Concurrency:
Foundations and Algorithms

The Basics

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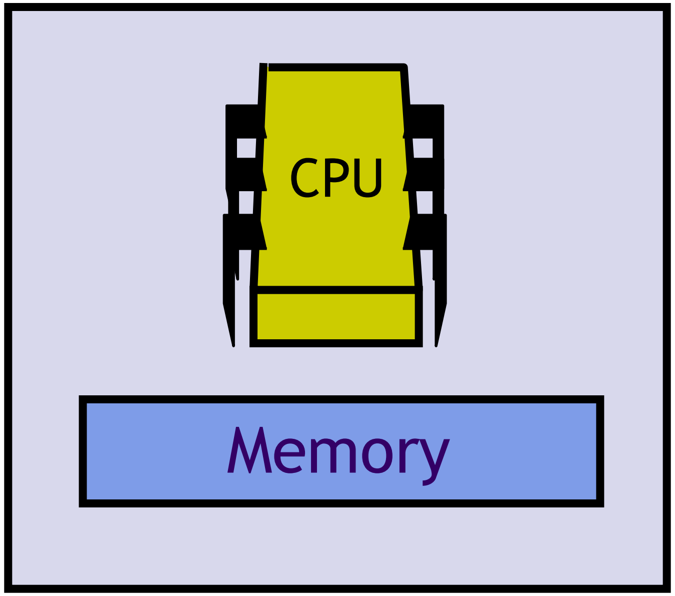
*Based on slides by **Maurice Herlihy** and **Nir Shavit***

From the New York Times…

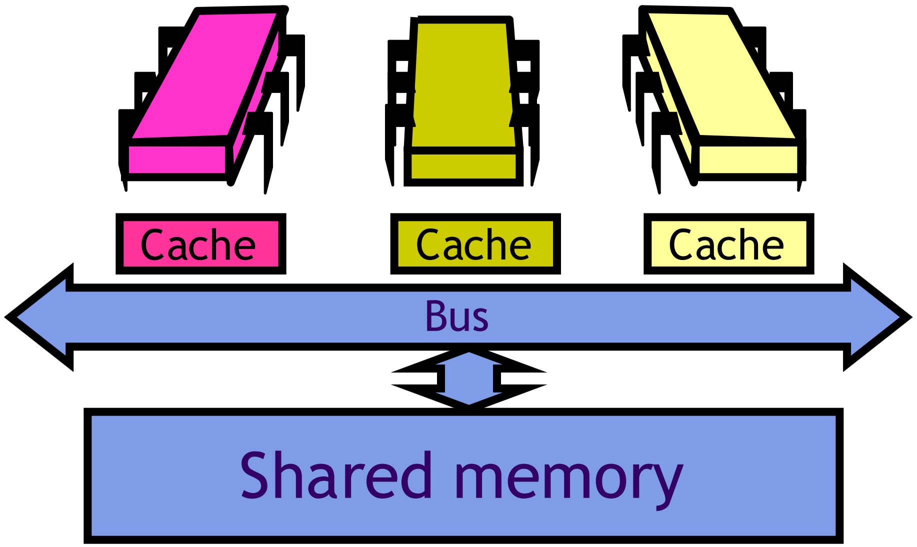
SAN FRANCISCO, May 7, 2004:

"Intel said on Friday that it was scrapping its development of two microprocessors, a move that is a shift in the company's business strategy…"

On Your Desktop: The Uniprocessor

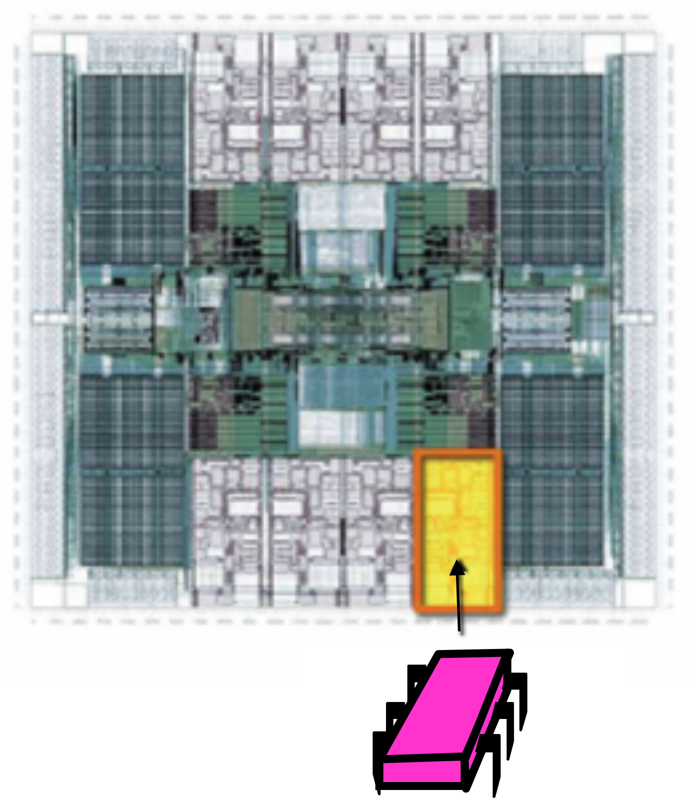


In the Enterprise: The Shared Memory Multiprocessor (SMP)



Your New Desktop: The Multicore Processor (CMP)

All on the same chip



Sun T2000 Niagara

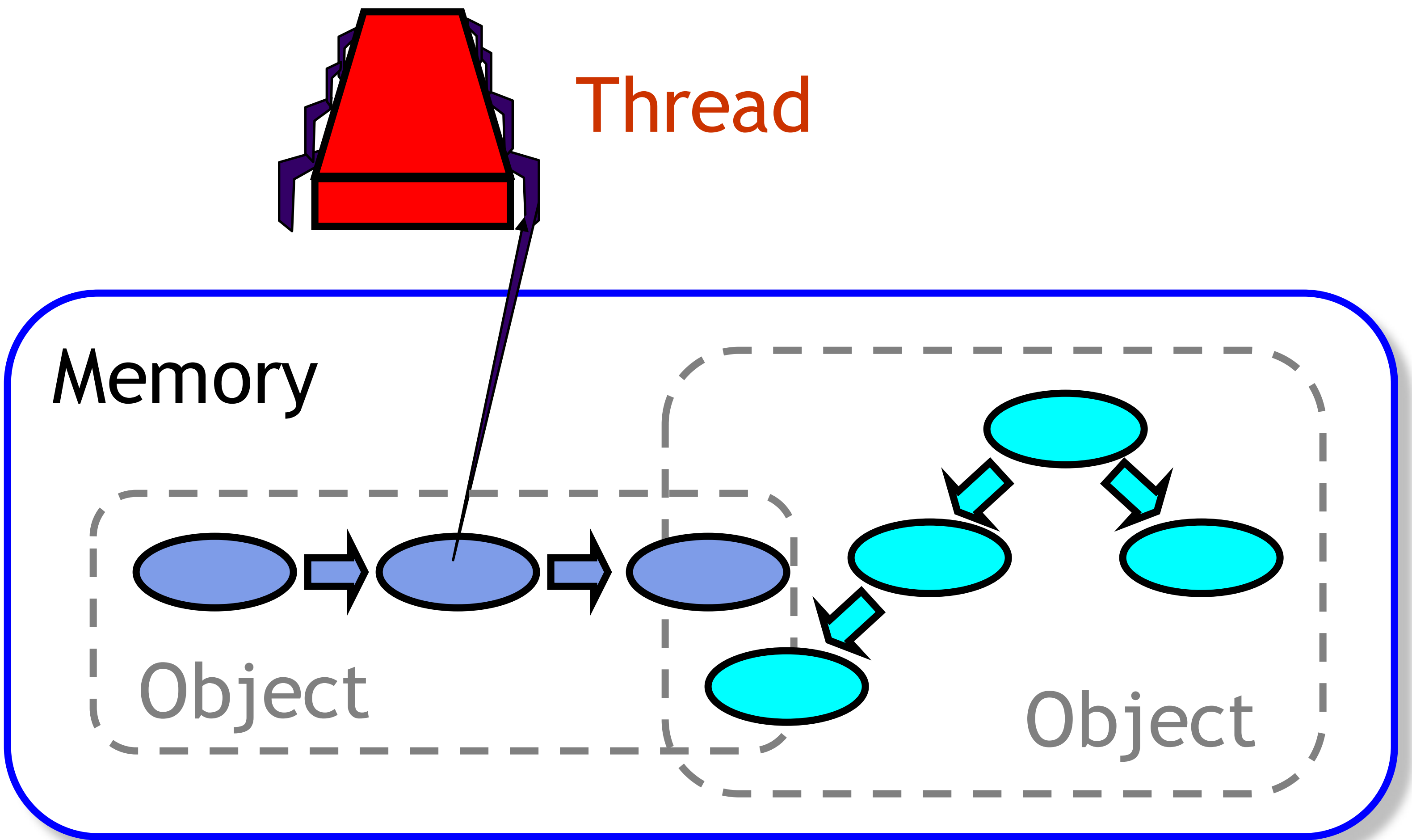
Why do we Care?

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

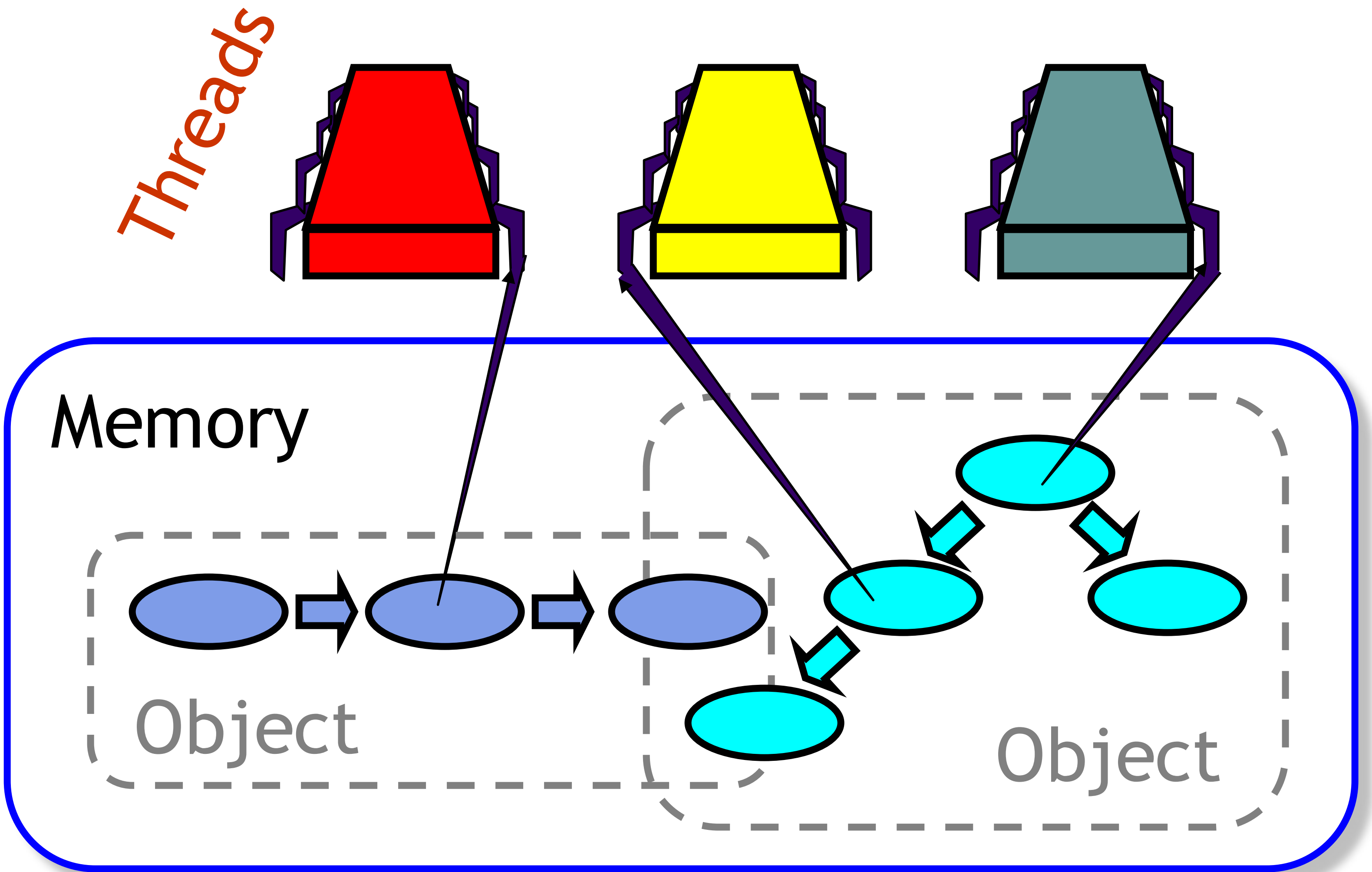
Multiprocessor Programming: Course Overview

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

Sequential Computation



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"

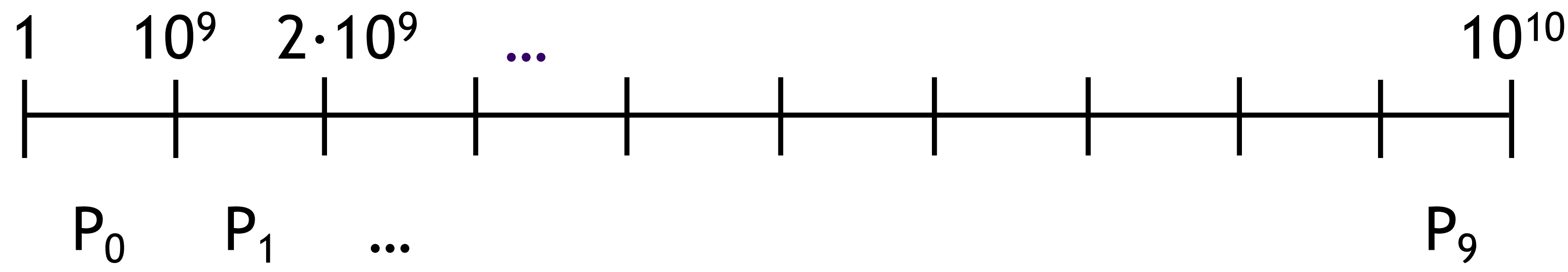
Concurrency Jargon

- Hardware
  - Processors
- Software
  - Threads, processes
- Sometimes OK to confuse these terms, 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*

