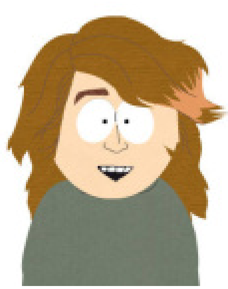
POSIX / System Programming

ECE-650 – Methods and Tools for Software Eng.
Guest lecture – 2017-10-06



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Outline

- **During today's lecture, we'll look at:**
  - Some of POSIX facilities
    - Main focus on processes, concurrency, communication, threads and synchronization.
    - Issues with concurrency: race conditions, deadlock, starvation.
    - Tools and techniques to deal with the above: critical sections, mutual exclusion / atomicity, semaphores, pipes, message queues, shared memory.

Systems Programming

- One of the most important notions is that of a *Process*.
- Possible definitions:
  - A program in execution / An instance of a program running on a computer
    - Not really: execution of a program can involve multiple processes!
  - A unit of activity characterized by the execution of a sequence of instructions, a current state, and an associated set of system instructions

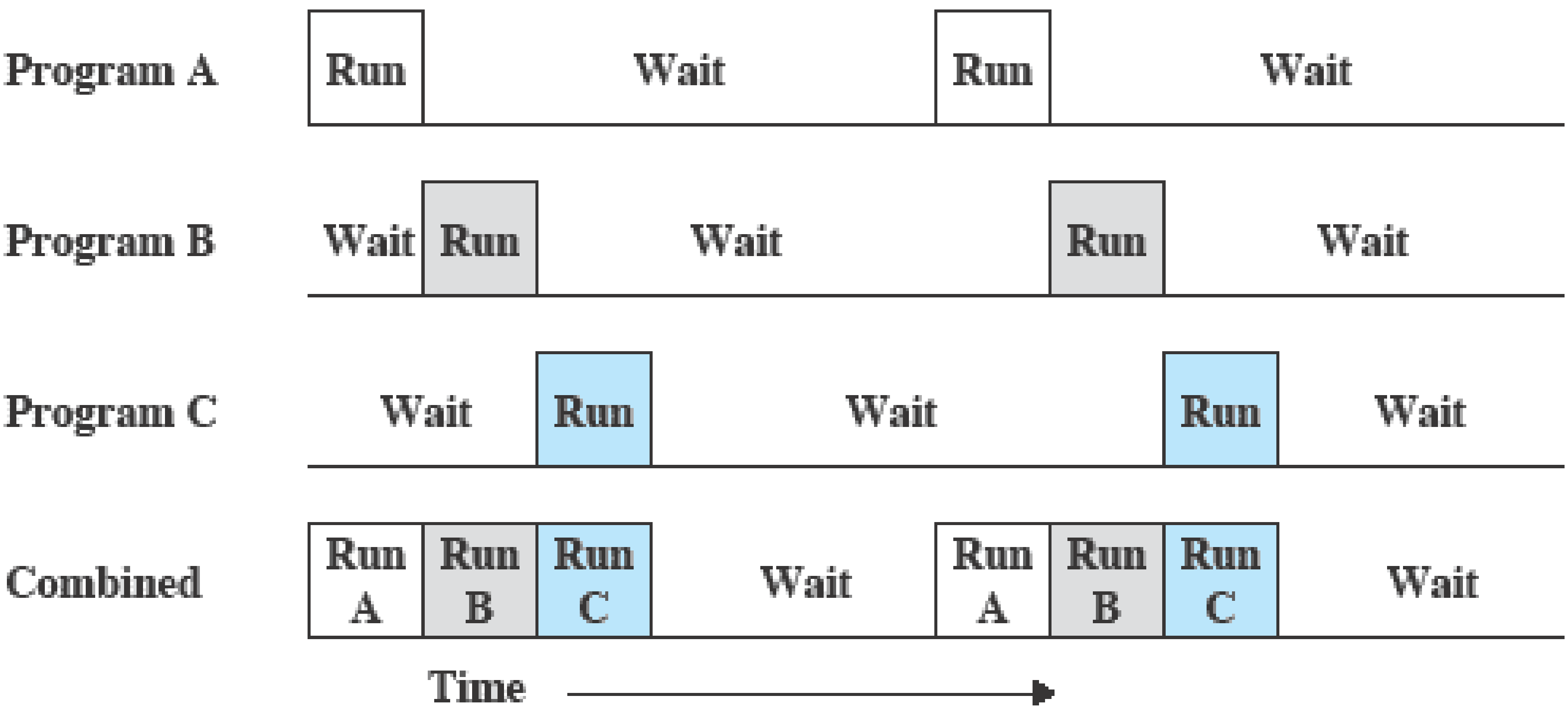
Process

- An entity representing activity consisting on three components:
  - An executable program
  - Associated data needed by the program
  - Execution context of the program (registers, PC, pending I/O operations, etc.)
- OS assigns a unique identifier (PID)
  - See command **`ps`**.
- Processes can create other processes (denoted *“child process”* in that context)
  - See **`ps --forest`**

