Concurrency: Running Together

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Methods & Tools for Software Engineering (MTSE)
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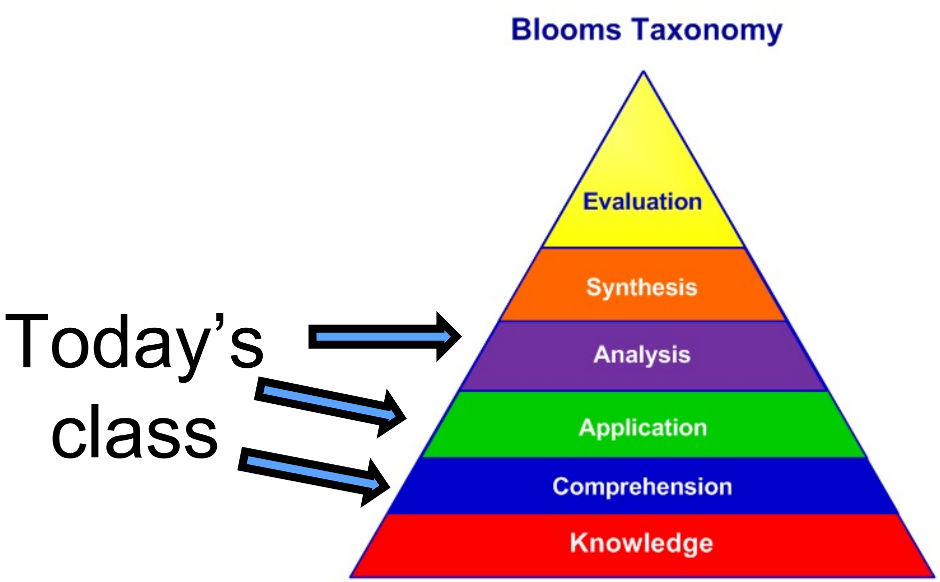
Learning Objectives

- By the end of this lecture you will be able to:
  - Explain the benefits of multiprogramming and multithreading
  - Apply multiprogramming and multithreading to run different tasks concurrently
  - Analyze different sources of concurrency issues and how to resolve them



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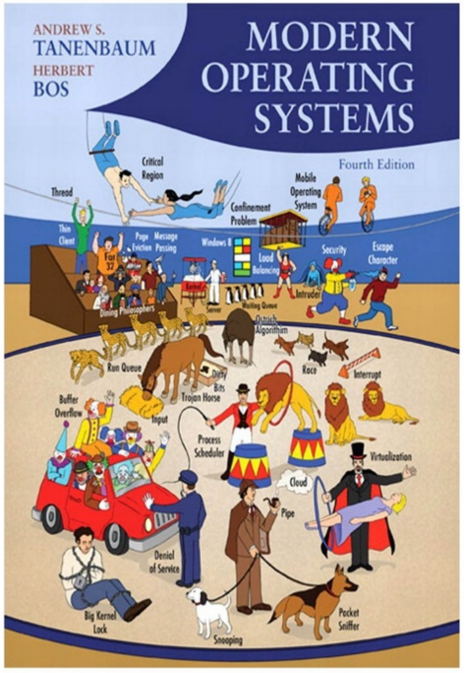
References

