CIS 5512 - Operating Systems
IPC for Data Passing and Synchronization

Professor Qiang Zeng

Fall 2017

TEMPLE UNIVERSITY

Previous class…

- Process state transition
  - Ready, blocked, running
- Call stack
  - Calling convention
- Context switch
  - Process switch
- Interrupt vs. exception vs. signal
- Mode switch
  - Interrupt/exception handling
- `fork()` and Shell

Previous class…

The three basic process states and the four transitions between them

Three states: Running, Blocked, Ready

(1) Running -> Blocked: I/O; wait for a lock

(2) Blocked -> Ready: I/O is ready; the lock is acquired

(3) Ready -> Running: a ready process is picked to run

(4) Running -> Ready: time slice used up

Previous class…

What is a Call Stack?

A stack data structure that stores the information for the active function calls; it consists of stack frames, each of which corresponds to an active function call

Previous class…

What is Execution Context? Give two examples that are part of the context

The contents of the CPU registers at any point of time.
Program counter: a register that points to the instruction to be executed
Call stack pointer: a register that points to the top of the call stack, e.g., esp in x86 CPU

Previous class…

What is Context Switch? When does it occur?

Also called process switch. Suspending one process and resuming another.

The current process has used up its time slice, blocks (due to I/O or requesting lock), or exits

Previous class…

What is Mode Switch? When does it occur?

Program execution switches between different CPU modes
User -> Kernel: system calls, interrupts, exceptions
Kernel -> User: finish handling of system calls / interrupts / exceptions

Previous class...

Difference between Interrupts, Exceptions, and Signals. Give examples

Interrupts: due to hardware; e.g., timer, I/O devices
Exceptions: due to software; e.g., breakpoints inserted by debugger, divide-by-zero, null pointer exceptions
Signals: due to exception handling or signaling API calls; e.g., SIGSEGV (due to illegal memory access)

Previous class…

How does a computer respond to a keystroke?

Hardware part: an interrupt is generated by the keyboard, and CPU automatically sets the program counter to the corresponding interrupt handler (recall IDT[n])
Software (Kernel): the interrupt handler executes the device driver for the keyboard, which reads the character from the keyboard buffer to the kernel-space buffer
Software (User and Kernel): the process that waits for the input is waken up (blocked -> ready), and the kernel copies the character from the kernel-space buffer to the user-space buffer

Previous class…

How does the system respond to divide-by zero (e.g., a/0) in user code?

1. When a divide-by-zero operation is performed, an exception (also called s/w interrupt or trap) is triggered
2. To handle the exception, execution switches to the kernel mode
3. The kernel handles the exception by generating a SIGFPE signal for the faulty process
4. After exception handling, execution switches back to the user mode
5. The signal handler is invoked (the default handler is implemented and registered by libc; it terminates the process)

Previous class…

Implement a simplest Shell using fork(), exec(), wait()

fork(): create a child process.
exec(): replace the execution of the current program with the designated one
wait(): suspend the calling process until any of its child process exits

Previous class…

What is a Zombie Process? Why is it harmful? Why is it necessary?

When a process exits, it becomes a zombie unless it is waited for by its parent or its parent has explicitly expressed no interest in the exit state

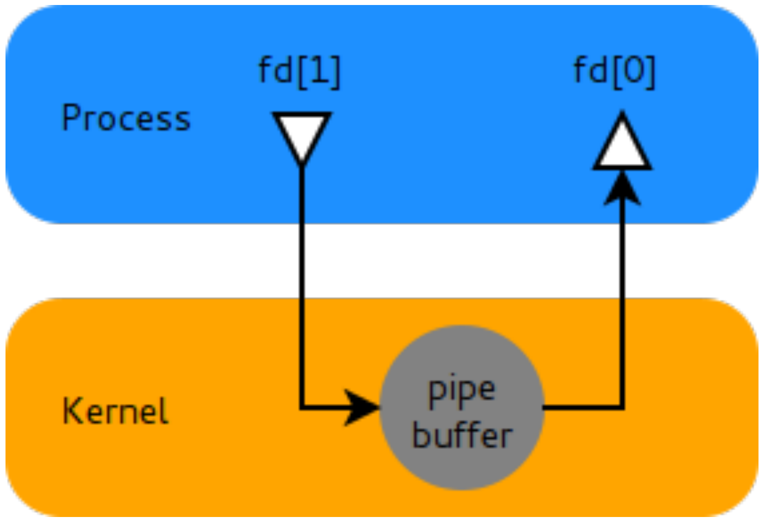
A zombie process occupies precious kernel resources, such as PCB

The PCB stores the exit value of the zombieprocess

Outline

- IPC for passing data
  - Pipe, FIFO, Message Queue, Shared Memory
- Concepts
  - Race condition, critical section, and mutual exclusion
- Sync. with busy waiting
  - Software-based solutions
  - Hardware-assisted solutions
- Sync. without busy waiting

IPC - Pipe

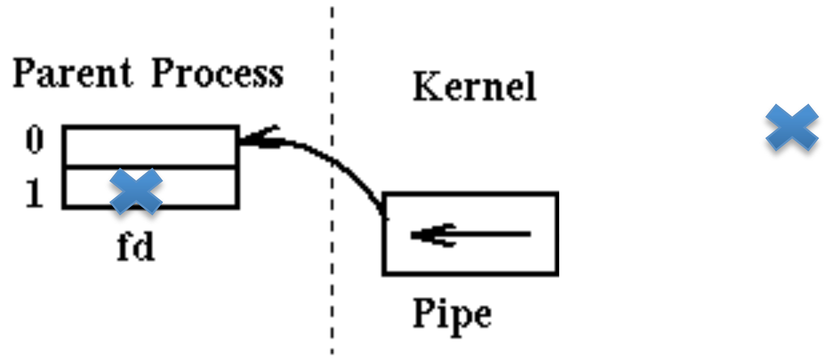


- Pipe is an IPC technique for passing information from one process to another
- Byte stream (like water); no notion of "message boundaries"
- Example:
  - Search lines that contain some word: cat * | grep "os"
  - # of files in a directory: ls | wc -l

`pipe()` - details

- `int pipe(int` *`fd`*`[2])`
  - creates a new pipe and returns two file descriptors
    - fd[0]: refers to the read end
    - fd[1]: refers to the write end

pipe(), fork(), and close() are good friends



- pipe(): create a pipe and return fd[0] and fd[1]
- fork(): child inherits fd[0] and fd[1]
- close(): close unused file descriptors

How do pipes work under the hood?

