Cooperating Threads and Synchronization

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COP 4610 Operating Systems

Teaching Assistants

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Outline

- Independent Threads
- Cooperating Threads
- Race Condition
- Loss of Atomicity
- Synchronization

Process

- An address space + at least one thread of execution
  - Address space offers protection among processes
  - Threads offer concurrency
- A fundamental unit of computation

This Is How Simple Operating Systems Are!

CPU Reset → Firmware (BIOS/UEFI) → Boot Loader (MBR, LILO/GRUB)

↓

Kernel_start()

↓

Process 1

↓

Application Program (state machine)
+
system call

↓ Process Management | ↓ Memory Management | ↓ File Management

Use **ls /sbin/init -l** to check if systemd is being used

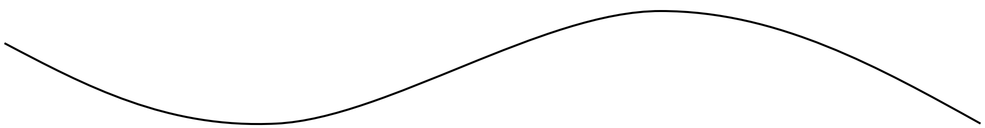
Read Latest Linux Kernel Code:
https://elixir.bootlin.com/linux/v6.10.9/source/init/main.c#L1523

- Process Management
  - fork, exec, and exit
- Memory Management
  - mmap –virtual address space
- File management
  - open, close, read, write
  - mkdir, link, unlink

You can use system call to create the world!

Thread

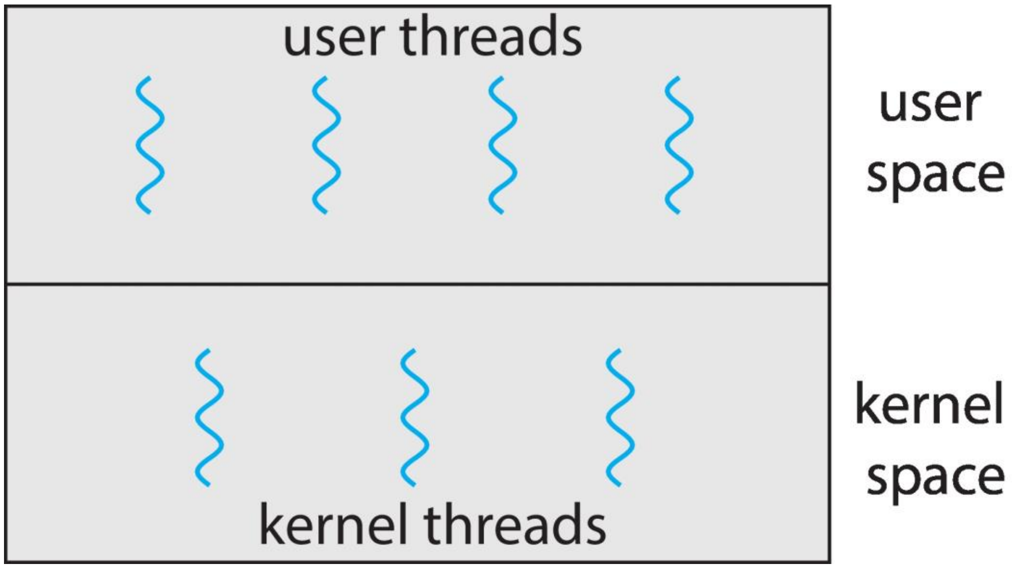
- A sequential execution stream
  - The smallest CPU scheduling unit
  - Can be programmed as if it owns the entire CPU
    - Implication: an infinite loop within a thread won't halt the system
  - Illusion of multiple CPUs on a single-CPU machine



Concurrency

- Allows multiple applications to run at the same time
  - Analogy: juggling

User and Kernel Threads



Independent Threads

- No states shared with other threads
- Deterministic computation
  - Output depends solely on the input
  - Same input always produces the same output
- Reproducible
  - Output does not depend on the order and timing of other threads
  - Scheduling order does not matter

Pthreads

- May be provided either as user-level or kernel-level
- A POSIX standard (IEEE 1003.1c) API for thread creation and synchronization
- ***Specification***, not ***implementation***
- API specifies behavior of the thread library, implementation is up to development of the library
- Common in UNIX operating systems (Linux & Mac OS X)

