department of computer science
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Internet Programming

Multiprocessing in Unix

Introduction

- Distributed programming is about **processes which communicate** over a network.
  - Obvious requirement: Excellent knowledge on managing them locally
- If there is ANYTHING you don't understand, scream!!
  - Else you'll be lost in later lessons!

Today's Agenda

- Managing Unix Processes
- Inter-Process Communication
- Posix Threads
- Java Threads

Managing Unix Processes

Programs vs. Processes

- Computers can execute **programs**
- A **process** is one **instance** of a program, while it is executing
  - For example: I can run a simulation for my research
  - At the same time, there are many other programs executing: they are other processes
- The **same program** can be executed **multiple times** in parallel
  - Somebody else may log on my computer and start that simulator too
  - These are several **separate processes**, executing the **same program**
- A process can only be created by another process
  - E.g., when I type a command, my Unix shell process will create a new process to execute it

Inside a Process

- One process is made of:
  - One executing **program** (i.e., a file containing the code to run)
  - **PID**: Process identifier (an integer)
  - **Memory** used to execute the program (text, data, heap, stack)
  - **PC**: Program counter
    - indicates where in the program the process currently is
  - A number of **signal handlers**
    - tells the program what to do when receiving signals

- One process can determine its own PID:

```
#include <sys/types.h>
#include <unistd.h>
pid_t getpid(void);
```

- Or the PID of its parent:

```
pid_t getppid(void);
```

The fork() System Call [1/3]

- In Unix systems, there is exactly **one way** to create a new process:

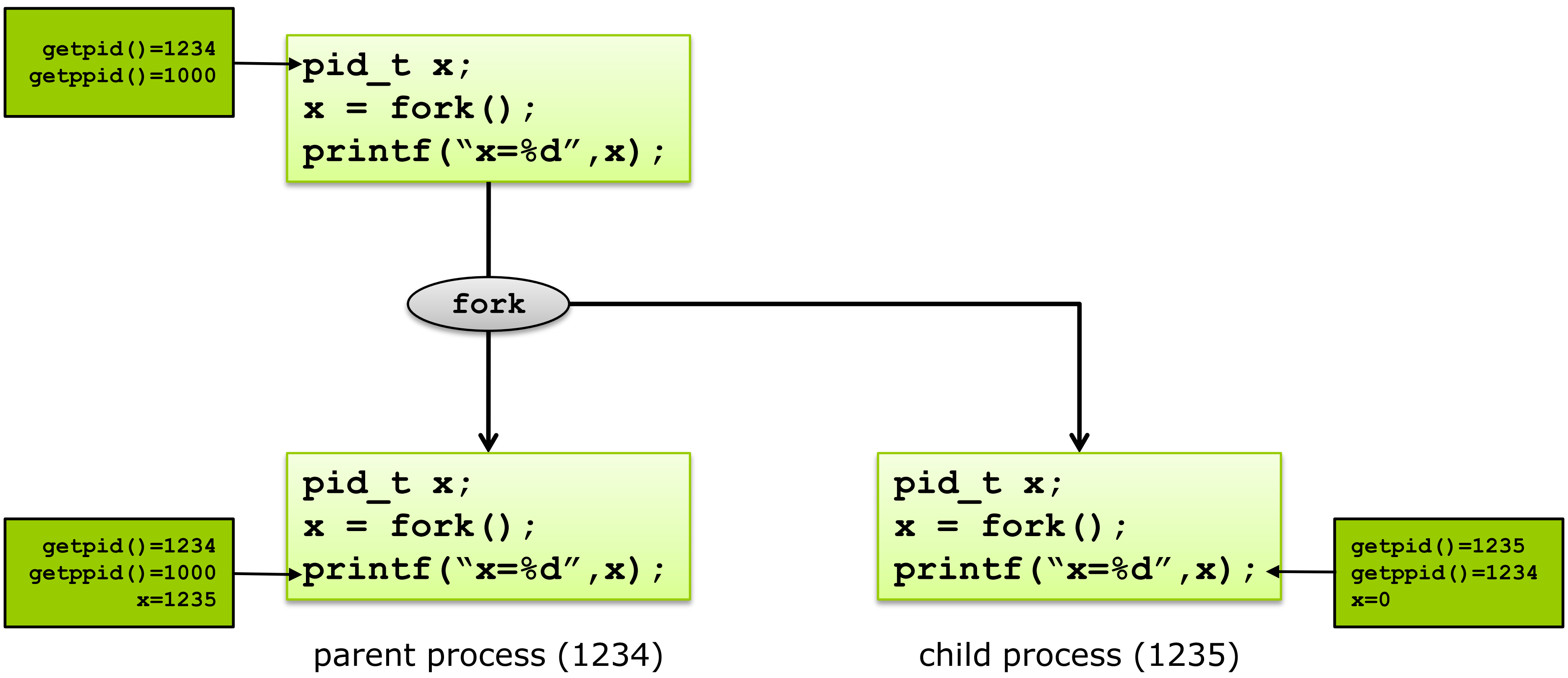
```
#include <sys/types.h>
#include <unistd.h>
pid_t fork(void);
```

