Introduction

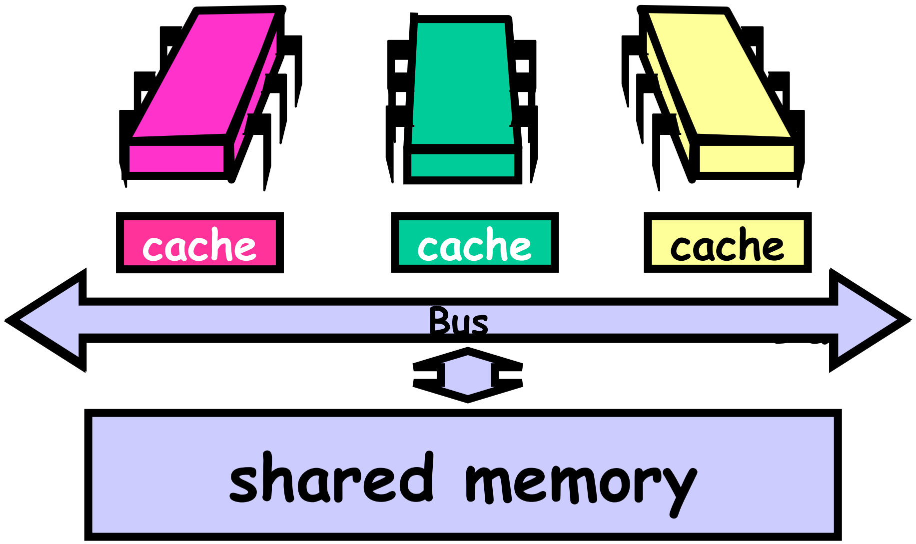
Companion slides for

The Art of Multiprocessor Programming

by Maurice Herlihy & Nir Shavit

(Abridged version. Original at http://booksite.elsevier.com/9780123705914/?ISBN=9780123705914)

In the Enterprise: The Shared Memory Multiprocessor (SMP)



Model Summary

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

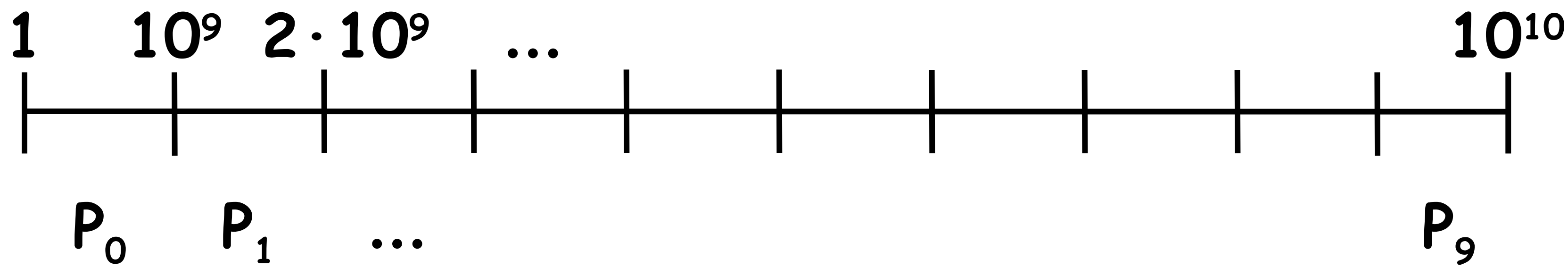
Concurrency Jargon

- 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*10⁹+1, j<(i+1)*10⁹; j++) {
    if (isPrime(j))
      print(j);
  }
}
```

Issues

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

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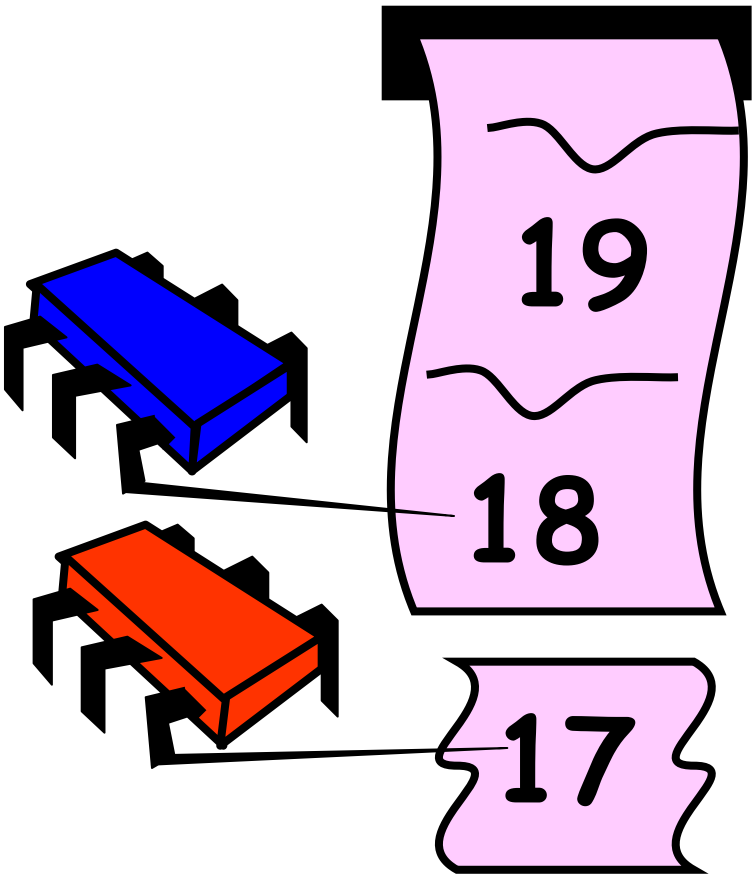
- Higher ranges have fewer primes
- Yet larger numbers harder to test
- Thread workloads
  - Uneven
  - Hard to predict
- Need *dynamic* load balancing

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);
  }
}
```

