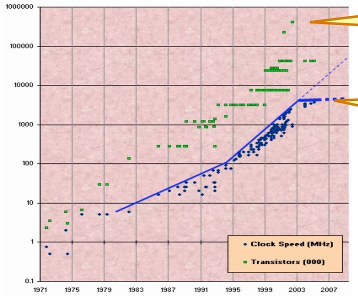
Introduction to Concurrency

Adapted by BCP from lectures
by Maurice Herlihy at Brown

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….

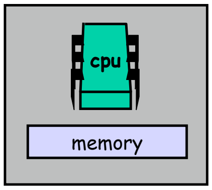
Moore's Law



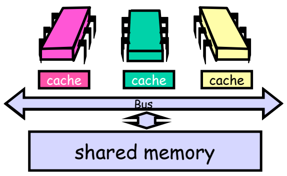
Transistor count still rising

Clock speed flattening sharply

On Your Desktop: The Uniprocessor

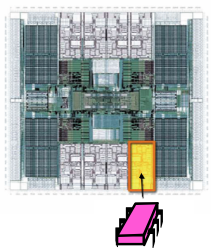


In the Enterprise: The Shared Memory Multiprocessor (SMP)



Your New Desktop: The Multicore processor (CMP)

All on the same chip



Sun T2000 Niagara

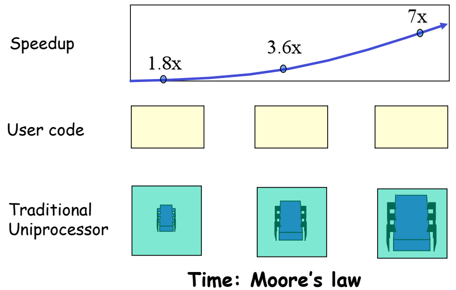
Multicores Are Here

- "Intel ups ante with 4-core chip. New microprocessor, due this year, will be faster, use less electricity..." [San Fran Chronicle]
- "AMD will launch a dual-core version of its Opteron server processor at an event in New York on April 21." [PC World]
- "Sun's Niagara…will have eight cores, each core capable of running 4 threads in parallel, for 32 concurrently running threads. …." [The Inquirer]

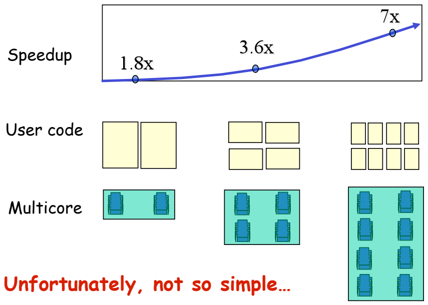
Why do we care?

- Time no longer cures software bloat
  - The "free ride" is over
- When you double the work your program is doing…
  - …you can't just wait 6 months for it to run the same speed again!
  - Your software must somehow exploit twice as much concurrency

