Concurrency

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Concurrency

- Concurrency (an informal term): doing multiple things at the same time
  - Program decomposition into order-independent chunks
- On UNIX concurrency is easy
  - Multiple processes *can* be running simultaneously
  - Multiple copies of the same program can be running
  - CPU time can be split and shared

- Concurrency is very powerful
  - Greatly increases the efficiency of an OS: while one process is waiting for I/O, another process can use the CPU

Definitions: System Calls vs. Library Functions

- System Calls
  - A request for service that causes the normal operation of a process to be *interrupted* and control passed to the OS
  - Typically, the process is now blocked and won't do anything else until the system call returns
  - read(), write(), etc.

- C Library Functions
  - Faster, as they have no permissions or blocking issues
  - sqrt(), printf(), etc.

Illusions of Simultaneous Execution

- Multiprogramming
  - More than one process can be ready to execute
  - System calls trigger “context switches”, which let the next process run
  - The process will not execute again until its system call returns

- Timesharing
  - CPU time split between multiple processes
    - Gives illusion that many processes are running at once

Processes can also communicate amongst themselves - more on this later

Multiprocessing

- Executing multiple processes at the actual same time is called **multiprocessing**

- Today's CPUs have 4, 6, 8, and 10 cores, with more coming
  - Each core acts like a mini-CPU, each of which can do **multiprogramming** AND **timesharing**

Possible Complications

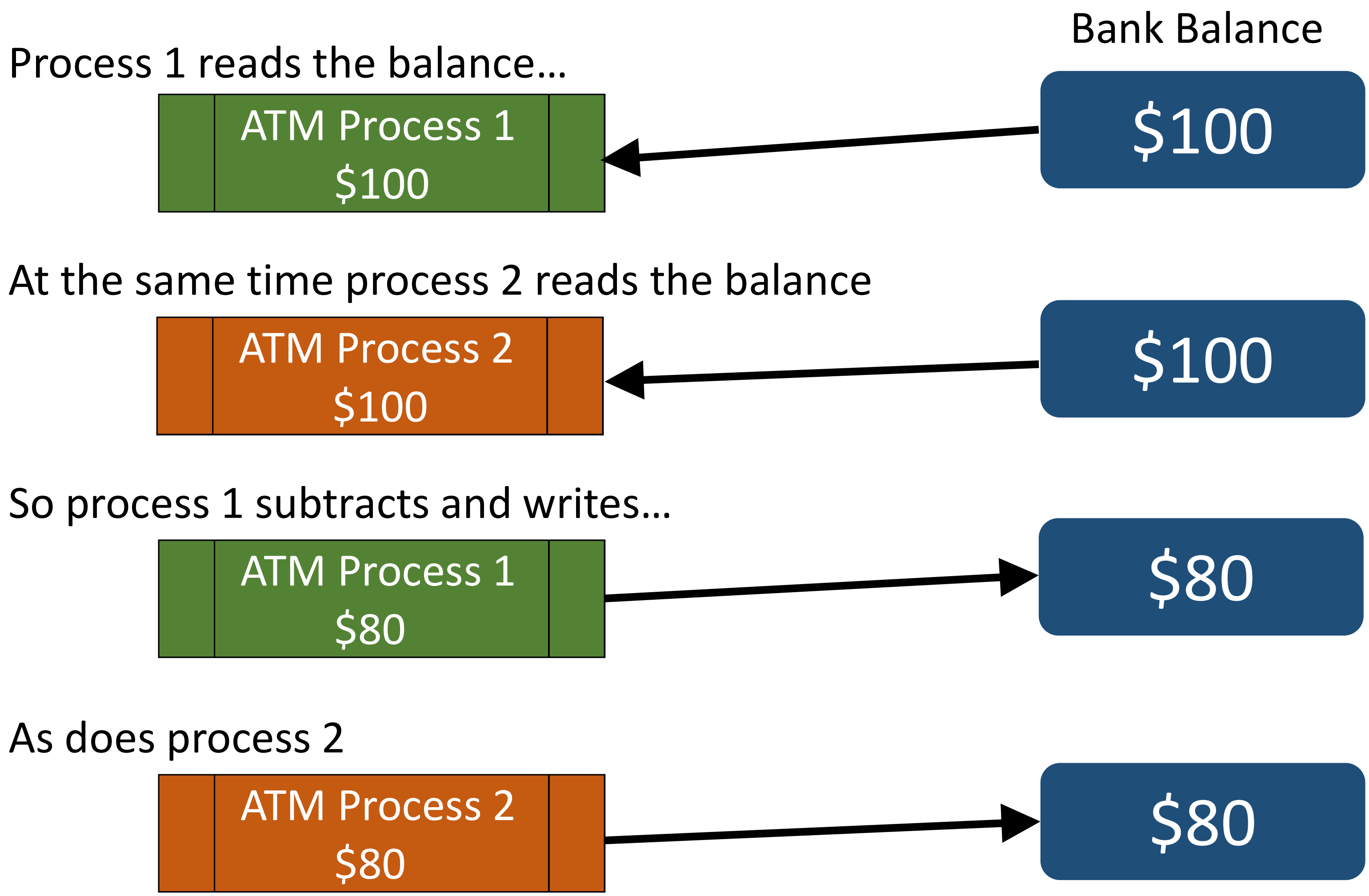
- Concurrently running processes can share data and/or resources
- What if multiple processes access the same resource at the same time?
- This is most likely a disaster
  - aka, “Race Condition”, “Oops”, or “Aw carp”