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);
  }
}
```

Shared counter object

Procedure for Thread *i*

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

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

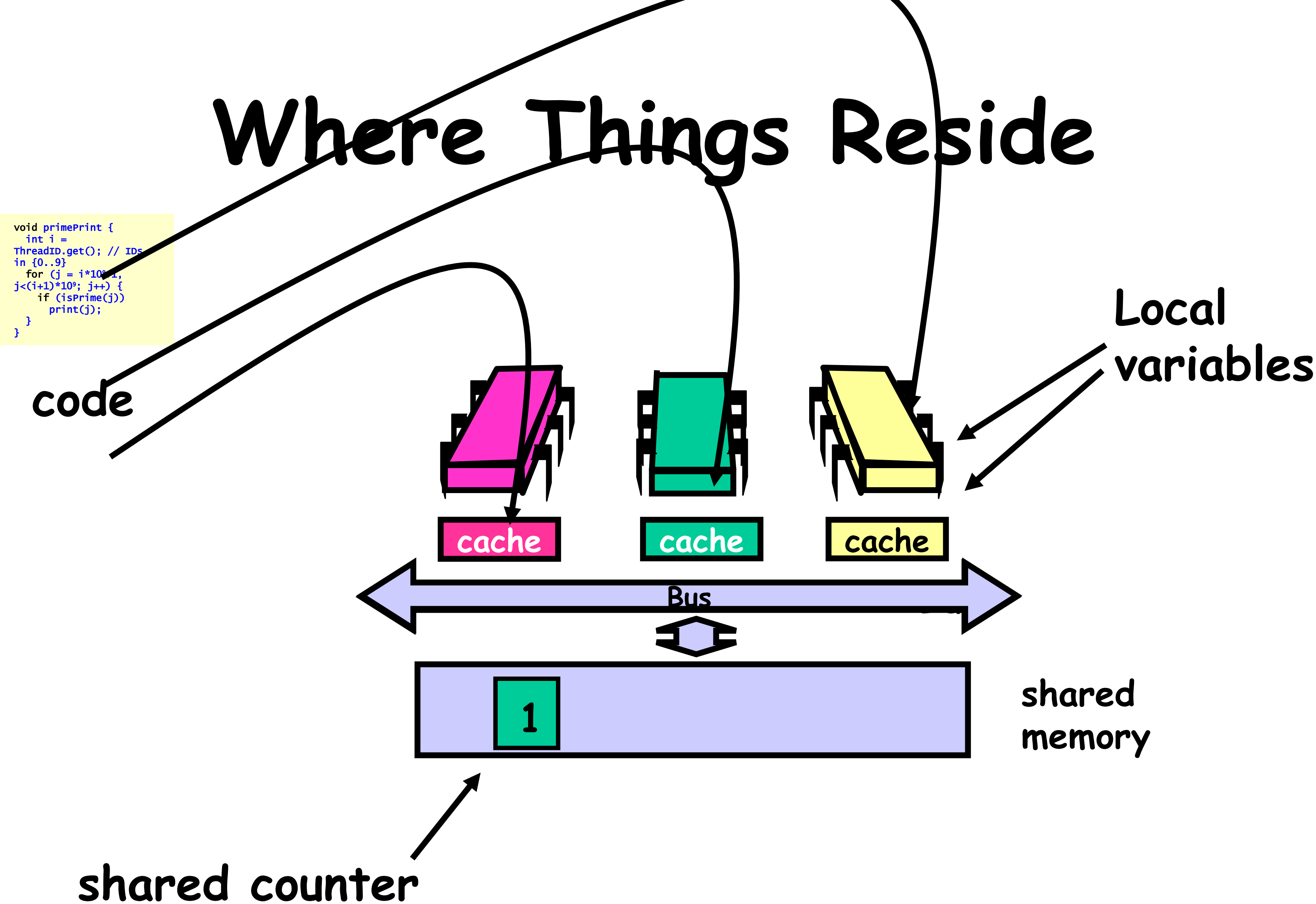
Increment & return each new value

Counter Implementation

```
public class Counter {
  private long value;