- pthread.h defines the interface for pthreads

Pthreads Example (Cont.)

```
#include <pthread.h>
#include <stdio.h>
#include <stdlib.h>

void *Ta(void *arg) {
  while (1) {
    printf("a");
  }
  return NULL;
}

void *Tb(void *arg) {
  while (1) {
    printf("b");
  }
  return NULL;
}
```

```
int main() {
  pthread_t thread1, thread2;

  if (pthread_create(&thread1, NULL, Ta, NULL) != 0) {
    fprintf(stderr, "Failed to create thread1\n");
    exit(1);
  }

  if (pthread_create(&thread2, NULL, Tb, NULL) != 0) {
    fprintf(stderr, "Failed to create thread2\n");
    exit(1);
  }

  pthread_join(thread1, NULL);
  pthread_join(thread2, NULL);

  return 0;
}
```

Pthreads Example (Cont.)

- The program utilizing pthread.h can be written to take advantage of multiple processors!
- The operating system will automatically place threads on different processors.
- When running in the background, you can observe the CPU usage exceeding 100%.

Concurrent Programming in HPC

- The World's Most Expensive Sofa
  - The First Supercomputer (1976)
  - Single-processor system
  - 138 million FLOPs (Floating Point Operations per Second)
    - 40 times faster than IBM 370 at the time
    - Slightly better than embedded chips today
  - Processed large data sets with one instruction

Features of HPC

> "A technology that harnesses the power of supercomputers or computer clusters to solve complex problems requiring massive computation."
>
> (IBM)

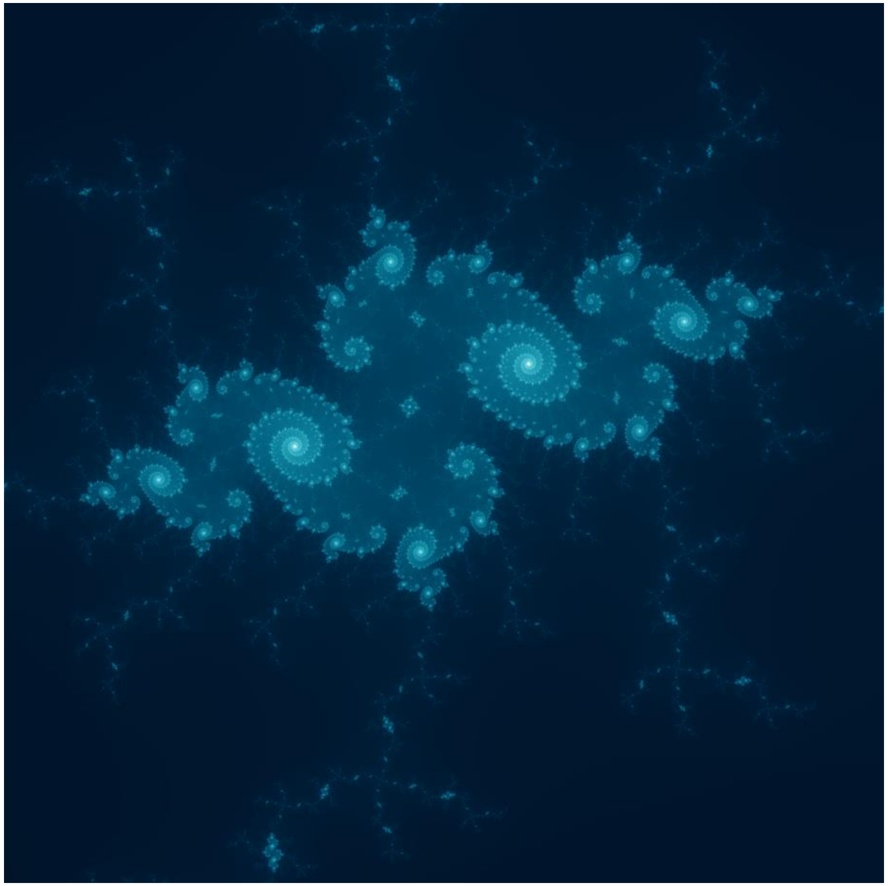
- Computation-Centric
  - System Simulation: Weather forecasting, energy, molecular biology
  - Artificial Intelligence: Neural network training
  - Mining: Pure hash computation
  - TOP 500 (https://www.top500.org/)
    - 1st: Frontier (8, 699,904 cores, 1206 PFLOS)

