Inter-process communication (IPC)

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Why inter-process communication

- Application logic in a single system is often distributed across multiple processes: why?
  - Different processes developed independently by different teams
  - Different programming languages and frameworks used for different tasks
- Processes in a system do not share any memory with each other by default, so how do they communicate information with each other?
  - Cannot share variables or data structures in programs across processes
  - Parent and child have identical but separate memory images after fork, changes made in one process and not seen by other
- Inter-process communication (IPC) mechanisms, available via operating system syscalls, allow processes to exchange information

Example: web application architecture

- Example: web applications typically composed of multiple processes
- Web server process handles HTTP (web) requests/responses
  - Written in a language like C/C++ for high performance
  - Returns responses for static content directly by reading files from disk
- Requests needing dynamic response are handled by application server
  - App server parses HTTP requests, generates HTTP response according to the business logic specified by user, sends response back to client via web server
  - Scripting languages may be used for easy text parsing and manipulation
- Application server stores/retrieves app data in a database
- Several web application frameworks available to build web applications having such architectures, e.g., Python Django, React etc.

IPC mechanisms

- Unix domain sockets: processes open sockets, send and receive messages to each other via socket system calls
- Message queues: sender posts a message to a mailbox, receiver retrieves message later on from mailbox
- Pipes: unidirectional communication channel between two processes
- Shared memory: same physical memory frame mapped into virtual address space of multiple processes in order to share memory
- Signals: specific messages via kill system call
- Different IPC mechanisms are useful in different scenarios

Sockets

- Sockets = abstraction to communicate between two processes
  - Each process opens socket, and pair of sockets can be connected
  - Client-server paradigm: one process opens socket first (server) and another process connects its socket to the first one (client)
  - One process writes a message into one socket, another process can read it, and vice versa (bidirectional communication)
  - Processes can be in same machine or on different machines
  - If processes on same machine, messages stored temporarily in OS memory before delivering to destination process
  - If processes on different machines, messages sent over network

Types of sockets (1)

- Unix domain (local) sockets are used to communicate between processes on the same machine
- Internet sockets are used to communicate between processes in different machines
- Local sockets identified by a pathname, Internet sockets identified by IP (Internet Protocol) address and port number
- Client and server sockets differentiated by who starts first and who connects later: server sockets started first on a well-known “address”, client process connects to server using the server address

Types of sockets (2)

- Connection-based sockets: one client socket and one server socket are explicitly connected to each other
  - After connection, the two sockets can only send and receive messages to each other
- Connection-less sockets: one socket can send/receive messages to/from multiple other sockets
  - Address of other endpoint can be mentioned on each message
- Type of socket (local or internet, connection-oriented or connection-less) is specified as arguments to system call that creates sockets
- In this course: Unix domain sockets, connection-less

Creating a socket

```
sockfd = socket(…)
bind(sockfd, address)
```

- System call "socket" used to create a socket
  - Takes type of socket as arguments
  - Returns socket file descriptor (similar to file descriptor when file is opened)
  - Used as handle for all future operations on the socket
- A socket can optionally bind to an address (pathname for Unix domain sockets or IP address/port number for Internet sockets) using "bind" system call
  - Server sockets bind to well known address, so that clients can connect
  - Client sockets need not bind, OS can assign temporary address
- Close system call closes a socket when done

The concept of file descriptors

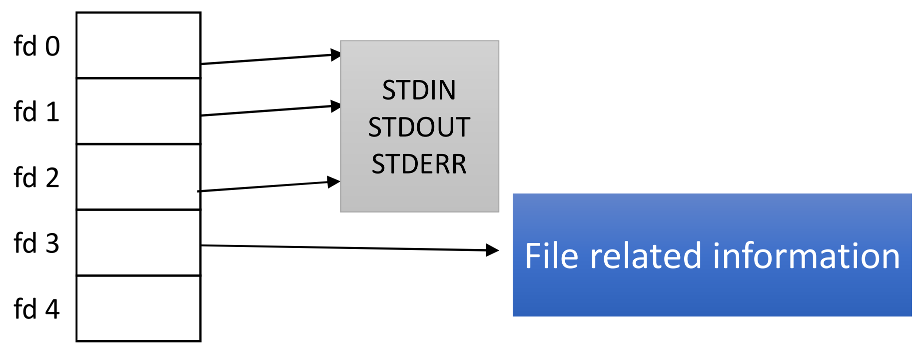
```
fd = open("/home/foo/a.txt")
char buf[64]
read(fd, buf, 64)
buf[0] = …
write(fd, buf, 64)
```

- Many IPC mechanisms like sockets return a file descriptor, which is simply an integer "handle" to access a file or socket or pipe
- PCB of process contains list of all open files in an array
- On file open, new entry is created in array, new index returned

First available is returned.

