Duke Systems

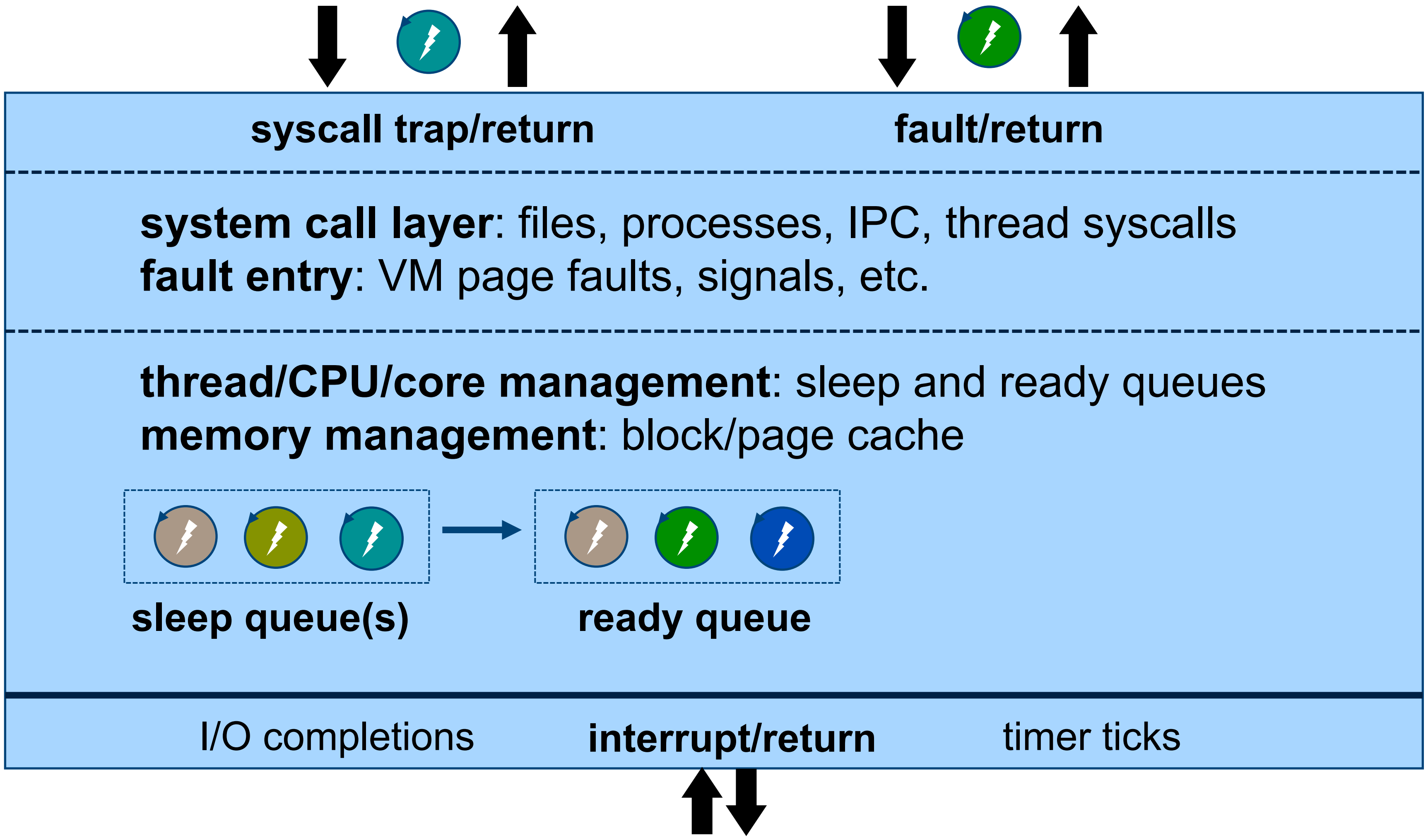
CPS 310
Unix I/O and Inter-Process Communication (IPC)