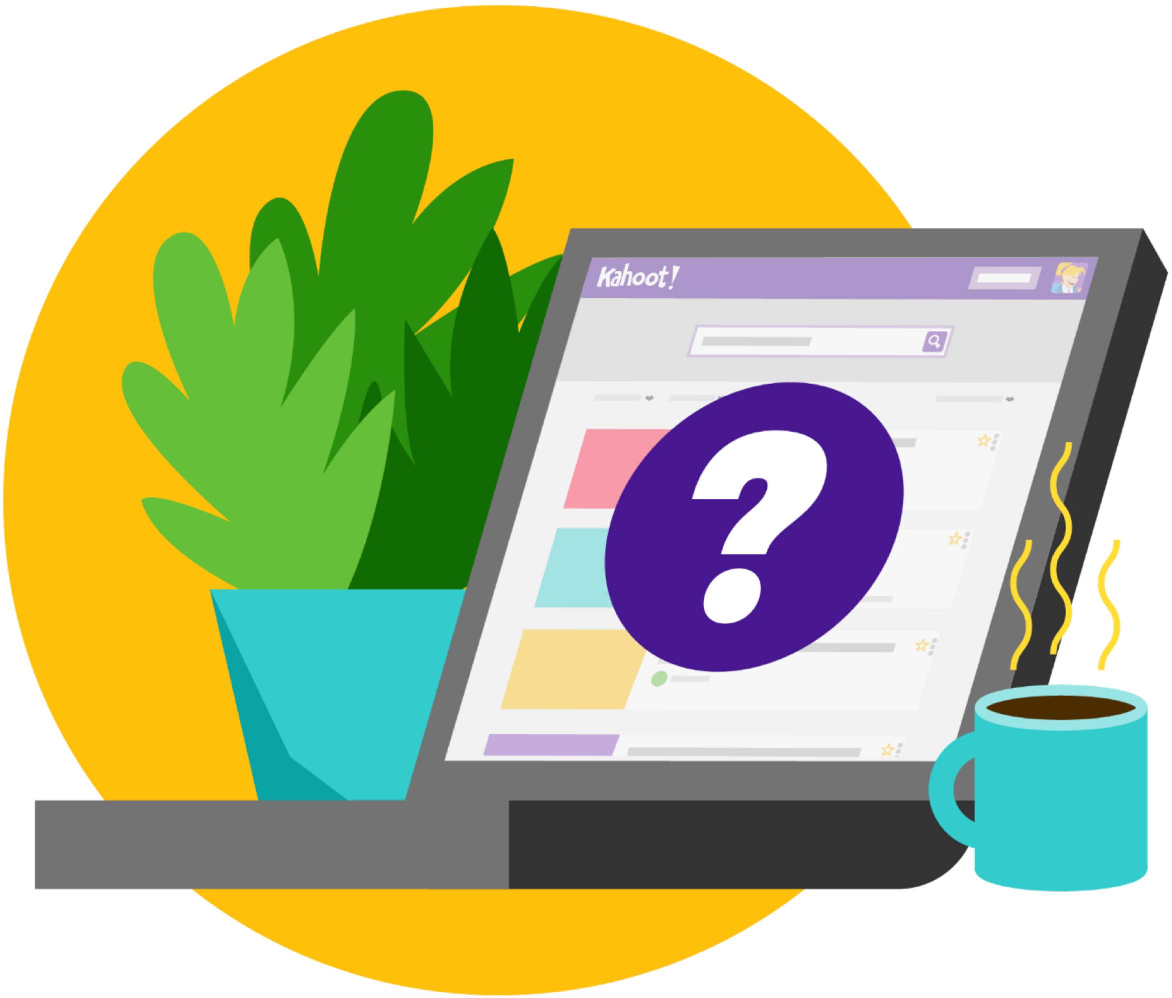
- (not comprehensive!)
- Modern Operating Systems by Andrew S. Tanenbaum, 4th Edition
  - Section 2.1.7
  - Sections 2.2.3 & 2.2.4
  - Sections 2.3.1 & 2.3.2 & 2.3.3
  - Sections 2.3.5 & 2.3.6
  - Section 6.2



- Slides & Demo credit:
  - Carlos Moreno (cmoreno@uwaterloo.ca)