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

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

- Processes typically have their own "isolated" memory space.
  - Memory protection schemes prevent a process from accessing memory of another process (more in general, any memory outside its own space).
  - The catch: if processes need to share data, then there may be some overhead associated with it.
- Threads are a "lighter version" of processes:
  - A process can have multiple threads of execution that all share the same memory space.
  - Sharing data between threads has little or no overhead
    - Good news? Bad news? (both?)

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.

Concurrency Issues

- **Race condition:**

  Example (x is a shared variable):

  Thread 1: Thread 2:

  x = x + 1; x = x – 1;

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

Concurrency Issues

- **Race condition:**

Thread 1:

x = x + 1;

Thread 2:

x = x – 1;

- In assembly code:

Thread 1:

R1 ← x
inc R1
R1 → x

Thread 2:

R1 ← x
dec R1
R1 → x

Concurrency Issues

- **And this is how it could go wrong:**

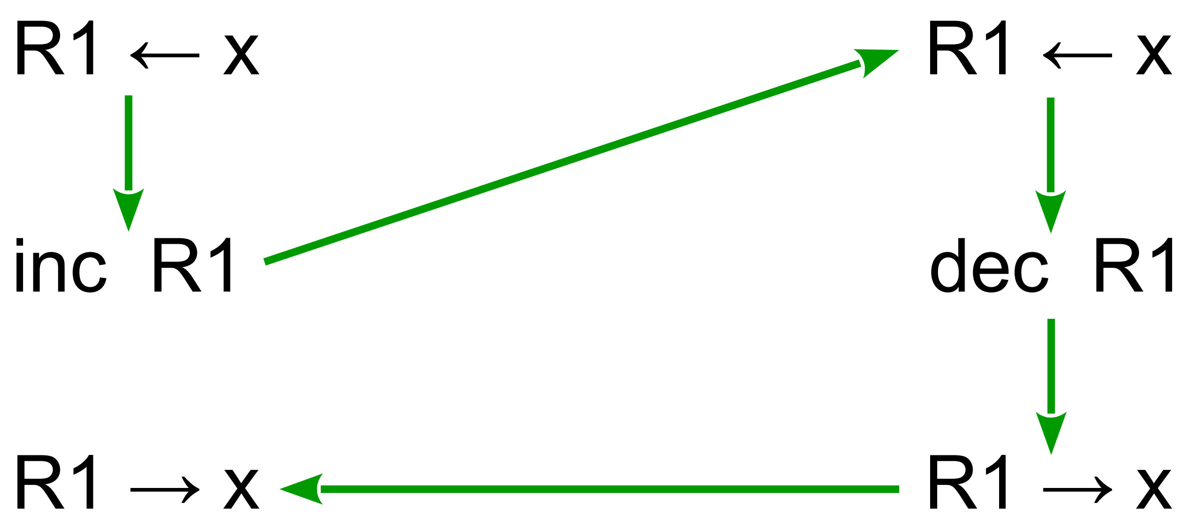
Thread 1:

x = x + 1;

Thread 2:

x = x – 1;

- In assembly code:



Concurrency Issues

- **Atomicity / Atomic operation:**

  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.

Concurrency Issues

- **Examples of atomic operations in POSIX:**
  - 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.

Concurrency Issues

- **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?)

Concurrency Issues

- **Critical section:**

  A section of code that requires atomicity and that needs to be protected by some mutual exclusion mechanism is referred to as a *critical section*.

  - In general, we say that a program (a thread) *enters* a critical section.