Jeff Chase

Duke University

http://www.cs.duke.edu/~chase/cps310

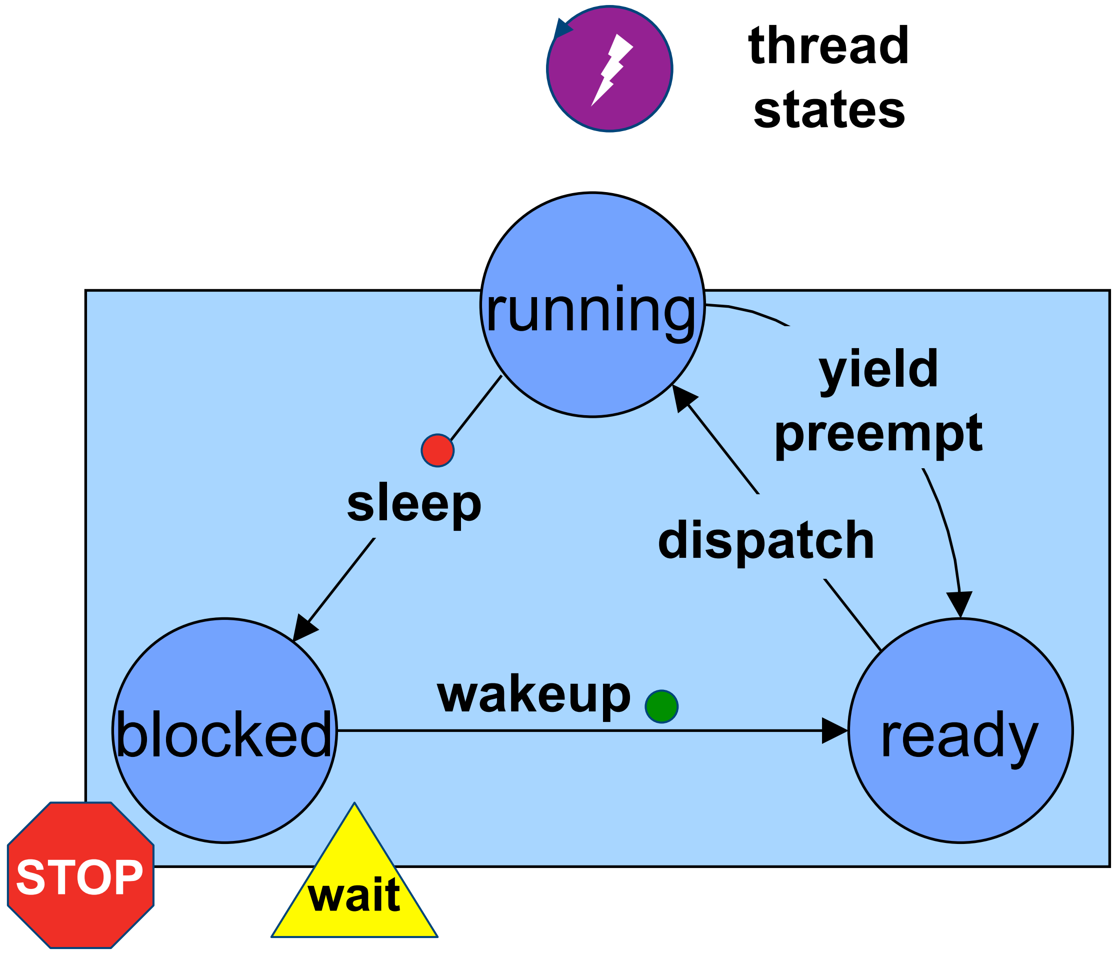
The kernel

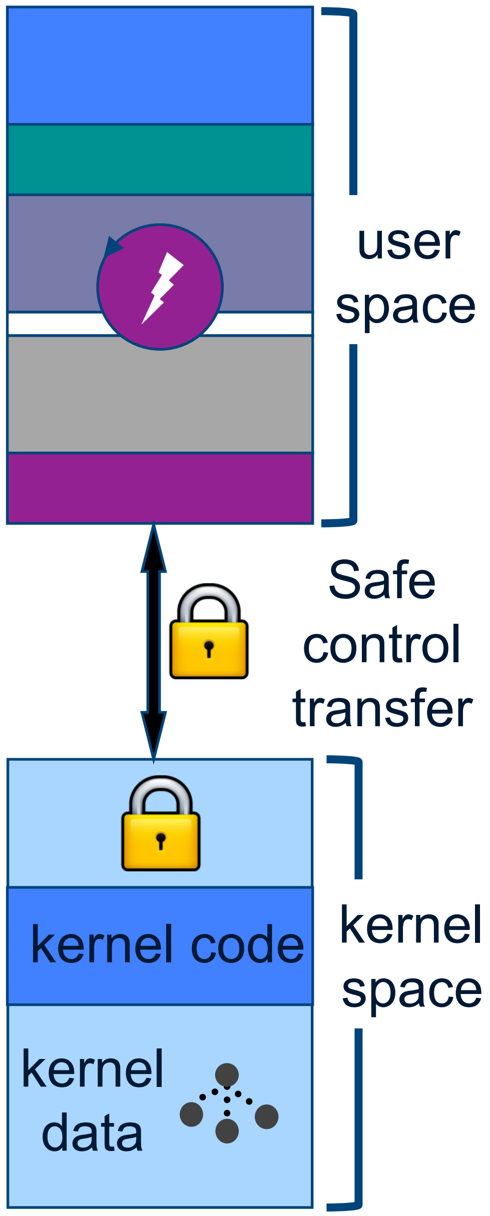


system call layer: files, processes, IPC, thread syscalls
fault entry: VM page faults, signals, etc.

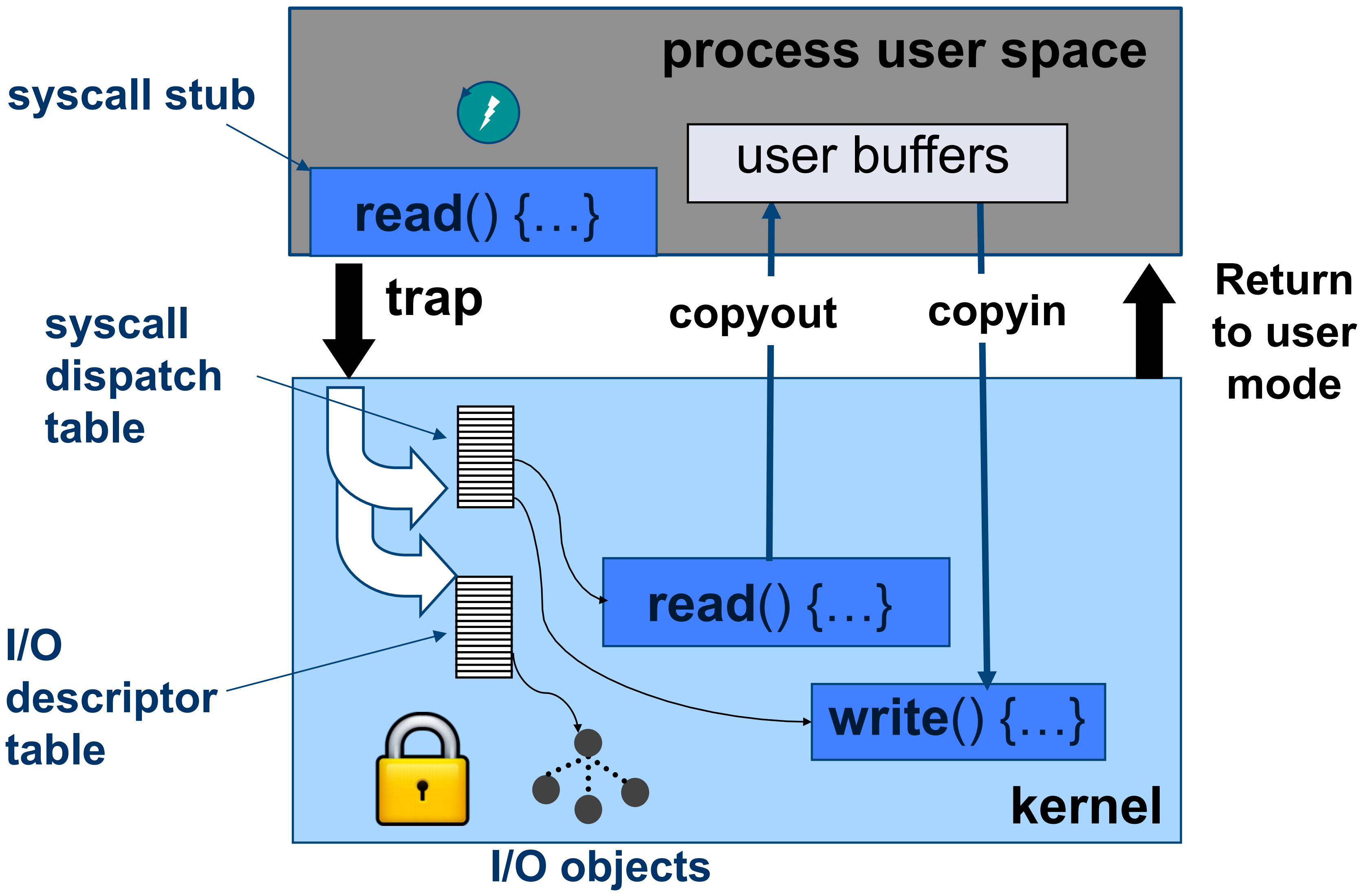
thread/CPU/core management: sleep and ready queues
memory management: block/page cache