Main Challenges of HPC

- How to Break Down Computation Tasks?
  - Computation Graphs need to be easy to parallelize
    - Task decomposition happens on two levels: machine and thread
  - Parallel and Distributed Computation: Numerical Methods

- How Do Threads Communicate?
  - Communication happens not only between nodes/threads but also with any shared memory access
  - MPI - "a specification for developers and users of message-passing libraries"
  - OpenMP - "multi-platform shared-memory parallel programming in C/C++ and Fortran“

Example: Mandelbrot Set



$$z_{n+1} = z_n^2 + c$$

Each point in the Mandelbrot set iterates independently and is only influenced by its complex coordinate

Cooperating Threads

- Shared states (address space -> memory)
  - The Root of All Evil
- Nondeterministic
  - Output depends on **input and other factors**
- Nonreproducible
  - Same input can produce **different outputs** in different runs
  - Influenced by factors such as thread scheduling, randomness, or external environment

Example: Share Memory

```
#include <pthread.h>
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>

#define NTHREAD
int x = 0;
pthread_t threads[NTHREAD];

void *Thello(void *arg) {
 int id = *(int *)arg;
 usleep(id * 100000);
 printf("Hello from thread #%c\n", "123456789ABCDEF"[x++]);
 return NULL;
}
```

```
int main() {
 int ids[NTHREAD];

 for (int i = 0; i < NTHREAD; i++) {
  ids[i] = i + 1;
  if (pthread_create(&threads[i], NULL, Thello, &ids[i]) != 0) {
   fprintf(stderr, "Error creating thread %d\n", i);
   return 1;
  }
 }

 for (int i = 0; i < NTHREAD; i++) {
  pthread_join(threads[i], NULL);
 }

 return 0;
}
```

Example: Share Memory

```
#include <pthread.h>
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>

#define NTHREAD
int x = 0;
pthread_t threads[NTHREAD];

void *Thello(void *arg) {
  int id = *(int *)arg;
  usleep(id * 100000);
  printf("Hello from thread #%c\n", "123456789ABCDEF"[x++]);
  return NULL;
}
```

```
int main() {
  int ids[NTHREAD];

  for (int i = 0; i < NTHREAD; i++) {
    ids[i] = i + 1;
    if (pthread_create(&threads[i], NULL, Thello, &ids[i]) != 0) {
      fprintf(stderr, "Error creating thread %d\n", i);
      return 1;
    }
  }

  for (int i = 0; i < NTHREAD; i++) {
    pthread_join(threads[i], NULL);
  }

  return 0;
}
```

So, Why Allow Cooperating Threads?

So, Why Allow Cooperating Threads?

- Shared resources
  - e.g., a single processor
- Speedup
  - Occurs when threads use different resources at the same times
- Modularity
  - An application can be decomposed into threads

However, Something Terrifying is Approaching..

- In a multiprocessor system, threads may execute code simultaneously.

- What will happen if two threads execute x++ at the same time?

Atomic Operations

- Atomicity refers to an operation or a sequence of operations that either completes fully or does not execute at all, without being interrupted by other operations during execution.
- It guarantees the indivisibility of an operation, ensuring that it cannot be partially completed or interrupted by another thread or process

- Key Characteristics:
  - Indivisibility: Atomic operations cannot be divided; no other thread or process can see or modify the operation's intermediate state.
  - Completeness: An atomic operation either fully succeeds and completes all its tasks, or it does not execute at all. There is no partial state.
  - No Interference: In a multi-threaded environment, atomic operations are not affected or interrupted by other threads.

Examples of Atomic Operations

- Simple Operation:
  - On most processors, an operation like int x = 1; is atomic because it involves a single memory action that cannot be interrupted.

- Non-Atomic Operation:
  - Operations like x++ involve multiple steps:
    - Read the current value of x.
    - Increment x by 1.
    - Write the new value back to x.