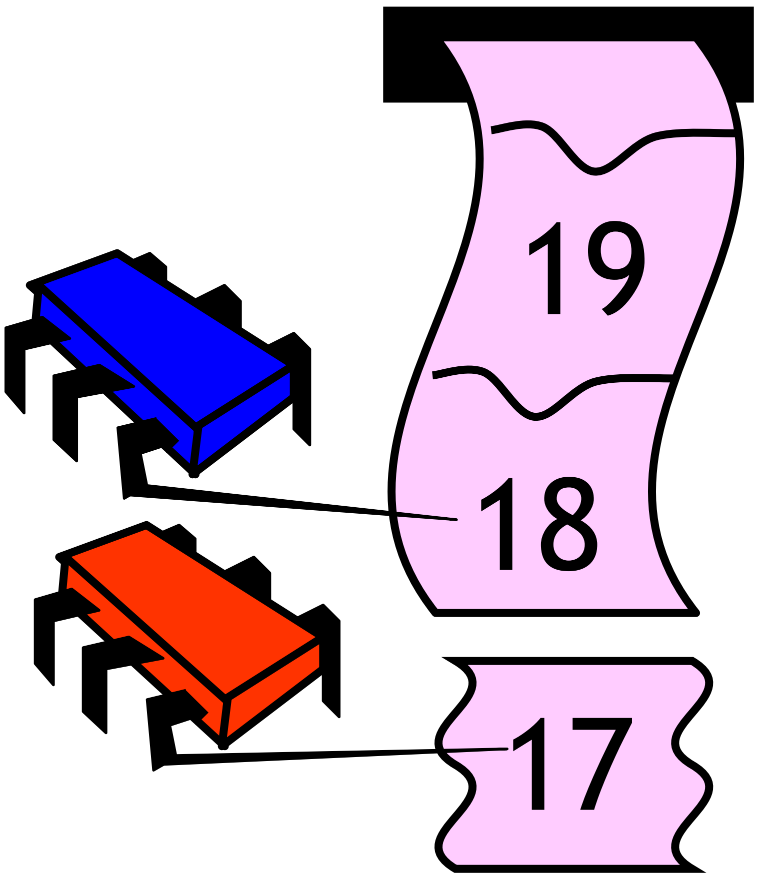
```
void primePrint {
  int i = ThreadID.get(); // IDs in {0..9}
  for (j = i*10^9+1; j <= (i+1)*10^9; j++) {
    if (isPrime(j))
      print(j);
  }
}
```

Issues

- Larger numbers imply 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*

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

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

Procedure for Thread *i*

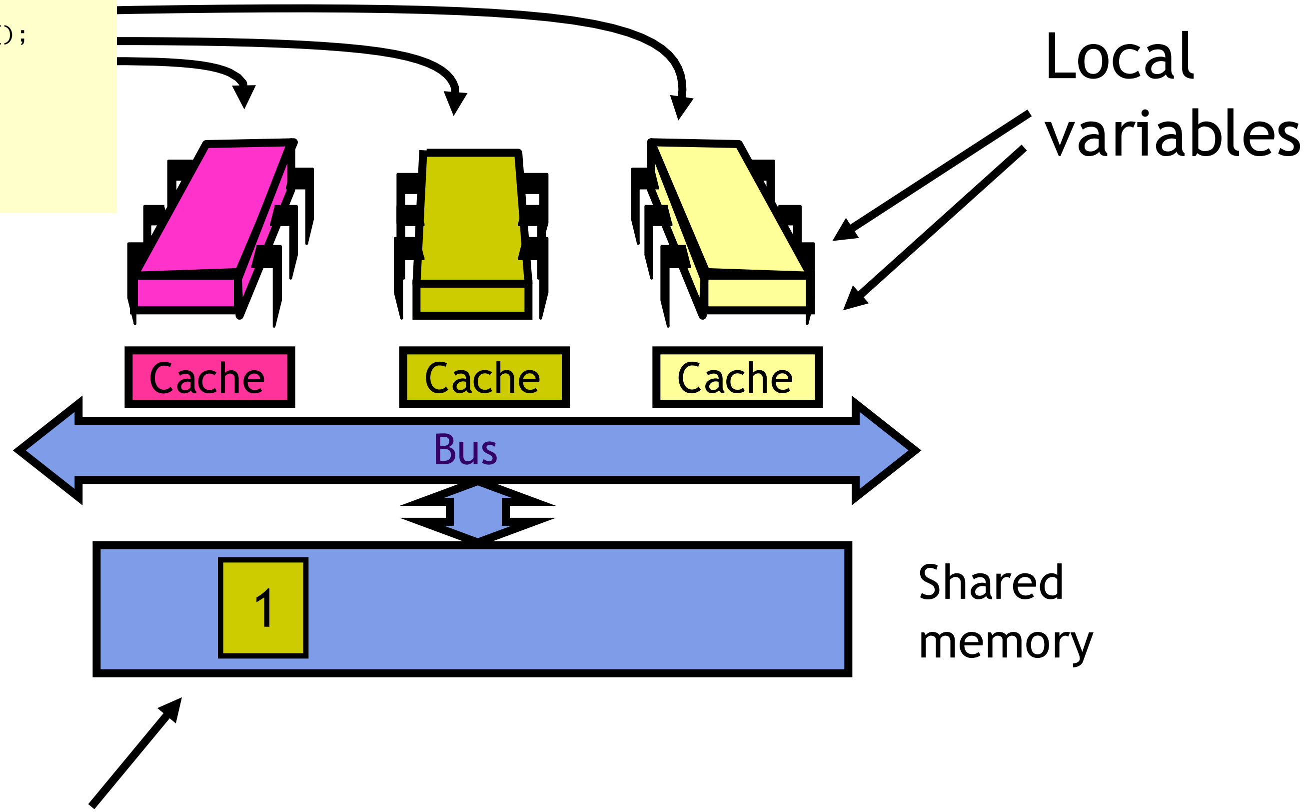
```
Counter counter = new Counter(1);

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

Shared counter object

Where Things Reside

```
Counter counter = new Counter(1);
void primePrint {
  while (true) {
    long j = counter.getAndIncrement();
    if (j > 10^10)
      break;
    if (isPrime(j))
      print(j);
  }
}
```

Code



Shared counter

Procedure for Thread *i*

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

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

Increment & return each new value

Procedure for Thread *i*

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

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

Stop when every value taken

Counter Implementation

```
public class Counter {
  private long value;

  public lon
    ret
  }
}
```

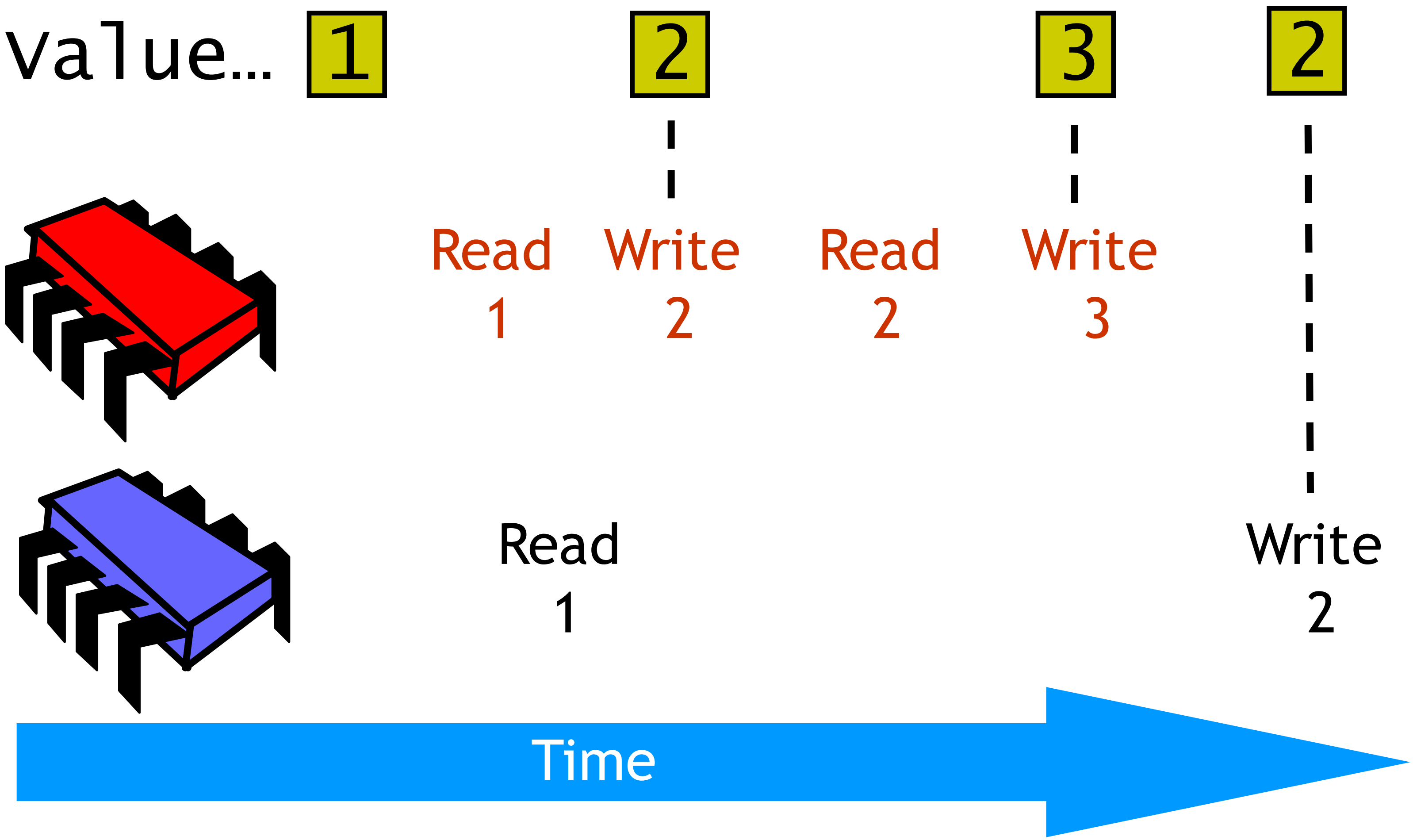
OK for uniprocessor,
not for multiprocessor

What It Means

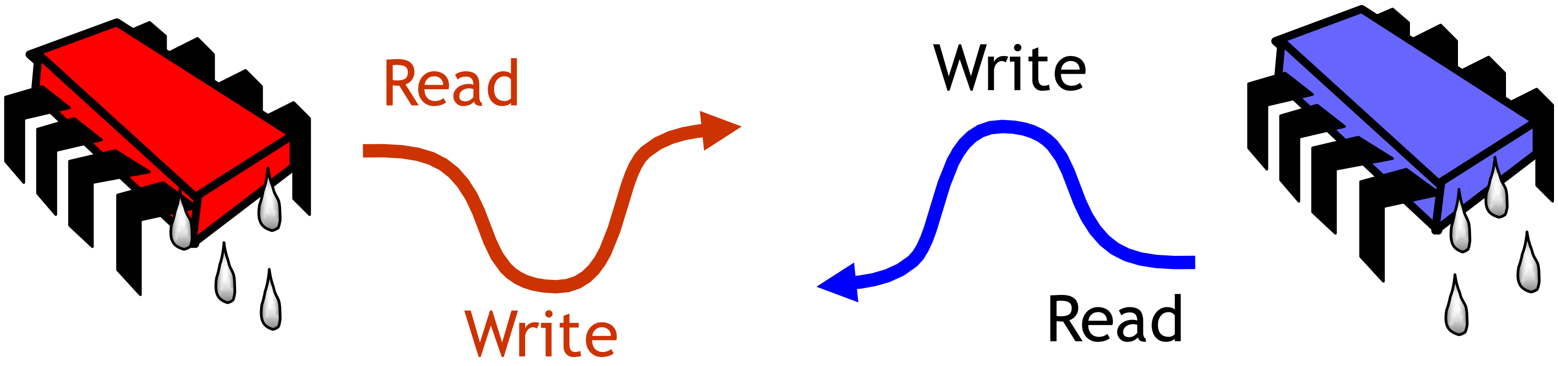
```
public class Counter {
  private long value;

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

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

Not so Good…



Is this Problem Inherent?



If we could only glue reads and writes…

Challenge

```
public class Counter {
  private long value;

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

Challenge

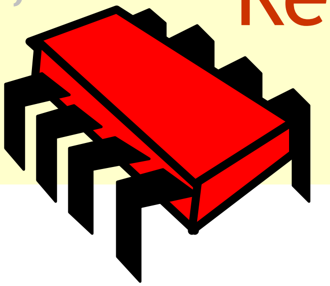
```
public class Counter {
  private long value;

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

Make these steps *atomic* (indivisible)

Hardware Solution

```
public class Counter {
  private long value;

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

Read-modify-write instruction



An Aside: Java

If you add a synchronized keyword to the method signature it will lock the whole instance. That's why this is a little smarter, but still slow.

