Introduction to Concurrency

CS 475, Fall 2019

Concurrent & Distributed Systems

GEORGE MASON UNIVERSITY

With material from Herlihy & Shavit, Art of Multiprocessor Programming

Today

- Distributed & Concurrent Systems: high level overview and key concepts

- Relevant links:
  - Syllabus: https://www.jonbell.net/gmu-cs-475-fall-2019/
  - Piazza: https://piazza.com/class/jzefzvsggtah2

Course Topics

- This course will teach you **how** and **why** to build distributed systems
- Distributed System is “a collection of independent computers that appears to its users as a single coherent system”
- This course will give you theoretical knowledge of the tradeoffs that you’ll face when building distributed systems

Course Staff

- Prof Jonathan Bell (me)
  - Office hour: ENGR 4422 Mon & Weds 10:15-11:00 am or by appointment
  - Areas of research: Software Engineering, Program Analysis, Software Systems

Two hobbies: cycling, ice cream

Course Staff

UTA: Isaiah King

GTA: Hamza Mughal

- Office Hours: TBA
- Please, **no emails** to instructor or TAs about the class: use Piazza

Grading

- 55% Homework
  - 4 assignments + final project, ~2 weeks to do each, all done individually
  - Your code will be autograded; you can resubmit and view your score
  - Also graded by hand for some non-functional issues
- 10% Checkpoint quizes
  - Pass/fail (Pass if you are in class and submit a quiz, fail if you don't)
  - Use laptop or phone to complete the quiz in class (please write your name and answers on a piece of paper and bring to me after class if you lost/broke/etc your smart phone or laptop)
- 15% Midterm Exam, 20% Final Exam


CAUTION
HEAVY PROGRAMMING
NEXT 13 WEEKS

But, seriously

- They may be unlike any assignments you have done so far
- By the end of the semester, you will have built a sizable and complicated, real, usable distributed system, using standard technologies like RMI and ZooKeeper
- Assignments are mostly out for 2 weeks: it will take 2 weeks to do the assignment
  - If you start the day before, there will not be enough hours in the day to complete the assignment
- Assignments are graded on functionality, with clear cut-offs for partial functionality. Focus on building incremental functionality (some, but very few points for trying to get everything and succeeding at nothing)
- First assignment out after Labor Day (woo)

Policies

- My promises to you:
  - Quiz results will be available instananeously in class; we will discuss quiz in real time
  - Homework will be graded within 3 days of submission
  - Exams will be graded within a week

Policies

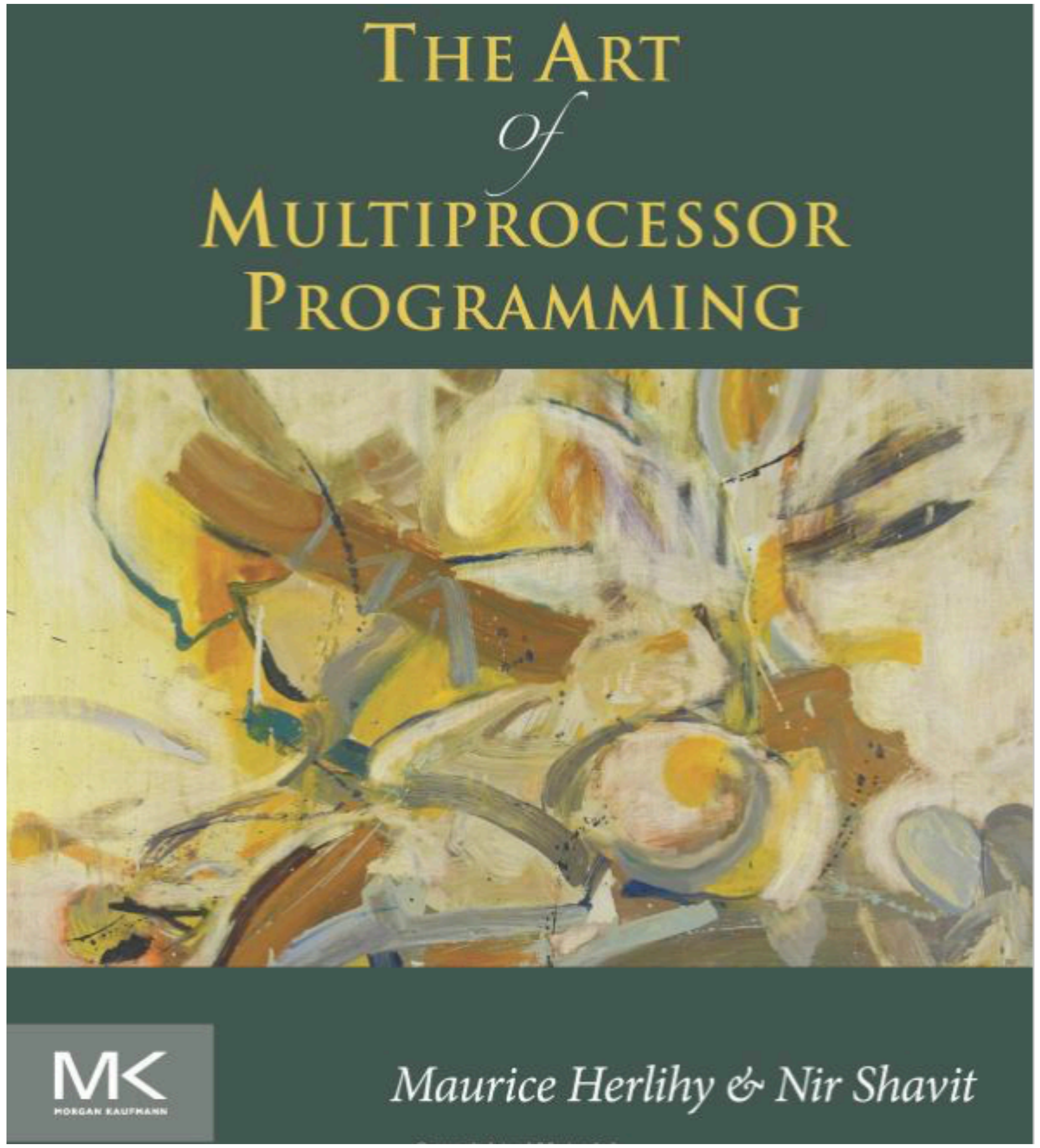
- Lateness on homework:
  - 10% penalty if submitted UP TO 24 hours after deadline
  - No assignments will be accepted more than 24 hours late
  - Out of fairness: **no exceptions**
- Attendance & Quizzes:
  - You can miss up to 3 with no penalty
  - Again, out of fairness: **no exceptions** beyond this

Honor Code

- Refresh yourself of the department honor code
- Homeworks are 100% individual
  - Discussing assignments at high level: ok, sharing code: not ok
  - If in doubt, ask the instructor
  - If you copy code, we WILL notice (see some of my recent research results in “code relatives”)
- Online activities/checkpoints/quizzes must be completed by you, and while in class
  - Nobody leaves the room until all responses are accounted