- There is an in-memory file system, pipefs, in the kernel memory address space
- Pipefs is mounted at system initialization
- A pipe corresponds to a file created in pipefs
- Pipe() creates a pipe and returns two file descriptors
  - One for the read end, opening using O_RDONLY, and
  - One for the write end, opened using O_WRONLY

More details about pipe()

- If read() from a write-closed pipe: end-of-file
- If write() to a read-closed pipe: SIGPIPE -> write failure
- By default, blocking I/O
  - If a process attempts to read from an empty pipe, then read() will block until data is available
  - If a process attempts to write buf to a full pipe, then write() blocks until min(buf, PIPE_BUF = 4KB) is available
  - fcntl() can change it to non-blocking behavior
- If write() too large a message: the message will be split into pieces with each = PIPE_BUF (4KB in Linux) by the system

Example: passing an integer between two processes

Child:

```
int n = something();
write(fd[1], &n, sizeof(n));
```

Parent:

```
int n;
read(fd[0], &n, sizeof(n));
```

Q1: How does a writer indicate the end of data sending?
A: Either send the size to the receiver in the beginning, so the receiver know how many to expect; or send an indicator char (e.g., EOF=-1) in the end

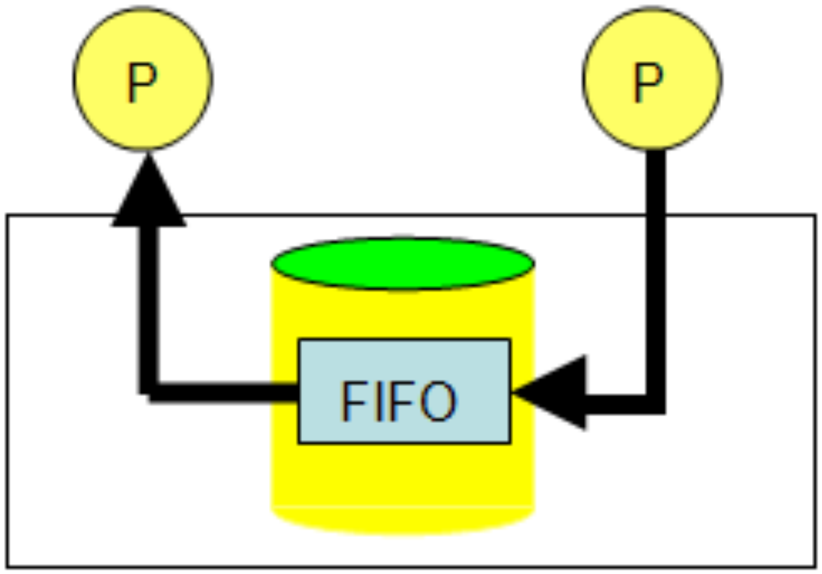
Q2: Can a writer close the pipe immediately after sending data?
A: No. read() will return 0 immediately without receiving the data in the buffer

Q3: Then how can the writer know when to close the pipe?
A: Semaphore (to be covered soon)

Explain what happens under the hood when you run the command “ls –ls | sort”

1. Process creation: fork and exec
2. Pipe creation
3. Redirection: set ls’s STDOUT to pipe’s write end, and set sort’s STDIN to pipe’s read end
4. Scheduling:
   - ls: write->block->write->…;
   - sort: read->block->read->….

IPC – FIFO (also called Named Pipe)



- Unlike a pipe, a FIFO is not limited to be used between the parent and child processes

Example of FIFO

```
#define FIFO_FILE      "MYFIFO”

      FILE *fp;
       char readbuf[80];

       /* Create the FIFO if it does not exist */
       mkfifo(myfifo, 0666);

       fp = fopen(FIFO_FILE, "r");
       fgets(readbuf, 80, fp);
       printf("Received string: %s\n", readbuf);
       fclose(fp); // fclose() will not delete fifo
```

```
#define FIFO_FILE      "MYFIFO”

       fp = fopen(FIFO_FILE, "w"))
       fputs(“Hello!”, fp);

       fclose(fp);
       return(0);
```

Comparison

- Unnamed pipes
  - Purely in-memory
  - The pipe is deleted after all file descriptors that refer to it are closed
  - Have to be used between parent and child
  - Typically, 1 writer and 1 reader

- FIFOs
  - A file is created in your hard disk, but the I/O is through the kernel memory
  - Not deleted even you close the file descriptor (you need to explicitly remove it like removing a file)
  - Not limited to parent-child processes
  - There can be multiple writers and one reader

