# Processes

## Operating System Design – MOSIG 1

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October 19, 2010

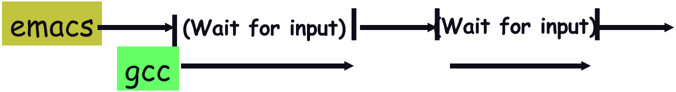
# Outline

# Processes

- **A process is an instance of a program running**
- **Modern OSes run multiple processes simultaneously**
- **Examples (can all run simultaneously):**
  - `gcc file_A.c` – compiler running on file A
  - `gcc file_B.c` – compiler running on file B
  - `emacs` – text editor
  - `firefox` – web browser
- **Non-examples (implemented as one process):**
  - Multiple firefox windows or emacs frames (still one process)
- **Why processes?**
  - Simplicity of programming
  - Higher throughput (better CPU utilization), lower latency

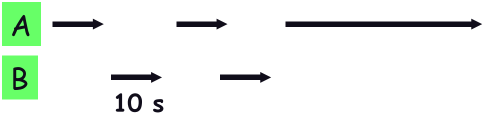
# Speed

- **Multiple processes can increase CPU utilization**
  - Overlap one process's computation with another's wait




- **Multiple processes can reduce latency**
  - Running *A* then *B* requires 100 sec for *B* to complete


  - Running *A* and *B* concurrently makes *B* finish faster



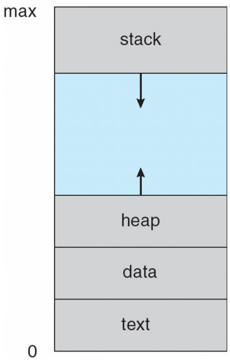

  - *A* slightly slower, but less than 100 sec unless *A* and *B* both completely CPU-bound

# Processes in the real world

- **Processes, parallelism fact of life much longer than OSes have been around**
  - E.g., say takes 1 worker 10 months to make 1 widget
  - Company may hire 100 workers to make 10,000 widgets
  - Latency for first widget $\gg 1/10$ month
  - Throughput may be $< 10$ widgets per month (if can't perfectly parallelize task)
  - Or $> 10$ widgets per month if better utilization (e.g., 100 workers on 10,000 widgets never idly waiting for paint to dry)
- **You will see this with your assignments**
  - Don't expect labs to take $1/3$ time with three people

# A process's view of the world

- **Each process has own view of machine**
  - Its own address space
  - Its own open files
  - Its own virtual CPU (through preemptive multitasking)
- `*(char *)0xc000` **different in $P_1$ & $P_2$**
- **Greatly simplifies programming model**
  - gcc does not care that `firefox` is running




- **Sometimes want interaction between processes**
  - Simplest is through files: `emacs` edits file, gcc compiles it
  - More complicated: Shell/command, Window manager/app.

# Outline

# UNIX files I/O

- **Applications "open" files (or devices) by name**
  - I/O happens through open files
- `int open(char *path, int flags, /*mode*/...);`
  - `flags`: `O_RDONLY`, `O_WRONLY`, `O_RDWR`
  - `O_CREAT`: create the file if non-existent
  - `O_EXCL`: (w. `O_CREAT`) create if file exists already
  - `O_TRUNC`: Truncate the file
  - `O_APPEND`: Start writing from end of file
  - `mode`: final argument with `O_CREAT`
- **Returns file descriptor—used for all I/O to file**

# Error returns

- **What if** `open` **fails? Returns -1 (invalid fd)**
- **Most system calls return -1 on failure**
  - Specific kind of error in global int `errno`
- `#include <sys/errno.h>` **for possible values**
  - 2 = `ENOENT` "No such file or directory"
  - 13 = `EACCES` "Permission Denied"
- `perror` **function prints human-readable message**
  - `perror ("initfile");`
    → "`initfile: No such file or directory`"

# Operations on file descriptors

- `int read (int fd, void *buf, int nbytes);`
  - Returns number of bytes read
  - Returns 0 bytes at end of file, or -1 on error
- `int write (int fd, void *buf, int nbytes);`
  - Returns number of bytes written, -1 on error
- `off_t lseek (int fd, off_t pos, int whence);`
  - `whence`: 0 – start, 1 – current, 2 – end
    - Returns previous file offset, or -1 on error
- `int close (int fd);`