MULTIPROGRAMMING

Review process – 06-review-process



Multiprogramming

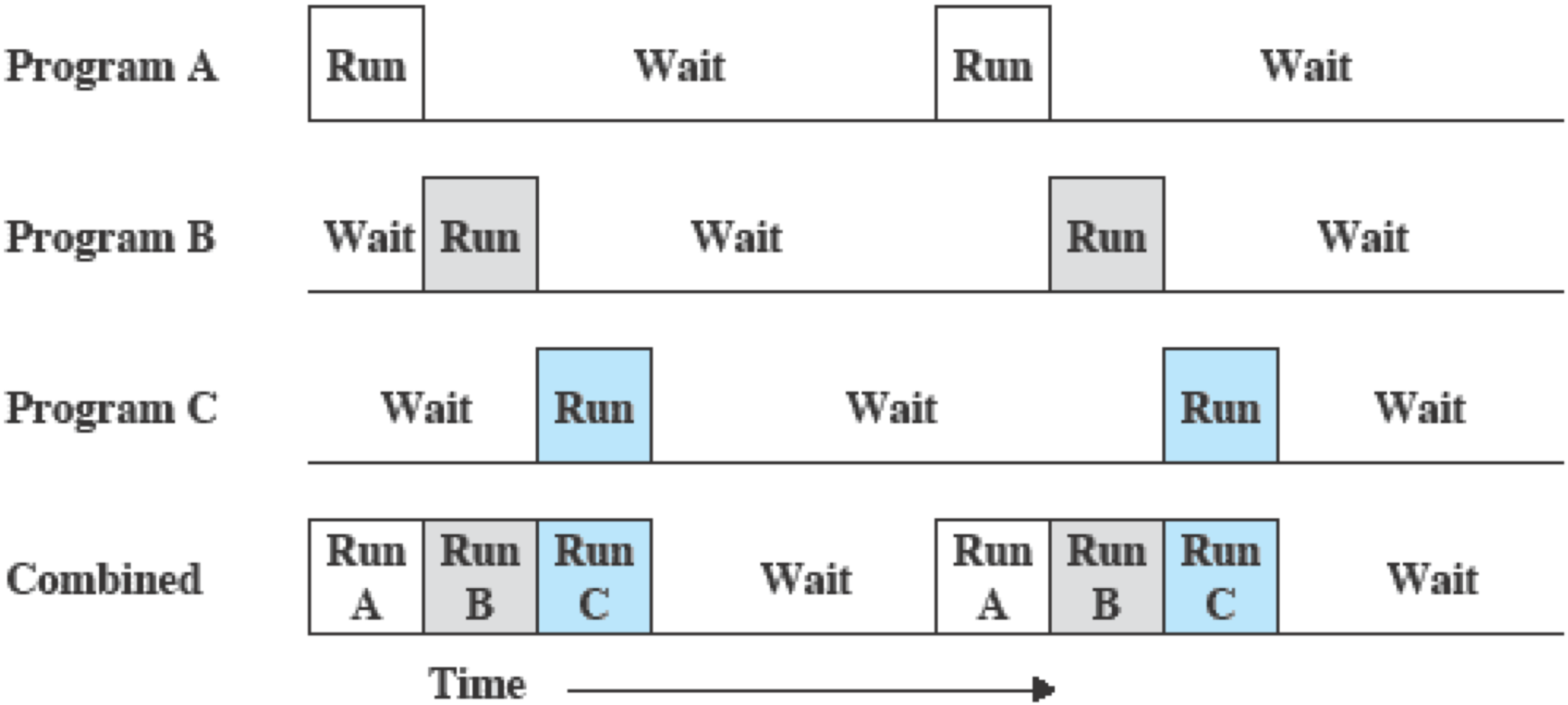
Concurrent execution of multiple tasks (e.g., processes)

- Each task runs as if it was the only task running on the CPU.

Benefits:

- When one task needs to wait for I/O, the processor can switch to the another task.
- (why is this potentially a *huge* benefit?)

Multiprogramming



(c) Multiprogramming with three programs

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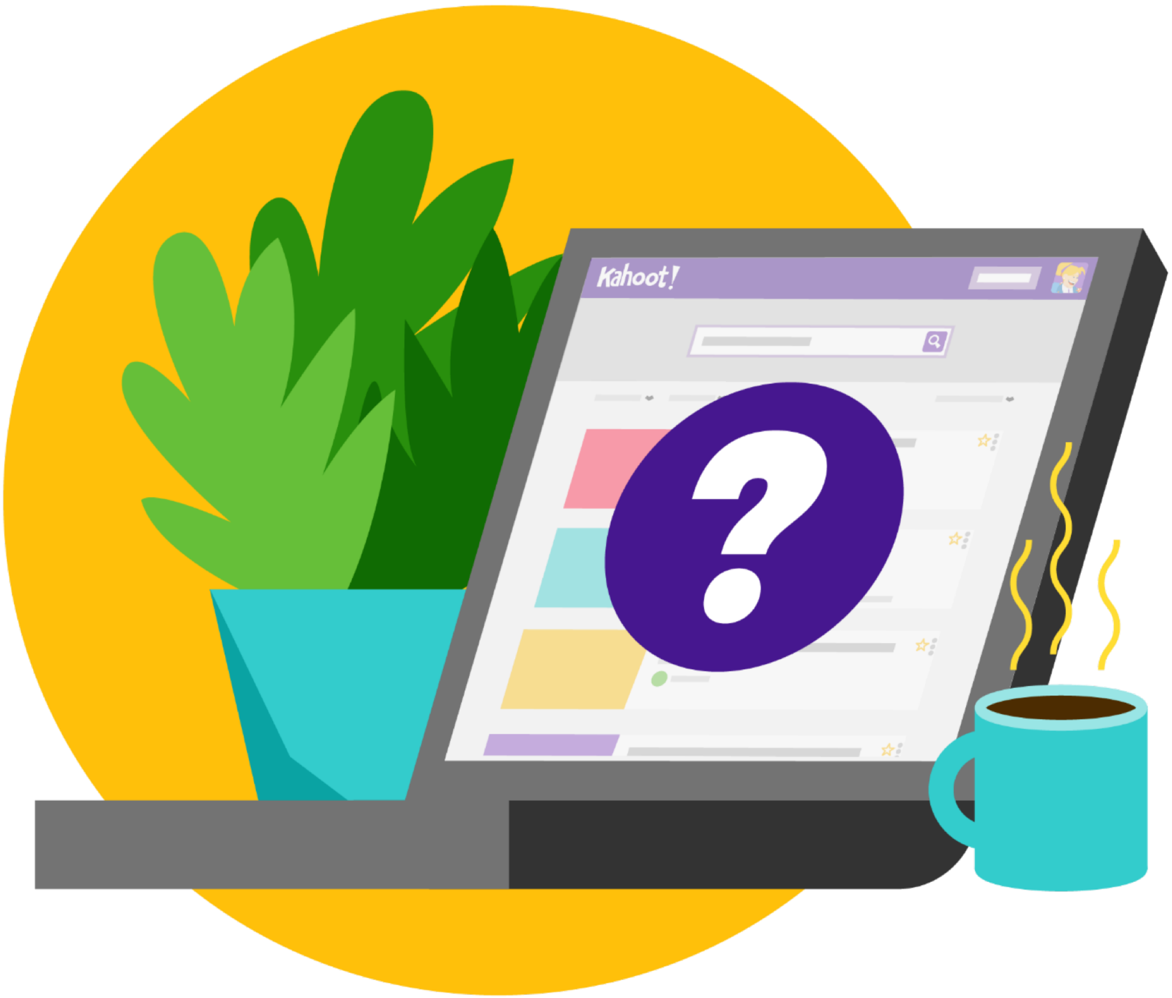
Multiprogramming