Some Concurrent Programs

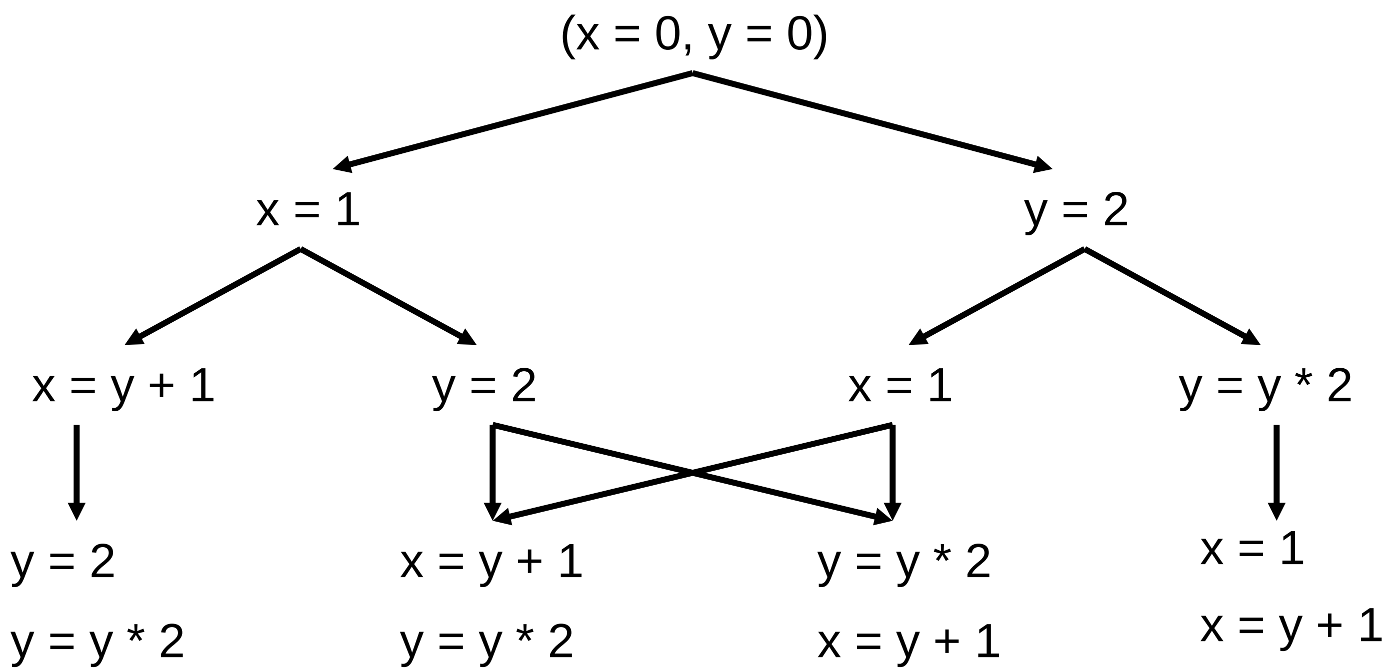
- If threads share data, the final values are not as obvious

Thread A	Thread B
x = 1;	y = 2;
x = y + 1;	y = y * 2;

- What are the indivisible operations?

