HARVARD
School of Engineering
and Applied Sciences

Synchronization Problems and Deadlock

CS61, Lecture 20

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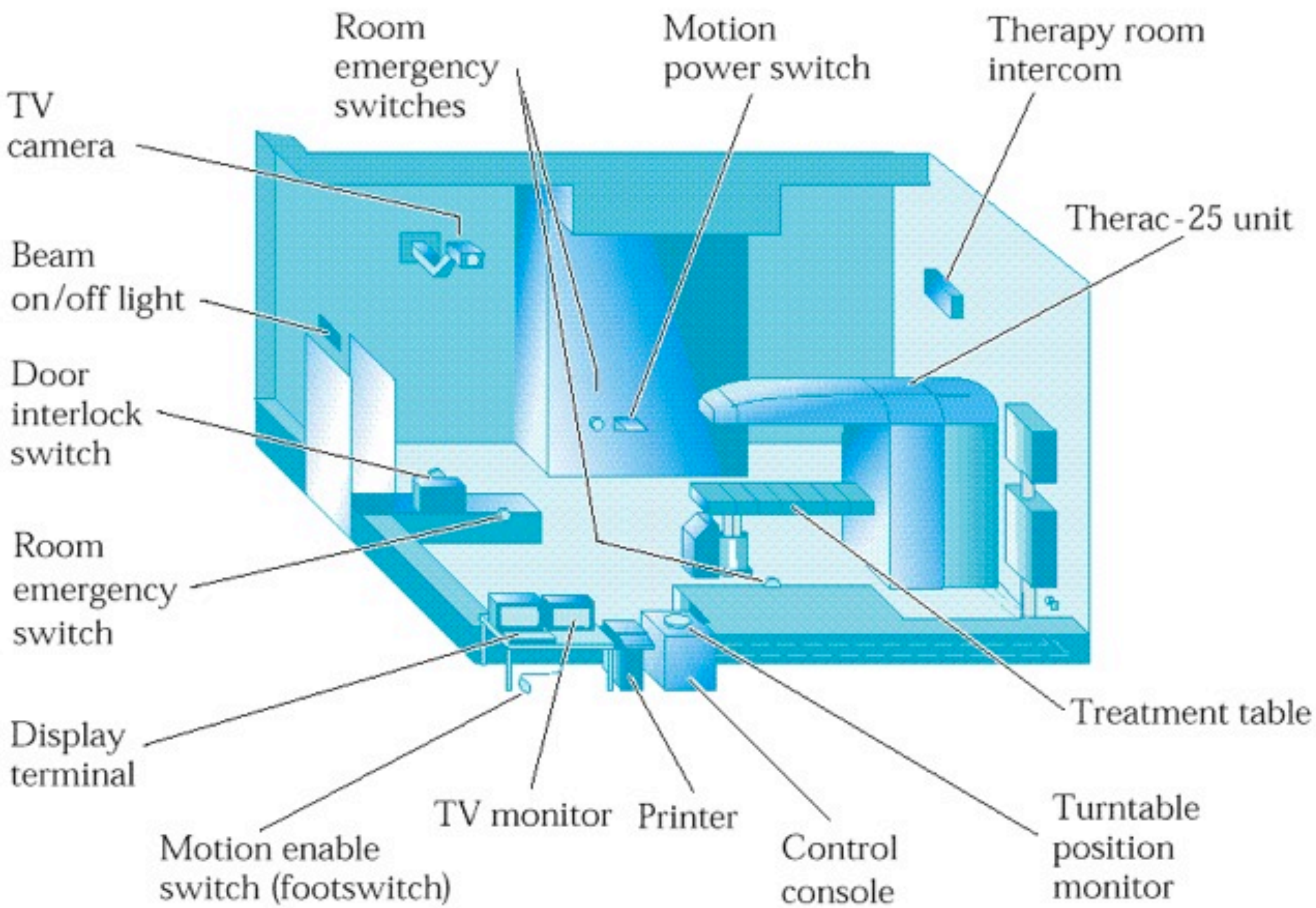
Today

- Race conditions
  - The THERAC-25 Accidents
- Priority inversion
  - Mars Pathfinder
- Deadlock and how to avoid it

Therac-25

- Computer-controlled radiation therapy machine
  - In operation between 1983 and 1987, 11 installations