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

Where Things Reside



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++;
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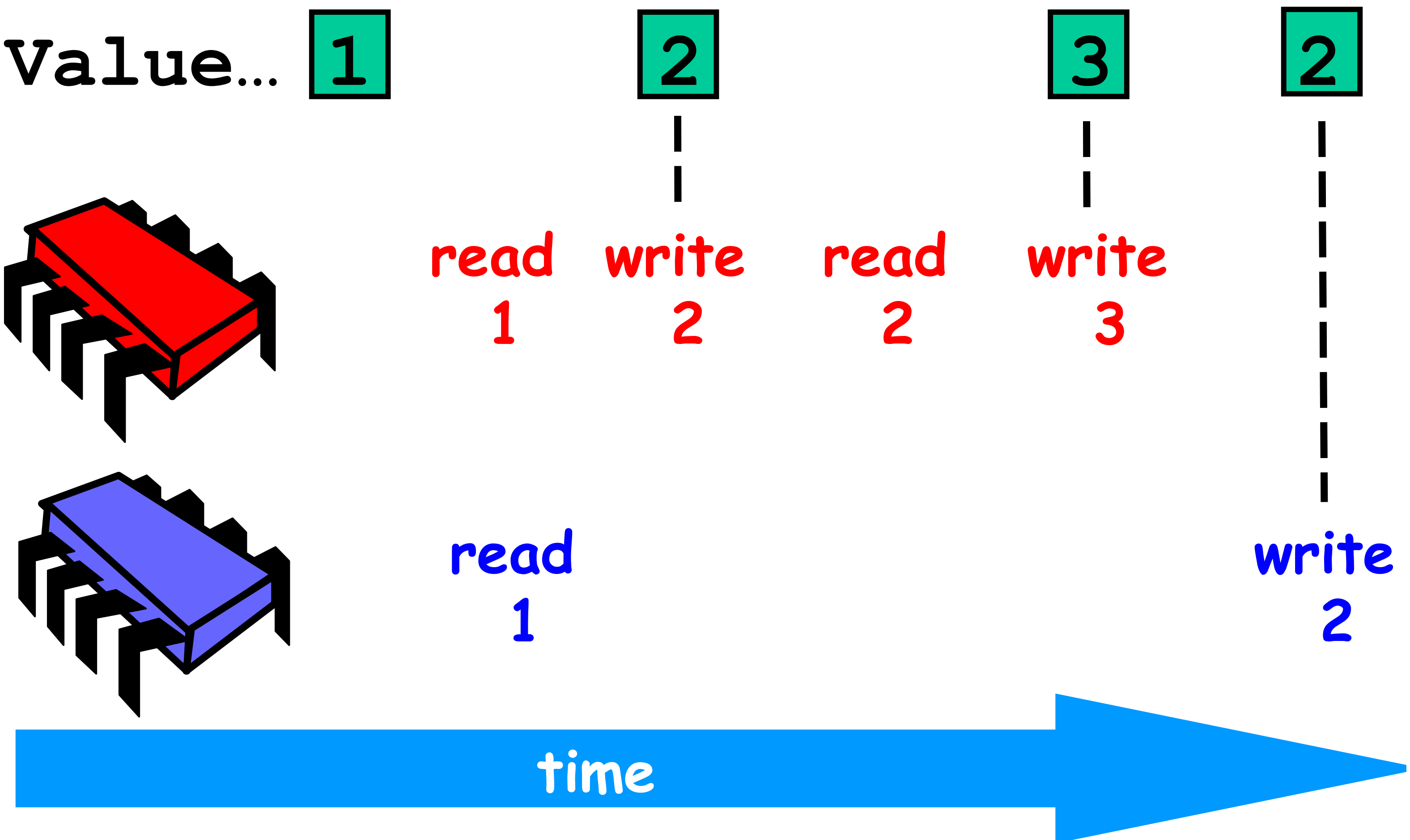
}
```

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

Not so good…



Counter Implementation

```
public class Counter {
  private long value;