The Classic Example

- Two ATM machines each withdraw $20 from the same account

- To update bank account balance:
  - Read current balance into memory
  - Subtract $20
  - Write new balance to the bank account

…
Profit!
…
$#!@7


Bank Balance
Process 1 reads the balance…
ATM Process 1
$100
$100
At the same time process 2 reads the balance
ATM Process 2
$100
$100
So process 1 subtracts and writes…
ATM Process 1
$80
$80
As does process 2
ATM Process 2
$80
$80

Race conditions

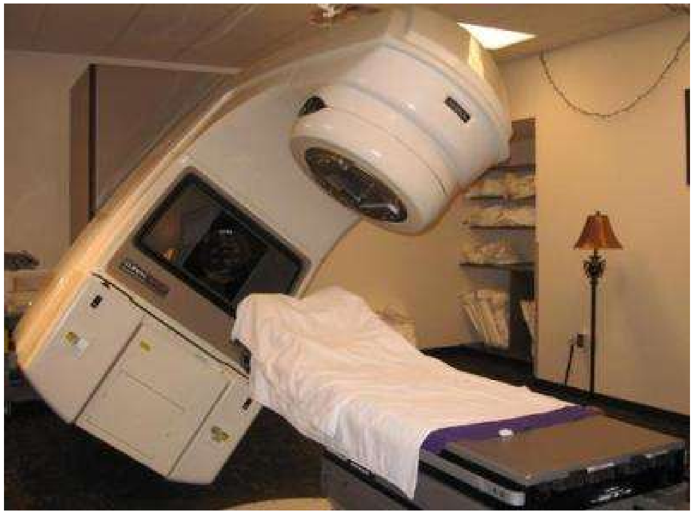
- Why are race conditions hard to detect?
  - They may only ever show up once, in a particularly strange set of conditions

- Another way of saying it: “A race hazard (or race condition) is a flaw in a system or process where the output exhibits unexpected critical **dependence** on the relative timing of events.”