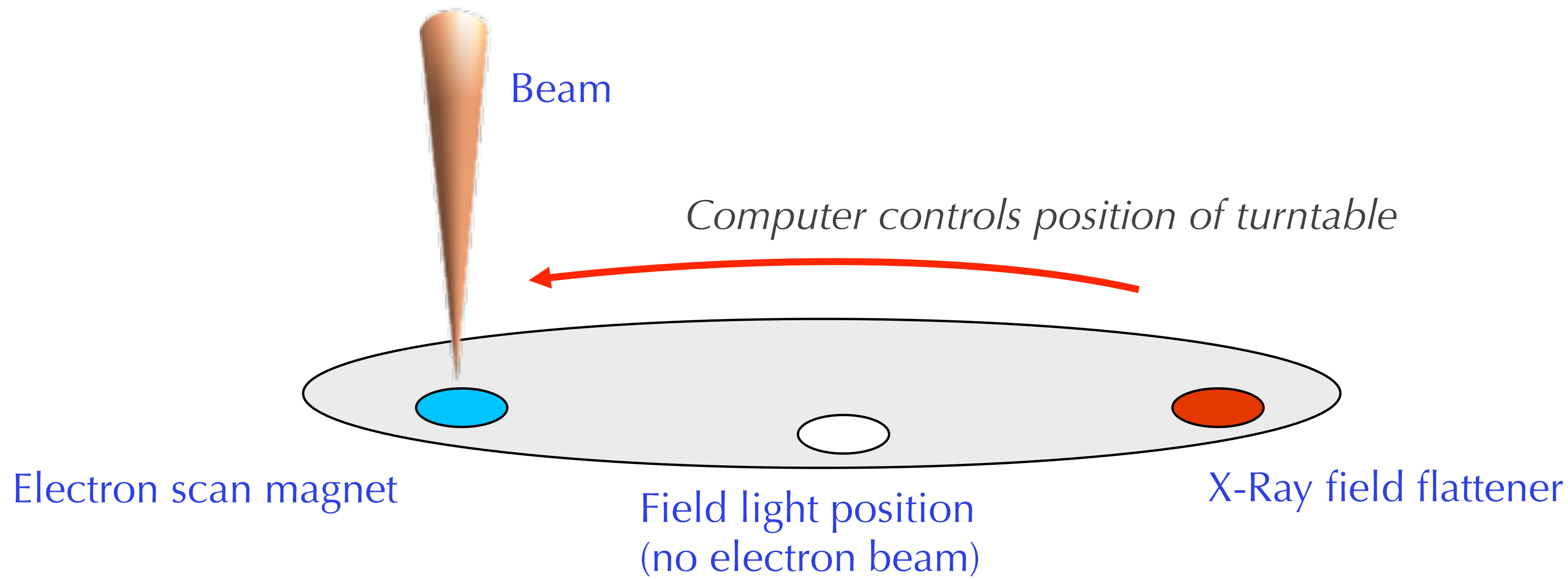


Accidents

- Capable of delivering electron and photon (X-Ray) treatments
- “Evolved” from earlier models, Therac-20 and Therac-6
- On several occasions between June '85 and Jan '87
  - Massive overdoses to six people, some lethal
  - Several overdoses delivered energy of 15,000 – 20,000 rads
    - Typical therapeutic doses in the 200 rad range
- Various lawsuits, all settled out of court
  - No formal investigation
- Initially, manufacturer claimed that overdoses were impossible
- Many issues with the Therac-25
  - Software design methodology
  - Software/hardware engineering
  - User interface
  - Concurrency

Therac-25 operation

- A turntable aperture that moves certain elements into the path of the beam



- Field light mode used to position beam on patient
  - No electron beam expected, instead, a light simulates the beam position
- Electron scan magnet and X-Ray field flattener used to attentuate and spread electron and X-Ray beams

Therac-25 operation

- Unlike previous models, completely computer controlled
  - No hardware interlocks to prevent misconfigurations or overdoses!
  - Software from old models re-used.
- All software written in PDP-11 assembly language
- Operator uses a VT-100 terminal to control machine
- Cryptic error messages delivered to operator console
  - e.g., "Malfunction 23"
  - No documentation of these error codes, no indication of which errors are potentially life-threatening

Therac-25 internals

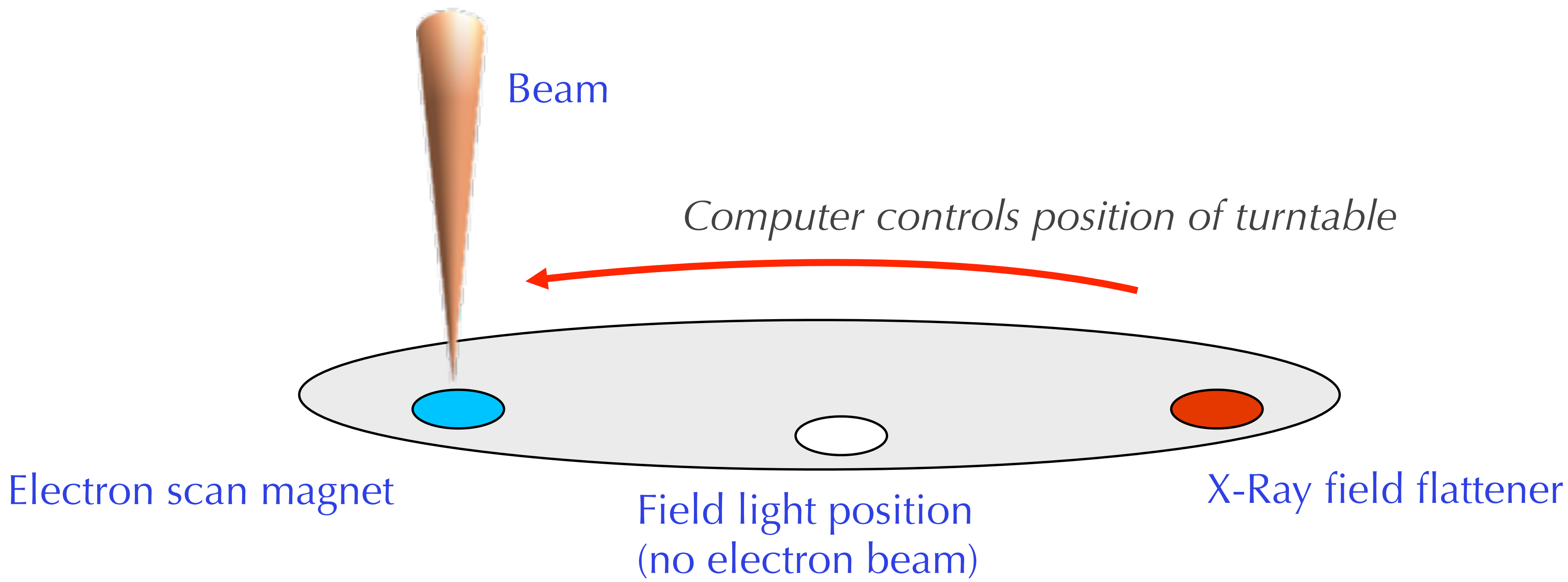
- 4 components: scheduler, critical and non-critical tasks, interrupt services, and stored data
  - Preemptive scheduler schedules critical and non-critical tasks
- Critical tasks include:
  - Treatment task
    - Directs and monitors patient setup and treatment
    - Interacts with keyboard and terminal interrupt services
  - Servo task
    - Controls gun emission, dose rate, turntable, and other machine motions
- Concurrent access to shared memory with no synchronization
  - Test and set are not atomic
  - Race conditions resulting from this play an important part in the accidents

Race Condition #1

- It was discovered that overdose could be caused by operator editing the dosage on the console too quickly
  - Operator enters dosage on screen, moves to bottom, moves back up to edit dosage, and back to bottom
  - Second edit displayed on screen, but ignored by machine
  - Bug not triggered in testing/training, since needs to be done quickly
- What happened?
- Treatment task
  - Periodically checks `entryDone` flag (which is set when cursor moved to bottom of screen)
  - If flag is set, calls subroutine to configure the magnets (takes about 8 seconds)
- Configure magnet task
  - Called periodically to check if magnets are ready
  - Checks if edits have been made to dosage; If so, exits back to calling subroutine to restart the process
  - Critical bug: Only checks if edits made on the first call!
- Also, `entryDone` flag indicates cursor was at bottom of screen, not that it is still there. Race condition between user editing dosage and reading dosage.