IPC – Message queues

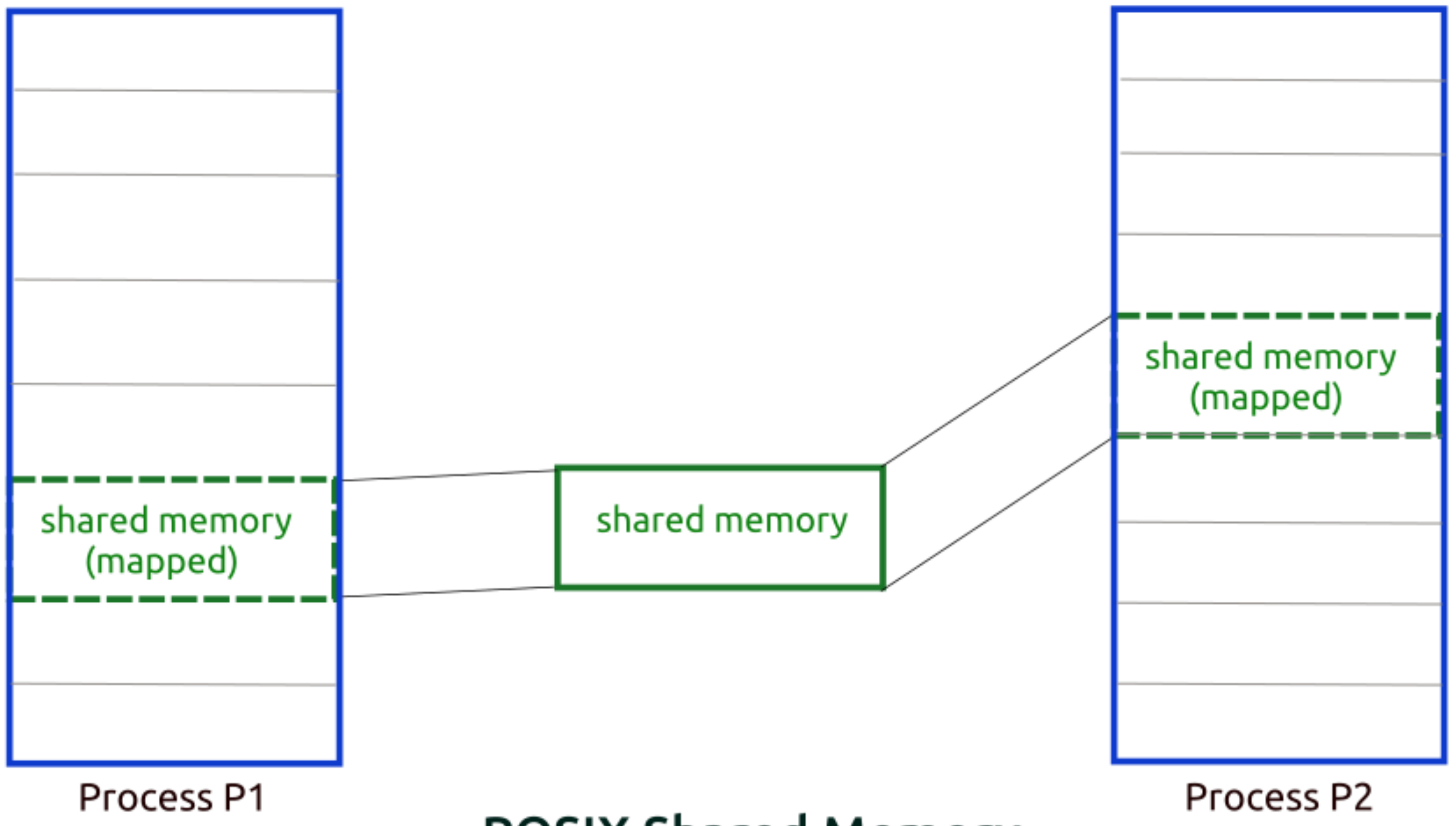
Conceptually, a queue in kernel

POSIX APIs	Description
qid = mq_open(QUEUE_NAME, O_CREAT | O_RDONLY, 0644, &attr);	Create a queue
qid = mq_open(QUEUE_NAME, O_WRONLY);	Open a queue
mq_send(mq, buffer, MAX_SIZE, 0)	Send a message; can specify the priority of the message
mq_receive(mq, buffer, MAX_SIZE, NULL)	Receive a message; can specify the priority also

IPC – Shared Memory

- A region of physical memory that is mapped to two (or more) processes, such that when a process updates the share memory the other process can see the modification immediately, and vice versa

Shared Memory



POSIX Shared Memory

Shared Memory

- The previous three mechanisms (Pipes, FIFOs, and Message Queues) all require mode switch when sending/receiving information (why? recall system calls), while shared memory does NOT

How to create a Shared Memory?

- shmget: System V API
- shm_open: POSIX API
- mmap + fork -> the easiest way to create a shared memory between processes
  - mmap(MAP_ANONYMOUS | MAP_SHARED)

Compare different IPCs

IPC method	Features
Pipes	Can only be used among parent and child
FIFO (named pipes)	Pipe is named using a string, so doesn't have the limitation above
Message Queues	Supports message boundary and message types / priorities
Shared Memory	Data passing doesn't go through kernel, so it is usually the most efficient one

Outline

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  - Race condition, critical section, and mutual exclusion
- Mutual exclusion based on busy waiting
  - Software-based solutions
  - Hardware-assisted solutions
- Synchronization without busy waiting

Race condition bug

- A race condition exists if the final program result depends on the execution sequence
- Let’s consider a counter, *c*, that is shared by two processes

```
++c;
```

```
(1) movl c, %eax // copy to eax
(2) addl $1, %eax // increment
(3) movl  %eax, c // copy back to c
```

- Assume `c= 0` initially, and the two processes both execute “++c”
- Consider the execution sequence: after process 0 executes (1) (2), it is scheduled out; and then process 1 executes (1) – (3)?
- You get c=1 here, while in other execution sequences you may get 2
- A concurrent program as simple as this has a race condition bug

Intuitive attempts to fix the bug

- Use atomic_add instructions
  - atomic_add supports you to do atomic increment
  - It works in that extremely simple example
  - But it is not a general solution; consider another example

```
// critical section: withdraw $100 from account
(1) if(account >= 100)
(2)     account -= 100;
// Is it possible to withdraw $200, given account = 100?
```

