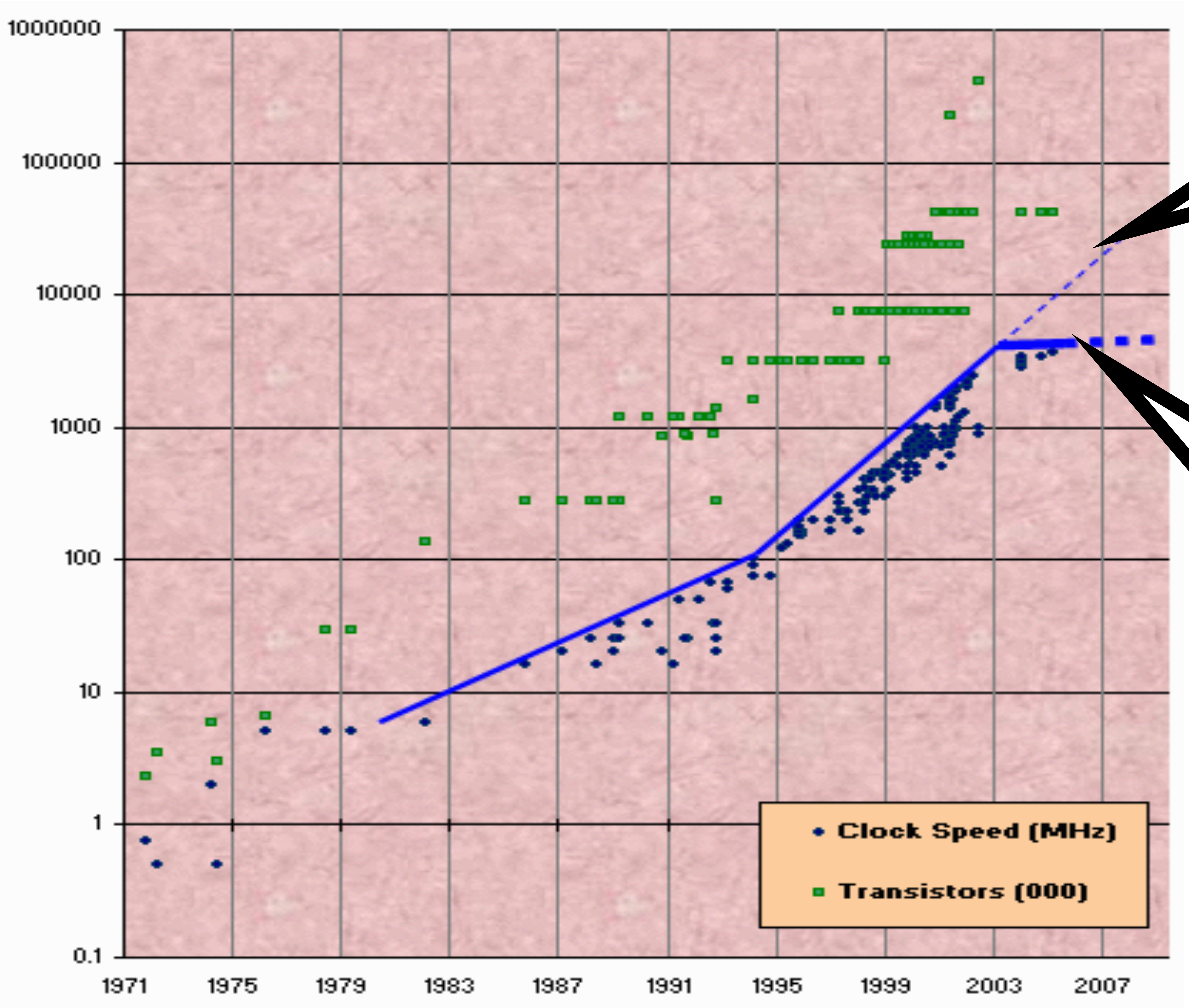
YSC3248: Parallel, Concurrent and Distributed Programming

Ilya Sergey

ilya.sergey@yale-nus.edu.sg

Moore’s Law

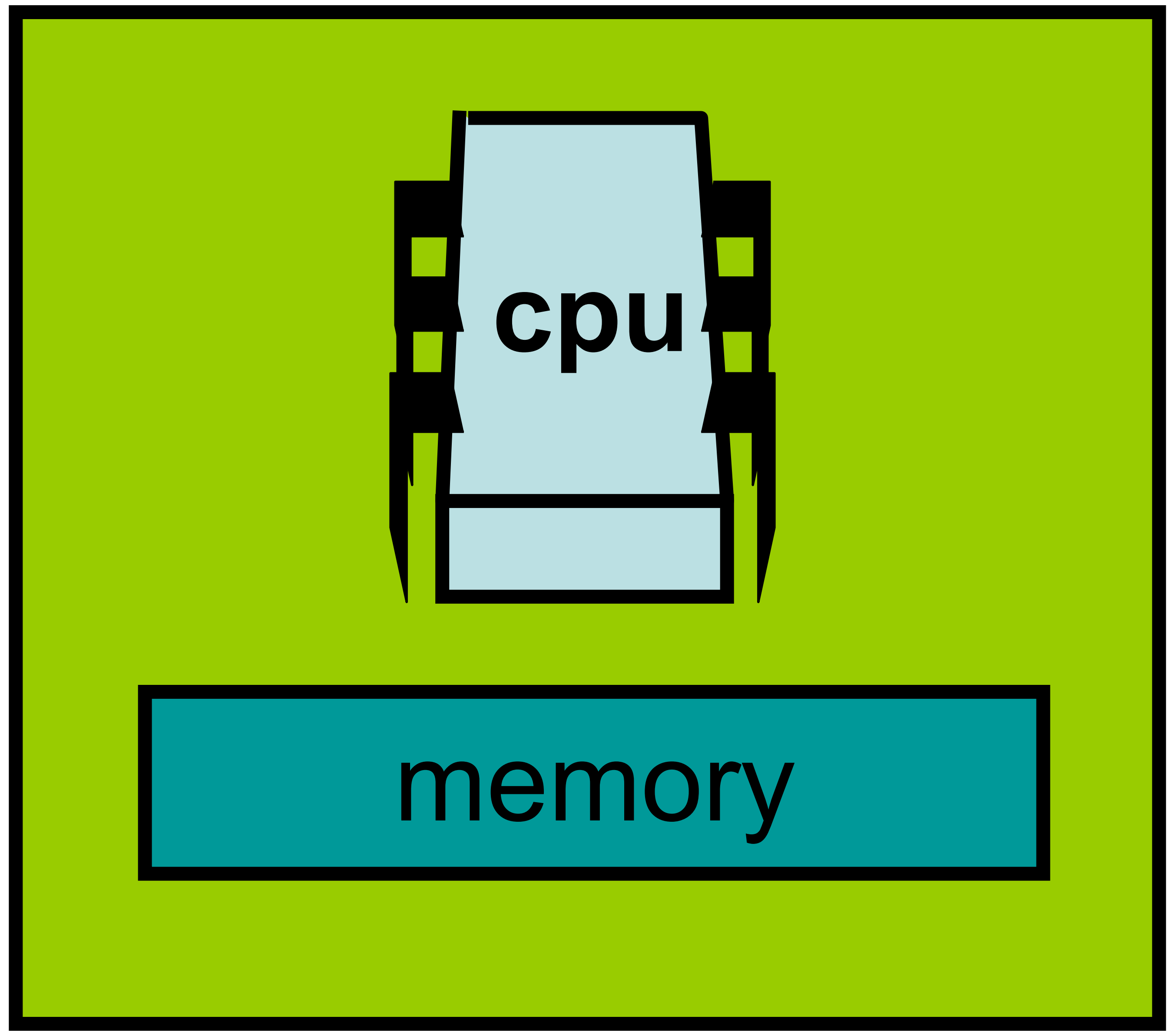


Transistor count still rising

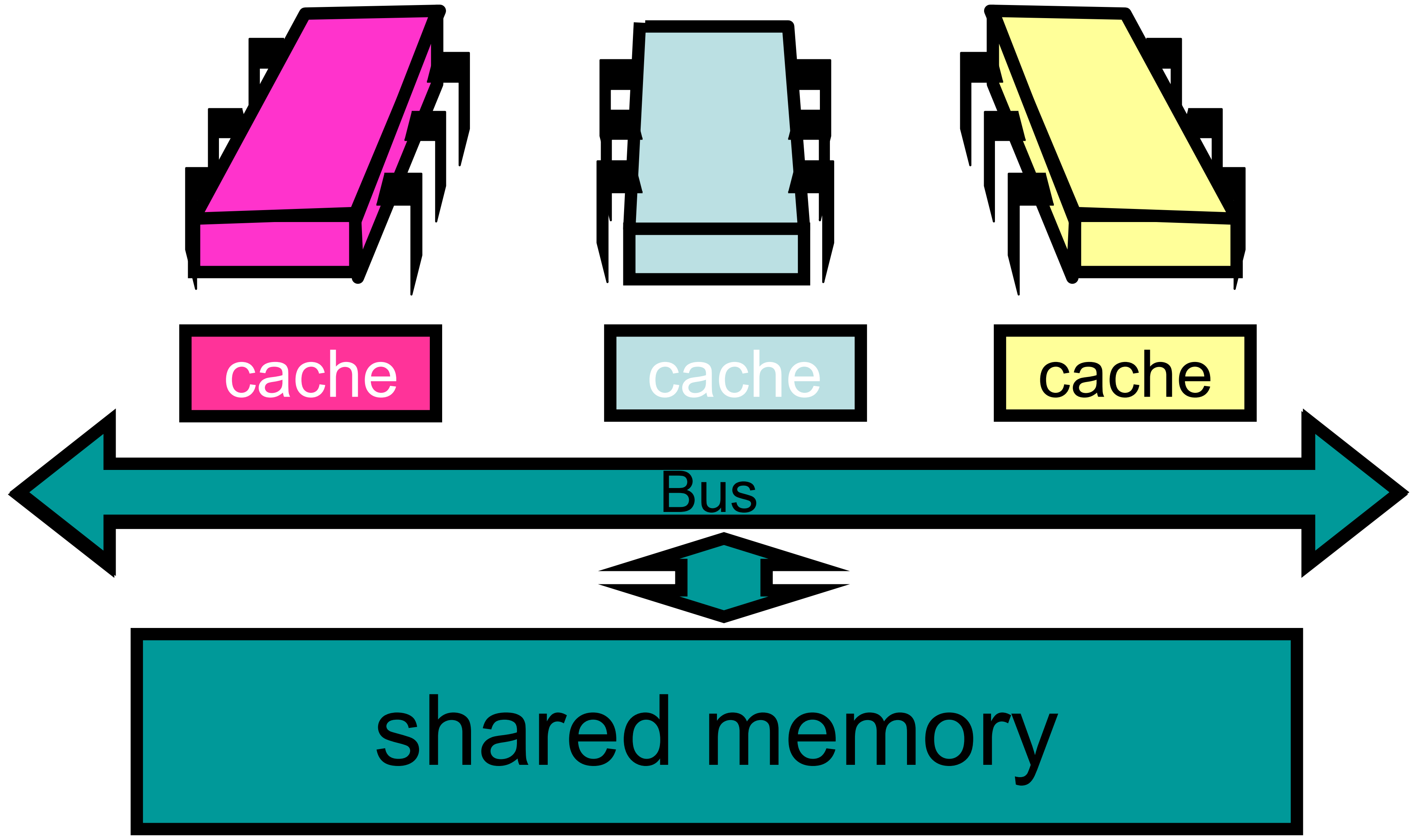
Clock speed flattening sharply

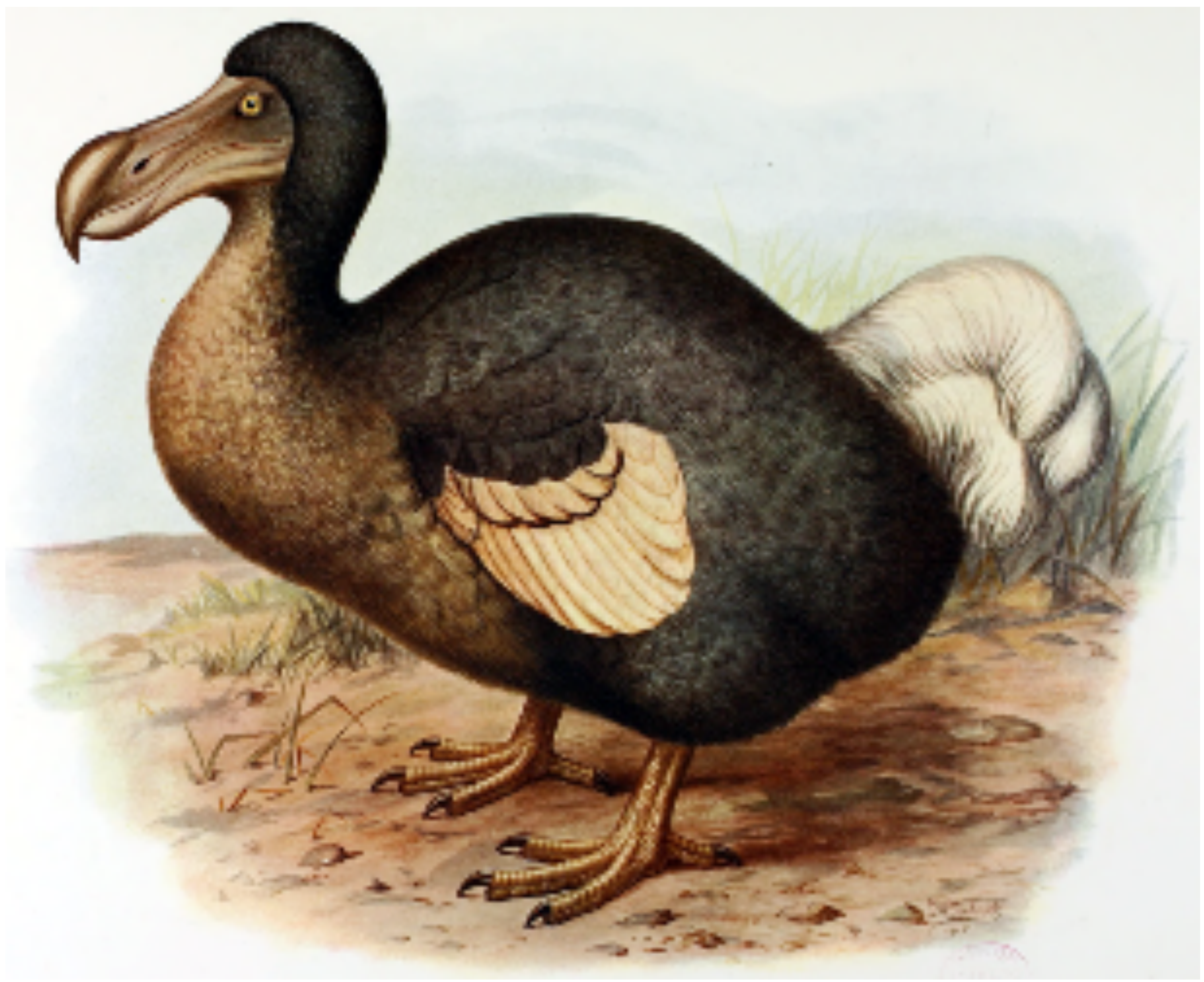
Moore’s Law (in practice)

Extinct: the Uniprocesor



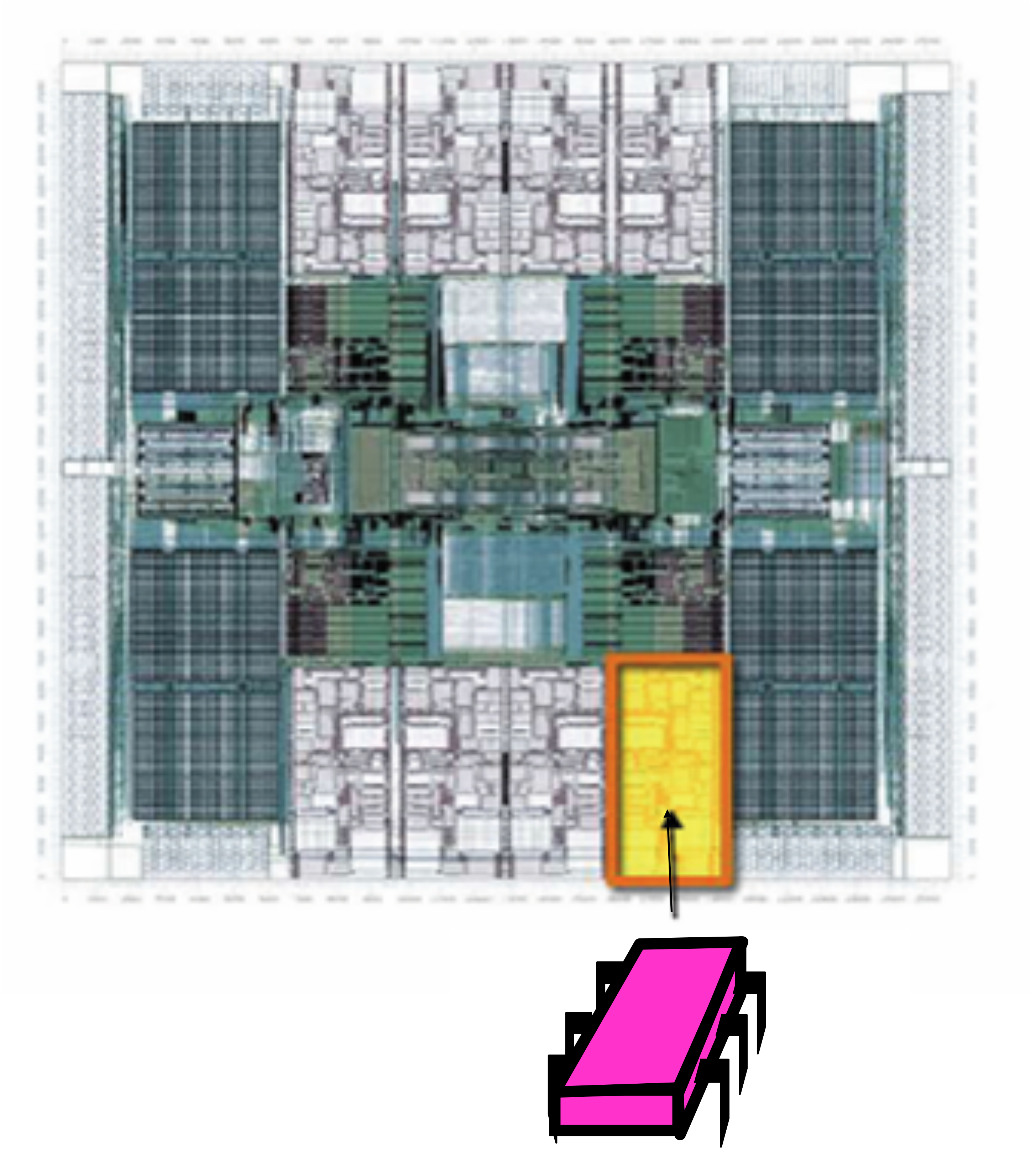
Extinct:
The Shared Memory Multiprocessor
(SMP)





The New Boss: The Multicore Processor (CMP)