  -Wikipedia

The Seriousness of Software Engineering

- Most infamous race condition:
  - http://en.wikipedia.org/wiki/Therac_25
- People could outrun the system
  - The system was counting on a normally slow human, and didn't take into account people learning to use the system faster
- 3 people died, and 3 were injured as a result of this software engineering disaster



http://hackaday.com/2015/10/26/killed-by-a-machine-the-therac-25

The Lesson - Provide Access Control

- Concurrent update situation
  - 2+ processes accessing resource concurrently
  - At least one process might write
- **Must provide access control**
  - If one process is writing, no other process should access (read OR write) the resource
- "Locks" solve these problems
  - Only process owning the lock may access (r/w) the resource
  - Many ways to do locking
  - Locking usually requires support from the OS
    - But you can do it in software, too

Access Control with a Lock File

```
do
{
   lock_fd = open(lock_file_path, O_WRONLY | O_CREAT | O_EXCL, 0644);

   if (lock_fd == -1)
   {
      if (errno == EEXIST)
      {
         // File already exists - wait a while, then try again
         sleep(1);
      }
      else
      {
         // An unexpected error - bail out
         perror("Couldn't open lock file\n");
         return(-1);
      }
   }
}
while (lock_fd == -1);
```

Deeper Definitions

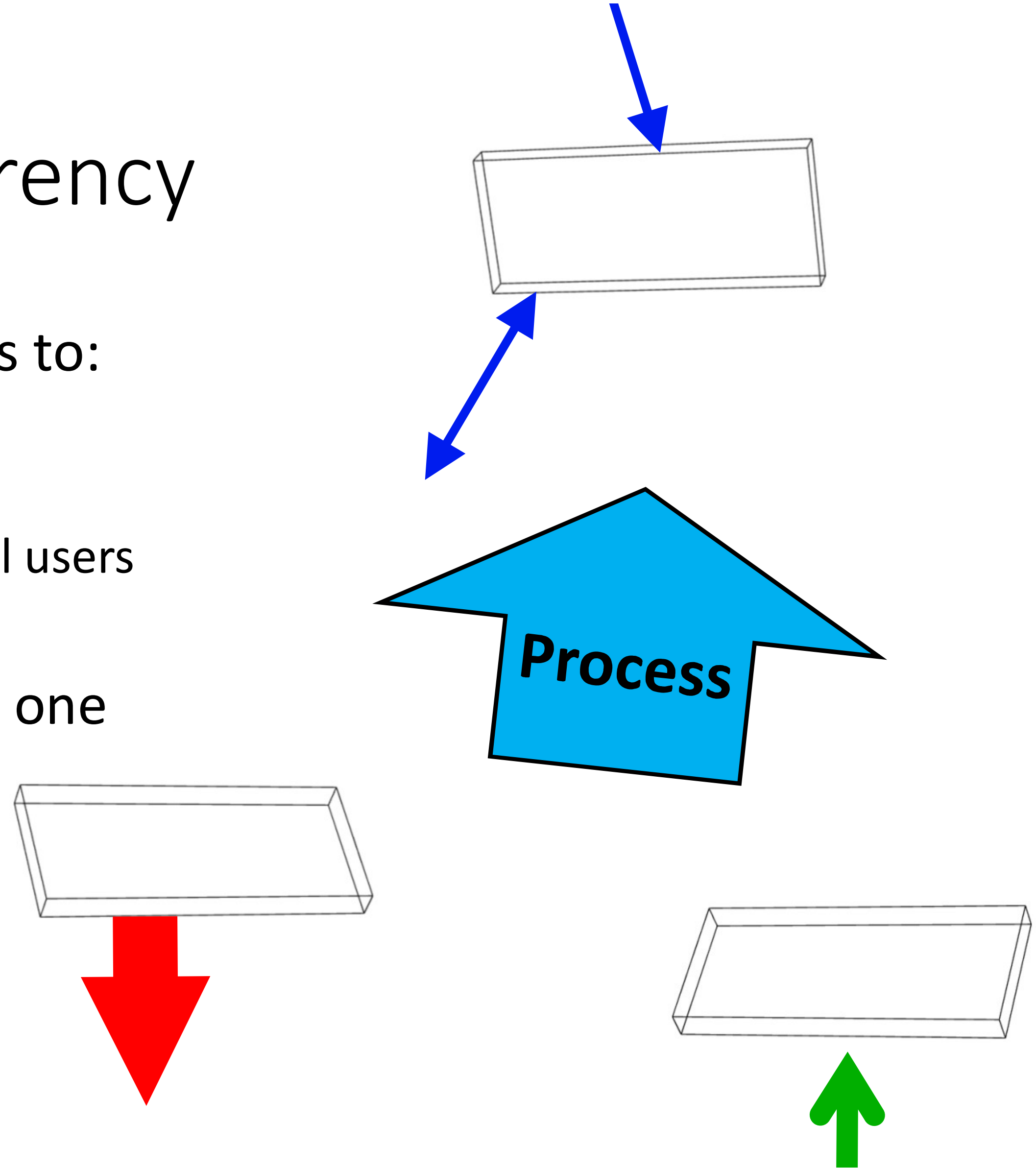
- Kernel
  - The central part of an Operating System
  - Manages hardware (and drivers)
  - Provides the Scheduler
  - Not interacted with by users: system calls are requests to the kernel