- Disabling interrupts to prevent the process from being schedule out
  - Does not work well on multi-core machines

Intuitive attempts don't work; we need a formal treatment by introducing new ideas and concepts

Critical section and mutual exclusion

- A Critical section is a program region that has to access shared data in a synchronized way (say, a mutual exclusion way); otherwise, race condition may occur
- Mutual exclusion is to make sure no two processes are simultaneously inside critical sections that access the same shared data
  - Each synchronization primitive that enforce mutex provides the two APIs: *enter_cs() / leave_cs()*
  - A critical section is surrounded by the two API calls

Why is Mutual Exclusion important?

```
// Why is it impossible to withdraw 200 given account = 100?
enter_cs();
// critical section
if(account >= 100)
     account -= 100;
exit_cs();
```

Mutual Exclusion (Mutex)

- A good solution to mutual exclusion should satisfy
  - Mutual exclusion
  - No assumptions made about processor speed or number
  - No outside blocker
  - No infinite wait

A failed attempt: strict alternation

```
// process 0
while(true) {
 while (turn != 0) ; //enter_cs()
 critical_section();
 turn = 1; // leave_cs();
 …
}
```

```
// process 1
while(true) {
 while (turn != 1) ; // enter_cs()
   critical_section();
 turn = 0; // leave_cs();
 …
}
```

- What if process 0 quickly finishes one iteration and wants to execute another, while process 1 has not entered the critical section?
- It violates Condition 3 “no outside blocker”

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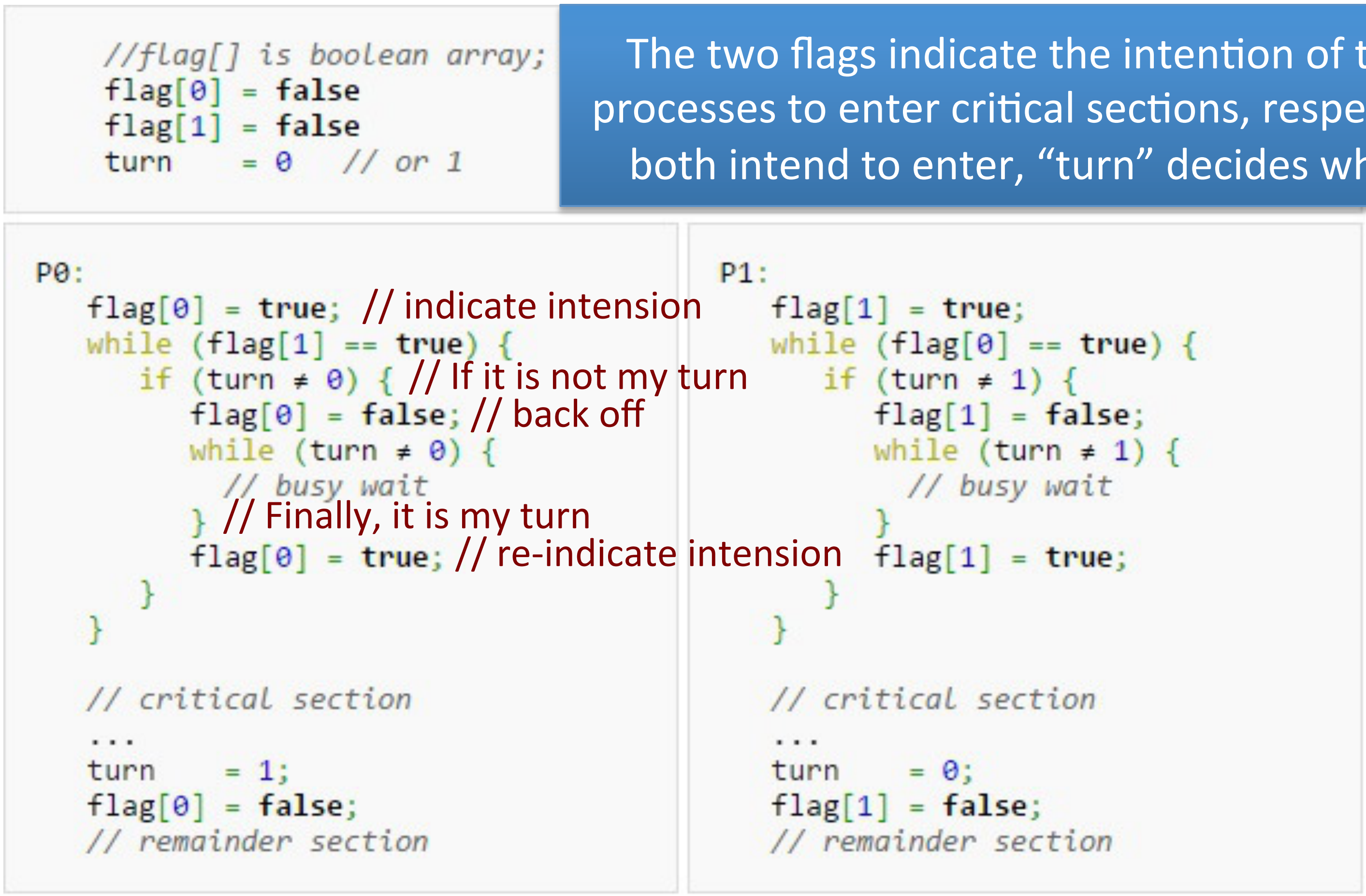
Dekker's algorithm – First solution



```
//flag[] is boolean array;
flag[0] = false
flag[1] = false
turn    = 0   // or 1
```