Readings

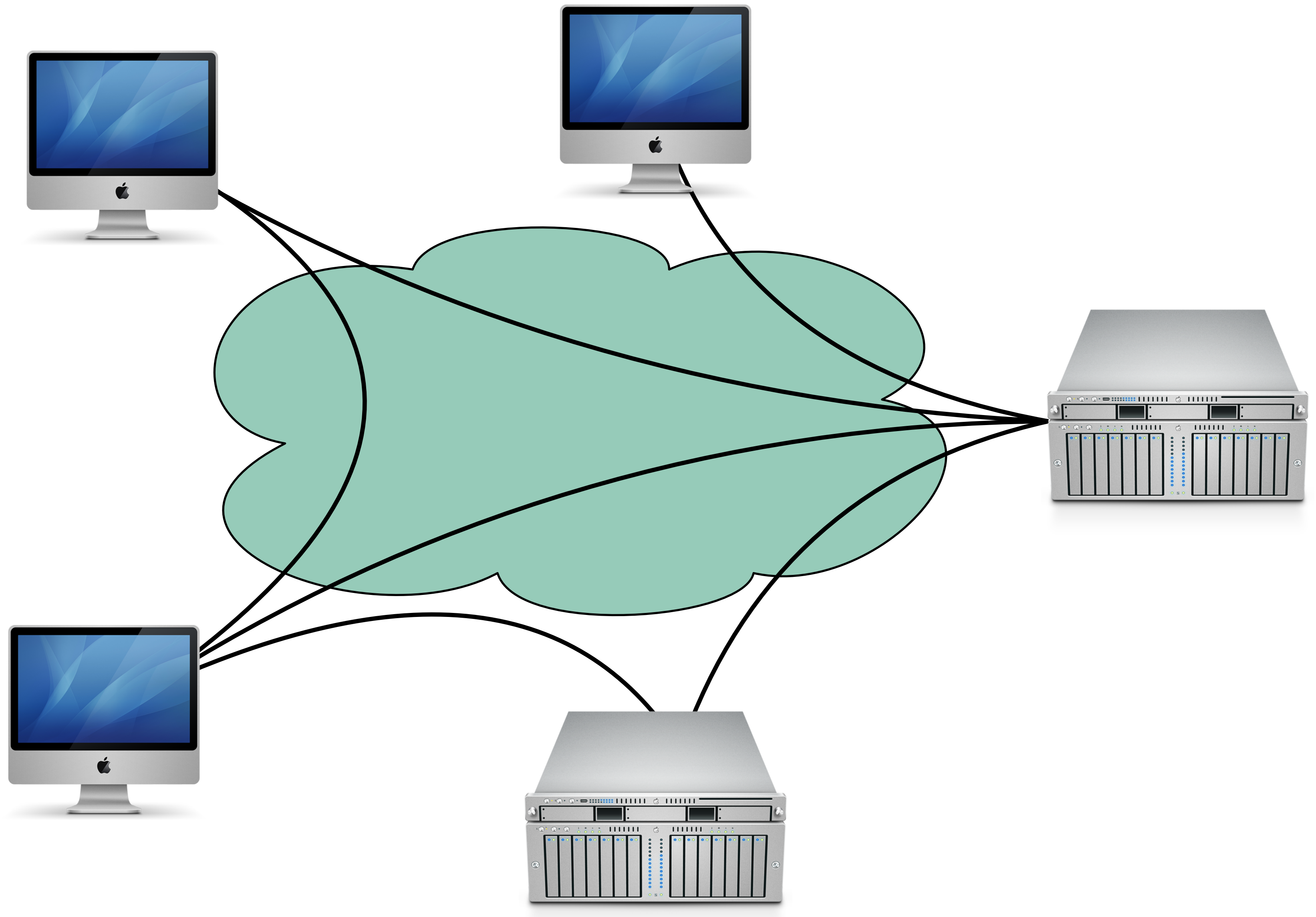
- This textbook is truly great, please get it
  - The Art of Multiprocessor Programming, Herlihy and Shavit
- Also recommended as a reference (free): Distributed Systems 3rd Edition (van Steen and Tanenbaum) https://www.distributed-systems.net/index.php/books/distributed-systems-3rd-edition-2017/



Course Topics

How do I run multiple things at once on my computer?

Concurrency, first half of course



How do I run a big task across many computers?

Distributed Systems, second half of course

Layers

- From hardware
- To OS
- To programming languages
- To networks
- To libraries and middleware
- To developers

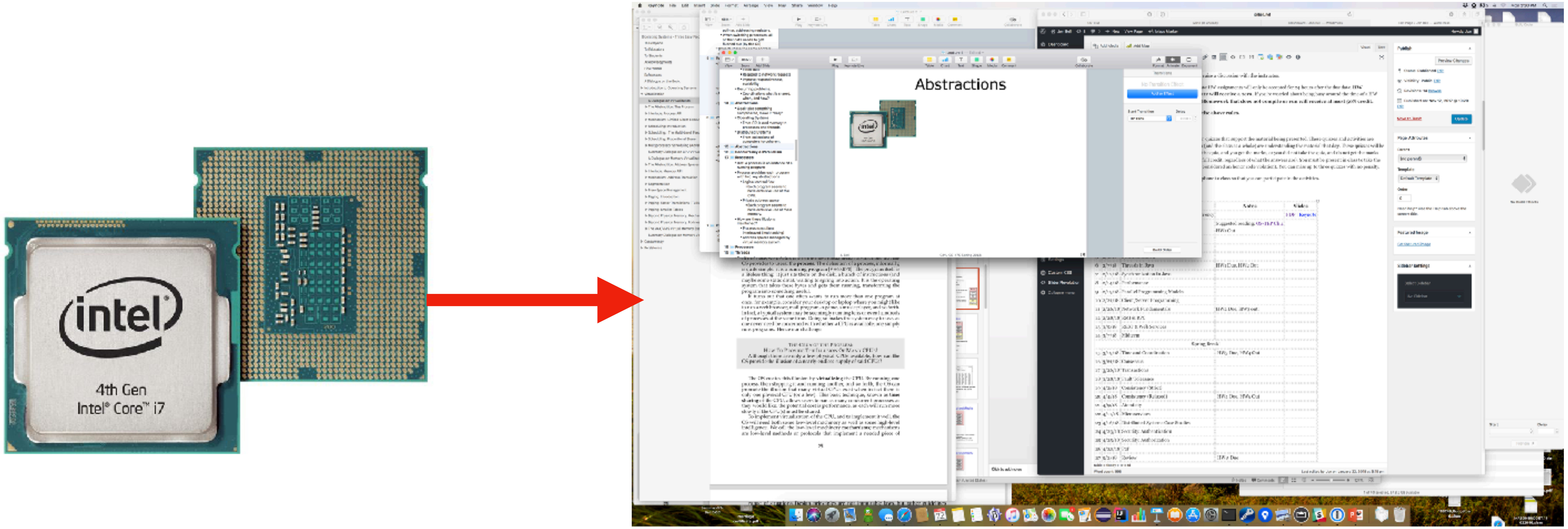
Concurrency

- Goal: do multiple things, at once, coordinated, on one computer
  - Update UI
  - Fetch data
  - Respond to network requests
  - Improve responsiveness, scalability
- Recurring problems:
  - Coordination: what is shared, when, and how?

Abstractions

- Goal: take something complicated, make it “easy”
- Operating Systems
  - From CPUs and memory to processes and threads
- Distributed Systems
  - From collections of computers to coherent applications

Abstractions



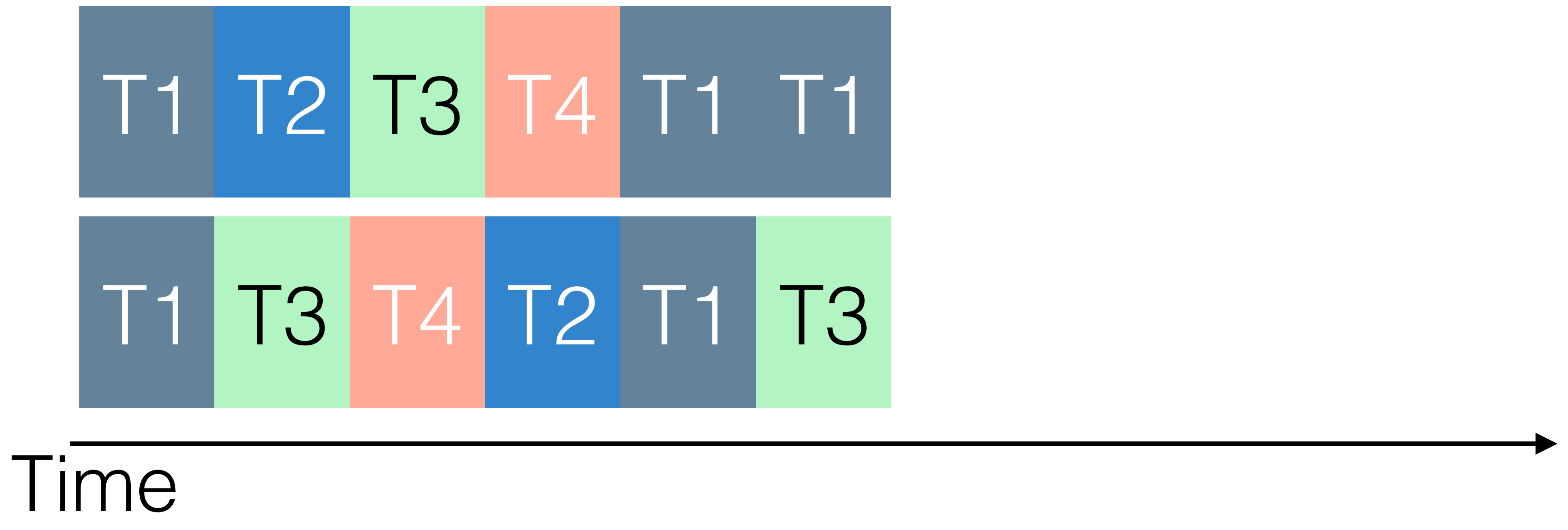
What are the abstractions that sit between the CPU and my multitasking operating system?