Example / case-study:

- Demo of web-based app posting jobs and a simple command-line program processing them.
  - Can run multiple instances of the job processing program.
  - Or we can have the program use **fork()** to spawn multiple processes that work concurrently

MULTITHREADING

Review thread – 06-review-threads



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Multithreading

Example/demo:

- With the multithreading demo, we'll look at a different application/motivation for the use of concurrency: performance boost through parallelism.
  - Possible when we have multiple CPUs (e.g., multicore processors)
  - Important to have multiple CPUs when the application is CPU-bound.

CONCURRENCY ISSUES

Race Condition

A situation where concurrent operations access data in a way that the outcome depends on the order (the timing) in which operations execute.

- Doesn't necessarily mean a bug! (like in the threads example with the linked list)
- In general it constitutes a bug when the programmer makes any assumptions (explicit or otherwise) about an order of execution or relative timing between operations in the various threads.

Race Condition – Example

Race condition:

Example (x is a shared variable):

Thread 1:

x = x + 1;

Thread 2:

x = x – 1;

(what's the implicit assumption a programmer could make?)

Race Condition – Example

Race condition:

Thread 1:	Thread 2:
x = x + 1;	x = x – 1;

In assembly code:

R1 $\leftarrow$ x	R1 $\leftarrow$ x
inc R1	dec R1
R1 $\rightarrow$ x	R1 $\rightarrow$ x

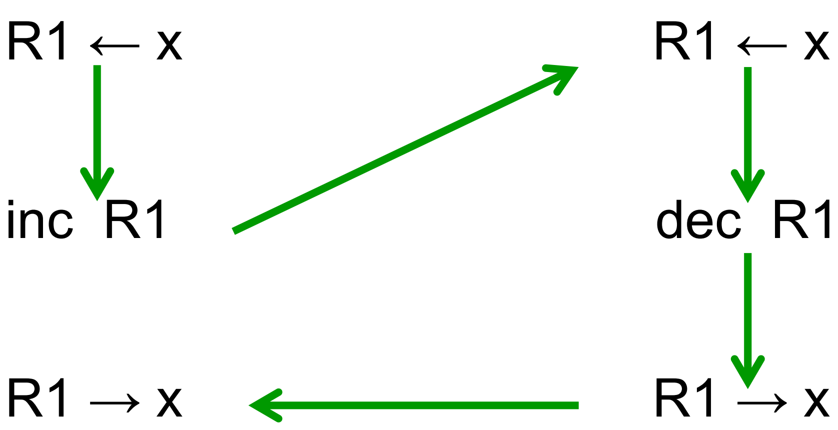
Race Condition – Example

And this is how it could go wrong:

Thread 1: | Thread 2:

x = x + 1; | x = x – 1;

In assembly code:



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Atomicity/ Atomic Operations

Atomicity is a characteristic of a fragment of a program that exhibits an observable behaviour that is non-interruptible – it behaves as if it can only execute entirely or not execute at all, such that no other threads deal with any intermediate outcome of the atomic operation.