- The child process is an **exact copy** of the parent
  - It is running the **same program**
  - Its **memory area** is an exact copy of the parent's memory
  - **Signal handlers** and **file descriptors** are copied too
  - Its **program counter (PC)** is at the same position within the program
    - I.e., just after the fork() call

- There is **one way** of distinguishing between the two processes:
  - `fork()` returns 0 to the child process
  - `fork()` returns the child's PID to the parent process
  - `fork()` returns -1 in case of error

- Most often, programs need to check the return value of `fork()`.

The fork() System Call [2/3]



The fork() System Call [3/3]

- Typically, processes diverge after fork() returns:

```
pid_t pid;
pid = fork();

if (pid<0) {perror("Fork error"); exit(1);}

if (pid==0)  /* child */
{
  printf("I am the child process\n");
  while (1) putchar('c');
}
else          /* parent */
{
  printf("I am the parent process\n");
  while(1) putchar('p');
}
```

The Fork of Death!

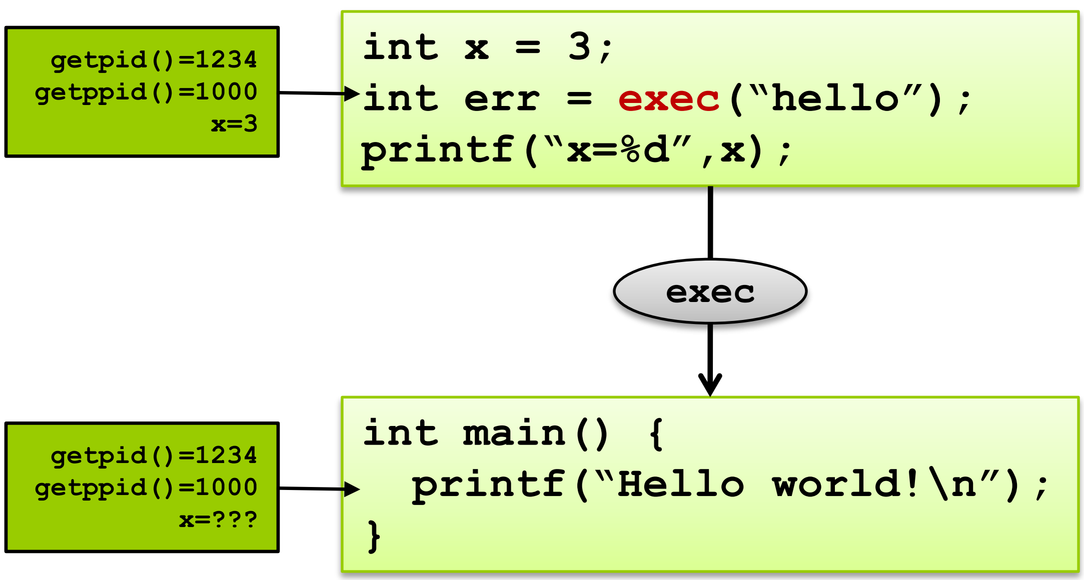
- You must be careful when using fork()!!
  - Very easy to create very harmful programs

```
while (1) {
  fork();
}
```

- Finite number of processes allowed
  - PIDs are 16-bit integers ➔ maximum 65536 processes!
- Administrators typically take precautions
  - Limited quota on the number of processes per user
  - <u>Make such experiments only at home ☺</u>

The exec() System Call [1/4]

- **`exec()`** allows a process to switch from one program to another
  - Code/Data for that process are destroyed
  - Environment variables are kept the same
  - File descriptors are kept the same
  - New program's code is loaded, then started (from the beginning)
  - There is no way to return to the previously executed program!



The exec() System Call [2/4]

- fork() and exec() could be used separately
  - Imagine examples when this could happen?