All on the same chip

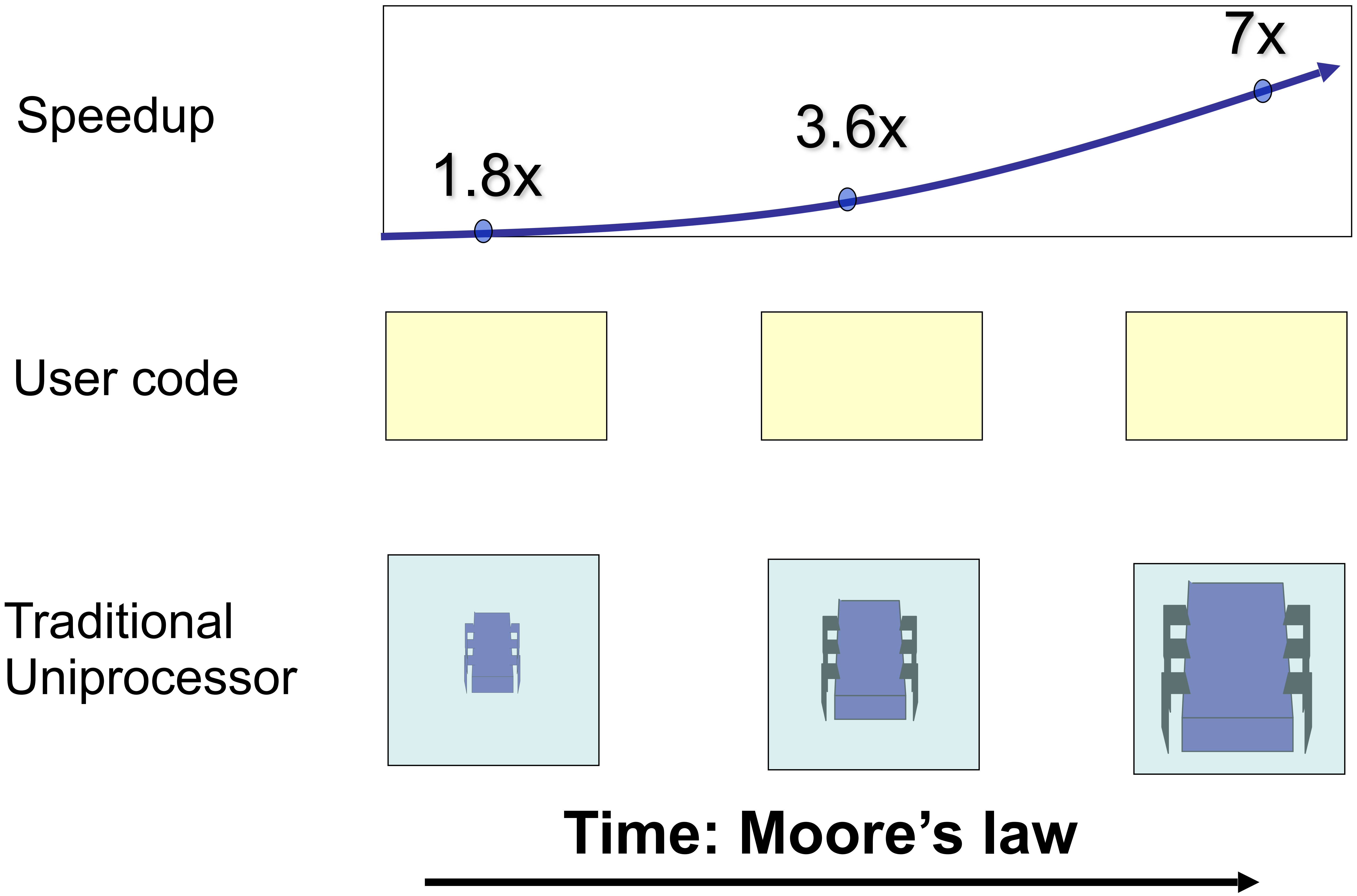


Sun T2000 Niagara

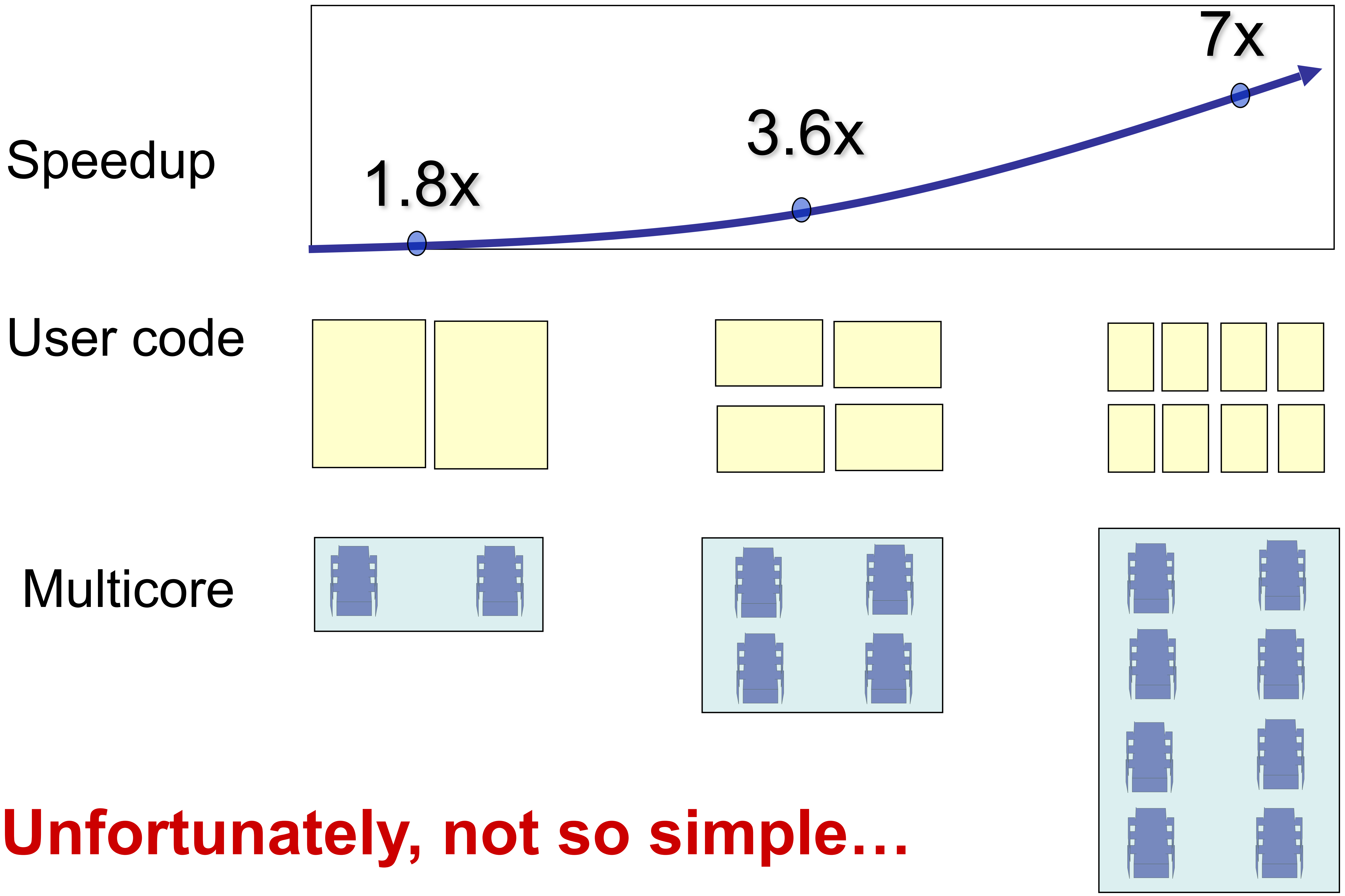
Why do we care?

- 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



Ideal Scaling Process



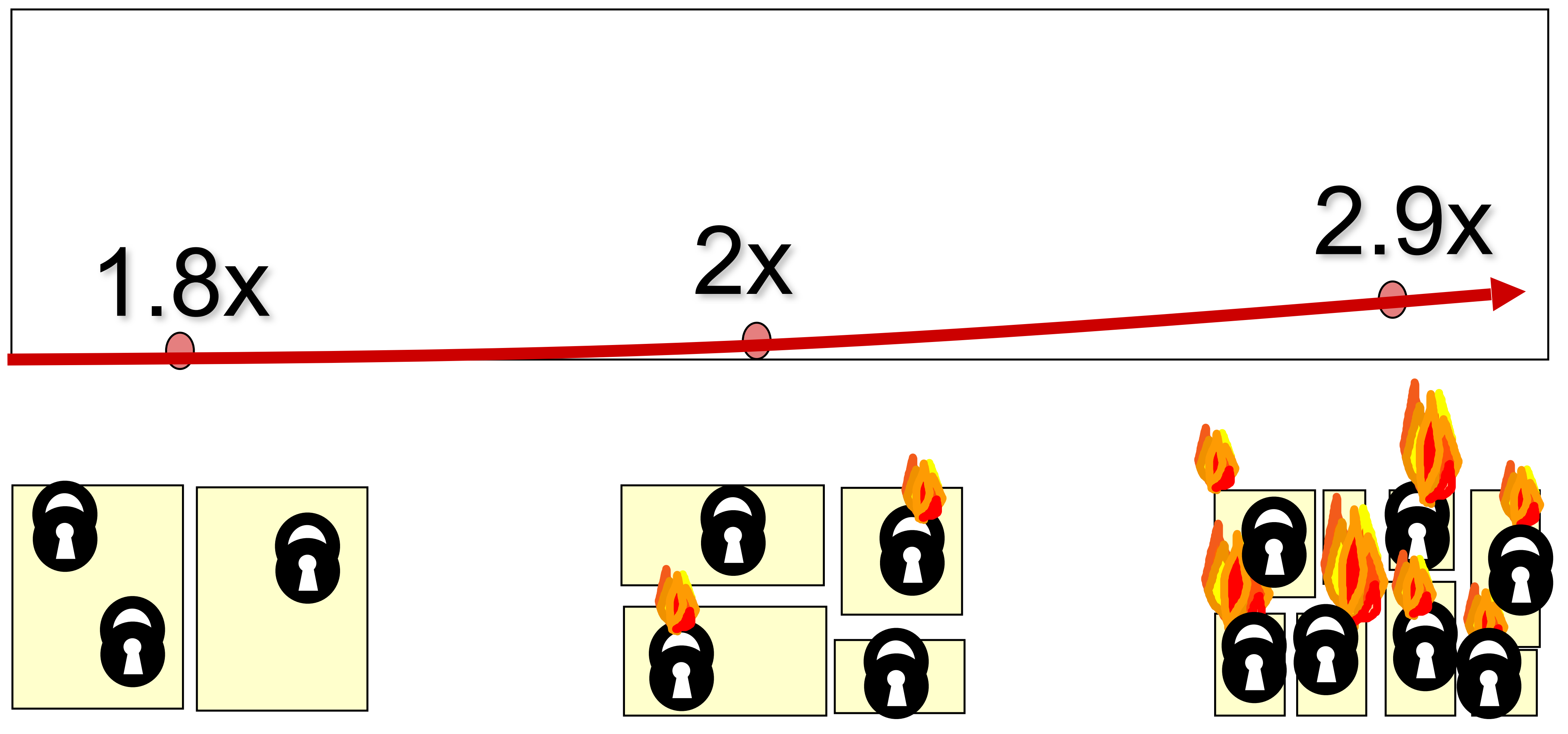
Unfortunately, not so simple…

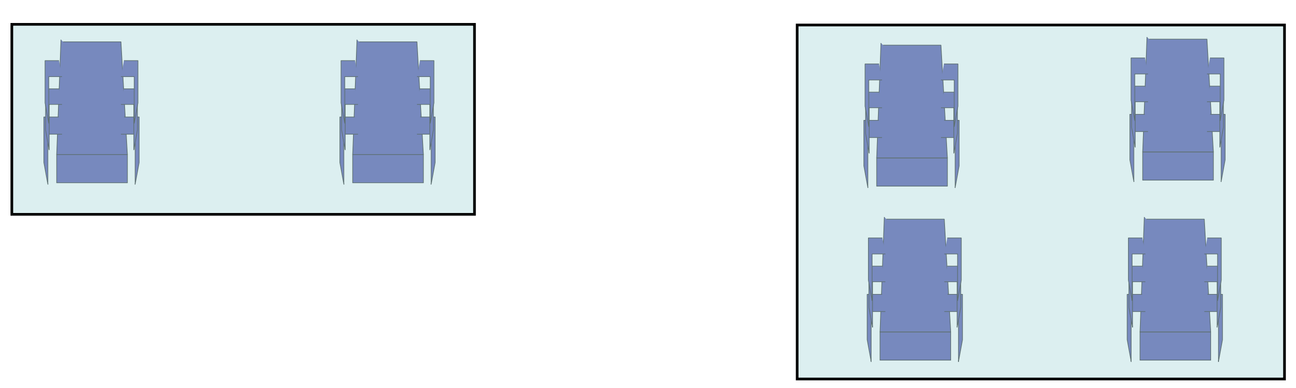
Actual Scaling Process

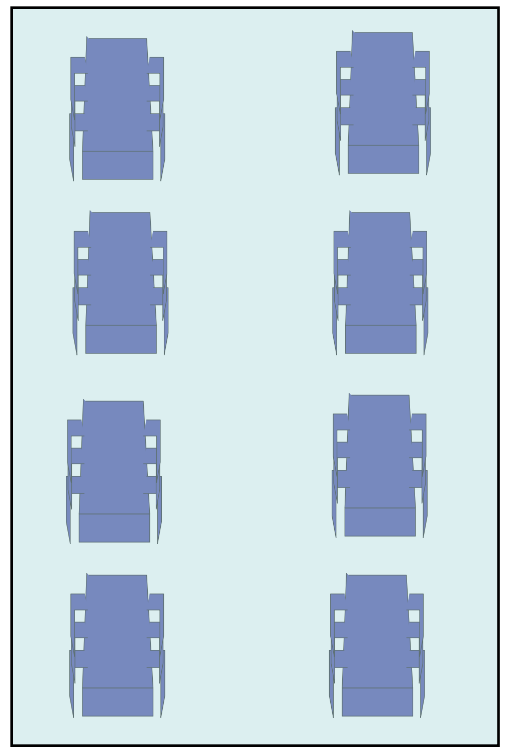
Speedup

User code

Multicore







Parallelization and Synchronization require great care…

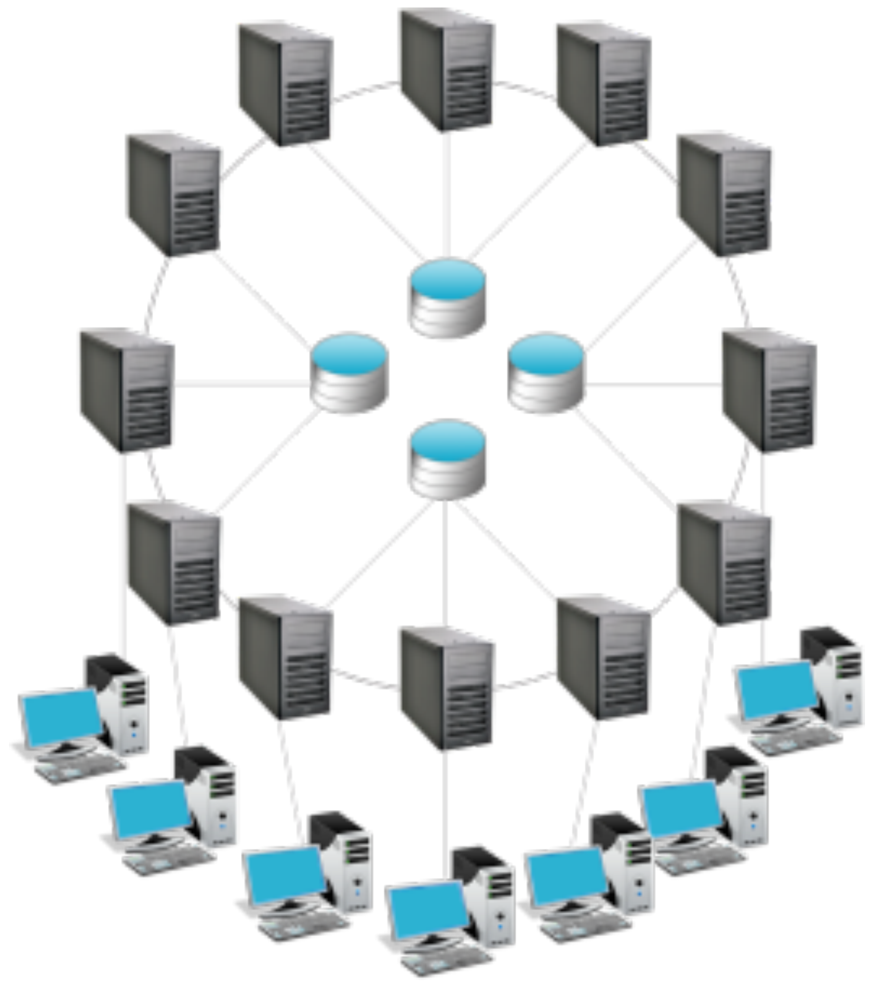
What this course is about?

- Writing *efficient* code by exploiting the *parallelism* offered by modern multiprocessors by means of writing *concurrent* programs

- Designing *concurrent* algorithms and data structures (executing on the same computer, possibly in parallel)

- Avoiding common mistakes when writing *concurrent* code; *formally reasoning* about its *correctness*.

- Basics of *distributed computing* (over multiple computers) in the presence of *communication* faults.



Programming Language

- A mix of functional and object-oriented programming
  (suitable for both OCaml and Java/C++ hackers)

- Supports almost all styles of concurrency
  (shared-memory, message-passing, transactional memory, *etc.*)

- Type-safe, garbage-collected.

- Interoperability with Java, compiling into JVM (Java Virtual Machine)

- Great IDE support (we'll be using IntelliJ IDEA with Scala plugin)

Grading

- 7 Written Theory Assignments: 35%
- 6 Programming Assignments: 30%
- Mid-Term Project: 15%
- Final Project: 15%
- In-class participation: 5%

Homework

- Two types: theoretical and programming assignments
- Complete *individually*
- Deliverables:
  - a PDF with typeset answers (theory) and occasionally some code
  - a .zip-archive with a Scala project (programming)
- Each assignment is graded out of 20 points

Collaboration

- Permitted:
  Talking about the homework problems with other students; using other textbooks; using the Internet.
- Not permitted:
  Obtaining the answer directly from anyone or anything else in any form.

