CS3281 / CS5281

Inter-Process Communications

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Overview

- Interprocess communication is about ways to make processes "talk" to one another or "synchronize" with one another
  - Recall that processes have separate virtual address spaces, so they can't just share variables
- Three big categories of IPC
  - Communication: how do processes exchange data
    - Example: send a list of files from one process to another
  - Synchronization: synchronize the actions of processes or threads
    - Think of synchronization as how to coordinate actions
      - Example: allow processes to avoid updating the same part of a file simultaneously
  - Signals: can be used for synchronization (but are primarily for other purposes)

Taxonomy

- The figure on the right shows a taxonomy of IPC mechanisms
    - We've looked at signals, mutexes, condition variables, and semaphores
    - We'll look at pipes next

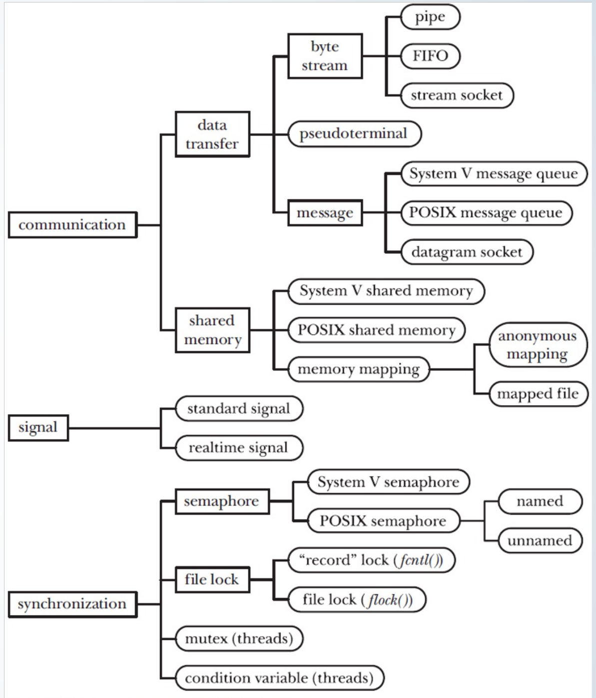

Figure 43-1: A taxonomy of UNIX IPC facilities

*Figure from *The Linux Programming Interface* by Michael Kerrisk

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Fundamental Concept: File Descriptors

- File descriptor: normally small, non-negative integers that the kernel uses to identify the files accessed by a process
  - Example: when a process opens an existing file or creates a new file, the kernel returns a file descriptor that can be used to read or write the file
- All shells open three descriptors when a new program is run:
  - 0: standard input
  - 1: standard output
  - 2: standard error
- If nothing special is done: all of them are connected to the terminal
  - In other words, input comes from the terminal, and output (including errors) are written to the terminal
- How does the kernel view and use file descriptors?

Kernel Data Structures for I/O

- (a) Per-process file descriptor table contains a pointer to a file table entry
- (b) Kernel maintains file table for all open files
  - Flags are read, write, append, sync, etc
  - V-node pointer is a pointer to v-node table entry
- (c) Kernel maintains V-node table
  - Each entry contains information about the type of file and pointers to functions that operate on the file
    - Usually also contains the file's *i-node*, which is its metadata
    - Note: Linux uses two i-nodes instead of a v-node: one generic and one specific

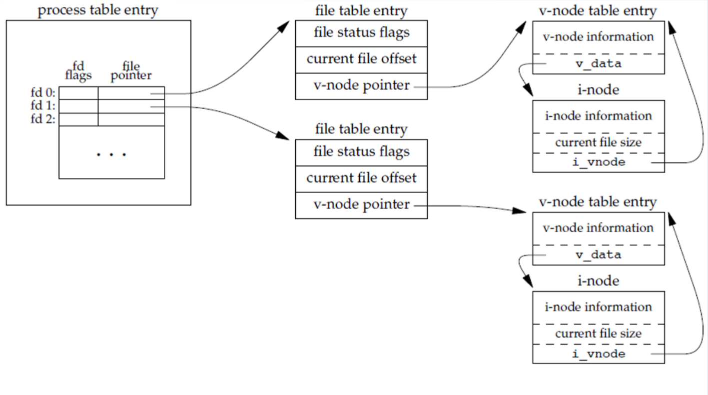

Figure 3.7 Kernel data structures for open files

*Figure from *Advanced Programming in the Unix Environment 3rd Edition* by Richard Stevens and Stephen Rago