# File descriptor numbers

- **File descriptors are inherited by processes**
  - When one process spawns another, same fds by default
- **Descriptors 0, 1, and 2 have special meaning**
  - 0 – "standard input" (`stdin` in ANSI C)
  - 1 – "standard output" (`stdout`, `printf` in ANSI C)
  - 2 – "standard error" (`stderr`, `perror` in ANSI C)
  - Normally all three attached to terminal
- **Example:** `type.c`
  - Prints the contents of a file to `stdout`

# Exemple: type.c

```
void typefile(char *filename)
{
  int fd, nread;
  char buf[1024];

  fd = open(filename, O_RDONLY);
  if (fd == -1) {
    perror(filename);
    return;
  }

  while ((nread = read(fd, buf, sizeof(buf))) > 0)
    write(1, buf, nread);

  close(fd);
}
```

# The rename system call

- `int rename (const char *p1, const char *p2);`
  - Changes name `p2` to reference file `p1`
  - Removes file name `p1`
- **Guarantees that `p2` will exist despite any crashes**
  - `p2` may still be old file
  - `p1` and `p2` may both be new file
  - but `p2` will always be old or new file
- `fsync/rename` **idiom used extensively**
  - E.g., emacs: Writes file `.#file#`
  - Calls `fsync` on file descriptor
  - `rename (".#file#", "file");`

# Creating processes

- `int fork (void);`
  - Create new process that is exact copy of current one
  - Returns *process ID* of new process in "parent"
  - Returns 0 in "child"
  - Actually, not `int` anymore, but `pid_t`
- `int get_pid (void); int get_ppid (void);`
  - Returns *process ID* of the calling process (resp. of its parent)
- `int waitpid (int pid, int *stat, int opt);`
  - `pid` – process to wait for, or -1 for any
  - `stat` – will contain exit value, or signal
  - `opt` – usually 0 or `WNOHANG`
  - Returns process ID or -1 on error
- **Hierarchy of processes**
  - run the `pstree -p` command

# Deleting processes

- `void exit (int status);`
  - Current process ceases to exist
  - `status` shows up in `waitpid` (shifted)
  - By convention, `status` of 0 is success, non-zero error
- `int kill (int pid, int sig);`
  - Sends signal `sig` to process `pid`
  - `SIGTERM` most common value, kills process by default (but application can catch it for "cleanup")
  - `SIGKILL` stronger, kills process always

# Process Termination

- **When a child terminates (either by calling exit or abnormally due to a fatal error or signal)**
  - An exit status is returne to the OS
  - Some of the process resources are deallocated by operating system.
  - A SIGCHLD signal is sent to the parent
  - Parent should retrieve the exit status using `wait`. If it does not, then the child process will remain in the system as a **zombi**.
- **When a parent process terminates before its child, there are two options:**
  - Operating system does not allow child to continue if its parent terminates $\rightsquigarrow$ cascading termination (VMS).
  - Re-parent the orphan (UNIX). The init process becomes the new parent and is specifically designed to handle orphan proces (and take care of zombis).

# Running programs

- `int execve (const char *prog, const char **argv, char **envp;)`
  - `prog` – full pathname of program to run
  - `argv` – argument vector that gets passed to `main`
  - `envp` – environment variables, e.g., `PATH`, `HOME`
- **Generally called through a wrapper functions**
  - `int execvp (char *prog, char **argv);`
    Search `PATH` for prog, use current environment
  - `int execlp (char *prog, char *arg, ...);`
    List arguments one at a time, finish with `NULL`
- **Example:** `minish.c`
  - Loop that reads a command, then executes it

# minish.c (simplified)

```
pid_t pid;
char **av;
void doexec() {
  execvp(av[0], av);
  perror(av[0]);
  exit(1);
}

      /* ... main loop: */
for (;;) {
  parse_next_line_of_input(&av, stdin);

  switch (pid = fork()) {
  case -1:
    perror("fork");
    break;
  case 0:
    doexec();
  default:
    waitpid(pid, NULL, 0);
    break;
  }
}
```