```
public class Counter {
  private long value;

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

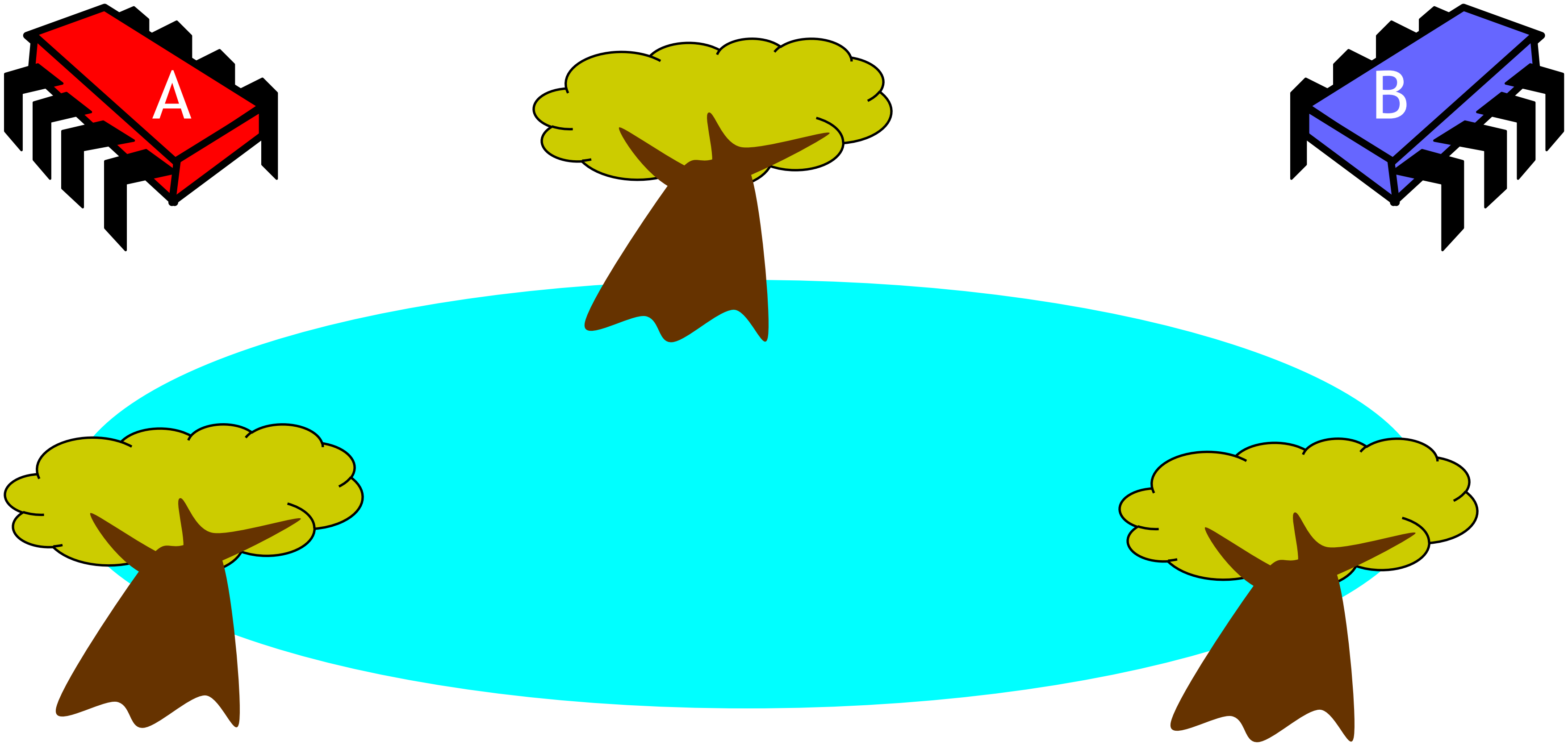
Synchronized block

An Aside: Java

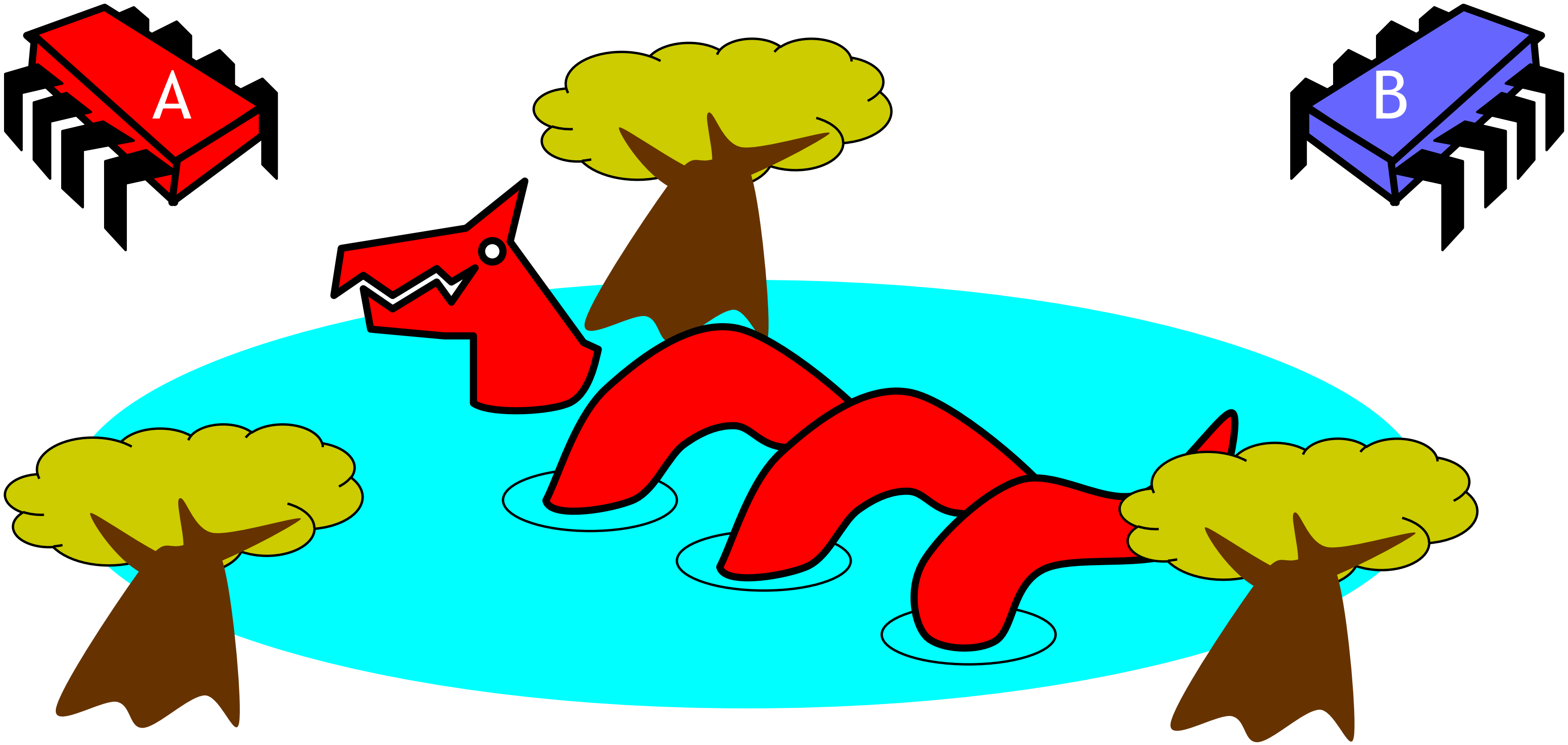
```java
public class Counter {
  private long value;

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

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   You should not lie
  - Nothing bad happens ever
- Liveness properties   You have to say something
  - Something good happens eventually

Formalizing the 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
  - Trees obscure the view

Interpretation

- Threads cannot “see” what other threads are doing
- Explicit communication required for coordination

Cell Phone Protocol

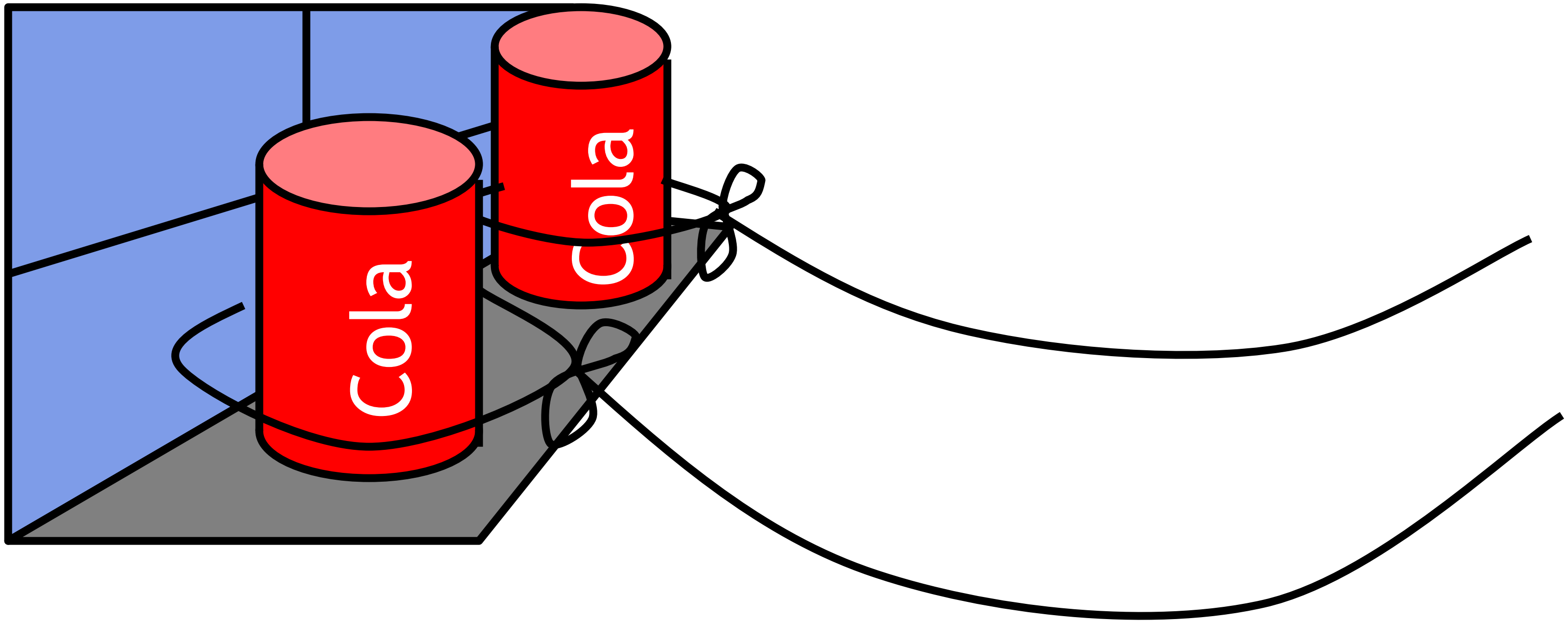
- Idea
  - Bob calls Alice (or vice-versa)
- Gotcha
  - Bob takes shower