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Kernel Data Structures for I/O

- Figure on the right shows two processes with the same open file
- Two fds from the same process can also point to the same file table entry
    - The dup() system call
- Two fds from different processes can also point to the same file table entry
    - For instance, after a fork()
- Let's use this knowledge to do something interesting

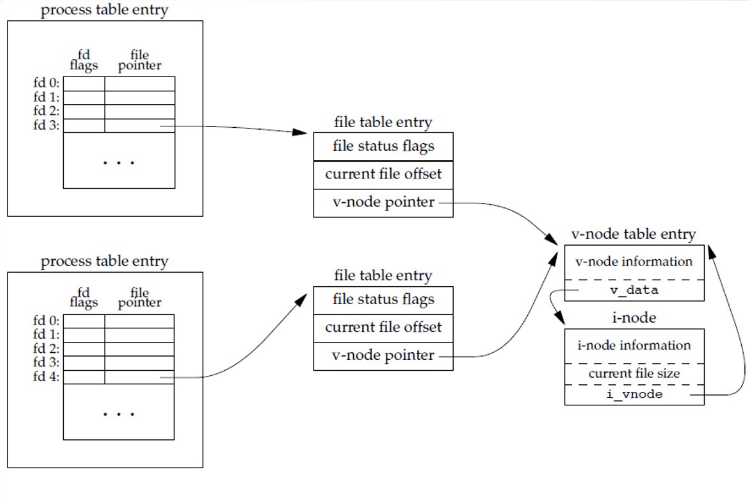

Figure 3.8 Two independent processes with the same file open

*Figure from *Advanced Programming in the Unix Environment 3rd Edition* by Richard Stevens and Stephen Rago

Pipes: Motivation

- Big “real-world” use: connecting programs
  - How can the shell send the output of one program to the input of another program?
- Example
  - The ls program will show the contents of a directory
  - The wc program will count the number of lines in its input
  - How can we use these together to count the number of files in a directory?
- One (poor) solution:
  - Run ls and send its output to a temporary file (temp.txt)
  - Run wc using temp.txt as the input
  - Delete temp.txt

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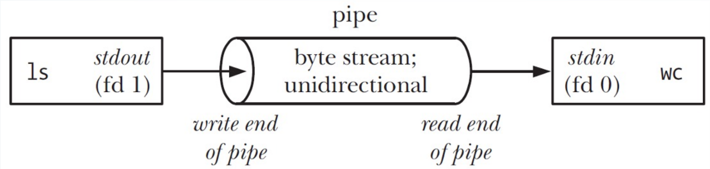
Pipes

- Better solution: use a pipe!
  - Think of it as a piece of “plumbing” that lets data flow from one process to another



- More formally: a pipe is a byte-stream IPC mechanism that provides a one-way flow of data between processes
  - All data written to the pipe is routed by the kernel to another process, which can then read it
  - Think of them as open files that have no corresponding image on your filesystem

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Using Pipes

- A process can create a pipe using the pipe system call:
  - `int pipe(int filedes[2]);`
  - That is, the pipe system call takes an integer array of size 2 (returns 0 on success)
    - filedes[0] can be used to read from the pipe
    - filedes[1] can be used to write to the pipe

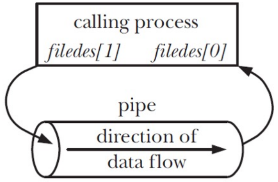

Figure 44-2: Process file descriptors after creating a pipe

*Figure from *The Linux Programming Interface* by Michael Kerrisk

The Shell and Pipes

- Back to our motivation: how can pipes help the shell connect the output of one program to the input of another program?
  - Recall how the shell works:
    - Read a command
    - Do a fork() to create a new process
    - Do an exec() in the new process to run the program
    - Repeat
- We need the “standard output” of one process to go to the “standard input” of another process
  - Solution: have the shell “fix-up” the two processes’ file descriptors!

The Shell and Pipes (cont.)

- **Step 0**: the shell has the three “standard” file descriptors open

Shell

fd[0]	stdin
fd[1]	stdout
fd[2]	stderr

The Shell and Pipes (cont.)