thread states




user
space
Safe
control
transfer
kernel code
kernel
data
kernel
space

Process, kernel, and syscalls

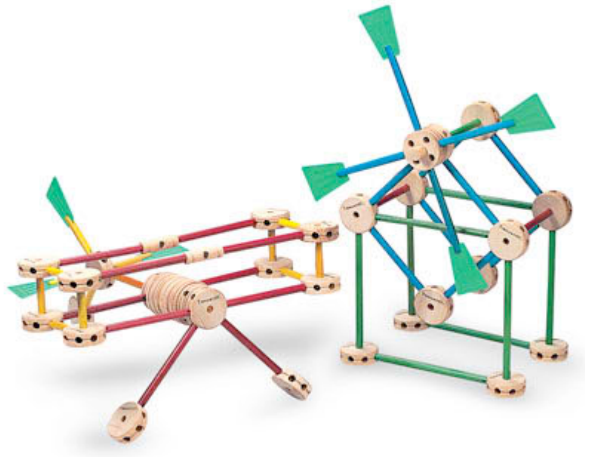


Unix syscalls we care about now

- fork, exec*, exit, wait*
  - Use execvp and waitpid
- open, read, write (+ lseek)
- pipe
- dup*
  - Use dup2
- close
- chdir
- (getpid, getpgid, setpgid, tcsetpgrp, kill, killpg)

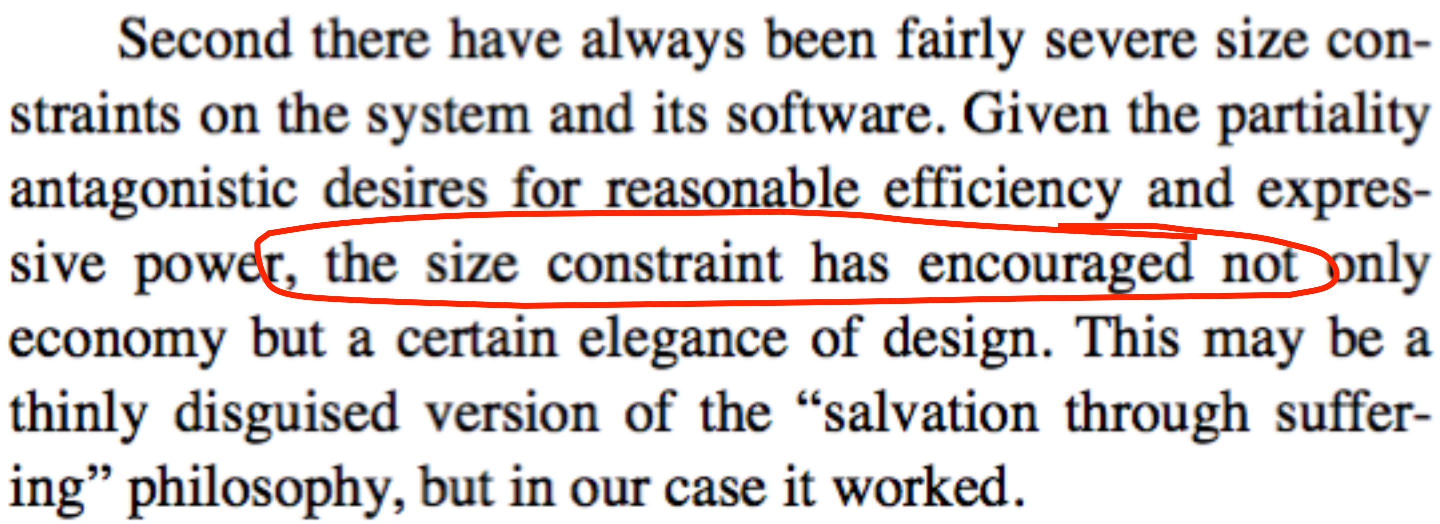
Platform abstractions

- Platforms provide “building blocks”…
- …and APIs to use them.
  - Instantiate/create/allocate
  - Manipulate/configure
  - Attach/detach
  - Combine in uniform ways
  - Release/destroy



The choice of abstractions reflects a philosophy of how to build and organize software systems.

