01% sequential
- How close to 10-fold speedup?



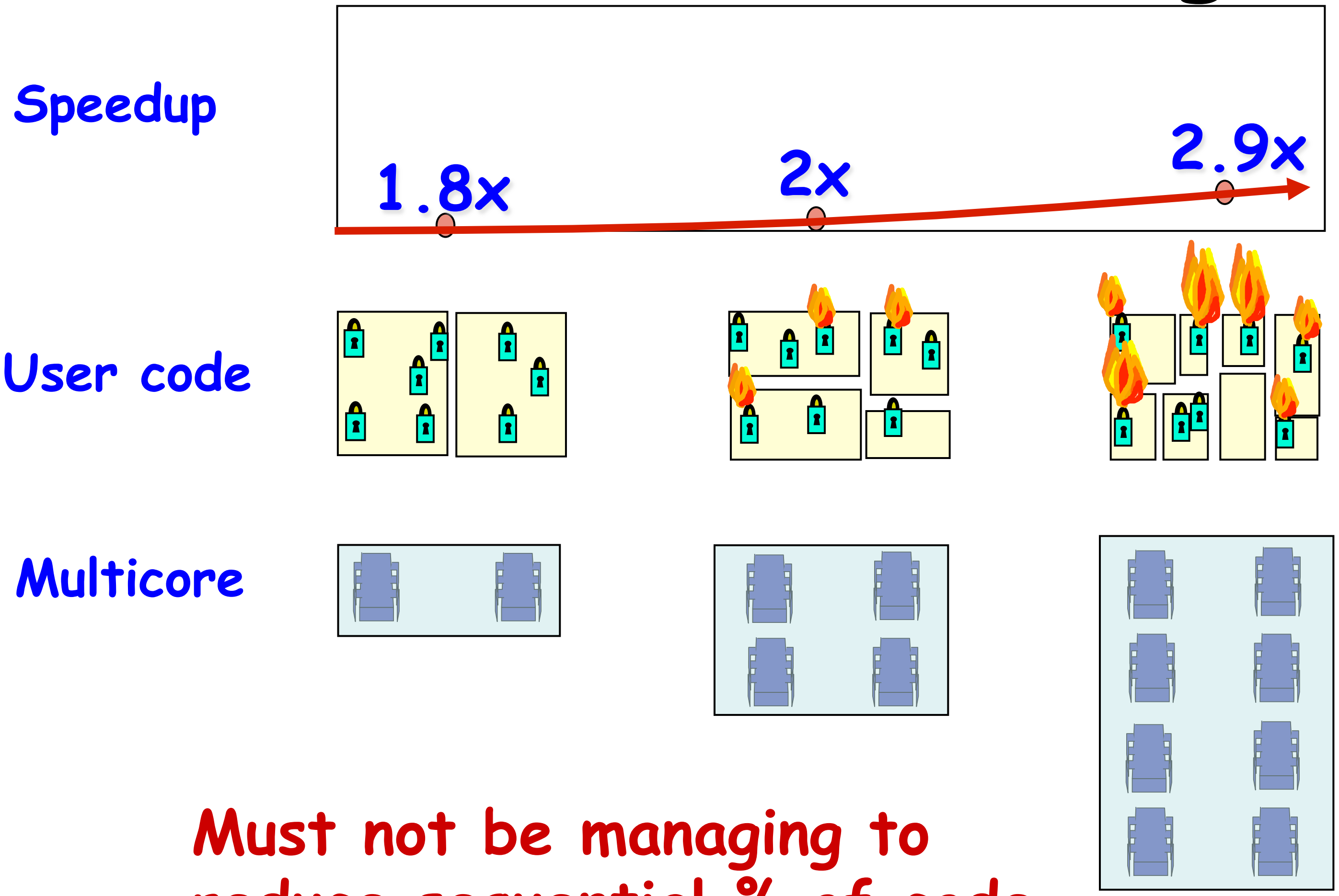
Example

- Ten processors
- 99% concurrent, 01% sequential
- How close to 10-fold speedup?

