Concurrency: Running Together

Methods & Tools for Software Engineering (MTSE)
Fall 2020

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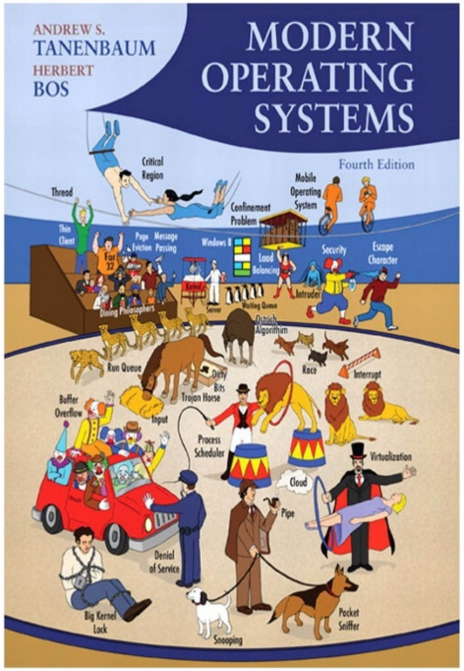
References

- (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)
  - Reza Babaee
  - Prof. Seyed M. Zahedi (ECE350 UWaterloo)

Concurrency vs. Parallelism

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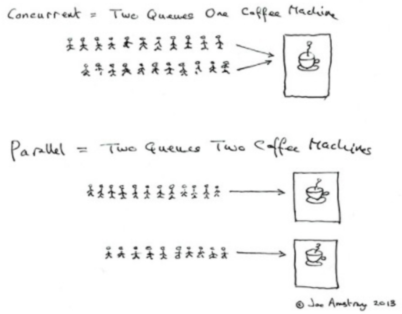

There is a subtle difference between these two concepts:

1. **Goal: Concurrency** is when two or more tasks can run in overlapping time **periods, not necessarily in parallel**. In this context, two threads or processes may or may not run simultaneously on a single-core machine. *The core idea here is to* ***share resources*** *when one process is waiting on I/O or memory access etc.*

2. **Goal: Parallelism** is when tasks/programs run **at the same time** on a multicore processor or a network of workstations etc. (best modern examples include GPUs, your laptop microprocessors,…). Dominant models include shared memory and MPI.

3. **It is clear that we may have to deal with both concurrency and parallelism issues on the same system (e.g., multi-core processor)**

multiprogramming 是 concurrency 一种情况

Concurrency

As noted above, the problem that concurrency is trying to solve is how do we optimally use shared resources (e.g., one CPU) among processes or threads.

Key concept is interleaving via context-switching: An ideal solution to the concurrency problem is a scheduling algorithm that interleave instructions from multiple processes/threads on a shared resource (CPU) in an optimal fashion (minimal running time over all possible schedules of all processes in a system). This is done via context-switching between processes. Of course, this a very hard problem in general.

Example: In a modern setting, consider two process P1 and P2. From years of experience, researchers know that the time to execute I/O or memory accesses are orders of magnitude slower than a single CPU cycle. Hence, it is more optimal to sequence/schedule instructions of P, whenever P1 is waiting for an I/O or memory access to complete, rather than letting the CPU idle.

Context-switch: To accomplish this the OS scheduler **context-switches process P1 out (i.e., save its registers) and context-switches P2 in (i.e., writes its saved register values into the CPU registers),** whenever P1 starts big I/O access

Parallelism

As noted above, in parallelism the problem we are trying to solve is how to use multiple resources (e.g., multi-processors) optimally (minimize time).

Key concepts is to identify and minimize dependencies between tasks (threads or processes) so that they can be run as independently as possible.

There are many kinds of parallelism such as fine-grained, coarse-grained, embarrassingly parallel etc.

Shared-memory: Different threads or processes in a multi-core setting communicate via shared memory

Message Passing Interface (MPI): Different threads processes pass information via an MPI interface/library

Issues in parallelism: how to communicate efficiently between threads/processes, how to identify dependencies and eliminate/minimize them, race conditions, dead locks, detect parallelism automatically etc.

MULTIPROGRAMMING

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 another task.
- (why is this potentially a *huge* benefit?)