The two flags indicate the intention of the two processes to enter critical sections, respectively. If both intend to enter, "turn" decides who wins

```
P0:
   flag[0] = true; // indicate intension
   while (flag[1] == true) {
      if (turn ≠ 0) { // If it is not my turn
         flag[0] = false; // back off
         while (turn ≠ 0) {
            // busy wait
         } // Finally, it is my turn
         flag[0] = true; // re-indicate intension
      }
   }

   // critical section
   ...
   turn    = 1;
   flag[0] = false;
   // remainder section
```

```
P1:
   flag[1] = true;
   while (flag[0] == true) {
      if (turn ≠ 1) {
         flag[1] = false;
         while (turn ≠ 1) {
            // busy wait
         }
         flag[1] = true;
      }
   }

   // critical section
   ...
   turn    = 0;
   flag[1] = false;
   // remainder section
```

Peterson’s algorithm – simplify Dekker’s

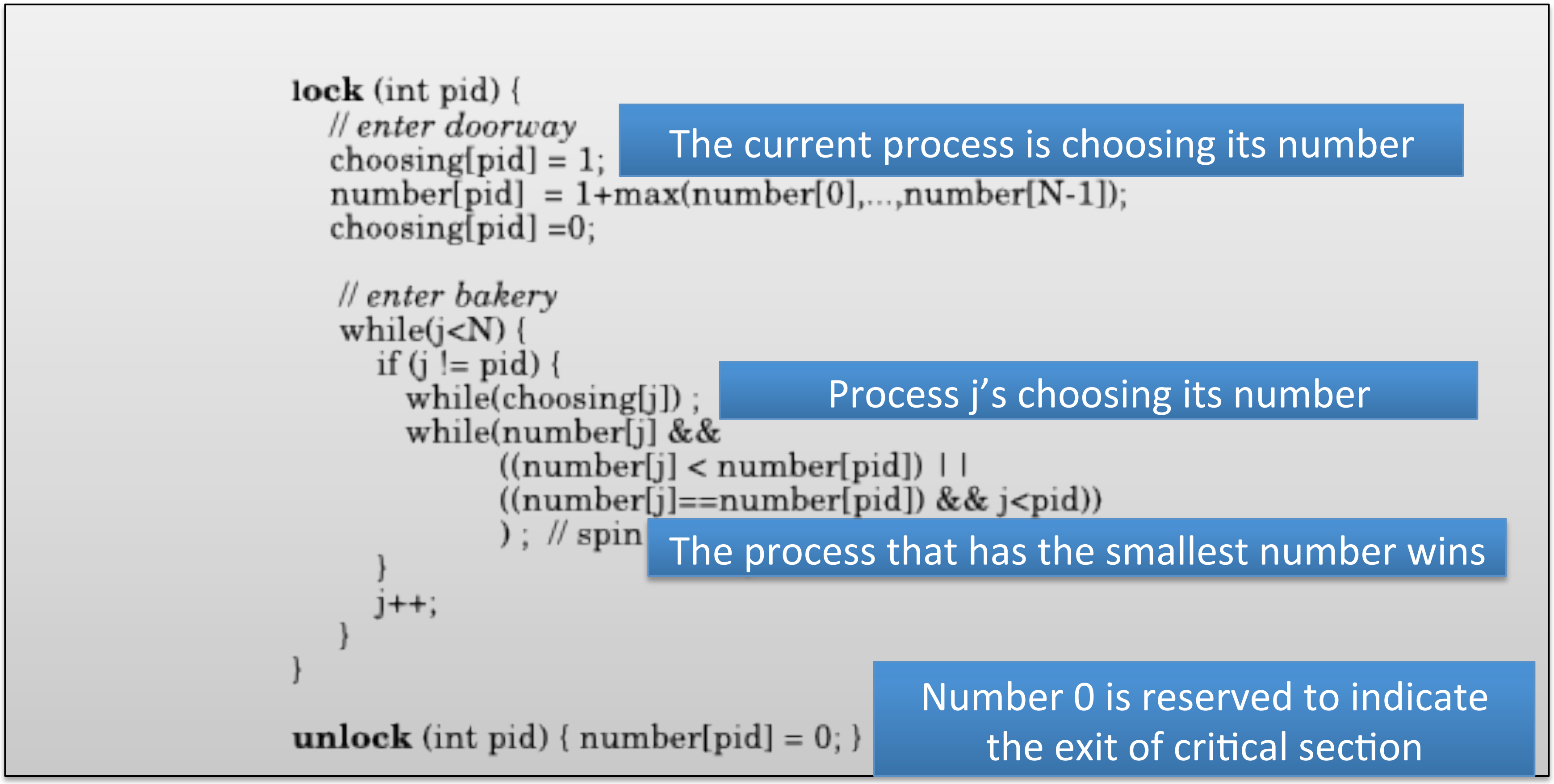
```
#define FALSE  0
#define TRUE   1
#define N      2                        /* number of processes */

int turn;                               /* whose turn is it? */
int interested[N];                      /* all values initially 0 (FALSE) */

void enter_region(int process);         /* process is 0 or 1 */
{
    int other;                          /* number of the other process */

    other = 1 – process;                /* the opposite of process */
    interested[process] = TRUE;         /* show that you are interested */
    turn = process;                     /* set flag */
    while (turn == process && interested[other] == TRUE) /* null statement */ ;
}

void leave_region(int process)          /* process: who is leaving */
{
    interested[process] = FALSE;        /* indicate departure from critical region */
}
```

What if two processes execute “turn = process” almost the same time?