- Scheduler
  - Distributes prioritized and/or fair CPU time

Process-Level Concurrency

- Imagine a chat server that needs to:
  - Watch for users connecting
  - Send chat output to all users
  - Receive chat input from individual users

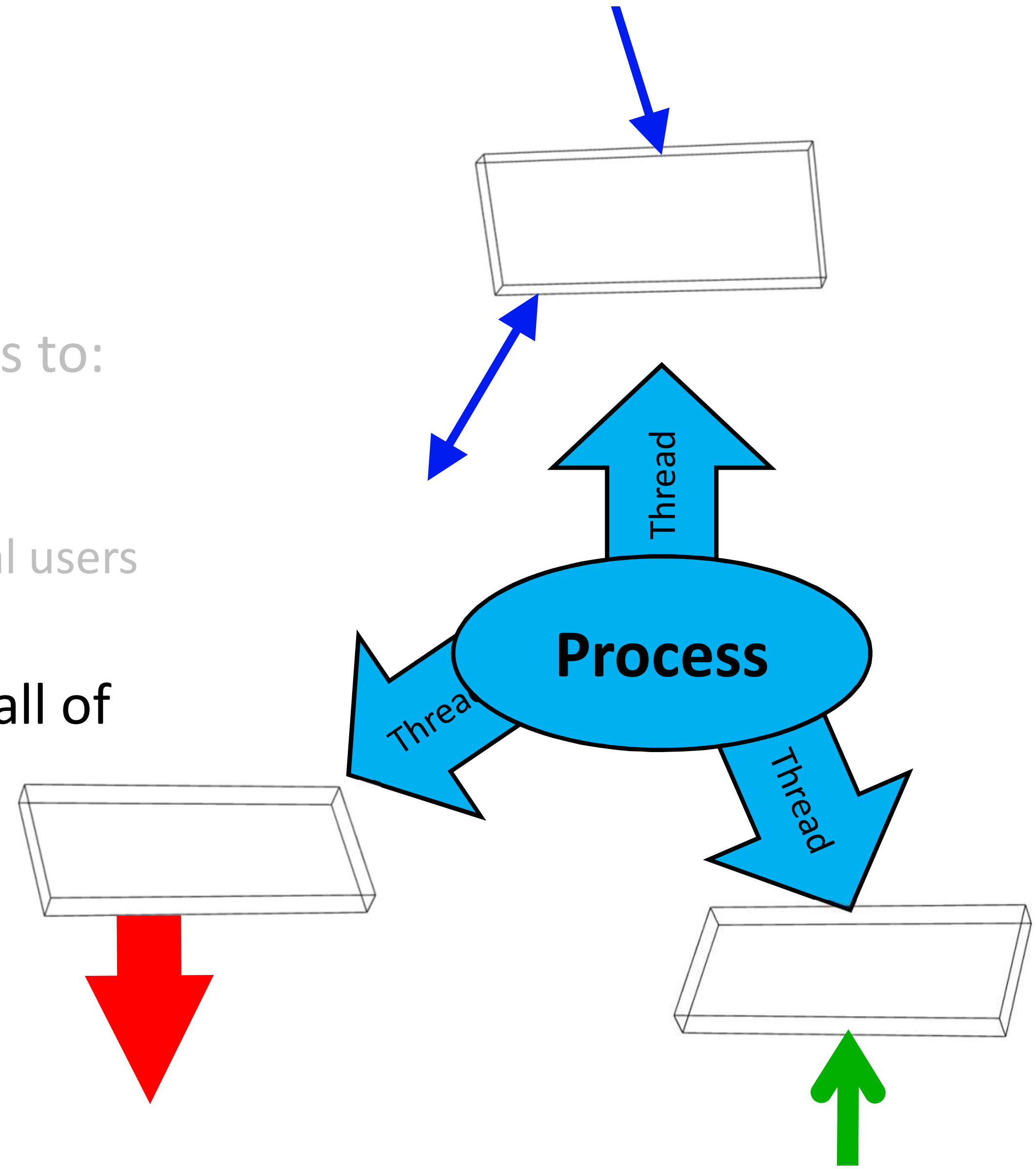
- But a single **process** can only do one of these things at a time!