Concurrency & Parallelism

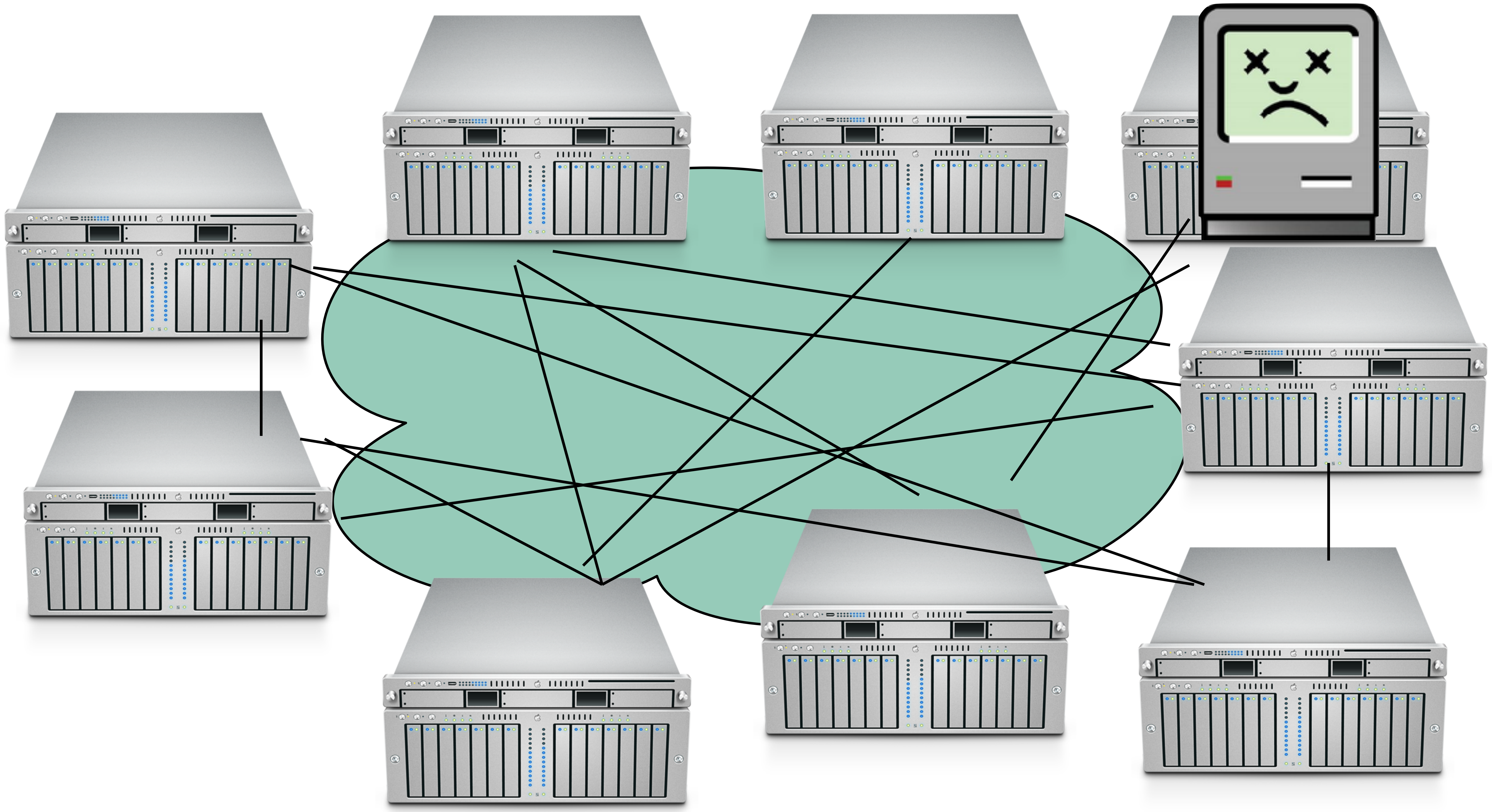
4 different things: T1 T2 T3 T4

Concurrency:
(1 processor)

Parallelism:
(2 processors)



More Abstractions



More machines, more problems

- Say there's a 1% chance of having some hardware failure occur to a machine (power supply burns out, hard disk crashes, etc)
- Now I have 10 machines
  - Probability(at least one fails) = 1 - Probability(no machine fails) = $1-(1-.01)^{10}$ = 10%
- 100 machines -> 63%
- 200 machines -> 87%
- So obviously just adding more machines doesn't solve fault tolerance

How much to hide?

- Completely abstracting all of the inner workings of a system is may be too much:
  - Communication latencies can't be hidden (pesky speed of light!)
  - Completely hiding failures is **impossible** (we will prove this later in the semester)
    - Can never distinguish a slow computer from one that is crashed
- Hiding more adds performance costs

Road Map

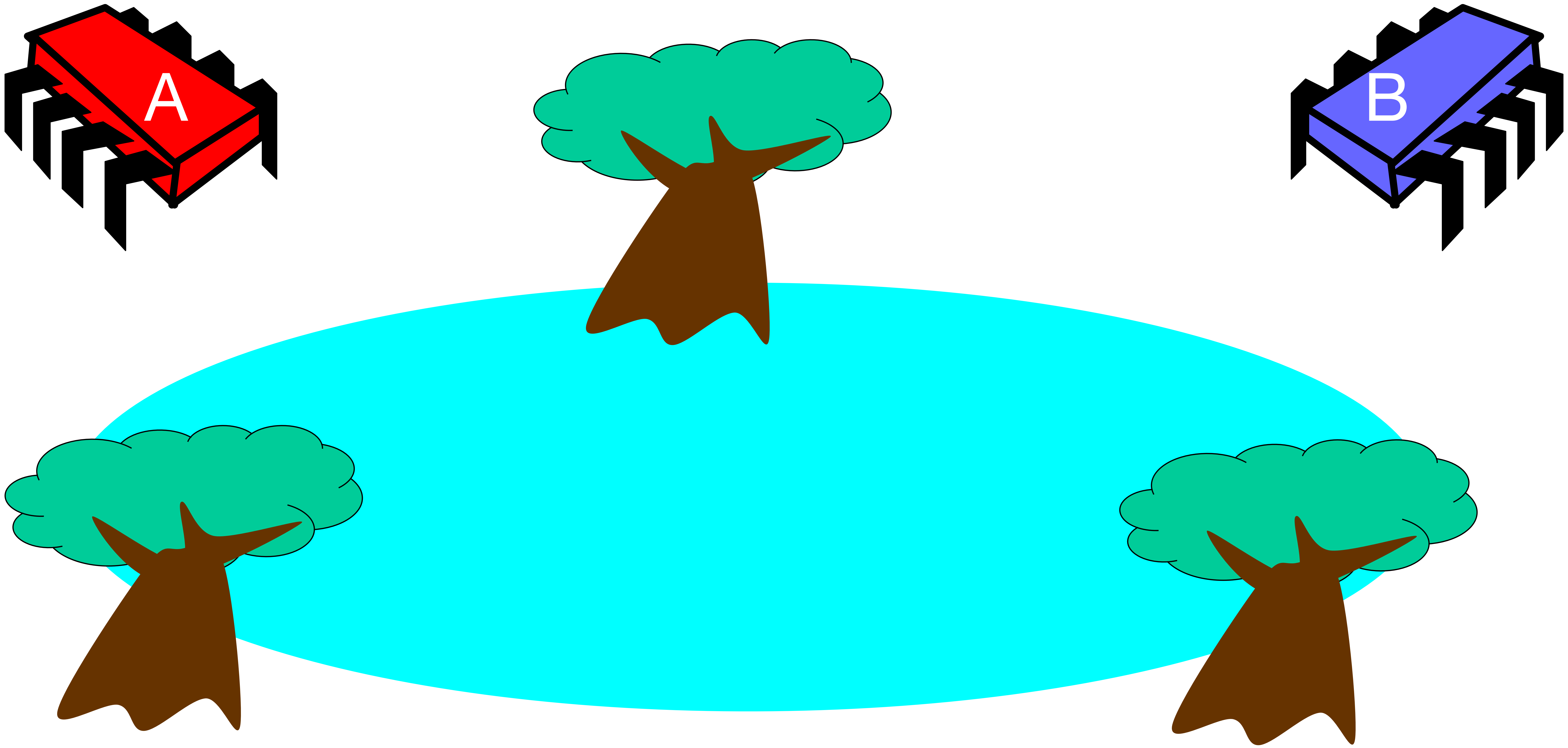
- We are going to focus on principles first, then practice
  - Start with idealized models
  - Look at simplistic problems
  - Emphasize correctness over pragmatism
  - “Correctness may be theoretical, but incorrectness has practical impact”
- First principle (today): Mutual Exclusion

Online activity

Go to b.socrative.com/student and select “Student Login” (works well on laptop, tablet or phone)