Traditional Scaling Process

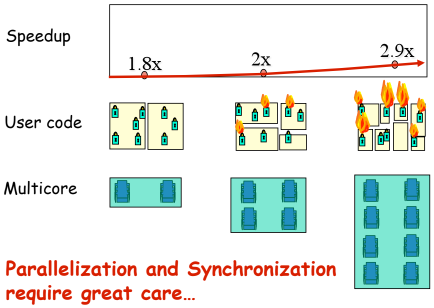


Multicore Scaling Process



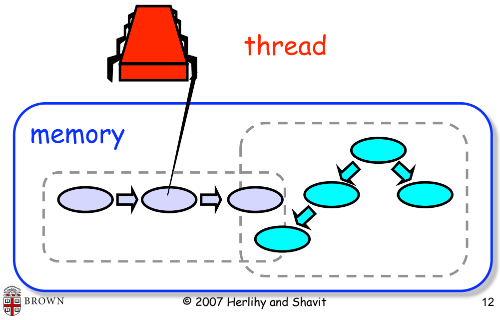
Unfortunately, not so simple…

Real-World Scaling Process

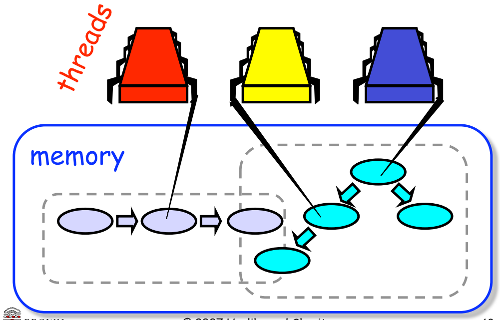


Parallelization and Synchronization require great care…

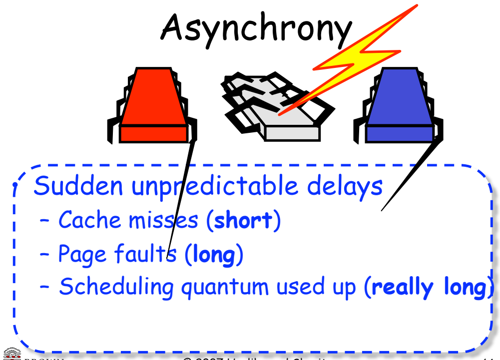
Sequential Computation



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**
- Unpredictable asynchronous delays

Road Map

- Today: background on concurrency
- Monday: semantics of Haskell's basic concurrency primitives (threads/ MVars)
- Wednesday: thread programming
- Following week: Software Transactional Memory (STM)

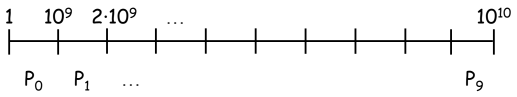
Concurrency Jargon

- 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



Idea:

- 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);
  }
}
```

Note Herlihy's slightly awkward pseudocode notation for Haskell

Issues

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

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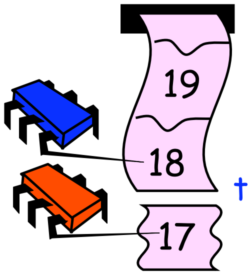
rejected

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);
  }
}
```

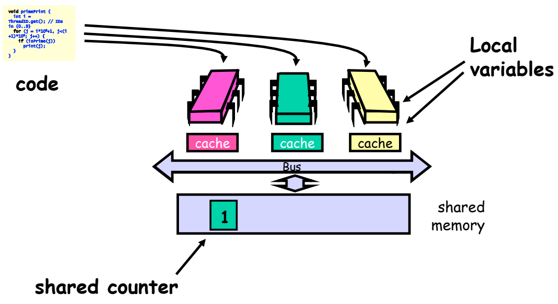
Procedure for Thread i

```
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

Where Things Reside



Procedure for Thread i

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  long j = 0;
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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();
    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 (i.e., not "thread safe")

What It Means

```
public class Counter {
  private long value;

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

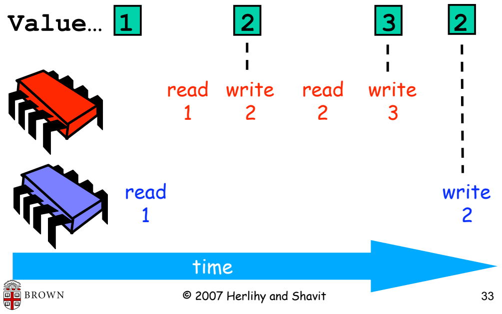
What It Means

```
public class Counter {
  private long value;

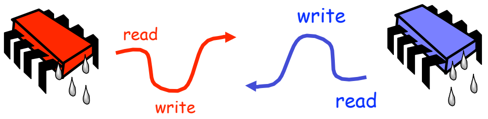
  public long getAndIncrement() {
    return value++;
  }
}
```

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

Challenge

```
public class Counter {
  private long value;

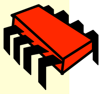
  public long getAndIncrement() {
    temp  = value;
    value = temp + 1;
    return temp;
  }
}
```