  - Alice recharges battery
  - Bob out shopping for pet food…

Interpretation

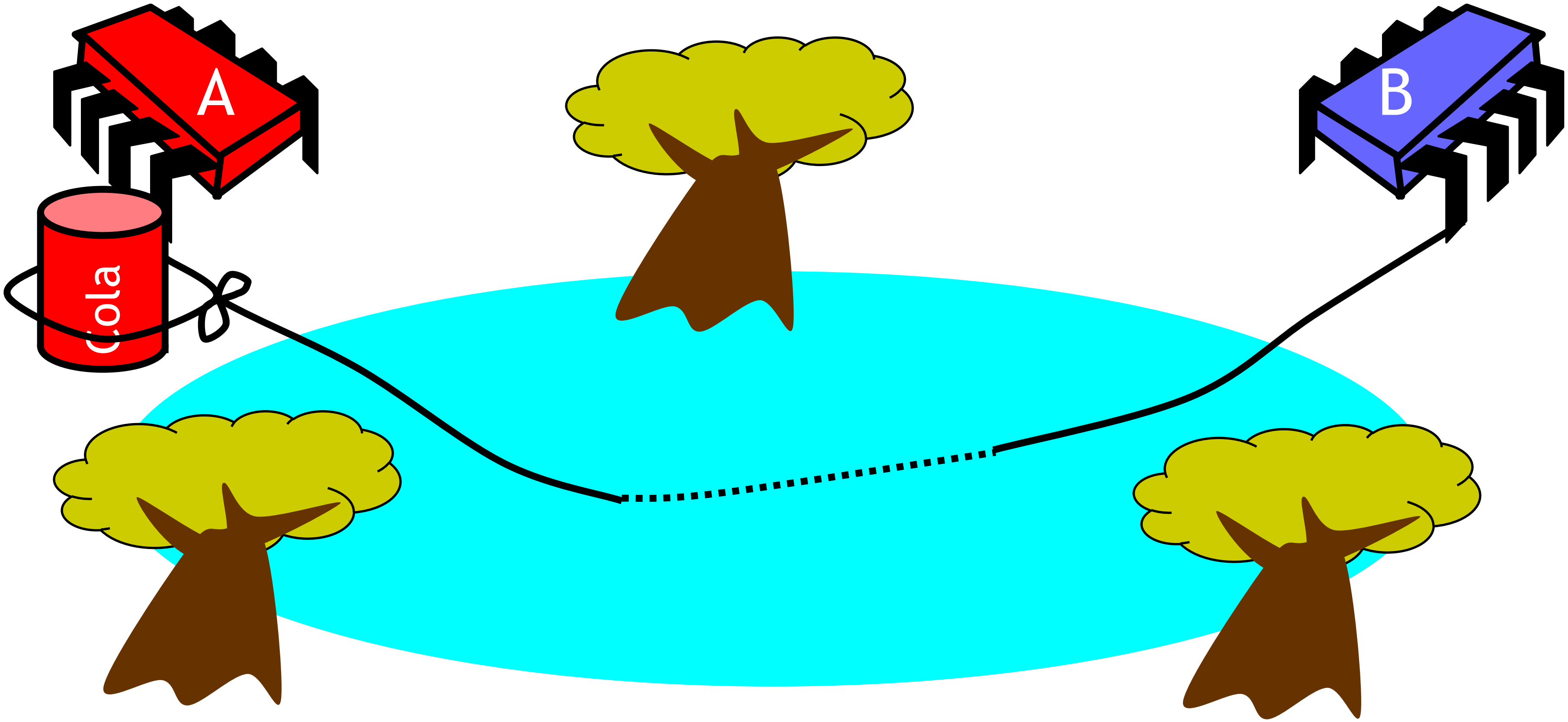
- Message-passing doesn't work
- Recipient might not be
  - Listening
  - There at all
- Communication must be
  - Persistent (like writing)
  - Not transient (like speaking)

Can Protocol

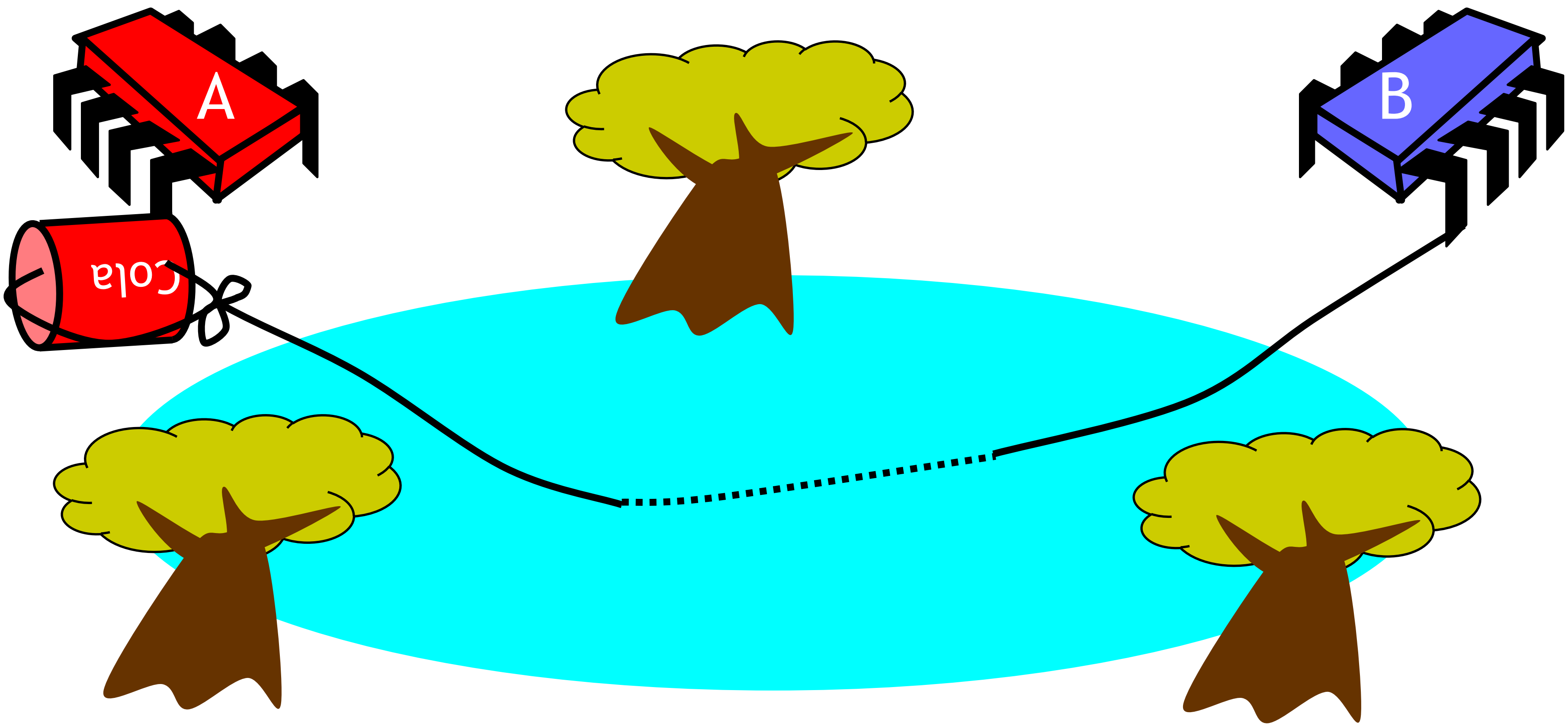
Interrupts



Bob Conveys a Bit



Bob Conveys a Bit



Can Protocol

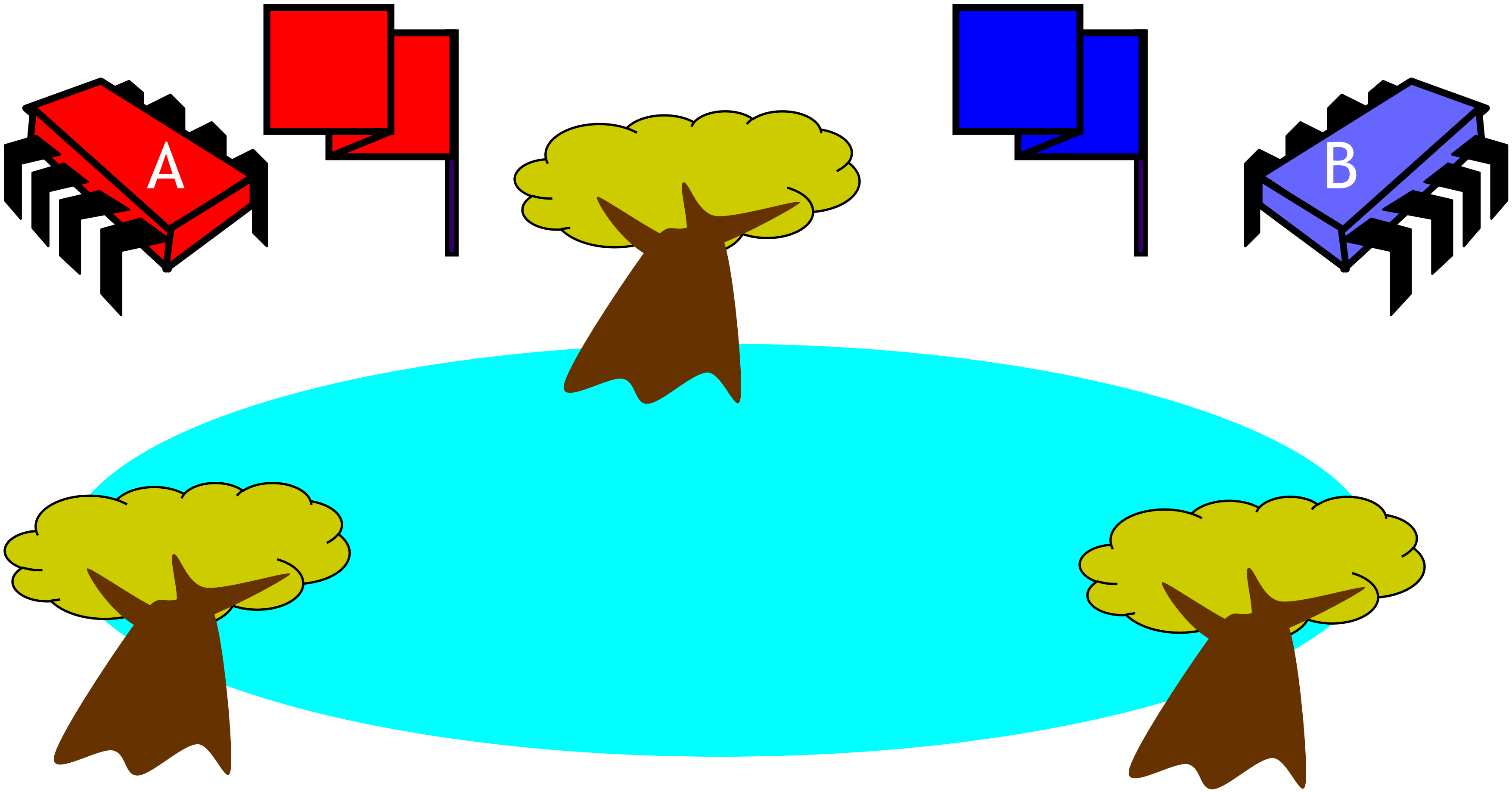
- Idea
  - Cans on Alice’s windowsill
  - Strings lead to Bob’s house
  - Bob pulls strings, knocks over cans
- Gotcha
  - Cans cannot be reused
  - Bob runs out of cans

Interpretation

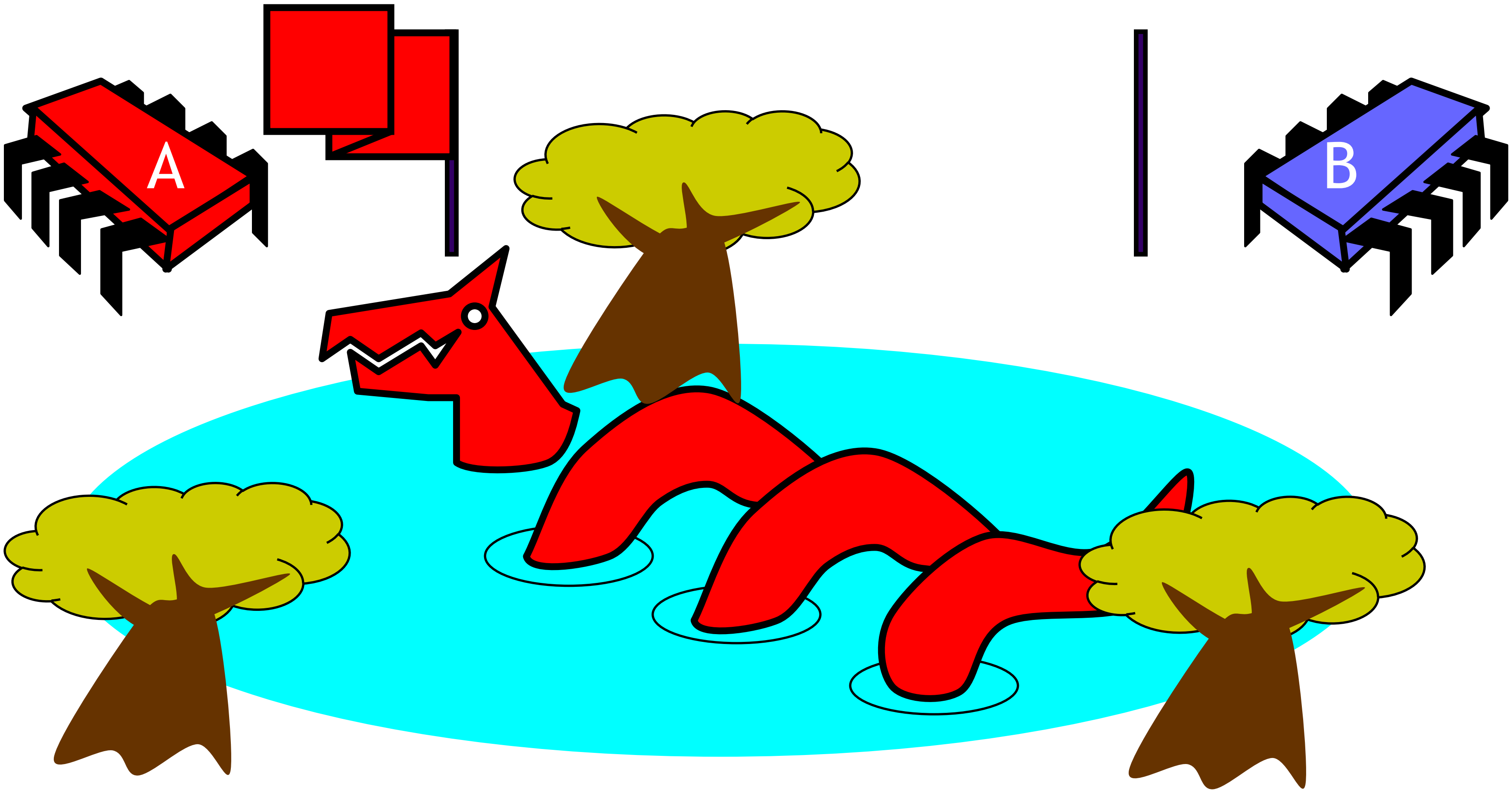
- Cannot solve mutual exclusion with interrupts
  - Sender sets fixed bit in receiver's space
  - Receiver resets bit when ready
  - Requires unbounded number of interrupt bits

Flag Protocol

