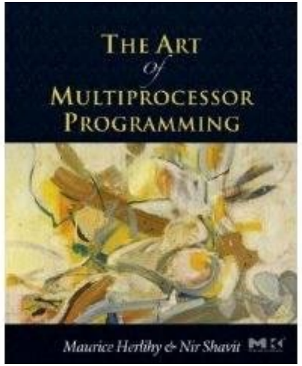
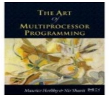
Introduction



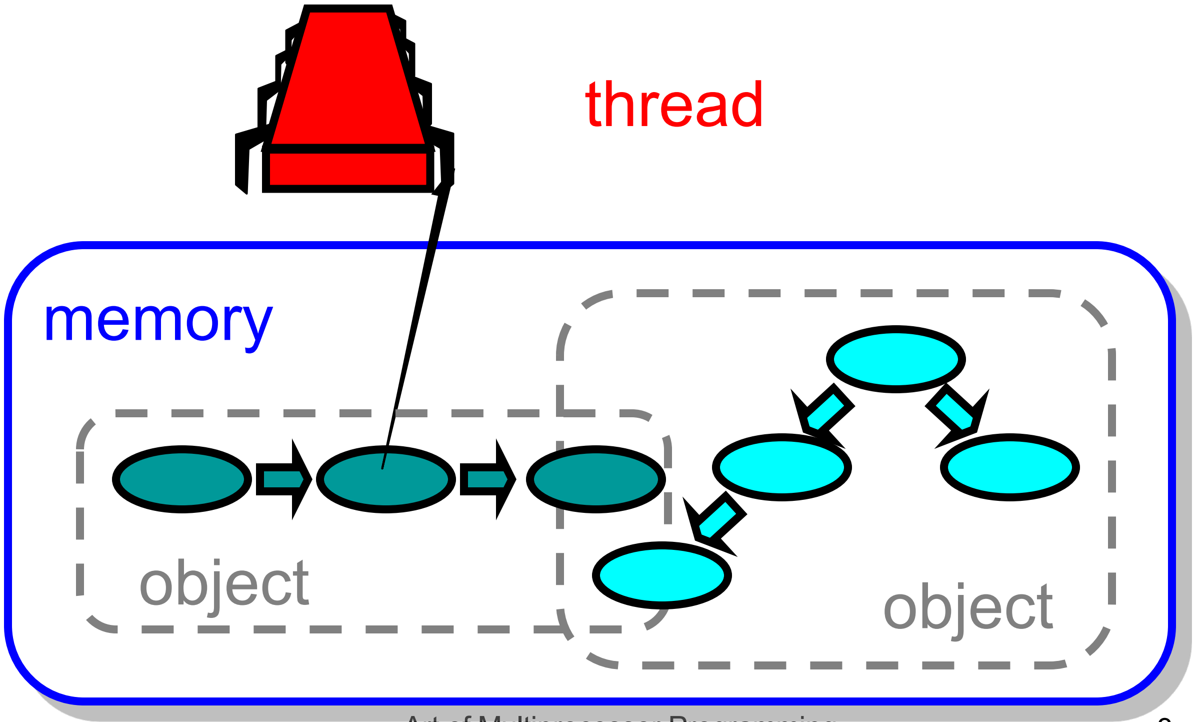
Hyungsoo Jung

Multicore Programming: Course Overview

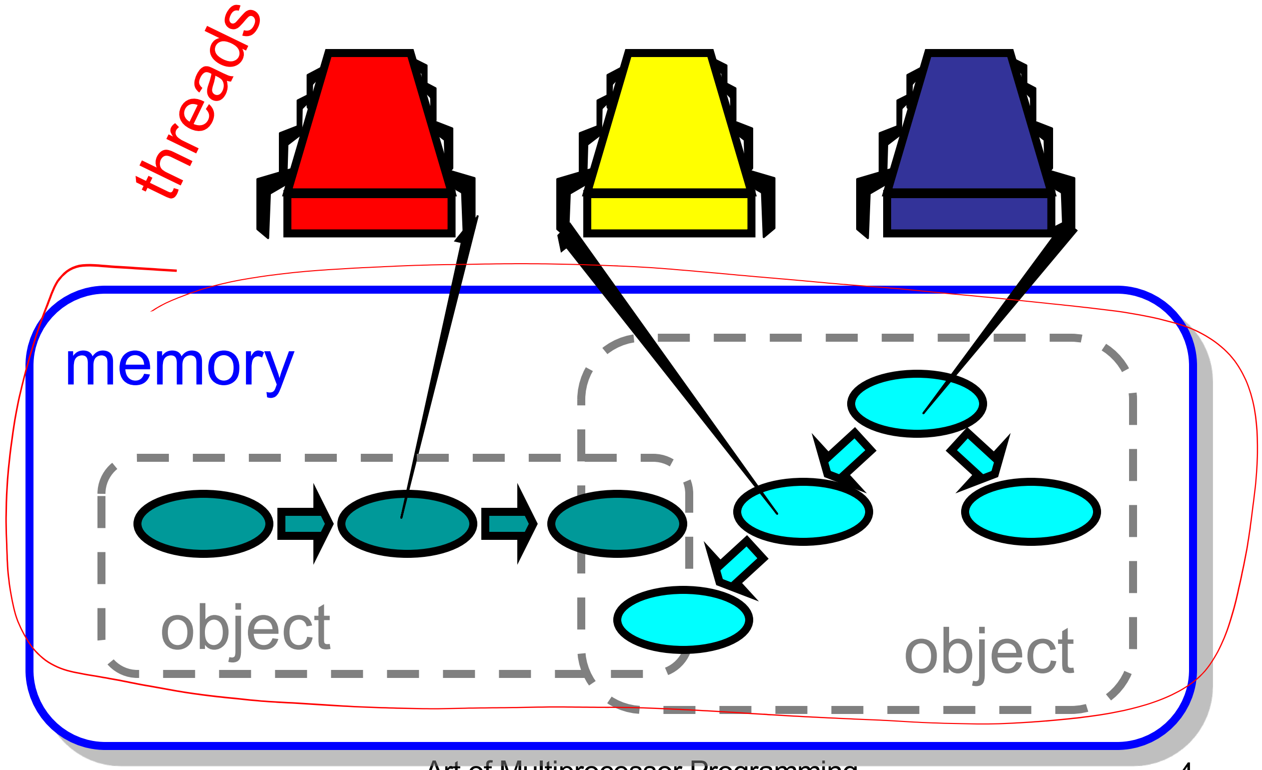
- Fundamentals
  - Models, algorithms, impossibility
- Real-world programming
  - Architectures
  - Techniques



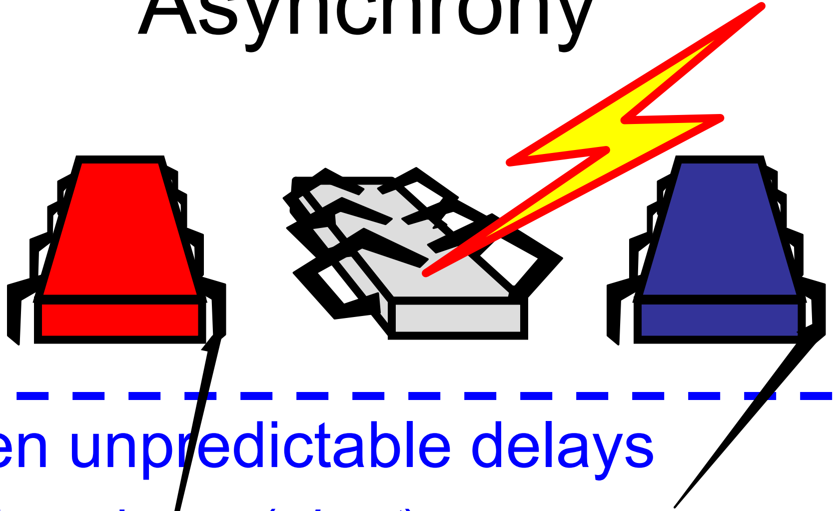
Sequential Computation



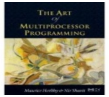
Concurrent Computation



Asynchrony

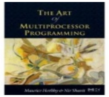


- Sudden unpredictable delays
  - Cache misses (*short*)
  - Page faults (*long*)
  - Scheduling quantum used up (*really long*)



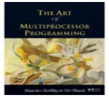
Model Summary

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



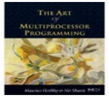
Road Map

- 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”