# Manipulating file descriptors

- `int dup2 (int oldfd, int newfd);`
  - Makes `newfd` be the *copy* of `oldfd`, *closing* `newfd` first if necessary.
  - Two file descriptors will share same offset (`lseek` on one will affect both)
- `int fcntl (int fd, F_SETFD, int val)`
  - Sets *close on exec* flag if `val` = 1, clears if `val` = 0
  - Makes file descriptor non-inheritable by spawned programs
- **Example:** `redirsh.c`
  - Loop that reads a command and executes it
  - Recognizes `command < input > output 2> errlog`

# redirsh.c

```
void doexec (void) {
  int fd;

  /* infile non-NULL if user typed "command < infile" */
  if (infile) {
    if ((fd = open (infile, O_RDONLY)) < 0) {
      perror (infile);
      exit (1);
    }
    if (fd != 0) {
      dup2 (fd, 0);
      close (fd);
    }
  }

  /* ... Do same for outfile -> fd 1, errfile -> fd 2 ... */

  execvp (av[0], av);
  perror (av[0]);
  exit (1);
}
```

# Why fork?

- **Most calls to `fork` followed by `execve`**
- **Could also combine into one spawn system call**
- **Occasionally useful to fork one process**
  - Unix *dump* utility backs up file system to tape
  - If tape fills up, must restart at some logical point
  - Implemented by forking to revert to old state if tape ends
- **Real win is simplicity of interface**
  - Tons of things you might want to do to child:
    Manipulate file descriptors, environment, resource limits, etc.
  - Yet `fork` requires *no* arguments at all

# Spawning process w/o fork

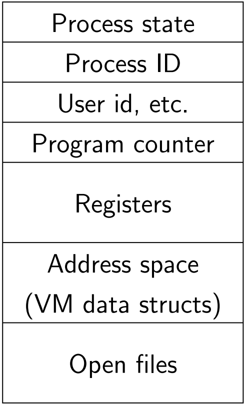
- **Without fork, require tons of different options**
- **Example: Windows `CreateProcess` system call**

**BOOL CreateProcess(**
**LPCTSTR** *lpApplicationName*, // pointer to name of executable module
**LPTSTR** *lpCommandLine*, // pointer to command line string
**LPSECURITY_ATTRIBUTES** *lpProcessAttributes*, // process security attr.
**LPSECURITY_ATTRIBUTES** *lpThreadAttributes*, // thread security attr.
**BOOL** *bInheritHandles*, // handle inheritance flag
**DWORD** *dwCreationFlags*, // creation flags
**LPVOID** *lpEnvironment*, // pointer to new environment block
**LPCTSTR** *lpCurrentDirectory*, // pointer to current directory name
**LPSTARTUPINFO** *lpStartupInfo*, // pointer to STARTUPINFO
**LPPROCESS_INFORMATION** *lpProcessInformation* // pointer to PROCESS_INFORMATION **);**

# Outline

# Implementing processes

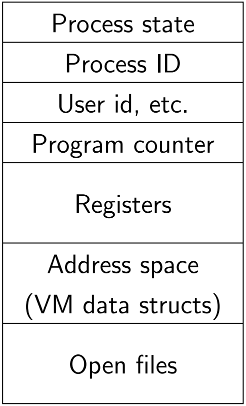
- **OS keeps data structure for each proc**
  - Process Control Block (PCB)
  - Called `proc` in Unix, `task_struct` in Linux
- **Tracks state of the process**
  - Running, runnable, blocked, etc.
- **Includes information necessary to run**
  - Registers, virtual memory mappings, etc.
  - Open files (including memory mapped files)
- **Various other data about the process**
  - Credentials (user/group ID), signal mask, controlling terminal, priority, accounting statistics, whether being debugged, which system call binary emulation in use, . . .