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;
  }
}
```

Mutual Exclusion

An Aside: Java™

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public class Counter {
  private long value;

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  }
}
```
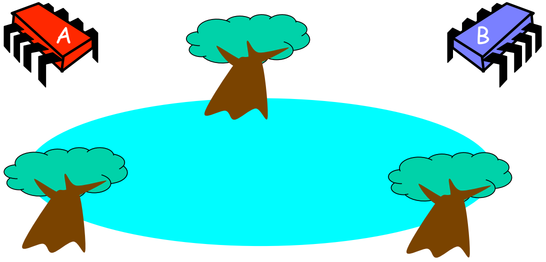
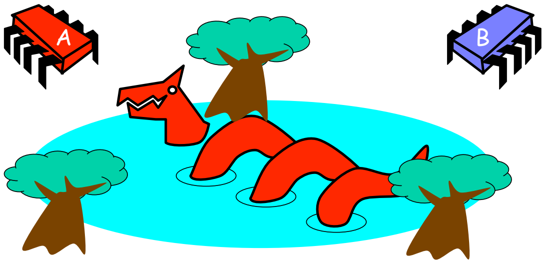

Haskell uses slightly different primitives to achieve the same effect

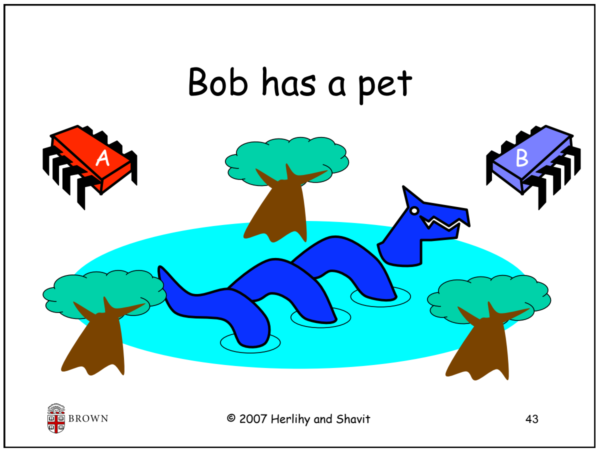
Synchronized block

Mutual Exclusion, or "Alice & Bob share a pond"

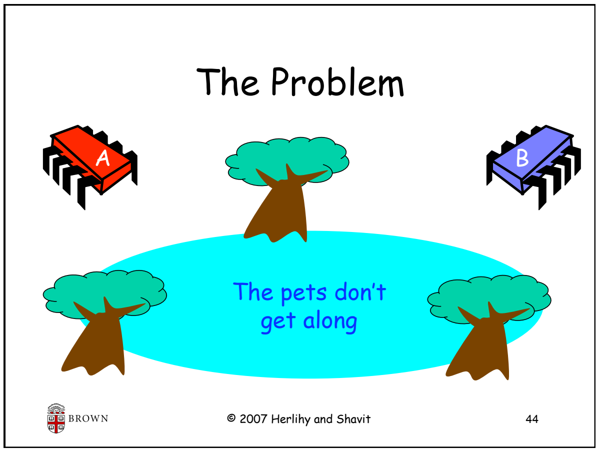


Alice has a pet





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, see if it is empty, and release pet if so
- Gotcha
  - Both look at the same instant
  - Both release pets
  - Bad thing happens in pond

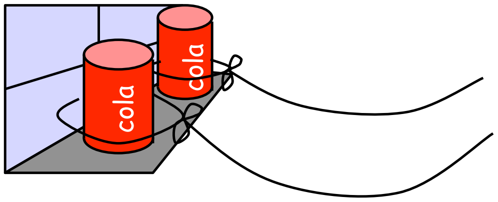
Telephone Protocol

- Idea
  - Bob calls Alice (or vice-versa)
- Gotcha
  - Alice in shower when Bob calls
  - Bob recharging phone battery when Alice calls
  - Alice out shopping for pet food when Bob calls…