- All future system calls (read, write) will be given the file descriptor as one of the arguments

File descriptor table
(list of open files of a process)
(part of PCB of process)



These are blocking data exchange.

Data exchange using connection-less sockets

- Function sendto is used to send a message from one socket to another connection-less socket in another process
  - Arguments: socket fd, message to send, address of remote socket
- Function recvfrom is used to receive a message from a socket
  - Arguments: socket fd, message buffer into which received message is copied, socket address structure into which address of remote endpoint is filled
  - When a process receives a message on connection-less socket, it can find out the address of other endpoint, and use this address to reply back

Client

```
sockfd = socket(..)
char message[1024]
sendto(sockfd, message, server_sockaddr, ..)
```

Server

```
sockfd = socket(..)
bind(sockfd, server_address)
recvfrom(sockfd, message, client_sockaddr, ..)
```

msgget() is used to create the message queue.

Message queues

```
msgid = msgget(key, …)
msgsnd(msgid, message, …)
msgrcv(msgid, message, …)
```

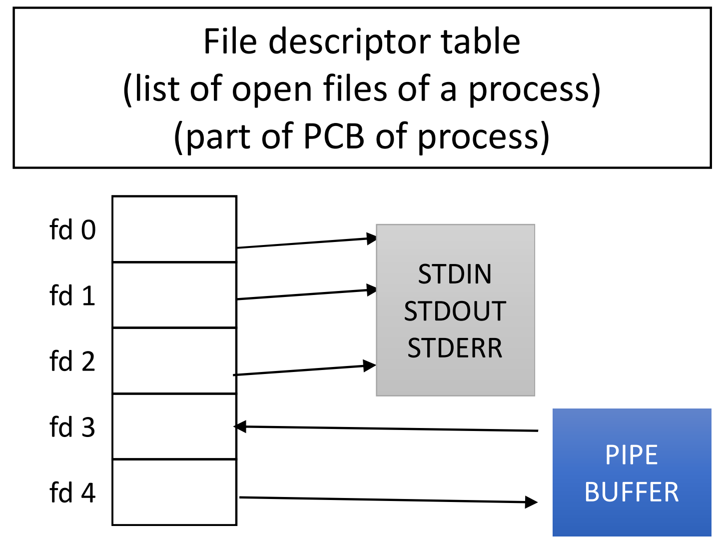
- Message queues used for exchanging messages between processes
  - Open connection to message queue identified by a “key”, get a handle
  - Sender opens connection to message queue, sends message
  - Receiver opens connection to message queue, retrieves message later on
  - Message buffered within message queue / mailbox until retrieved by receiver
- Example: IPC in web application using message queues
  - Web server posts dynamic HTTP requests into message queue
  - App server retrieves requests and processes them
  - App server posts responses into message queue for web server

message queues identified by a key.
Structured communication (each message has a type and data).
Non-blocking operations (messages can be retrieved selectively): Asynchronous.
Persistence (messages remain in the queue even if no process is reading them immediately).
it is managed by kernel and there can be multiple sender and receiver.
Once msg read using msgrcv() it is deleted immediately.

Pipes

```
int fd[2]
pipe(fd) //anonymous
read(fd[0], message, ..)
write(fd[1], message, ..)
```

- Pipe is a unidirectional FIFO channel into which bytes are written at one end, read from other end
- System call "pipe" creates a pipe channel, with two file descriptors for endpoints, returns 2 integers
- One file descriptor used to write into pipe, one to read from pipe
- Data written into pipe is stored in a buffer of the pipe channel until read
- Bi-directional communication needs two pipes

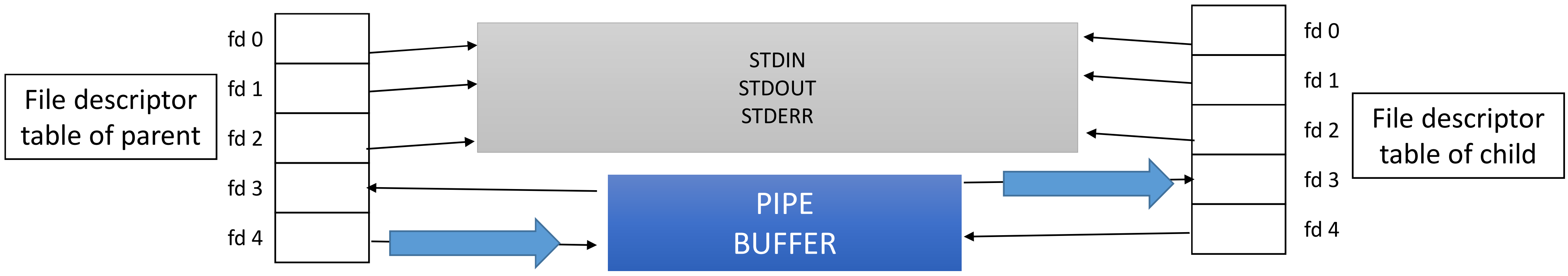


Since pipes are unidirectional, if both processes need to communicate both ways, two pipes are required.