Coding Assignments

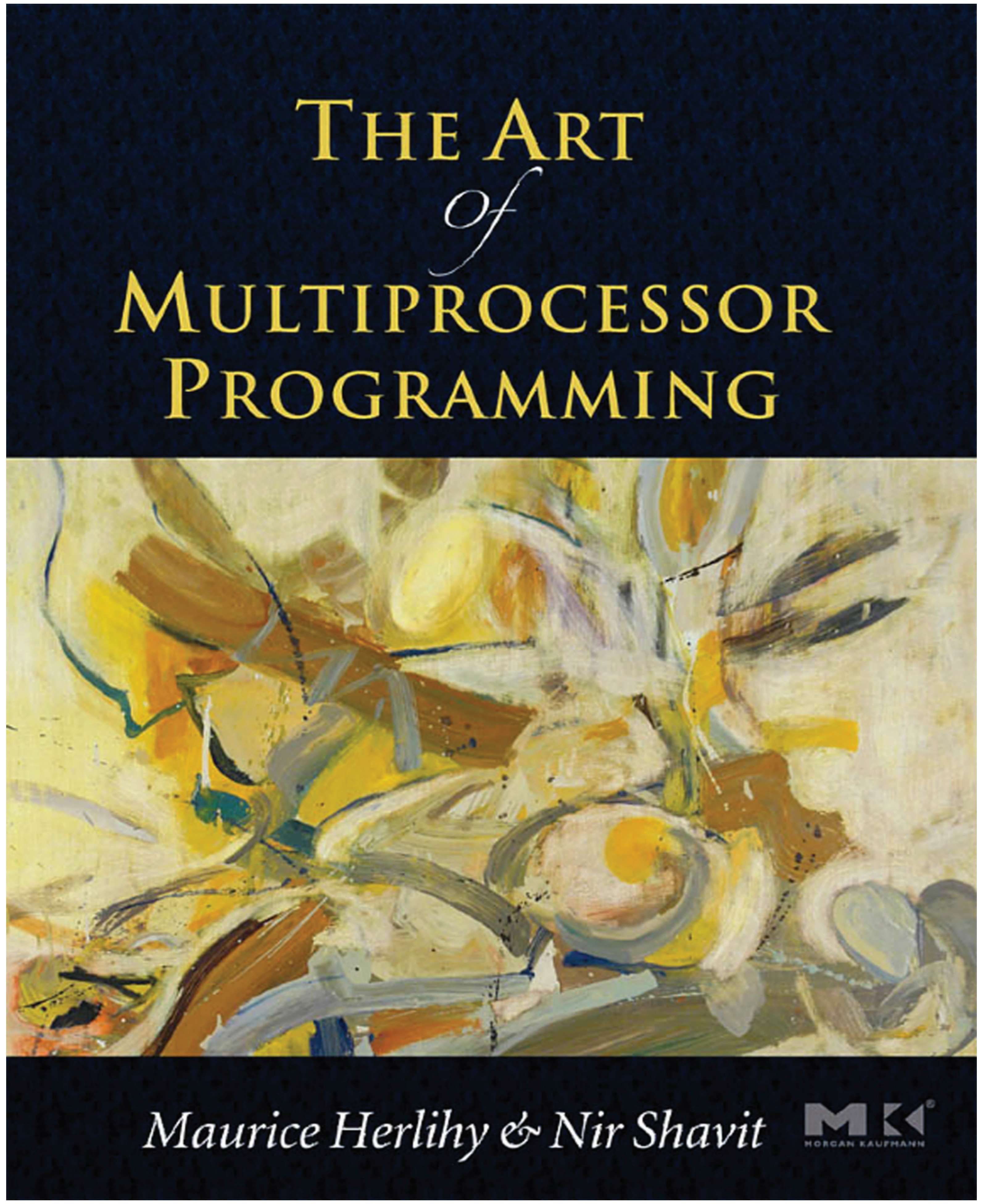
Please, send me your GitHub name by this Friday!

Most of this course: Multicore Programming

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

Resources

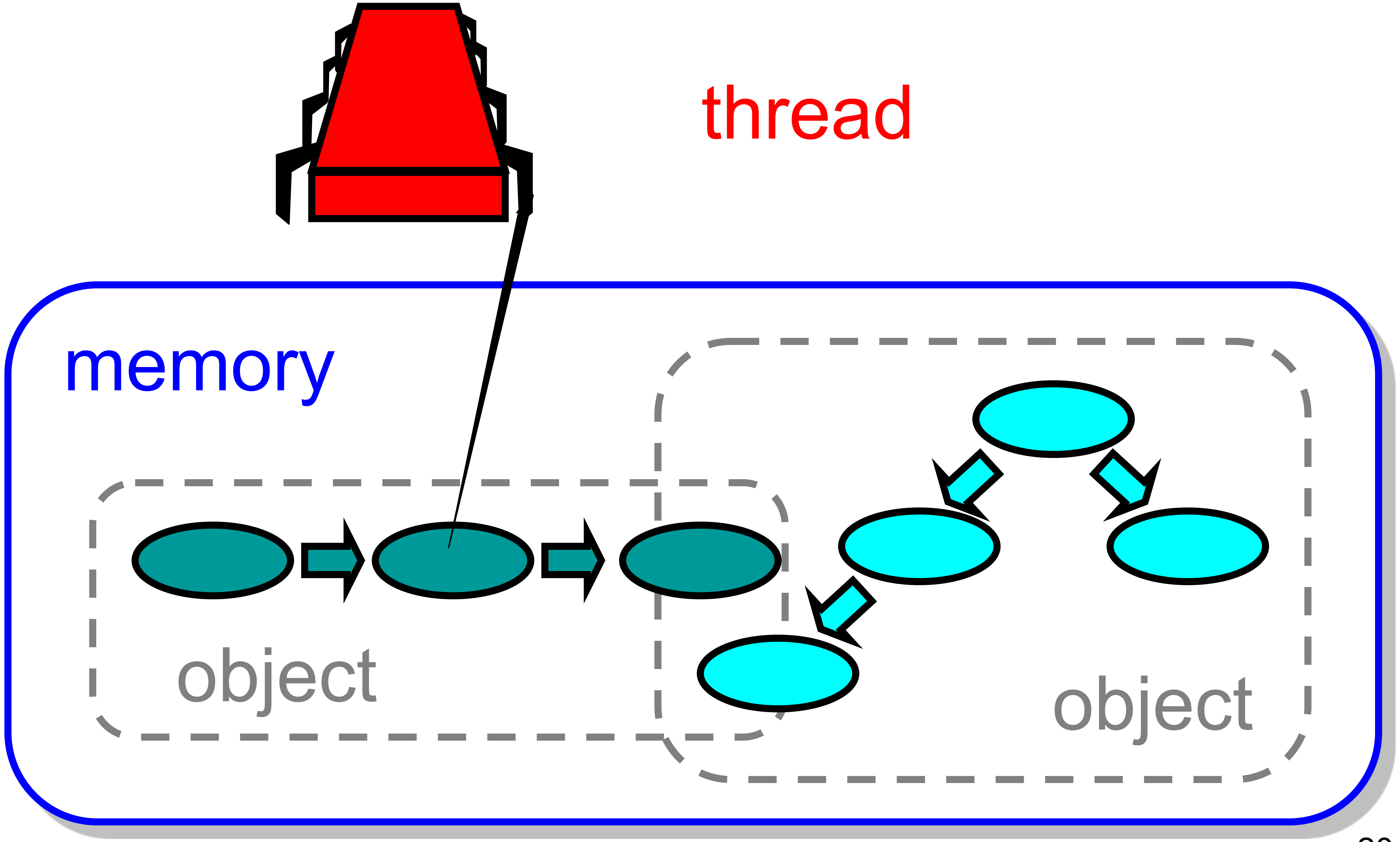
About 65% of the material



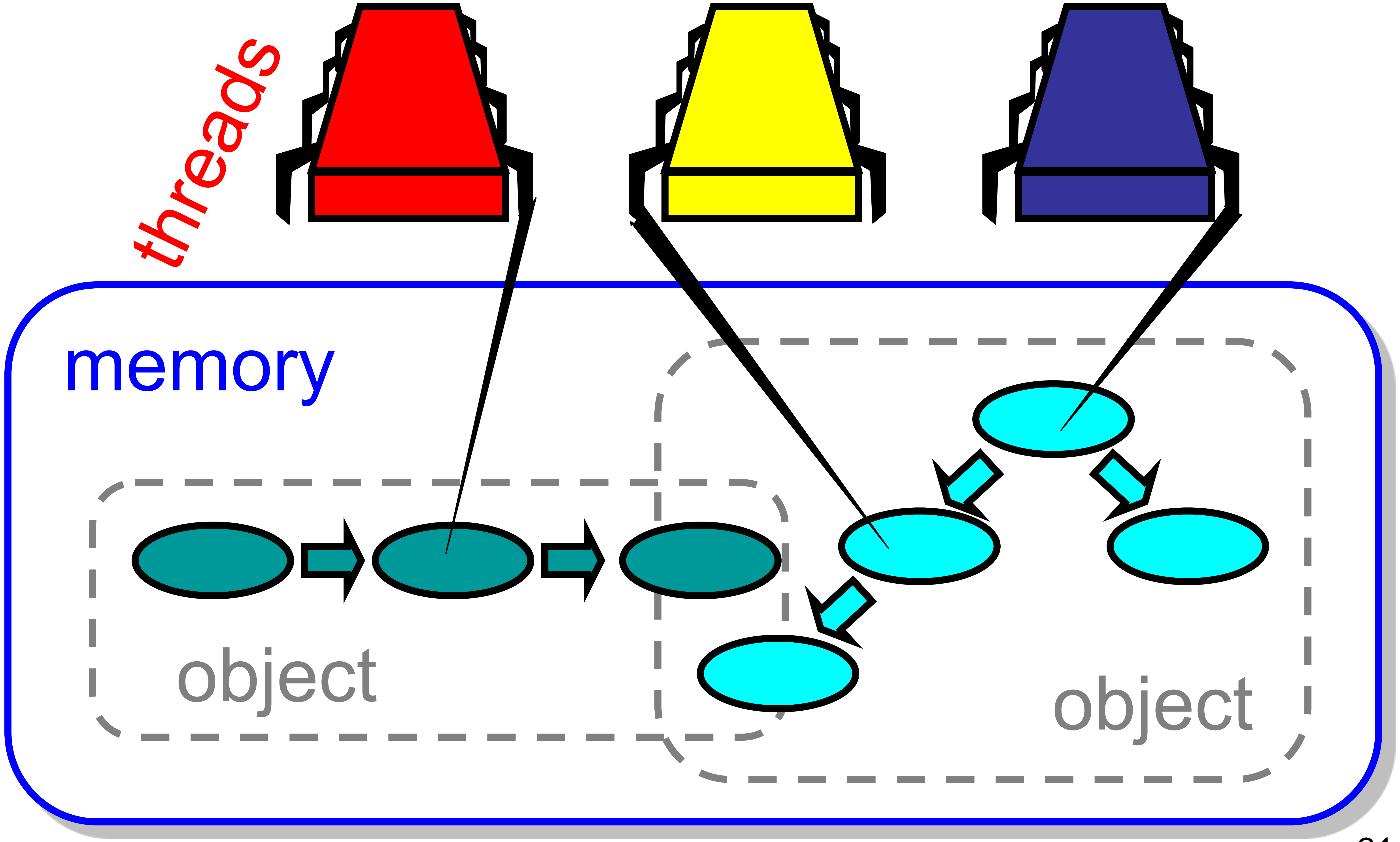
The rest

- Lecture slides
- Lecture notes
- The Internet

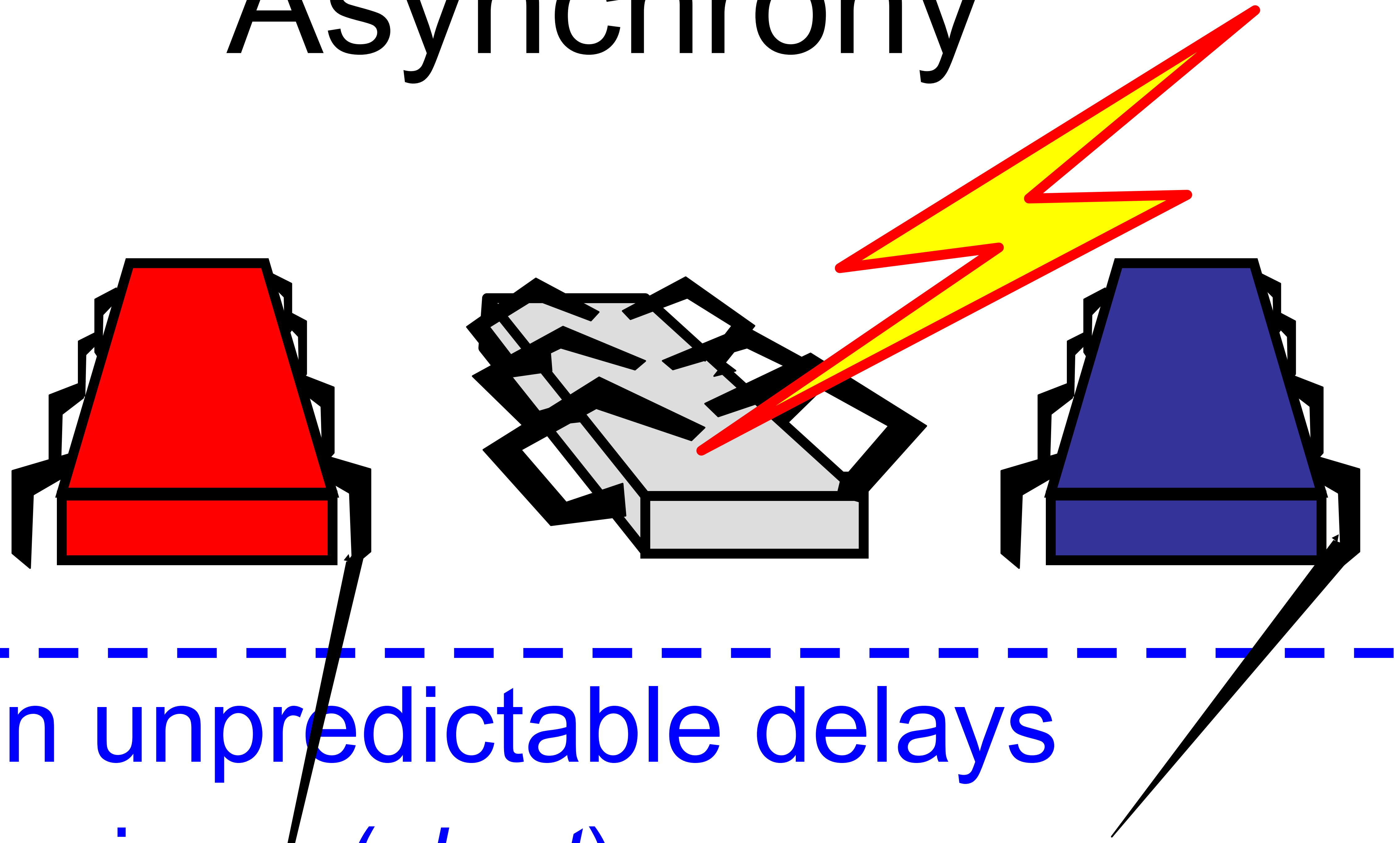
Sequential Computation



Concurrent Computation

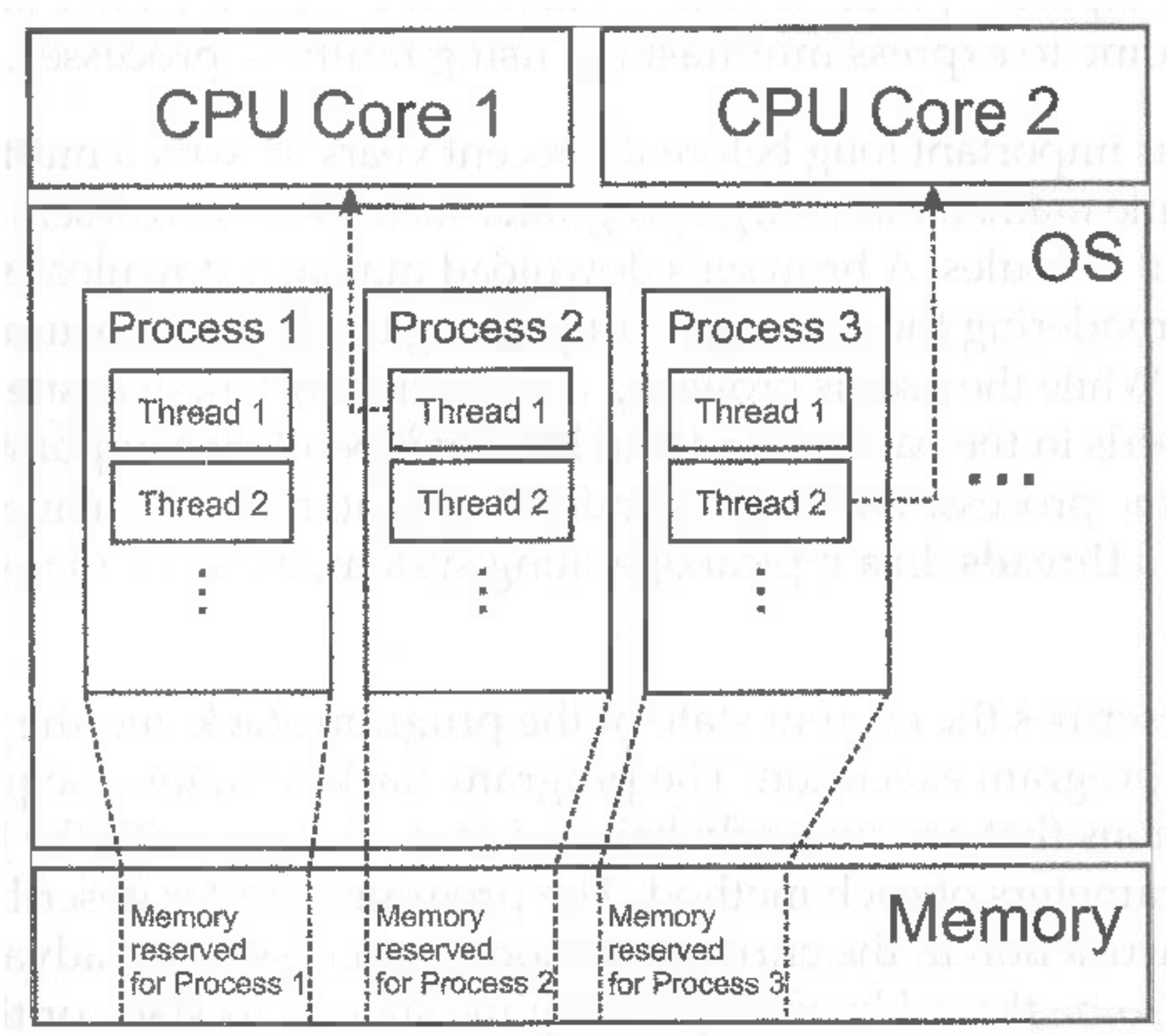


Asynchrony



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

Threads, Processes and Processors



Picture credit: *Learning Concurrent Programming in Scala*, A. Prokopec, 2014

Model Summary

- Multiple *threads* (within processes)
  - Sometimes also 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 idealised models of concurrent computations
  - Look at simplistic problems
  - Emphasise correctness over pragmatism
  - “Correctness may be theoretical, but incorrectness has practical impact”

Concurrency Jargon

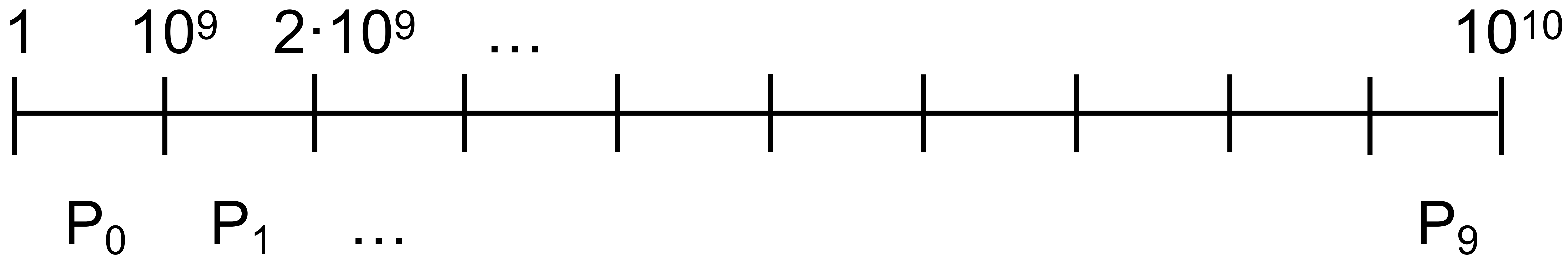
- Hardware
  - Processors
- Software
  - Threads, processes
    (one process may have several threads)
- Sometimes OK to confuse them, sometimes not.