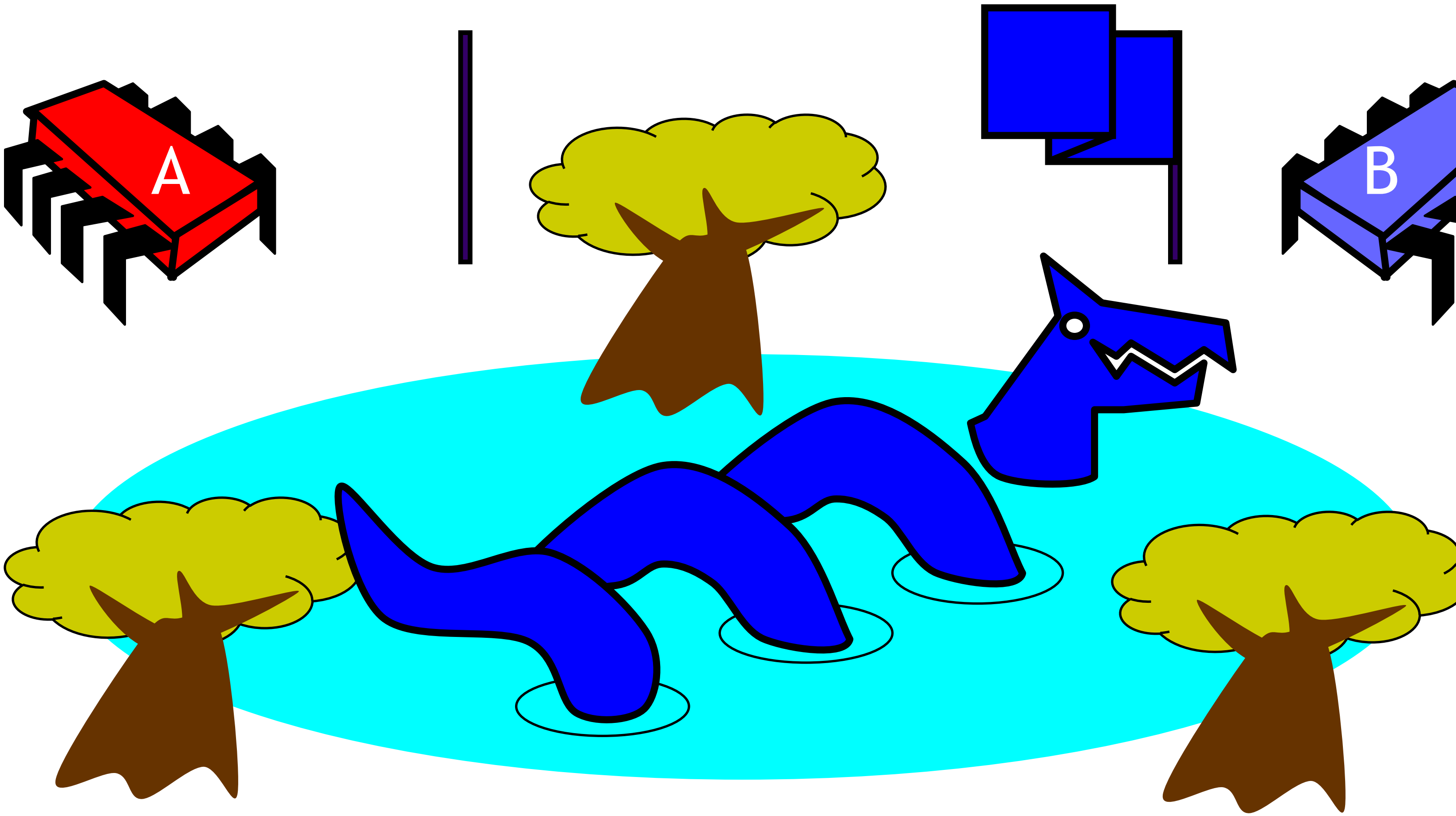
Approach to mutual exclusion that actually works



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)

Asymmetrie Protocol. Both save and live.

- 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

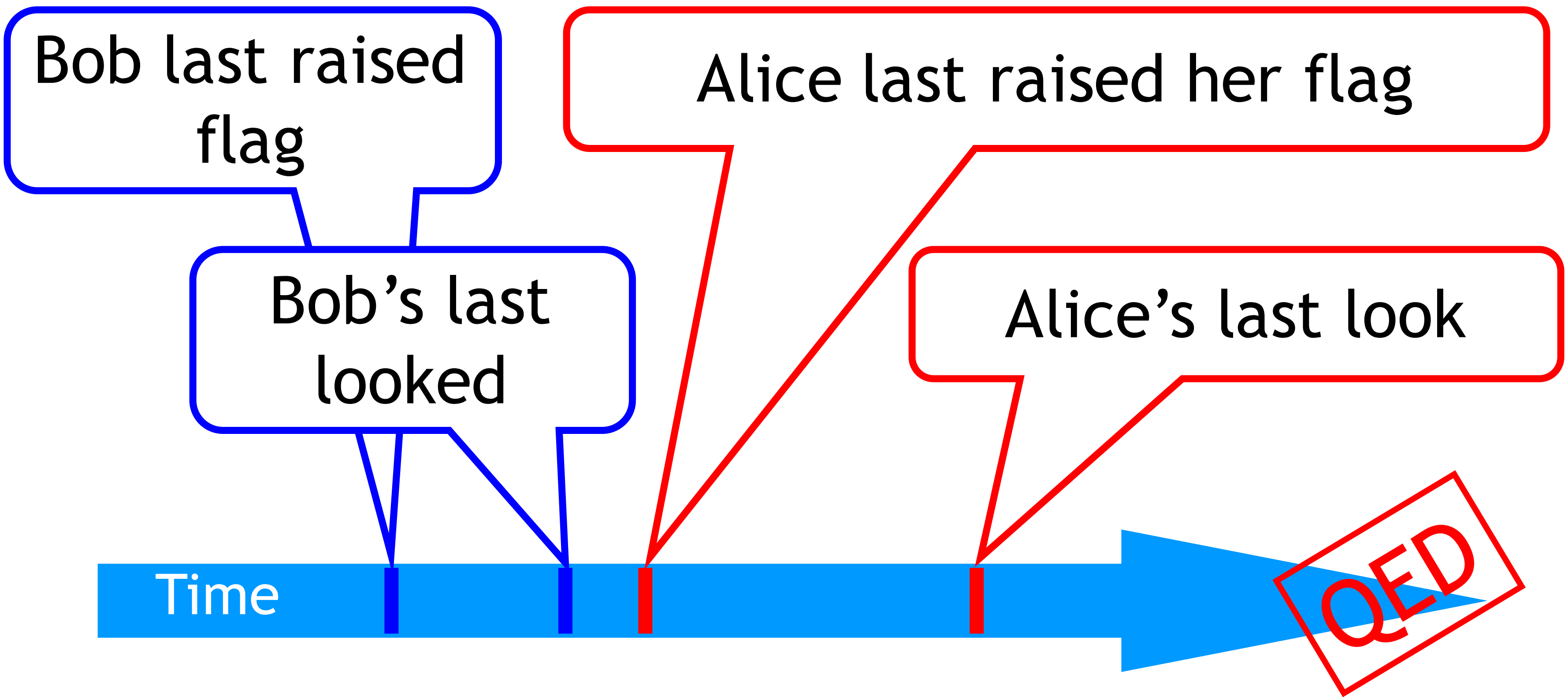
The Flag Principle

- 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
- 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

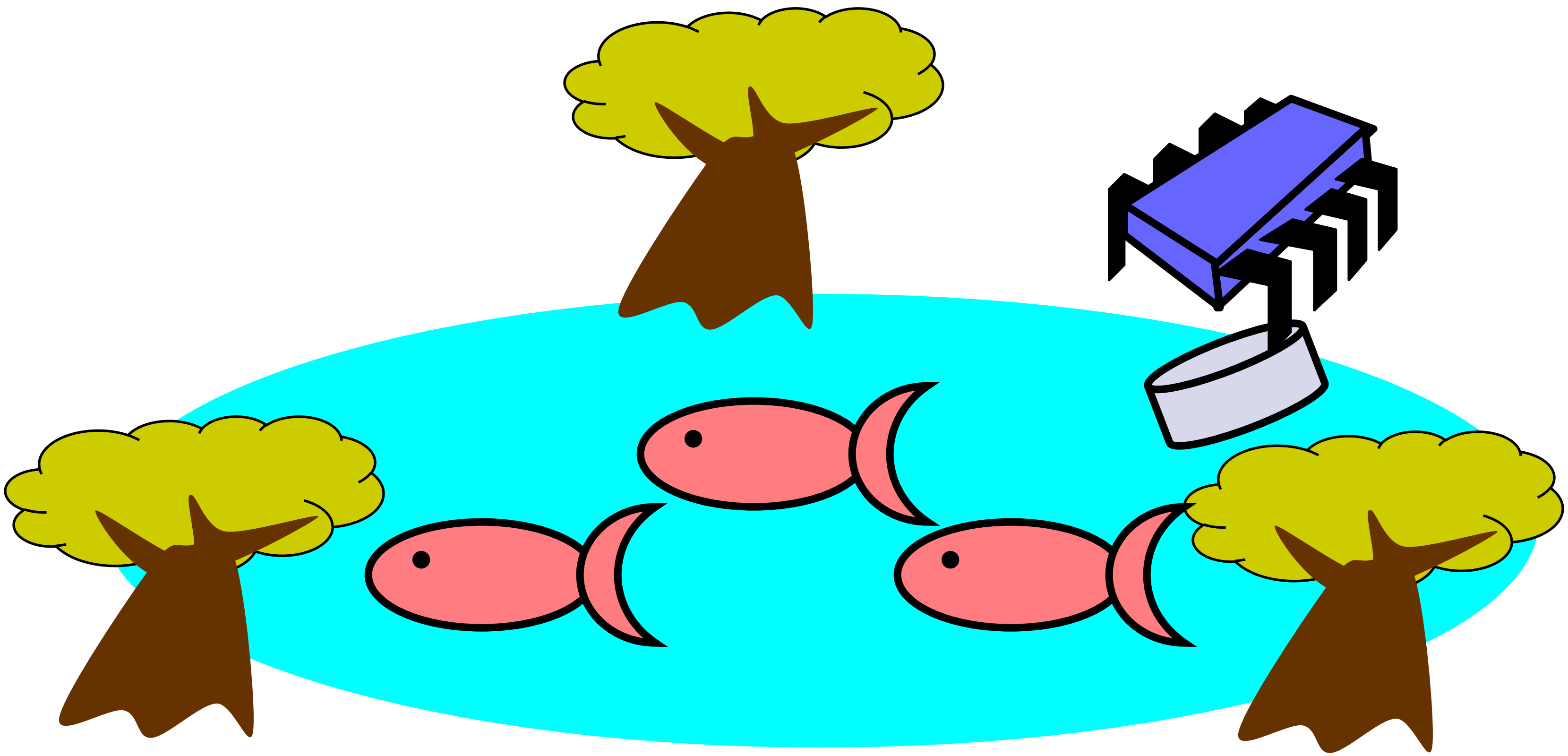
Moral of Story

- 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

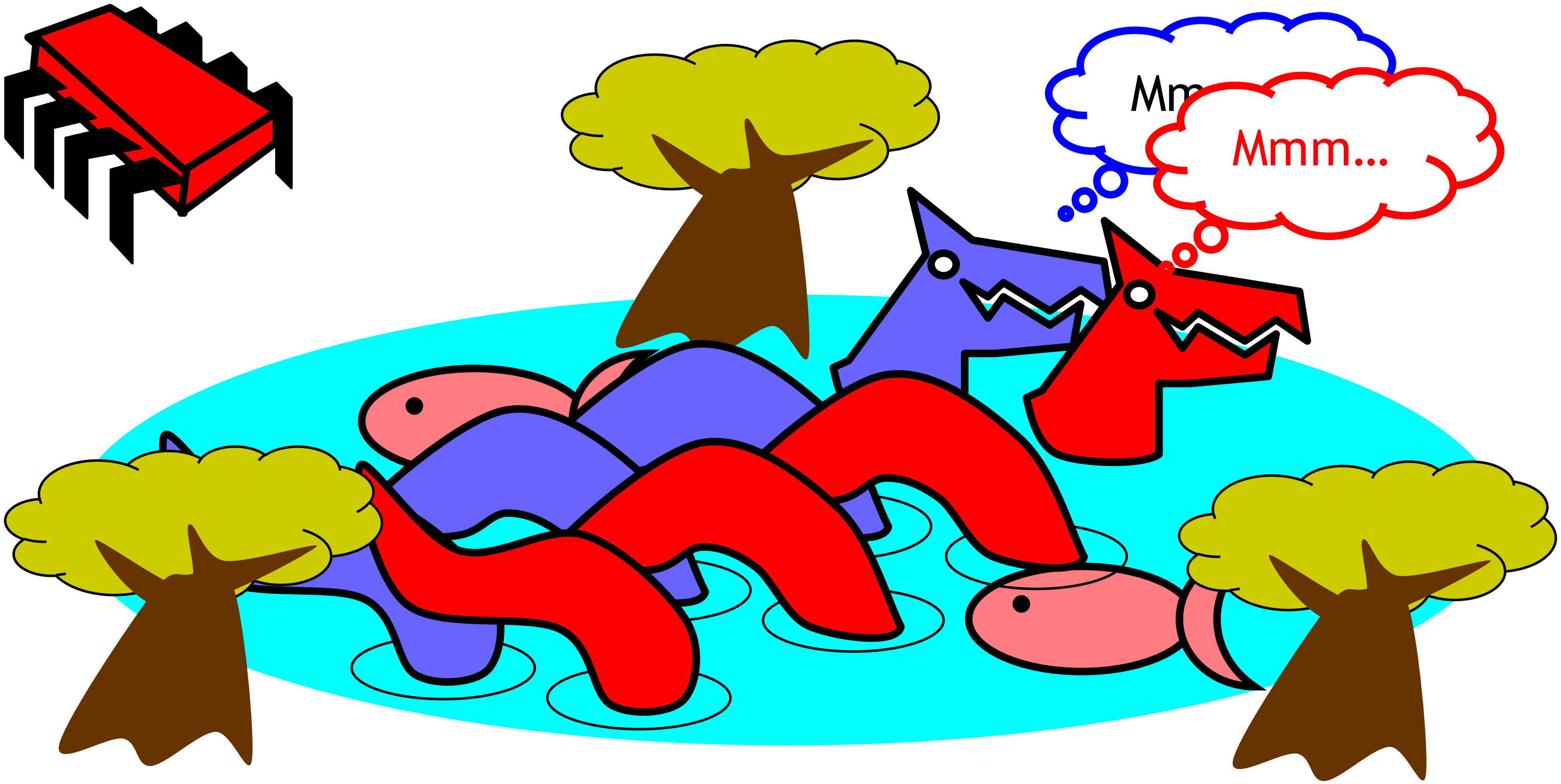
The Fable Continues

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

Bob Puts Food in the Pond



Alice Releases her Pets to Feed



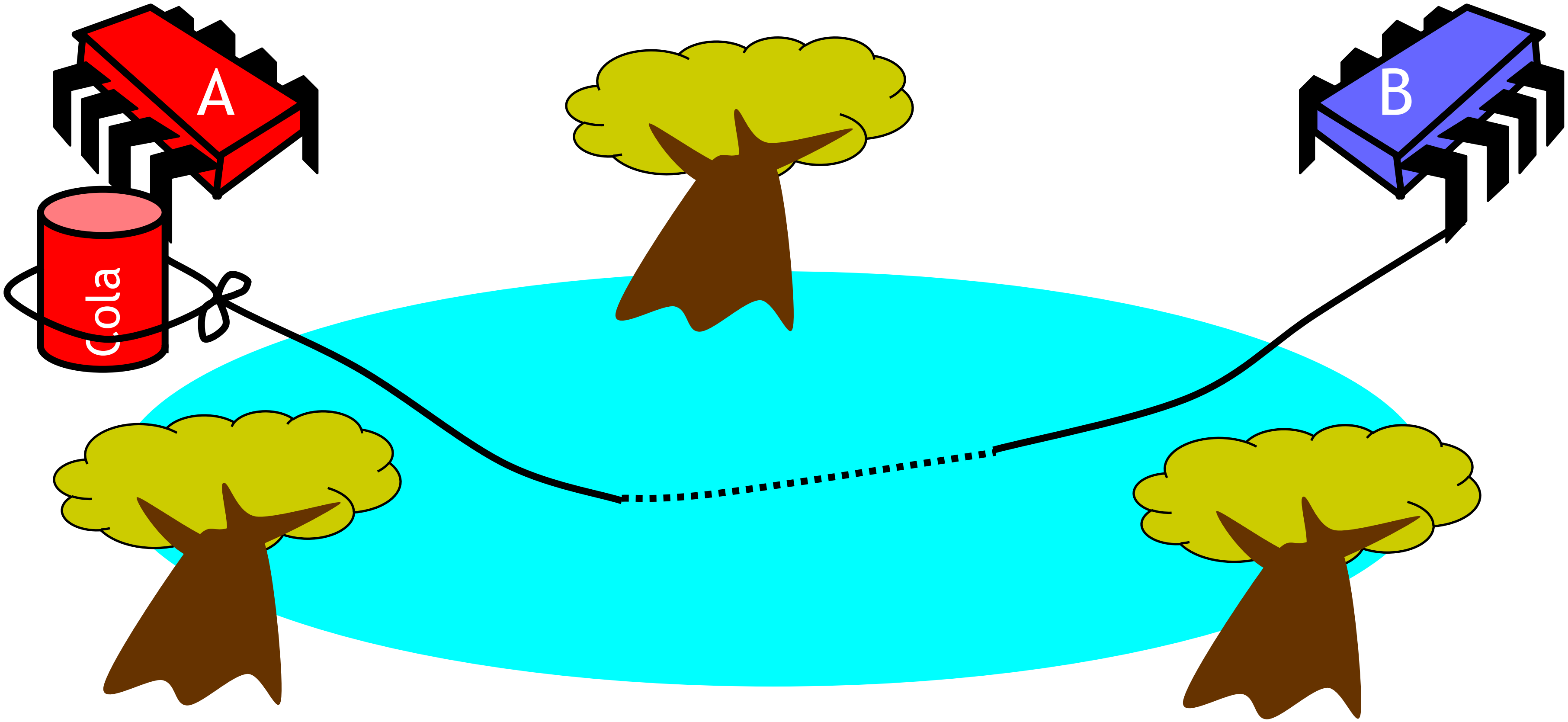
Producer/Consumer

- Alice and Bob cannot 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 is no food
  - Putting out food if uneaten food remains