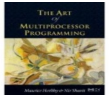
Concurrency Jargon

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

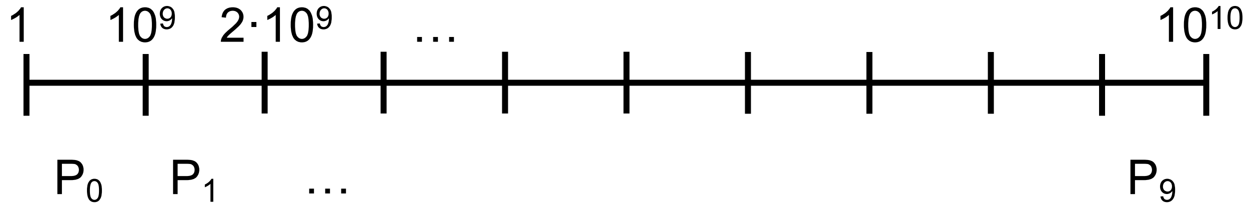


Parallel Primality Testing

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



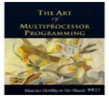
Load Balancing



- 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

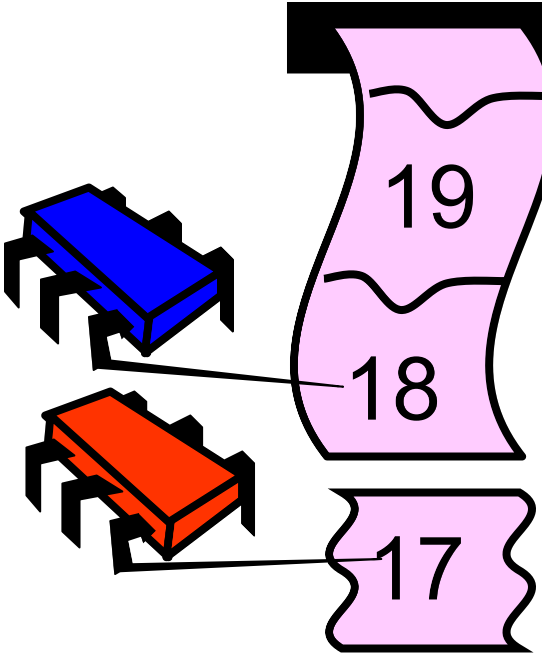
- Higher ranges have fewer primes
- Yet larger numbers harder to test
- Thread workloads
  - Uneven
  - Hard to predict

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

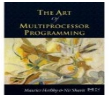


each thread takes a number

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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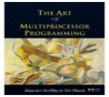
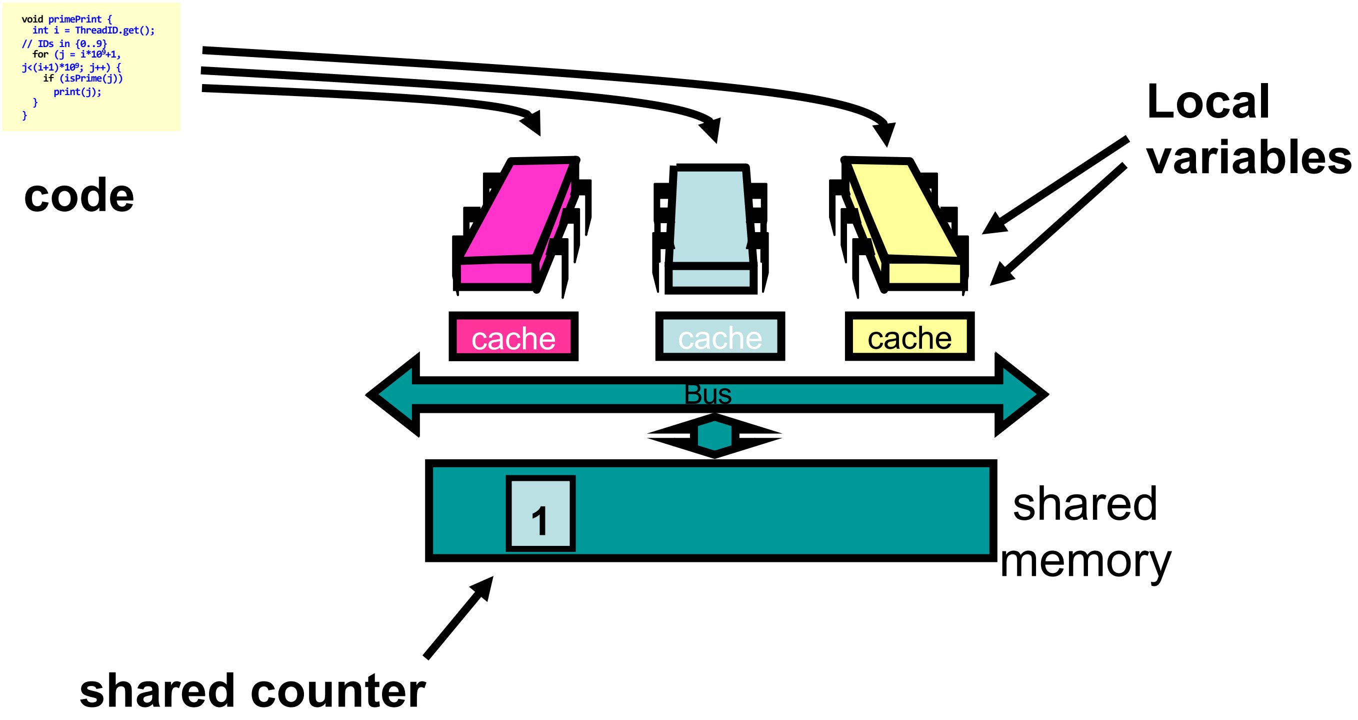
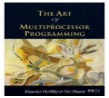
```

Shared counter object



Where Things Reside





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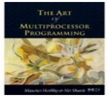
```

Stop when every value taken



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      print(j);
  }
}
```

Increment & return each new value

Counter Implementation

```
public class Counter {
  private long value;

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

Counter Implementation

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public class Counter {
  private long value;

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```

OK for single thread,
not for concurrent threads

What It Means

```
public class Counter {
  private long value;

  public long getAndIncrement() {
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```

What It Means

```
public class Counter {
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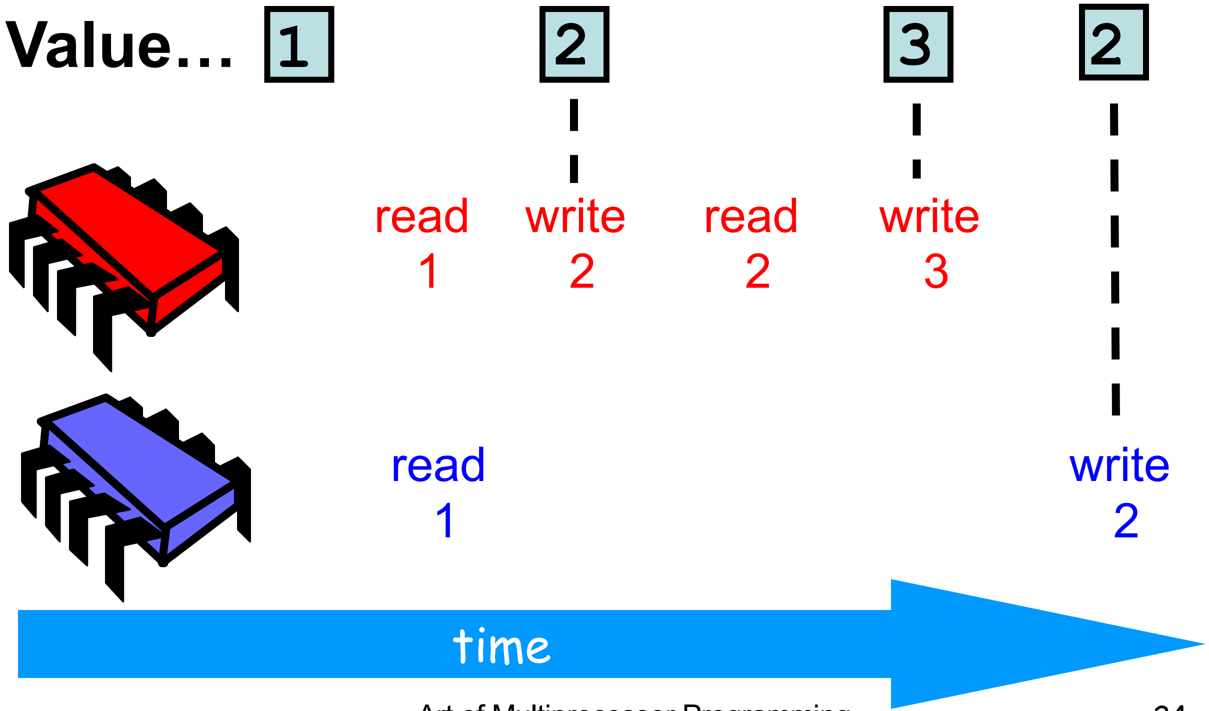
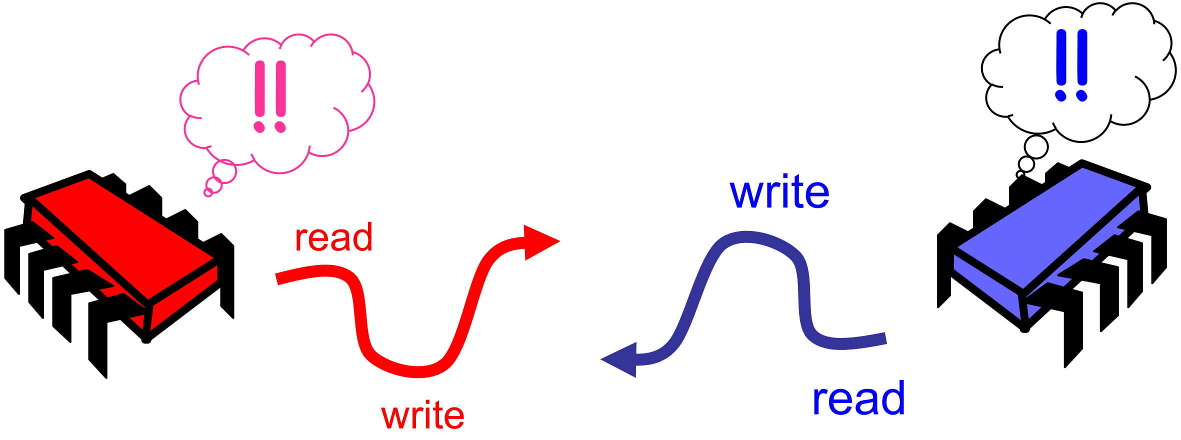
```

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

Not so good…



Is this problem inherent?

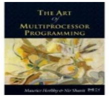


If we could only glue reads and writes together…

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;
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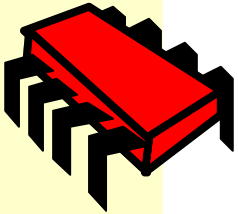
    return temp;
  }
}
```