Designing Concurrent Programs

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*

```
def primePrint(): Unit = {
  val i = ThreadID.get // Thread IDs in 0..9
  val block = math.pow(10, 10⁹)
  for (j <- (i * block) + 1 to (i + 1) * block) {
    if (isPrime(j)) {
      println(j)
    }
  }
}
```

Issues

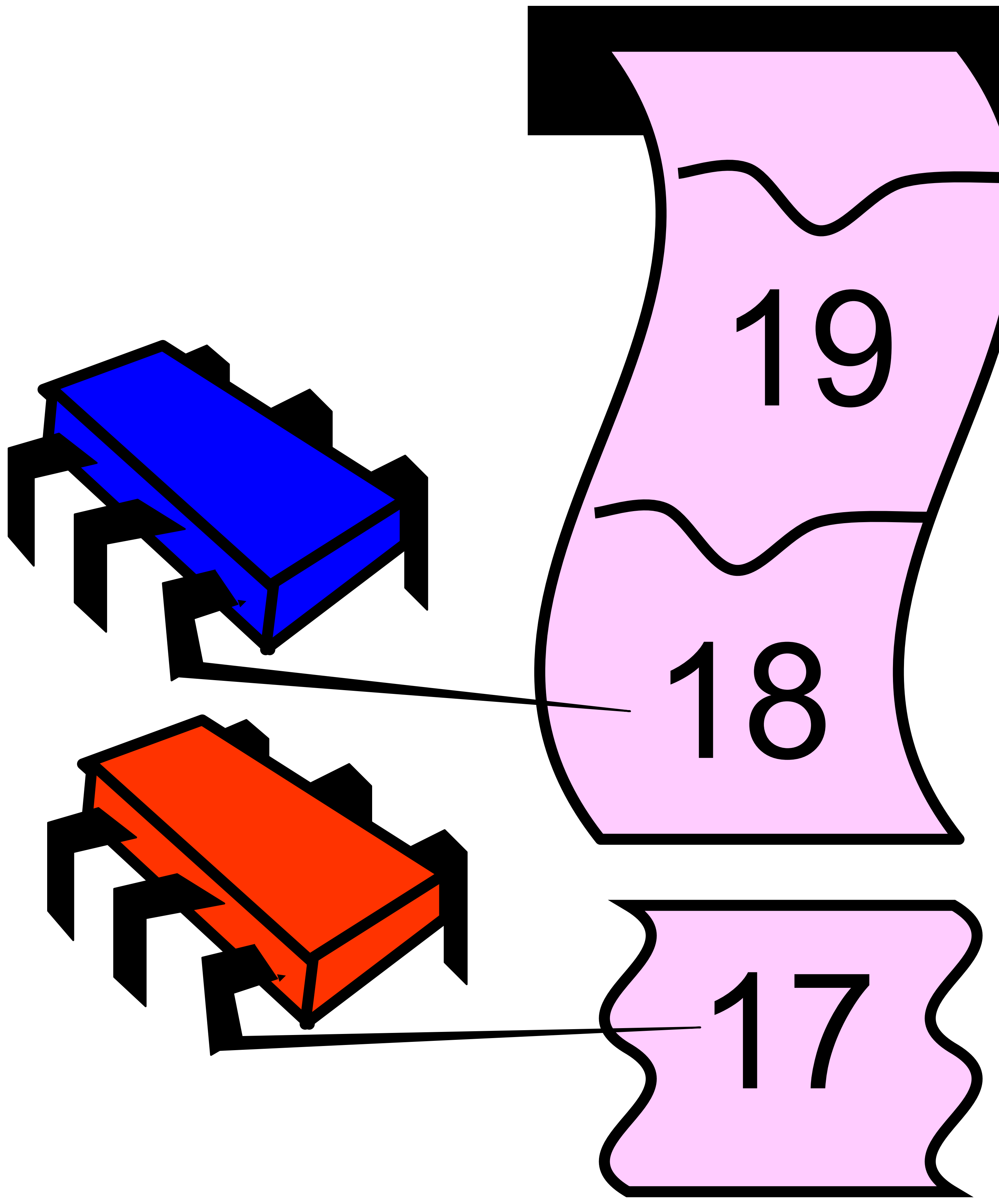
- Higher ranges have fewer primes
- Yet larger numbers harder to test
- Thread workloads
  - Uneven
  - Hard to predict

Issues

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

rejected

Shared Counter



each thread
takes a number

Procedure for Thread *i*

```
val counter = new Counter

def primePrint(): Unit = {
  var i: Int = 1
  val limit = math.pow(10, 9).intValue
  while (i < limit) {
    i = counter.getAndIncrement
    if (isPrime(i)) {
      println(i)
    }
  }
}
```

Procedure for Thread *i*

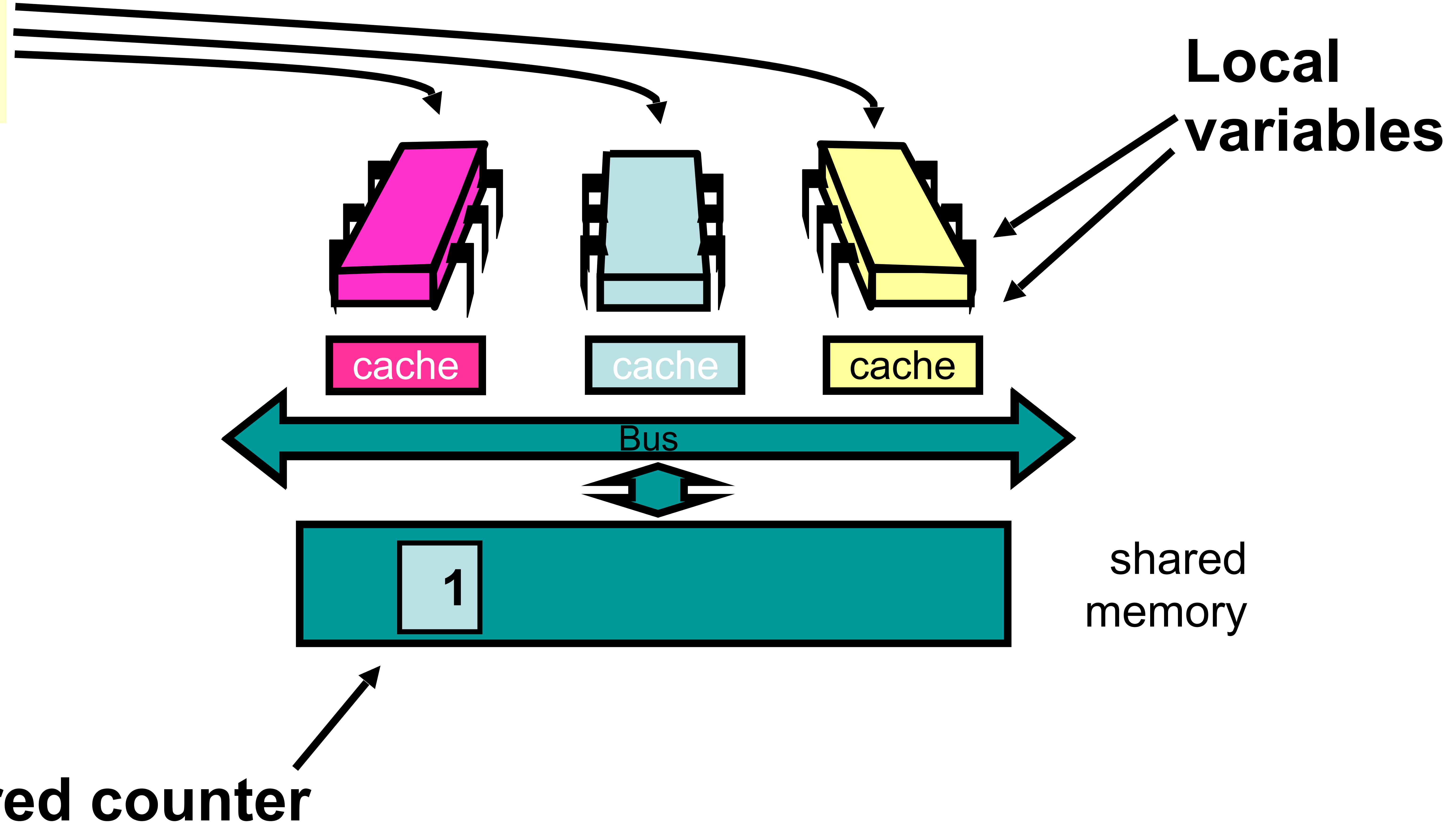
```
val counter = new Counter

def primePrint(): Unit = {
  var i: Int = 1
  val limit = math.pow(10, 9).intValue
  while (i < limit) {
    i = counter.getAndIncrement
    if (isPrime(i)) {
      println(i)
    }
  }
}
```

Shared counter object

Where Things Reside

```
val counter = new Counter

def primePrint(): Unit = {
  var i: Int = 1
  val limit = math.pow(10, 9).intValue
  while (i < limit) {
    i = counter.getAndIncrement
    if (isPrime(i)) {
      println(i)
    }
  }
}
```

code



Procedure for Thread *i*

```
val counter = new Counter

def primePrint(): Unit = {
  var i: Int = 1
  val limit = math.pow(10, 9).intValue
  while (i < limit) {
    i = counter.getAndIncrement
    if (isPrime(i)) {
      println(i)
    }
  }
}
```

Stop when every value taken

Procedure for Thread *i*

```
val counter = new Counter

def primePrint(): Unit = {
  var i: Int = 1
  val limit = math.pow(10, 9).intValue
  while (i < limit) {
    i = counter.getAndIncrement
    if (isPrime(i)) {
      println(i)
    }
  }
}
```

Increment & return each new value

Demo

Counter Implementation

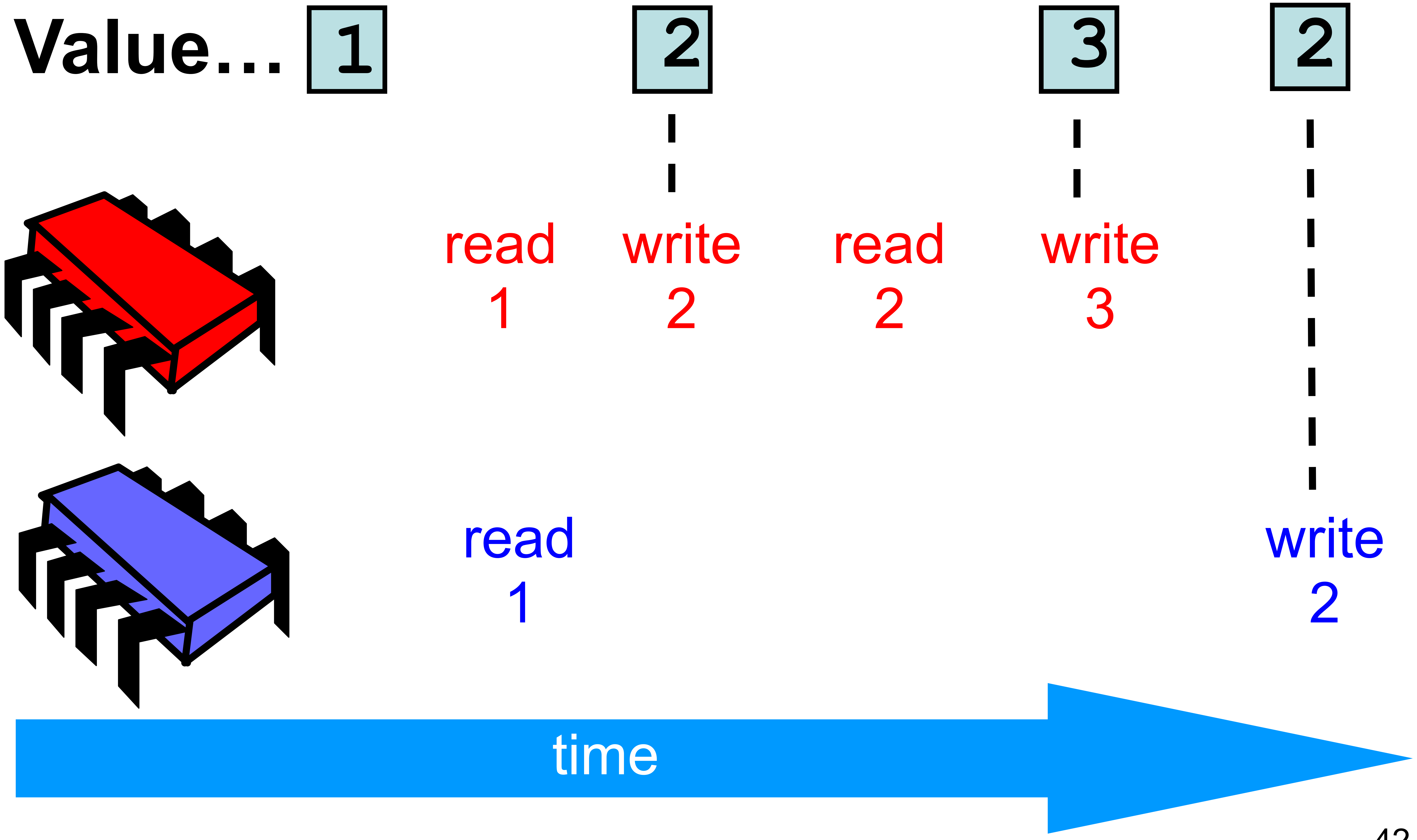
```
class Counter {
  private var count = 0

  def getAndIncrement: Int = {
    val tmp = count
    count = tmp + 1
    tmp
  }
}
```

Counter Implementation

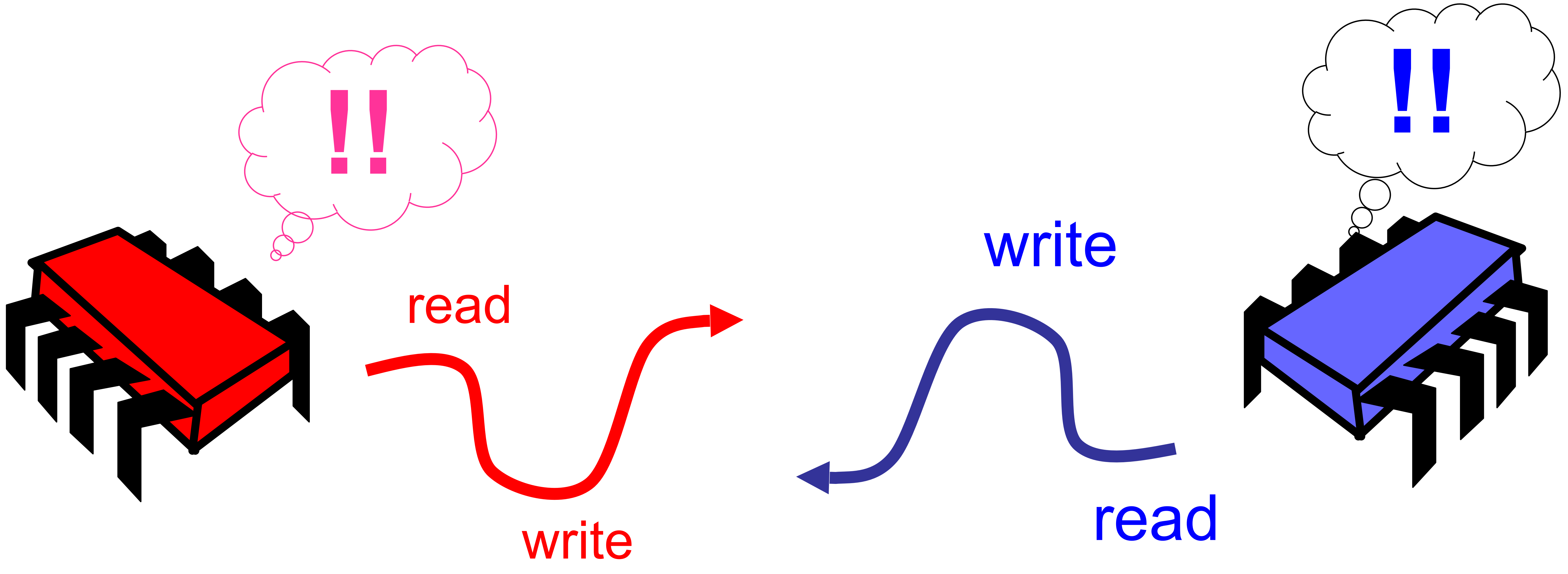
```
class Counter {
  private var count = 0

  def getAndIncrement: Int = {
    val tmp = count
    count = tmp + 1
    tmp
  }
}
```

OK for single thread, not for concurrent threads

Not so good…



Is this problem inherent?



If we could only glue reads and writes together…

Challenge

```
class Counter {
  private var count = 0

  def getAndIncrement: Int = {
    val tmp = count
    count = tmp + 1
    tmp
  }
}
```

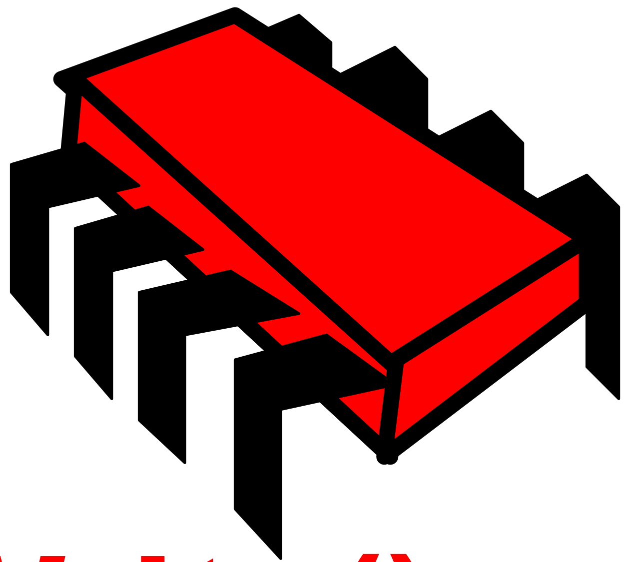
Challenge

```
class Counter {
  private var count = 0

  def getAndIncrement: Int = {
    val tmp = count
    count = tmp + 1
    tmp
  }
}
```

Make these steps *atomic* (indivisible)

Hardware Solution

```
class Counter {
  private var count = 0

  def getAndIncrement: Int = {
    val tmp = count
    count = tmp + 1
    tmp
  }
}
```



ReadModifyWrite() instruction

Java / Scala solution

```
class Counter {
  private var count = 0

  def getAndIncrement: Int = {
    this.synchronized {
      val tmp = count
      count = tmp + 1
      tmp
    }
  }
}
```

Java / Scala solution

```
class Counter {
  private var count = 0

  def getAndIncrement: Int = {
    this.synchronized {
      val tmp = count
      count = tmp + 1
      tmp
    }
  }
}
```