All Possible Execution Orders

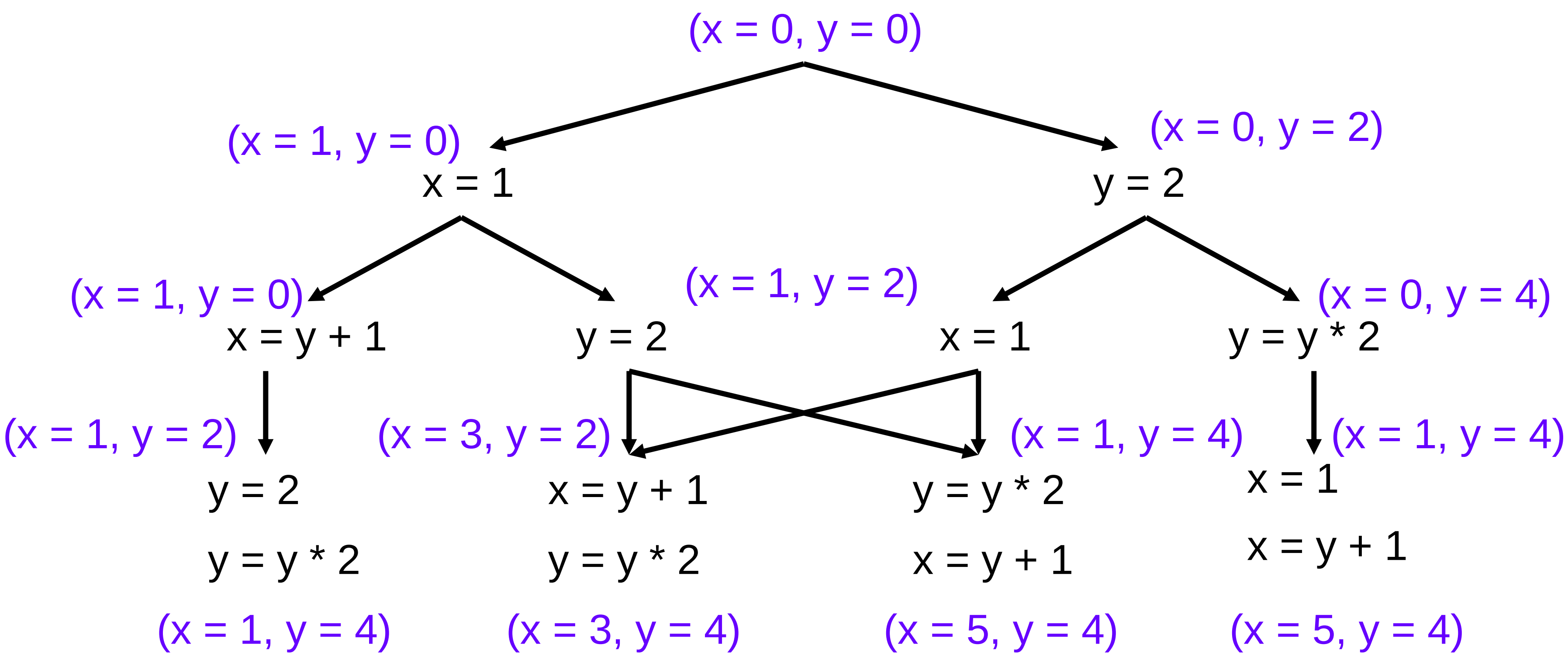
Thread A	Thread B
x = 1;	y = 2;
x = y + 1;	y = y * 2;



A decision tree

All Possible Execution Orders

Thread A	Thread B
x = 1;	y = 2;
x = y + 1;	y = y * 2;



Race Condition

- Race conditions occur when threads share data, and their results depend on the timing of their execution.

- If we replace the x++ operation in C with a single assembly instruction…
  - The atomicity of the operation is lost, as x++ is not a single instruction but a series of steps (load, increment, store).

- Can this lead to race conditions in multithreaded environments?

- The atomicity of the operation is still lost.

Loss of Atomicity in Modern Multiprocessor Systems

- The basic assumption that "a program (or even a single instruction) exclusively executes on the processor" no longer holds true in modern multiprocessor systems.

- Single Processor, Multithreading:
  - A thread may be interrupted and switched to another thread during execution.
- Multiprocessor, Multithreading:
  - Threads are executed truly in parallel.

- Historical Context (1960s):
  - There was a race to implement atomicity (mutual exclusion) in shared memory systems.
  - Almost all implementations were flawed until Dekker's Algorithm, which could only ensure mutual exclusion between two threads.