small is Beautiful



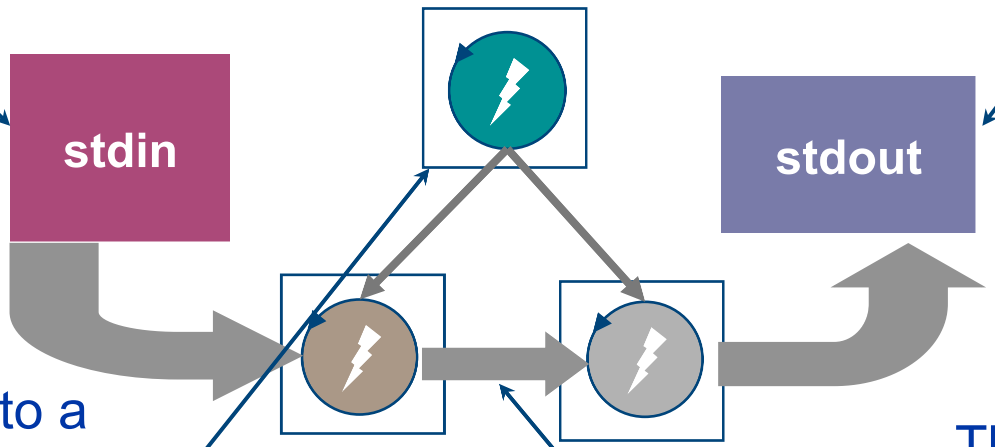
Second there have always been fairly severe size constraints on the system and its software. Given the partiality antagonistic desires for reasonable efficiency and expressive power, the size constraint has encouraged not only economy but a certain elegance of design. This may be a thinly disguised version of the "salvation through suffering" philosophy, but in our case it worked.

The UNIX Time-Sharing System*
D. M. Ritchie and K. Thompson
1974

Unix programming environment

Standard unix programs read a byte stream from standard input (fd==0).

They write their output to standard output (fd==1).



Stdin or stdout might be bound to a file, pipe, device, or network socket.

If the parent sets it up, the program doesn't even have to know.

That style makes it easy to combine simple programs using pipes or files.

The processes may run **concurrently** and are synchronized automatically.

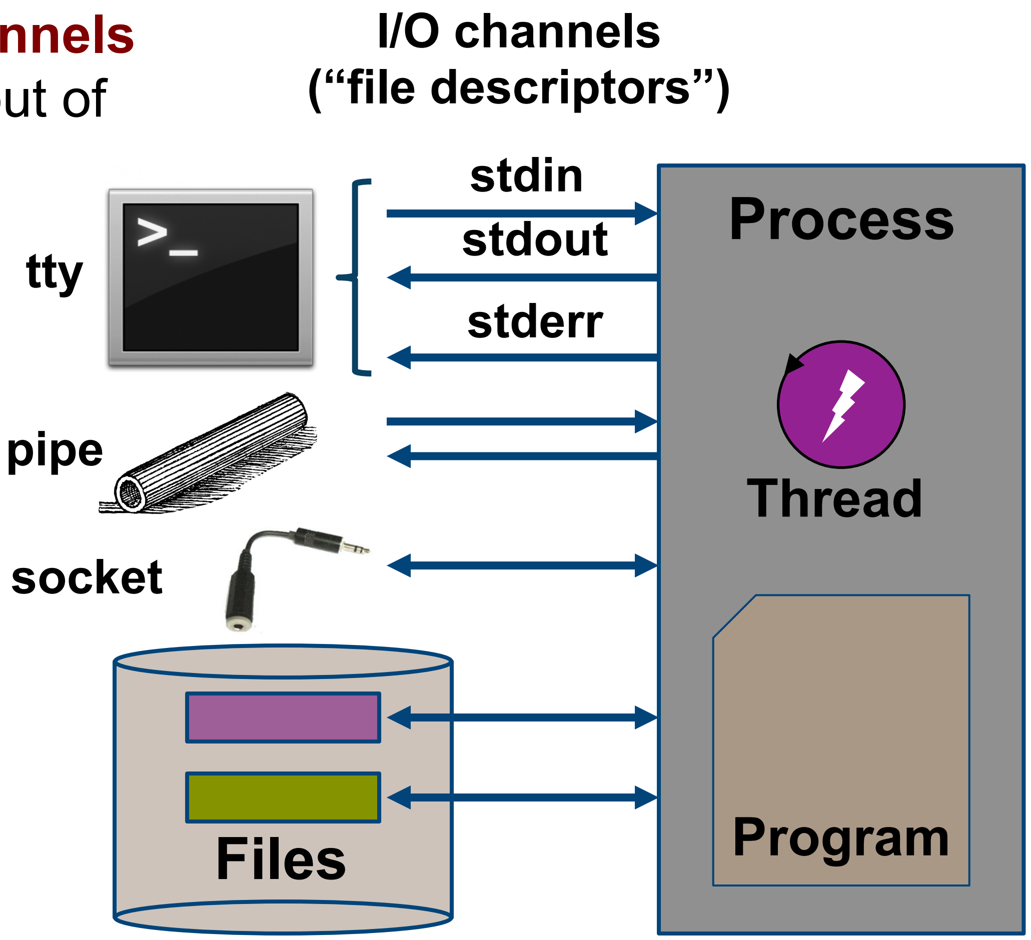
Unix process view: data

A process has multiple **channels** for data movement in and out of the process (I/O).

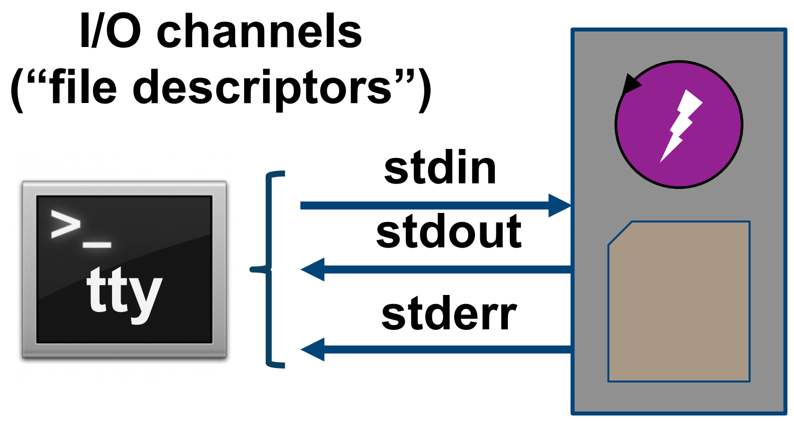
The channels are typed.