Concurrency Issues

- **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)

Concurrency Issues

- **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)

Concurrency 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
```

Concurrency Issues

- **Mutual Exclusion – How?**

Another problem: an if statement just doesn't cut it! We need to insert an element – if some other thread is inserting an element at this time, we need to wait until the other thread finishes:

```
while (locked) {}
locked = 1;
// ... critical section
locked = 0;
```

There are two problems with this: one is that it doesn't work (for the same reason as with the if) What's the other problem?

Concurrency Issues

- **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.

Concurrency Issues

- **Using a Mutex:**

  lock (mutex)
  critical section
  unlock (mutex)

- For example, with POSIX threads (pthreads):

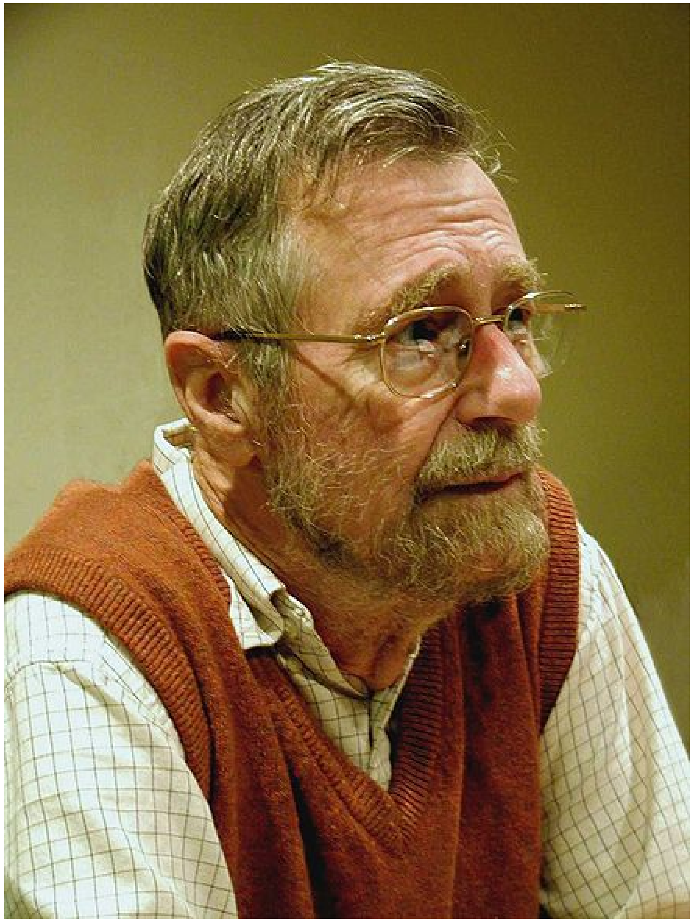
```
pthread_mutex_t mutex = PTHREAD_MUTEX_INITIALIZER;
// ...
pthread_mutex_lock (&mutex);
// ... critical section
pthread_mutex_unlock (&mutex);
```

Concurrency Issues

- **Using a 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)

Concurrency and synchronization

- **Another synchronization primitive: Semaphores**



(image courtesy of wikipedia.org)

Concurrency and synchronization

- **Another synchronization primitive: Semaphores**
  - Semaphore: A counter with the following properties:
    - Atomic operations that increment and decrement the count
    - Count is initialized with a non-negative value
    - `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.

Concurrency and synchronization

- **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();
    }
}
```

Concurrency and synchronization

- **Mutual Exclusion with semaphores**
  - 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 */
    }
}
```

Concurrency and synchronization

- **Producer / consumer with semaphores only**

```
semaphore items = 0;
semaphore lock = 1;
```

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

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

Concurrency and synchronization

- **Producer / consumer with semaphores only**
  - Interestingly, POSIX does provide inter-process semaphores!

Concurrency and synchronization

- **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)

Concurrency and synchronization

- **POSIX semaphores:**
  - For unnamed semaphores:
    - 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)
```