Race Condition #2

- Second bug – totally different causes from the first



- Software interlocks intended to stop beam from being turned on unless turntable in correct position
- Problem: Turntable could be in field light position while X-Ray beam on

Race Condition #2

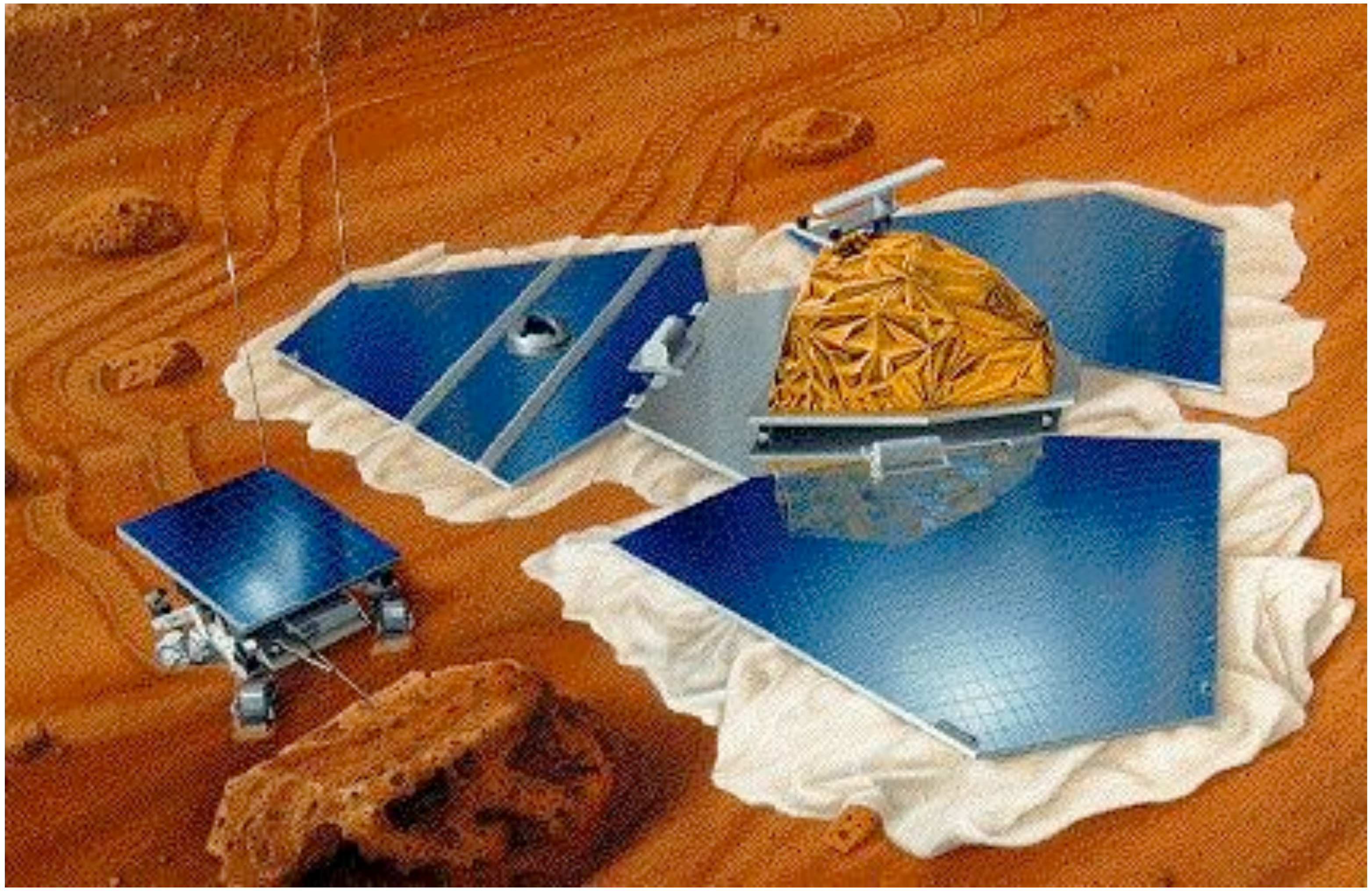
- Dosage entered on console; Operator then presses `SET` button to set turntable to correct position
- Software interlock:
  - Shared variable `Class3` indicates whether machine configuration consistent with dosage: zero == OK, non-zero == inconsistent
  - Shared variable `Fmal` indicates whether a malfunction exists
  - Set up test task runs after dosage entered, and periodically checks if machine configured consistently with dosage
    - Increments variable "Class3" on each iteration
    - Will be run many times
    - If position correct and no malfunctions (Fmal == 0), sets "Class3 := 0"
- When `SET` button is pressed, Housekeeping task runs
  - If Class3 != 0 check whether turntable in place (set a bit of Fmal)
  - Skip check if Class3 == 0.
- Can you spot the bug?

Race Condition #2

- The bug: `Class3` variable is 8 bits wide
  - After 256 iterations of "set up test" routine, overflows and becomes zero!
  - So if operator presses `SET` button during short interval that Class3 overflows, does not check turntable position
- Fix: Set `Class3` to some nonzero value, rather than incrementing it
  - Why was this done? Probably because `inc` instruction was easy enough...