Each channel is named by a file **descriptor**.

The parent process and parent program set up and control the channels for a child (until **exec**).



Standard I/O descriptors



Open files or other I/O channels are named within the process by an integer **file descriptor** value.

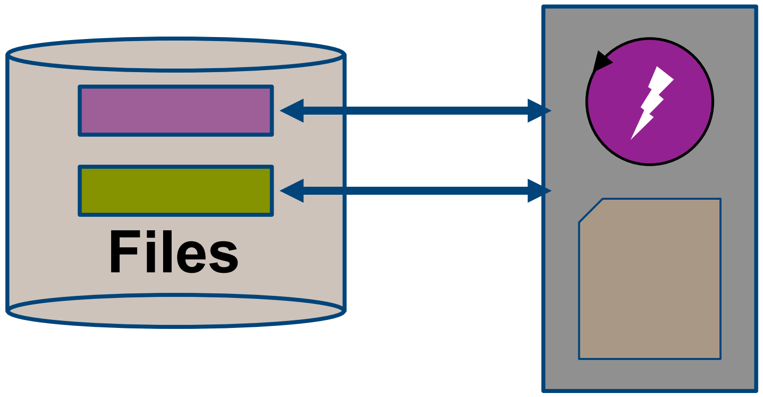
Standard descriptors for primary input (stdin=0), primary output (stdout=1), error/status (stderr=2).

Their bindings are **inherited** from the parent process and/or set by the parent program.

By default they are bound to the **controlling tty**.

```
count = read(0, buf, count);
if (count == -1)  {
          perror("read failed");  /* writes to stderr */
          exit(1);
}
count = write(1, buf, count);
if (count == -1) {
          perror("write failed");  /* writes to stderr */
          exit(1);
}
```

Files: open syscall



```
fd = open(pathname, <options>);
write(fd, “abcdefg”, 7);
read(fd, buf, 7);
lseek(fd, offset, SEEK_SET);
close(fd);
```

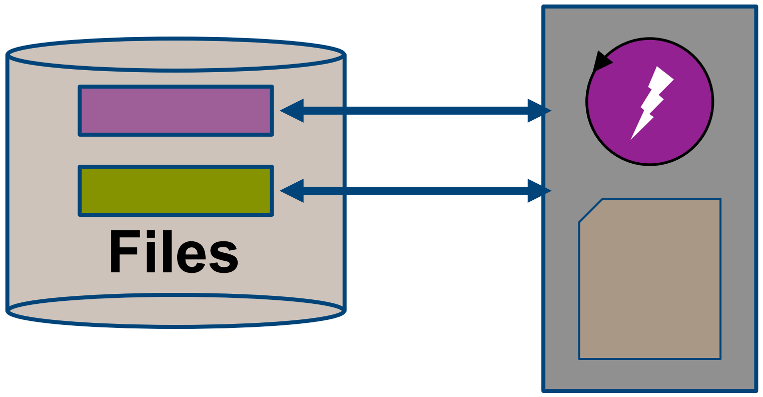
Possible <option> flags for **open**:

O_RDONLY	open for reading only
O_WRONLY	open for writing only
O_RDWR	open for reading and writing
O_APPEND	append data to end of file on each write
O_CREAT	create file if it does not already exist
O_TRUNC	truncate size to 0 if it exists
O_EXCL	give an error if O_CREAT and the file exists

Example:

```
#include <fcntl.h>
fd = open(“somefile”, O_CREAT | O_TRUNC | O_WRONLY);
```

Files: open and chdir



```
fd = open(pathname, <options>);
write(fd, “abcdefg”, 7);
read(fd, buf, 7);
lseek(fd, offset, SEEK_SET);
close(fd);
```

Syscalls like **open** (or **exec***) interpret a file **pathname** relative to the **current directory** of the calling process.

If the pathname starts with “/” then it is relative to the **root directory**.

A process **inherits** its current directory from parent process across **fork**.

A process can change its current directory with the **chdir** syscall.

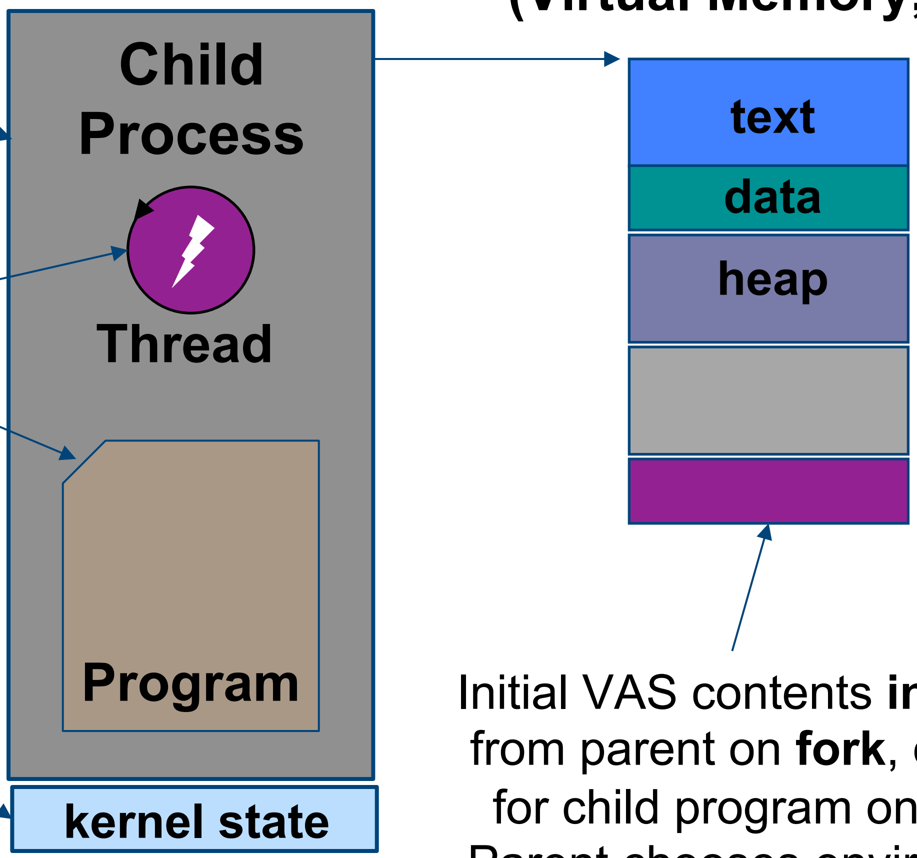
“.” in a pathname means current directory (curdir).
“..” in a pathname means parent directory of curdir.