Process 0: “turn = 0” // then Process 1: “turn = 1”
Process 0: while(turn == process && …) // loop ends as “turn == 1”
It means whoever executes “turn = process” first wins

Lamport's bakery algorithm – N processes

"A New Solution of Dijkstra's Concurrent Programming Problem", Lamport 1974



```
lock (int pid) {
   // enter doorway
   choosing[pid] = 1;
   number[pid]  = 1+max(number[0],...,number[N-1]);
   choosing[pid] =0;

   // enter bakery
   while(j<N) {
      if (j != pid) {
         while(choosing[j]) ;
         while(number[j] &&
                  ((number[j] < number[pid]) ||
                  ((number[j]==number[pid]) && j<pid))
                  ) ;  // spin
      }
      j++;
   }
}

unlock (int pid) { number[pid] = 0; }
```

The current process is choosing its number

Process j's choosing its number

The process that has the smallest number wins

Number 0 is reserved to indicate the exit of critical section

Hardware-assisted solutions

```
test_and_set(int* p){
   int t = *p;
   *p = 1;
   return t;
}
```

```
//compare-and-swap
CAS(p, old, nvalue){
   if(*p != old)
      return false;
   *p = nvalue;
   return false;
}
```

Load-link/store-conditional,
or LL/SC // CAS - equivalent in RISC architectures

```
XCHG(int *x, int *p){
   int  t = *x;
   *x = *p;
    *p = t;
}
```

```
enter_region() {
   while(test_and_set(&lock) == 1) ;
}


leave_region() { lock = 0;}
```

```
enter_region() {
   a = 1;
   do {  XCHG(&a, &lock);
   } while ( a == 1);
}

leave_region() { lock = 0;}
```

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  - Hardware-assisted solutions
- Synchronization without busy waiting
  - Kernel-assisted solutions: semaphore
  - Language-assisted solutions: monitor

Semaphore – avoids busy-waiting

"Cooperating Sequential Processes". Dijkstra, 1965 Sept.

- Previous solutions perform busy waiting
- Semaphore internals:
  - A counter to indicate the number of resources
  - A queue for processes waiting for the semaphore
- Semaphore needs operating system support

Semaphore – Two main APIs

```
// Atomic
down(S) { // also called P operation
  if(S.num>0)
    S.num--;
  else
    put the current process in queue;
    the current process blocks;
}
```

```
// Atomic
up(S) { // also called V operation
  if(any process is in S's wait queue)
    pop a process from the queue;
    resume this process;
  else
    S.num++;
}
```

Enforcing Mutex (mutual exclusion) using a binary semaphore

- If a semaphore's counter value is restricted to 0 and 1, this semaphore is a binary semaphore
- A binary semaphore can be used to enforce mutual exclusion
  - The semaphore's counter is initialize to 1
  - After a process X calls P(), all other process that call P() sleep in the wait queue of the semaphore
  - After X calls V(), one of the processes in the wait queue is waken up

Cons of Semaphore?

- When the competition for the resources is intense, suspending and resuming processes, (i.e., process switching) frequently is expensive
- Assume a critical section contains *N* instructions and a context switch takes *M* instructions.
- If $N < M$, it actually saves CPU cycles to use busy waiting, compared to using Semaphore
- That is why some systems use a hybrid method
  - The process first spins for a while, and then
  - Blocks