- But most commonly they are used together:

```
if (fork()==0)    /* child */
{
  exec("hello");  /* load & execute new program */
  perror("Error calling exec()!\n");
  exit(1);
}
else  /* parent */
{
  ...
}
```

The exec() System Call [3/4]

- Command-line arguments are passed as an array of strings:
  - first argument should be argv[0] (i.e., the program name)
  - last argument should be NULL (to denote the end of the array)

- If you do not respect these constraints, **the program behavior is unspecified**!
  - Very strange behavior sometimes…

- E.g., to execute "`ls -l /home/spyros`",
  - the program name is "`/bin/ls`"
  - and the arguments array is

    `{"ls", "-l", "/home/spyros", NULL}`

The exec() System Call [4/4]

- There are 4 versions of exec(), depending on 2 criteria
  - Search for program in (i) absolute path, or (ii) $PATH
  - Command-line arguments passed as **l**ist or single **v**ector (array)

	absolute path	$PATH
list (*n+1* parameters)	`execl()`	`execlp()`
vector (2 parameters)	`execv()`	`execvp()`

- execl() example:

```
execl("/bin/ls", "ls", "-l", "/home/spyros", NULL);
```

- execv() example:

```
char *params[4] = {"ls", "-l", "/home/spyros", NULL};
execv("/bin/ls", params);
```

Questions

- Q1: What happens when you type a command in the shell?
  - The shell process **forks** (so, makes a copy of itself)
  - The child process **execs** the required program
- Q2: What if the command contains pipes?

  e.g.: `ls | grep ".txt" | wc`
  - The shell forks once per process
  - Creates **pipes** and arranges output of P_i to be input of P_{i+1}
- Q3: How does a process end?
  - See next slides!

Stopping a Process

- A process stops (without error) when:
  - The `main()` function returns

    \- or -
  - the program calls `exit()`

- No process can directly kill another process, not even the kernel!
  - It can only send a **signal** to it
    - …asking it to terminate itself
  - The signal will invoke the appropriate **signal handler** (a function)
  - By default, the signal **SIGINT** stops the process
    - This is what happens when you type ^C
    - The handler for that signal can be overwritten
  - Signal **SIGKILL** has the same effect
    - But it cannot be overwritten

Signal Handling [1/3]

- Signals can be sent by one process (including a kernel process) to another
  - **SIGSEGV**: segmentation fault (non-authorized memory access)
  - **SIGBUS**: bus error (non-aligned memory access)
  - **SIGPIPE**: you tried to write in a pipe with no reader
  - **SIGCHLD**: one of your children processes has stopped
  - **SIGSTOP**, **SIGCONT**: pause and continue a process
  - **SIGUSR1**, **SIGUSR2**: two generic signals to be used by user programs
  - You can get a complete list of signals with **`kill -l`**

- Signals can also be sent explicitly: kill()

```
#include <sys/types.h>
#include <signal.h>
int kill(pid_t pid, int sig);
```

- **This function does not necessarily kill processes**!

Signal Handling [2/3]

- To setup a custom signal handler:

```
#include <signal.h>
void (*signal(int signum, void (*sighandler)(int)))(int);
```

informally: `HANDLER *signal(int signum, HANDLER *sighandler);`

where HANDLER would be a function like this: `void sighandler(int)`

- Example:

```
#include <signal.h>

void myhandler(int sig) {
  printf("I received signal number %d\n", sig);
  signal(sig, myhandler);  /* set it again it */
}

int main() {
  void (*oldhandler)(int);
  oldhandler = signal(SIGINT, myhandler);
  signal(SIGUSR1, myhandler);
  ...
}
```

Signal Handling [3/3]

- When a signal handler is run, the signal gets associated back to its default behavior
  - You must call signal() **again** in the signal handler
- Attention: Unix normally does not queue signals
  - If the same signal is sent multiple times to the same process at short time intervals, **the signal may be delivered only once**
- Recent Unix systems have other signal handling calls that queue signals
  - We will not study them here

Zombie Processes

- When a process terminates, it is not immediately removed from the system
  - The process which created it may be interested in its return value
- It gets to zombie state:
  - Its memory and resources are freed
  - It stays in the process table until its parent has received its termination status
  - If the parent has already finished, it is adopted by process 1 (init)
- Zombie processes must be dealt with!
  - Otherwise we eventually run out of PIDs
  - Prevention: The administrator should limit the number of processes a user can spawn
- To allow a zombie to die, its parent must explicitly “wait” for its children to finish
  - It can block until one of its children has died
  - Or it can setup a signal handler for the SIGCHLD signal to be asynchronously notified

Waiting for Children Processes [1/2]

- To block until some child process completes:

```
#include <sys/types.h>
#include <sys/wait.h>
pid_t wait(int *status);
```

- **`wait()`** waits for **any child** to complete
  - Also handles an already completed (zombie) child → returns instantly
  - Returns the PID of the completed child
  - **`status`** indicates the process' return status

Waiting for Children Processes [2/2]

- waitpid() gives you more control:

```
pid_t waitpid(pid_t pid, int *status, int option);
```

  - pid specifies which child to wait for (-1 means any)
  - option=WNOHANG makes the call return immediately, if no child has already completed (otherwise use option=0)

- Example: a SIGCHLD signal handler

```
void sig_chld(int sig) {
  pid_t pid;
  int stat;
  while ( (pid=waitpid(-1, &stat, WNOHANG)) > 0 ) {
    printf("Child %d exited with status %d\n", pid, stat);
  }
  signal(sig, sig_chld);
}
```

- **Question:** Why is the while statement necessary?