Unix process: parents rule

Created with **fork** by parent program running in parent process.

Parent program running in child process, or **exec**'d program chosen by parent program.

Inherited from parent process, or modified by parent program in child (e.g., using **dup*** to remap descriptors).



Virtual address space (Virtual Memory, VM)

Initial VAS contents **inherited** from parent on **fork**, or reset for child program on **exec**. Parent chooses environment (argv[] and envp[]) on **exec**.

Unix shell(s)
An early interactive programming environment

- Classical Unix programs are packaged software components: specific functions with narrow, text-oriented interfaces.
- Shell is a powerful (but character-based) user interface.
  - Shell is a user program that uses kernel syscalls to execute utility programs as child processes.
  - A typical shell command is just the name of a program to run.
- Shell is also a programming environment for composing and coordinating programs interactively.
- So: it's both an interactive programming environment and a programmable user interface.
  - Both ideas were "new" at the time (late 1960s).
- Its powerful scripting capabilities are widely used in large-scale system administration and services, for 40+ years!

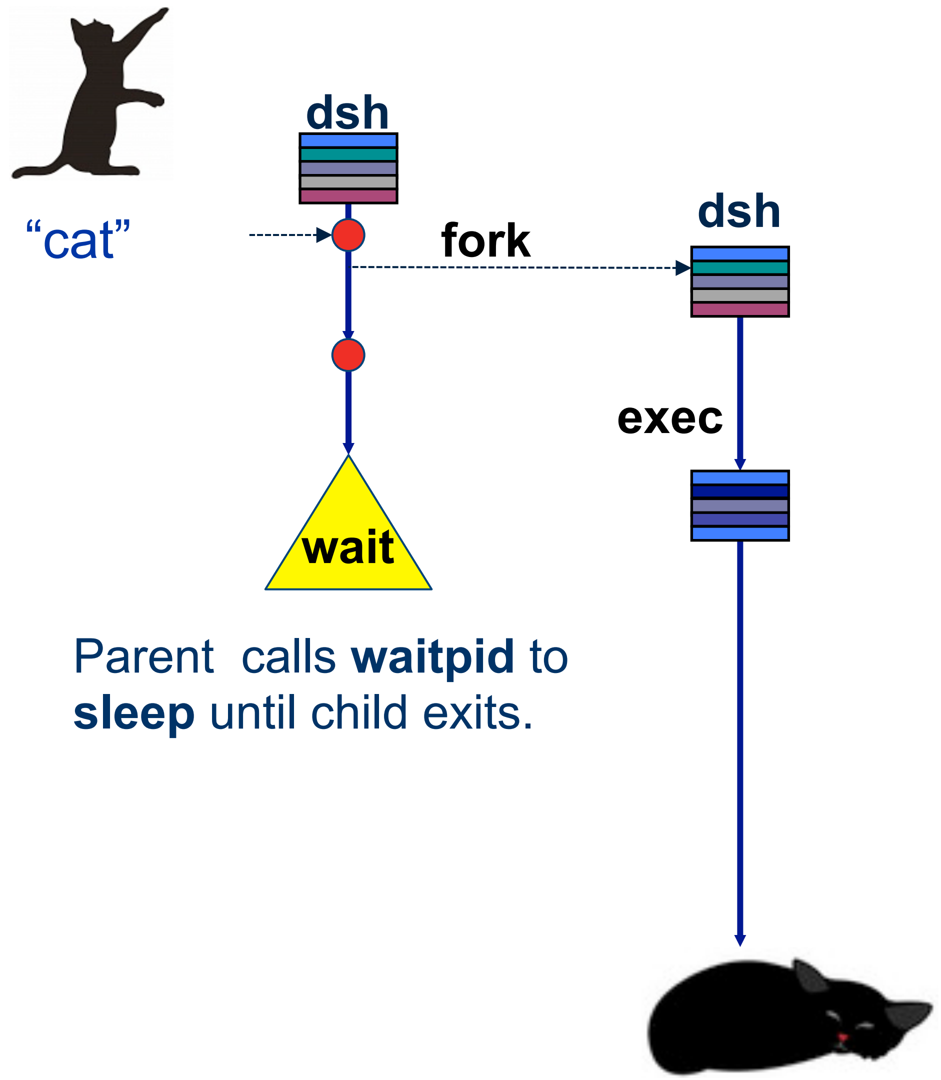
A simple program: cat

- /bin/cat is a standard Unix utility program.
- By default it copies stdin to stdout in a loop of read/write syscalls.
- It sleeps as needed and exits only if an error occurs or it reads an EOF (end-of-file) from its input.
- We can give cat arguments with a list of files to read from, instead of stdin. It copies all of these files to stdout. ("concatenate")

```
while ((nr = read(rfd, buf, bsize)) > 0) {
        for (off = 0; nr; nr -= nw, off += nw) {
                if ((nw = write(wfd, buf + off, (size_t)nr)) < 0)
                        err(1, "stdout")
        }
}
```