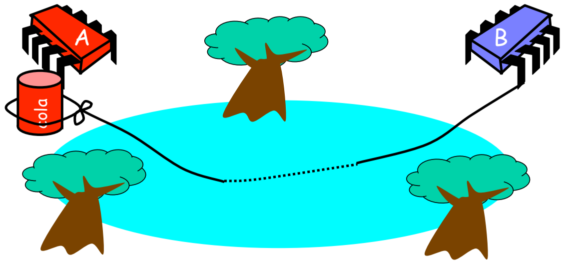
Patient Telephone Protocol

- Idea
  - Bob calls Alice (or vice-versa) and lets phone ring until Alice answers
- Gotcha
  - Alice goes on vacation for a month…
- Lesson
  - Need to be able to leave **persistent** messages (like writing, not speaking)

Can Protocol



Bob conveys a bit



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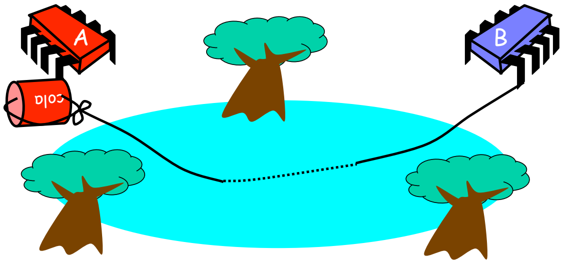
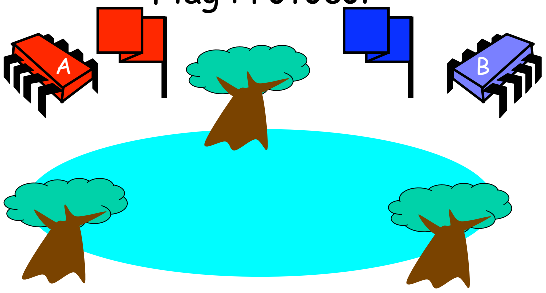
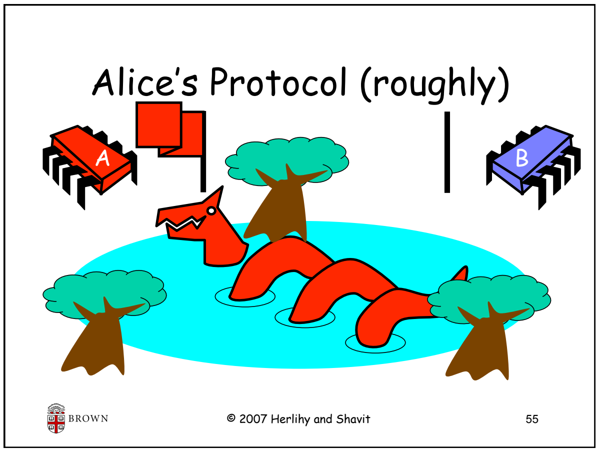


Can Protocol

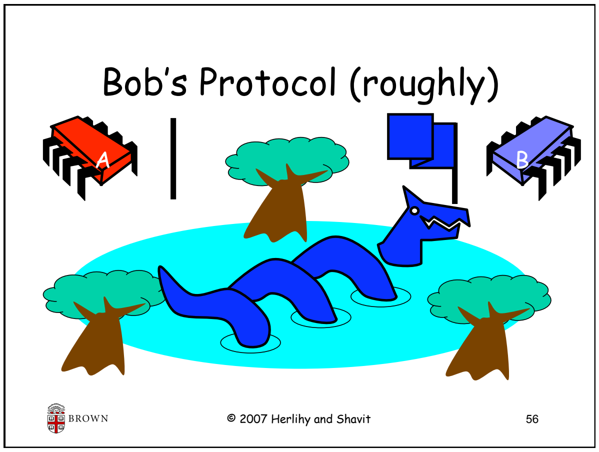
- Idea
  - Cans on Alice's windowsill
  - Strings lead to Bob's house
  - Bob pulls strings, knocks over cans
- Gotcha
  - Cans cannot be reused
  - Bob runs out of cans

Flag Protocol





Alice's Protocol (roughly)



Bob's Protocol (roughly)

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!