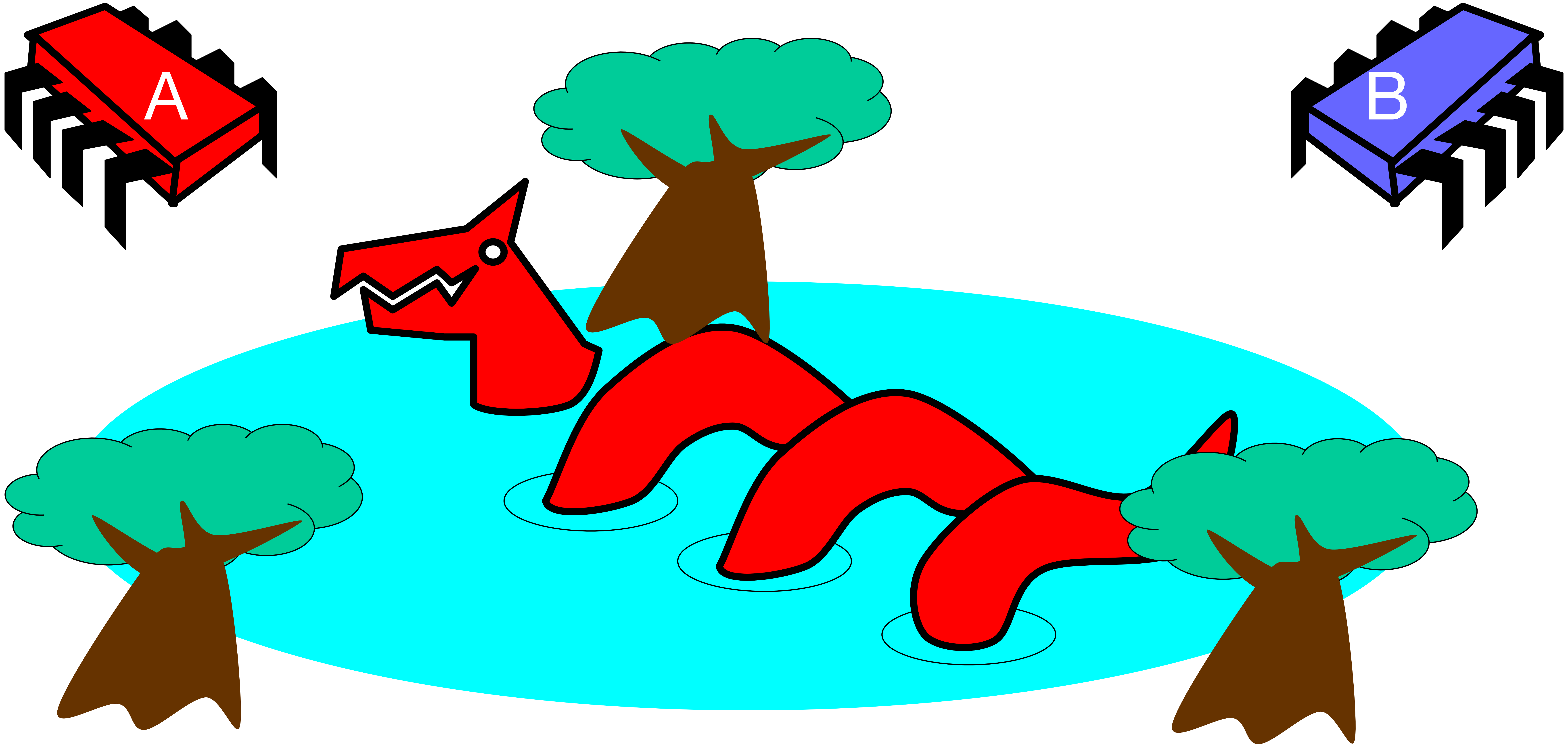
Room Name: CS475

Mutual Exclusion or “Alice & Bob share a pond”



Art of Multiprocessor Programming

Alice has a pet



Art of Multiprocessor Programming

Bob has a pet

Art of Multiprocessor Programming

The Problem

Art of Multiprocessor Programming

(the pond is the critical section)

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
  - Trees obscure the view

Interpretation

- Threads can't "see" what other threads are doing
- Explicit communication required for coordination