They are strictly unidirectional, only one can read, and one will write. If multiple child tries to read then race condition, whichever first gets the read.

Anonymous pipes

- Anonymous pipes (using pipe system call) only available for use within process and its children
- Open pipe before fork, so pipe file descriptors shared between parent and child, point to same pipe structure
- One of parent/child closes read end, other closes write end
- Pipe file descriptors used to read/write messages between parent/child

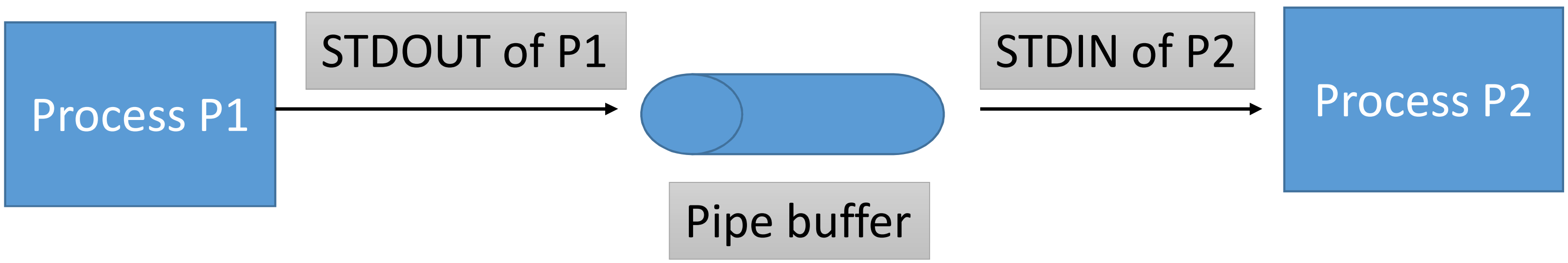


Anonymous pipe.

Pipes in shell commands

$cat foo.txt | grep something

- How does shell run commands with pipes (output of one command given as input to another command)?
- Shell opens a pipe, shared with child processes that run commands
- Shell duplicates stdout of first child to write end of pipe, read end of pipe to stdin of second process
- Processes must close file descriptors they are not using



Yes, in blocking mode (default behavior), a write to a named pipe (FIFO) will block if no process is reading from the pipe.

Non-Blocking Mode (O_NONBLOCK flag)
If no reader is present: write() fails immediately with an EPIPE error.
If the pipe buffer is full, write() fails with EAGAIN

Named pipes

- How to use pipes between unrelated processes? Named pipes
- Named pipes opened with a pathname, accessible across processes
- One process accesses read end of pipe, another opens write end
- Named pipe also provides uni-directional communication
- Writing to pipe with no reader open will throw an error

Reader

```
mkfifo(name, ..)
fd = open(name, O_RDONLY)
read(fd, message, ..)
```

Writer

```
fd = open(name, O_WRONLY)
write(fd, message, ...)
```

Blocking vs. non-blocking IPC

- Same high level concept across sockets, pipes, message queues
  - Sender sends message, temporarily stored in some memory inside OS
  - Receiver retrieves message later on from temporary OS memory
- Send/receive system calls can block
  - Sender can block if temporary buffer is full
  - Receiver can block if temporary buffer is empty
- Possible to configure IPC to be non-blocking using syscalls
  - Send/receive will return with error instead of blocking

Shared memory

```
shmid = shmget(key, ..)
char *data = shmat(shmid, ..)
```

- Processes in a system do not share any memory by default
  - Child process gets copy of parent memory image, modifies independently
- Shared memory: a way for two processes to share memory
  - Same memory appears in memory image of multiple processes
  - Shared memory segment identified by a unique key
  - Process can request to map or "attach" a specific shared memory segment into its memory image by using key
- Processes may need extra mechanisms for coordination besides shared memory
  - E.g., how does one process know when another process has modified shared memory?

Signals

- Signals are also a type of IPC
- But can only send limited amount of information
- Signals can be used with other IPC mechanisms
- Example: P1 places data in shared memory, signals P2 that data is ready
- User-defined signals can be used to avoid terminating process