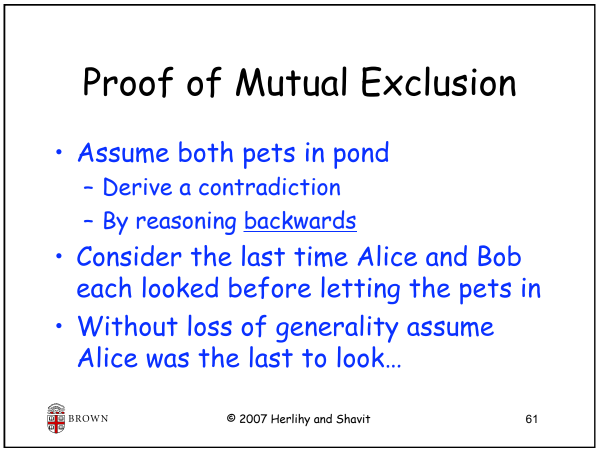
Bob's Protocol (2nd try)

- 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 defers to Alice

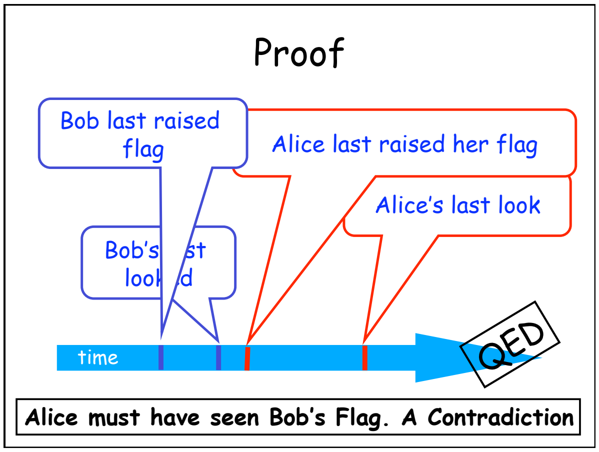
The Flag Principle

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



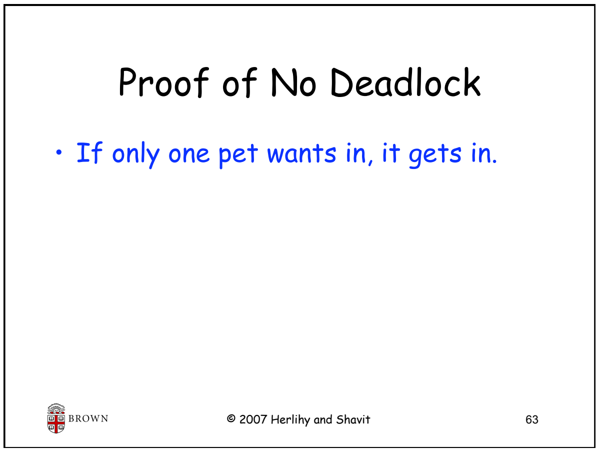
Proof of Mutual Exclusion

- 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…