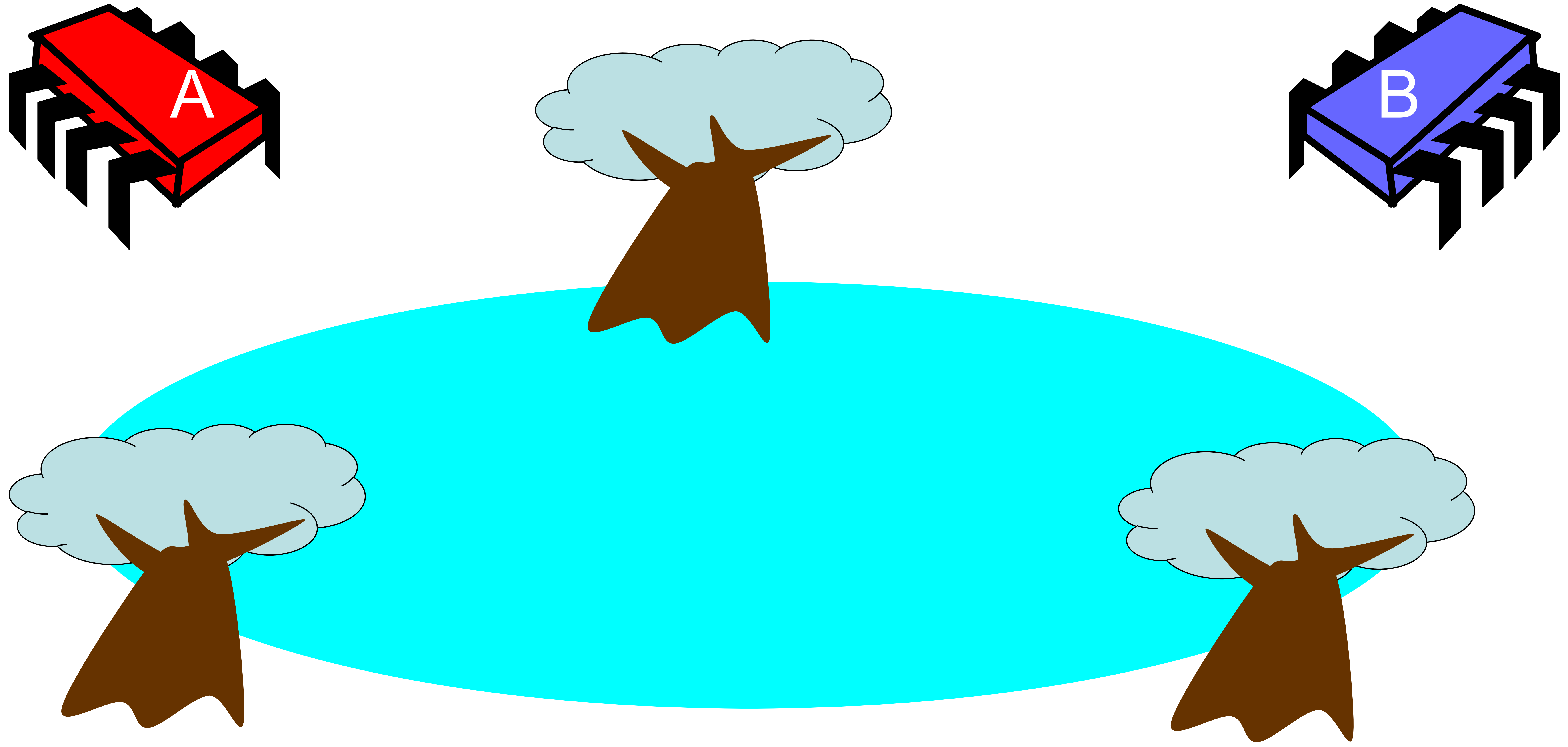
Synchronized block

Java / Scala solution

```
class Counter {
  private var count = 0

  def getAndIncrement: Int = {
    this.synchronized {
      val tmp = count
      count = tmp + 1
      tmp
    }
  }
}
```

Mutual Exclusion

Mutual Exclusion, or “Alice & Bob share a pond”



Alice has a pet

Bob has a pet

The Problem

Formalizing the Problem

- Two types of formal properties in asynchronous computation:
- Safety Properties
  - Nothing bad happens ever
  - If is violated, this is done by a *finite* computation
- Liveness Properties
  - Something good happens eventually
  - Cannot be violated by a finite computation (intuition we can always run longer and see what happens)