Mars Pathfinder

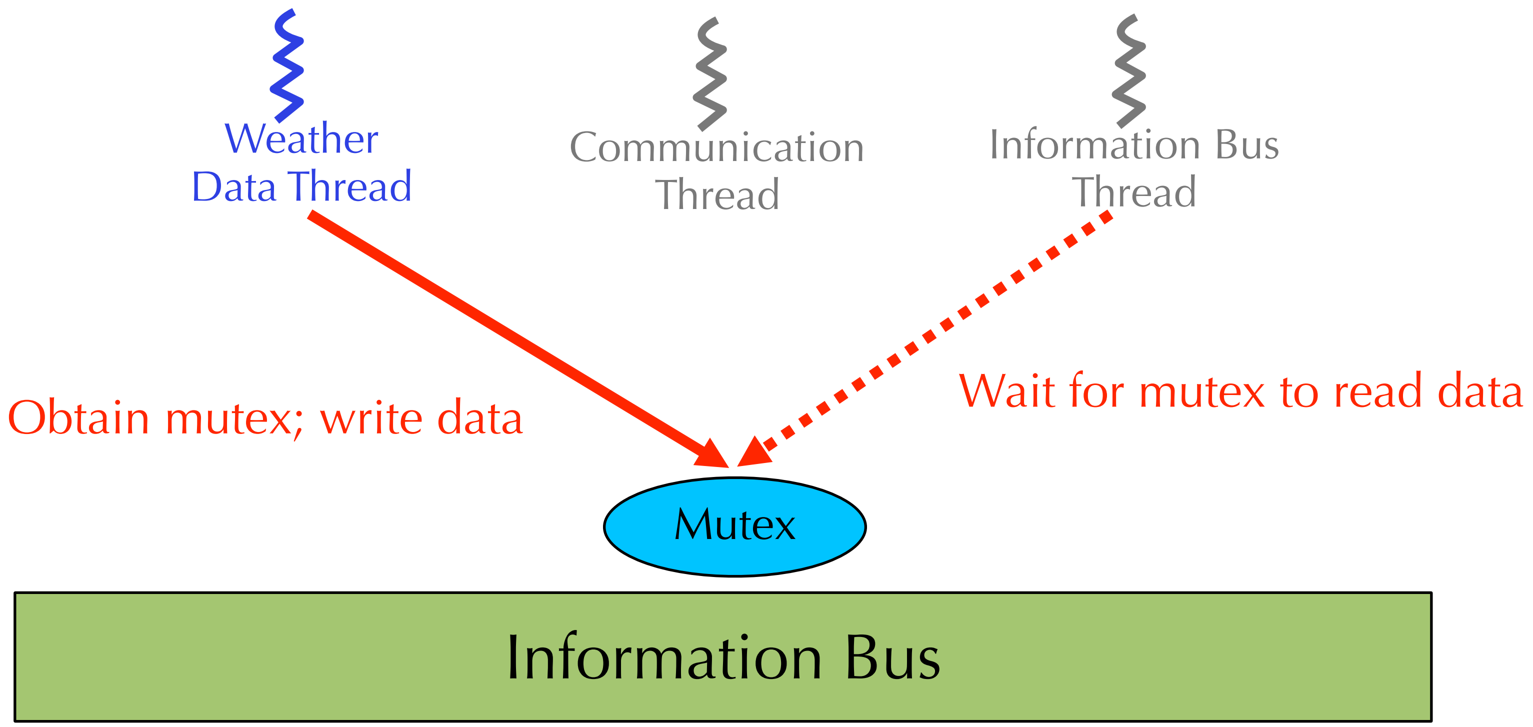
- July 4, 1997 landing on Martian surface, followed by expeditions by Sojourner rover



- Series of software glitches started a few days after landing
- Eventually debugged and patched remotely from Earth!

VxWorks Operating System

- Developed by Wind River Systems – premier real time OS
- Multiple tasks, each with an associated **priority**
  - Higher priority tasks get to run before lower-priority tasks
- Information bus – shared memory area used by various tasks
  - Thread must obtain mutex to write data to the info bus – a monitor



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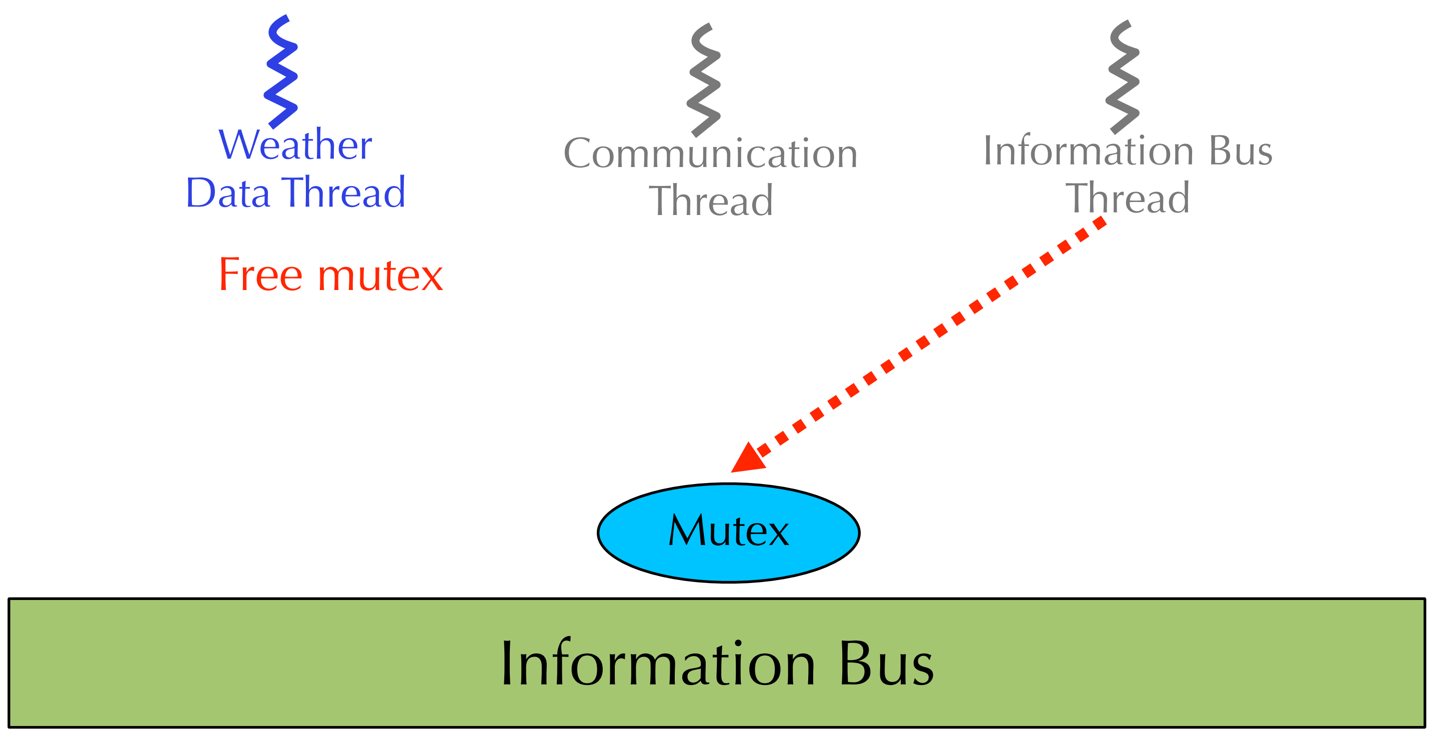