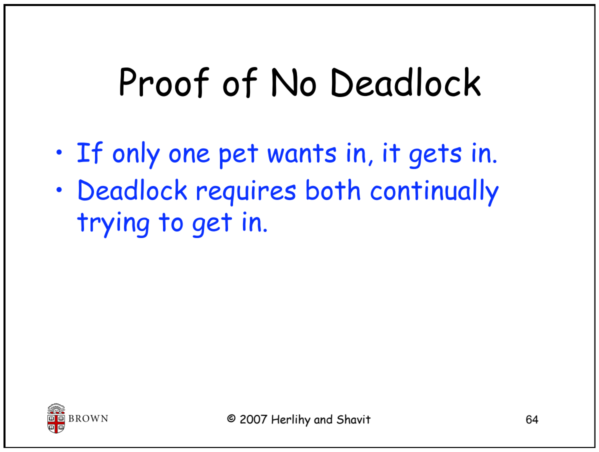
Proof

Alice must have seen Bob's Flag. A Contradiction



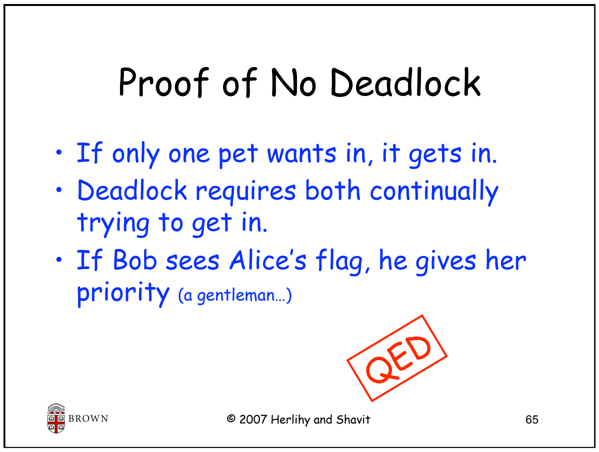
Proof of No Deadlock

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



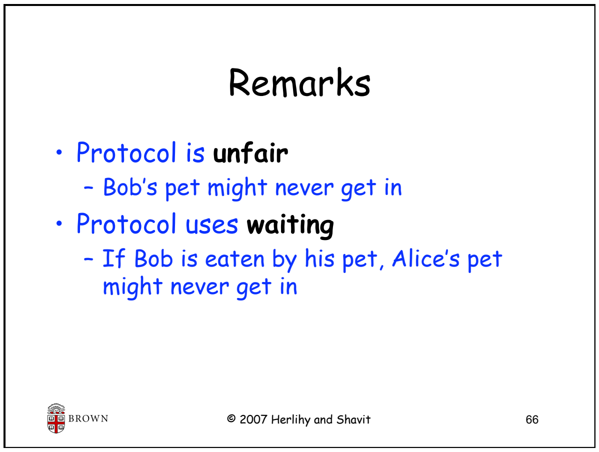
Proof of No Deadlock

- 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 gives her priority (a gentleman…)