Concurrency and synchronization

- **POSIX semaphores:**
  - For named semaphores:
    - 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)
```

Concurrency and synchronization

- **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!

Concurrency and synchronization

- **Consumable vs. Reusable Resource:**
  - With a consumable resource, we want to:
    - Try to lock it.
      - If failed, then forget about it (someone else locked it and will make it disappear – will “consume” it).
  - With a reusable resource:
    - Wait until you can lock it (as in, attempt to lock it blocking if it is already locked)
      - When unlocked by the other thread/process, then we lock it and (re)use it.

Concurrency and synchronization

- **Consumable vs. Reusable Resource:**
  - See code for demo — locking has to be done atomically!
  - We recall that renaming a file with `rename` is an atomic operation!

Concurrency and synchronization

- **More on locking granularity:**
- Consider the following scenario:
  - One thread writes to some shared resource (e.g., a linked list)
  - Many threads need to read that shared resource
    - Observation: concurrent reads don't cause a race condition (right?)
    - Do we need to lock the resource when reading?

Concurrency and synchronization

- **More on locking granularity:**
- Consider the following scenario:
  - Problem:
  - Concurrent reads do not need mutual exclusion
  - But since a write could be taking place, we need to define the read operation as a critical section, in case there is a concurrent write operation!

Concurrency and synchronization

- **More on locking granularity:**
- Consider the following scenario:
  - Problem:
  - Concurrent reads do not need mutual exclusion
  - But since a write could be taking place, we need to define the read operation as a critical section, in case there is a concurrent write operation!

  - Solution:
  - Finer granularity!
    - Locking for write vs. locking for read!

Concurrency and synchronization

- **More on locking granularity:**
- Read/Write locks implement this functionality:
  - Threads calling read_lock do not exclude each other.
  - A thread calling write_lock excludes any other threads requesting write_lock and also any other threads requesting read_lock
    - It blocks if some thread is holding a read lock!

Concurrency and synchronization

- **More on locking granularity:**
- Read/Write locks implement this functionality:
  - Threads calling read_lock do not exclude each other.
  - A thread calling write_lock excludes any other threads requesting write_lock and also any other threads requesting read_lock
    - It blocks if some thread is holding a read lock!
  - POSIX R/W Locks:

```
pthread_rwlock_t
pthread_rwlock_rdlock ( ... )
pthread_wrlock_wrlock ( ... )
pthread_rwlock_unlock ( ... )
```

Concurrency and synchronization

- **More on locking granularity:**
- Big problem with Read/Write locks?
  - Hint: what happens if many threads are reading very frequently?

Concurrency and synchronization

- **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!

Concurrency – Deadlock

- **Deadlock:**
  - Consider the following scenario:
  - A Bank transaction where we transfer money from account A to account B
  - 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!

Concurrency – Deadlock

- **Deadlock:**
  - Problem with this?
  - Two concurrent transfers — one from account 100 to account 200, one from account 200 to account 100.
    - If the programming is written as:
      Lock source account
      Lock destination account
      Transfer money
      Unlock both accounts

Concurrency – Deadlock

- **Deadlock:**
  - Problem with this?
  - Two concurrent transfers — one from account 100 to account 200, one from account 200 to account 100.
    - Process 1 locks account 100, then locks account 200
    - Process 2 locks account 200, then locks account 100

Concurrency – Deadlock

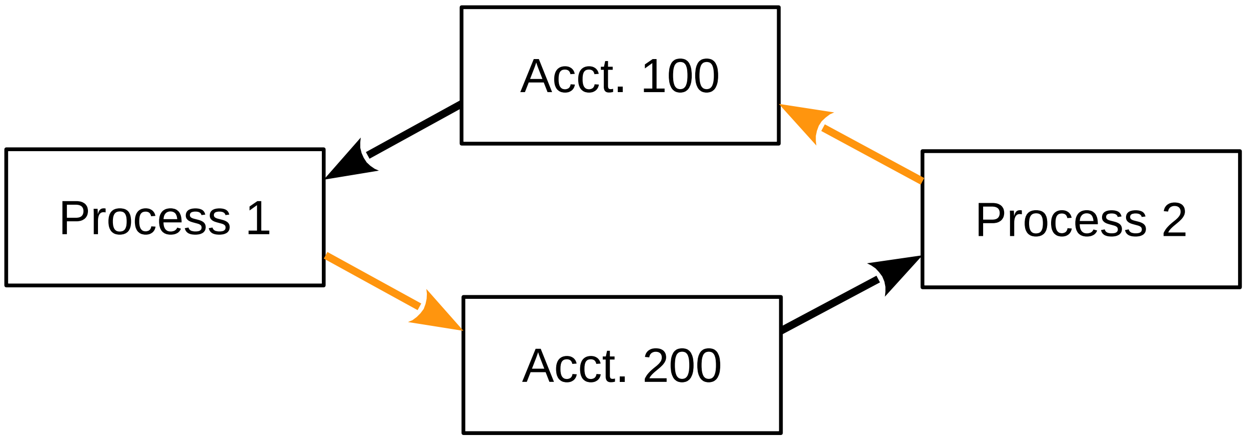
- **Deadlock:**
  - What about the following interleaving?
    - Process 1 locks account 100
    - Process 2 locks account 200
    - Process 1 attempts to lock account 200 (blocks)
    - Process 2 attempts to lock account 100 (blocks)
  - When do these processes unblock?

Concurrency – Deadlock

- **Deadlock:**
  - What about the following interleaving?
    - Process 1 locks account 100
    - Process 2 locks account 200
    - Process 1 attempts to lock account 200 (blocks)
    - Process 2 attempts to lock account 100 (blocks)
  - When do these processes unblock?
  - Answer: under some reasonable assumptions, *never!*

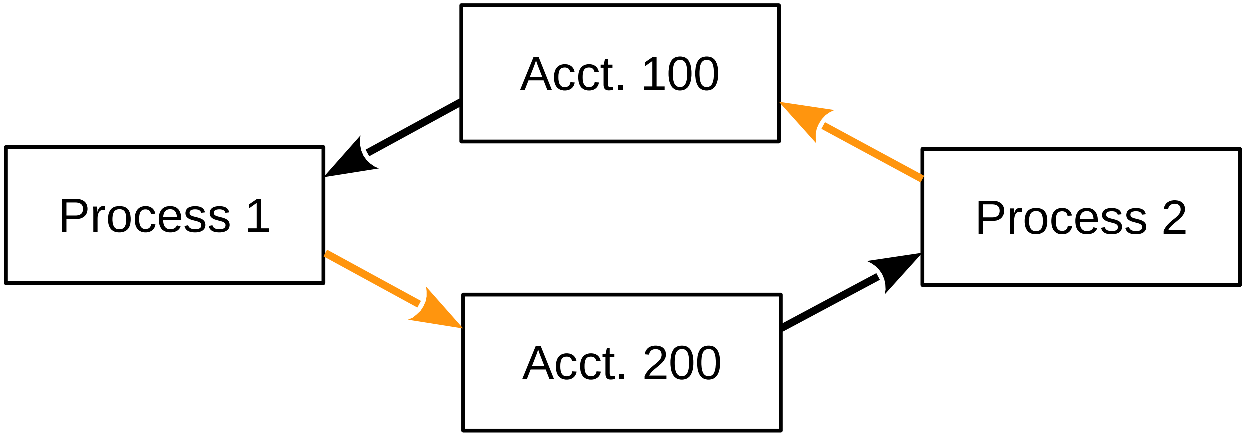
Concurrency – Deadlock

- **Deadlock:**
  - Graphically:



Concurrency – Deadlock

- **Deadlock:**



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

Interprocess Communication

- **Sharing data between processes:**
  - Requires synchronization (to avoid race conditions, and to access data when there is data to be accessed!)
  - Typical mechanisms:
    - Through designated files (obvious, but inefficient)
    - Through pipes (very simple, but limited)
    - Through shared memory (efficient, but dangerous!)
    - Through message queues (convenient, though not particularly simple)

Interprocess Communication

- **Sharing data through files:**
  - Not much to say – one process writes data to a file, another process reads data from the file.
    - Still need synchronization

Interprocess Communication

- **Pipes:**
  - A pipe is a mechanism to set up a “conduit” for data from one process to another.
  - It is unidirectional (i.e., we have to predefine who transmits and who receives data)
  - Simplest form is with **popen**:
    - It executes a given command (created as a child process) and returns a stream (a FILE *) to the calling process:
    - It then connects either the standard output of that command to the (input) stream, or the standard input of that command to the (output) stream.

Interprocess Communication

- **Pipes – example:**
  - To read the output from a program:

```
FILE * child = popen (“/path/command”, “r”);
if (child == NULL)  { /* handle error condition */ }

Now read data with, e.g., fread ( … , … , … , child);
and NEVER forget to pclose (child);
```

  - Whatever data the child process sends to its standard output (e.g., with printf) will be read by the parent.
  - Conversely, if we popen (…. , “w”), then whatever data we write to it (e.g., with fprintf or fwrite) will appear through the standard input of the child.

Interprocess Communication

- **Pipes:**
  - For more details, see `man popen`
  - For the more general form, including named pipes, see `man 7 pipe` and `man 2 pipe`.

Interprocess Communication

- **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)

Interprocess Communication

- **Shared memory:**
  - For more information, see `man shmget` and `man shmat`

Interprocess Communication

- **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.

Interprocess Communication

- **Message queues:**
  - Big advantages:
    - Allows multiple processes to communicate with other multiple processes
    - Synchronization is somewhat implicit!
  - See `man mq_overview` for details.