Make these steps *atomic* (indivisible)

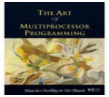
Hardware Solution

```
public class Counter {
  private long value;

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



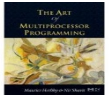
ReadModifyWrite() instruction



An Aside: Java™

```
public class Counter {
  private long value;

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



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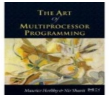
Synchronized block



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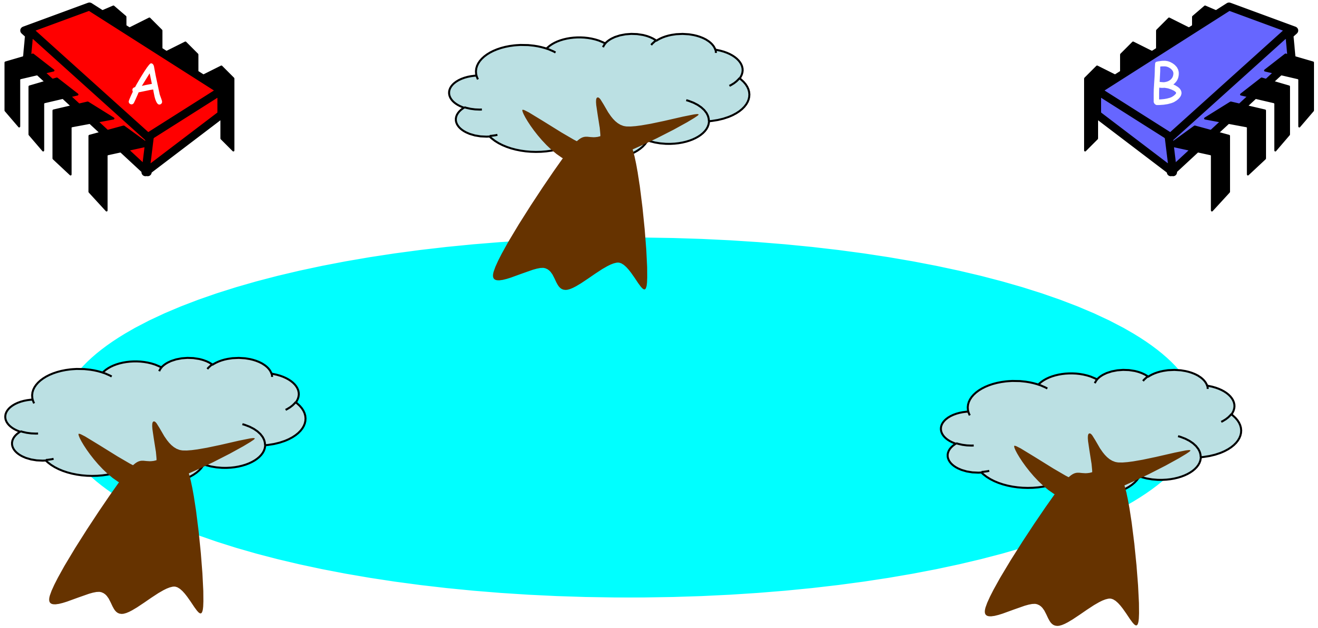
}
```

Mutual Exclusion

Mutual Exclusion or "Alice & Bob share a pond"

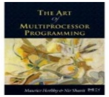


Alice has a pet

Bob has a pet

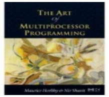
The Problem


A
B
The pets don't
get along


The Art of Multiprocessor Programming

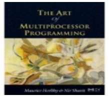
Formalizing the Problem

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



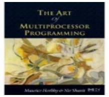
Formalizing our Problem

- 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

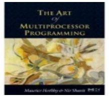