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

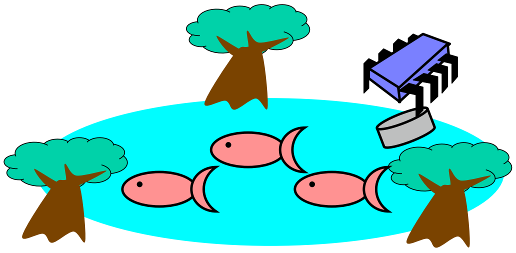
The Fable Continues

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

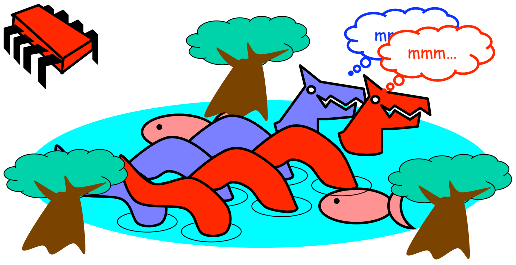
The Fable Continues

- 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



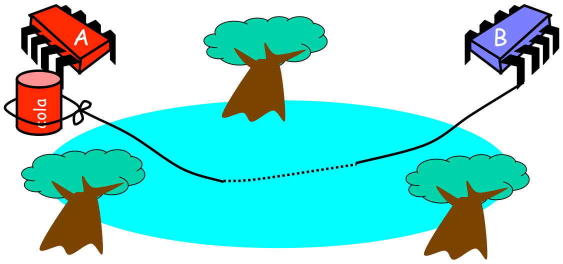
Producer/Consumer

- 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

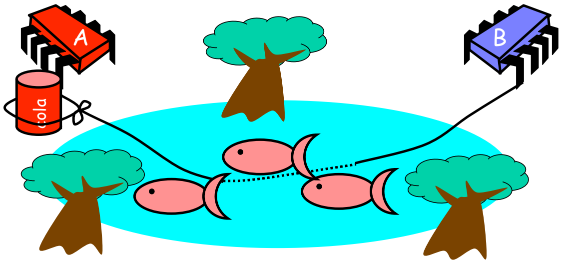
Producer/Consumer

- 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

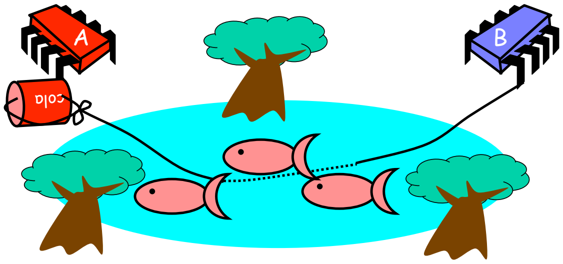
Surprise Solution



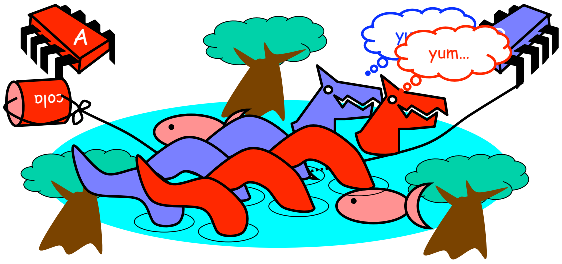
Bob puts food in Pond



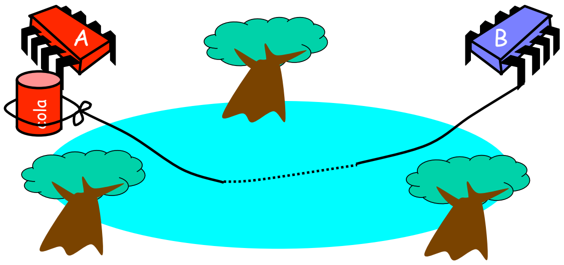
Bob knocks over Can



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

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

Alice's code

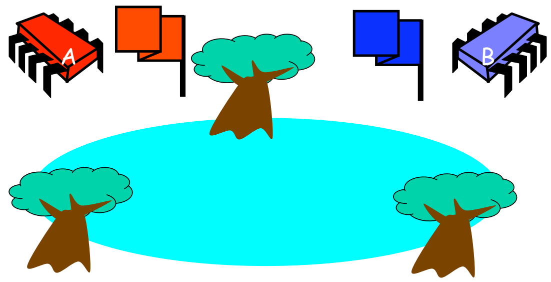
Bob's code

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

Correctness

- Mutual Exclusion — 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
  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 & unpredictable