Enter Threads

- Imagine a chat server that needs to:
  - Watch for users connecting
  - Send chat output to all users
  - Receive chat input from individual users

- **Threads** allows a process to do all of these things at the same time



Thread Advantages over Processes

- Communication between threads is vastly simpler than IPC:
  - Threads share the following:
    - Code, Heap, Data
  - They each have their own Stack, but they can access the Stacks of other threads(!)
- The CPU switches between executing threads much faster than switching between processes, because of what’s shared above
  - On a multi-core CPU, the CPU can run each kernel-level thread on a separate core, yielding true concurrence

Thread Disadvantages

- Shared resources means increased possibilities of:
  - Race conditions
  - Resource contention, including file access
  - Leaking of sensitive data across threads

Types of Threads

- Kernel-Level Threads
  - Controlled by the kernel, given time by the scheduler
  - Akin to a mini-process

- User-Level Threads
  - The kernel doesn’t know about these – they are entirely within a process and do not involve the scheduler; switching between them is done cooperatively by the protocol of the software itself to manage the task
  - Really just *emulation* of threading
  - Sometimes called green threads

Thread Type Comparison

- Kernel-Level Threads
  - Controlled by the kernel, given time by the scheduler
  - Simple to create with built-in libraries in UNIX
  - Generally considered the better choice in almost all circumstances
- User-Level Threads
  - Switching between user-level threads is even faster than switching between kernel-level threads, because it doesn't require swapping memory protection to the in-kernel scheduler and back to the process
  - The entire process can be pre-empted by the scheduler
  - A blocking system call blocks the entire process, and thus all of the threads
  - More difficult to use; libraries aren't built-in to UNIX

Thread Implementation in UNIX

- Implemented with the POSIX Threads API in UNIX

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

Compile with `–lpthread` option in `gcc`

Creating a Thread

```
int pthread_create(     pthread_t* thread,
                        const pthread_attr_t* attr,
                        void* (*start_routine) (void *),
                        void* arg
                  );
```

- **`thread`**: points to the variable in which the ID of the new thread is written into; depending on OS implementation, sometimes this is an int, sometimes it's a struct

Creating a Thread

```
int pthread_create(     pthread_t* thread,
                        const pthread_attr_t* attr,
                        void* (*start_routine) (void *),
                        void* arg
                  );
```

- **`attr`**: points to a `pthread_attr_t` struct that contains option flags (`NULL` if none)

Creating a Thread

```
int pthread_create(     pthread_t* thread,
                        const pthread_attr_t* attr,
                        void* (*start_routine) (void *),
                        void* arg
                  );
```

- **`start_routine`**: points to a function (in the current program) that will be the start point of execution for the *new* thread that copies this one

Similar to `fork()`, which we'll cover later

Creating a Thread

```
int pthread_create(     pthread_t* thread,
                        const pthread_attr_t* attr,
                        void* (*start_routine) (void *),
                        void* arg
                  );
```

- **`arg`**: points to the sole argument that is passed into `start_routine` (`NULL` if none); if multiple arguments are desired, pass a struct