Inter-Process Communication

Inter-Process Communication

- By default, processes cannot influence each other
  - Executed in isolation
  - Different address spaces

- There are 4 mechanisms for processes of the **same computer** to communicate
  - **Signals:** Send a signal to another process (SIGINT, SIGKILL, etc.)
  - **Pipes:** Communication channel to transfer data
  - **Shared memory:** the same memory area accessible to multiple processes
  - **Semaphores:** perform synchronization (e.g., to regulate access to shared memory)

- All these IPC methods work only between processes of the **same computer**!

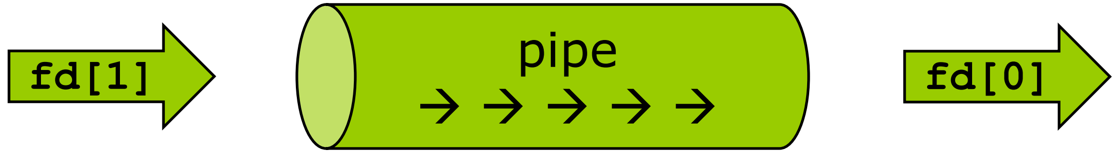
Pipes [1/3]

- A pipe is a unidirectional communication channel between processes
  - Write data on one end – Read it at the other end
  - Bidirectional communication? Use TWO pipes.

- Creating a pipe

```
#include <unistd.h>
int pipe(int fd[2]);
```

- The return parameters are:
  - **`fd[0]`** is the file descriptor for reading
  - **`fd[1]`** is the file descriptor for writing



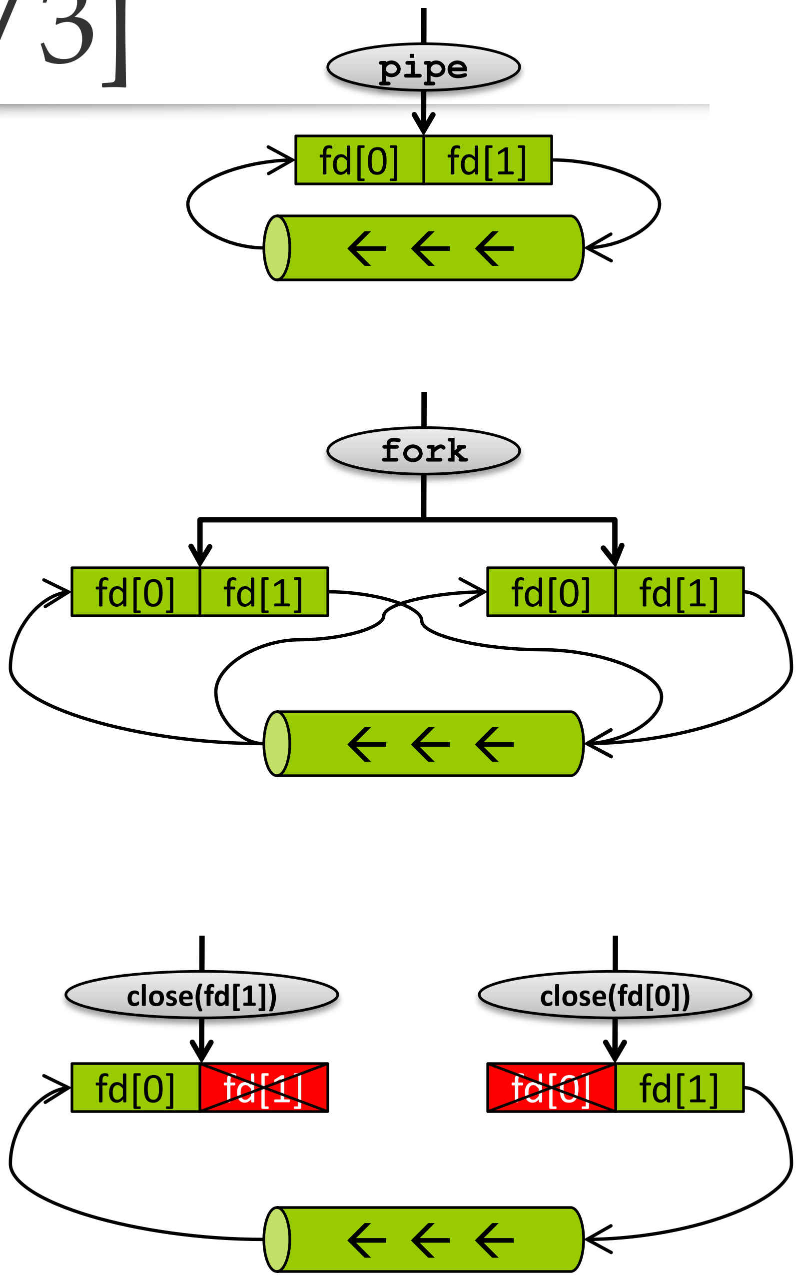
Pipes [2/3]