- Threads can’t “see” what other threads are doing
- Explicit communication required for coordination

Cell Phone Protocol

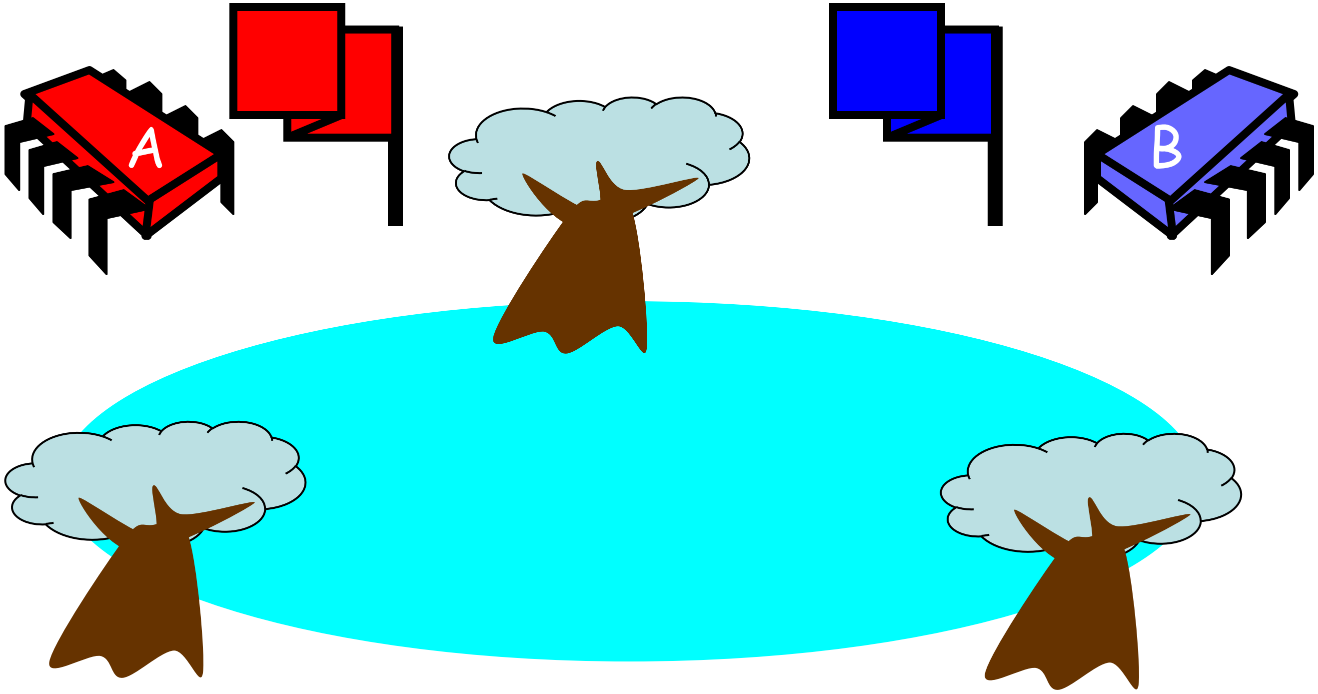
- Idea
  - Bob calls Alice (or vice-versa)
- Gotcha
  - Bob takes shower
  - Alice recharges battery
  - Bob out shopping for pet food …

Interpretation

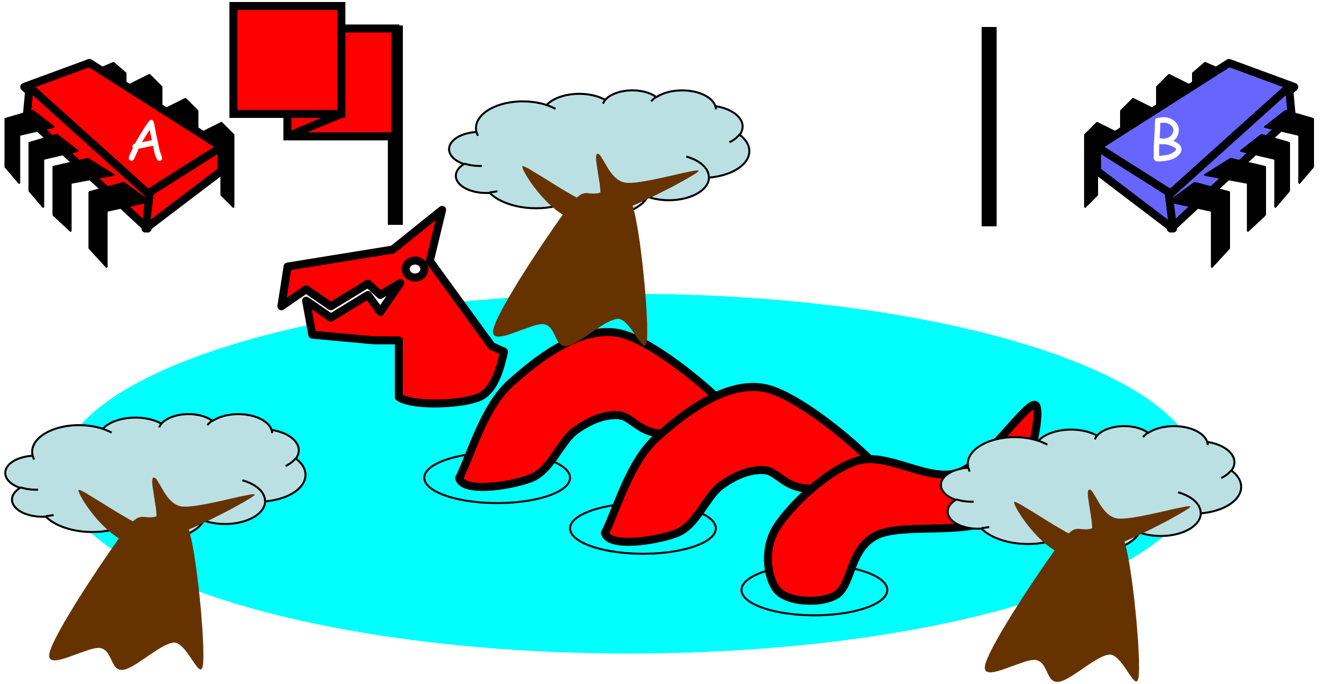
- Message-passing doesn’t work
- Recipient might not be
  - Listening
  - There at all
- Communication must be
  - Persistent (like writing)
  - Not transient (like speaking)

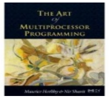


Flag Protocol

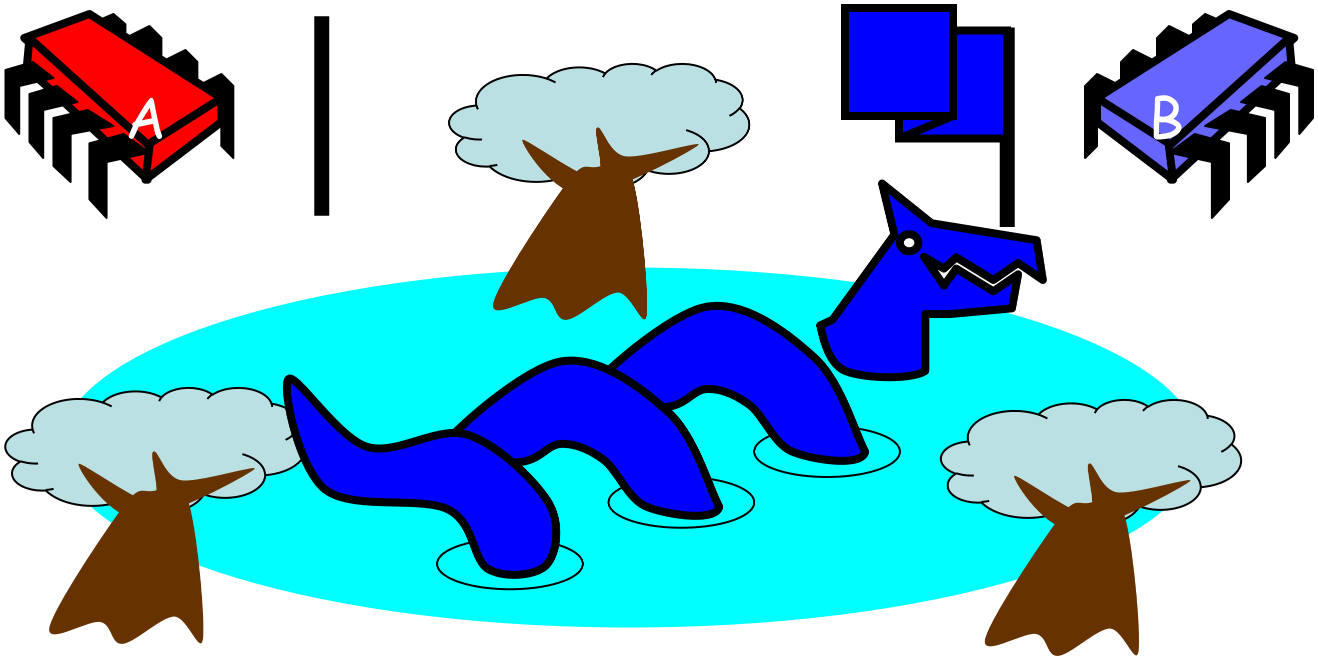


Alice’s Protocol (sort of)





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!

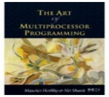
Bob's Protocol (2nd try)

- 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

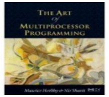


The Flag Principle

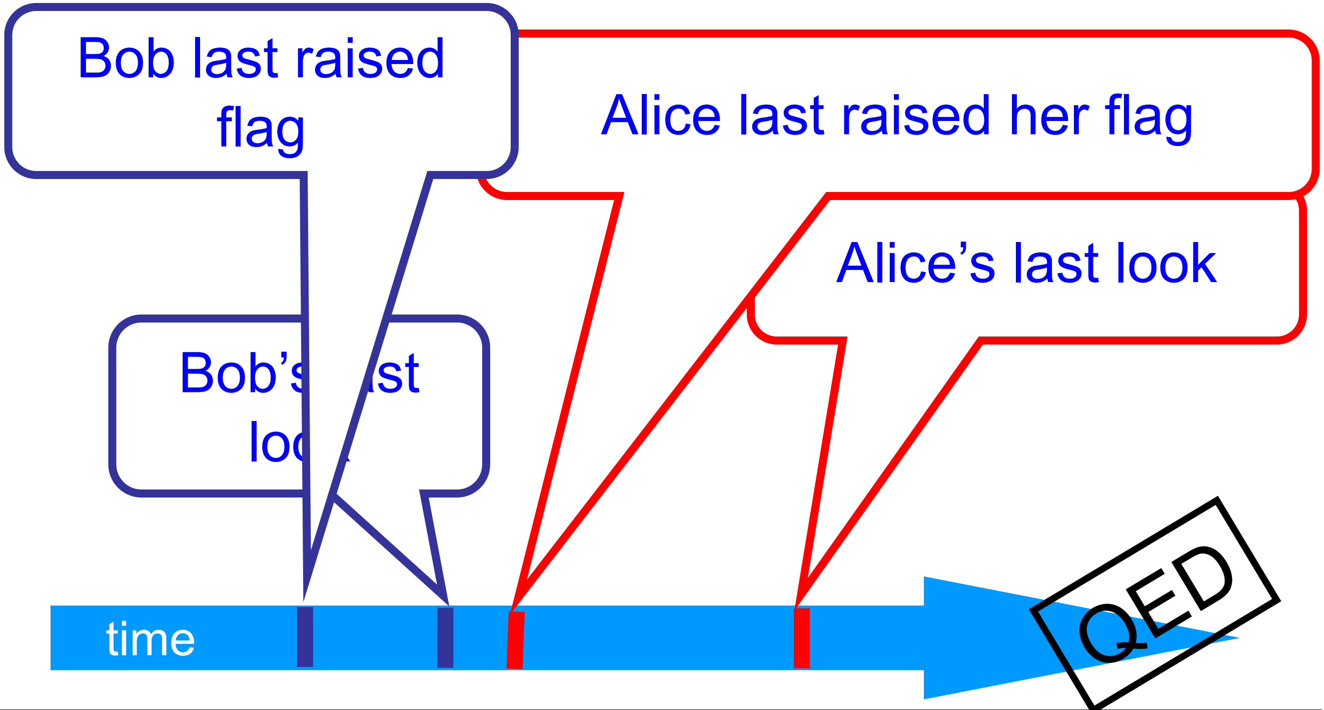
- Raise the flag
- Look at other's flag
- Flag Principle:
  - If each raises and looks, then
  - Last to look must see both flags up

Proof of Mutual Exclusion

- Assume both pets in pond
  - Derive a contradiction