Concurrent Programming in Data Centers

- Google Data Center

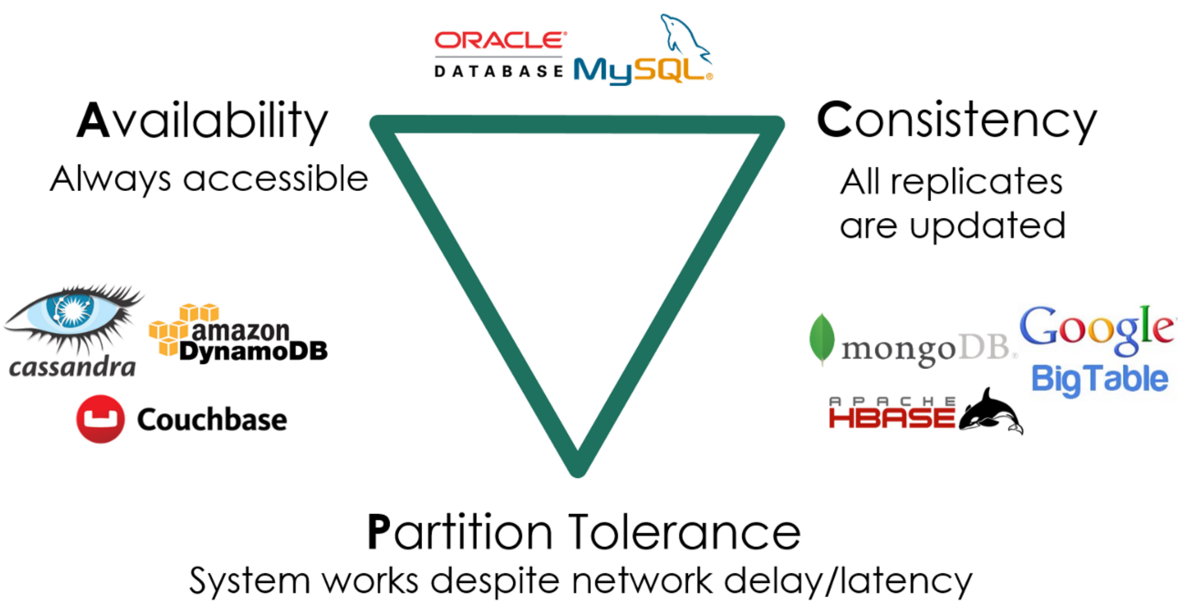
Features of Data Center

> “A network of computing and storage resources that enable the delivery of shared applications and data.”
>
> (CISCO)

- Data-Centric (Storage-Focused) Approach
  - Originated from internet search (Google), social networks (Facebook/Twitter)
  - Powers various internet applications: Gaming/Cloud Storage/ WeChat/Alipay/…
- The Importance of Algorithms/Systems for HPC and Data Centers
  - You manage 1,000,000 servers
  - A 1% improvement in an algorithm or implementation can save 10,000 servers

Main Challenges of Data Center

- Highly Reliable and Low-Latency Data Access in Multi-Replica Systems
  - Serving massive, geographically distributed requests
  - Data must remain consistent (Consistency)
  - Services must always be available (Availability)
  - Must tolerate machine failures (Partition Tolerance)



How to Maximize Parallel Request Handling with a Single Machine

- Key Metrics: QPS, Tail Latency, ...

- Tools We Have
  - Threads

```
thread(start = true) {
   println("${Thread.currentThread()} has run.")
}
```

  - Coroutines
    - Multiple execution flows that can be paused/resumed (M2 - libco)
    - More lightweight than threads (no system calls, thus no OS state)
  - GO
    - Threads + Coroutines

Concurrent Programming Around Us

- Web 2.0 Era (1999)
  - The Internet that connects people more closely.
  - “Users were encouraged to provide content, rather than just viewing it.”
  - You can even find some traces of “Web 3.0” / Metaverse.

- What Enabled Today’s Web 2.0?
  - Concurrent Programming in Browsers: Ajax (Asynchronous JavaScript + XML)
  - HTML (DOM Tree) + CSS
    - Represent everything you can see
  - JavaScript
    - Modify the page content
    - Connect local and server resources
  - You have the whole world at your fingertips!

Features of Human-Computer Interaction

- As few concurrent tasks as possible, but just enough to meet requirements.
- One thread, a global event queue, and sequential execution.
- Run-to-completion: Each task runs to completion before the next one starts.

Concurrent Programming - Real-world Applications

- High-Performance Computing
  - Focus: Task Decomposition
  - Pattern: Producer-Consumer
  - Technologies: MPI / OpenMP
- Data Centers
  - Focus: System Calls
  - Pattern: Threads-Coroutines
  - Technologies: Goroutine
- Human-Computer Interaction
  - Focus: Usability
  - Pattern: Event-Stream Graph
  - Technologies: Promise.

