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
  - 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

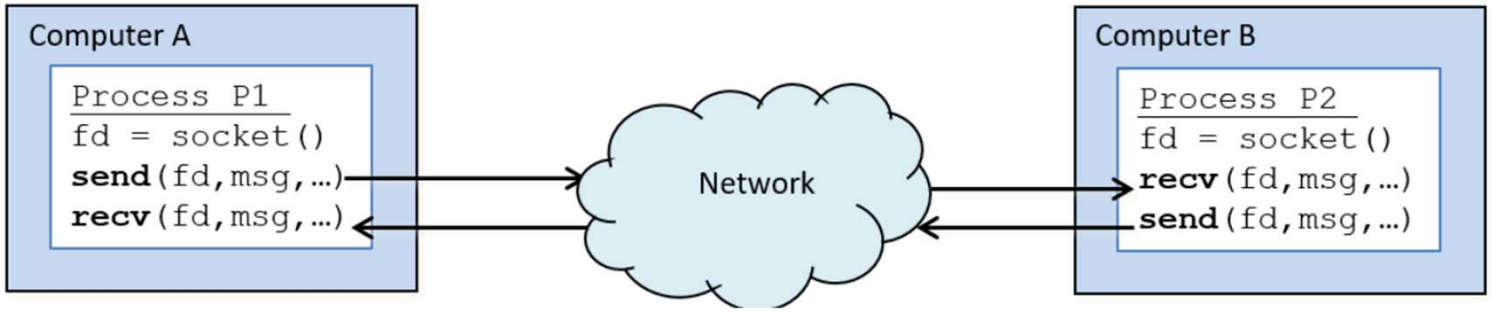


Image credit: Dive Into Systems

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-server paradigm: one process opens socket first (server) and another process connects its socket to the first one (client)
  - Client/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

Creating a socket

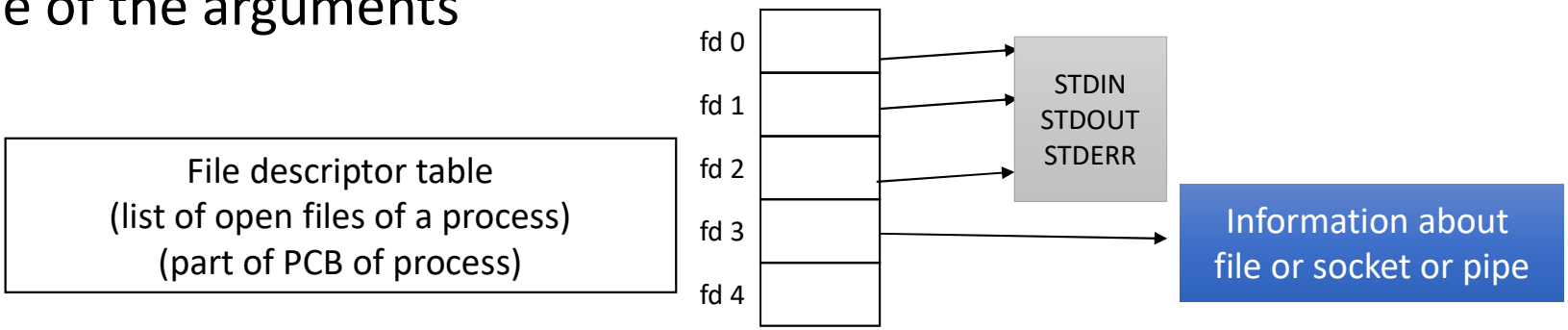
```
sockfd = socket(…)
bind(sockfd, address)
```

- 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/sockets/pipes in an array
- When file or socket or pipe is opened, new entry is created in array, new index returned
- All future system calls (read, write) will be given the file descriptor as one of the arguments



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, ..)
```

Connecting sockets

- Connection-oriented sockets must be explicitly connected to each other before exchanging messages
- After server binds socket to well-known address, it uses “listen” system call to make the socket listen for new connections
- Client uses “connect” system call to connect to a server listen socket
  - Connect system call blocks until messages exchanged with server to complete connection procedure (more later)
- Server uses “accept” system call to accept new connection requests
  - Accept system call blocks until new connection is received
  - Returns a new socket file descriptor to communicate exclusively with a connected client
- At server: one listen socket to accept new connections, one connected socket for every connected client to send/recv messages

Client