  - By reasoning **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.

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- 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…)

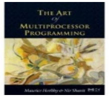
QED

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

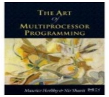
Moral of Story

- 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



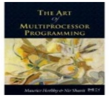
The Fable Continues

- Alice and Bob fall in love & marry



The Fable Continues

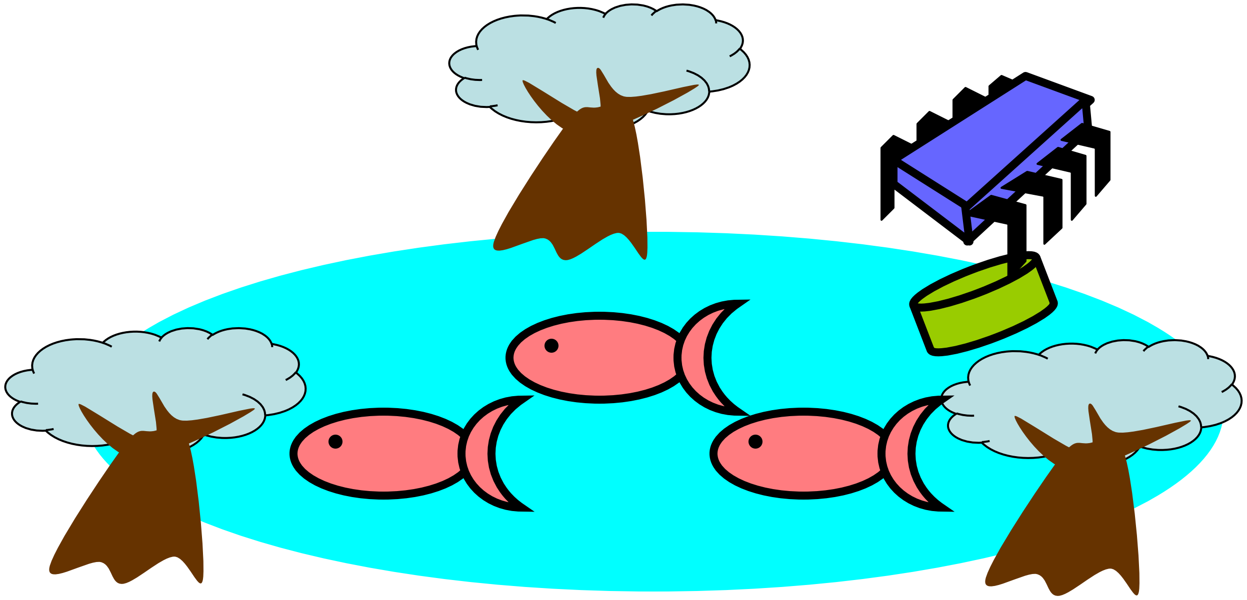
- Alice and Bob fall in love & marry
- Then they fall out of love & divorce
  – She gets the pets
  – He has to feed them



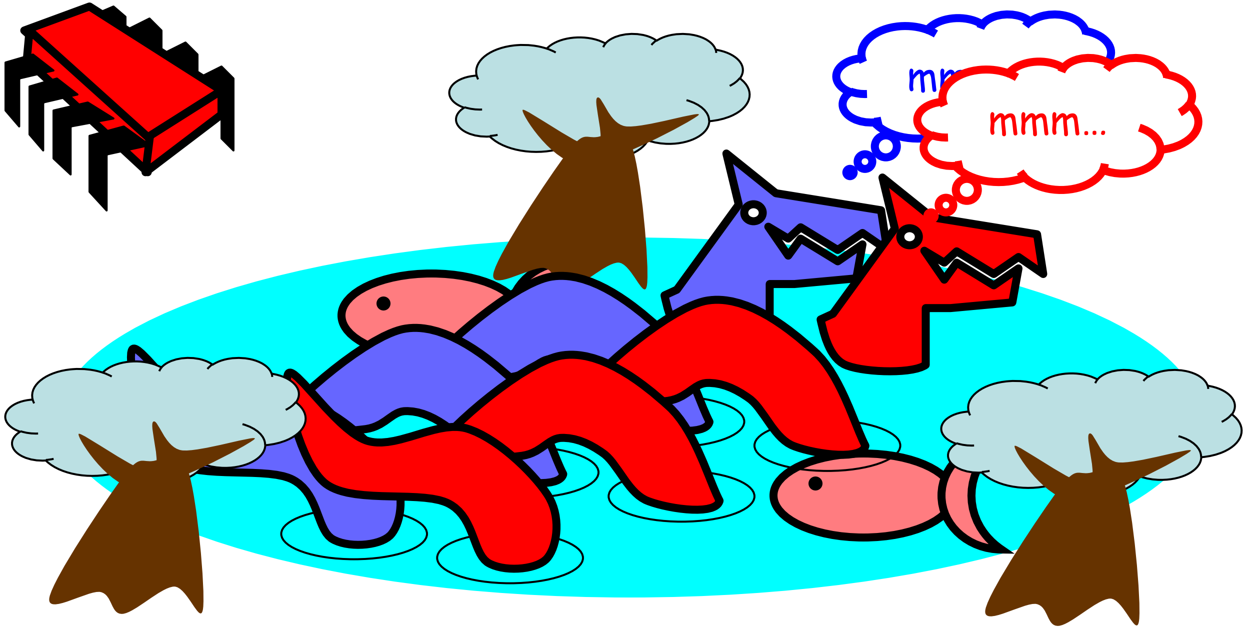
The Fable Continues

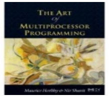
- Alice and Bob fall in love & marry
- Then they fall out of love & divorce
  - She gets the pets
  - He has to feed them
- Leading to a new coordination problem: Producer-Consumer

Bob Puts Food in the Pond



Alice releases her pets to Feed





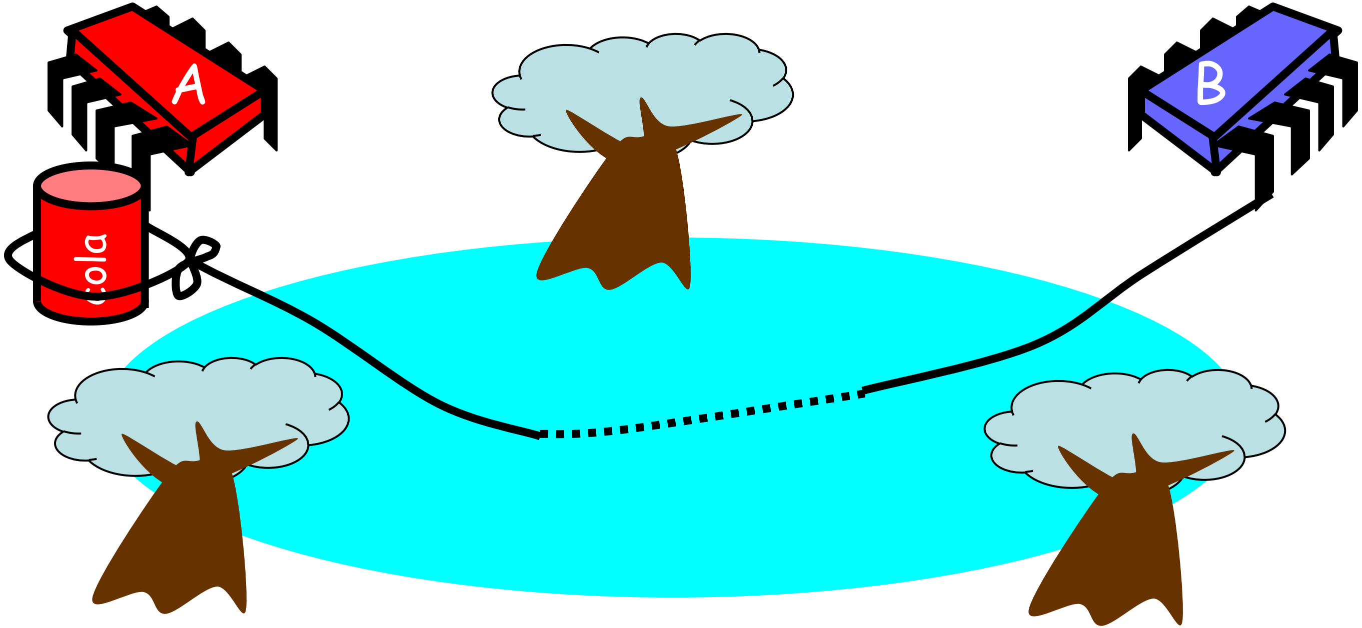
Producer/Consumer

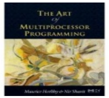