PCB

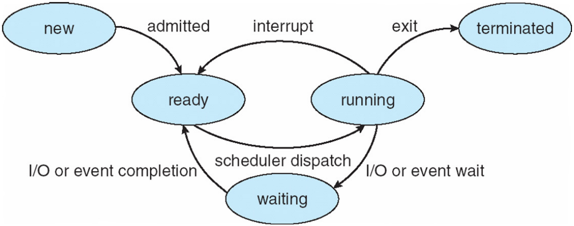
# Fork & Exec

- **The fork system call creates a copy of the PCB**
  - Open files and memory mapped files are thus similar
  - Open files are thus opened by both father and child. They should both close the files
  - The pages of many memory segments are shared (text, r/o data,...)
  - Many others are lazily copied (copy on write)
- **The exec system call replaces the address space, the registers, the program counter by the one of the program to exec.**
  - Open files are thus inherited (hence, the need for the `fcntl` function sometimes)




PCB

# Process states




- **Process can be in one of several states**
  - *new* & *terminated* at beginning & end of life
  - *running* – currently executing (or will execute on kernel return)
  - *ready* – can run, but kernel has chosen different process to run
  - *waiting* – needs async event (e.g., disk operation) to proceed
- **Which process should kernel run?**
  - if 0 runnable, run idle loop, if 1 runnable, run it
  - if >1 runnable, must make scheduling decision

# Scheduling

- **How to pick which process to run**
- **Scan process table for first runnable?**
  - Expensive. Weird priorities (small pids better)
  - Divide into runnable and blocked processes
- **FIFO?**
  - Put process on back of list, pull them off from front

- **Priority?**
  - Give some process a better shot at the CPU

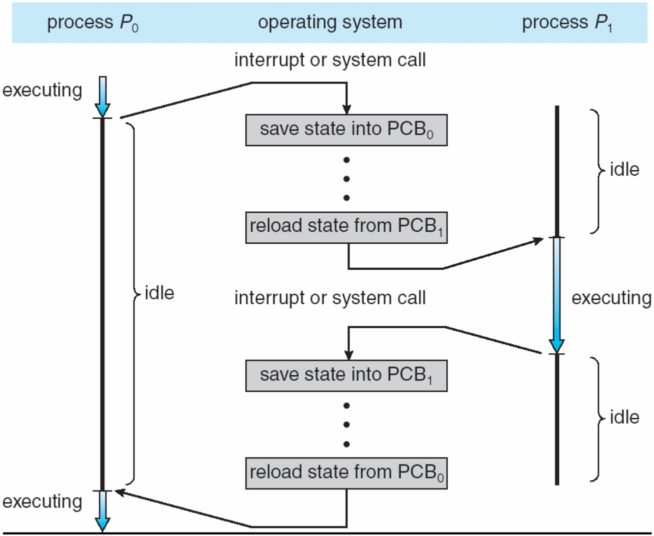
# Scheduling policy

- **Want to balance multiple goals**
  - *Fairness* – don't starve processes
  - *Priority* – reflect relative importance of procs
  - *Deadlines* – must do $x$ (play audio) by certain time
  - *Throughput* – want good overall performance
  - *Reactivity* – minimize response time
  - *Efficiency* – minimize overhead of scheduler itself
- **No universal policy**
  - Many objectives, can't optimize for all
  - Conflicting goals (e.g., throughput or priority vs. fairness)
- **We will spend a lecture on this topic**

# Preemption

- **Can preempt a process when kernel gets control**
- **Running process can vector control to kernel**
  - System call, page fault, illegal instruction, etc.
  - May put current process to sleep—e.g., read from disk
  - May make other process runnable—e.g., fork, write to pipe
- **Periodic timer interrupt**
  - If running process used up quantum, schedule another
- **Device interrupt**
  - Disk request completed, or packet arrived on network
  - Previously waiting process becomes runnable
  - Schedule if higher priority than current running proc.
- **Changing running process is called a context switch**