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

OK for single thread,
not for concurrent threads

Challenge

```
public class Counter {
  private long value;

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

Challenge

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public class Counter {
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  public long getAndIncrement() {
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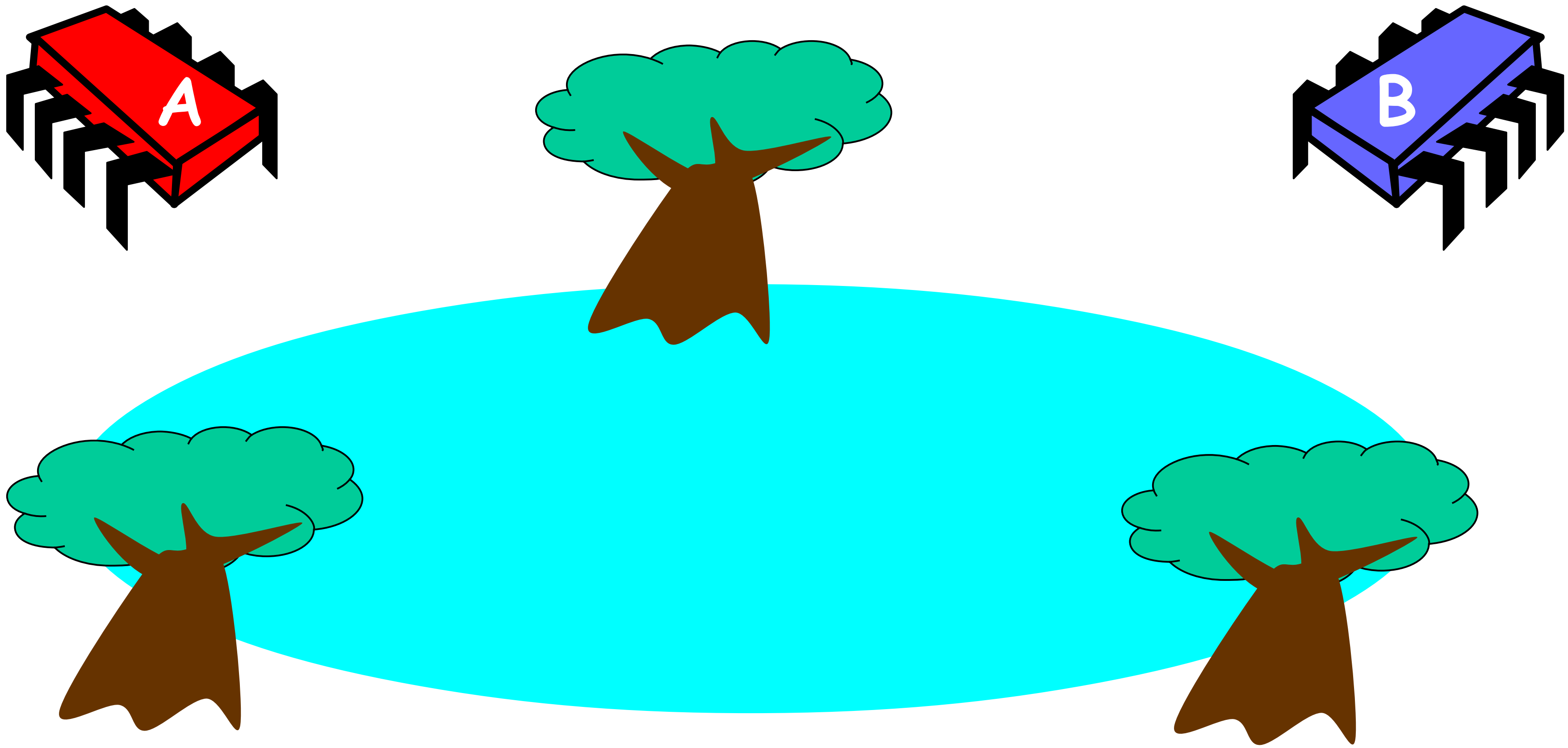
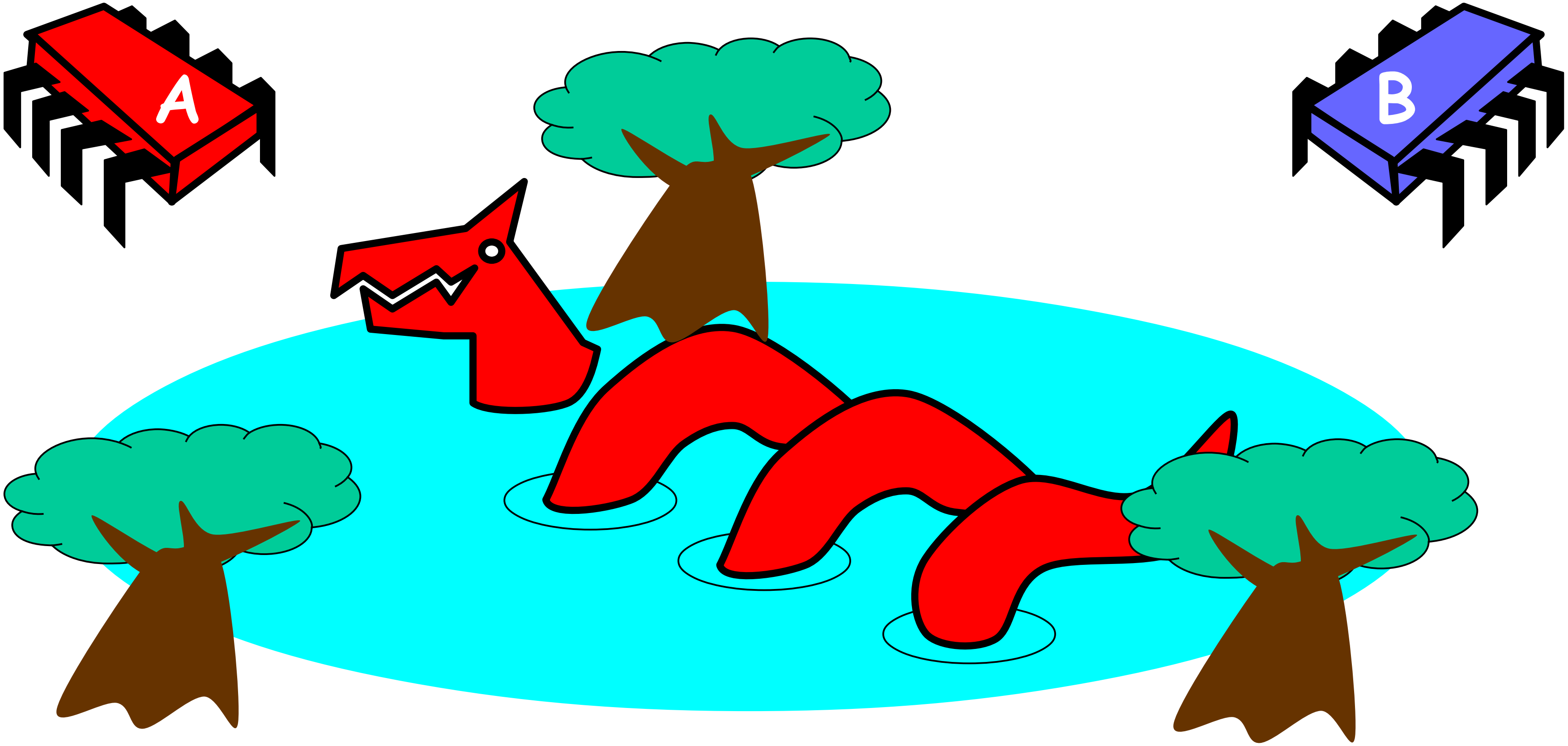
}
```