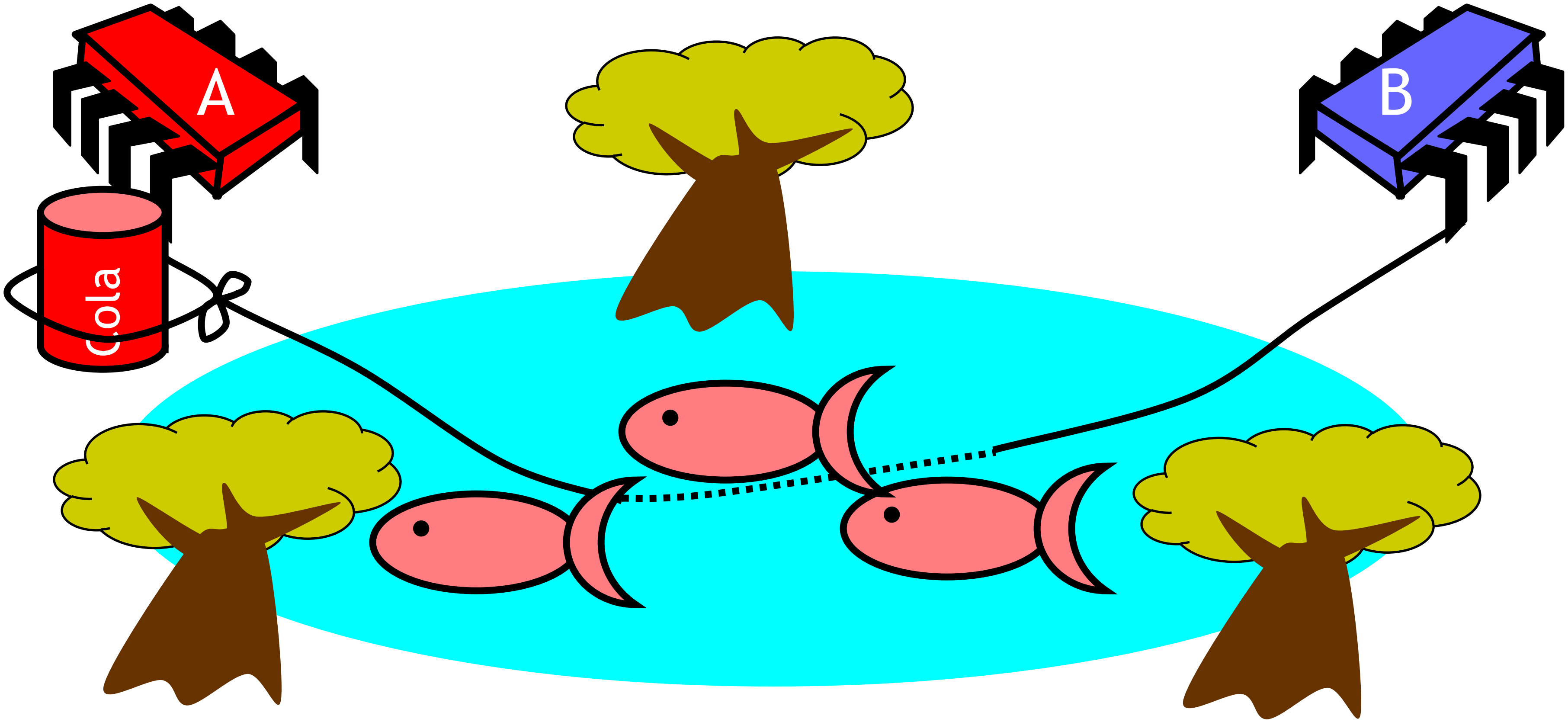
Producer/Consumer

- 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

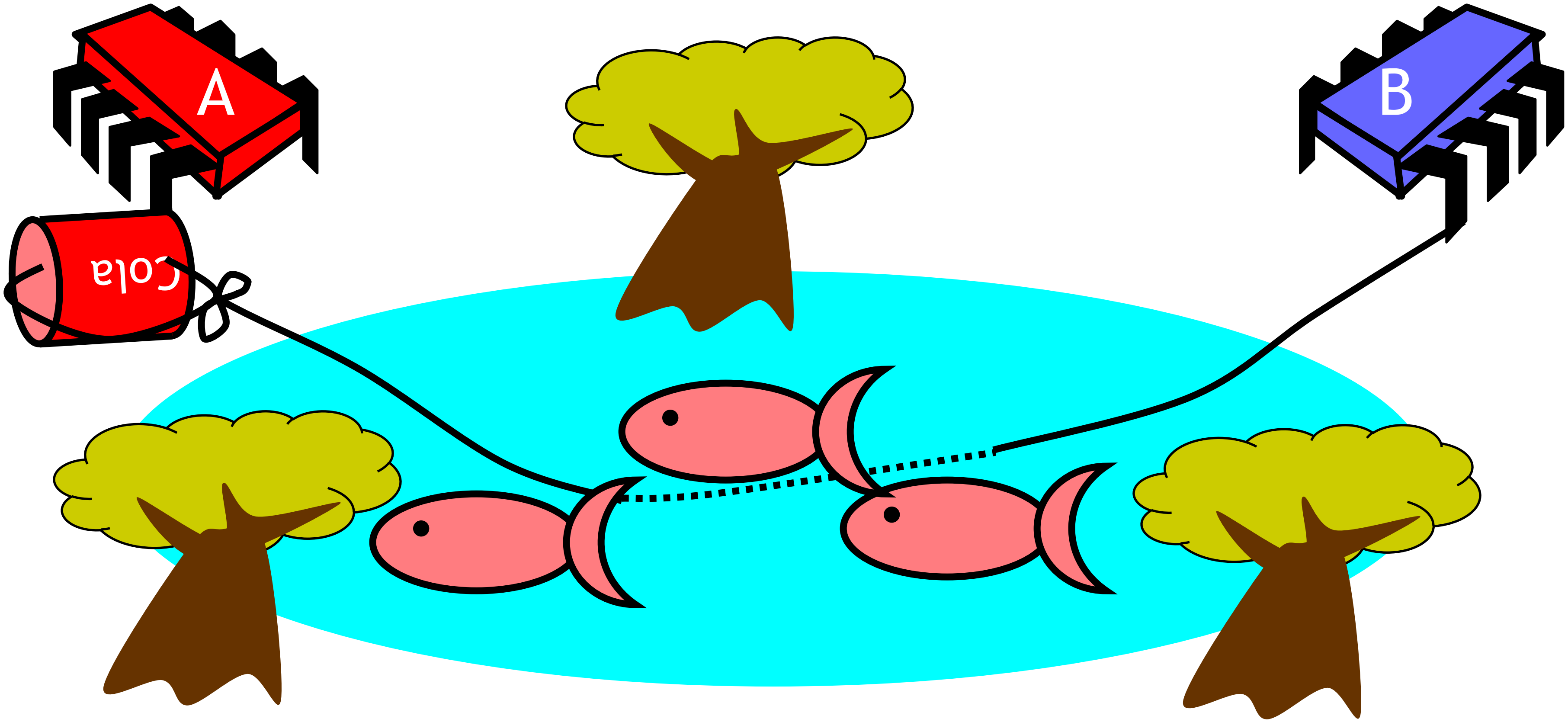
Surprise Solution



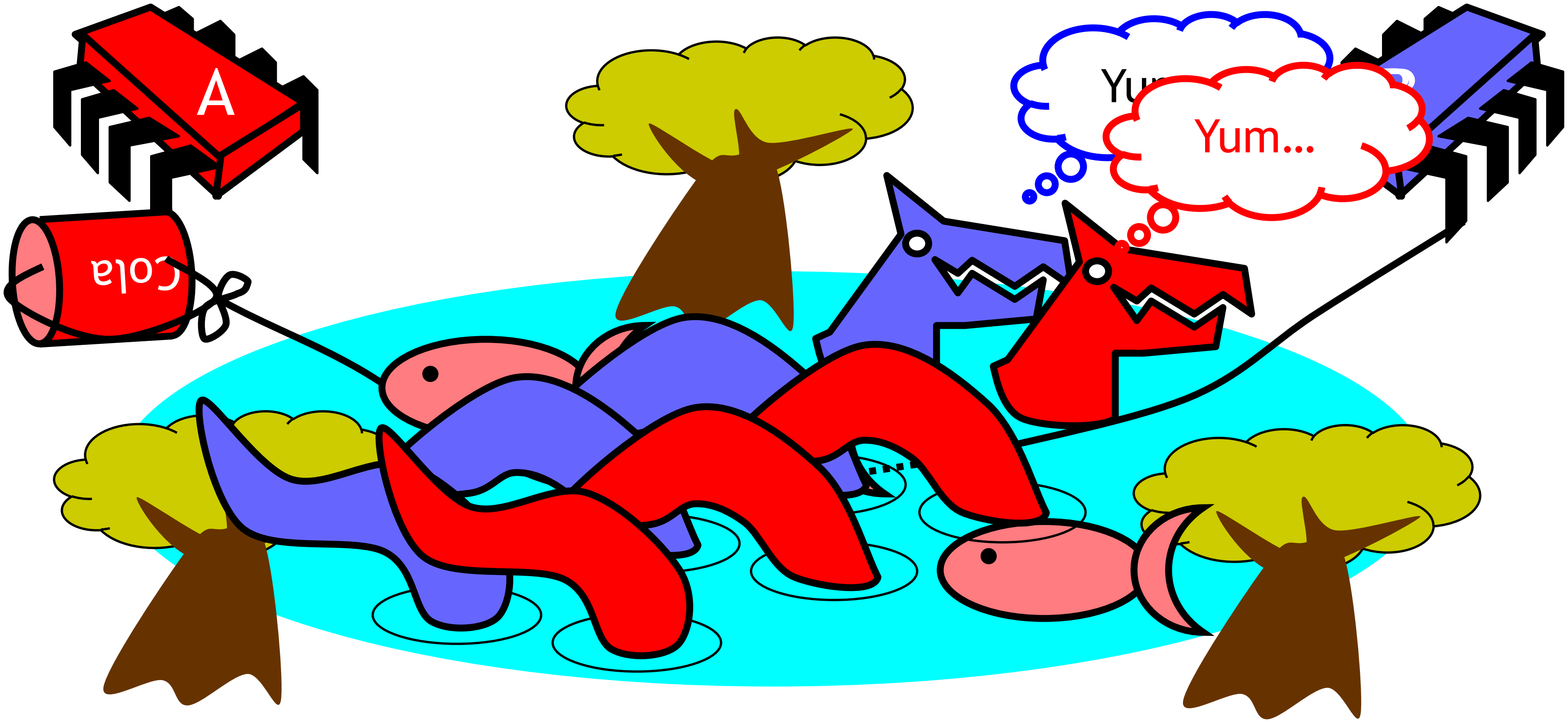
Bob Puts Food in Pond



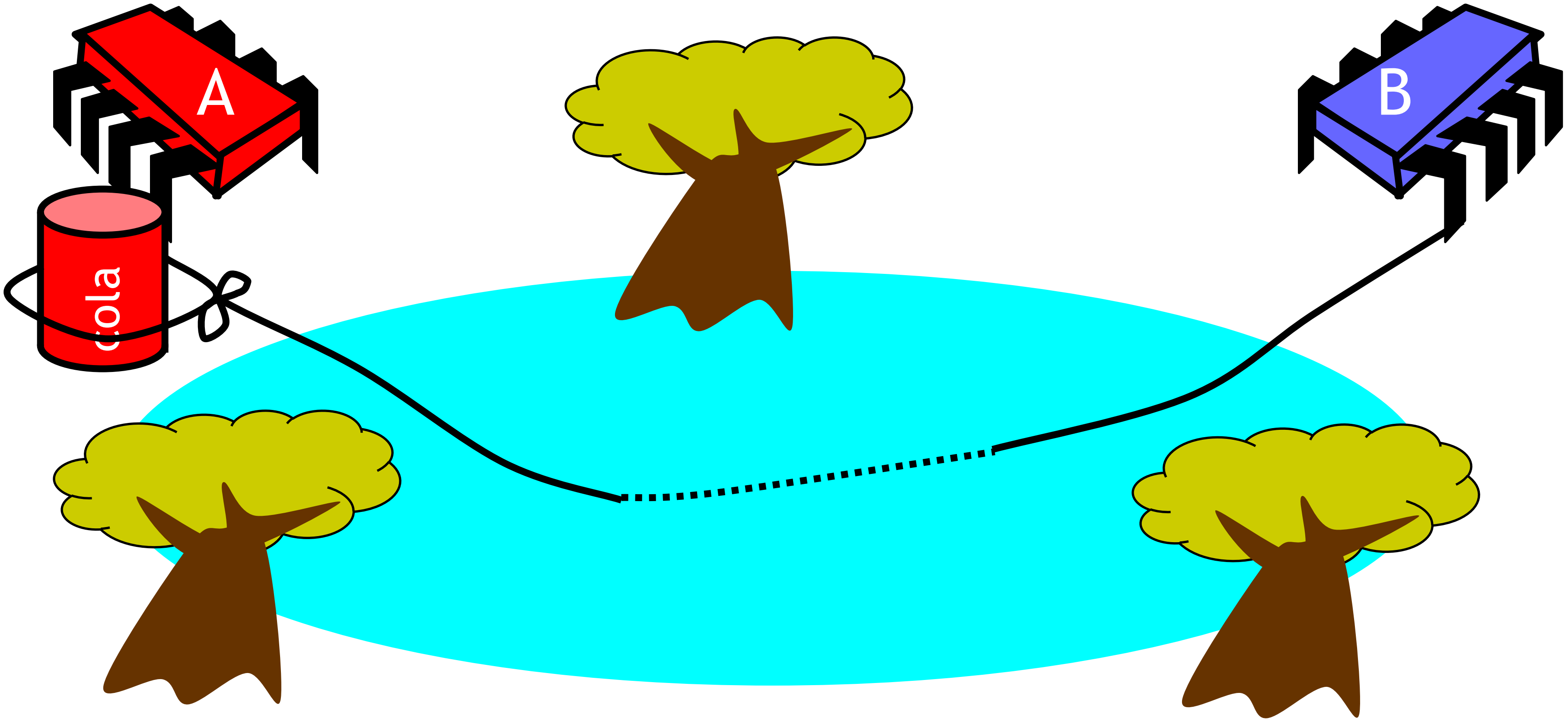
Bob Knocks over Can



Alice Releases Pets



Alice Resets Can once Pets Fed



Pseudocode

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

Alice's code

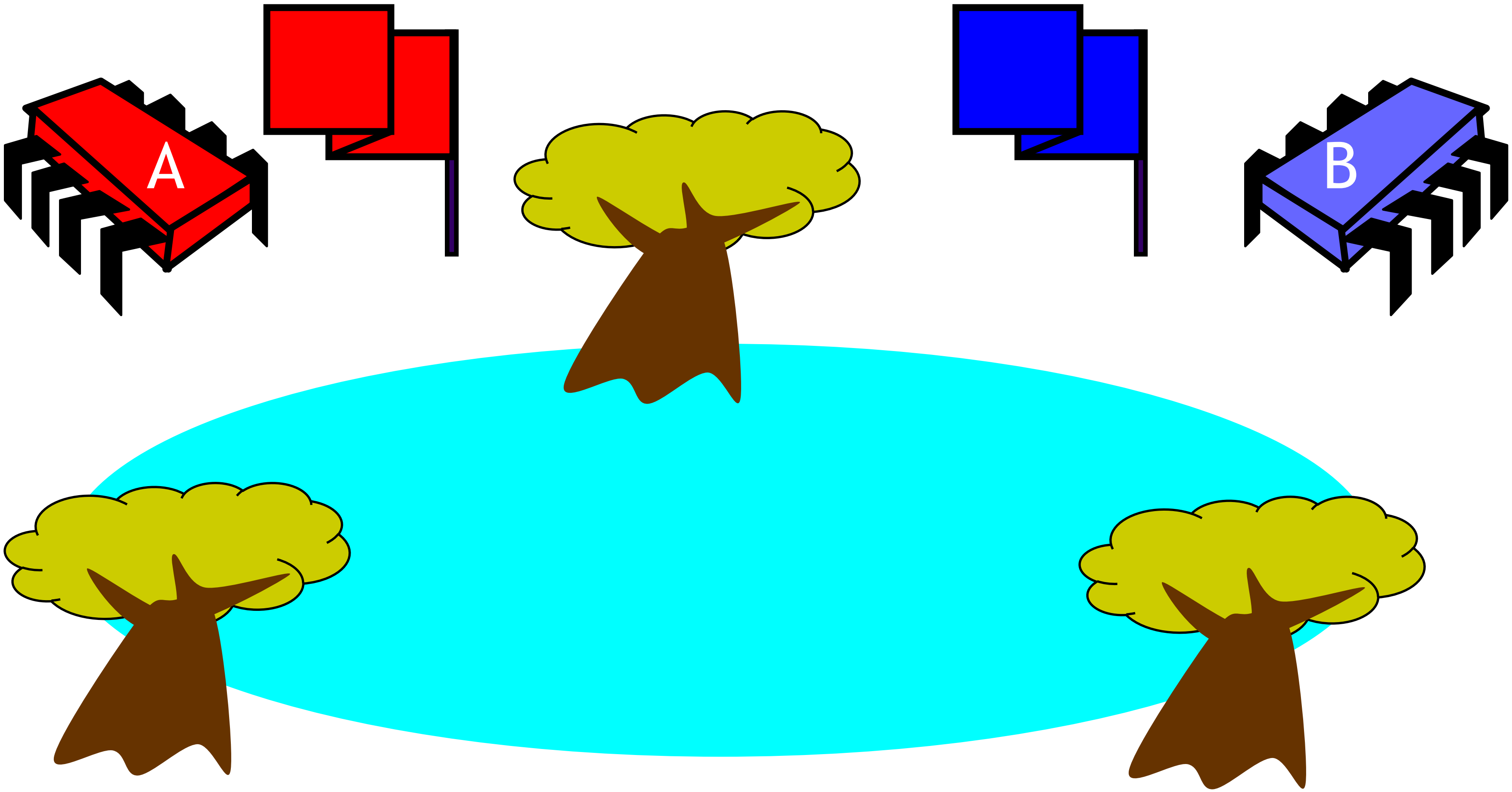
Bob's code

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

Correctness

- $\boxed{\text{Mutual exclusion}}$ — Safety
  - Pets and Bob never together in pond
- $\boxed{\text{No starvation}}$ — Liveness
  - If Bob always willing to feed, and pets always famished, then pets eat infinitely often
- $\boxed{\text{Producer/consumer}}$ — 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) { }
```