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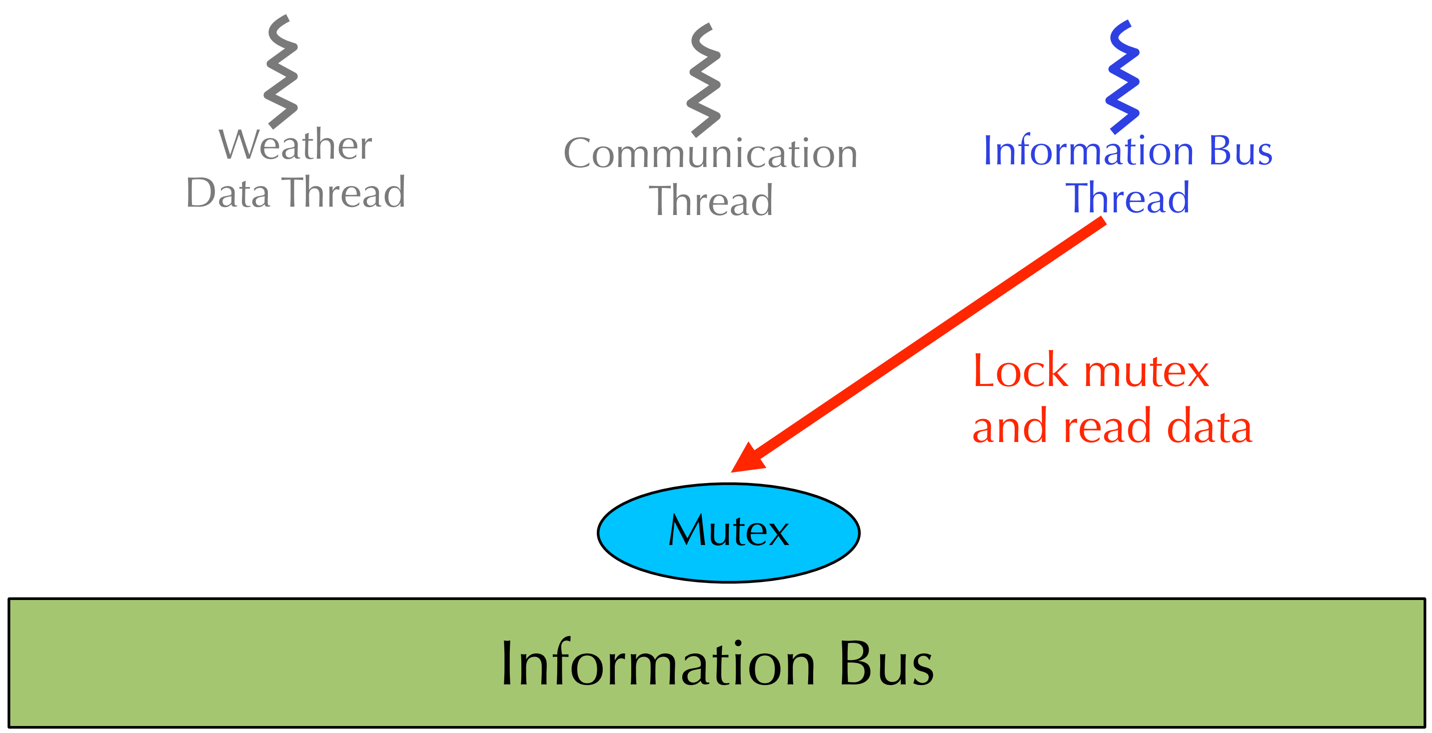
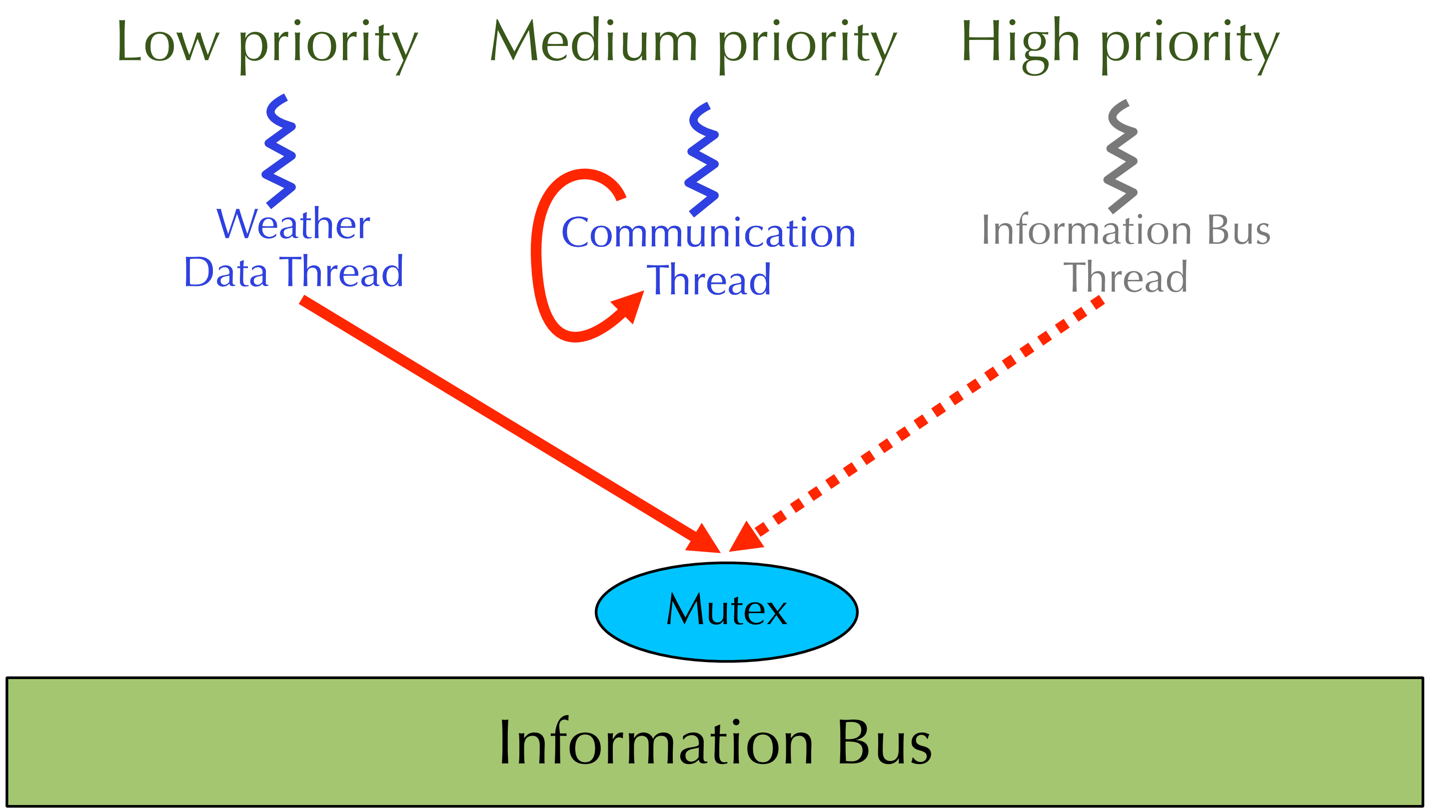


Priority inversion

- What happens when threads have different priorities?
- Suppose the low priority thread has the mutex, and medium priority thread needs the CPU
  - Medium thread has higher priority than Low thread, so gets the CPU. Runs for a long time.
  - But High thread waiting for Low thread to finish! Medium thread running instead of High!
- This is called **priority inversion**



How to fix priority inversion?