- Non-interruptible applies in the context of other threads that deal with the outcome of the operation, or with which there are race conditions.
- For example: in the pthreads demo, if the insertion of an element in the list was atomic, there would be no problem.

Atomicity/ Atomic Operations – Examples

- Renaming / moving a file with
  int rename (const char * old, const char * new);
  Any other process can either see the old file, or the new file – not both and no other possible "intermediate" state.

- **open**ing a file with attributes **O_CREAT** and **O_EXCL** (that is, creating a file with exclusive access). The operation atomically attempts to create the file: if it already exists, then the call returns a failure code.

Mutual Exclusion

Atomicity is often achieved through mutual exclusion – the constraint that execution of one thread excludes all the others.

- In general, mutual exclusion is a constraint that is applied to sections of the code.
- For example: in the pthreads demo, the fragment of code that inserts the element to the list should exhibit mutual exclusion: if one thread is inserting an element, no other thread should be allowed to access the list
  - That includes main, though not a problem in this particular case (why?)

Mutual Exclusion – How?

Attempt #1: We disable interrupts while in a critical section (and of course avoid any calls to the OS)

- There are three problems with this approach
  - Not necessarily feasible (privileged operations)
  - Extremely inefficient (you're blocking everything else, including things that wouldn't interfere with what your critical section needs to do)
  - *Doesn't always work!!* (keyword: multicore)

Mutual Exclusion – How?

Attempt #2: We place a flag (sort of telling others "don't touch this, I'm in the middle of working with it).

```
int locked;  // shared between threads
  // ...
  if (! locked)
  {
     locked = 1;
     // insert to the list (critical section)
     locked = 0;
  }
```

Why is this flawed? (there are *several* issues)

Mutual Exclusion – How?

One of the problems: does not really work!

This is what the assembly code could look like:

```
R1 ← locked
  tst R1
  brnz somewhere_else
  R1 ← 1
  R1 → locked
```

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Mutual Exclusion – How? → Mutex

A mutex (for MUTual EXclusion) provides a clean solution: In general we have a variable of type mutex, and a program (a thread) attempts to *lock* the mutex. The attempt *atomically* either succeeds (if the mutex is unlocked) or it *blocks* the thread that attempted the lock (if the mutex is already unlocked).

- As soon as the thread that is holding the lock unlocks the mutex, this thread's state becomes ready.

Mutual Exclusion – How? → Mutex

Using a Mutex:

lock (mutex)
critical section
unlock (mutex)

For example, with POSIX threads (pthreads):

```
pthread_mutex_t mutex =
PTHREAD_MUTEX_INITIALIZER;
// ...
pthread_mutex_lock (&mutex);
// ... critical section
pthread_mutex_unlock (&mutex);
```

Mutual Exclusion – How? → Mutex

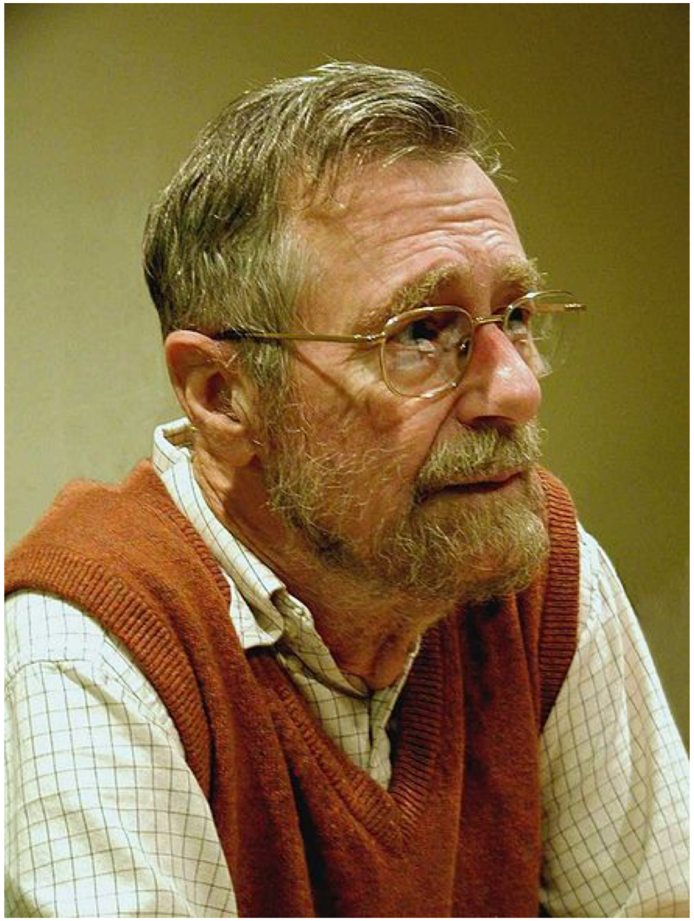
- One issue is that POSIX only defines mutex facilities for threads --- not for processes!
- We could still implement it through a “lock file” (created with **open** using flags **O_CREAT** and **O_EXCL**)
  - Not a good solution (it *does* work, but is has the same issues as the lock variable example)