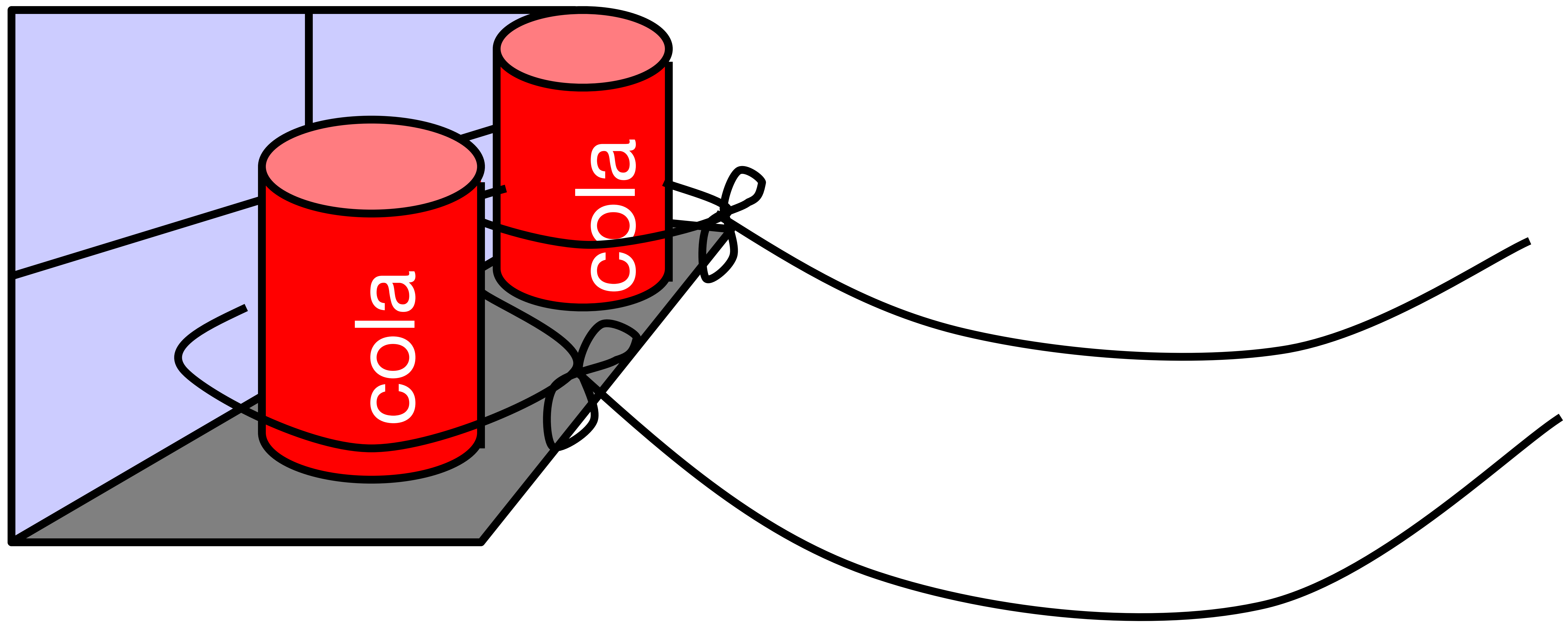
Cell Phone Protocol

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

Interpretation

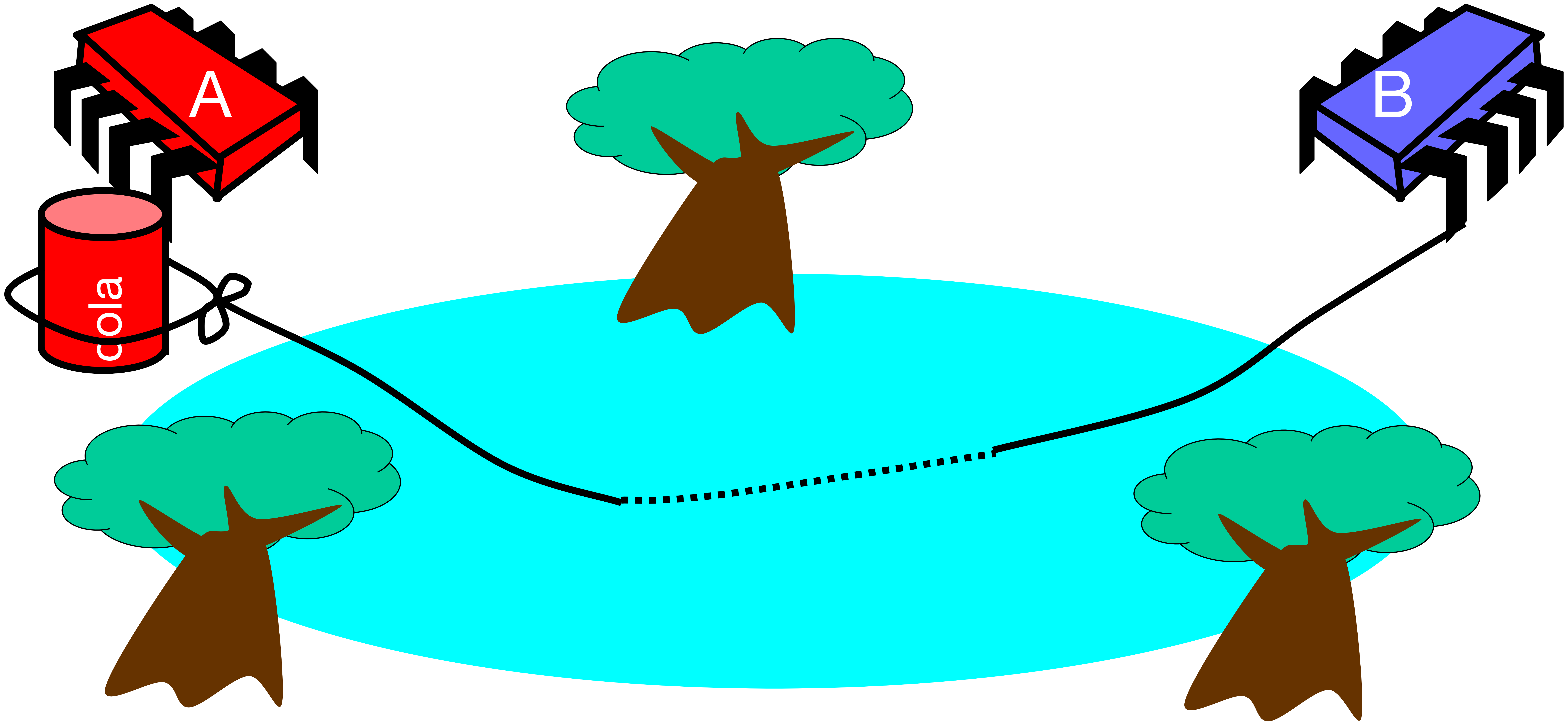
- Message-passing doesn't work
- Recipient might not be
  - Listening
  - There at all
- Communication must be
  - Persistent (like writing)
  - Not transient (like speaking)