- **Step 0**: the shell has the three “standard” file descriptors open
- **Step 1**: the shell process calls pipe() to create the pipe

Shell

fd[0]	stdin
fd[1]	stdout
fd[2]	stderr
fd[3]	Read end of pipe
fd[4]	Write end of pipe

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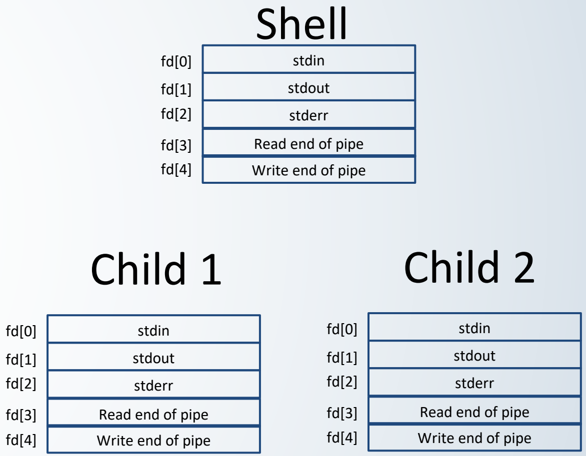
The Shell and Pipes (cont.)

- **Step 0**: the shell has the three “standard” file descriptors open
- **Step 1**: the shell process calls pipe() to create the pipe
- **Step 2**: the shell process calls fork() twice to create the two child processes



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The Shell and Pipes (cont.)

- **Step 0**: the shell has the three "standard" file descriptors open
- **Step 1**: the shell process calls pipe() to create the pipe
- **Step 2**: the shell process calls fork() twice to create the two child processes
- **Step 3**: in the first child process, the write end of the pipe is dup'ed onto the file descriptor for standard output

Shell

fd[0]	stdin
fd[1]	stdout
fd[2]	stderr
fd[3]	Read end of pipe
fd[4]	Write end of pipe

Child 1

fd[0]	stdin
fd[1]	Write end of pipe
fd[2]	stderr
fd[3]	Read end of pipe
fd[4]	Write end of pipe

Child 2

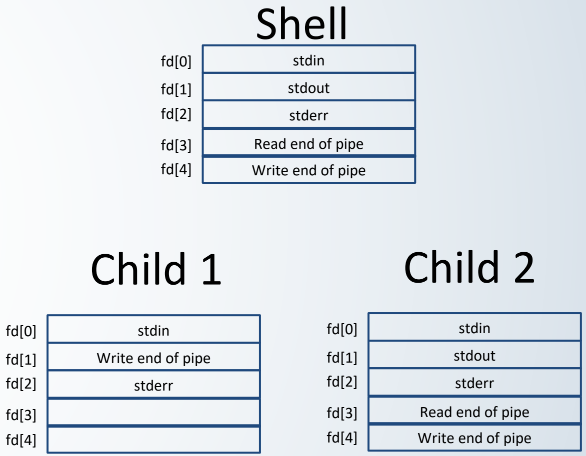
fd[0]	stdin
fd[1]	stdout
fd[2]	stderr
fd[3]	Read end of pipe
fd[4]	Write end of pipe

- The dup system call:
  - `int dup2(int oldfd, int newfd);`
  - Duplicates the descriptor in oldfd to the descriptor in newfd

in xv6 is it just dup(oldfd)

The Shell and Pipes (cont.)

- **Step 0**: the shell has the three “standard” file descriptors open
- **Step 1**: the shell process calls pipe() to create the pipe
- **Step 2**: the shell process calls fork() twice to create the two child processes
- **Step 3**: in the first child process, the write end of the pipe is dup’ed onto the file descriptor for standard output
    - Child process closes both pipe fds and calls exec



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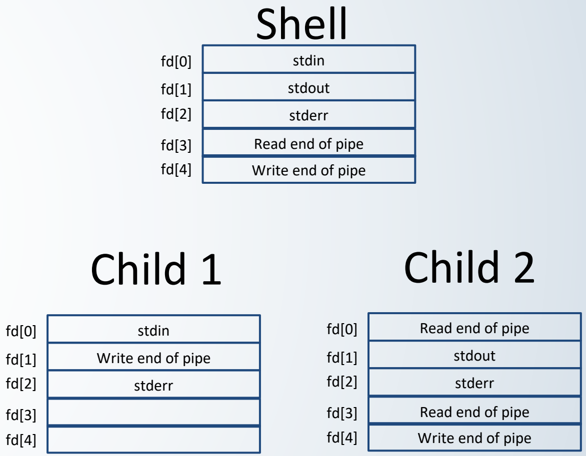
- **Step 4**: in the second child process, the read end of the pipe is dup’ed onto the file descriptor for standard input



The Shell and Pipes (cont.)