```
sockfd = socket(..)
connect(sockfd, server_sockaddr, ..)
```

Server

```
sockfd = socket(..)
bind(sockfd, server_address)
listen(sockfd, ..)
newsockfd = accept(sockfd, ..)
```

Data exchange using connected sockets

- After client connects to server, pair of sockets used to exchange data
  - Note that per-client connected socket is used at server, not listen socket
  - System calls send/write used to send message on a connected socket
  - System calls recv/read used to receive message on a connected socket
- Arguments to send/recv: socket fd, message buffer, buffer length, flags
  - Return value is number of bytes read/written or error
  - No need to specify socket address on every message, as connected already
  - Send/recv has extra flags argument, as compared to read/write system calls
  - Flags control where system call blocks and other behavior

Client

```
sockfd = socket(..)
connect(sockfd, server_sockaddr, ..)
n = send(sockfd, req_buf, req_len, ..)
n = recv(sockfd, resp_buf, resp_len, ..)
```

Server

```
sockfd = socket(..)
bind(sockfd, server_address)
listen(sockfd, ..)
newsockfd = accept(sockfd, ..)
n = recv(newsockfd, req_buf, req_len, ..)
n = send(newsockfd, resp_buf, resp_len, ..)
```

Message queues

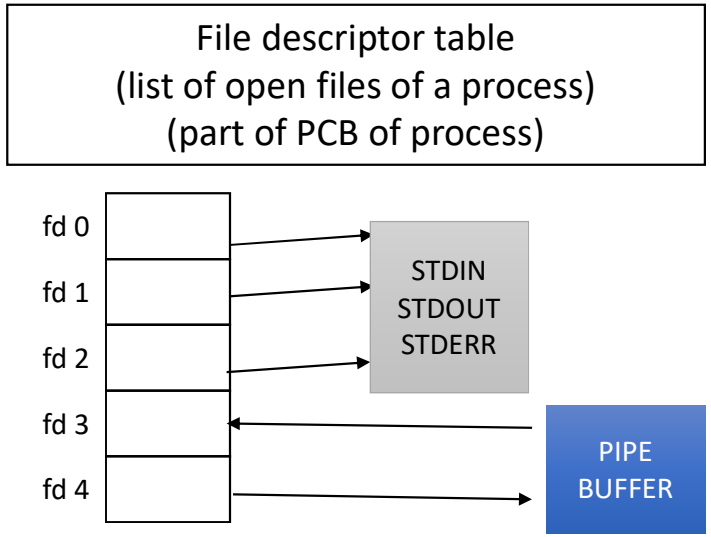
```
msgid = msgget(key, …)
msgsnd(msgid, message, …)
msgrcv(msgid, message, …)
```

- 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

Pipes

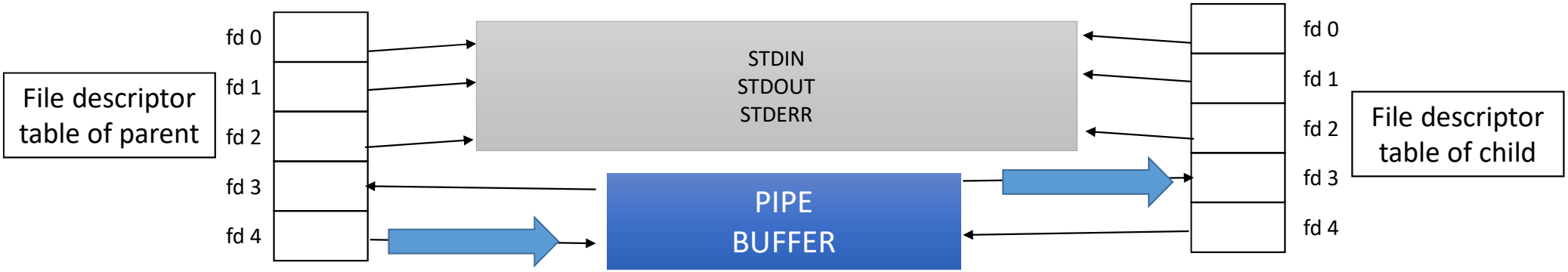
- Pipe is a unidirectional FIFO channel into which bytes are written at one end, read from other end
- System call “pipe” creates a pipe channel, with two file descriptors for endpoints, returns 2 integers
- One file descriptor used to write into pipe, one to read from pipe
- Data written into pipe is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

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



Anonymous pipes

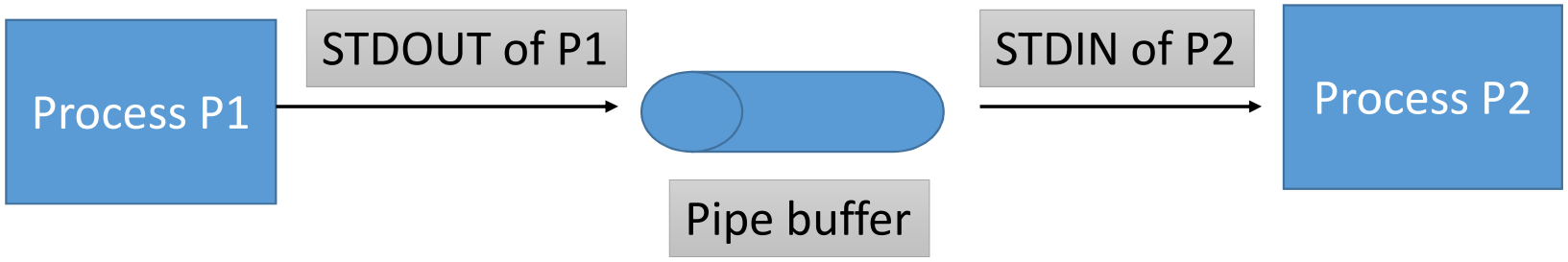
- Anonymous pipes (using pipe system call) only available for use within process and its children
- Open pipe before fork, so pipe file descriptors shared between parent and child, point to same pipe structure
- One of parent/child closes read end, other closes write end
- Pipe file descriptors used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



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



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

- Signal: a way to send notifications to processes
- Standard signals available in operating systems, each corresponding to a specific event, and with a specific signal number

Signal Name	Description
`SIGSEGV`	Segmentation fault (e.g., dereferencing a null pointer)