Motivating Example: Too Much Milk

- Two robots are programmed to maintain the milk inventory at a store…
- They are not aware of each other's presence…

Robot: Dumb

Robot: Dumber

Motivating Example: Too Much Milk

Dumb | Dumber

10:00 Look into fridge:

Out of milk

Motivating Example: Too Much Milk

Dumb

10:00 Look into fridge:

Out of milk

10:05 Head for the warehouse

Dumber

Motivating Example: Too Much Milk

Dumb

10:05 Head for the warehouse

Dumber

10:10 Look into fridge: Out of milk

Motivating Example: Too Much Milk

Dumb

Dumber

10:10 Look into fridge:

Out of milk

10:15 Head for the warehouse

Motivating Example: Too Much Milk

Dumb

10:20 Arrive with milk

Dumber

10:15 Head for the warehouse

Motivating Example: Too Much Milk

Dumb

Dumber

10:15 Head for the warehouse

10:20 Arrive with milk

Motivating Example: Too Much Milk

Dumb		Dumber
10:20	Arrive with milk	
10:25	Go party	

Motivating Example: Too Much Milk

Dumb

10:20 Arrive with milk

10:25 Go party

Dumber

10:30 Arrive with milk:
“Uh oh…”

Definitions

- ***Synchronization***: uses atomic operations to ensure cooperation among threads
- ***Mutual exclusion***: ensures one thread can do something without the interference of other threads
- ***Critical section***: a piece of code that only one thread can execute at a time

More on Critical Section

- A ***lock*** prevents a thread from doing something
  - A thread should lock before entering a critical section
  - A thread should unlock when leaving the critical section
  - A thread should wait if the critical section is locked
    - Synchronization often involves waiting

Too Much Milk: Solution 1

- Two properties:
  - Only one robot will go get milk
  - Someone should go get the milk if needed
- Basic idea of solution 1
  - Leave a note (kind of like a lock)
  - Remove the note (kind of like a unlock)
  - Don’t go get milk if the note is around (wait)

Too Much Milk: Solution 1

```
if (no milk) {
 if (no note) {
    // leave a note;
    // go get milk;
    // remove the note;
 }
}
```

Too Much Milk: Solution 1

Dumb

```
10:00 if (no milk) {
```

Dumber

Too Much Milk: Solution 1

Dumb

```
10:00 if (no milk) {
```

Dumber

```
10:01 if (no milk) {
```

Too Much Milk: Solution 1

Dumb

```
10:00 if (no milk) {
```

Dumber

```
10:01 if (no milk) {
10:02   if (no note) {
```

Too Much Milk: Solution 1

Dumb

```
10:00 if (no milk) {
10:03   if (no note) {
```

Dumber

```
10:01 if (no milk) {
10:02   if (no note) {
```

Too Much Milk: Solution 1

Dumb

```
10:00 if (no milk) {
10:03   if (no note) {
10:04     // leave a note
```

Dumber

```
10:01 if (no milk) {
10:02   if (no note) {
```

Too Much Milk: Solution 1

Dumb

```
10:03   if (no note) {
10:04     // leave a note
```

Dumber

```
10:01 if (no milk) {
10:02   if (no note) {
10:05     // leave a note
```

Too Much Milk: Solution 1

Dumb

```
10:03   if (no note) {
10:04     // leave a note

10:06     // go get milk
```

Dumber

```
10:02   if (no note) {

10:05     // leave a note
```

Too Much Milk: Solution 1

Dumb

```
10:03   if (no note) {
10:04     // leave a note
10:06     // go get milk
```

Dumber

```
10:05     // leave a note
10:07     // go get milk
```

Too Much Milk: Solution 2

- Okay…solution 1 does not work
- The notes are posted too late…
- What if both robots begin by leaving their own notes?