- **Step 0**: the shell has the three “standard” file descriptors open
- **Step 1**: the shell process calls pipe() to create the pipe
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Shell

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fd[1]	stdout
fd[2]	stderr
fd[3]	Read end of pipe
fd[4]	Write end of pipe

Child 1

fd[0]	stdin
fd[1]	Write end of pipe
fd[2]	stderr
fd[3]	
fd[4]	

Child 2

fd[0]	Read end of pipe
fd[1]	stdout
fd[2]	stderr
fd[3]	
fd[4]	

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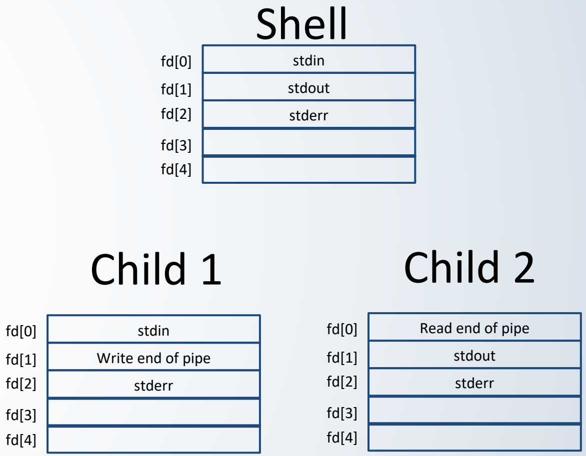
The Shell and Pipes (cont.)

- **Step 0**: the shell has the three “standard” file descriptors open
- **Step 1**: the shell process calls pipe() to create the pipe
- **Step 2**: the shell process calls fork() twice to create the two child processes
- **Step 3**: in the first child process, the write end of the pipe is dup’ed onto the file descriptor for standard output
  - Child process closes both pipe fds and calls exec
- **Step 4**: in the second child process, the read end of the pipe is dup’ed onto the file descriptor for standard input
  - Child process closes both pipe fds and calls exec
- **Step 5**: shell process closes both pipe fds



Other types of IPC

- Message queues let processes exchange data in the form of messages
  - Contrast to pipes, which are streams of data
- POSIX shared memory lets us share a mapped region between unrelated processes without needing to create a corresponding mapped file

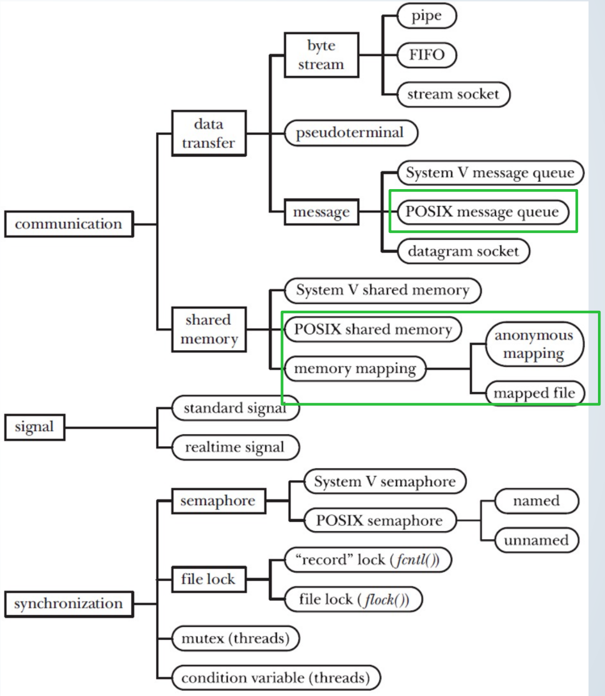


Figure 43-1: A taxonomy of UNIX IPC facilities

*Figure from *The Linux Programming Interface* by Michael Kerrisk

Recall User-Level Memory Mapping (Linux)

```
void *mmap(void *start, int len,
           int prot, int flags, int fd, int offset)
```