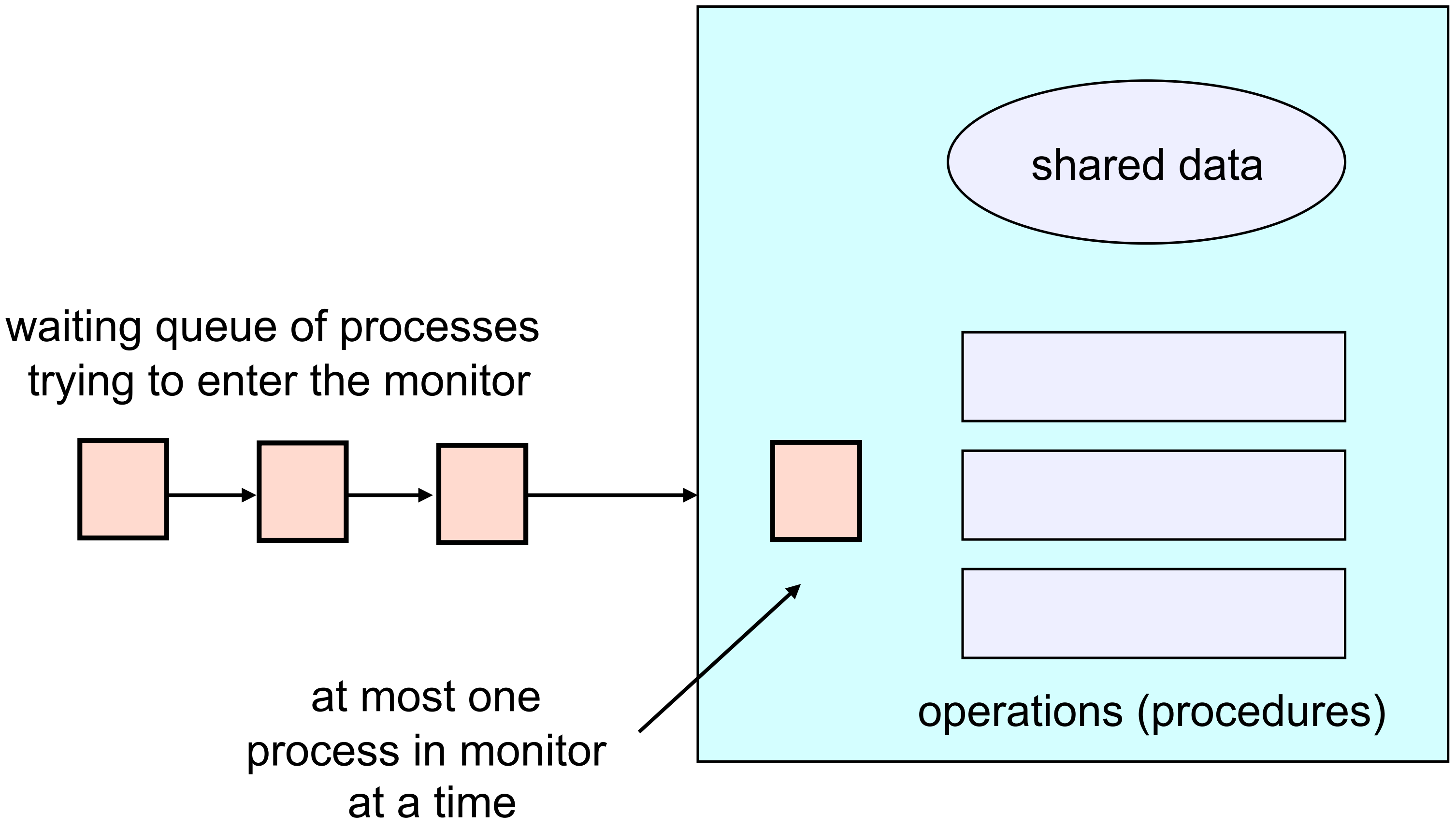
Semaphore and pthread_mutex in Linux

function	explanation
sem_open()	Create or connect to a named semaphore (and increment the reference count), which can be conveniently shared inter-process
sem_unlink()	Remove the named semaphore once its reference count = 0
sem_close()	Decrement the reference count (exit() does this automatically)
sem_init()	Create an unnamed semaphore (usually a global variable)
sem_destroy()	Destroy an unnamed semaphore
sem_wait()	P operation
sem_post()	V operation
pthread_mutex_init()	PTHREAD_PROCESS_SHARED: process-shared mutex Other APIs: *_destroy(), *_lock(), *_trylock(), *_unlock()

Monitor

- A programming language construct that supports controlled access to shared data; it encapsulates
  - Shared data
  - Procedures that operate on the shared data
  - Synchronization between concurrent processes that invoke those procedures (only one thread can execute any of the procedures at a time)
- A Monitor has a mutex lock and a queue
  - Processes has to acquire the lock before invoking a procedure in the monitor
  - If the lock has been acquired by a process, other requesting processes are put in the queue

(1) Shared data can only be accessed through procedures
(2) Only one thread can enter the monitor to invoke procedures at a time
(1) + (2) => It is guaranteed that all threads access the shared data in a mutual exclusive way
Monitor is easy to use and fool-proof, but less flexible than semaphores


shared data
waiting queue of processes trying to enter the monitor
at most one process in monitor at a time
operations (procedures)

Graph credit: Michael Swift @ wisc univ

Monitor in Java

- “Synchronized” non-static methods are to implement a Monitor object
  - A thread acquires the lock of an object to execute a synchronized method
  - If another thread tries to execute any of the synchronized methods, the thread blocks
- “synchronized” static method is to implement a Monitor class
- “synchronized block” is more flexible

Problem

- Consider that, inside a monitor procedure, the execution may can't continue unless some condition is met (and the condition satisfaction relies on another thread)
- But recall that the thread executing the procedure is occupying the lock of the monitor object; so it has to relinquish the lock to allow other threads to come in
- Seems that the thread has to exit the procedure immaturely (and re-executes it later)?
- Any better solution?

Condition Variable (CV)

- Condition variables provide such a solution
  - So that the thread can be suspended at the condition evaluation location, and resumes from where it is suspended when the condition changes
- Each condition variable correspond to a wait queue, and there are three operations
  - Wait(c): perform the following two actions atomically
    - The calling process is put in the wait queue
    - Release the monitor lock (so somebody else can get in)
  - Signal(c)
    - Wake up one process in the wait queue, and the process goes to wait in the queue of the lock
    - If the queue is empty, the signal is lost
  - Broadcast(c)
    - Wake up all processes in the wait queue

Condition Variable

Operations	Posix	Java
Wait(c)	pthread_cond_wait (cond, mutex)	wait()
Signal(c)	*pthread_cond_signal(cond)*	notify()
Broadcast(c)	*pthread_cond_broadcast(cond)*	notifyAll()

How to use a Condition Variable

```
pthread_mutex_t m = PTHREAD_MUTEX_INITIALIZER;
pthread_cond_t c = PTHREAD_COND_INITIALIZER;
```

```
Strange_withdraw(x) {
  …
  pthread_mutex_lock(&m);
  while(account < x) // "if" will not work
          pthread_cond_wait(&c, &m);
  account -= x;
  pthread_mutex_unlock(&m);
}
```

```
Deposit(y){
  pthread_mutex_lock(&m);
  account += y;
  pthread_cond_signal(&c);
  pthread_mutex_unlock(&m);
}
```

1. Always hold the lock while performing CV operations
2. Always put the wait operation in a loop
   – In order to check whether the condition is true
   – Note the the *signal(c)* only hints the conditions changes; it does not imply that the condition is definite true. Moreover, after signaling, some other processes may affect the condition

"Always hold the lock while performing CV operations", why?

- The correct use of "Wait(c)" requires that the caller holds the lock, since the semantics of this call implies the release of the lock
- If the caller of "signal(c)" does not hold the lock, there may be race conditions
  - Consider w.1 -> s.1 -> s.2 -> w.2 => signal lost

```
Strange_withdraw(x) {
  …
  pthread_mutex_lock(&m);
  while(account < x) // w.1
    pthread_cond_wait(&c, &m); // w.2
  account -= x;
  pthread_mutex_unlock(&m);
}
```

```
Deposit(y){
  // pthread_mutex_lock(&m);
  account += y; // s.1
  pthread_cond_signal(&c); // s.2
  // pthread_mutex_unlock(&m);
}
```

Relations between Condition Variable & Monitor

- A Monitor may contain zero or more CVs
  - Very often, procedures in Monitor rely on CVs to implement complex synchronization
  - Recall that a CV has to be used with a lock; a Monitor can provide the lock, so you do not have to explicitly use a lock for employing a CV in a Monitor
- The use of CVs is not limited to Monitors
  - E.g., Pthread library provides CVs but not Monitors