From http://svnweb.freebsd.org/base/head/bin/cat/cat.c

A shell running a command



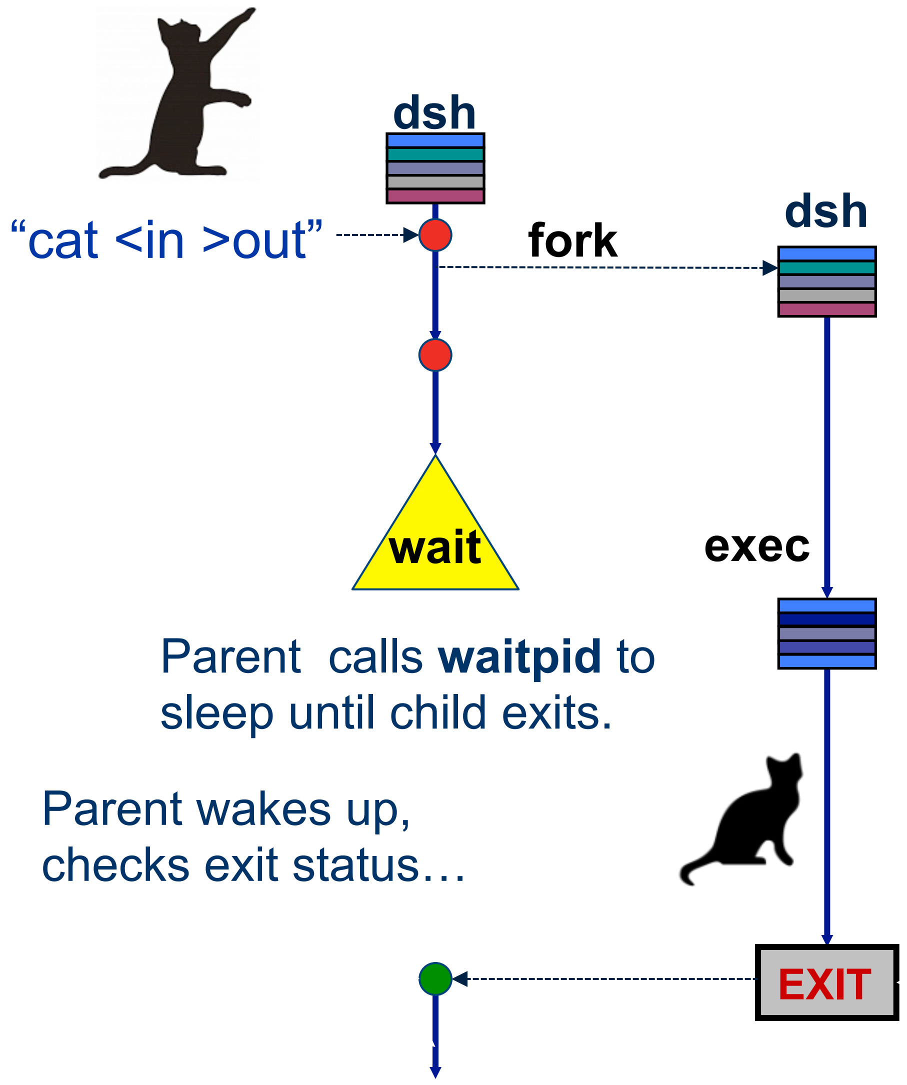
Parent calls **waitpid** to **sleep** until child exits.

dsh runs in child to initialize kernel state and launch the program. The child inherits stdin and stdout bound to the controlling terminal.

dsh calls **execvp** to overlay itself with a child program in a named file (**/bin/cat**). It passes the empty argv array (argv[0] == “cat”) and the env array inherited from the parent.

cat executes, starting with main(). It issues a **read** syscall on stdin and **sleeps** until an input line is entered on the terminal….

A shell running a command



Parent calls **waitpid** to sleep until child exits.

Parent wakes up, checks exit status…

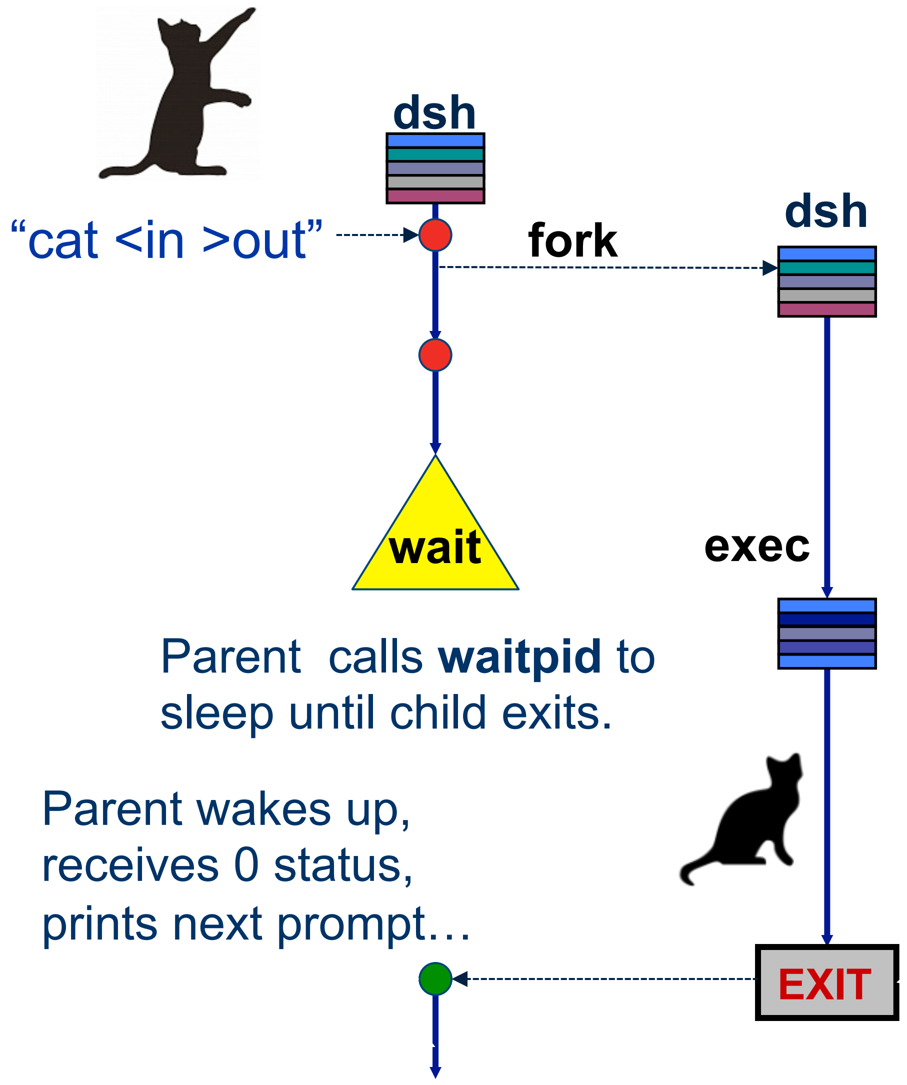
Child process running **dsh**: it is a clone of the parent, including a snapshot of parent's internal data (from parser, etc.), and any open descriptors, current directory, etc.