- Alice and Bob can't meet
  - Each has restraining order on other
  - So he puts food in the pond
  - And later, she releases the pets
- Avoid
  - Releasing pets when there's no food
  - Putting out food if uneaten food remains

Producer/Consumer

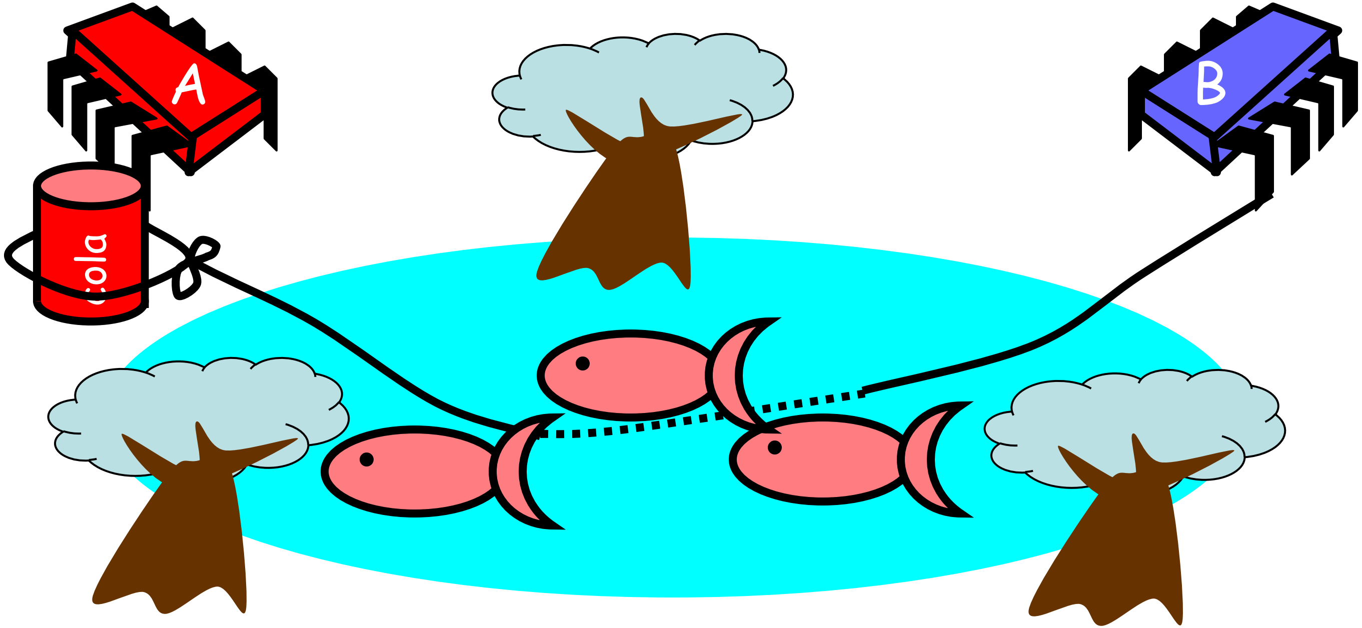
- Need a mechanism so that
  - Bob lets Alice know when food has been put out
  - Alice lets Bob know when to put out more food

Surprise Solution

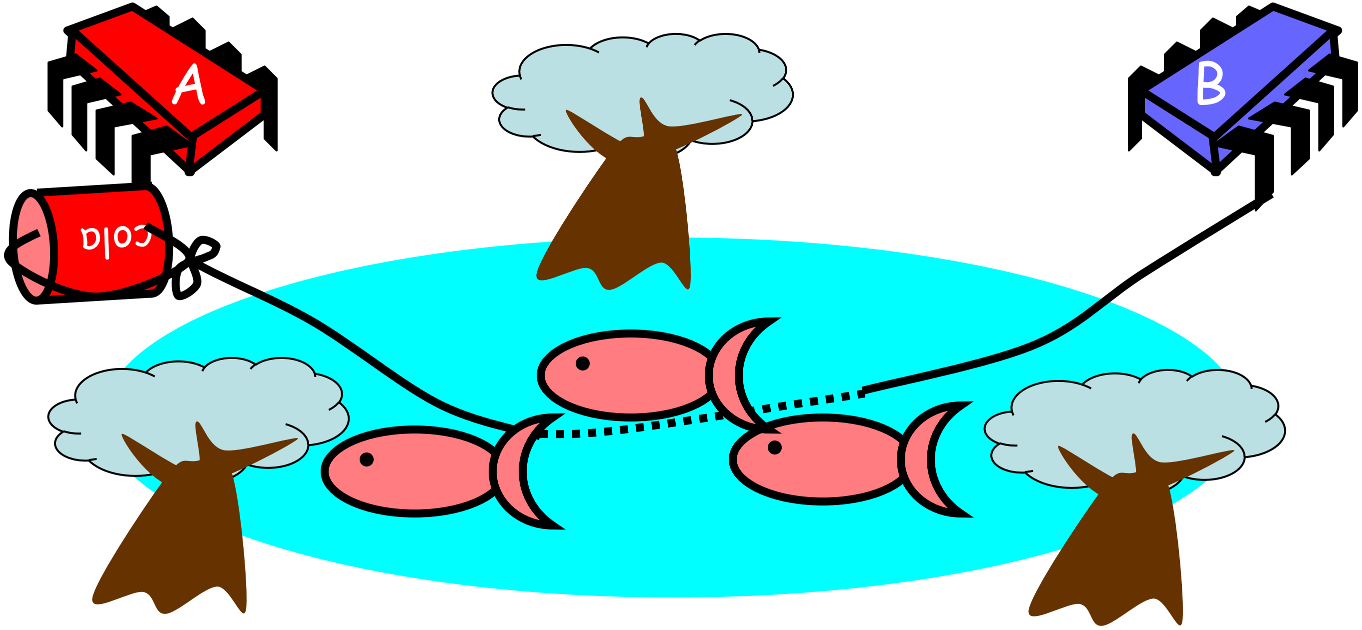


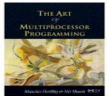


Bob puts food in Pond

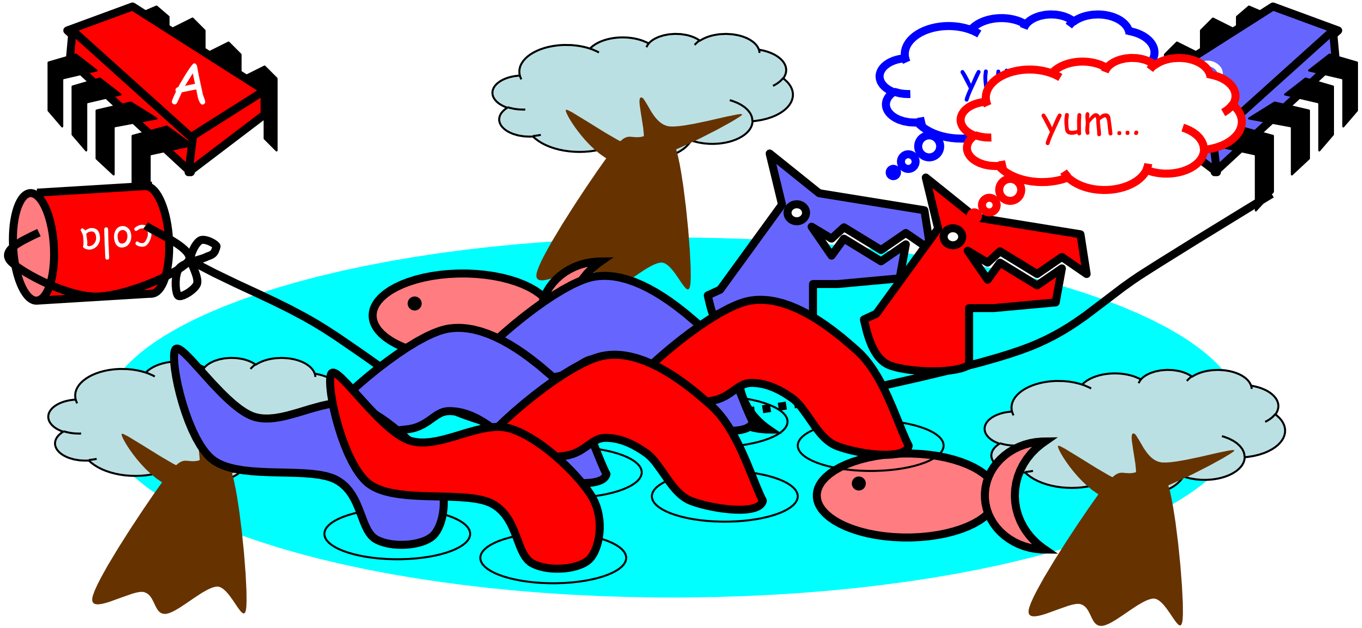


Bob knocks over Can

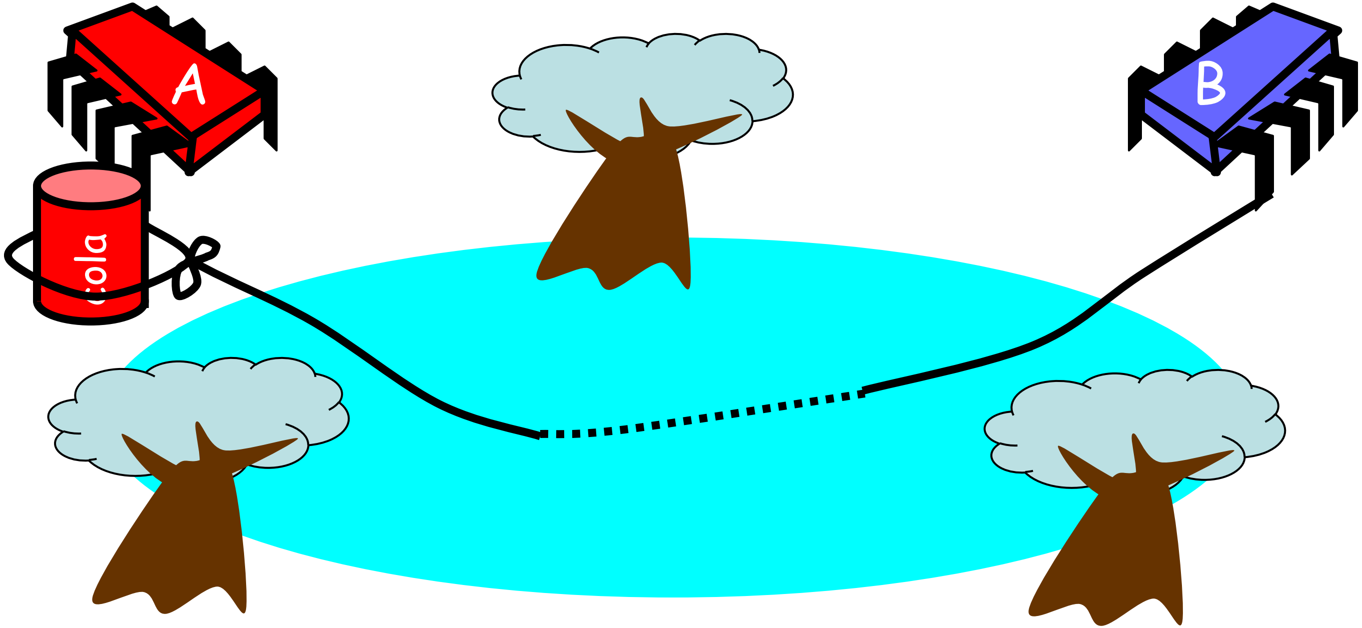


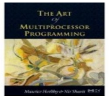


Alice Releases Pets



Alice Resets Can when Pets are Fed





Pseudocode

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

Alice's code

Pseudocode

Alice's code

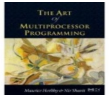
```
while (true) {
   while (can.isUp()){};
   pet.release();
   pet.recapture();
   can.reset();
}
```

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

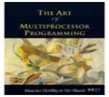
  if Bob always willing to feed, and pets always famished, then pets eat infinitely often.