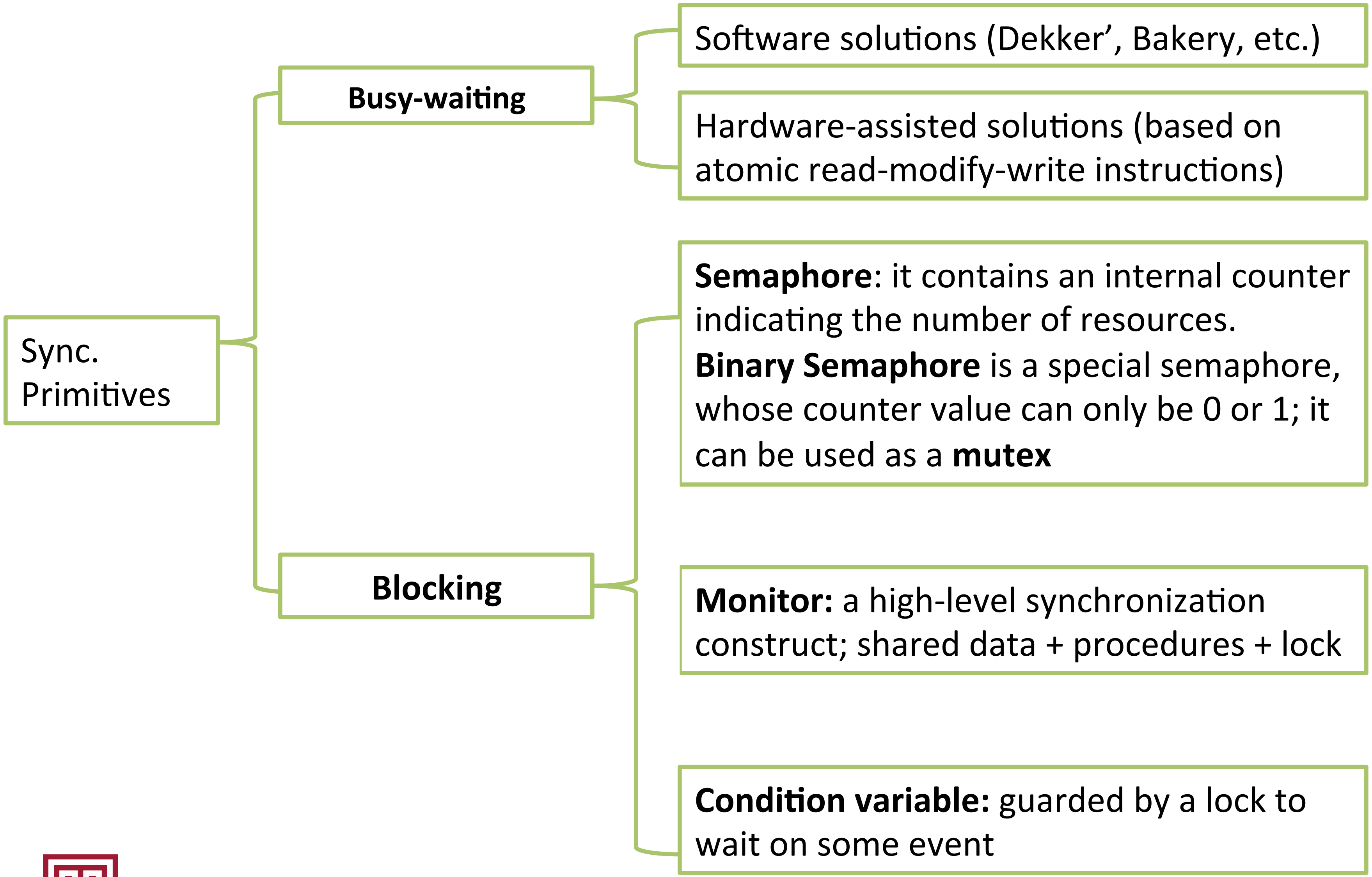
Condition variable VS Semaphore

- A Semaphore has a counter and a wait queue, while a Condition Variable only has a wait queue
  - Plus, you need to initialize the counter when using a Semaphore, and the initialization value means the number of resources. A Condition Variable has no notion of “the number of resources”
- Condition Variables allow broadcast() operation, while Semaphores do not

Issues with locks (mutex and semaphore)

- You may introduce deadlock
- Nobody can make progress sometimes (when the lock owner is scheduled out)
- Priority inversion: a high priority thread is waiting for the lock occupied by a low priority thread, which is then preempted by a medium priority thread
- Solution: **non-blocking** programming / data structures (but they are very complex and, very often, slow)

Big picture of synchronization primitives



- Sync. Primitives
  - **Busy-waiting**
    - Software solutions (Dekker', Bakery, etc.)
    - Hardware-assisted solutions (based on atomic read-modify-write instructions)
  - **Blocking**
    - **Semaphore**: it contains an internal counter indicating the number of resources. **Binary Semaphore** is a special semaphore, whose counter value can only be 0 or 1; it can be used as a **mutex**
    - **Monitor:** a high-level synchronization construct; shared data + procedures + lock
    - **Condition variable:** guarded by a lock to wait on some event

Take away…

- IPC
  - Pipes, FIFO, message queues, and shared memory
- Concepts
  - Race condition, critical section, mutual exclusion
- Pure software based locks
  - Dekker’s, Peterson’s, Bakery algorithms
- Atomic read-modify-write (RMW) instructions
  - Test-and-set, xchg, compare-and-swap
  - Mutex based on (RMW)
- Semaphores and binary semaphores
- Monitors and Conditional variables
- Lock-free concurrent computing