BREAK
TIME !!

Another synchronization primitive

SEMAPHORES

Edsger W. Dijkstra



(image courtesy of wikipedia.org)

Definition

- Semaphore: A counter with the following properties:
  - Atomic operations that increment and decrement the count
  - Count is initialized with a non-negative value

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Operations

- **wait** operation decrements count and causes caller to block if count becomes negative (if it was 0)
- **signal** (or **post**) operation increments count. If there are threads blocked (waiting) on this semaphore, it unblocks one of them.

Example

Producer / consumer with semaphores

```
semaphore items = 0;
mutex_t mutex;  // why also a mutex?
```

```
void producer()
{
   while (true)
   {
      produce_item();
      lock (mutex);
      add_item();
      unlock (mutex);
      sem_signal (items);
   }
}
```

```
void consumer()
{
   while (true)
   {
      sem_wait (items);
      lock (mutex);
      retrieve_item();
      unlock (mutex);
      consume_item();
   }
}
```

Implementing Mutex with a Semaphore

Interestingly enough – Mutexes can be implemented in terms of semaphores!

```
semaphore lock = 1;

void process ( … )
{
   while (1)
   {
      /* some processing */
      sem_wait (lock);
         /* critical section */
      sem_signal (lock);
      /* additional processing */
   }
}
```

Exercise

Producer / consumer with semaphores only

POSIX Semaphores

- Defined through data type sem_t
- Two types:
  - Memory-based or unnamed (good for threads)
  - Named semaphores (system-wide — good for processes synchronization)

POSIX Semaphores – unnamed

- Declare a (shared – possibly as global variable) sem_t variable
- Give it an initial value with sem_init
- Call sem_wait and sem_post as needed.

```
sem_t items;
sem_init (&items, 0, initial_value);
// ...
sem_wait (&items)  or  sem_post (&items)
```

POSIX Semaphores – named

– Similar to dealing with a file: have to "open" the semaphore – if it does not exist, create it and give it an initial value.

–

```
sem_t * items = sem_open (semaphore_name, flags,
                          permissions, initial_value);
// should check if items == SEM_FAILED

// ...

sem_wait (items)  or  sem_post (items)
```

POSIX Semaphores – Example

Producer-consumer:

- We'll work on the example of the web-based demo as a producer-consumer with semaphores.
- Granularity for locking?
  - Should we make the entire process_requests a critical section?
    - Clearly overkill! No problem with two separate processes working each on a different file!
    - We can lock the file instead — no need for a mutex, since this is a *consumable* resource.
    - For a reusable resource, we'd want a mutex – block while being used, but then want to use it ourselves!

STARVATION & DEADLOCKS

Starvation

- One of the important problems we deal with when using concurrency:
- An otherwise ready process or thread is deprived of the CPU (it's *starved*) by other threads due to, for example, the algorithm used for locking resources.
  - Notice that the writer starving is *not* due to a defective scheduler/dispatcher!

Deadlocks

- Consider the following scenario:
- A Bank transaction where we transfer money from account A to account B and vice versa at the same time
- Clearly, there is a (dangerous) race condition
  - Want granularity — can not lock the entire bank so that only one transfer can happen at a time
  - We want to lock at the account level:
    - Lock account A, lock account B, then proceed!

Deadlocks – cont.