# Context switch



# Context switch details

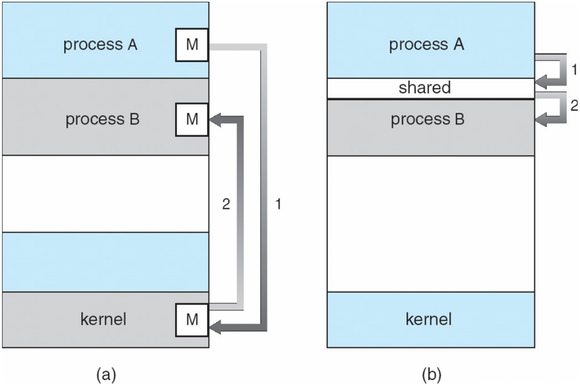
- **Very machine dependent. Typical things include:**
  - Save program counter and integer registers (always)
  - Save floating point or other special registers
  - Save condition codes
  - Change virtual address translations
- **Non-negligible cost**
  - Save/restore floating point registers expensive
    - Optimization: only save if process used floating point
  - May require flushing TLB (memory translation hardware)
    - Optimization: don't flush kernel's own data from TLB
  - Usually causes more cache misses (switch working sets)

# Outline

# Cooperating Processes

- **Independent process cannot affect or be affected by the execution of another process**
  - We put a lot of effort on this... remember all the previous lectures
- **Cooperating process can affect or be affected by the execution of another process. Advantages:**
  - Information sharing
  - Computation speed-up
  - Modularity
  - Convenience

# Process Interaction




- **How can processes interact in real time?**
  (1) Through files but it's not really "real time".
  (2) Through asynchronous signals or alerts but again, it's not really "real time".
  (3) By sharing a region of physical memory
  (4) By passing messages through the kernel

# Asynchronous notification

- **As we have seen earlier**
  - Children process send a SIGCHLD signal to their parents upon termination.
  - One may send a SIGINT/SIGTERM/SIGSTOP/SIGKILL signal to CTRL-C/suspend (CTRL-Z)/terminate/kill a process using the kill function:

    ```
    int kill (int pid, int sig);
    ```
  - Upon reception of a signal, a given handler is called. This handler can be obtained and modified using the `signal` function:

    ```
    typedef void (*sighandler_t)(int);
    sighandler_t signal(int signum, sighandler_t handler);
    ```
- **Some common signals:**
  - SIGSEGV (segfault), SIGFPE (floating-point exception), SIGALRM (timer alarm), SIGABRT (abort is catched by gdb), SIGILL (illegal instruction!), SIGCONT (resume if suspended)
  - SIGUSR1, SIGUSR2
- **Some signals cannot be blocked** (SIGSTOP and SIGKILL)

# Illustrating shm

```
#define DELAY  1     /* secondss */

void handler(int signal_num)
{
  printf("Signal %d => ", signal_num);
   switch (signal_num) {
   case SIGTSTP:
       printf("Let's sleep!");
       kill(getpid(), SIGSTOP);
       printf("Waking up!");
       signal(SIGTSTP, handler);
       break;
   case SIGINT:
   case SIGTERM:
       printf("End of the program");
       exit(EXIT_SUCCESS);
       break;
   }
}
```

```
#include <stdlib.h>
#include <signal.h>
#include <errno.h>
#include <unistd.h>
#include <stdio.h>

int main(void)
{
   signal(SIGTSTP, handler);
                  /* if control-Z */
   signal(SIGINT, handler);
                  /* if control-C */
   signal(SIGTERM, handler);
            /* if kill  processus */
   while (1) {
       sleep(DELAI);
       printf(".");
       fflush(stdout);
   }
   printf("fin");
   exit(EXIT_SUCCESS);
}
```

# Shared Memory Segment

- **A process can create a shared memory segment using:**

  ```
  int shmget(key_t key, size_t size, int shmflg);
  ```

  - The returned value identifies the segment and is called the shmid
  - The `key` is used so that process indeed get the same segment.
- **The original owner of a shared memory segment can assign ownership to another user with `shmctl()`.**
  - It can also revoke this assignment.
- **Once created, a shared segment should be attached to a process address space using**

  ```
  void *shmat(int shmid, const void *shmaddr, int
                                   shmflg);
  ```

- **It can be detached using** `int shmdt(const void *shmaddr);`
- **Can also be done with the `mmap` function**