- Map **`len`** bytes starting at offset **`offset`** of the file specified by file description **`fd`**, preferably at address **`start`**
  - **`start:`** may be 0 for “pick an address”
  - **`prot`**: PROT_READ, PROT_WRITE, ...
  - **`flags`**: MAP_ANON, MAP_PRIVATE, MAP_SHARED, ...
- Return a pointer to start of mapped area (may not be **`start`**)

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User-Level Memory Mapping

```
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```

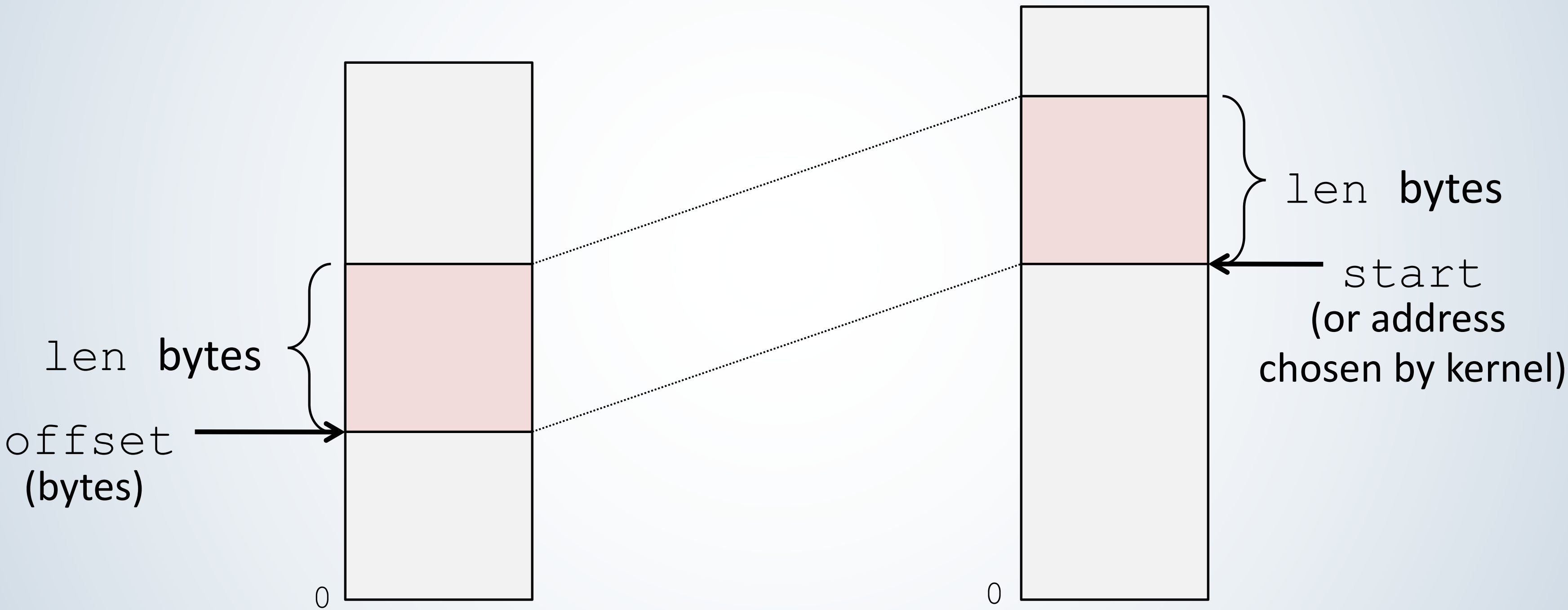

Disk file specified by file descriptor `fd`

Process virtual memory

Shared Memory

- Can use mmap to create a shared memory region
  - Only accessible to future children processes
- Can also use mmap to map a region of memory to a file that may not be stored on disk
- By "naming" that memory as a file in the filesystem, other processes can map it into their own address space
- mmap can therefore be used to share memory between processes, and allow for shared-memory based IPC
  - Have to worry about shared-memory synchronization!