- Problem with this?
- Two concurrent transfers — one from Account A to Account B ($100), and the other one from account B to account A ($300).
  - If the programming is written as:
    Lock source account
    Lock destination account
    Transfer money
    Unlock both accounts

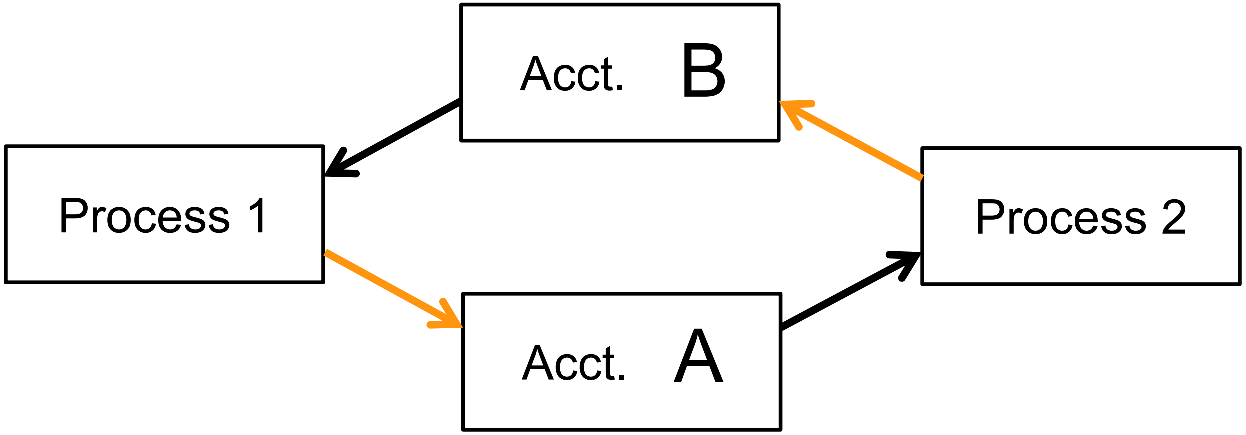
Deadlocks – cont.

- Problem with this?
- Two concurrent transfers — one from Account A to Account B ($100), and the other one from account B to account A ($300).
  - Process 1 locks account A, then locks account B
  - Process 2 locks account B, then locks account A

Deadlocks – cont.

- What about the following interleaving?
  - Process 1 locks account A
  - Process 2 locks account B
  - Process 1 attempts to lock account B (blocks)
  - Process 2 attempts to lock account A (blocks)
- When do these processes unblock?
- Answer: under some reasonable assumptions, *never!*

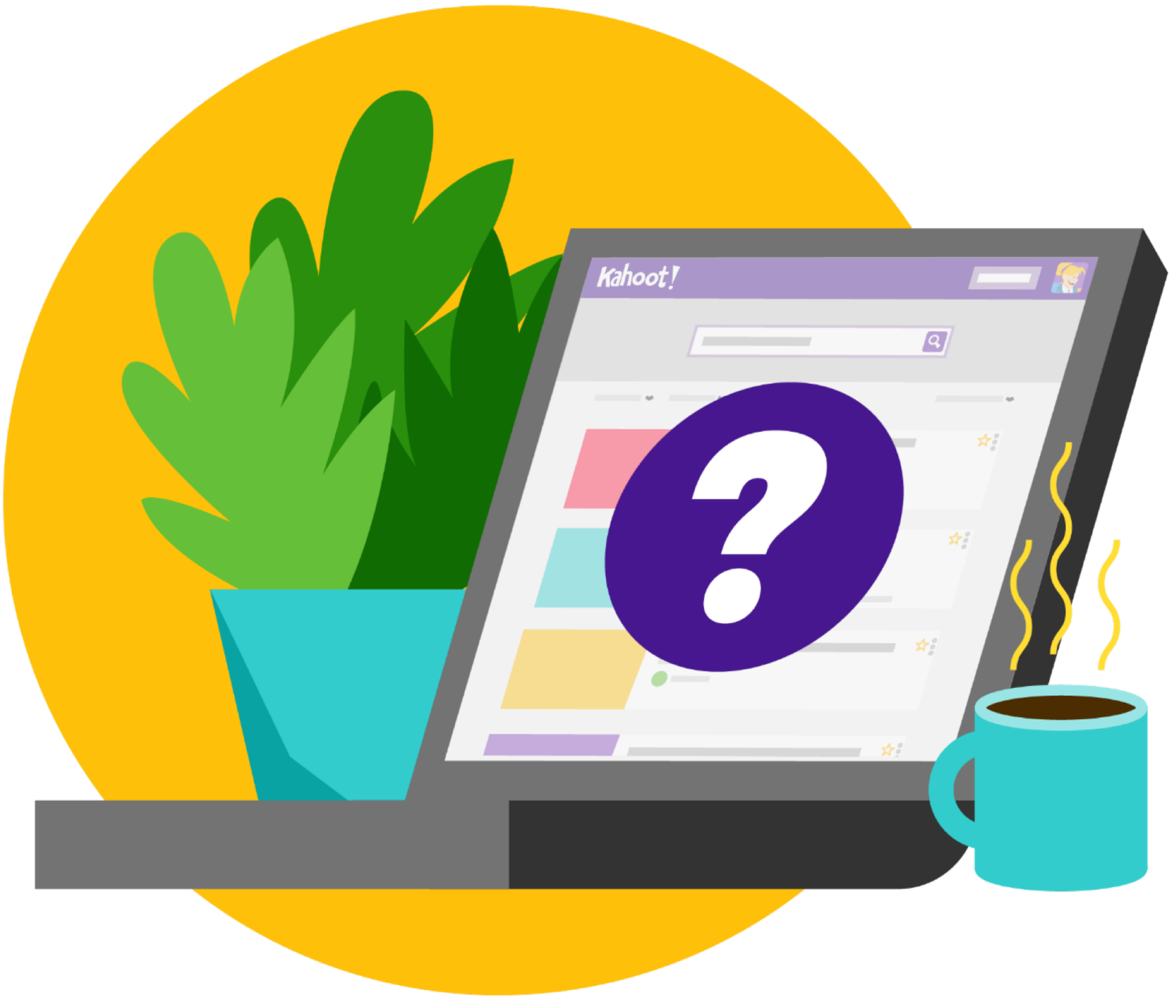
Deadlocks – cont.