Can Protocol



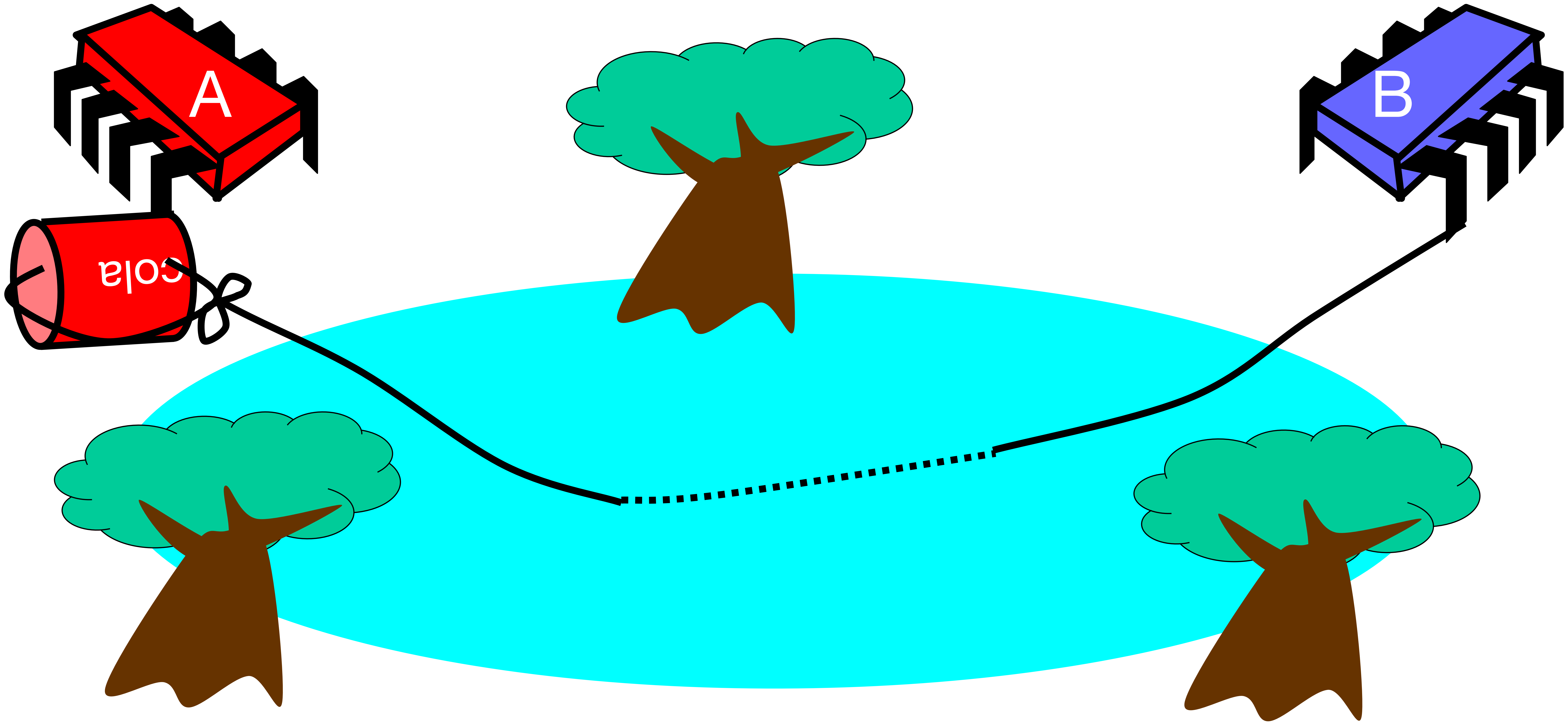
Art of Multiprocessor Programming

Bob conveys a bit



Art of Multiprocessor Programming

Bob conveys a bit



Art of Multiprocessor Programming

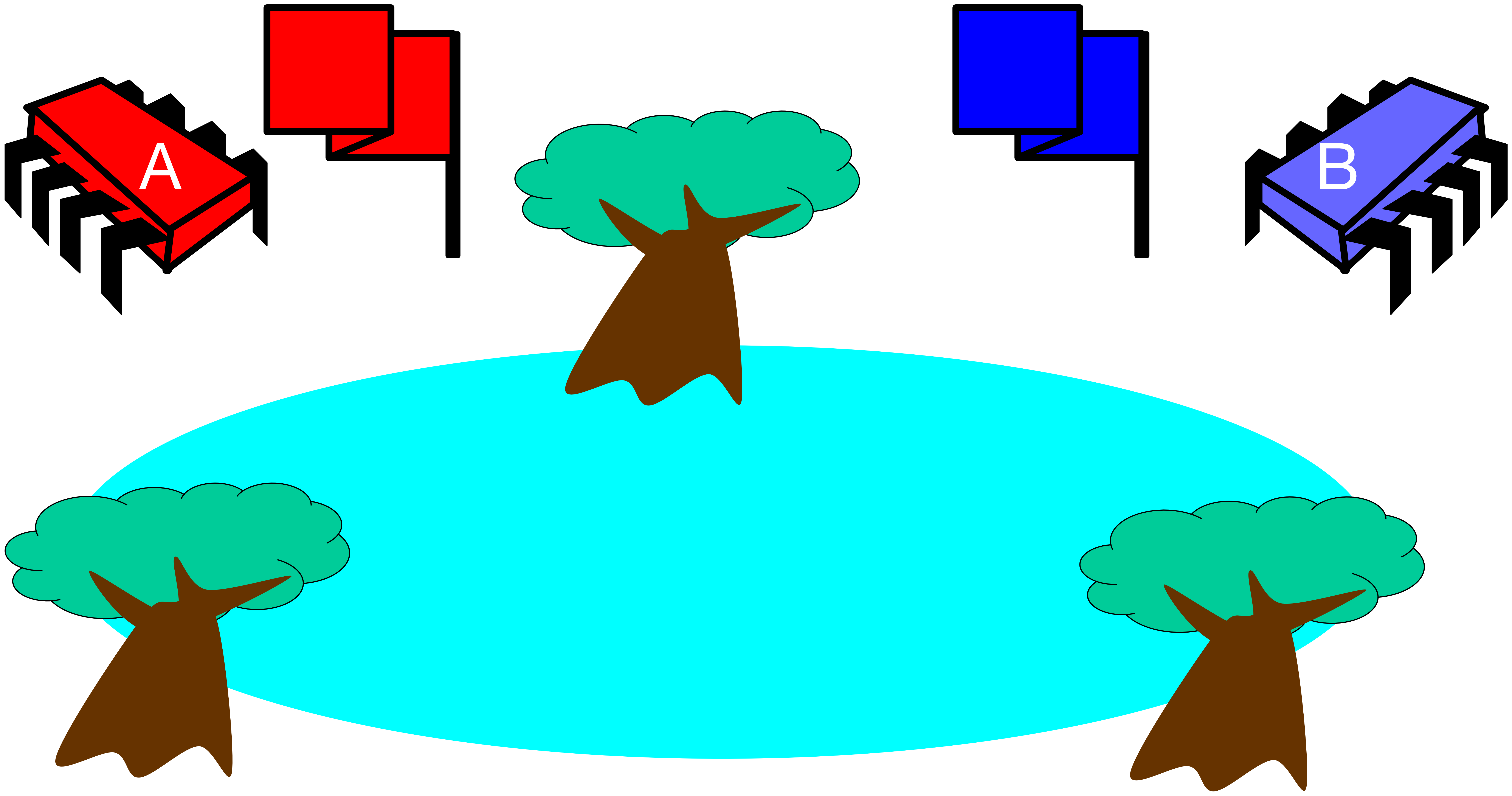
Can Protocol

- 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

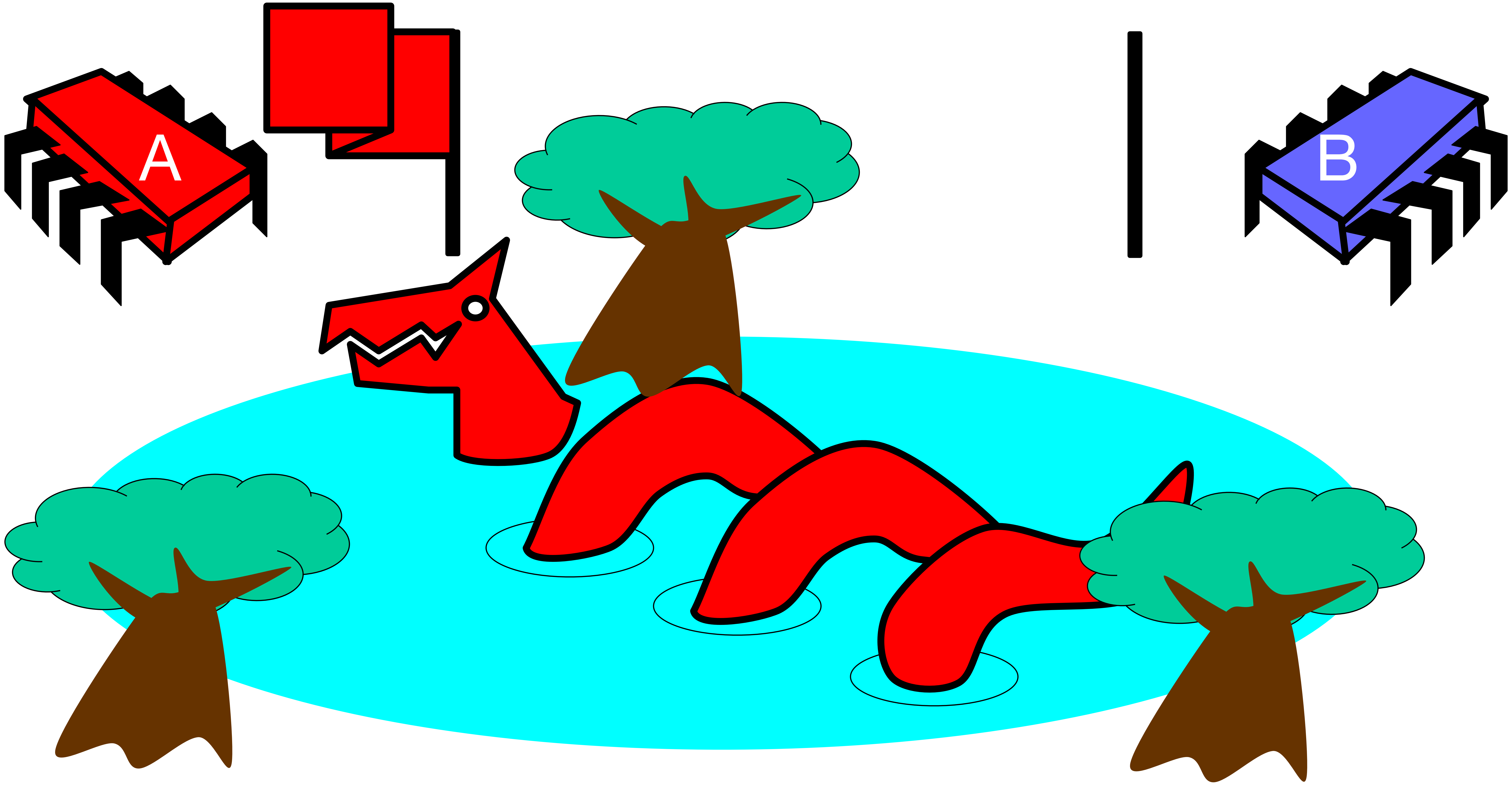
- Cannot solve mutual exclusion with interrupts
  - Sender sets fixed bit in receiver's space
  - Receiver resets bit when ready
  - Requires unbounded number of inturrupt bits

Flag Protocol



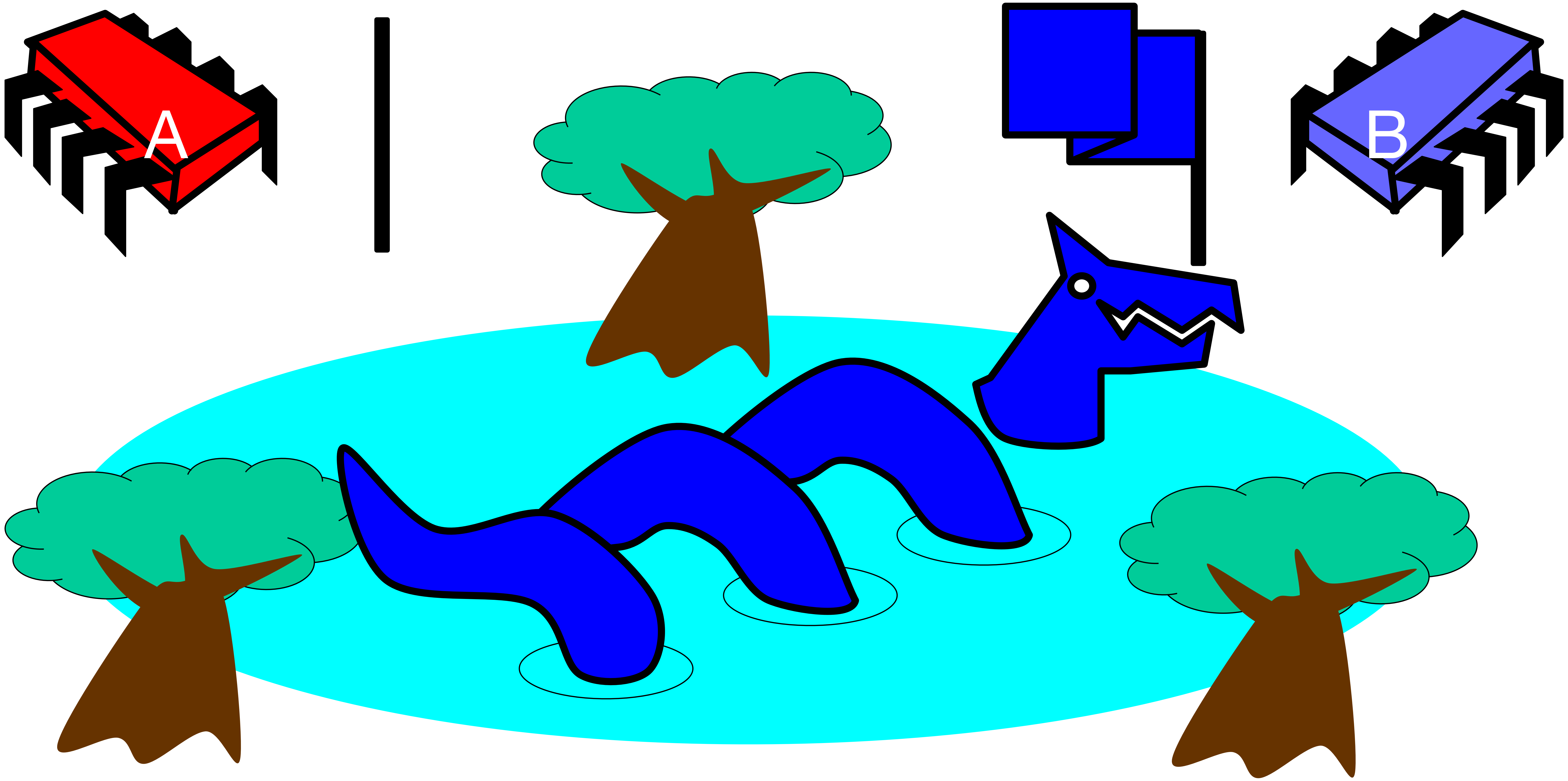
Art of Multiprocessor Programming

Alice's Protocol (sort of)