`SIGINT`	Interrupt process (e.g., Ctrl-C in terminal window to kill process)
`SIGCHLD`	Child process has exited (e.g., a child is now a zombie after running `exit`)
`SIGALRM`	Notify a process a timer goes off (e.g., `alarm(2)` every 2 secs)
`SIGKILL`	Terminate a process (e.g., `pkill -9 a.out`)
`SIGBUS`	Bus error occurred (e.g., a misaligned memory address to access an `int` value)
`SIGSTOP`	Suspend a process, move to Blocked state (e.g., Ctrl-Z)
`SIGCONT`	Continue a blocked process (move it to the Ready state; e.g., `bg` or `fg`)

Image credit: Dive Into Systems

How to send signals?

- System call kill can be used to send a signal from one process to other
  - Kill system call can send all signals, not just SIGKILL
  - Some restrictions on who can send to whom for isolation and security
- Kill command uses this syscall, e.g., “kill -9 <pid>” sends SIGKILL (#9)
- Signals can also be generated by OS for a process, e.g., when it handles interrupt due to Ctrl+C keyboard event
  - Interrupt handler for Ctrl+C sends the signal to the process in foreground

Signal handling

- Signals to a process are queued up by OS and delivered when process goes from kernel mode to user mode next
- Default behavior defined by OS for a process receiving a signal
  - Ignore some signals (e.g., SIGCHLD)
  - Terminate when some signals are received (e.g., SIGINT)
- User processes can define their own signal handler functions to be executed when a signal is received
  - Override default behavior defined for a signal
  - Some signals (e.g., SIGKILL) cannot be overridden
- Process jumps to signal handler, executes it, resumes normal execution afterwards (if still alive)

Process groups

- When we type Ctrl+C on keyboard, which processes get the signal?
- Processes are organized into process groups, every process belongs by default to process group of its parent
- When signal is sent to a process, it is delivered to all processes in its process group by default
- Example: when we hit Ctrl+C on keyboard, signal sent to all processes in the foreground process group
- System call setpgid can be used to change process group of signals, to control signal distribution

Examples: sending and catching signals

- Parent sends SIGKILL to child using kill system call
- Child runs in infinite loop until killed by parent

```
int pid = fork()
if(pid == 0) {
  while(1); //infinite loop
  //terminates on SIGKILL
}
//parent
kill(pid, SIGKILL)
```

- Default SIGINT hander overridden
- Process prints message before terminating on SIGINT

```
void sigint_handler(int sig) {
  print “caught signal”
  exit()
}
int main() {
  signal(SIGINT, sigint_handler)
  …
}
```