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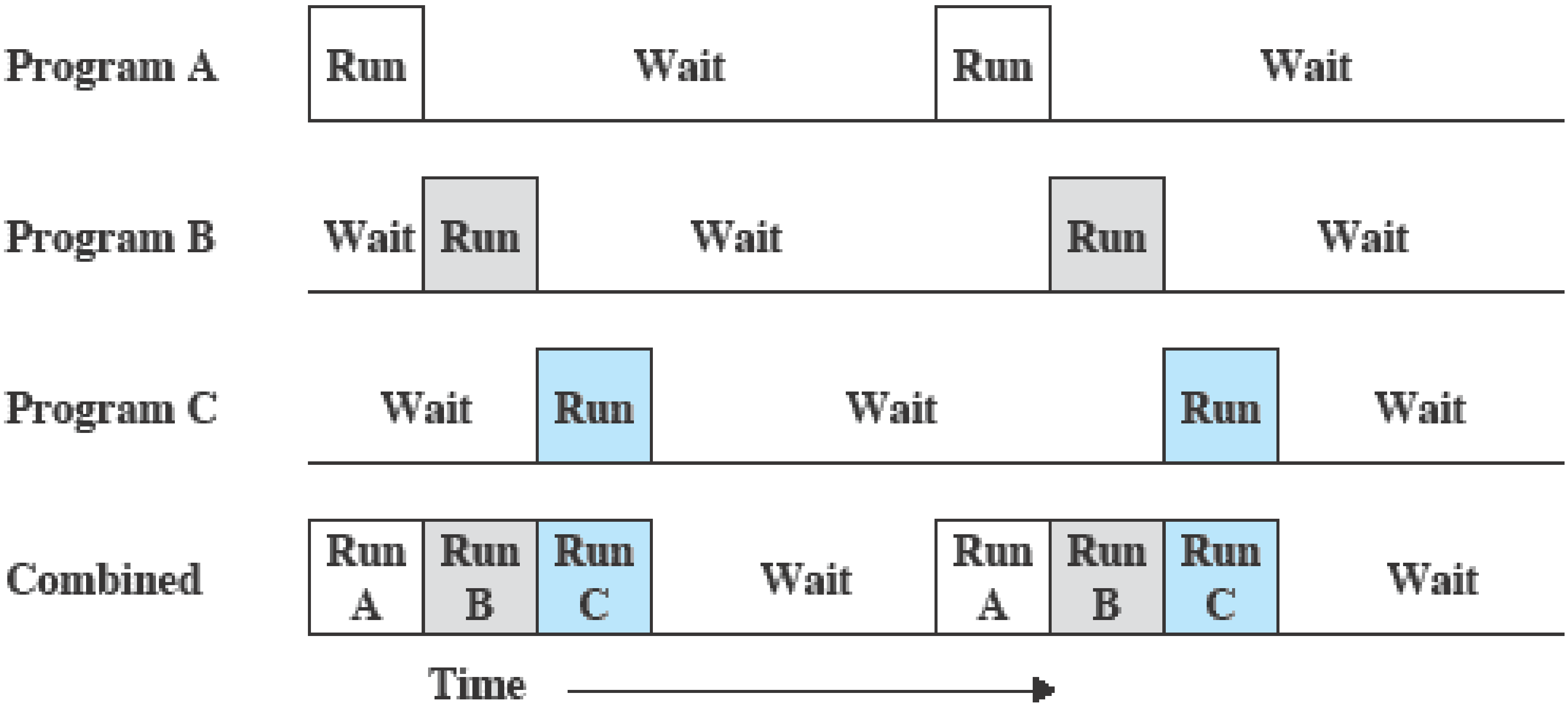
Multiprogramming



(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

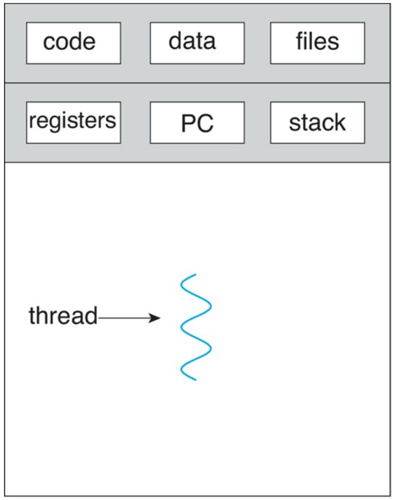
Traditional UNIX Process

Process is OS abstraction of what is needed to run single program

- Often called “heavyweight process”