Art of Multiprocessor Programming

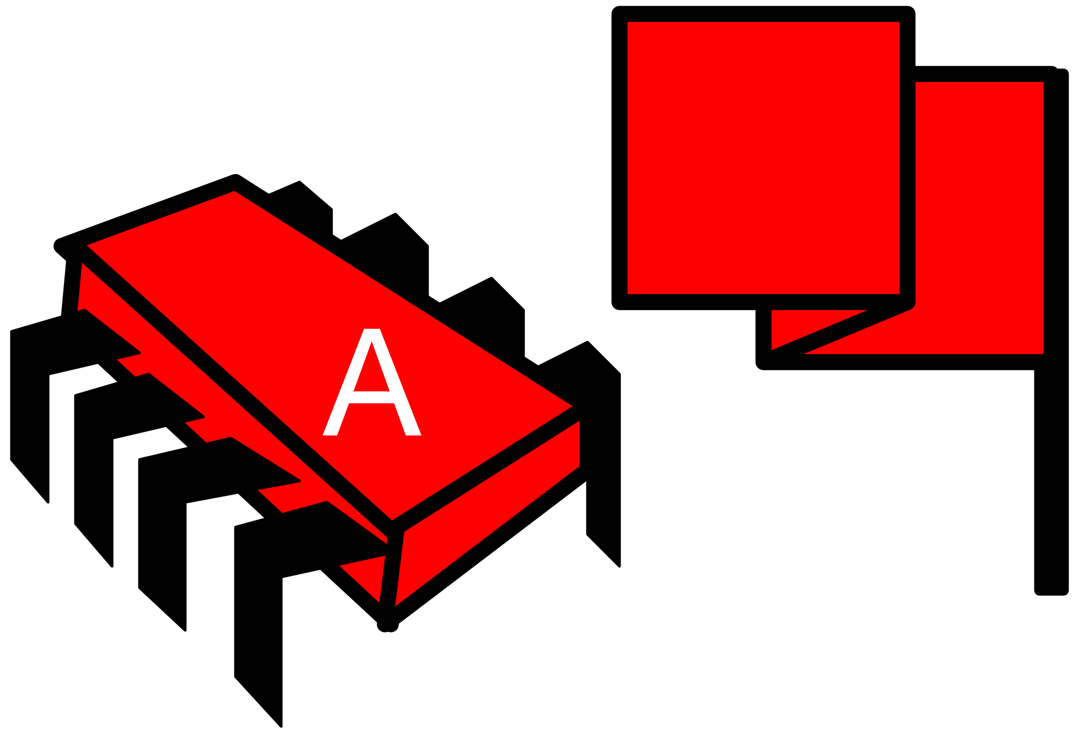
Bob's Protocol (sort of)



Art of Multiprocessor Programming

Alice's Protocol

- Raise flag
- Wait until Bob's flag is down
- Unleash pet
- Lower flag when pet returns

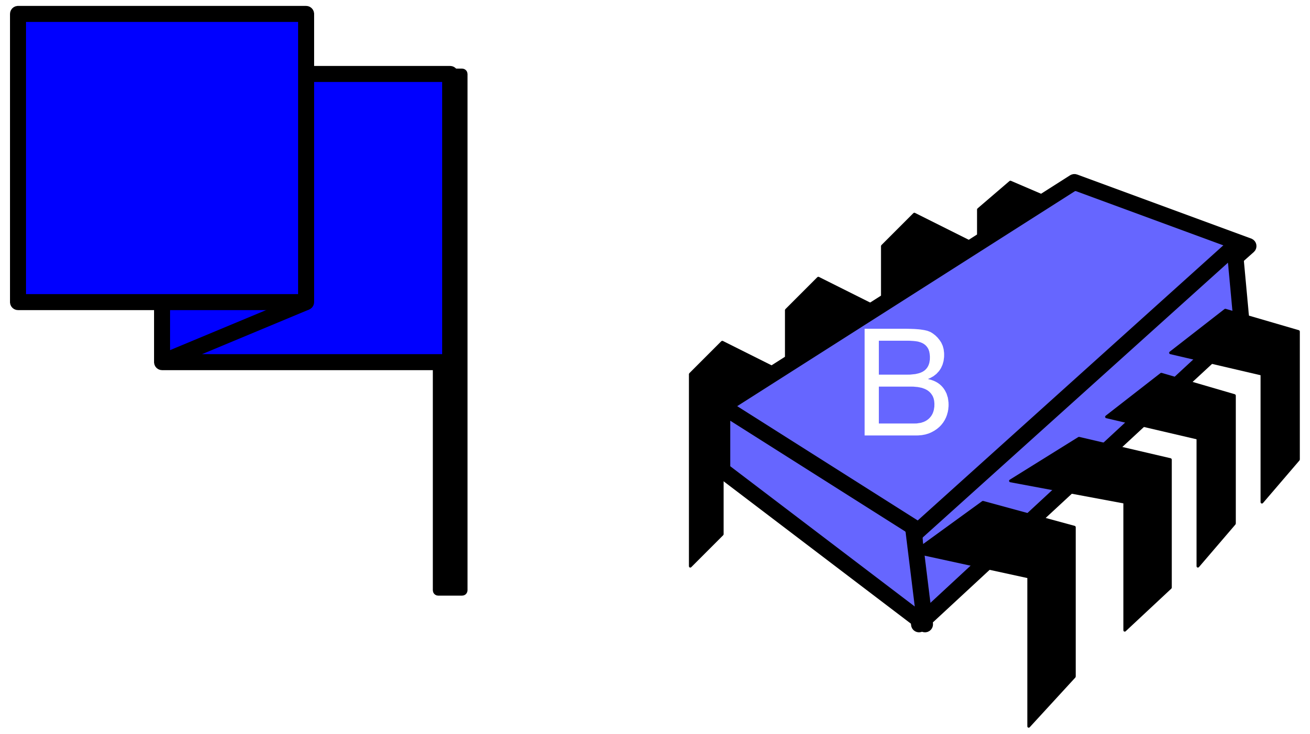


After you!

Bob's Protocol

- Raise flag
- Wait until Alice's flag is down
- Unleash pet
- Lower flag when pet returns

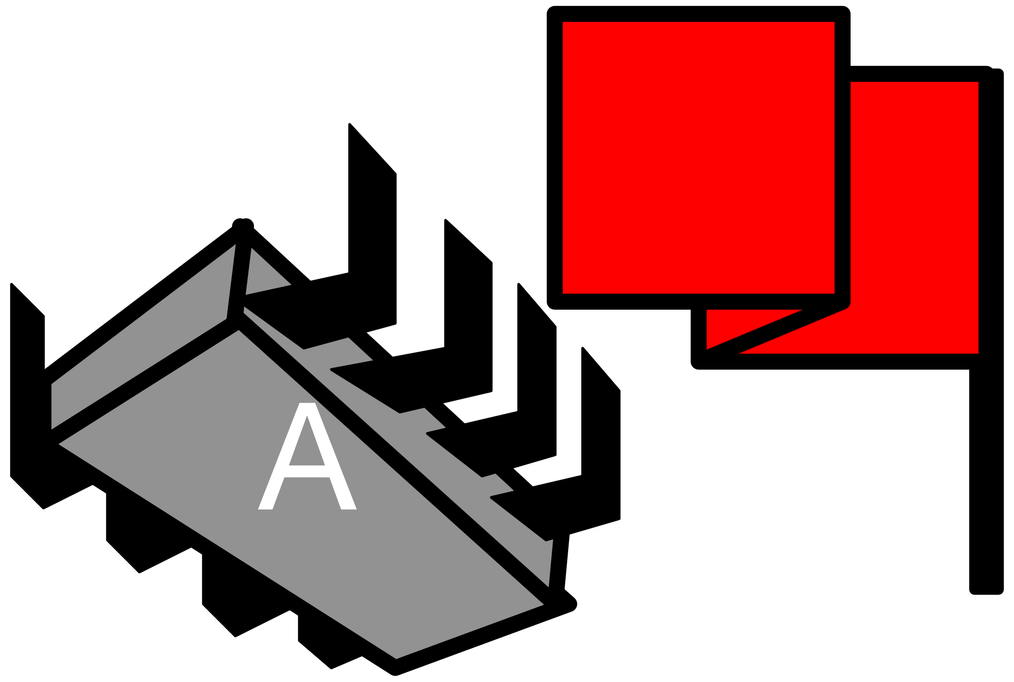
danger!