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

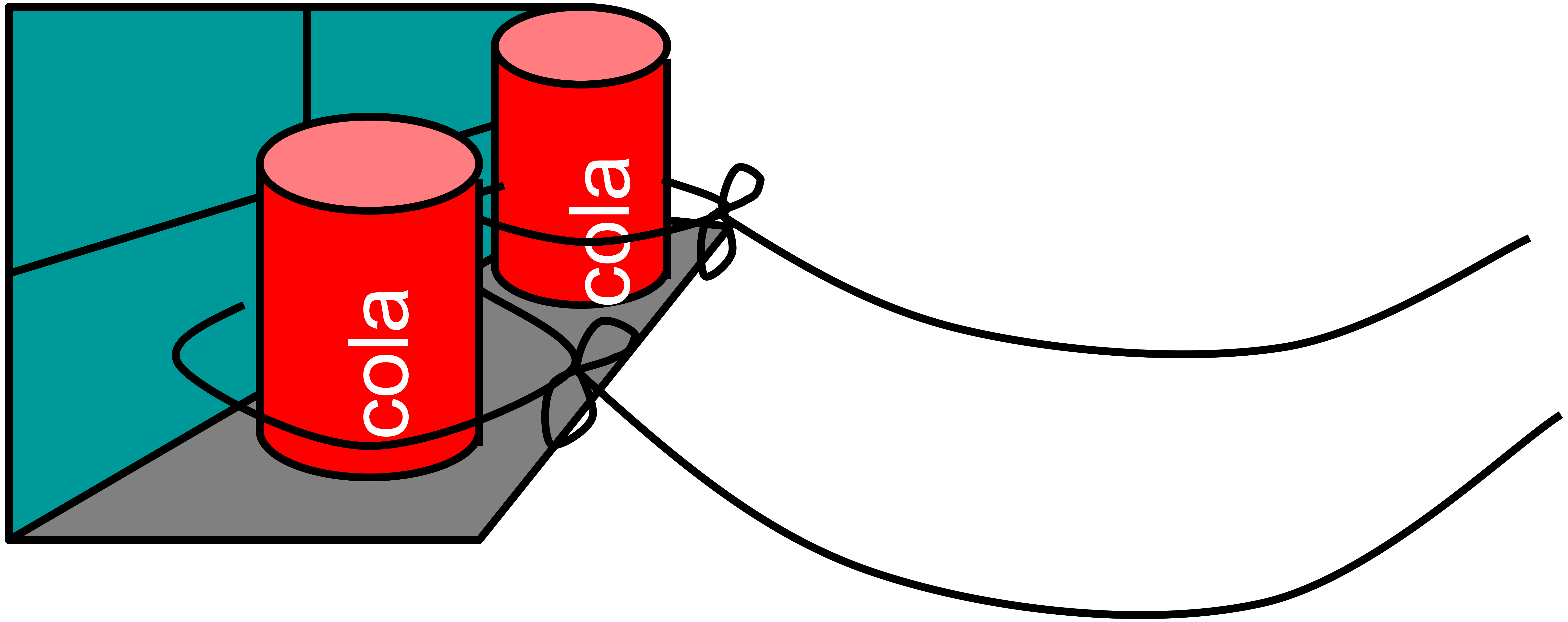
Cell Phone Protocol

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

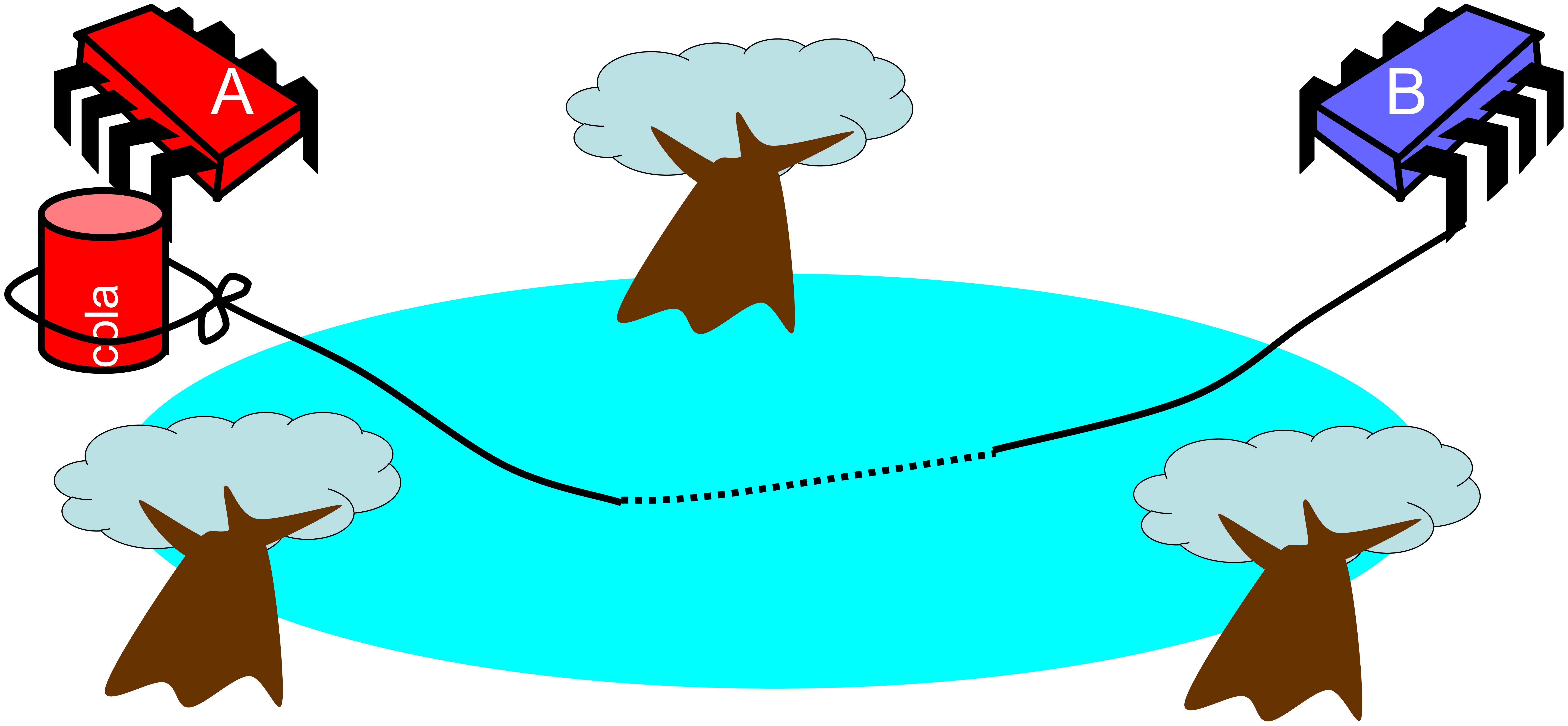
Interpretation

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

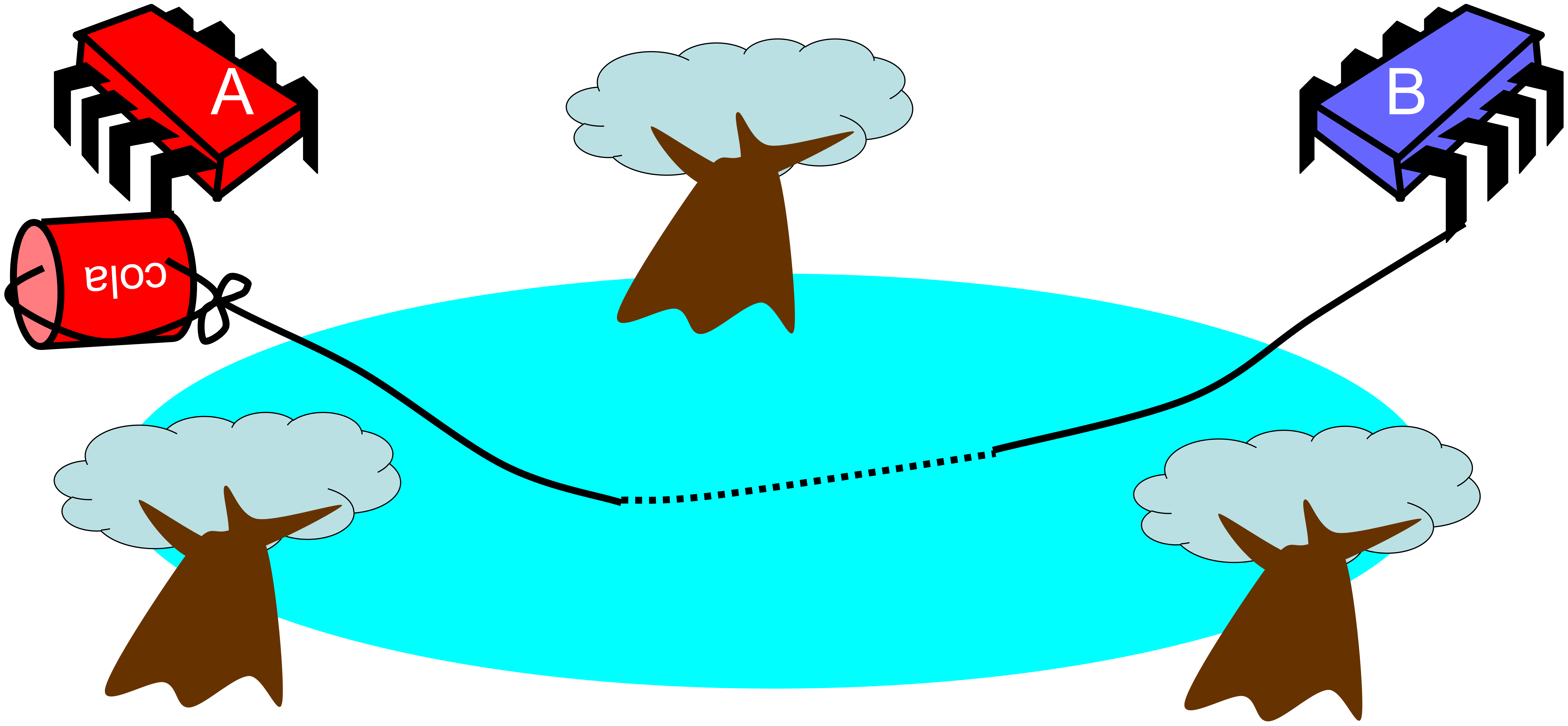
Can Protocol



Bob conveys a bit



Bob conveys a bit



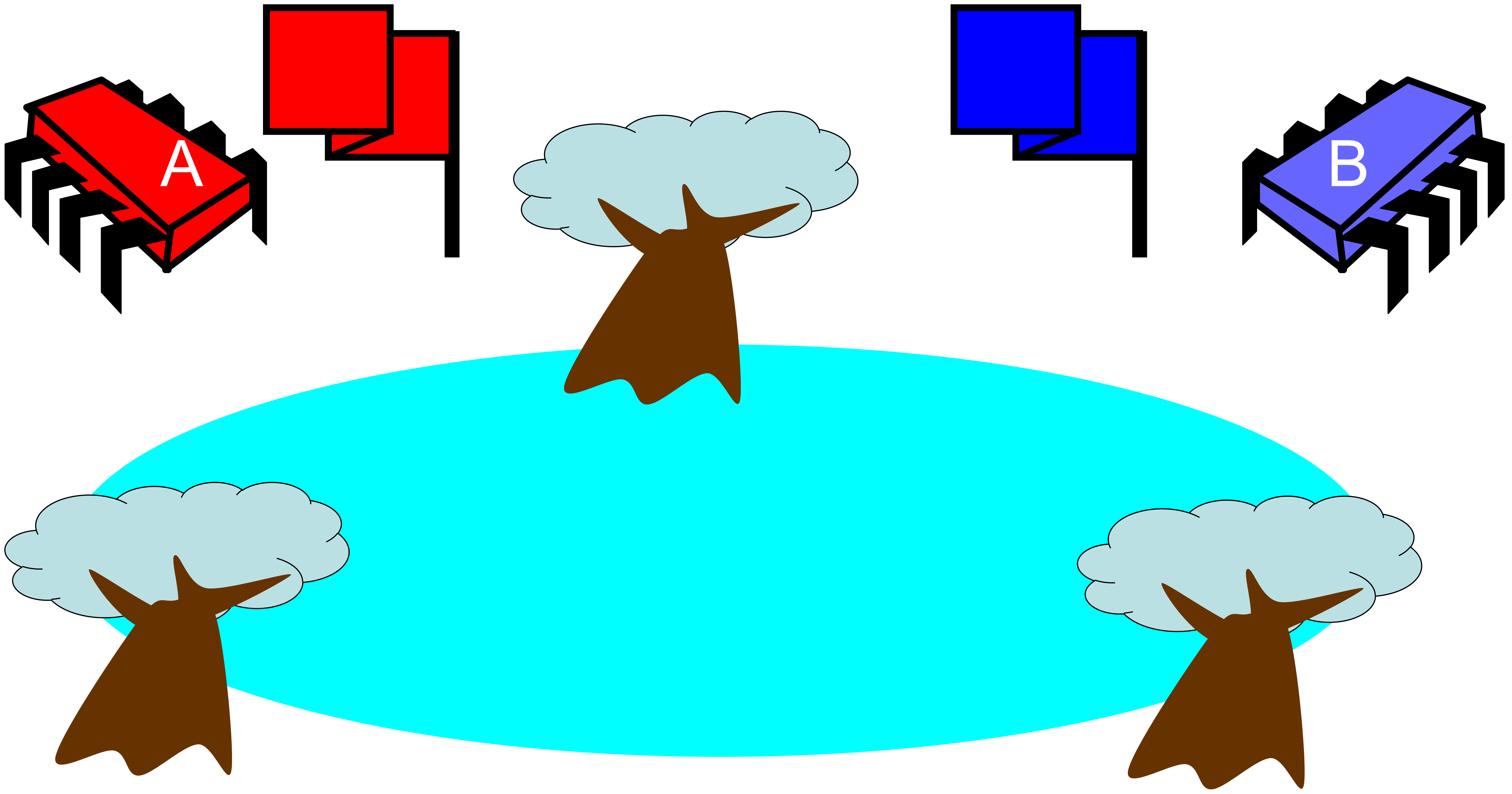
Can Protocol

- 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

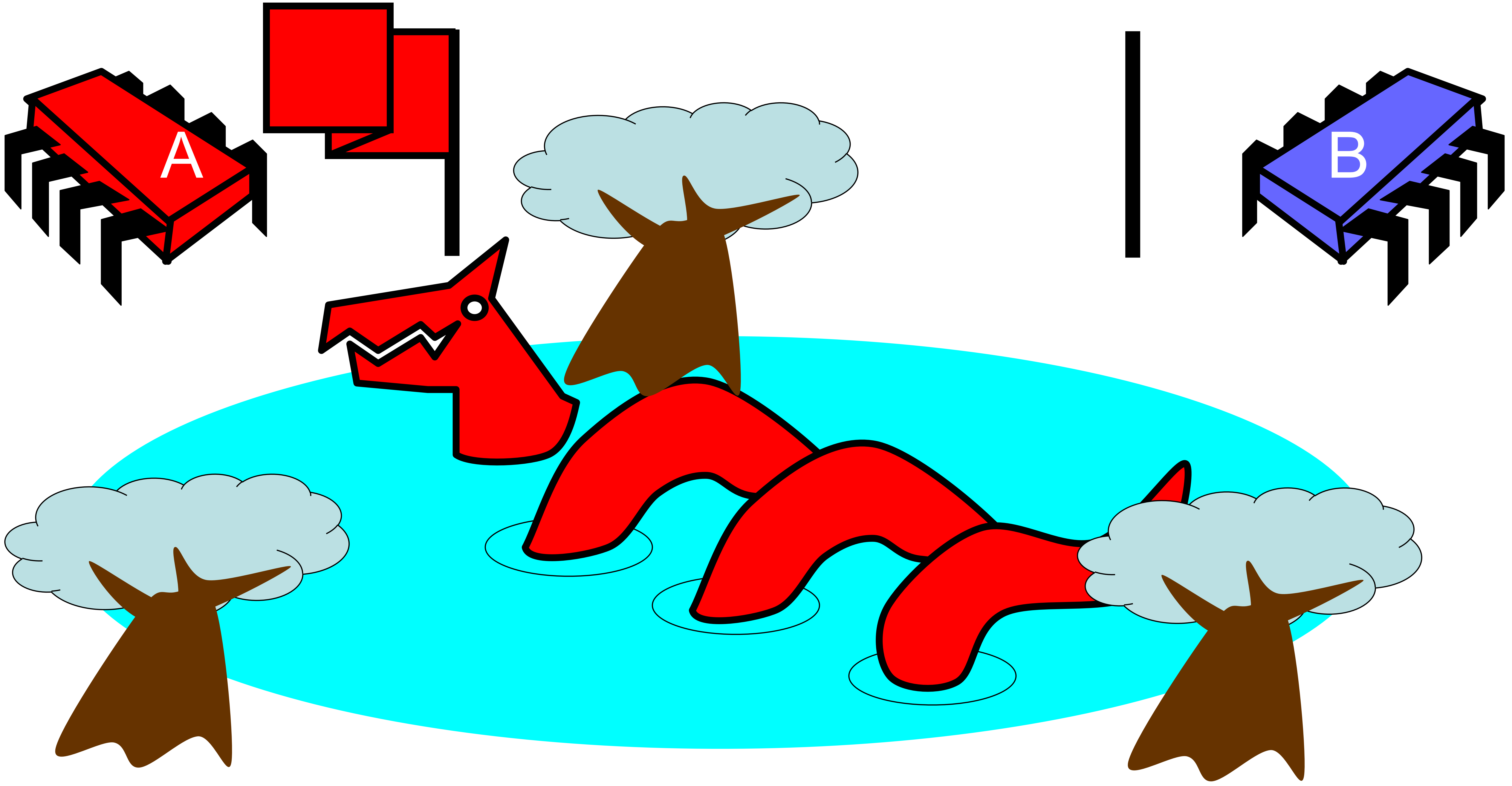
Interpretation

- 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

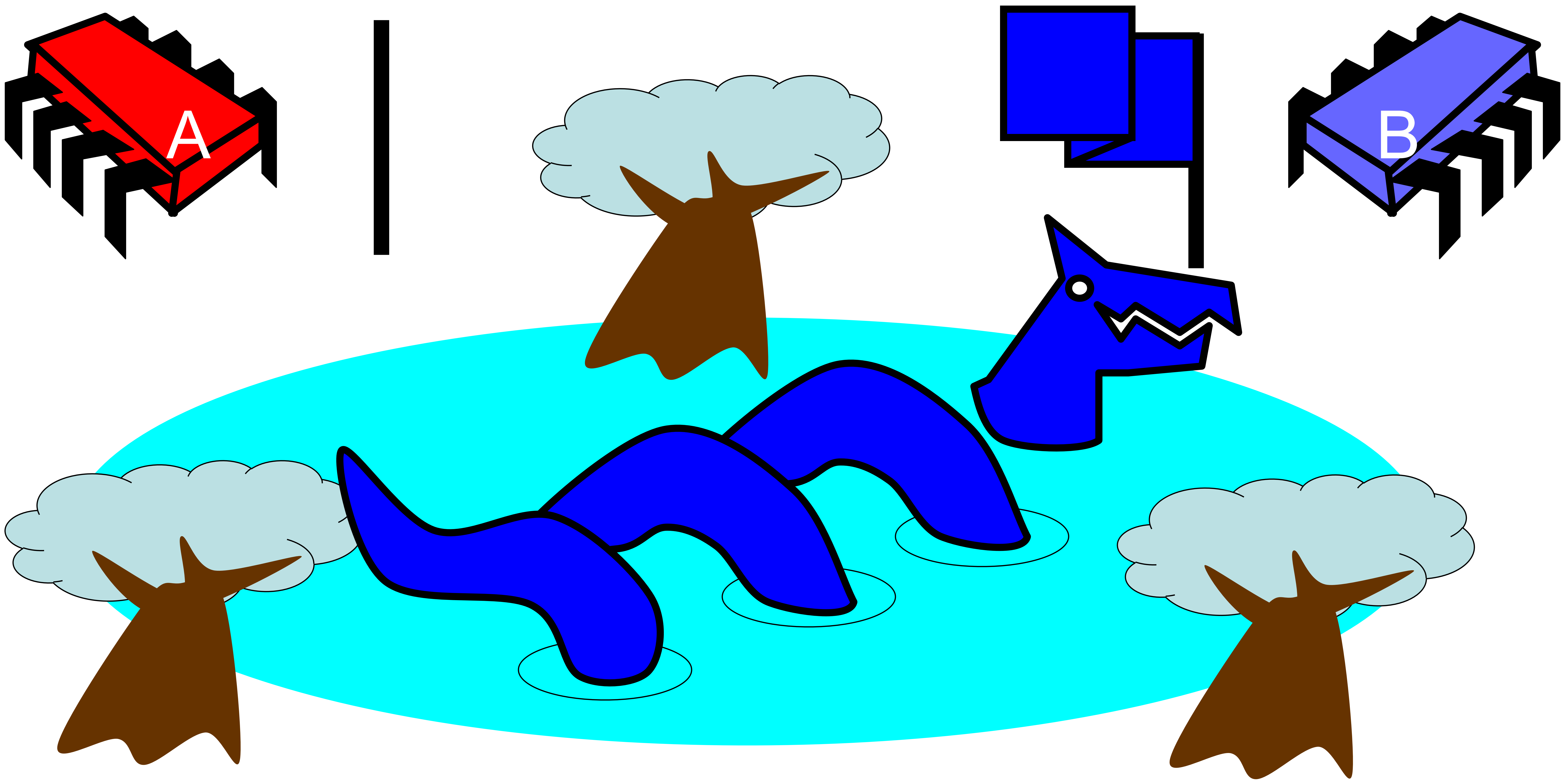
Flag Protocol



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

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: deadlock!

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

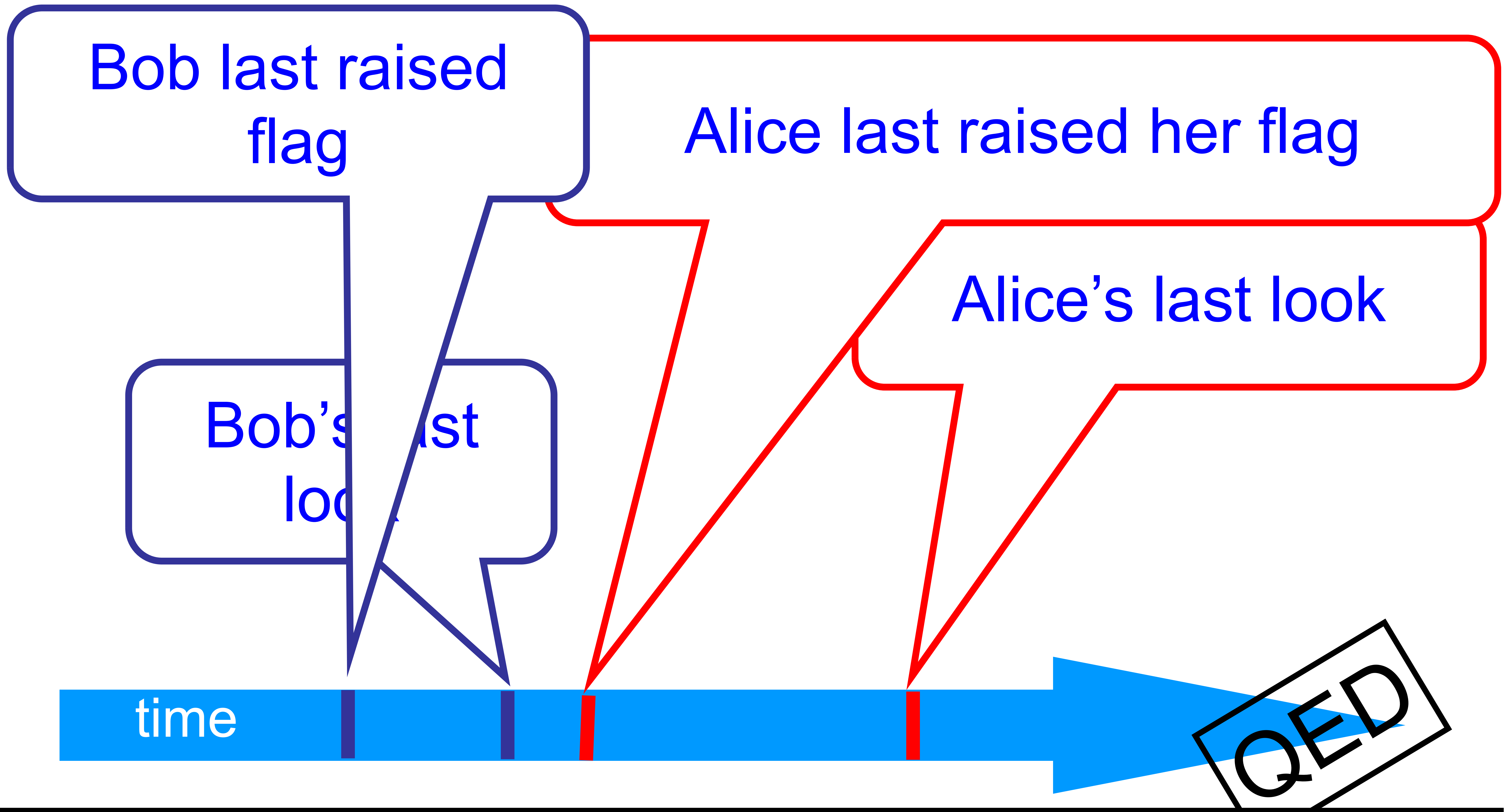
The Flag Principle

- 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



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 backs off, gives her priority (Alice's lexicographic privilege)

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

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

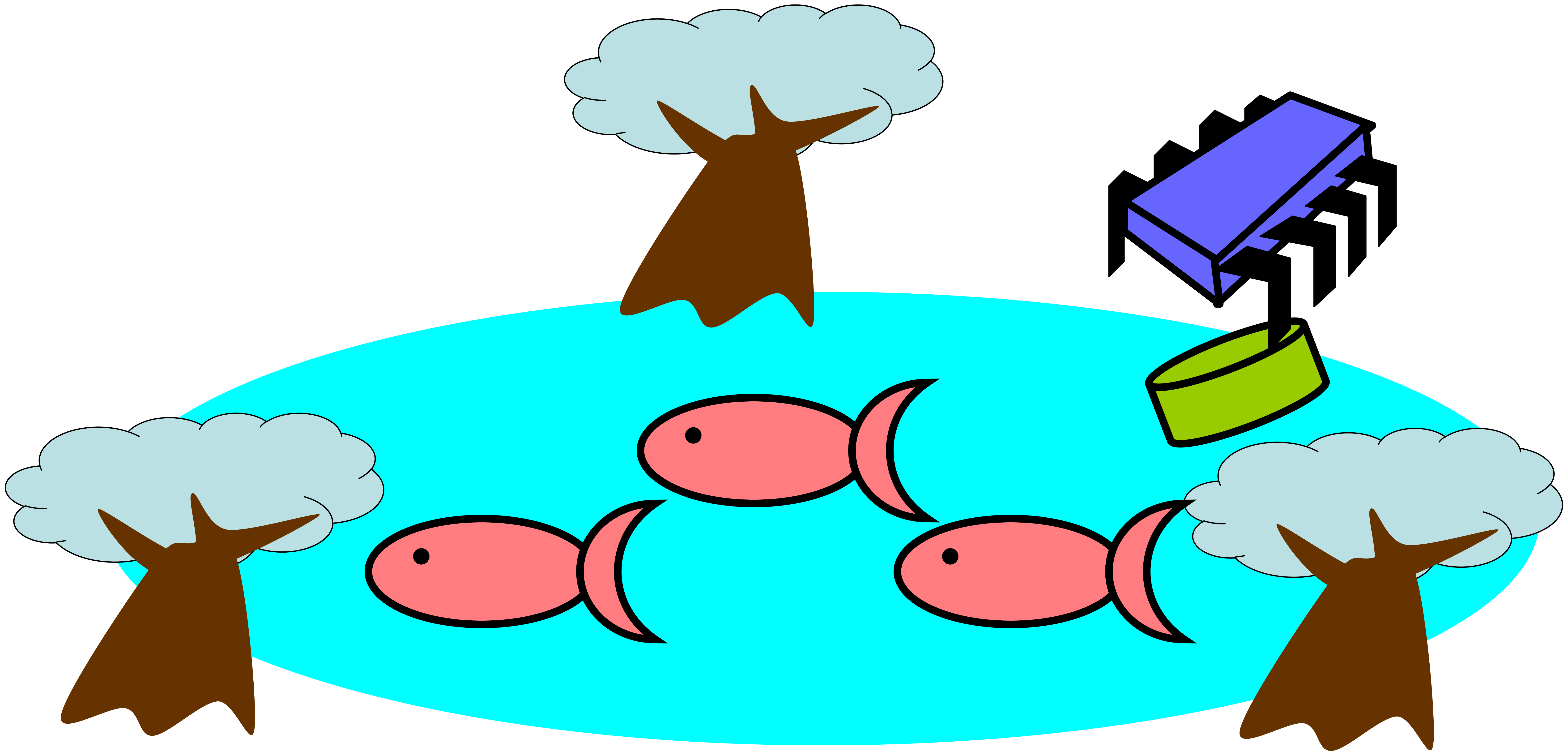
The Fable Continues

- Alice and Bob fall in love & marry
- Then they fall out of love & divorce
  - After a coin flip, she gets the pets
  - He has to feed them