- Priority inversion:
  - A high priority thread is waiting for a low priority thread to finish (this is OK)
  - Medium priority thread comes along and preempts Low thread
  - Now Medium thread running instead of finishing Low thread
- General solution: Priority inheritance
  - If high priority thread is waiting for a low priority thread, temporarily give low thread high priority
  - High priority thread "donates" its priority to the low priority thread
- Why does this fix the problem?
  - Weather task inherits high priority while it is being waited on
  - Now medium priority communications task cannot preempt weather task

How was this problem fixed?

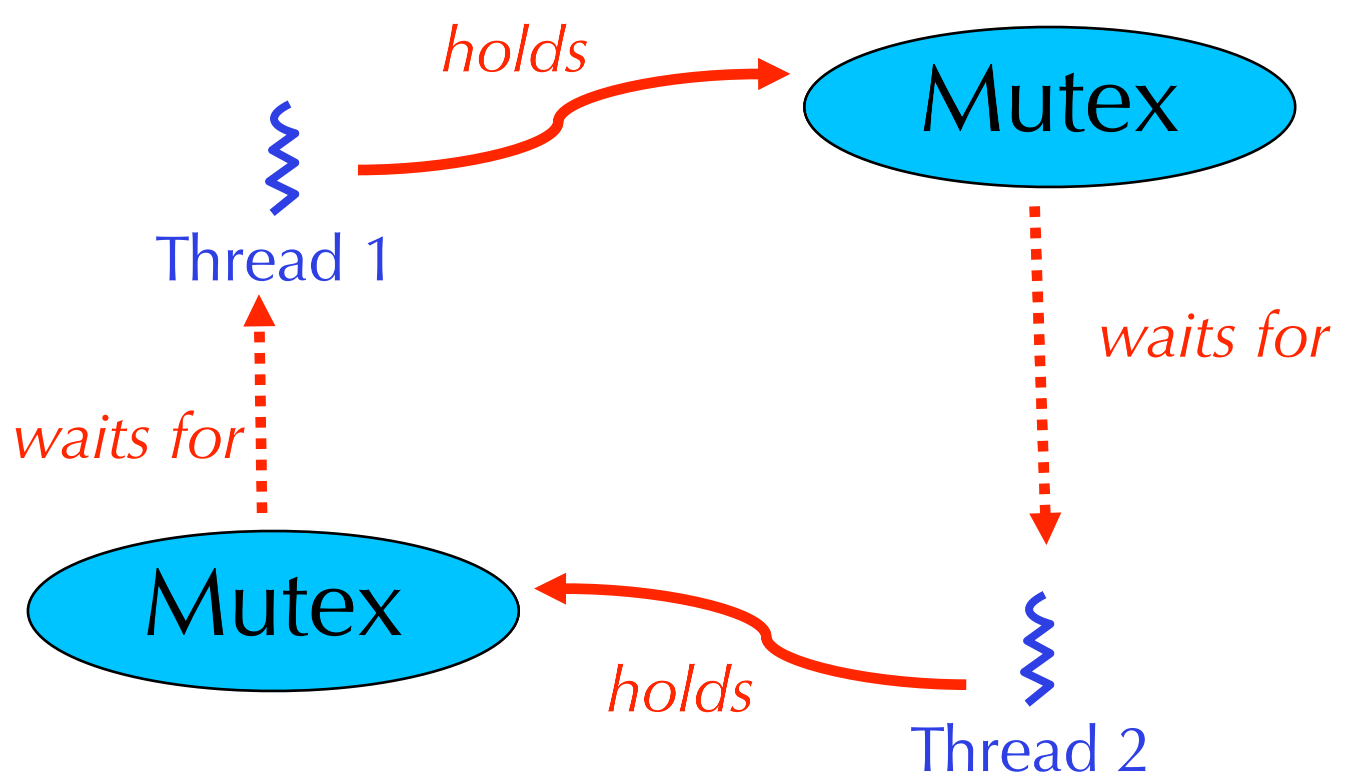
- JPL had a replica of the Pathfinder system on the ground
  - Special tracing mode maintains logs of all interesting system events
    - e.g., context switches, mutex lock/unlock, interrupts
  - After much testing were able to replicate the problem in the lab
- VxWorks mutex objects have an optional priority inheritance flag
  - Engineers were able to upload a patch to set this flag on the info bus mutex
  - After the fix, no more system resets occurred
- Lessons:
  - Automatically reset system to “known good” state if things run amuck
    - Far better than hanging or crashing
  - Ability to trace execution of complex multithreaded code is useful
  - Think through all possible thread interactions carefully!!

Today

- Race conditions
  - The THERAC-25 Accidents
- Priority inversion
  - Mars Pathfinder
- Deadlock and how to avoid it

Deadlock

- With priority inversion, eventually the system makes progress
  - e.g., Comm. thread eventually finishes and rest of system proceeds
  - Pathfinder watchdog timer reset the system too quickly!
- A far more serious situation is **deadlock**
  - Two (or more) threads waiting for each other
  - None of the deadlocked threads ever make progress



Deadlock Definition

- **Deadlock**: A circular waiting for resources
  - E.g., Thread A is waiting for a mutex Thread B has
    Thread B is waiting for a mutex Thread C has
    Thread C is waiting for a mutex Thread A has
- **Starvation**: a thread never makes progress because other threads are using resources it needs
- Starvation ≠ Deadlock
  - Deadlock can be seen as a special case of starvation

Conditions for Deadlock

- Limited access to a resource
  - Means some threads will have to wait to access a shared resource. E.g., mutual exclusion
- No preemption
  - Means resource cannot be forcibly taken away from a thread
  - Two kinds of resources:
    - Preemptible: Can take away from a thread (e.g., the CPU)
    - Non-preemptible: Can't take away from a thread (e.g., mutex, lock, virtual memory region, etc.)