Make these steps *atomic* (indivisible)

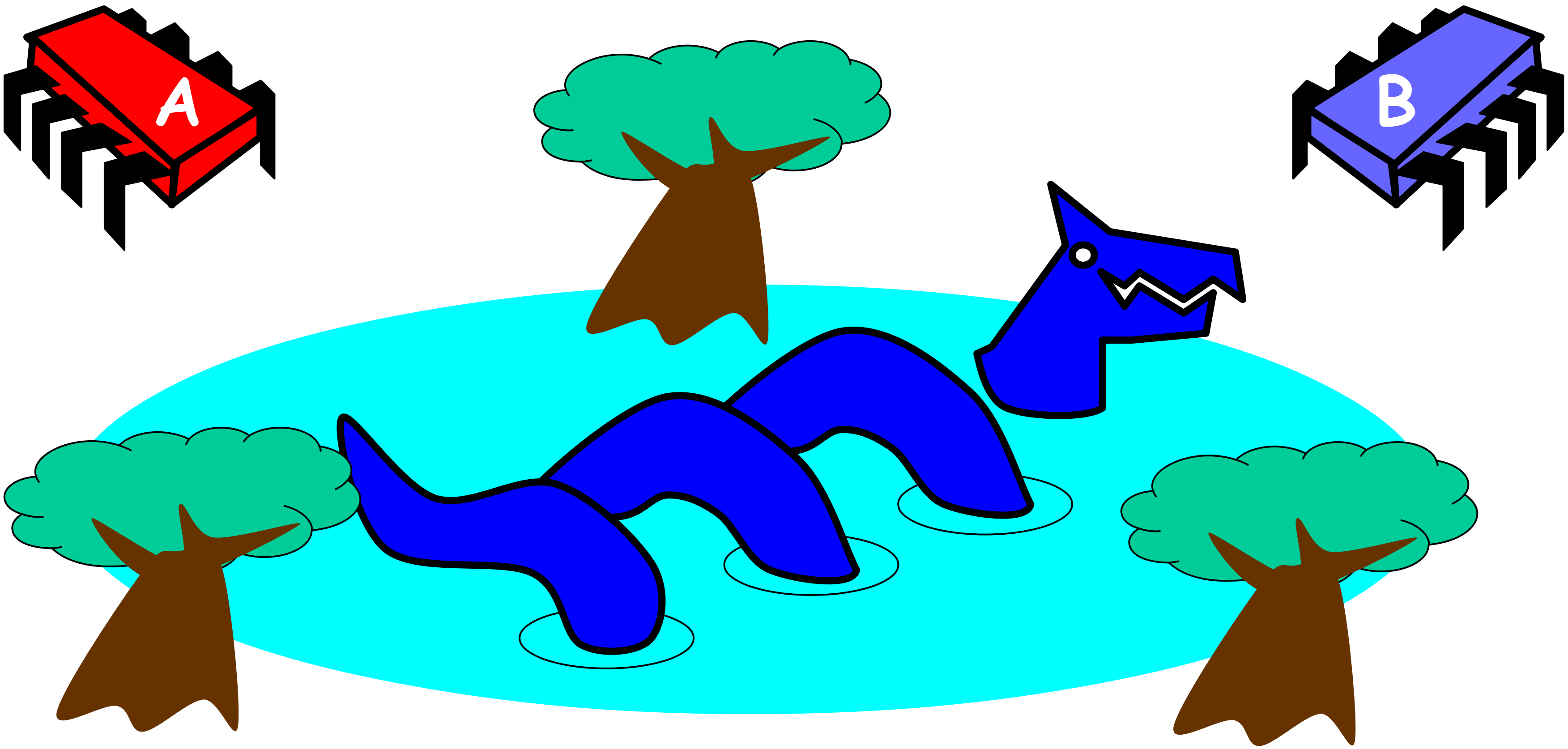
Mutual Exclusion or "Alice & Bob share a pond"