# Illustrating shm

```
char c;
int shmid;
key_t key;
char *shm, *s;

key = 5678;

/* Create the segment */
if ((shmid = shmget(key, SHMSZ,
      IPC_CREAT | 0666)) < 0) {
    perror("shmget");
    exit(1);
}

/* Attach the segment */
if ((shm = shmat(shmid, NULL, 0)) ==
     (char *) -1) {
    perror("shmat");
    exit(1);
}
```

```
int shmid;
key_t key;
char *shm, *s;


key = 5678;

/* Locate the segment */
if ((shmid = shmget(key, SHMSZ, 0666))
        < 0) {
    perror("shmget");
    exit(1);
}

/* Attach the segment */
if ((shm = shmat(shmid, NULL, 0)) ==
        (char *) -1) {
    perror("shmat");
    exit(1);
}
```

# Producer-Consumer Problem

- **Paradigm for cooperating processes**
  - Producer process produces information that is consumed by a consumer process
  - unbounded-buffer places no practical limit on the size of the buffer
  - bounded-buffer assumes that there is a fixed buffer size
- **Shared-Memory Solution**

```
/*Shared data structure*/

#define BUFFER_SIZE 10
typedef struct {
...
} item;
item buffer[BUFFER_SIZE];
int in = 0;
int out = 0;
```

```
/*        Producer        */

item nextProduced;
while (1) {
  while(((in + 1)%BUFFER_SIZE)
         ==out)
       ; /* do nothing */
  buffer[in]=nextProduced;
  in=(in+1)%BUFFER_SIZE;
}
```

```
/*        Consumer        */

item nextConsumed;
while (1) {
  while (in == out)
       ; /* do nothing */
  nextConsumed=buffer[out];
  out=(out+1)%BUFFER_SIZE;
}
```

- **Drawbacks:**
  - Solution is correct, but can only use BUFFER_SIZE-1 elements
  - Works only with one producer and one consumer
  - Busy waiting

# Pipes

- `int pipe (int fds[2]);`
  - Returns two file descriptors in `fds[0]` and `fds[1]`
  - Writes to `fds[1]` will be read on `fds[0]`
  - When last copy of `fds[1]` closed, `fds[0]` will return EOF
  - Returns 0 on success, -1 on error
- **Operations on pipes**
  - `read`/`write`/`close` – as with files
  - When `fds[1]` closed, `read(fds[0])` returns 0 bytes
  - When `fds[0]` closed, `write(fds[1])`:
    - Kills process with `SIGPIPE`, or if blocked
    - Fails with EPIPE
- **Example:** `pipesh.c`
  - Sets up pipeline `command1 | command2 | command3 ...`

# pipesh.c (simplified)

```
void doexec (void) {
  int pipefds[2];
  while (outcmd) {
    pipe (pipefds);
    switch (fork ()) {
    case -1:
      perror ("fork"); exit (1);
    case 0:
      dup2 (pipefds[1], 1);
      close (pipefds[0]); close (pipefds[1]);
      outcmd = NULL;
      break;
    default:
      dup2 (pipefds[0], 0);
      close (pipefds[0]); close (pipefds[1]);
      parse_command_line (&av, &outcmd, outcmd);
      break;
    }
  }
  /* ... */
}
```

# Inter Process Communications (IPC)

- **Mechanism for processes to communicate and to synchronize their actions**
- **Message system processes communicate with each other without resorting to shared variables**
- **IPC facility provides two operations:**
  - send(message) message size fixed or variable
  - receive(message)
- **If P and Q wish to communicate, they need to:**
  - establish a communication link between them
  - exchange messages via send/receive
- **Implementation of communication link**
  - physical (e.g., shared memory, hardware bus)
  - logical (e.g., logical properties)

# Implementation Issues

- **How are links established?**
- **Can a link be associated with more than two processes?**
- **How many links can there be between every pair of communicating processes?**
- **What is the capacity of a link?**
- **Is the size of a message that the link can accommodate fixed or variable?**
- **Is a link unidirectional or bi-directional?**

# Direct Communication

- **Processes must name each other explicitly:**
  - send (P, message) send a message to process P
  - receive(Q, message) receive a message from process Q
- **Properties of communication link**
  - Links are established automatically
  - A link is associated with exactly one pair of communicating processes
  - Between each pair there exists exactly one link.
  - The link may be unidirectional, but is usually bi-directional