Why is it unsafe to take a lock away from a thread?

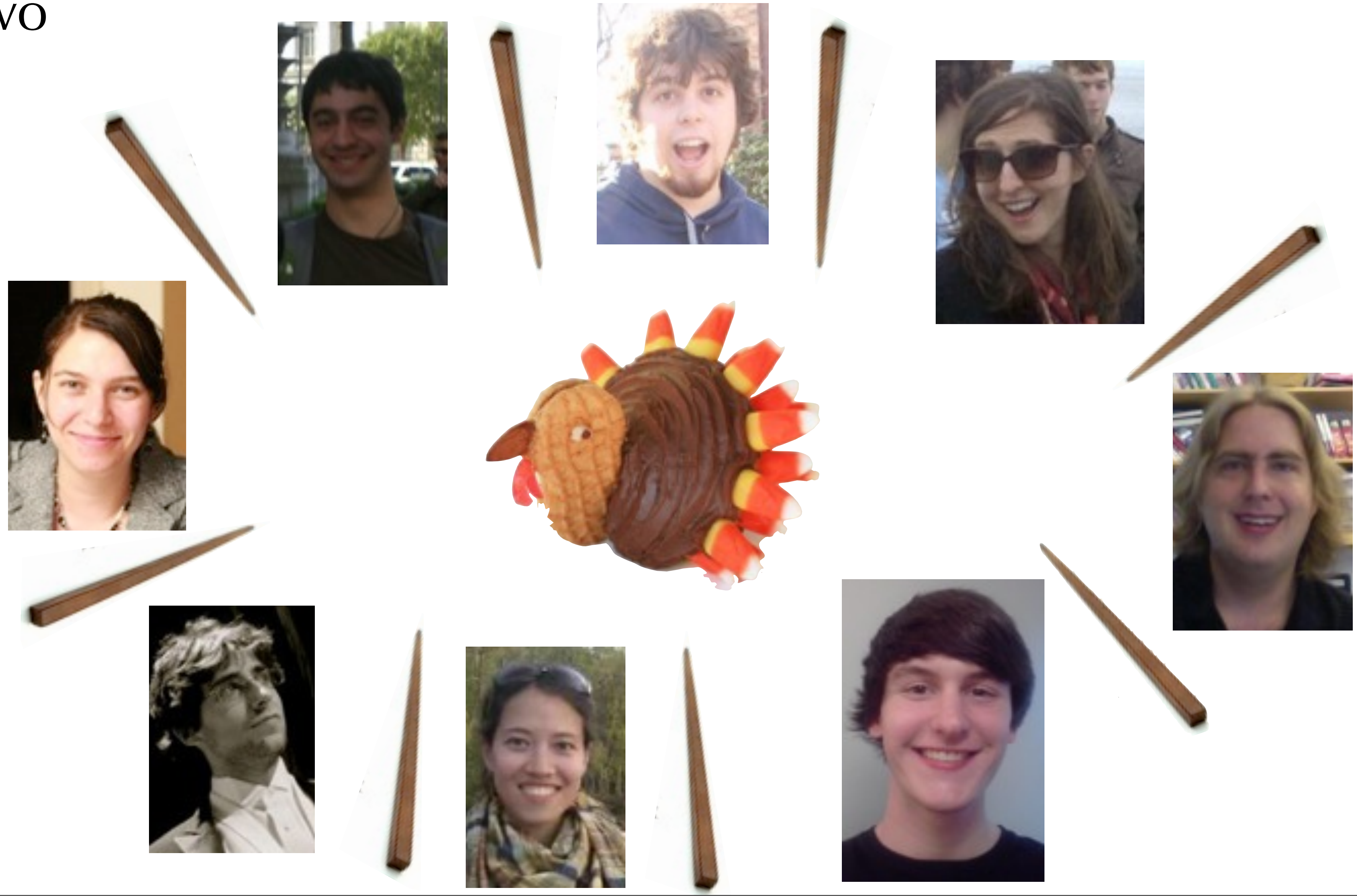
- Multiple independent requests
  - Means a thread can wait for some resources while holding others
- Circular dependency graph
  - Just as in previous example
- Without **all** of these conditions, can't have deadlock!
  - This suggests several ways to get rid of deadlock

Getting rid of deadlock

- Unlimited access to a resource?
  - Requires that all resources allow arbitrary number of concurrent accesses
    - Probably not too feasible!
- Always allow preemption?
  - Is it safe to let multiple threads into a critical section?
- No multiple independent requests?
  - This might work!
  - Require that threads grab all resources they need before using any of them!
    - Not allowed to wait while holding some resources!
- No circular chains of requests?
  - This might work too!
  - Require threads to grab resources in some predefined order!