- Solution in this case is really simple:
  - Lock the resources in a given order (e.g., by ascending account number).

INTER-PROCESS COMMUNICATION

Review – 06-review-IPC



Shared Memory

- Mechanism to create a segment of memory and give multiple processes access to it.
- **shmget** creates the segment and returns a handle to it (just an integer value)
- **shmat** creates a logical address that maps to the beginning of the segment so that this process can use that memory area
  - If we call **fork()**, the shared memory segment is inherited shared (unlike the rest of the memory, for which the child gets an independent copy)

Message Queues

- Mechanism to create a queue or “mailbox” where processes can send messages to or read messages from.
- **mq_open** opens (creating if necessary) a message queue with the specified name.
- **mq_send and mq_receive** are used to transmit or receive (receive by default blocks if the queue is empty) from the specified message queue.
- Big advantages:
  - Allows multiple processes to communicate with other multiple processes
  - Synchronization is somewhat implicit!

Assignment 3

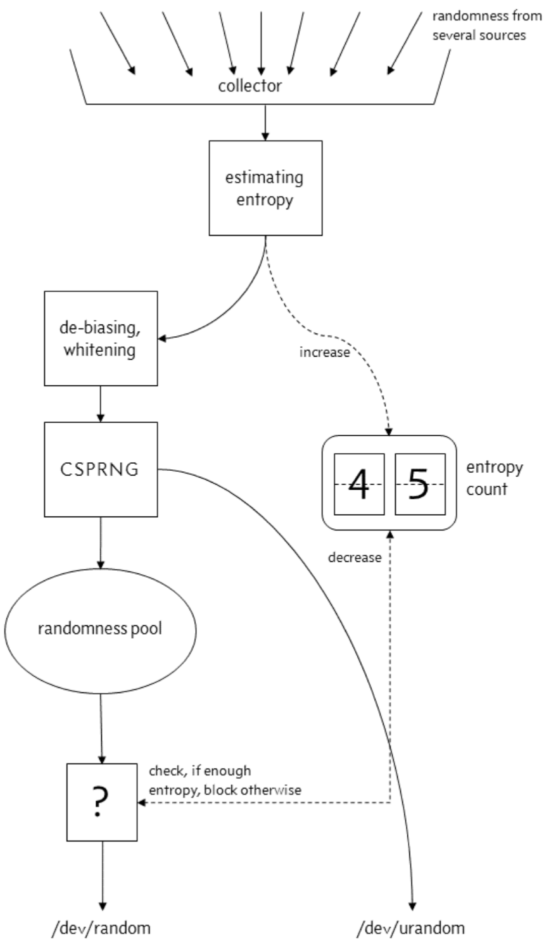
/dev/urandom is a special file (device) that provides supply of “truly” random numbers

”infinite size file” – every read returns a new random value

To get a random value, read a byte/word from the file

see `using_rand.cpp` for an example

Have to use it for Assignment 3!



https://www.2uo.de/myths-about-urandom/

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