Processes have two parts

- Sequential program execution stream (active part)
  - Code executed as sequential stream of execution (i.e., thread)
  - Includes state of CPU registers
- Protected resources (passive part)
  - Main memory state (contents of Address Space)
  - I/O state (i.e. file descriptors)



single-threaded process

Modern Process with Threads

Thread: sequential execution stream within process
(sometimes called "lightweight process")

- Process still contains single address space
- No protection between threads

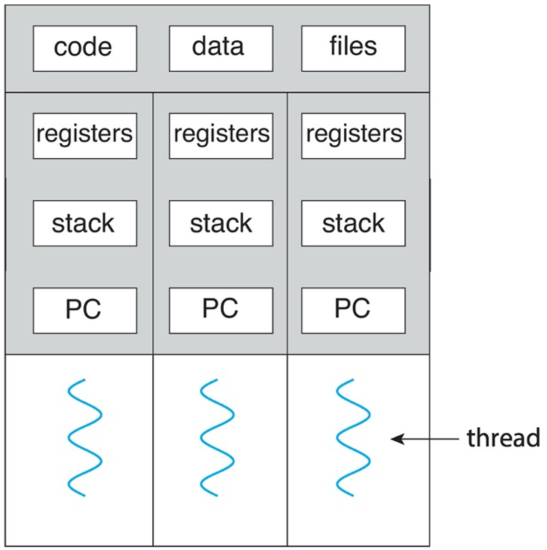
Multithreading: single program made up of different concurrent activities (sometimes called multitasking)

Some states are shared by all threads

- Content of memory (global variables, heap)
- I/O state (file descriptors, network connections, etc.)

Some states "private" to each thread

- CPU registers (including PC) and stack



multithreaded process

Threads Motivation

OS's need to handle multiple things at once (MTAO)

- Processes, interrupts, background system maintenance

Servers need to handle MTAO

- Multiple connections handled simultaneously

Parallel programs need to handle MTAO

- To achieve better performance

Programs with user interfaces often need to handle MTAO

- To achieve user responsiveness while doing computation

Network and disk programs need to handle MTAO

- To hide network/disk latency

Multithreading: Process versus Thread

Process provides an execution context for the program

- **unit of ownership**
- Memory, I/O resources, console, etc.
- Process pretends like it is a single entity controlling the execution environment
- Inter Process Communication (IPC) is “like” communicating between individual machines (but connected with super-fast network)

Thread represent a single execution unit (i.e., CPU)

- unit of scheduling
- ancient time: a process has one thread running on one physical CPU
- old time: a process has many threads sharing one physical CPU
- today: a process has many threads sharing many physical CPUs (multicore)
- all threads of a process share the same memory space!

Threads: Programmer's Perspective

A thread is a function that is ran concurrently with other functions

- It is like `fork()` followed by a call to a child process function
- **Except**: no new process is created. The new thread can access **all** the data of the **current** process

```
void * foo(void*) {...}
void * bar(void*) {...}

int main(void) {
  pthread_t t1, t2;
  void *data;
  ...
  pthread_create(&t1, NULL, foo, data);
  pthread_create(&t2, NULL, bar, data);

  pthread_join(t1, NULL);
  pthread_join(t2, NULL);
}
```

Threads: Programmer's Perspective

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  pthread_create(&t2, NULL, bar, data);

  pthread_join(t1, NULL);
  pthread_join(t2, NULL);
}
```

Code that will execute concurrently

Start of concurrent execution

Main thread waits for others to finish

Multi-programming vs. multi-tasking vs. multi-threading vs. multi-processing

1. Multi-programming: The classic concurrency problem, namely, how can one schedule many processes on a single CPU such that the overall time is minimized?

Solution: interleave instructions of different processes (via context-switching) so that when one process waits for memory or I/O access, another one can use the CPU.

2. Multi-tasking: the scheduler context-switches not only when there are long I/O accesses, but also time-slices. In time-slicing, every process gets a small quantum of time on the CPU, and then you context-switch.

3. **Multi-threading: Extend all of the above ideas from processes to threads**

4. Multi-processing: solutions to optimally take advantage of multiple cores/processors on your system.

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.

- Not necessarily a bug!

- But often is the main source of bugs because programmers assume that order of execution does not influence the result, or, implicitly assume that only certain order of operations is possible

Race Condition – Example

Race condition:

Assume that `x` is a variable shared between the two threads

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:

```
x = x + 1;
```

In assembly code:

```
R1 ← x
inc  R1
R1 → x
```

Thread 2:

```
x = x – 1;
```

```
R1 ← x
dec  R1
R1 → 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:

`R1 ← x`	`R1 ← x`
`inc  R1`	`dec  R1`
`R1 → x`	`R1 → x`

Atomicity/ Atomic Operations

Atomicity is a characteristic of a fragment of a program that exhibits an observable behavior 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 mails++ operation 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

- It is achieved via the concept of a lock, as shown in the pthreads demo

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, because in multicore systems, multiple threads may be running on different cores. Not easy to make other cores wait till your core has completed the critical section)

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;  // variable 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
```

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 locked).

- 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)
```

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Mutual Exclusion – How? → Mutex

Using a Mutex:

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)

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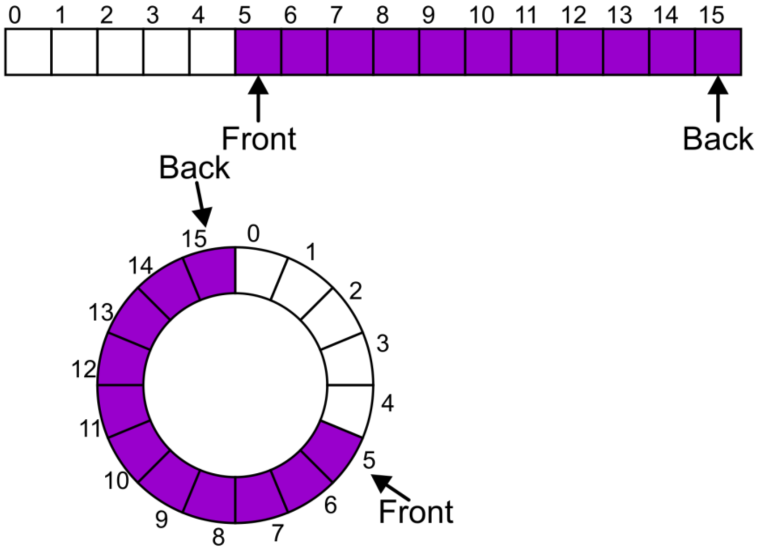
Queue Implementation as a Ring Buffer

Queue Abstract Data Type supports the following operations:

- `pop_front()` remove top element
- `push_back()` end element to the back

Implementation

- finite data buffer to store elements
- front (or head) pointing to next free entry, back (or tail) pointer to last used

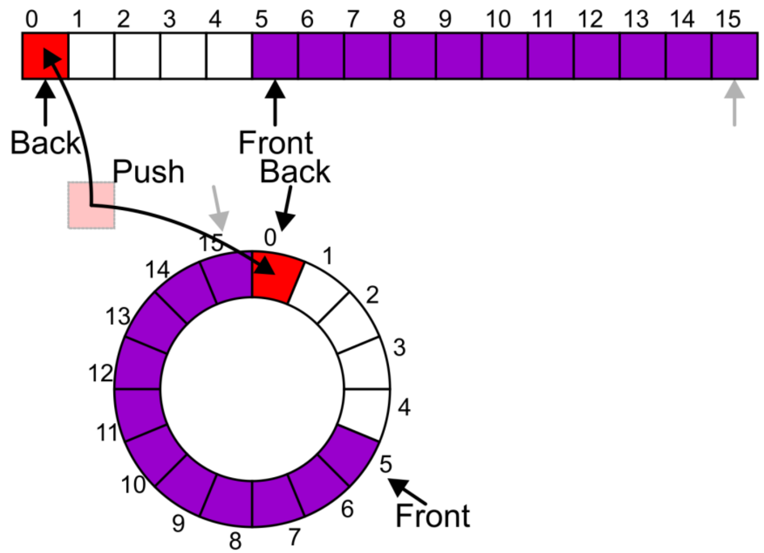


Queue as a Ring Buffer

Inserting an element might “overflow” the tail, in which case the tail must wrap around to the beginning of the buffer

Properties:

- head + 1 == tail --- queue is full, no more space
- head == tail --- queue is empty



Producer-Consumer Problem

A classic multi-process example that captures many common use cases of multi-processing and multi-threading applications