The Fable drags on …

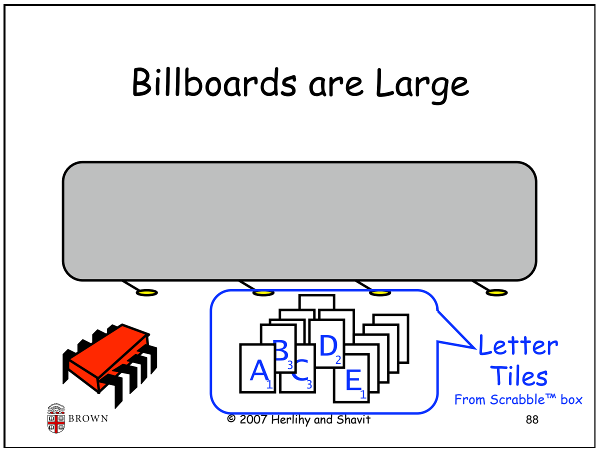
- Bob and Alice still have issues

The Fable drags on …

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

The Fable drags on …

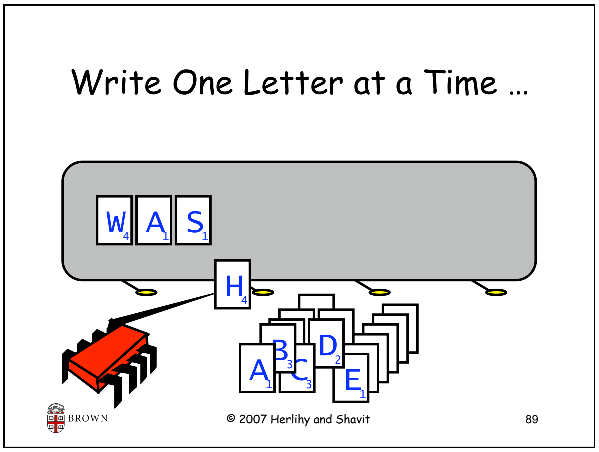
- Bob and Alice still have issues
- So they need to communicate
- So they agree to use billboards …



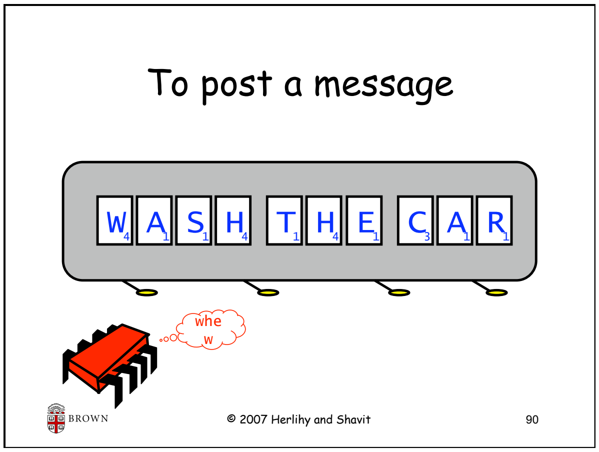
Billboards are Large

Letter Tiles

From Scrabble™ box

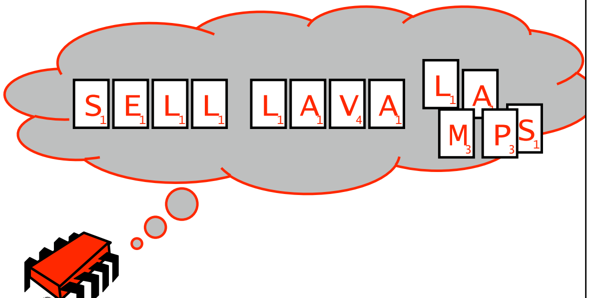


Write One Letter at a Time …

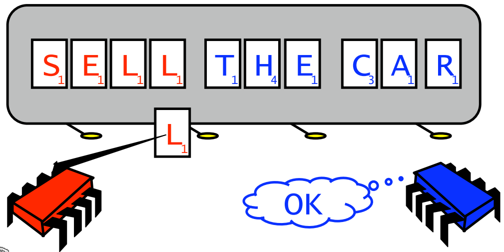


To post a message

Let’s send another mesage



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?

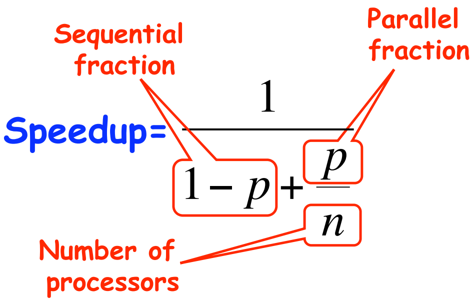
- We want as much of the code as possible to execute concurrently (in parallel)
- A larger sequential part implies reduced performance
- Amdahl’s law: this relation is not linear…

Amdahl’s Law

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

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

Amdahl's Law



Sequential fraction

Parallel fraction

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

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?

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

The Moral

- The small % of a program that is hard to parallelize may have a large impact on overall speedup.

☹