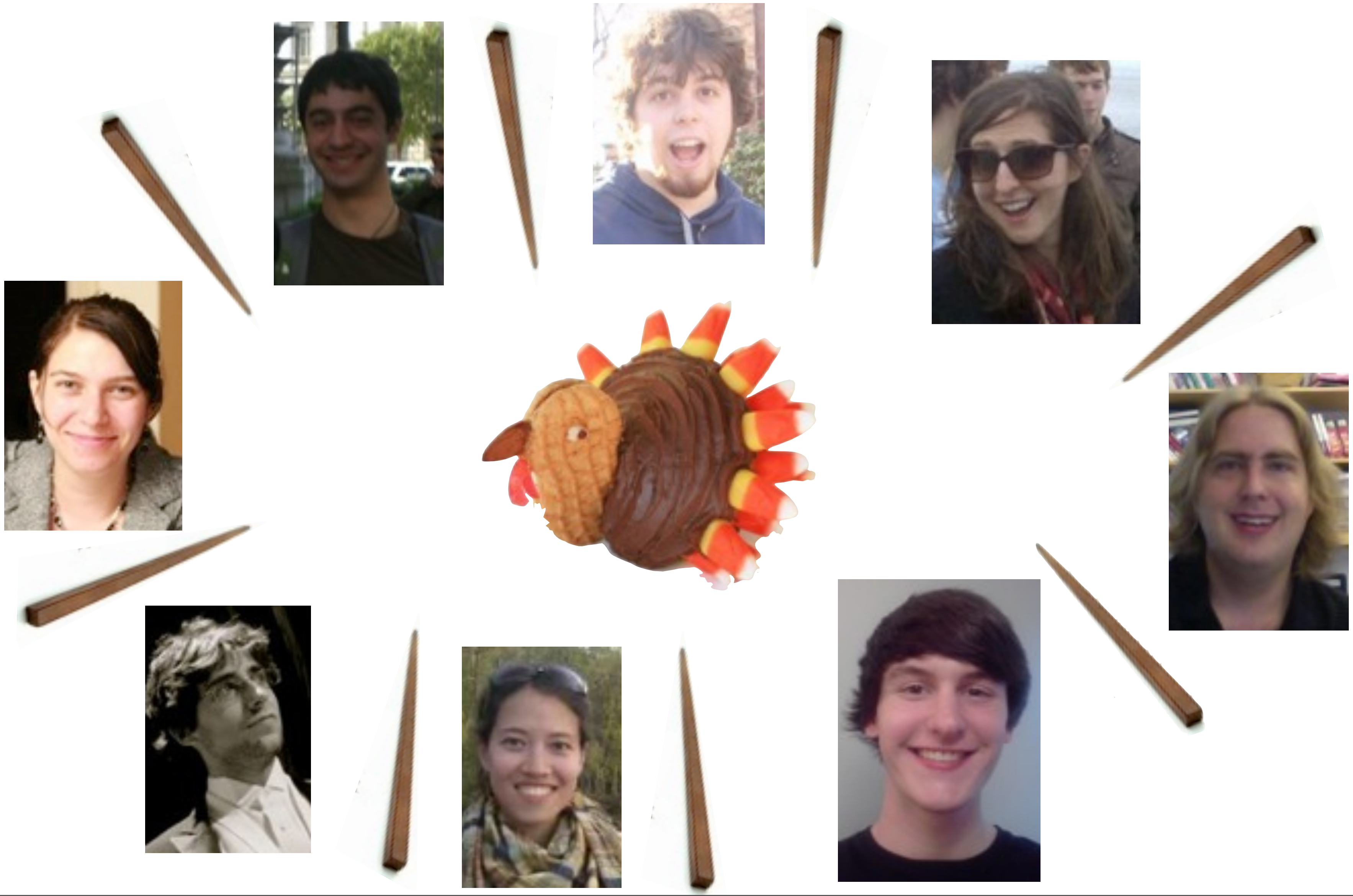
Dining Philosophers

- Classic deadlock problem
  - Multiple philosophers trying to have Thanksgiving lunch
  - One chopstick to left and right of each philosopher
  - Each one needs two chopsticks to eat



Dining Philosophers

- What happens if everyone grabs the chopstick to their right?
  - Everyone gets one chopstick and waits forever for the one on the left
  - All of the philosophers starve!!!



How to solve this problem?

- Solution 1: Don't wait for chopsticks
  - Grab the chopstick on your right
  - Try to grab chopstick on your left
  - If you can't grab it, put the other one back down
  - Breaks “no preemption” condition – no waiting!
- Solution 2: Grab both chopsticks at once
  - Requires some kind of extra synchronization to make it atomic
  - Breaks “multiple independent requests” condition!

How to solve this problem?

- Solution 3: Grab chopsticks in a globally defined order
  - Number chopsticks 0, 1, 2, 3, 4, 5, 6, 7
  - Grab lower-numbered chopstick first
    - Means one person grabs left hand rather than right hand first!
  - Breaks "circular dependency" condition
- Solution 4: Detect the deadlock condition and break out of it
  - Scan the waiting graph and look for cycles
  - Shoot one of the threads to break the cycle

Another problem: child care

- Fun problem, from The Little Book of Semaphores, by Allen B. Downey
- State law requires that at a child care center, there is always one adult present for every three children.
- Suppose that there are adult threads and child threads, each of which has a critical section. Write the code for adult threads and child threads to enforce this constraint.
- Hint: Can almost do it with 1 semaphore

```
semaphore multiplex = 0
```

Adult thread

```
// Add code here?
…
critical section
…
// Add code here?
```

Child thread

```
// Add code here?
…
critical section
…
// Add code here?
```

Almost solution

Adult thread

```
semaphore multiplex = 0;

// signal 3 times
signal(multiplex);
signal(multiplex);
signal(multiplex);
…
critical section
…
// wait 3 times
wait(multiplex);
wait(multiplex);
wait(multiplex);
```

Child thread

```
// wait for a token
wait(multiplex)
…
critical section
…
// signal
signal(multiplex)
```

- Semaphore counts number of tokens
  - Adult adds three tokens
  - Child takes one
- What's wrong with this code?

Almost solution

Adult thread

```
semaphore multiplex = 0;

// signal 3 times
signal(multiplex);
signal(multiplex);
signal(multiplex);
…
critical section
…
// wait 3 times
wait(multiplex);
wait(multiplex);
wait(multiplex);
```

Child thread

```
// wait for a token
wait(multiplex)
…
critical section
…
// signal
signal(multiplex)
```

- Potential deadlock!
  - Imagine 3 children and two adults arrive in the center
  - Value of multiplex is 3, so either adult should be able to leave
  - But if they start to leave at the same time, they will both block.
- Solve this problem...

Solution!

Adult thread

```
semaphore multiplex = 0;
semaphore mutex = 1;
// signal 3 times
signal(multiplex);
signal(multiplex);
signal(multiplex);
…
critical section
…
// wait 3 times
wait(mutex);
  wait(multiplex);
  wait(multiplex);
  wait(multiplex);
signal(mutex);
```

Child thread

```
// wait for a token
wait(multiplex)
…
critical section
…
// signal
signal(multiplex)
```

- Add a mutex for the adults leaving
  - Now the three wait operations are atomic. If there are three token available, adult thread with mutex will get all 3 tokens.

And for those with too much time...

Adult thread

```
semaphore multiplex = 0;
semaphore mutex = 1;
// signal 3 times
signal(multiplex);
signal(multiplex);
signal(multiplex);
…
critical section
…
// wait 3 times
wait(mutex);
  wait(multiplex);
  wait(multiplex);
  wait(multiplex);
signal(mutex);
```

Child thread

```
// wait for a token
wait(multiplex)
…
critical section
…
// signal
signal(multiplex)
```

- But in this solution an adult thread leaving can prevent children from entering…
  - E.g., 4 children and 2 adults. multiplex = 2, so adult leaving will take two tokens and block.
  - Child comes along, and cannot enter, even though it is legal!