- Pipes are often used in combination with fork()

```
int main() {
  int pid, fd[2];
  char buf[64];

  if (pipe(fd)<0) exit(1);

  pid = fork();
  if (pid==0)        /* child */
  {
    close(fd[0]);    /* close reader */
    write(fd[1],"hello, world!",14);
  }
  else {             /* parent */
  {
    close(fd[1]);    /* close writer */
    if (read(fd[0],buf,64) > 0)
      printf("Received: %s\n", buf);
    waitpid(pid,NULL,0);
  }
}
```



Pipes [3/3]

- Pipes are used for example for shell commands like:

  ```
  sort foo | uniq | wc
  ```

- Pipes can only link processes which have a common ancestor
  - Because children processes inherit the file descriptors from their parent
- What happens when two processes with no common ancestor want to communicate?
  - Named pipes (also called FIFO)
  - A special file behaves like a pipe
  - Assuming both processes agree on the pipe's filename, they can communicate
    - mkfifo() for creating a named pipe
    - open(), read(), write(), close()

Shared Memory [1/5]

- Shared memory allows multiple processes to have direct access to the same memory area
  - They can interact through the shared memory segment
- Shared memory segments must be **created**, then **attached** to a process to be usable. Then, you must **detach** and **destroy** them.
- When using shared memory, you must be very careful about **race conditions**, and solve them using semaphores.
  - If you don't know what a race condition is, then:
    - There will be an example later in this course
    - Shouldn’t you attend the Operating Systems course? ☺

Shared Memory [2/5]

- To **create** a shared memory segment:

```
#include <sys/ipc.h>
#include <sys/shm.h>
int shmget(key_t key, int size, int shmflg);
```

  - **key**: rendezvous point (key=IPC_PRIVATE if it will be used by children processes)
  - **size**: size of the segment in bytes
  - **shmflg**: options (access control mask)
  - **Return value**: a shm identifier (or -1 for error)

Shared Memory [3/5]

- To **attach** a shared memory segment:

```
#include <sys/types.h>
#include <sys/shm.h>
void *shmat(int shmid, const void *shmaddr, int shmflg);
```

  - **shmid**: shared memory identifier (returned by shmget)
  - **shmaddr**: address where to attach the segment, or NULL if you don't care
  - **shmflg**: options (access control mask)
    - SHM_RDONLY: read-only

- To **detach** a shared memory segment:

```
int shmdt(const void *shmaddr);
```

  - shmaddr: segment address
  - **Attention**: shmdt() does **not** destroy the segment!

Shared Memory [4/5]

- To **destroy** a shared memory segment:

```
#include <sys/ipc.h>
#include <sys/shm.h>
int shmctl(int shmid, int cmd, struct shmid_ds *buf);
```

  - **shmid**: shared memory identifier (returned by shmget)
  - **cmd=IPC_RMID** to destroy the segment
  - **buf**: NULL as far as we are concerned

- Shared memory segments stay persistent even after all processes have died!
  - You **must** destroy them in your programs
  - The `ipcs` command shows existing segments (and semaphores)
  - You can destroy them by hand with: `ipcrm shm <id>`

Shared Memory [5/5]

- Example:

```
int main() {
  int shmid = shmget(IPC_PRIVATE, sizeof(int), 0600);
  int *shared_int = (int *) shmat(shmid, 0, 0);
  *shared_int = 42;

  if (fork()==0) {
    printf("The value is: %d\n", *shared_int);
    *shared_int = 12;
    shmdt((void *) shared_int);
  }
  else {
    sleep(1);
    printf("The value is: %d\n", *shared_int);
    shmdt((void *) shared_int);
    shmctl(shmid, IPC_RMID, 0);
  }
}
```