Creating a Thread - Example

```
int resultInt;
pthread_t myThreadID;

resultInt =  pthread_create( &myThreadID,
             NULL,
             start_routine,
             NULL );
```

Destroying a Thread

- Threads can be killed by:
  - The thread calling `pthread_exit()`
  - The thread returns from `start_routine()`
  - The thread gets cancelled by another thread calling `pthread_cancel()`
  - Any thread in the process calls `exit()`

Identifying the Executing Thread

- Here's the function for getting the "thread ID" of an executing thread; note that this ID is not necessarily an integer:

```
pthread_t myThreadID = pthread_self();
```

- Testing for equality:

```
pthread_equal(myThreadID, unknownThreadID);
```

Thread Example – Page 1 of 3

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

#define NUM_THREADS     5

void* perform_work(void* argument)
{
   int passed_in_value;

   passed_in_value = *((int *) argument);
   printf("Hello World! It's me, thread with argument %d!\n", passed_in_value);
   return NULL;
}
```

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```
int main(void)
{
   pthread_t threads[NUM_THREADS];
   int thread_args[NUM_THREADS];
   int result_code, index;

   for (index = 0; index < NUM_THREADS; ++index) {
      // create all threads one by one
      thread_args[index] = index;
      printf("In main: creating thread %d\n", index);
      result_code = pthread_create(&threads[index], NULL,
                                    perform_work, (void *) &thread_args[index]);
      assert(0 == result_code);
   }
…
```

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```
…
   // wait for each thread to complete
   for (index = 0; index < NUM_THREADS; ++index)
   {
      result_code = pthread_join(threads[index], NULL);
      printf("In main: thread %d has completed\n", index);
      assert(0 == result_code);
   }

   printf("In main: All threads completed successfully\n");
   exit(EXIT_SUCCESS);
}
```

Block until thread 'index' completes

Thread Example - Results

```
$ gcc -o threadtest threadtest.c -lpthread
$ threadtest
In main: creating thread 0
In main: creating thread 1
In main: creating thread 2
Hello World! It's me, thread with argument 0!
In main: creating thread 3
Hello World! It's me, thread with argument 1!
Hello World! It's me, thread with argument 2!
In main: creating thread 4
Hello World! It's me, thread with argument 3!
In main: thread 0 has completed
In main: thread 1 has completed
In main: thread 2 has completed
Hello World! It's me, thread with argument 4!
In main: thread 3 has completed
In main: thread 4 has completed
In main: All threads completed successfully
```

Mutexes

- An abbreviation for "mutual exclusion"
- Implemented as part of the POSIX `pthread` API to provide thread synchronization via "locks"
- Provides the programmer the ability to protect data from multiple reads and writes on the same files
- There are several types which check variously for errors, perform faster, etc.

The Lifespan of a Mutex

```
pthread_mutex_t myMutex = PTHREAD_MUTEX_INITIALIZER;
pthread_mutex_destroy(myMutex);
```

Mutex Locking

- A thread acquires a lock on a mutex variable by attempting to call a special lock function:

```
pthread_mutex_t myMutex = PTHREAD_MUTEX_INITIALIZER;
pthread_mutex_lock(myMutex);
```

- Once the mutex is locked, any other thread attempting to lock it will block!

Mutex Unlocking

- A thread unlocks a mutex variable *that it has previously locked* like so:

```
pthread_mutex_unlock(myMutex);
```

- Once unlocked, one of the other blocked threads (chosen essentially randomly) currently blocked on the mutex will unblock and gain the lock

- A non-blocking attempt to lock the mutex:

```
int resultCode = pthread_mutex_trylock(myMutex);
```

Mutexes Generalized

- A mutex is a form of *semaphore*, which come in two types:
  - Counting semaphore
    - Allow some sort of arbitrary resource count, e.g number of available buffers
  - Binary semaphore
    - Equal to 1 or 0, indicating locked/unavailable or unlocked/available

- Invented by Edsger Dijkstra in 1962 or 1963
  - More on him later!