Correctness

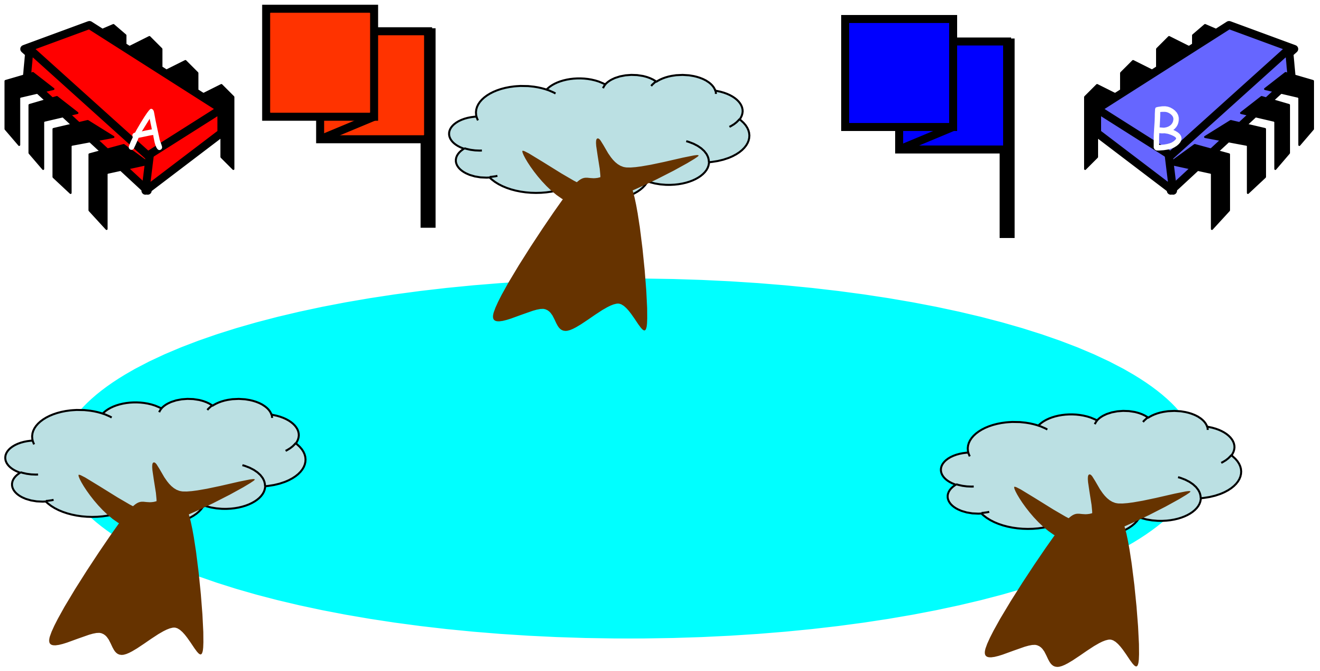
- Mutual Exclusion safety
  – Pets and Bob never together in pond
- No Starvation liveness

  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.

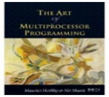


Could Also Solve Using Flags



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

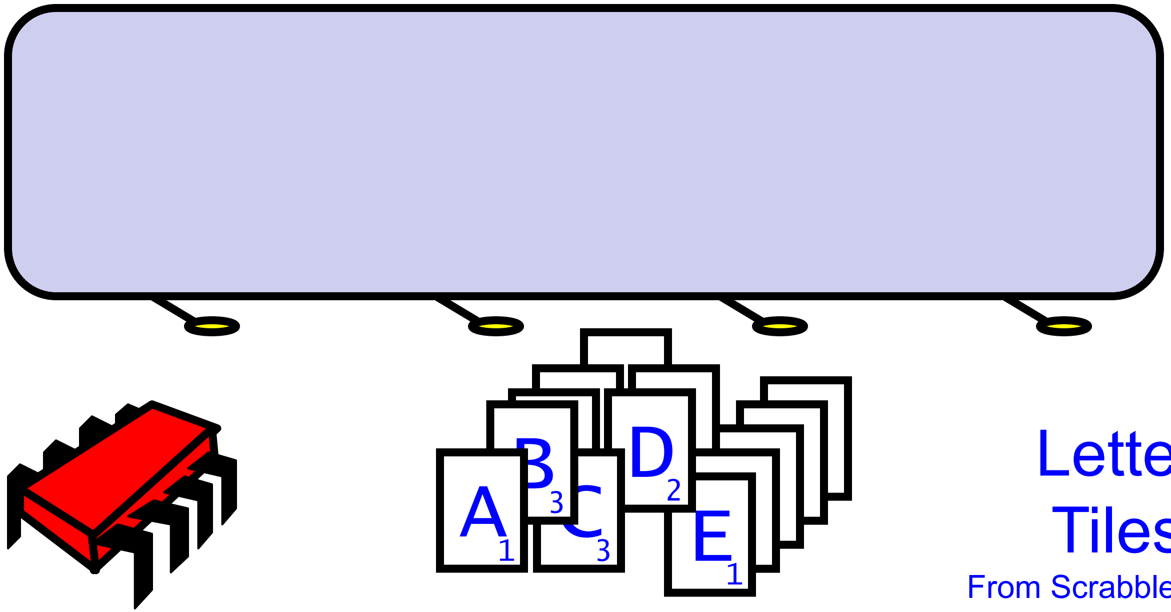
The Fable drags on …

- 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 …

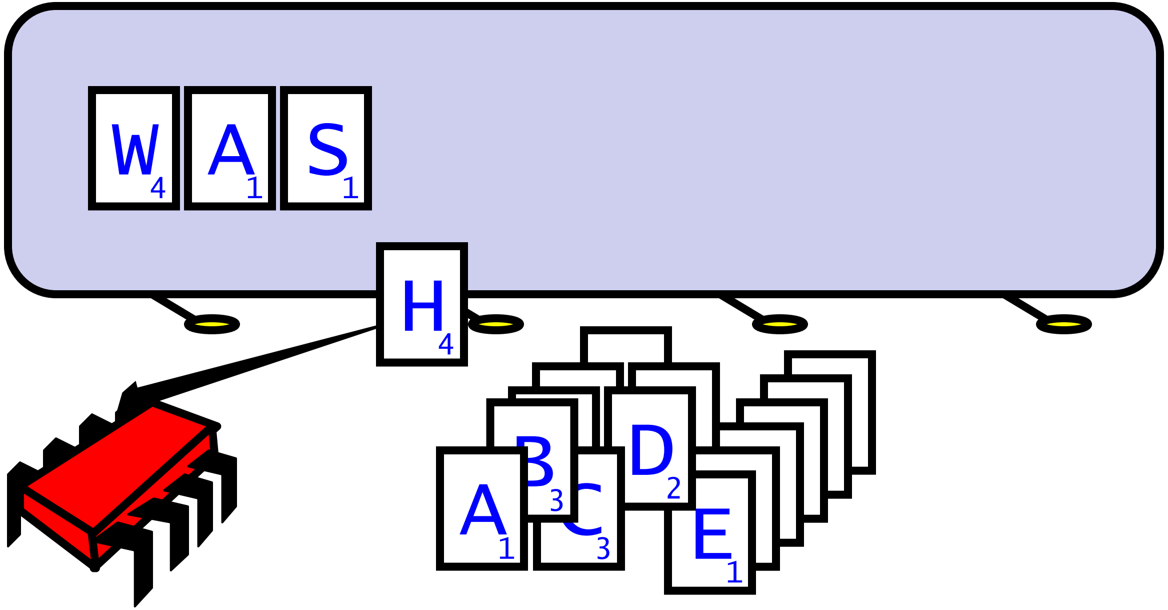
Billboards are Large



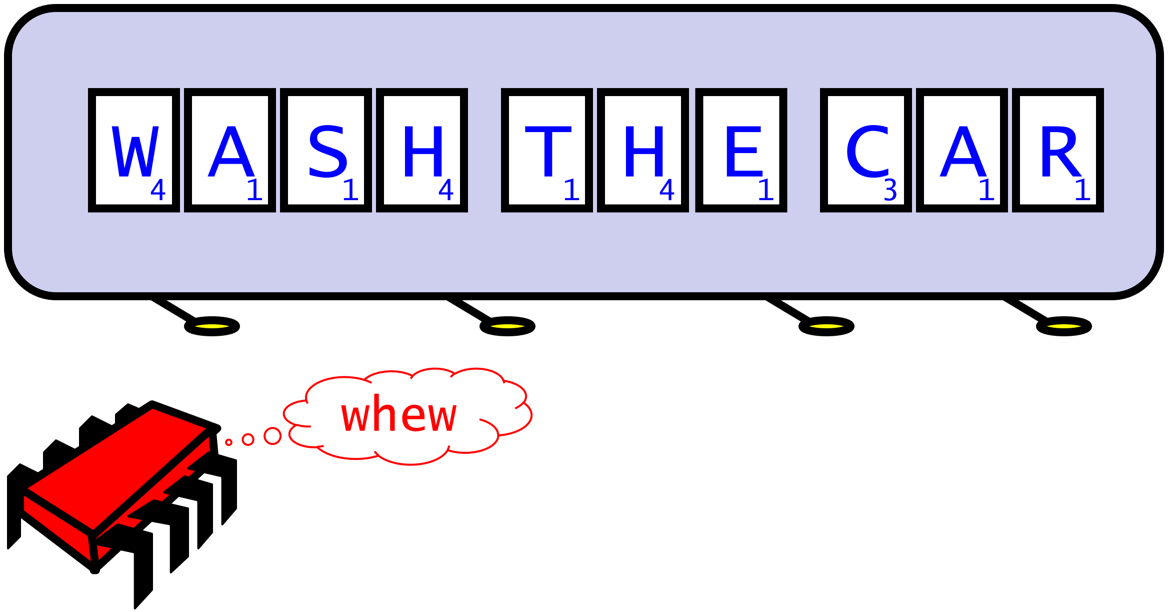
Letter Tiles

From Scrabble™ box

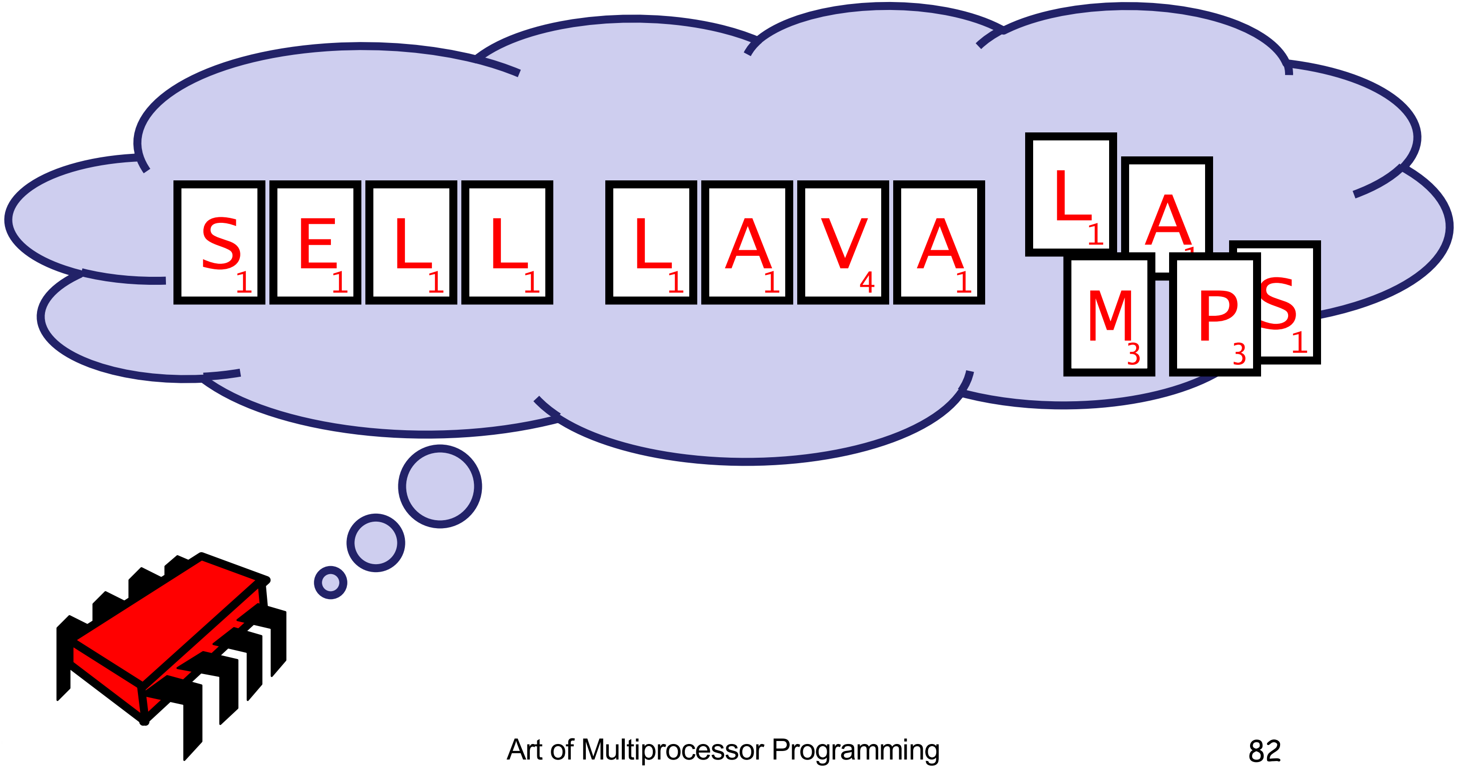
Write One Letter at a Time …

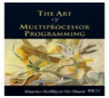


To post a message

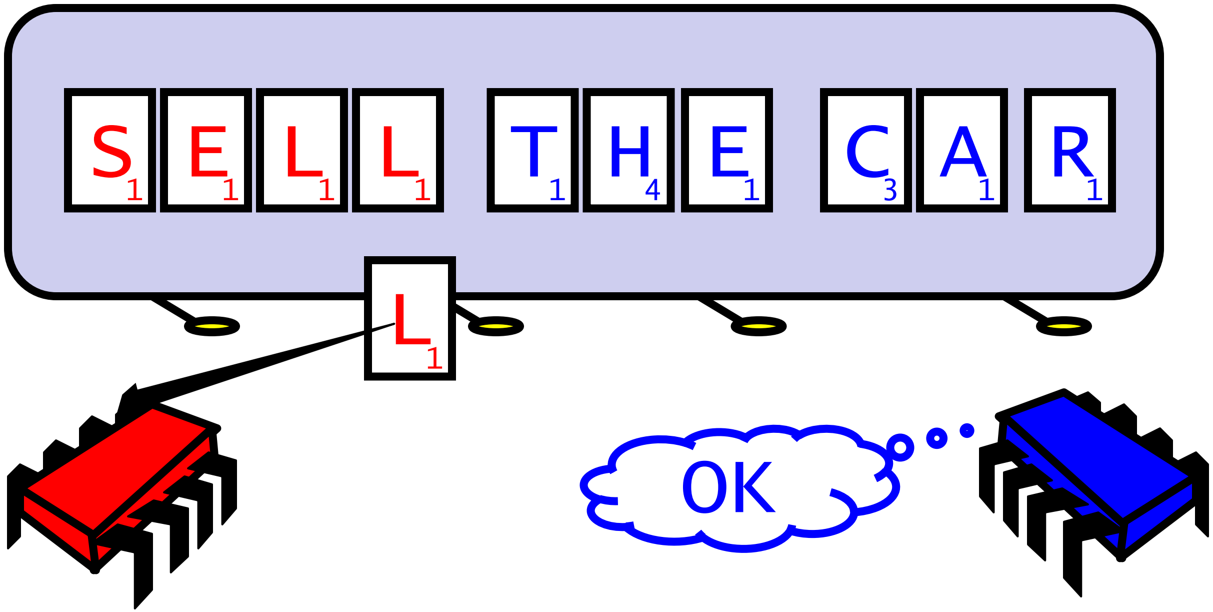


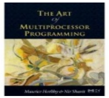
Let's send another message





Uh-Oh





Amdahl's Law

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

Amdahl’s Law

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

Amdahl's Law

Speedup=

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

Parallel fraction

Amdahl's Law

Sequential fraction

Parallel fraction