Race Conditions [1/2]

- When several processes share a resource, you **must always** wonder if synchronization is needed

- Example: Add an element to the end of an array

```
int array[32], size;

int add_elem(int elem)
{
  if (size==32) return -1;
  array[size] = elem;
  size = size + 1;
}
```

- This is a **race condition**: if two processes execute the function simultaneously, the result can be **wrong**

Race Conditions [2/2]

size=0

add_elem(10)

add_elem(50)

thread 1 running

thread 2 waiting

```
int add_elem(int elem) {
  if (size==32) return -1;
  array[size] = elem;
  size = size + 1;
}
```

```
int add_elem(int elem) {
  if (size==32) return -1;
  array[size] = elem;
  size = size + 1;
}
```

context switch

thread 1 waiting

thread 2 running

```
int add_elem(int elem) {
  if (size==32) return -1;
  array[size] = elem;
  size = size + 1;
}
```

```
int add_elem(int elem) {
  if (size==32) return -1;
  array[size] = elem;
  size = size + 1;
}
```

How many elements are there in the array?

Semaphores [1/6]

- In many cases you need to synchronize processes
  - When they share a resource (shared memory, file descriptor, device, etc.)
  - When a process needs to wait for a given event

- Semaphores are positive integers with two methods: **UP()** and **DOWN()**
  - **DOWN():**
    - If sem>=1 then sem=sem-1
    - Otherwise, block the process
  - **UP():**
    - If there are blocked processes, then unblock one of them
    - Otherwise, sem=sem+1
  - **Semaphore operations are <u>atomic</u>**

Semaphores [2/6]

- Semaphores are generally used for two goals:
  - **Mutual exclusion**: only one process at a time can be within a section of code
    - Start with **sem=1**
    - To **enter** the mutex section: DOWN(sem)
    - To **leave** the mutex section: UP(sem)
  - **Process synchronization**: wait for a given event
    - Start with **sem=0**
    - To **wait** for the event: DOWN(sem)
    - To **trigger** the event: UP(sem)
    - What happens if the event is triggered before the other process waits for it?
- QUESTION: How can you solve the race condition in add_elem()?
- QUESTION: What if a critical region should accept up to K>1 processes?

Semaphores [3/6]

- Semaphores are created in arrays

- To **create** an array of semaphores:

```
#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/sem.h>
int semget(key_t key, int nsems, int semflg);
```

  - **key**: rendezvous point or IPC_PRIVATE
  - **nsems**: number of semaphores to create
  - **semflg:** access rights
  - Return value: a semaphore array identifier

Semaphores [4/6]

- UP() and DOWN() are realized with the same function:

```
#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/sem.h>
int semop(int semid, struct sembuf *sops, unsigned nsops);
```

  - **semid**: the semaphore array identifier
  - **sops**: an array of commands to be issued
  - **nsops**: the size of sops

- Here's the sembuf struct:

```
struct sembuf {
  short sem_num;  /* semaphore number: 0 = first */
  short sem_op;   /* semaphore operation */
  short sem_flg;  /* operation flags */
};
```

  - **sem_op**: 1 for UP(), -1 for DOWN()
  - **All operations are executed together atomically as a whole**

Semaphores [5/6]

- To manipulate a semaphore:

```
#include <sys/types.h>
#include <sys/ipc.h>
#include <sys/sem.h>
int semctl(int semid, int semnum, int cmd, ...);
```

  - **semid**: the semaphore array identifier
  - **semnum**: the semaphore number
  - **cmd**: command
    - IPC_RMID: destroy the semaphore
    - GETVAL: return the value of the semaphore

- Like shared memory segments, semaphores persist in the system after all processes have completed
  - You must destroy them in your programs
  - By hand: ipcs, ipcrm

Semaphores [6/6]

- A (rather meaningless) example:

```
int main() {
  struct sembuf up   = {0,  1, 0};
  struct sembuf down = {0, -1, 0};
  int my_sem, v1, v2, v3, v4;

  my_sem = semget(IPC_PRIVATE, 1, 0600); /* create semaphore */
  v1 = semctl(my_sem, 0, GETVAL);

  semop(my_sem, &up, 1);                 /* UP() */
  v2 = semctl(my_sem, 0, GETVAL);

  semop(my_sem, &down, 1);               /* DOWN() */
  v3 = semctl(my_sem, 0, GETVAL);

  semctl(my_sem, 0, IPC_RMID);           /* destroy */
  v4 = semctl(my_sem, 0, GETVAL);

  printf("Semaphore values: %d %d %d %d\n", v1, v2, v3, v4);
}
```