No, no… after you!

Alice's Protocol

- Raise flag
- Wait until Bob's flag is down
- Unleash pet
- Lower flag when pet returns

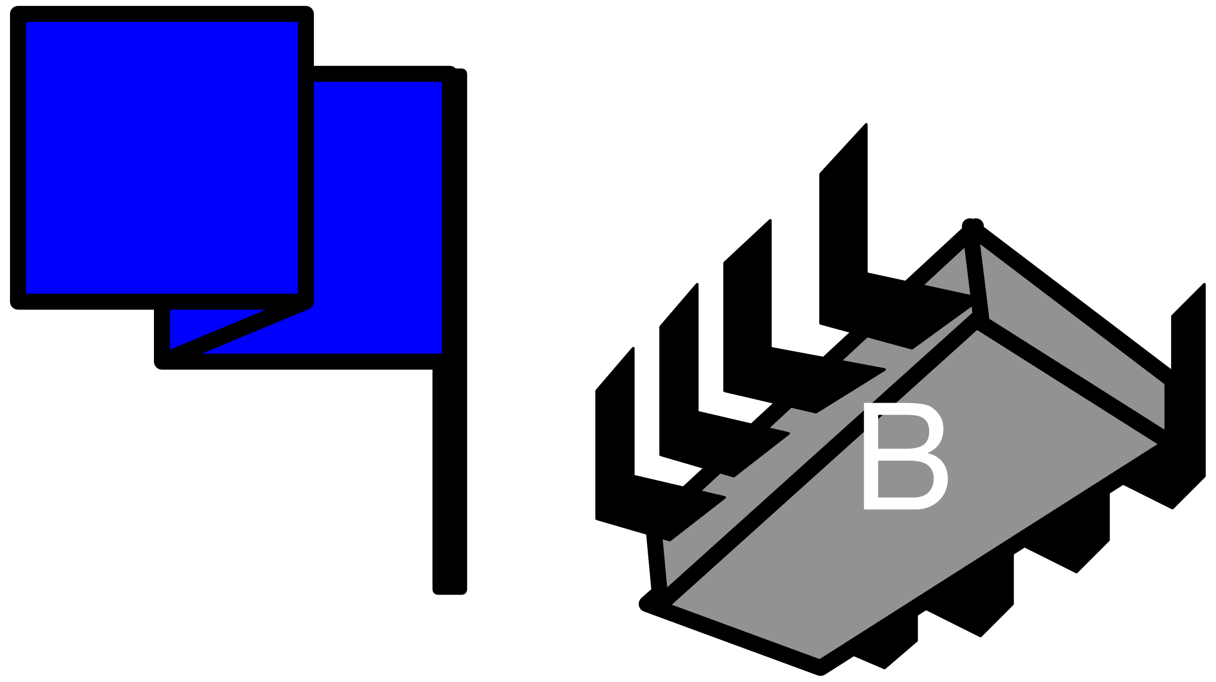


After you!

Bob's Protocol

- Raise flag
- Wait until Alice's flag is down
- Unleash pet
- Lower flag when pet returns

danger!



No, no… after you!

Alice's Protocol

- Raise flag
- Wait until Bob's flag is down
- Unleash pet
- Lower flag when pet returns

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

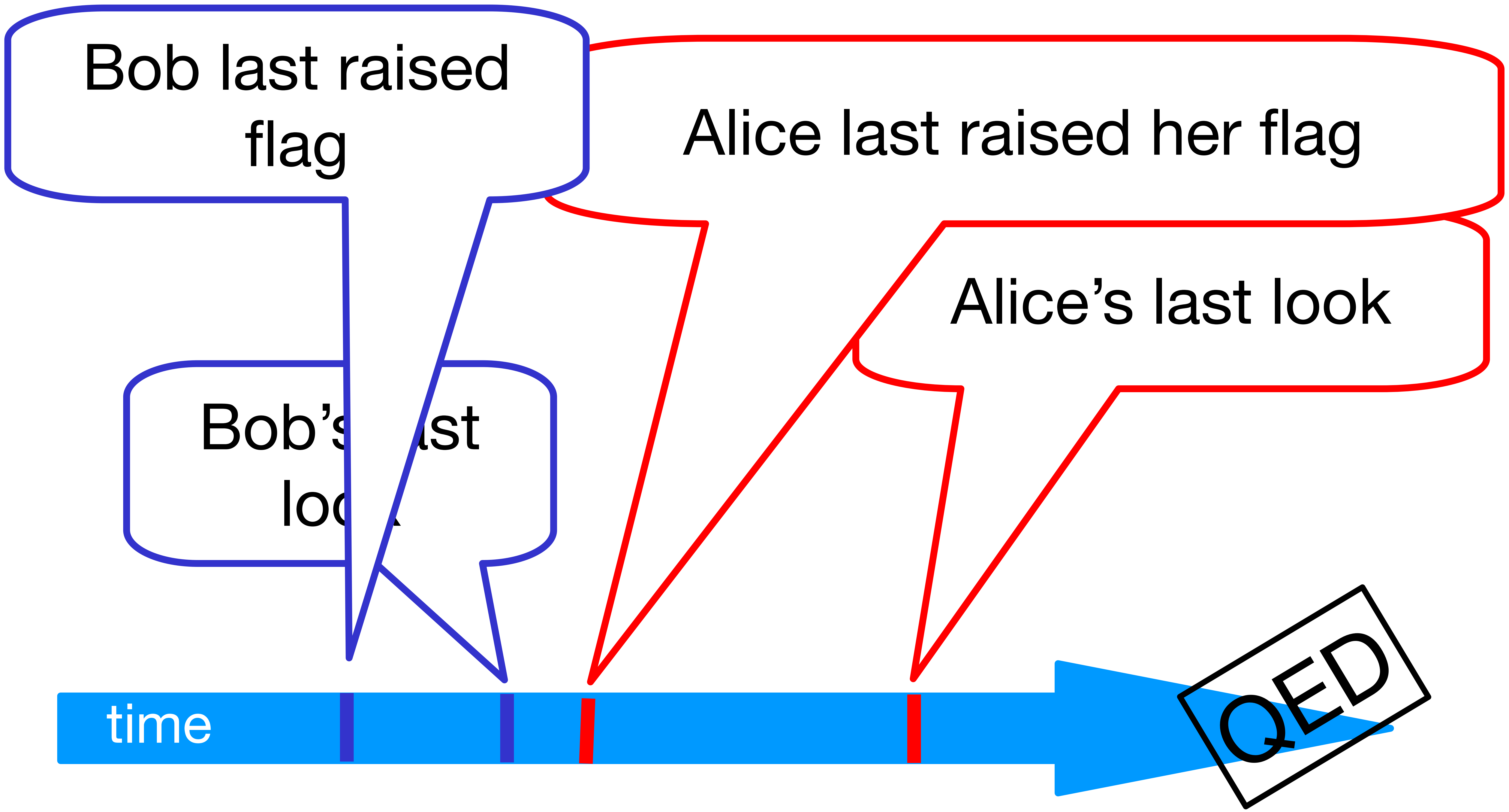
The Flag Principle

- 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.
- Deadlock requires both continually trying to get in.
- If Bob sees Alice's flag, he gives her priority (a gentleman…)

QED

Formalizing the Problem

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

Remarks

- Protocol is unfair
  - Bob’s pet might never get in (**starvation**)
- 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 (flags)

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”
- HW 1 will be posted Monday

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Mutual Exclusion

If two threads run the same code (at once), what is the value of i at the end?

```
static int i = 0;
public static void increment()
{
    i = i + 1;
}
```

Is it guaranteed to be 2? No - it can also be 1 at the end!

Thread 1	Thread 2
increment()	increment()
read i = 0	
write i = 1	read i = 0
	write i =1

This is one possible interleaving

Mutual Exclusion

- Mutual exclusion: how can we guarantee that multiple threads do **not** enter the same *critical region* at the same time

Critical Region

```
static int i = 0;
public static void increment()
{
    i = i + 1;
}
```