Too Much Milk: Solution 2

```
// leave a note;
if (no note from the other) {
 if (no milk) {
    // go get milk;
 }
}
// remove the note;
```

Too Much Milk: Solution 2

Dumb

```
10:00 // leave a note
```

Dumber

Too Much Milk: Solution 2

Dumb

```
10:00 // leave a note
```

Dumber

```
10:01 // leave a note
```

Too Much Milk: Solution 2

Dumb

```
10:00 // leave a note

10:02 if (no note from
 Dumber) {…}
```

Dumber

```
10:01 // leave a note
```

Too Much Milk: Solution 2

Dumb

`10:00 // leave a note`

`10:02 if (no note from Dumber) {…}`

Dumber

`10:01 // leave a note`

`10:03 if (no note from Dumb) {…}`

Too Much Milk: Solution 2

Dumb

```
10:00 // leave a note

10:02 if (no note from
 Dumber) {…}

10:04 // remove the note
```

Dumber

```
10:01 // leave a note

10:03 if (no note from Dumb)
 {…}
```

Too Much Milk: Solution 2

Dumb

```
10:00 // leave a note

10:02 if (no note from
 Dumber) {…}

10:04 // remove the note
```

Dumber

```
10:01 // leave a note

10:03 if (no note from Dumb)
  {…}
```

Too Much Milk: Solution 2

Dumb

```
10:02 if (no note from
  Dumber) {…}

10:04 // remove the note
```

Dumber

```
10:01 // leave a note

10:03 if (no note from Dumb)
  {…}

10:05 // remove the note
```

Too Much Milk: Solution 2

Dumb

```
10:02 if (no note from
 Dumber) {…}

10:04 // remove the note
```

Dumber

```
10:01 // leave a note

10:03 if (no note from Dumb)
  {…}

10:05 // remove the note
```

Too Much Milk: Solution 2

- Solution 2 does not work
- The notes are found too late…
- What if both robots wait for the other to leave a note?

Too Much Milk: Solution 3

Dumb

```
// leave Dumb's note
while (Dumber's note) { };
if (no milk) {
 // go get milk
}
// remove Dumb's note
```

Dumber

```
// leave Dumber's note
if (no Dumb's note) {
  if (no milk) {
    // go get milk
  }
}
// remove Dumber's note
```

Too Much Milk Solution 3

- How do we verify the correctness of a solution?
- Test arbitrary interleaving of locking and checking locks
  - In this case, leaving notes and checking notes

Dumber Challenges Dumb: Case 1

Dumb

```
// leave Dumb's note
while (Dumber's note) { };
if (no milk) {
  // go get milk
}
// remove Dumb's note
```

Dumber

```
// leave Dumber's note
if (no Dumb's note) {
}
// remove Dumber's note
```

Time

Dumber Challenges Dumb: Case 2

Dumb

```
// leave Dumb's note

while (Dumber's note) { };

if (no milk) {
  // go get milk
}
// remove Dumb's note
```

Dumber

```
// leave Dumber's note

if (no Dumb's note) {
}
// remove Dumber's note
```

Time

Dumber Challenges Dumb: Case 3

Dumb

```
// leave Dumb's note

while (Dumber's note) { };

if (no milk) {
  // go get milk
}
// remove Dumb's note
```

Dumber

```
// leave Dumber's note
if (no Dumb's note) {
}
// remove Dumber's note
```

Time

Dumb Challenges Dumber: Case 1

Dumb

```
// leave Dumb's note
while (Dumber's note) { };
if (no milk) {
}
// remove Dumb's note
```

Dumber

```
// leave Dumber's note
if (no Dumb's note) {
  if (no milk) {
    // go get milk
  }
}
// remove Dumber's note
```

Time

Dumb Challenges Dumber: Case 2

Dumb

```
// leave Dumb's note

while (Dumber's note) { };

if (no milk) {
  // go get milk
}
// remove Dumb's note
```

Dumber

```
// leave Dumber's note

if (no Dumb's note) {
}
// remove Dumber's note
```

Time

Dumb Challenges Dumber: Case 3

Time

Dumb

```
// leave Dumb's note
while (Dumber's note) { };

if (no milk) {
  // go get milk
}
// remove Dumb's note
```

Dumber

```
// leave Dumber's note

if (no Dumb's note) {
}
// remove Dumber's note
```

Lessons Learned

- Although it works, Solution 3 is ugly
  - Difficult to verify correctness
  - Two threads have different code
    - Difficult to generalize to N threads
  - While Dumb is waiting, it consumes CPU time (***busy waiting***)
- More elegant with higher-level primitives

```
lock→acquire();
if (no milk) { // go get milk }
lock→release();
```

Takeaways

- Independent Threads
- Cooperating Threads
- Race Condition
- Loss of Atomicity
- Synchronization