Posix Threads

Threads vs. Processes

- Multi-process programs are expensive:
  - fork() needs to copy all the process' memory, etc.
  - interprocess communication is hard
- Threads: "lightweight processes"
  - One process contains several "threads of execution"
  - All threads execute the same program (but can be at different stages within it)
  - All threads share process instructions, global memory, open files, and signal handlers
  - Each thread has its own thread ID, program counter (PC), stack and stack pointer (SP), errno, and signal mask
  - There are special synchronization primitives between threads of the same process

Threads in C and Java

- Posix Threads
  - Posix Threads (pthreads) are standard among Unix systems
    - Also available on Windows through 3rd party libraries (Pthreads-w32)
  - The operating system must have special support for threads
    - Linux, Solaris, and virtually all Unix systems have it
  - Programs must be linked with –lpthread
    - Beware: Solaris will compile fine even if you forget the –lpthread (but your program will not work)

- Java Threads
  - Threads are a native feature of Java: every virtual machine has thread support
  - They are portable on any Java platform
  - Java threads can be:
    - mapped to operating system threads (kernel threads or native threads)
    - or emulated in user space (user threads or green threads)

Creating a pthread

- To create a pthread:

```
#include <pthread.h>
int pthread_create(pthread_t *thread,
                   pthread_attr_t *attr,
                   void *(*start_routine)(void *),
                   void *arg);
```

  - **thread**: thread id (this is a return argument)
  - **attr**: attributes (i.e., options)
  - **start_routine**: function that the thread will execute
  - **arg**: parameter to be passed to the thread
  - Return value: 0 on success, error value on failure

- To initialize and destroy the default pthread attributes

```
int pthread_attr_init(pthread_attr_t *attr);
int pthread_attr_destroy(pthread_attr_t *attr);
```

Stopping a pthread

- A pthread stops when:
  - Its process stops
  - Its parent thread stops
  - Its `start_routine()` function returns
  - It calls pthread_exit:

```
#include <pthread.h>
void pthread_exit(void *retval);
```

- Like processes, stopped threads must be waited for:

```
#include <pthread.h>
int pthread_join(pthread_t th, void **thread_return);
```

pthread Create/Delete Example

- To create a pthread:

```
#include <pthread.h>

void *func(void *param) {
  int *p = (int *) param;
  printf("New thread: param=%d\n",*p);
  return NULL;
}

int main() {
  pthread_t id;
  pthread_attr_t attr;
  int x = 42;

  pthread_attr_init(&attr);
  pthread_create(&id, &attr, func, (void *) &x);
  pthread_join(id, NULL);
}
```

Detached Threads

- A "detached" thread:
  - does not need to be joined by `pthread_join()`
  - does not stop when its parent thread stops
- By default, threads are "joinable" (i.e. "attached")
- To create a detached thread, set an attribute before creating the thread:

```
pthread_t id;
pthread_attr_t attr;

pthread_attr_init(&attr);
pthread_attr_setdetachstate(&attr, PTHREAD_CREATE_DETACHED);
pthread_create(&id, &attr, func, NULL);
```

- You can also detach a thread later with `pthread_detach()`
  - But you cannot reattach it!

Race Conditions with Threads

- Threads share most resources by default
  - memory , file descriptors, etc.
- Attention! Danger!
  - It is very easy to make race conditions without even noticing
- You must always wonder if synchronization is needed
  - And solve them with special thread synchronization primitives
- Pthreads have two synchronization concepts:
  - Mutex
  - Condition Variables

Pthread Sync with Mutex [1/2]

- Mutex (mutual exclusion)

```
#include <pthread.h>
int pthread_mutexattr_init(pthread_mutexattr_t *attr);
int pthread_mutex_init(pthread_mutex_t *mutex,
                       const pthread_mutexattr_t *mutexattr);
int pthread_mutex_lock(pthread_mutex_t *mutex));
int pthread_mutex_trylock(pthread_mutex_t *mutex);
int pthread_mutex_unlock(pthread_mutex_t *mutex);
int pthread_mutex_destroy(pthread_mutex_t *mutex);
```

Pthread Sync with Mutex [2/2]

- Example

```
pthread_mutex_t mutex;

int add_elem(int elem) {
  int n;
  pthread_mutex_lock(&mutex);
  if (size==32) {
    pthread_mutex_unlock(&mutex);
    return -1;
  }
  array[size++] = elem;
  n = size;
  pthread_mutex_unlock(&mutex);
}

int main() {
  pthread_mutexattr_t attr;
  pthread_mutexattr_init(&attr);
  pthread_mutex_init(&mutex, &attr);
  ...
  pthread_mutex_destroy(&mutex);
}
```