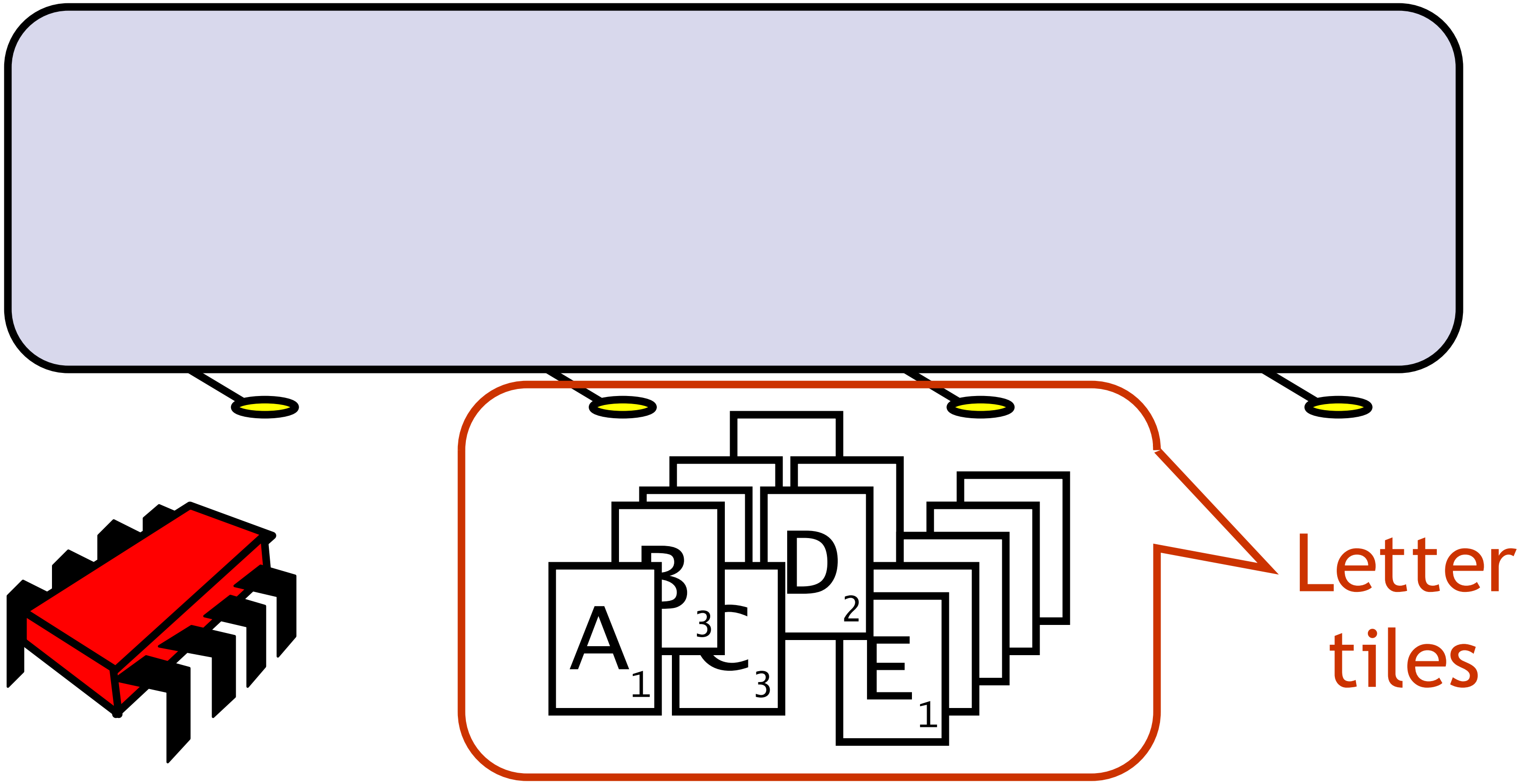
- Waiting is *problematic*
  - If one participant is delayed
  - So is everyone else
  - But delays are common and unpredictable