Alice has a pet



Bob has a pet



The Problem

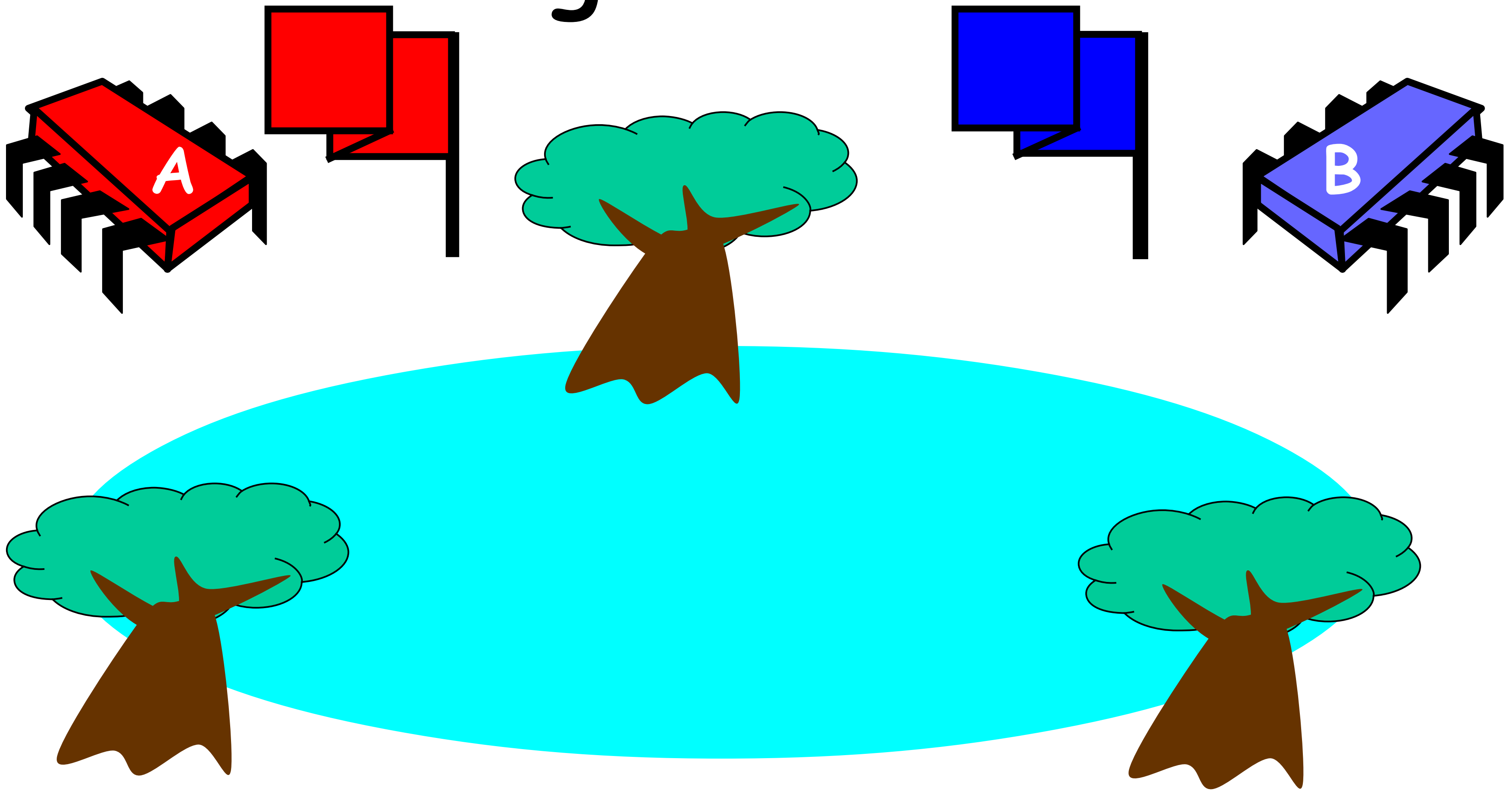
Formalizing the Problem

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

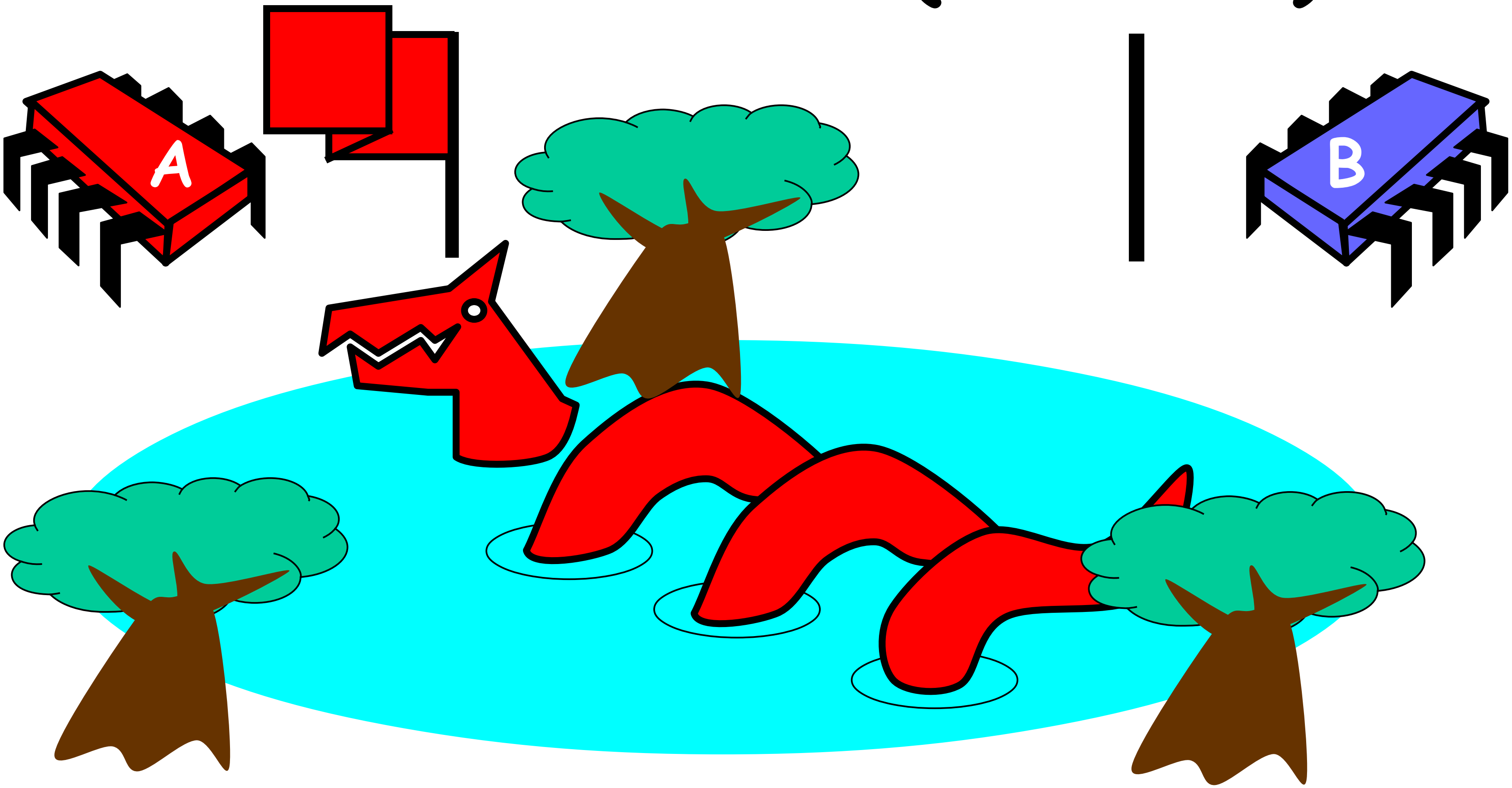
Formalizing our Problem