Thread Safety with Unix Primitives

- Attention: Some Unix primitives and library functions have similar internal race conditions
  - Many primitives were not designed with threads in mind
  - When writing a multi-threaded program, you must always check in the man pages if library functions are thread-safe

- Example:
  - **`gethostbyname()`** is not thread-safe
  - You can still use it in multi-threaded programs
    - but only within a mutex protection

Pthread Sync with Condition Variables

- Condition Variables
  - One thread waits for an event triggered by another thread
- Condition variables always work together with a mutex and a predicate variable (e.g., a boolean, an int, etc.)
  - The predicate variable is used to make sure the event has really been triggered
    - Sometimes threads are woken up without the event having been triggered!
  - The mutex is used to synchronize access to the condition variable and the predicate variable
- Details are out of the scope of Internet Programming
  - You can find a detailed explanation at:
    http://www.ibm.com/developerworks/linux/library/l-posix3/
    https://computing.llnl.gov/tutorials/pthreads/

API for Condition Variables

- At init time:

```
pthread_mutex_t mutex;
pthread_cond_t cond_var;
int predicate = FALSE;

pthread_mutex_init(&mutex, NULL);
pthread_cond_init(&cond_var, NULL);
```

- To wait for an event:

```
pthread_mutex_lock(&mutex);
while (predicate==FALSE)
  pthread_cond_wait(&cond_var,&mutex);
predicate = FALSE;
pthread_mutex_unlock(&mutex);
```

- To trigger an event:

```
pthread_mutex_lock(&mutex);
predicate = TRUE;
pthread_cond_signal(&cond_var);
pthread_mutex_unlock(&mutex);
```

Java Threads

Creating Java Threads

- A thread is a class that inherits from Thread

- You must overload its run() method:

```
public class MyThread extends Thread {
  private int argument;

  MyThread(int arg) {
    argument = arg;
  }

  public void run() {
    System.out.println("New thread started! arg=" + argument);
  }
}
```

- To start the thread:

```
MyThread t = new MyThread(1050);
t.start();
```

Stopping Java Threads

- A thread stops when its run() method returns
- You do not need to join() for a Java thread to finish
  - But you can, if you want:

```
MyThread t = new MyThread(1050);
t.start();
...
t.join();
```

Synchronization with Monitors [1/2]

- A monitor is similar to a mutex:

```
public class AnotherClass {
  synchronized public void methodOne() { ... }
  synchronized public void methodTwo() { ... }
  public void methodThree()            { ... }
}
```

- Each object contains one mutex, which is locked when entering a synchronized method and unlocked when leaving

- Locking is at the object (instance) level
  - Two threads cannot be executing synchronized methods of a given object at the same time
    - But this is allowed by the same thread (e.g., one synchronized method calls another)
  - No restrictions apply to different objects of a given class

Synchronization with Monitors [2/2]

- So, the previous class:

```
public class AnotherClass {
  synchronized public void methodOne()  { ... }
  synchronized public void methodTwo()  { ... }
  public void methodThree()              { ... }
}
```

- …is equivalent to:

```
public class AnotherClass {
  private Mutex mutex;
  public void methodOne() { mutex.lock(); ...; mutex.unlock();}
  public void methodTwo() { mutex.lock(); ...; mutex.unlock();}
  public void methodThree() { ... }
}
```

…except that the Mutex class does not exist!

- **QUESTION:** Can you implement a Mutex class using monitors?

Condition Variables in Java [1/2]

- There is no real condition variable in Java
  - But you can explicitly block a thread

- All Java classes inherit from class Object the following:

```
class Object {
  void wait();      /* blocks the calling thread */
  void notify();    /* unblocks ONE thread blocked by this object*/
  void notifyAll(); /* unblocks ALL threads blocked by this object*/
}
```

  - **wait()**: causes current thread to wait until another thread invokes the notify() or notifyAll() method for this object
  - **notify()**: wakes up a single thread that is waiting on this object's monitor
  - **notifyAll()**: wakes up all threads that are waiting on this object's monitor

Condition Variables in Java [2/2]

- This means, each object contains exactly one (and no more) condition variable

- The `wait()`,`notify()` and `notifyAll()` methods can only be called inside a monitor of that same instance. E.g.:

```
Integer myObj;  // or any other type of object

synchronized(myObj)
{
  myObj.wait();
}
```

- **Questions:**
  - **[1/3]** What if you need several condition variables in a given object?
  - **[2/3]** Can you implement a ConditionVariable class in Java?
  - **[3/3]** Can you implement a Mutex class in Java?