lock-free design: don' use lock at all -- wait-free: no delays.

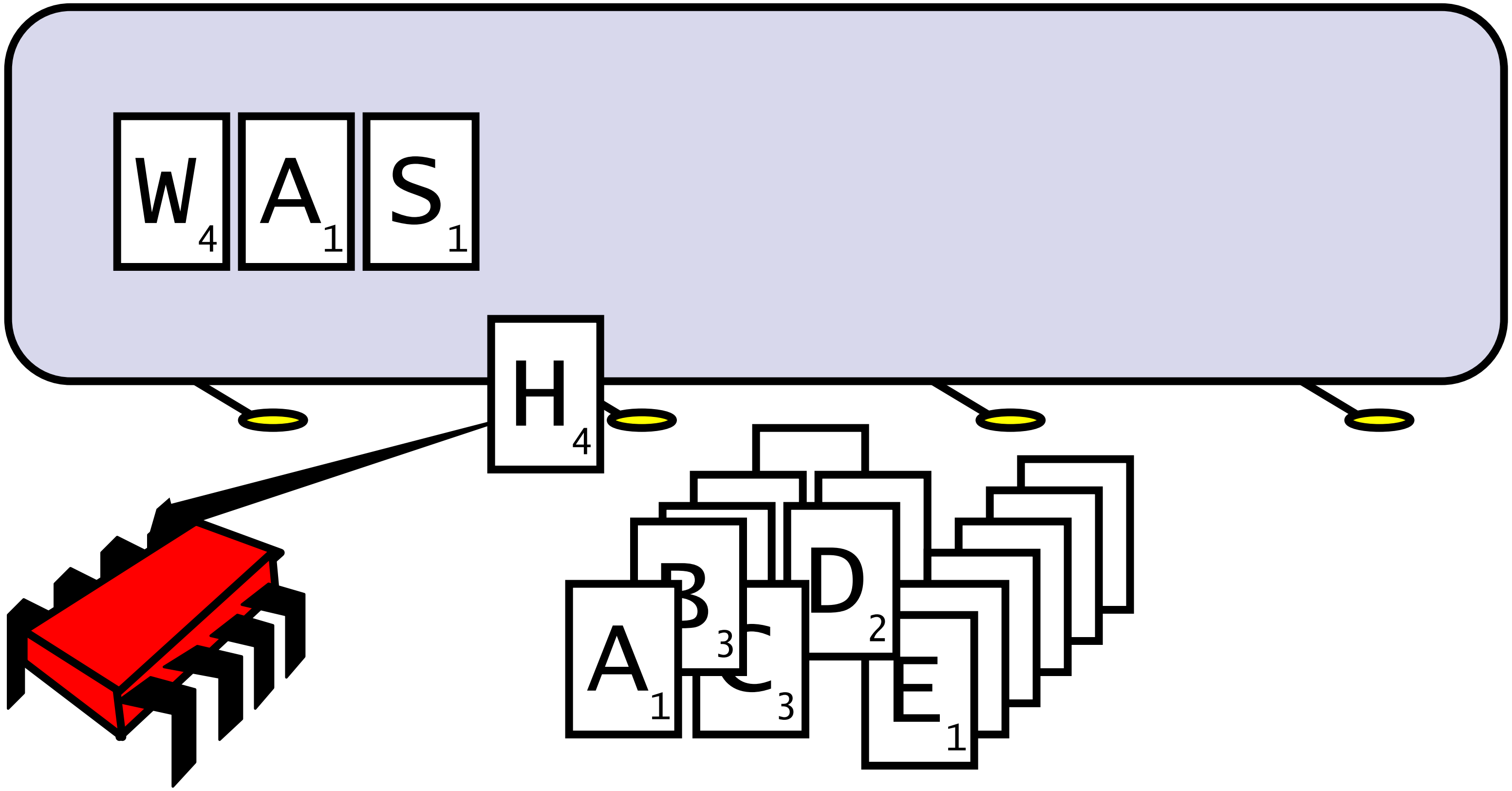
The Fable Drags on…

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

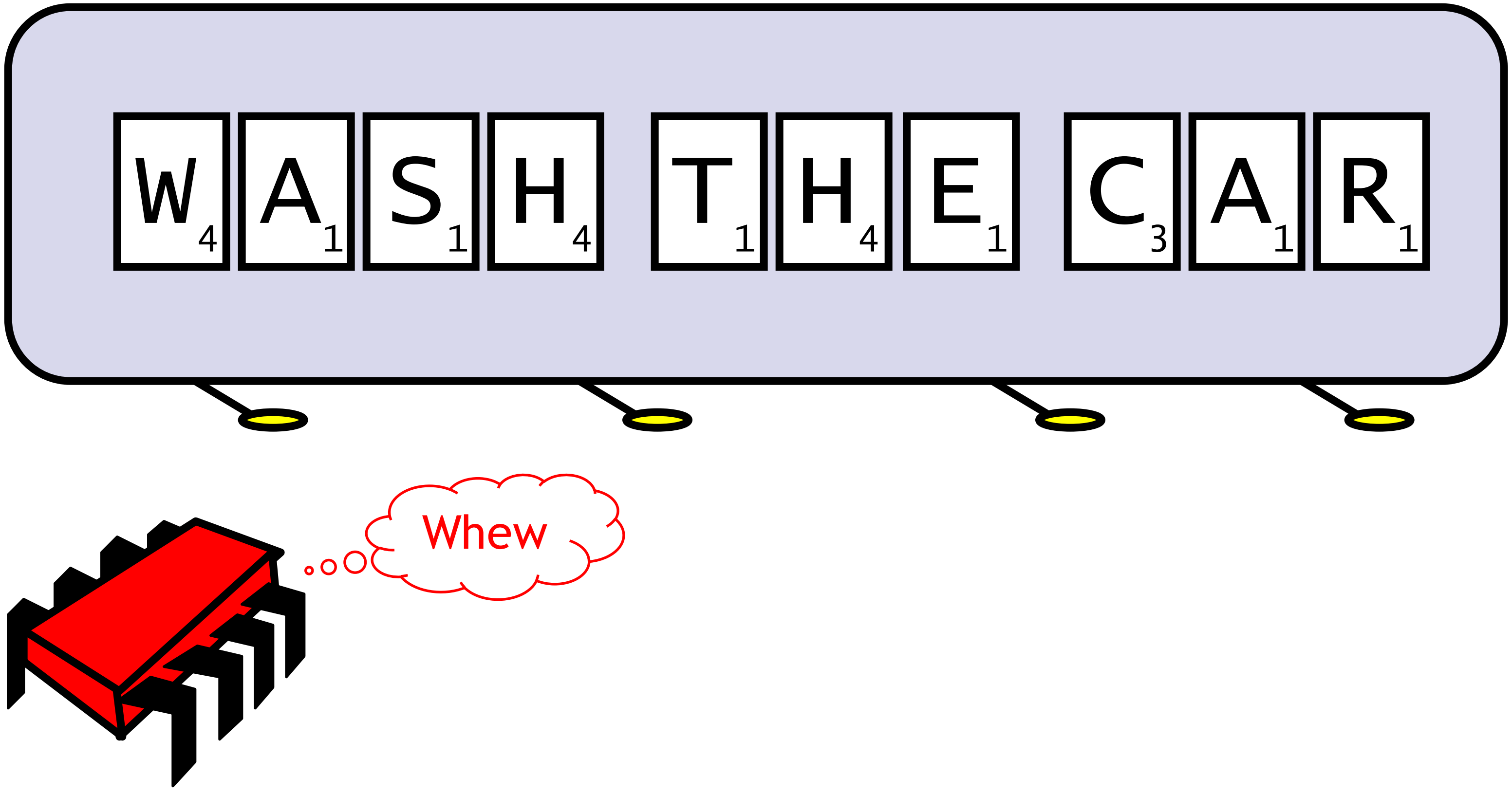
Billboards are Large



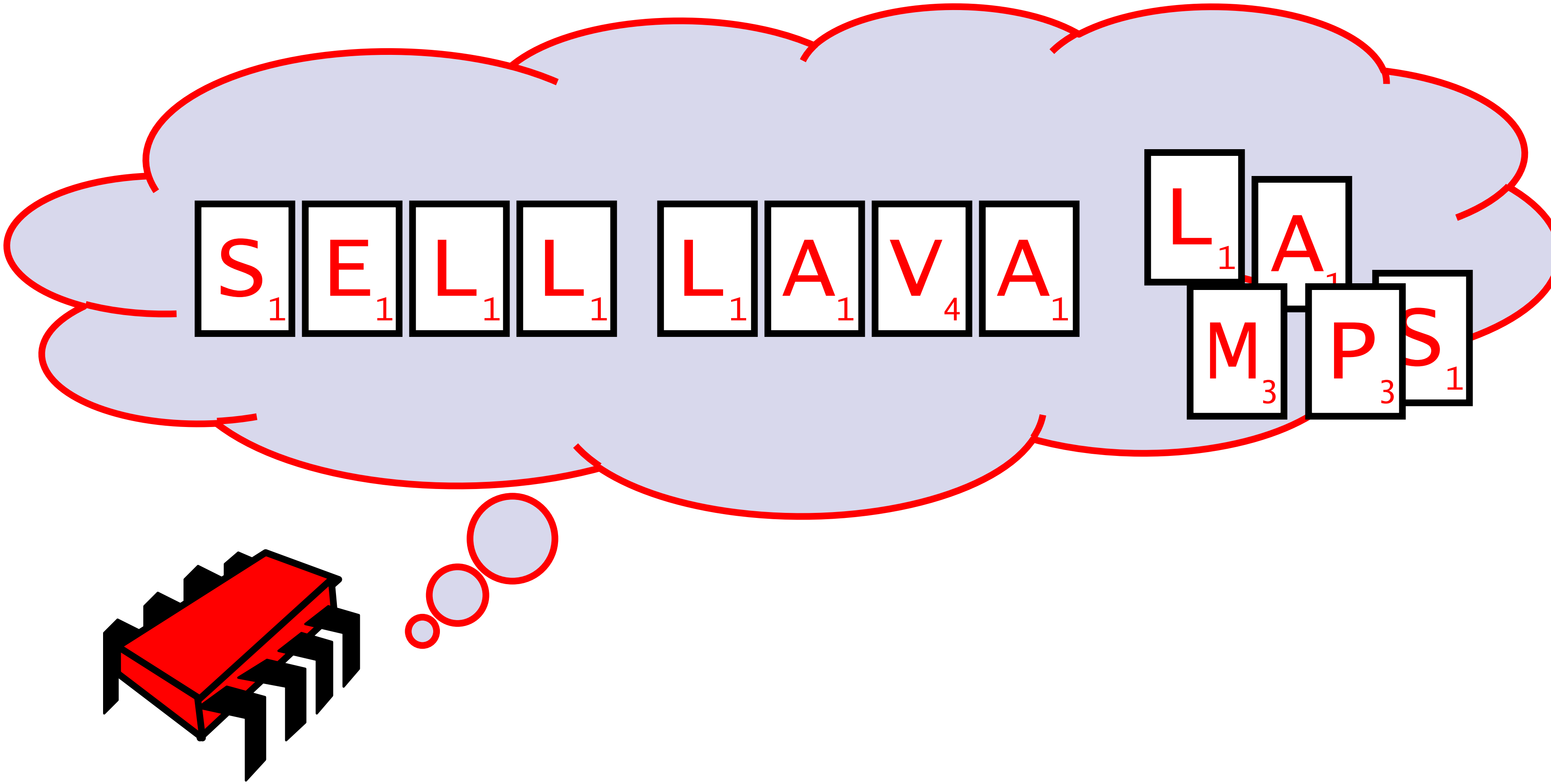
Write One Letter at a Time…



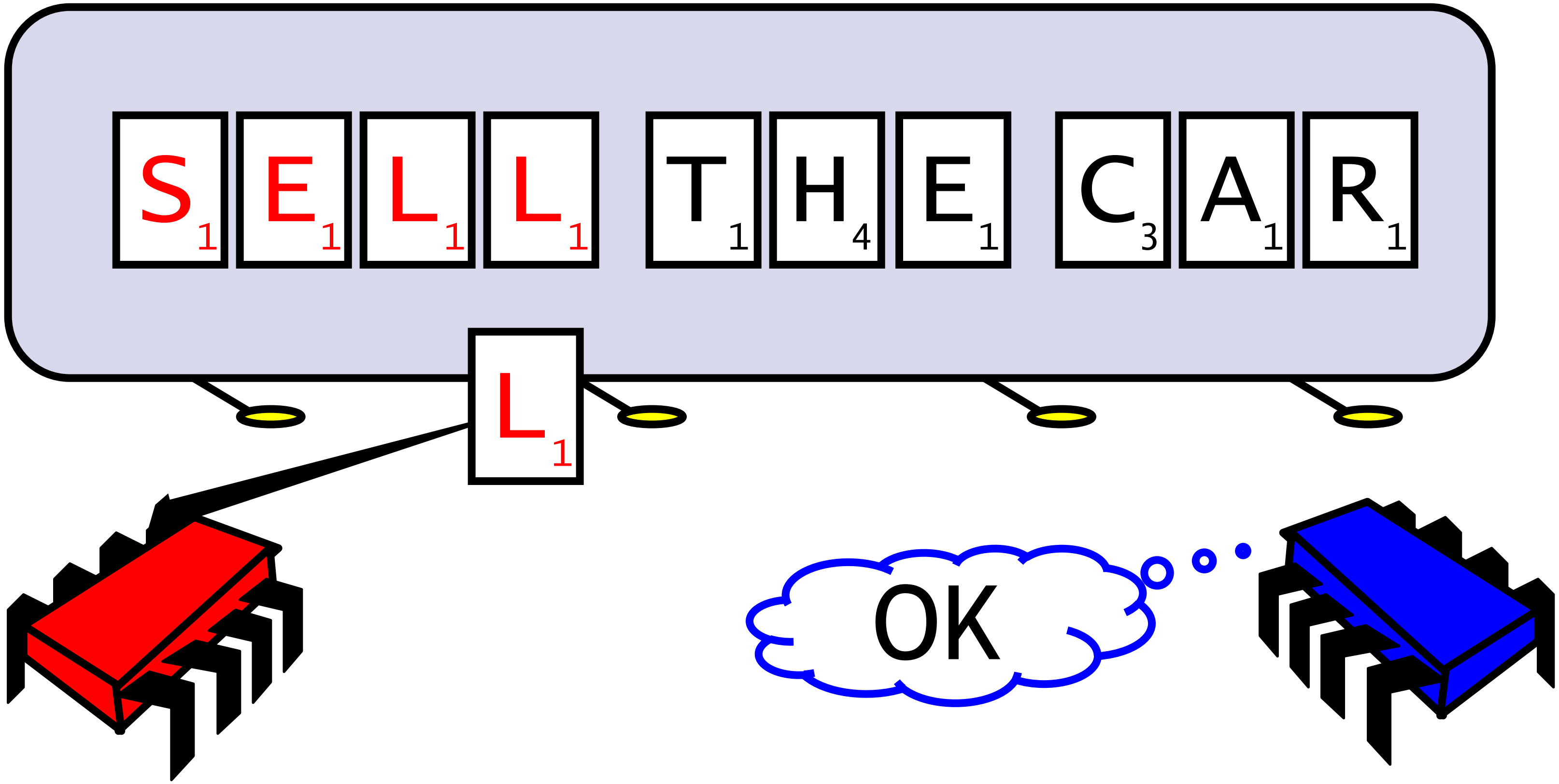
To Post a Message



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
    - 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

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

…of computation given *n* CPUs instead of *1*

Amdahl's Law

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

Parallel fraction

Sequential fraction

Number of processors

Example

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

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

Example

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

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

Example

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

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

Example

- Ten processors
- 99% concurrent, 1% sequential
- How close to 10-fold speedup?

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

The Moral

- Making good use of our multiple processors (cores) means
- Finding ways to effectively parallelize our code
  - Minimize sequential parts
  - Reduce time in which threads wait idle
- This is what this course is about…
  - The % that is not easy to make concurrent yet may have a large impact on overall speedup