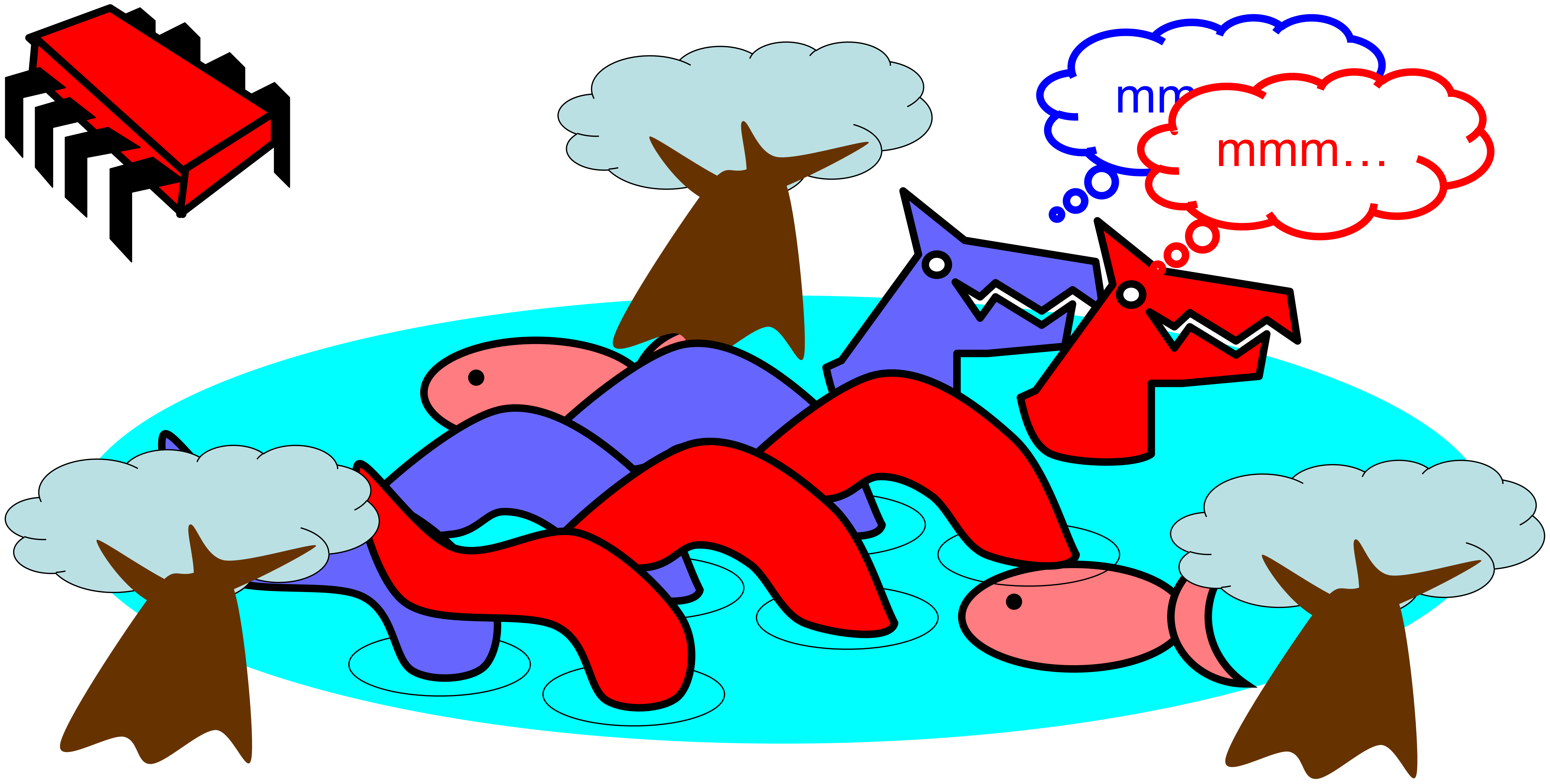
The Fable Continues

- 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



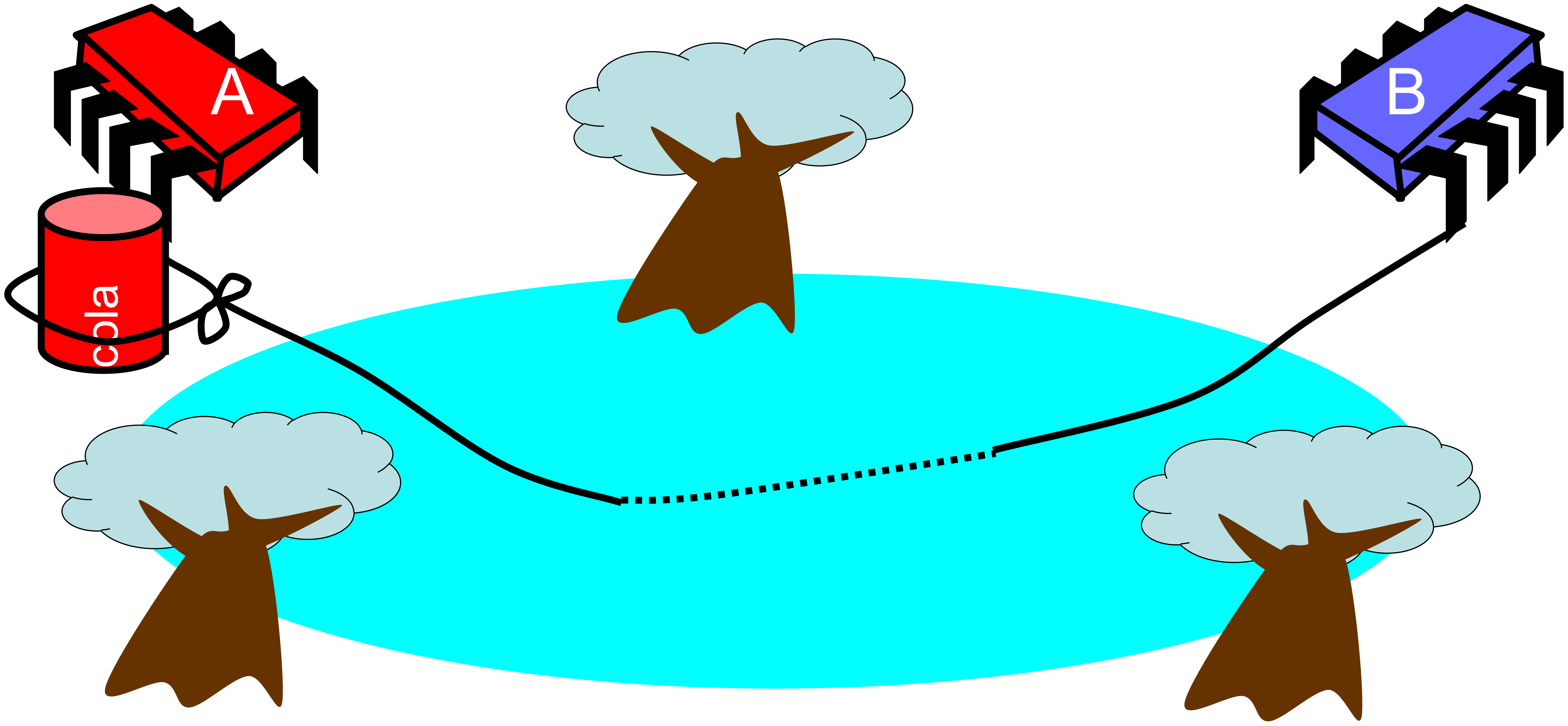
Producer/Consumer

- 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

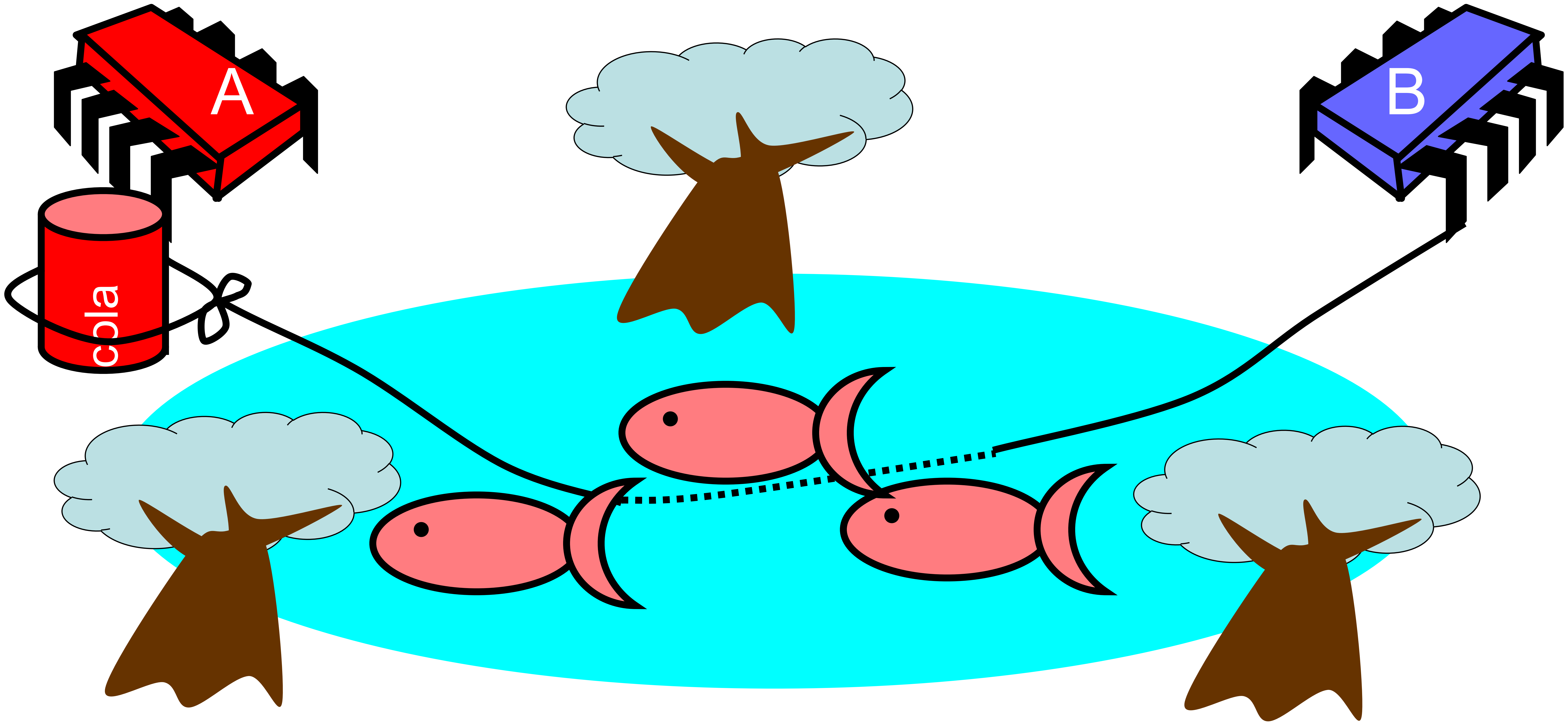
Producer/Consumer

- 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

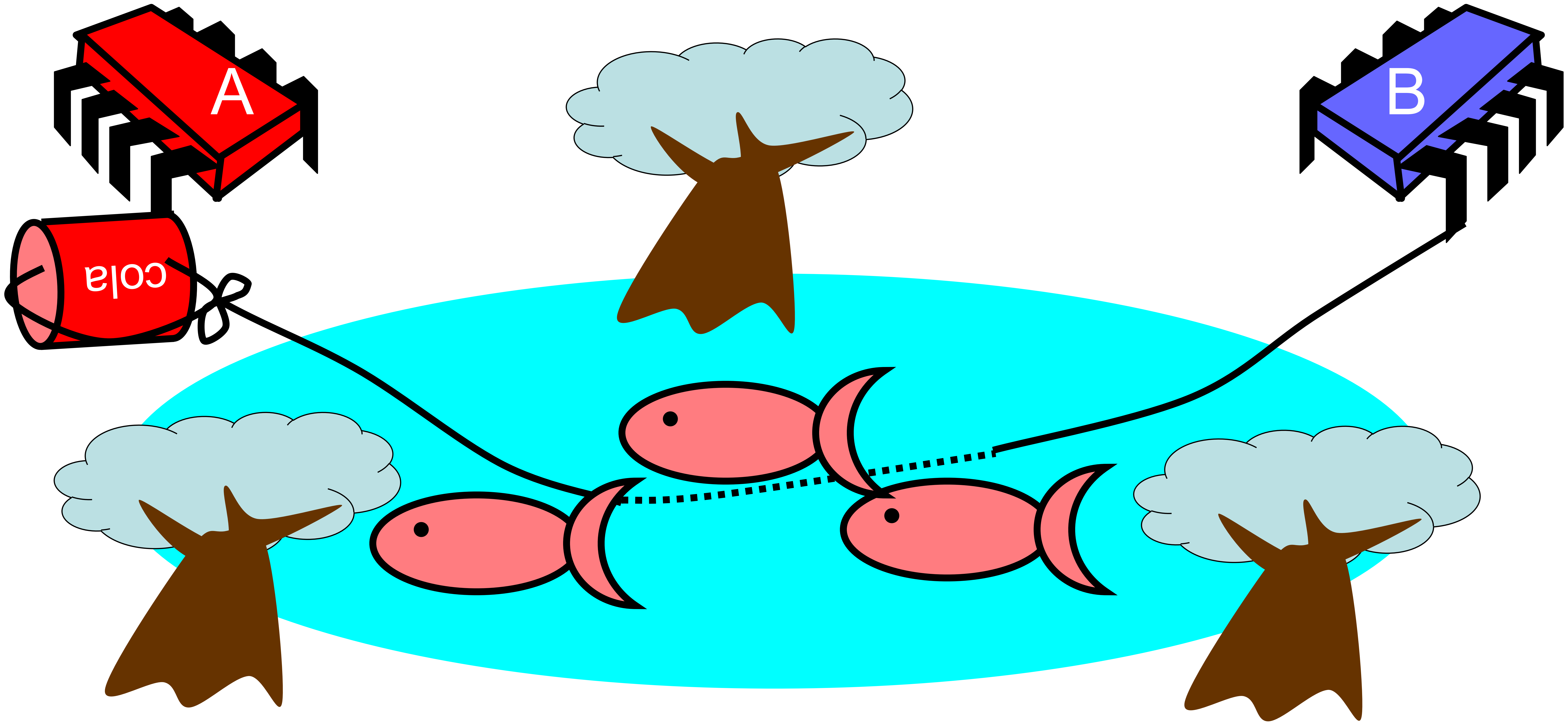
Surprise Solution



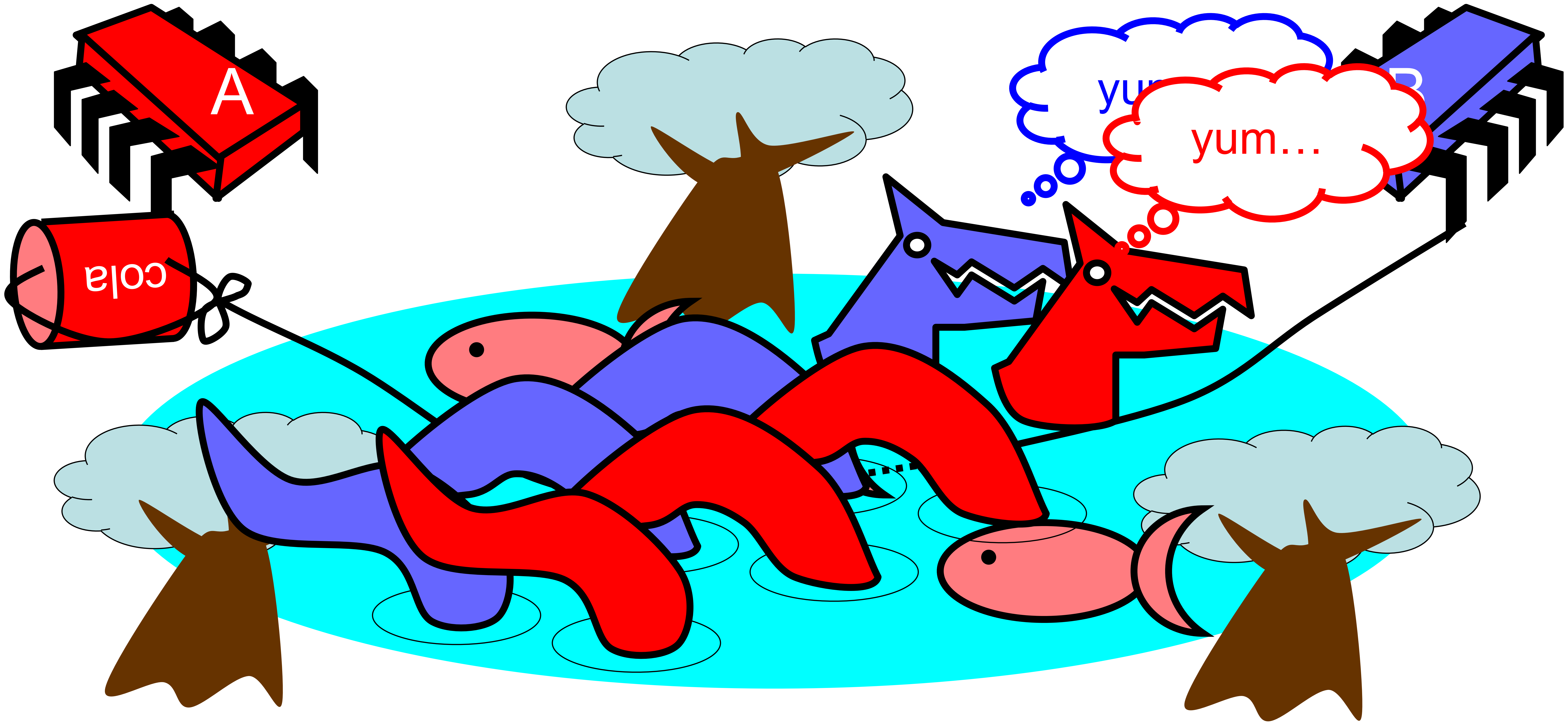
Bob puts food in Pond



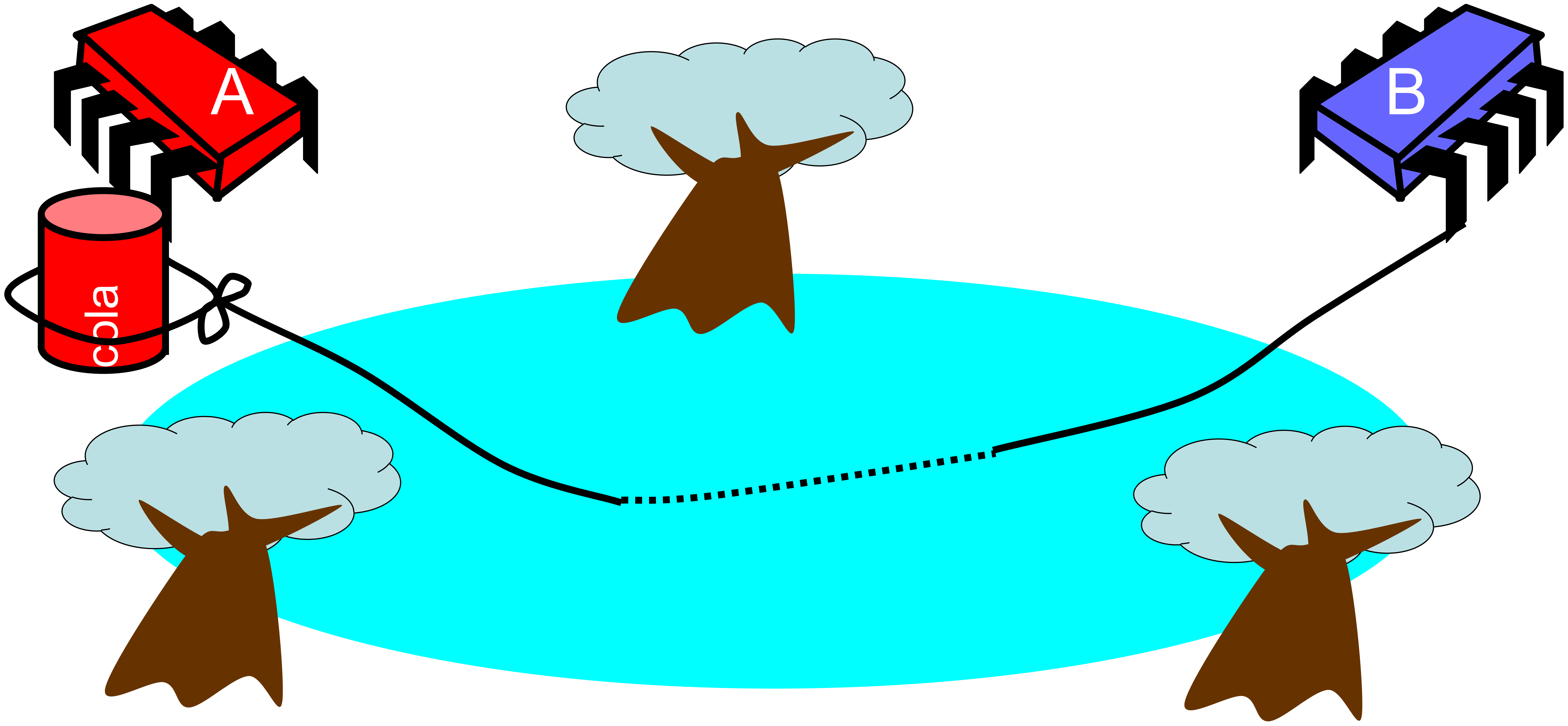
Bob knocks over Can



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();
  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.

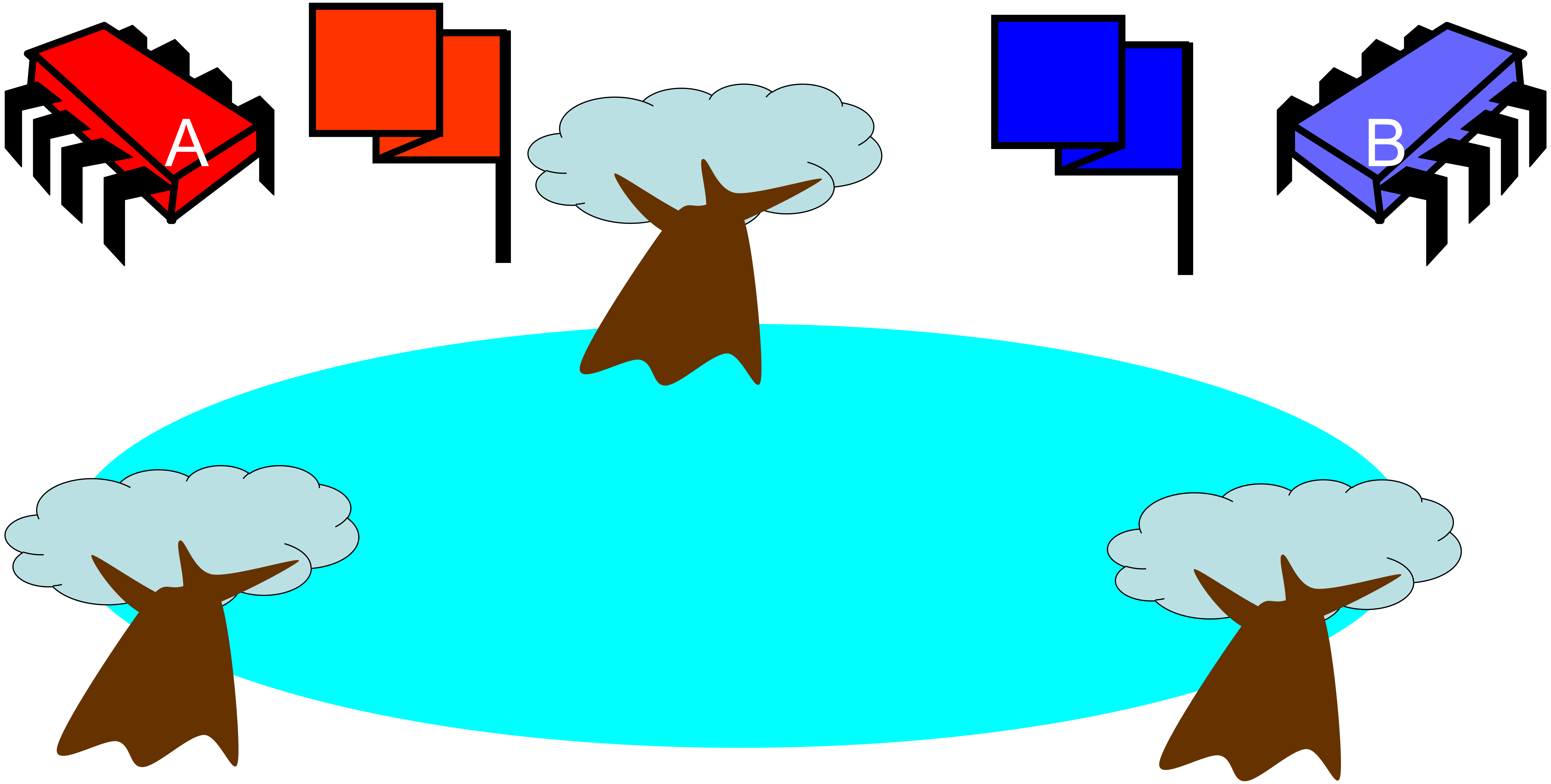
Correctness

- 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.