# Indirect Communication

- **Messages are directed and received from mailboxes (also referred to as ports)**
  - Each mailbox has a unique id
  - Processes can communicate only if they share a mailbox
- **Properties of communication link**
  - Link established only if processes share a common mailbox
  - A link may be associated with many processes
  - Each pair of processes may share several communication links
  - Link may be unidirectional or bi-directional
- **Operations**
  - create a new mailbox
  - send and receive messages through mailbox
  - destroy a mailbox
- **Primitives are defined as:**
  - send(A, message) send a message to mailbox A
  - receive(A, message) receive a message from mailbox A

# Indirect Communication Issues

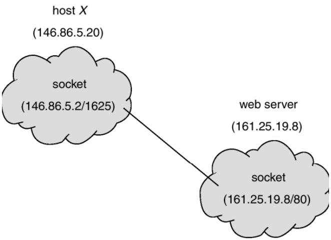
- **Mailbox sharing**
  - P1, P2, and P3 share mailbox A
  - P1, sends; P2 and P3 receive
  - Who gets the message?
- **Solutions**
  - Allow a link to be associated with at most two processes
  - Allow only one process at a time to execute a receive operation
  - Allow the system to select arbitrarily the receiver. Sender is notified who the receiver was

# Synchronization Issues

- **Synchronization**
  - Message passing may be either blocking or non-blocking
  - Blocking is considered synchronous
  - Non-blocking is considered asynchronous
  - send and receive primitives may be either blocking or non-blocking
- **Queue of messages attached to the link; implemented in one of three ways.**
  - Zero capacity 0 messages. Sender must wait for receiver (*rendezvous*)
  - Bounded capacity finite length of n messages. Sender must wait if link full
  - Unbounded capacity infinite length. Sender never waits
- **Pipes, just like most I/Os are buffered**
  - Hence, when you pipe process, the initial producer process will "wait" for the child process to read the data

# Sockets

- A socket is defined as an endpoint for communication
- Concatenation of IP address and port
- The socket 161.25.19.8:1625 refers to port 1625 on host 161.25.19.8
- Communication consists between a pair of sockets and is bidirectionnal




```
(int) sock_id = socket(int domain, int type, int protocol);
(int) error bind(int sock_id,sockaddr localaddr, int addrlen);
(int) error = listen(int sock_id,int backlog);
(int) new_sock_id = accept(int sock_id, struct sockaddr *client_addr,
                           int * client_addrlen);
(int) error = connect(int sock_id, struct sockaddr *server_addr,
                           int * server_addrlen);
ssize_t recv(int sock_id,char * buffer,int len,int flags);
ssize_t send(int sock_id,char * buffer,int len,int flags);
(int) error = close(int sock_id);
```

# Sockets

To accept connections, the following steps are performed:

1. A socket is created with **socket**
2. The socket is bound to a local address using **bind** (*assigning a name to a socket*), so that other sockets may be **connect**ed to it
3. A willingness to accept incoming connections and a queue limit for incoming connections are specified with **listen**.
4. Connections are accepted with **accept**.

```
(int) sock_id = socket(int domain, int type, int protocol);
(int) error bind(int sock_id,sockaddr localaddr, int addrlen);
(int) error = listen(int sock_id,int backlog);
(int) new_sock_id = accept(int sock_id, struct sockaddr *client_addr,
                            int * client_addrlen);
(int) error = connect(int sock_id, struct sockaddr *server_addr,
                            int * server_addrlen);
ssize_t recv(int sock_id,char * buffer,int len,int flags);
ssize_t send(int sock_id,char * buffer,int len,int flags);
(int) error = close(int sock_id);
```

# Higher level APIs

- **Message Passing Interface (MPI)**
  - Used for High Performance Computing with high-speed network implementations
  - Proposes send/recv but many others (Isend/Irecv, collective operations)
  - Uses structured types instead of char * (for portability)
- **Remote procedure call (RPC) abstracts procedure calls between processes on networked systems**
  - Stubs client-side proxy for the actual procedure on the server
  - The client-side stub locates the server and **marshalls** the parameters
  - The server-side stub receives this message, unpacks the marshalled parameters, and peforms the procedure on the server
- **Remote Method Invocation**
  - Remote Method Invocation (RMI) is a Java mechanism similar to RPCs
  - RMI allows a Java program on one machine to invoke a method on a remote object