Producer – produces data

- One or more producers generate data asynchronously
- writer

Consumer – consumes data

- One (but usually more) consumers process data
- reader

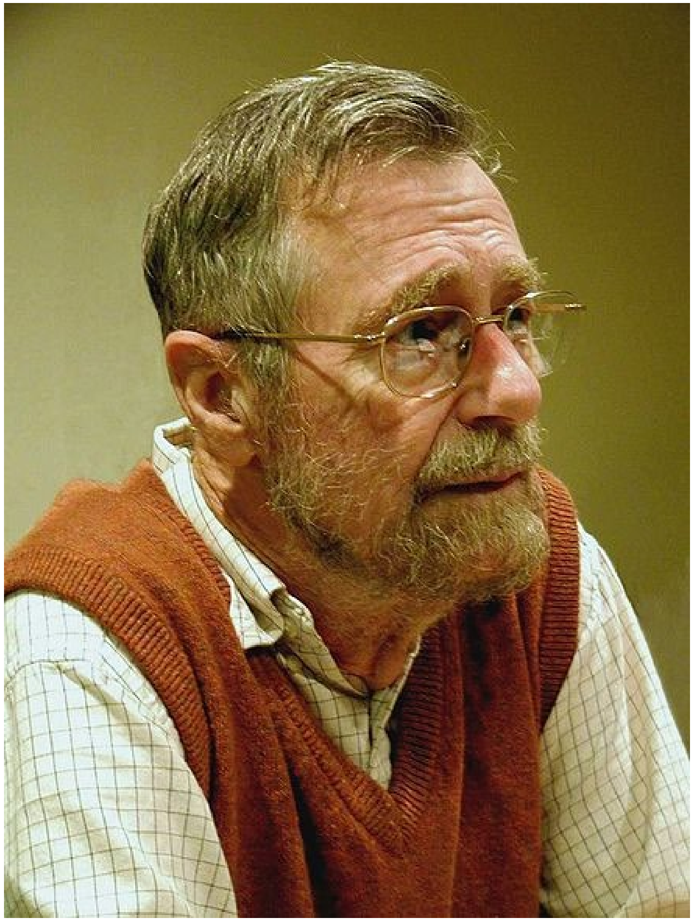
Communicate via a shared fixed size buffer

- when the buffer is full, producer stops and waits
- when the buffer is empty, consumer waits

Another synchronization primitive

SEMAPHORES

Edsger W. Dijkstra



(image courtesy of wikipedia.org)

Semaphore: Definition

Semaphore is a counter with the following properties

is a signaling mechanism and

- Initialized with a non-negative value
  - `count := 2`
- Atomic increment
  - `count := count + 1`
- Atomic decrement
  - `count := count - 1`

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();
    }
}
```

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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!*

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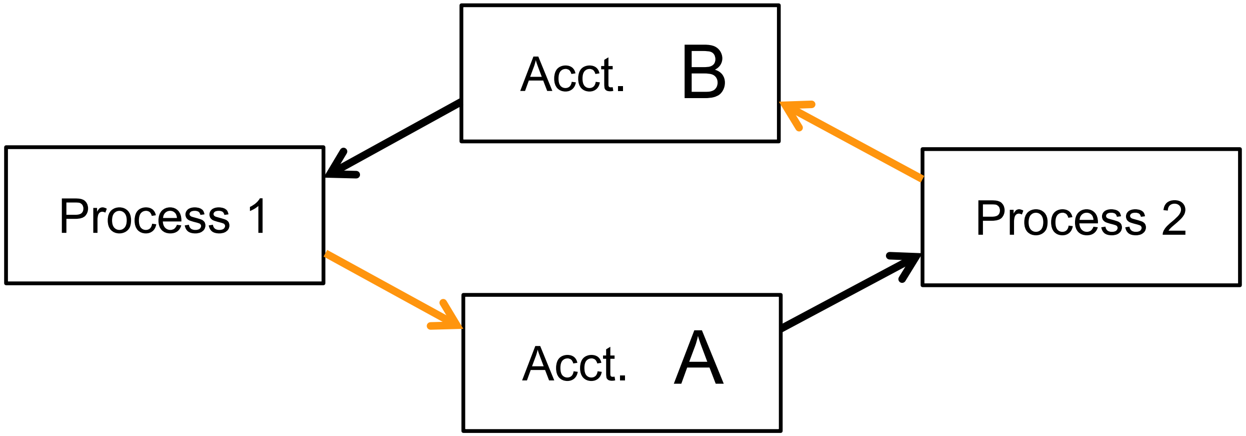
Deadlocks – cont.



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

INTER-PROCESS COMMUNICATION

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)

https://www.geeksforgeeks.org/ipc-shared-memory/

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!

https://www.geeksforgeeks.org/ipc-using-message-queues/