Could Also Solve Using Flags



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

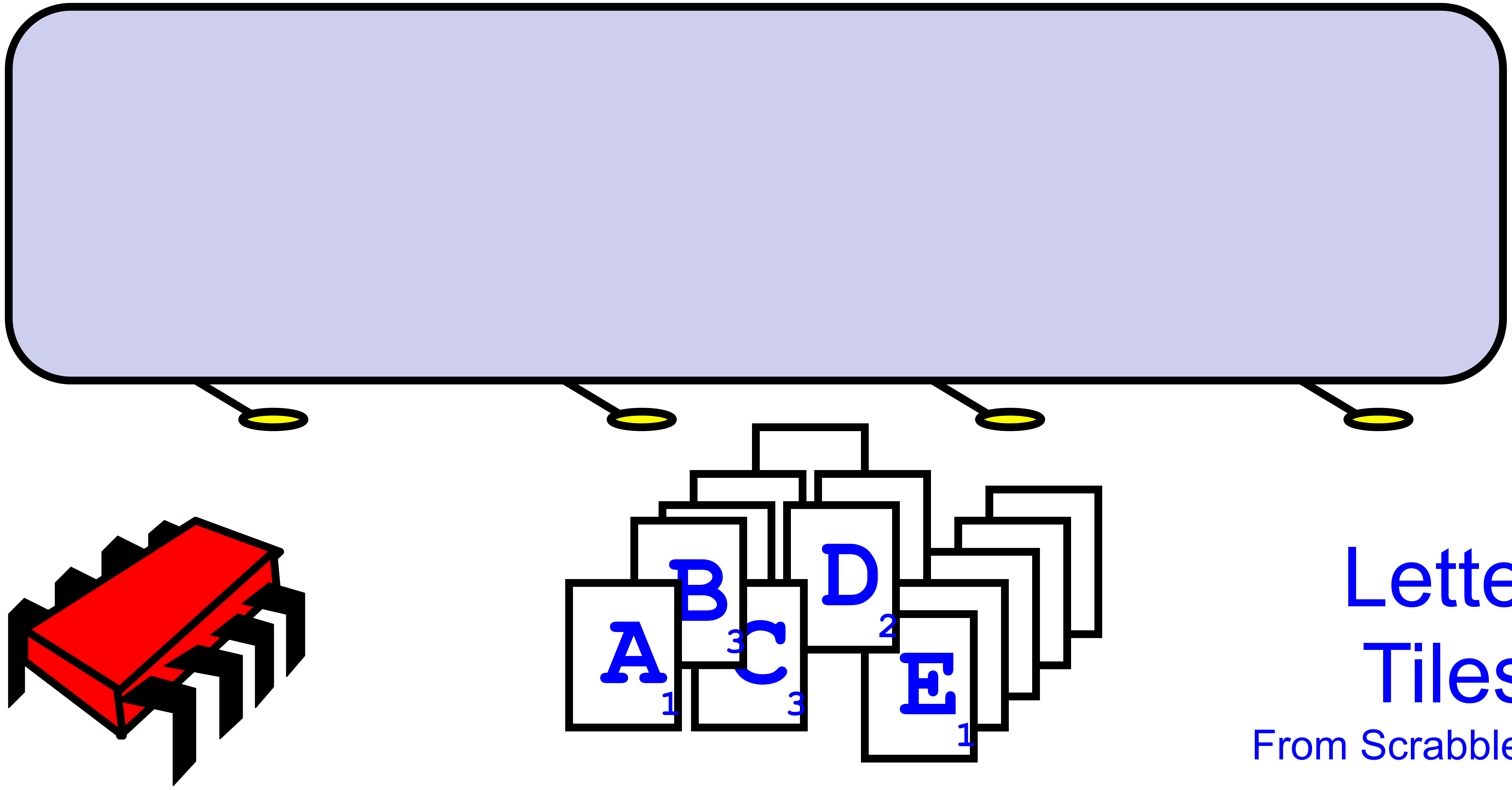
The Fable drags on …

- 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 …

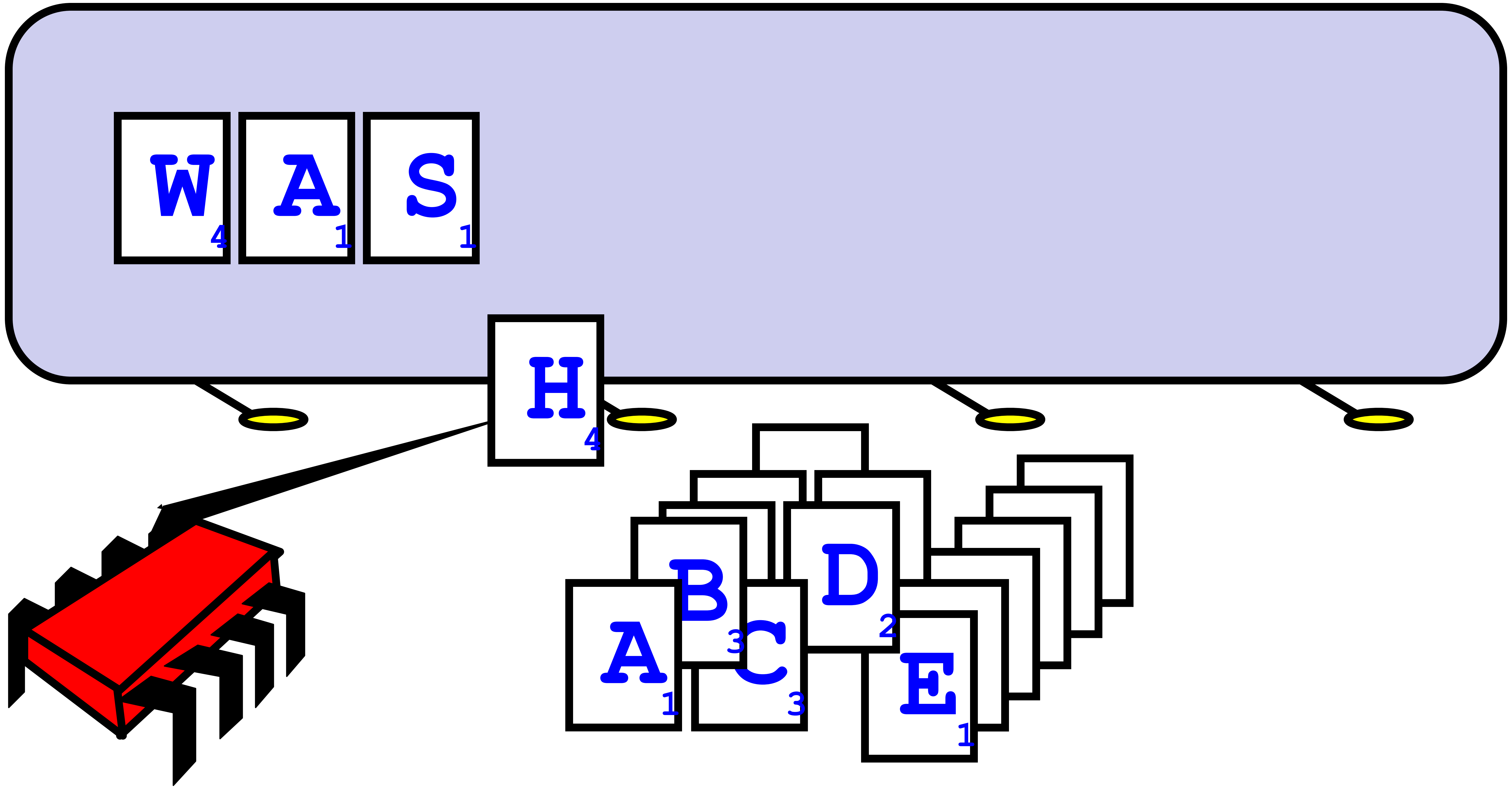
Billboards are Large



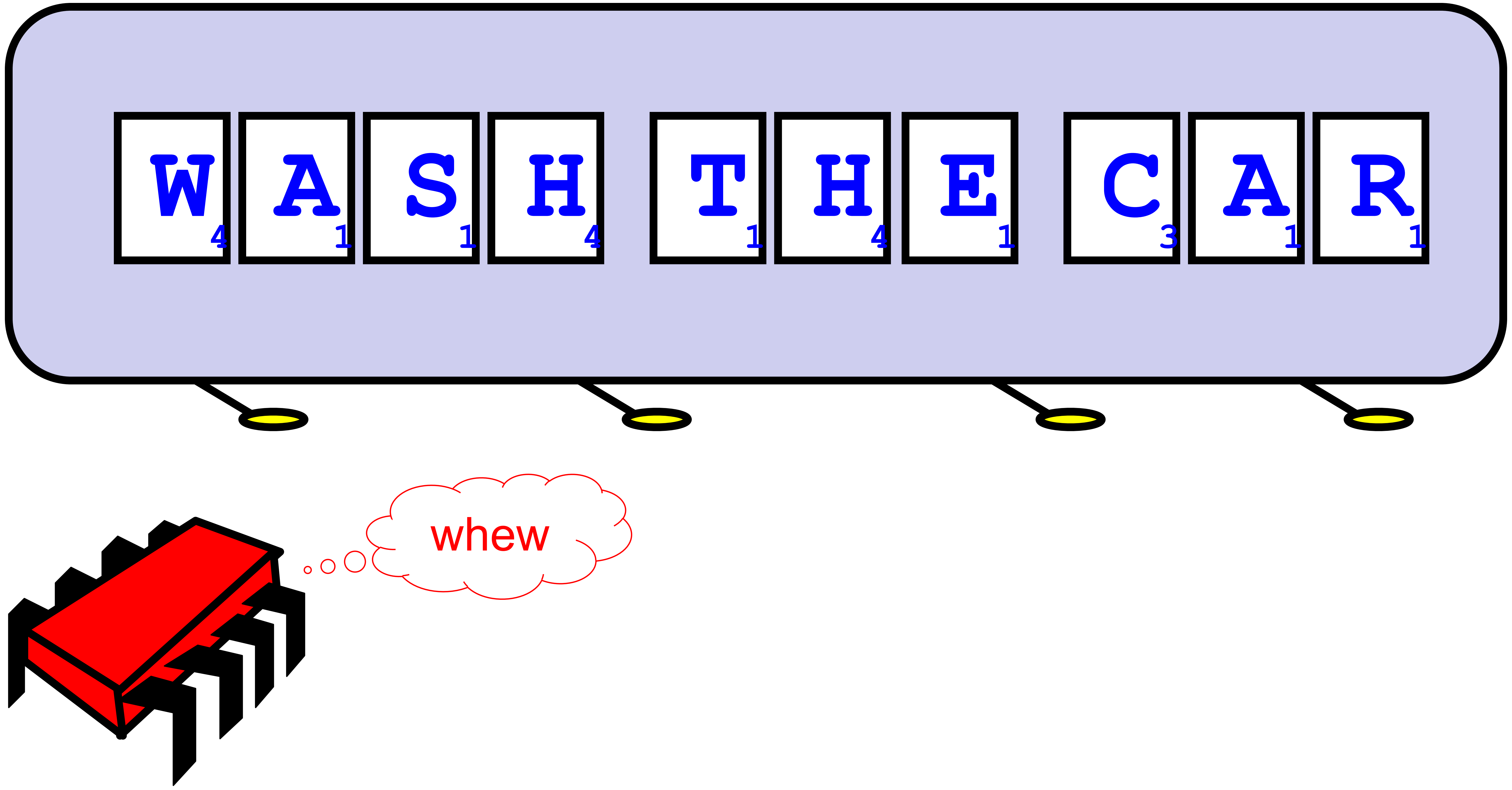
Letter Tiles

From Scrabble™ box

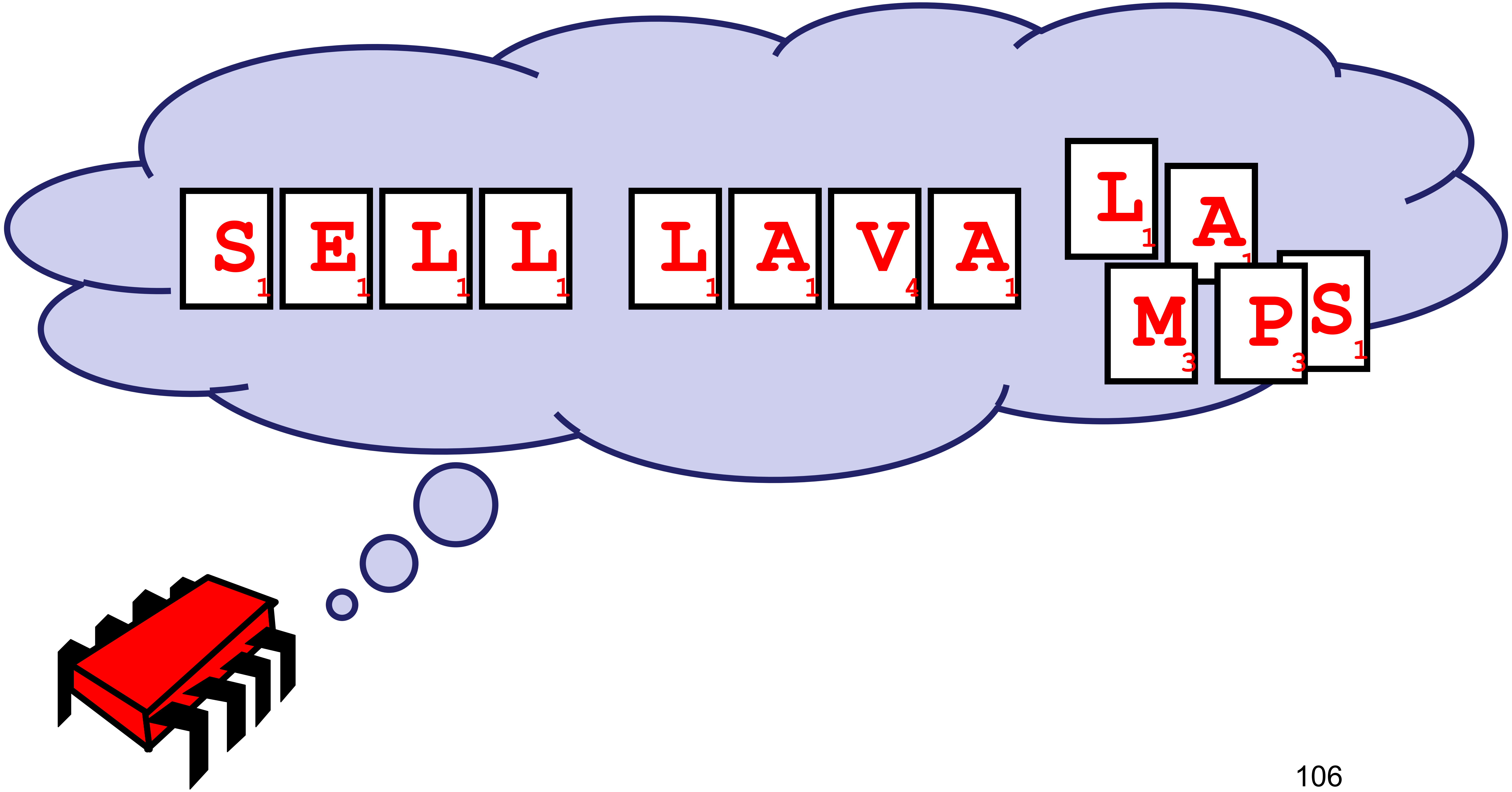
Write One Letter at a Time …



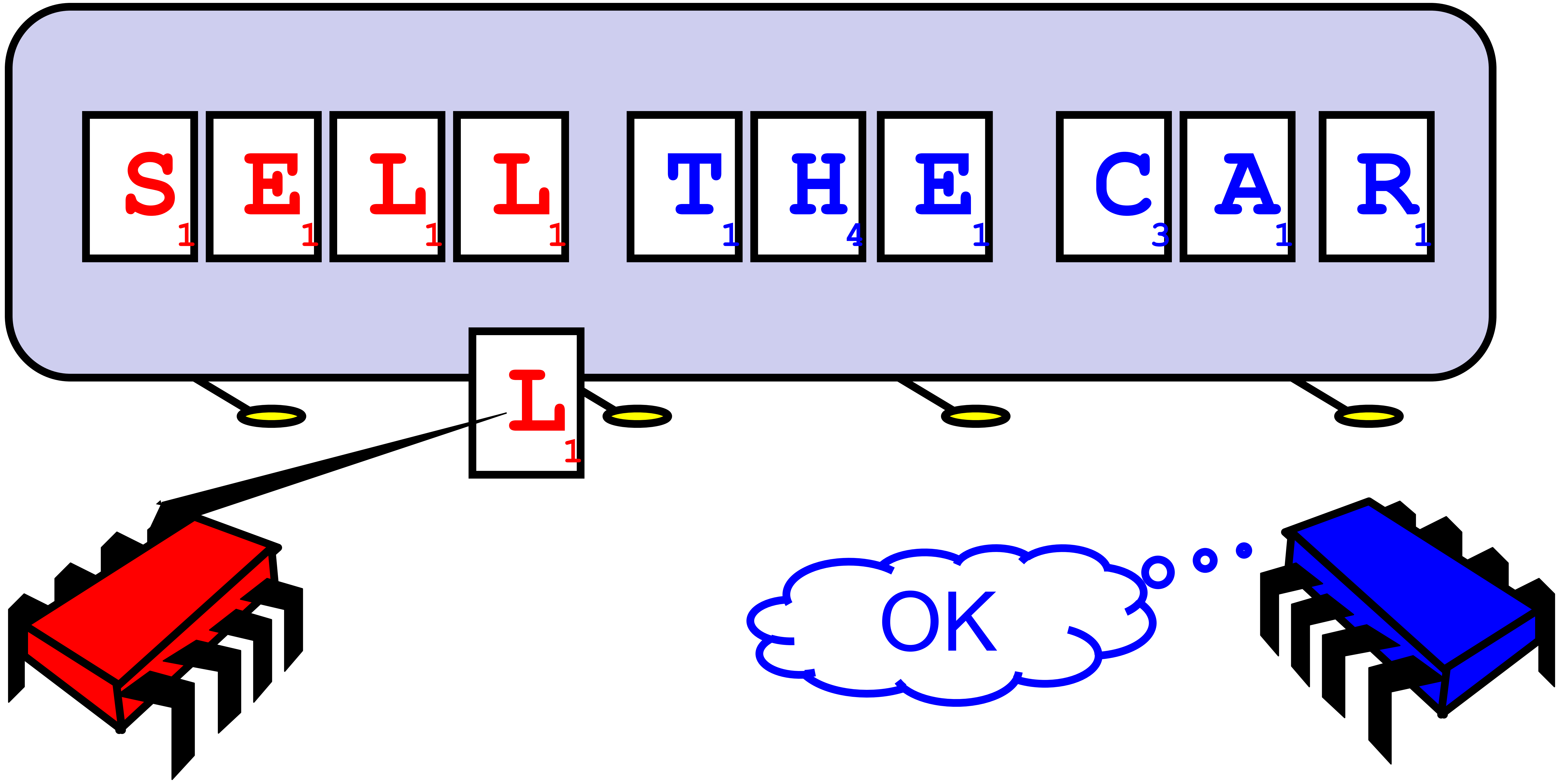
To post a message



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

Esoteric?

- Java container **`size()`** method
- Single shared counter?
  - incremented with each **`add()`** and
  - decremented with each **`remove()`**
- Threads wait to exclusively access [illegible]er

performance bottleneck

Readers/Writers Solution

- Each thread i has `size[i]` counter
  - only it increments or decrements.
- To get object's size, a thread reads a "snapshot" of all counters
- This eliminates the bottleneck

Mutual Exclusion = Sequential Execution

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

$$\text{Speedup} = \frac{1\text{-thread execution time}}{n\text{-thread execution time}}$$

Amdahl's Law

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

Amdahl's Law

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

Parallel fraction

Amdahl's Law

Sequential fraction

Parallel fraction

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

Amdahl's Law

Sequential fraction

Parallel fraction

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

Number of threads

Amdal’s Law

Bad synchronization ruins everything

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, 1% sequential
- How close to 10-fold speedup?

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

In the Next Lecture

- *Formal model* for thinking about concurrency
- Algorithms for *mutual exclusion*