- 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

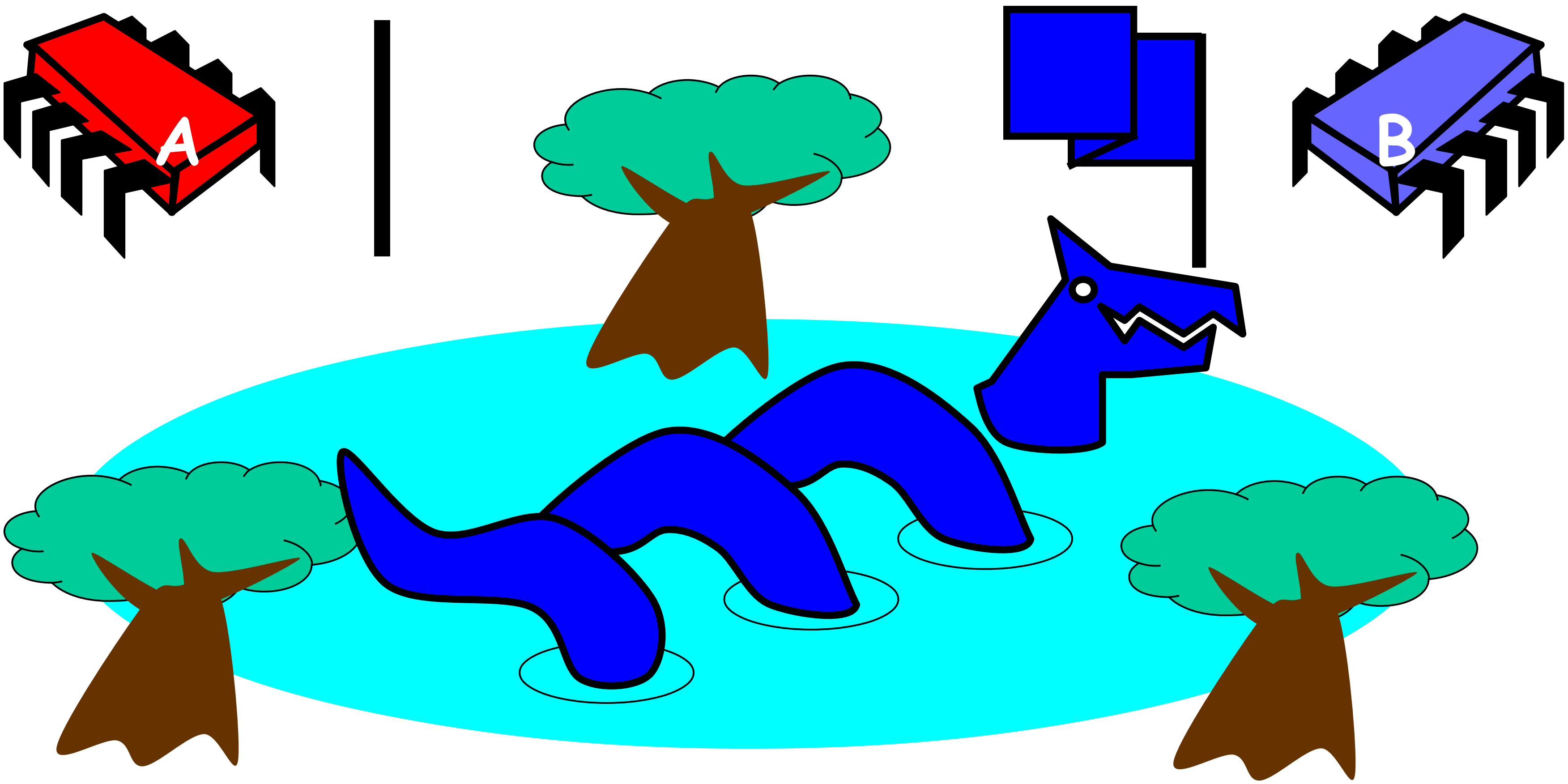
Flag Protocol



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

Bob defers to Alice

- 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

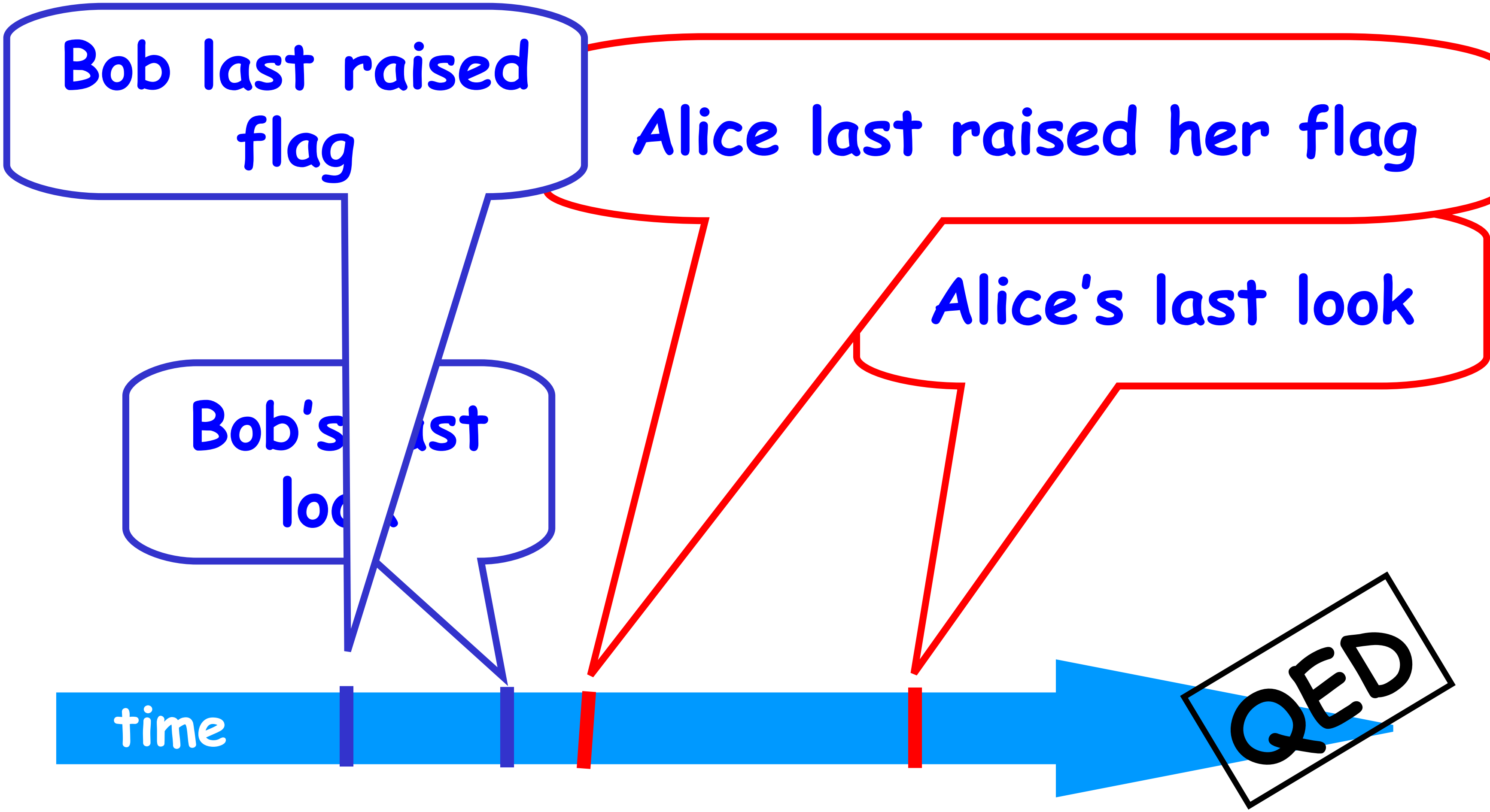
The Flag Principle

- 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 <u>backwards</u>
- 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.

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- 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