$$\text{Speedup} = 9.17 = \frac{1}{1 - 0.99 + \frac{0.99}{10}}$$

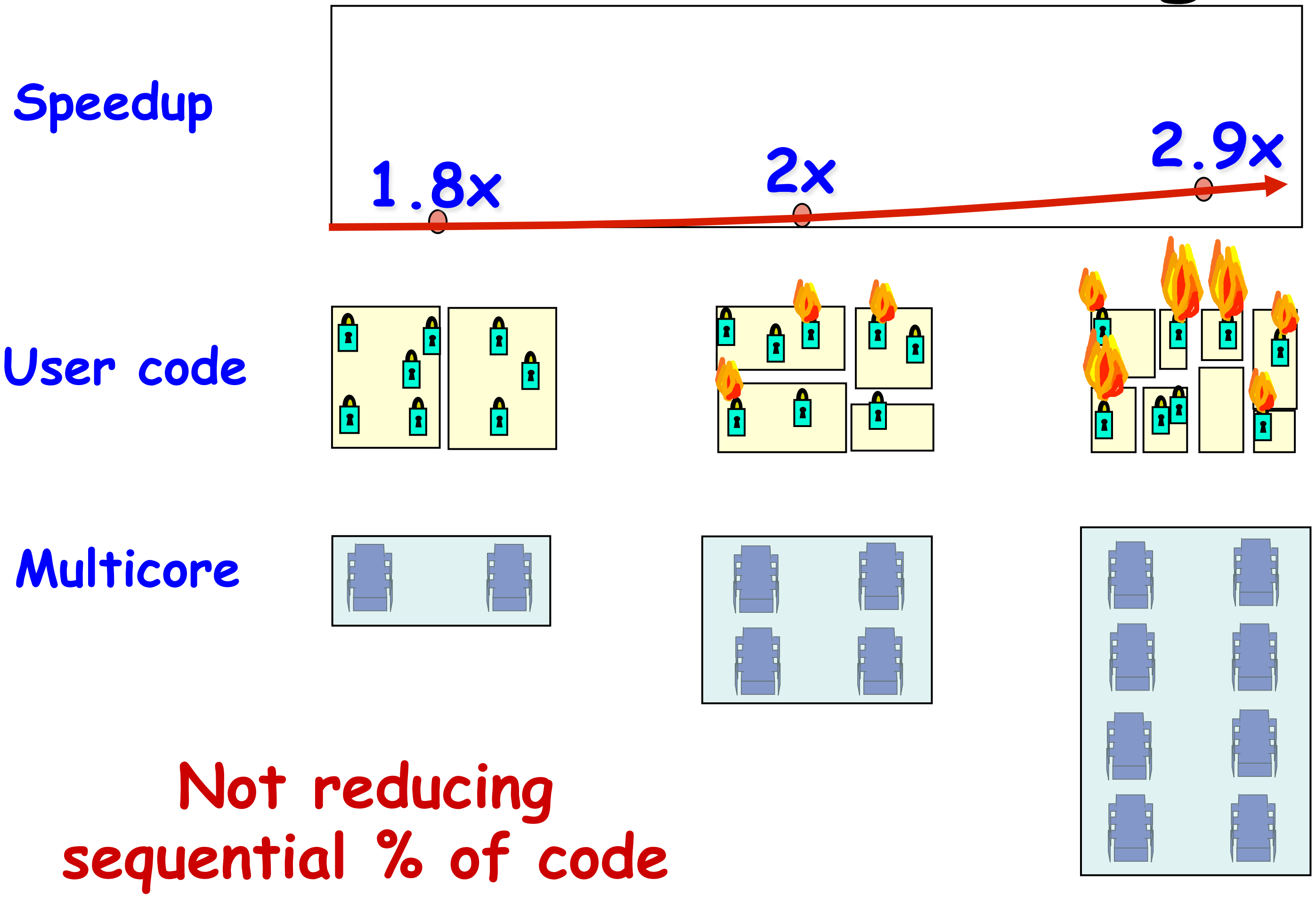


Back to Real-World Multicore Scaling



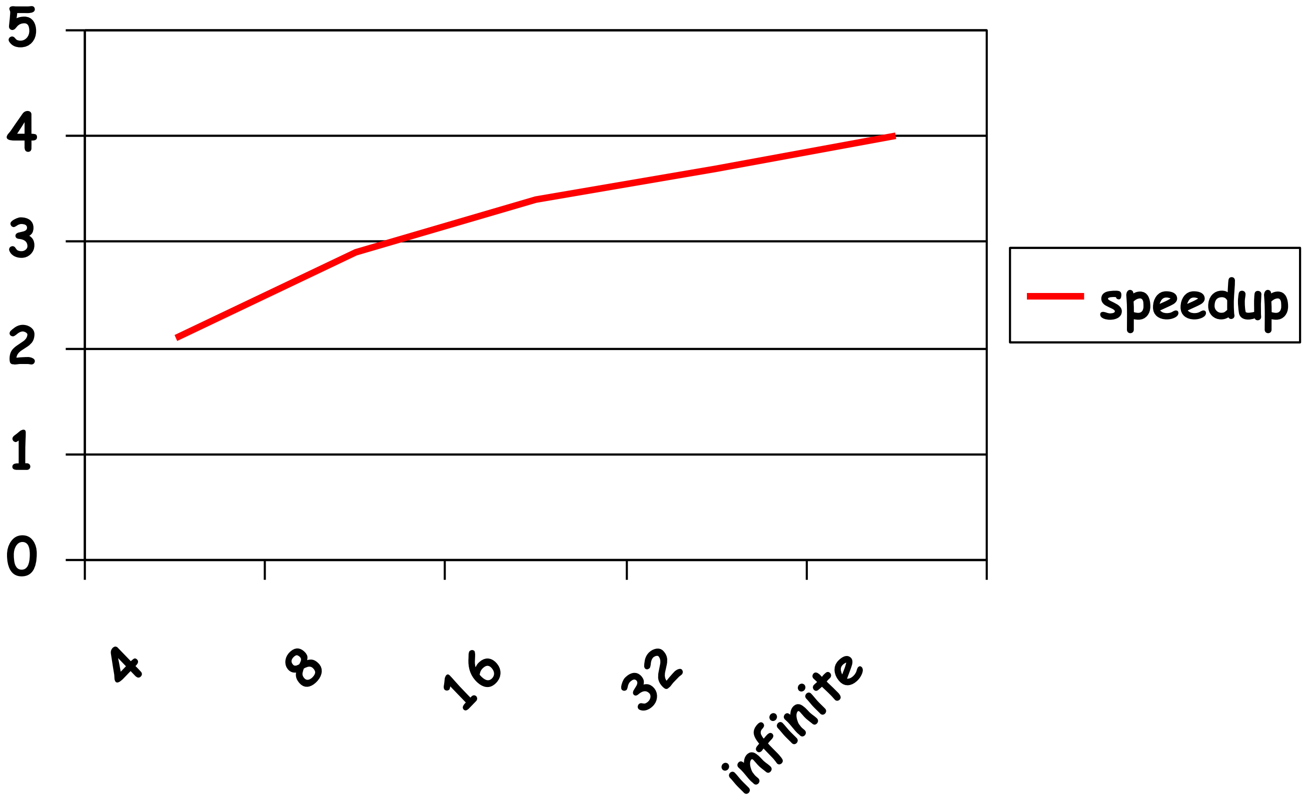
Must not be managing to reduce sequential % of code

Back to Real-World Multicore Scaling



Not reducing sequential % of code

Diminishing Returns



Multicore Programming

- This is what this course is about…
  - The % that is not easy to make concurrent yet may have a large impact on overall speedup
- Next:
  - A more serious look at mutual exclusion