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

Amdahl's Law

Sequential fraction

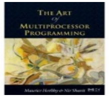
Parallel fraction

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

Number of threads

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?

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

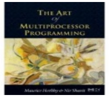
Example

- 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?

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

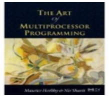
Example

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

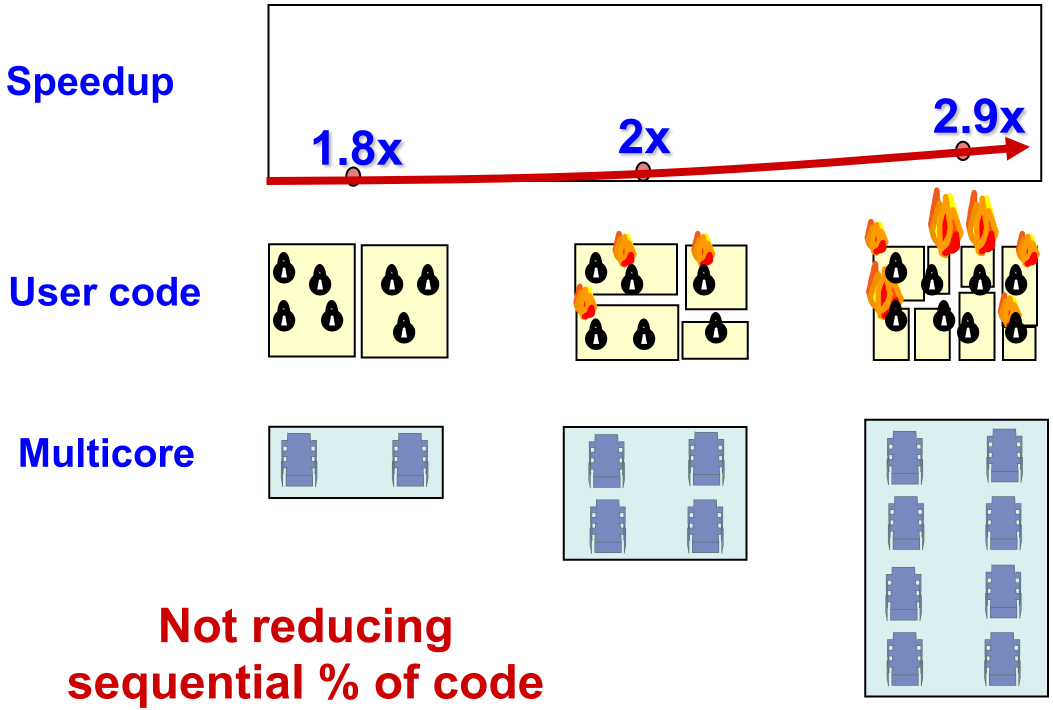
Example

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

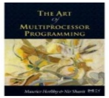
$$\text{Speedup} = 9.17 = \frac{1}{1 - 0.99 + \frac{0.99}{10}}$$



Back to Real-World Multicore Scaling



Not reducing sequential % of code



Why?

Amdahl's Law:

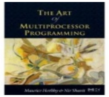
Speedup = 1/(ParallelPart/N + SequentialPart)

Pay for N = 8 cores

SequentialPart = 25%

As num cores grows the effect of 25% becomes more accute

2.3/4, 2.9/8, 3.4/16, 3.7/32….



Shared Data Structures