Parent program (**dsh**) runs in child to initialize kernel state: e.g.: **open** files, **close** descriptors, remap descriptors with **dup2**, modify argv/env arrays.

dsh calls **execvp** to overlay itself with a child program in a named file (**cat**), passing arg/env arrays.

cat executes, starting with main(argc, argv, envp). It copies data with **read**(stdin) and **write**(stdout) syscalls until it is done, then exits the child.

A shell running a command



Parent calls **waitpid** to sleep until child exits.

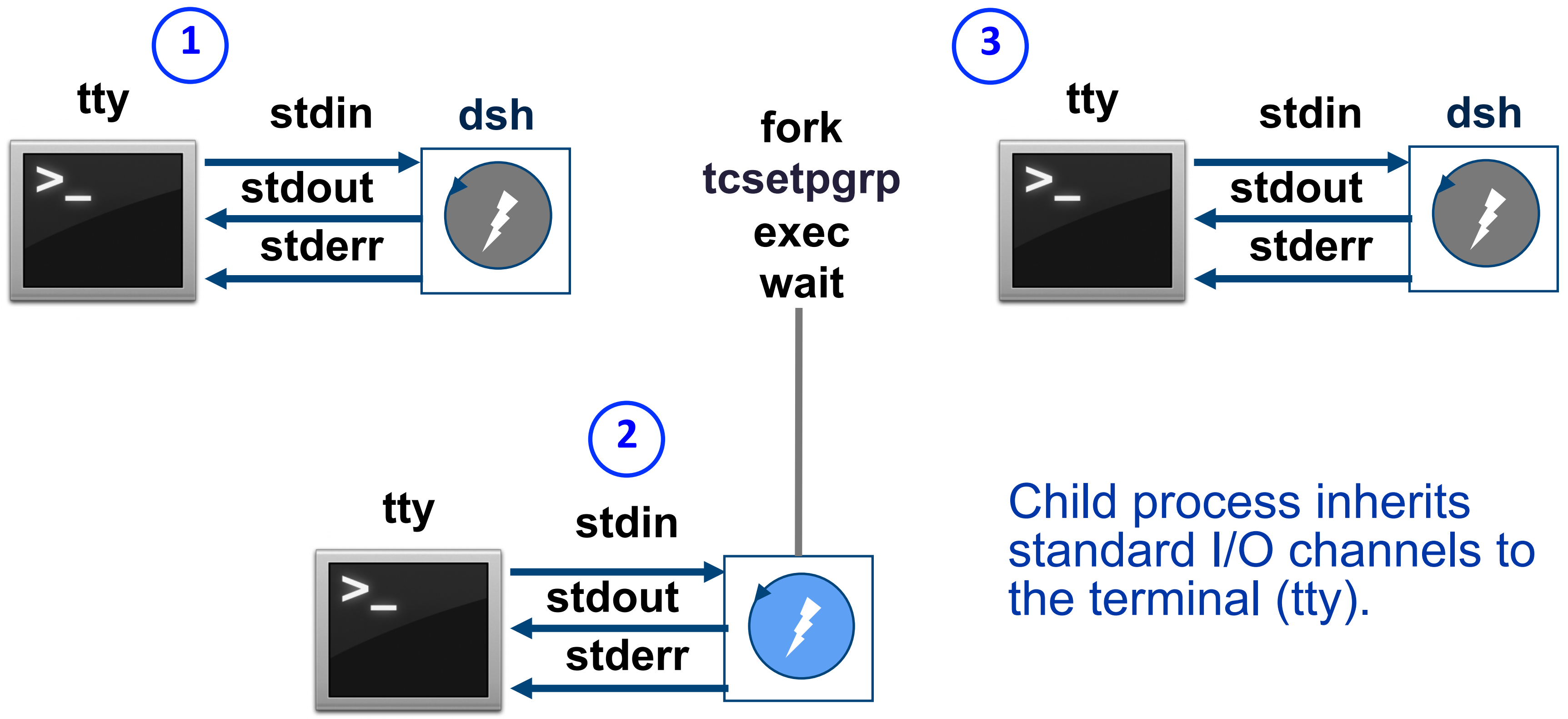
Parent wakes up, receives 0 status, prints next prompt…

dsh runs in child to initialize kernel state. **Open** file "in" in the current directory and use **dup2** to map it to stdin. **Open/truncate/create** file "out" and use **dup2** to map it to stdout. **Close** any unneeded descriptors.

dsh calls **execvp** to overlay itself with a child program in a named file (**/bin/cat**). It passes the empty argv array (argv[0] == "cat") and the env array inherited from the parent.

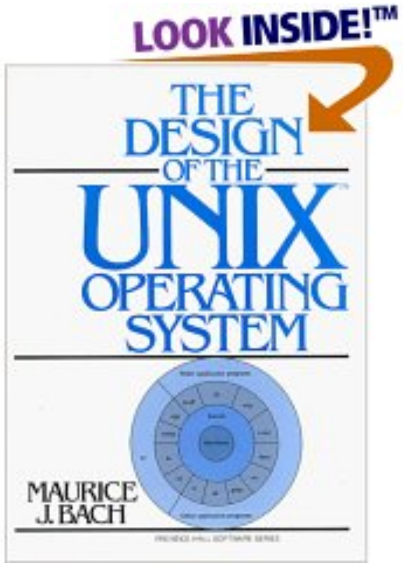
cat executes, starting with main(). It copies data from stdin to stdout with a loop of **read/write** syscalls until a syscall fails or **read** gets an EOF. If EOF, it exits with status 0.

Shell and child (example)

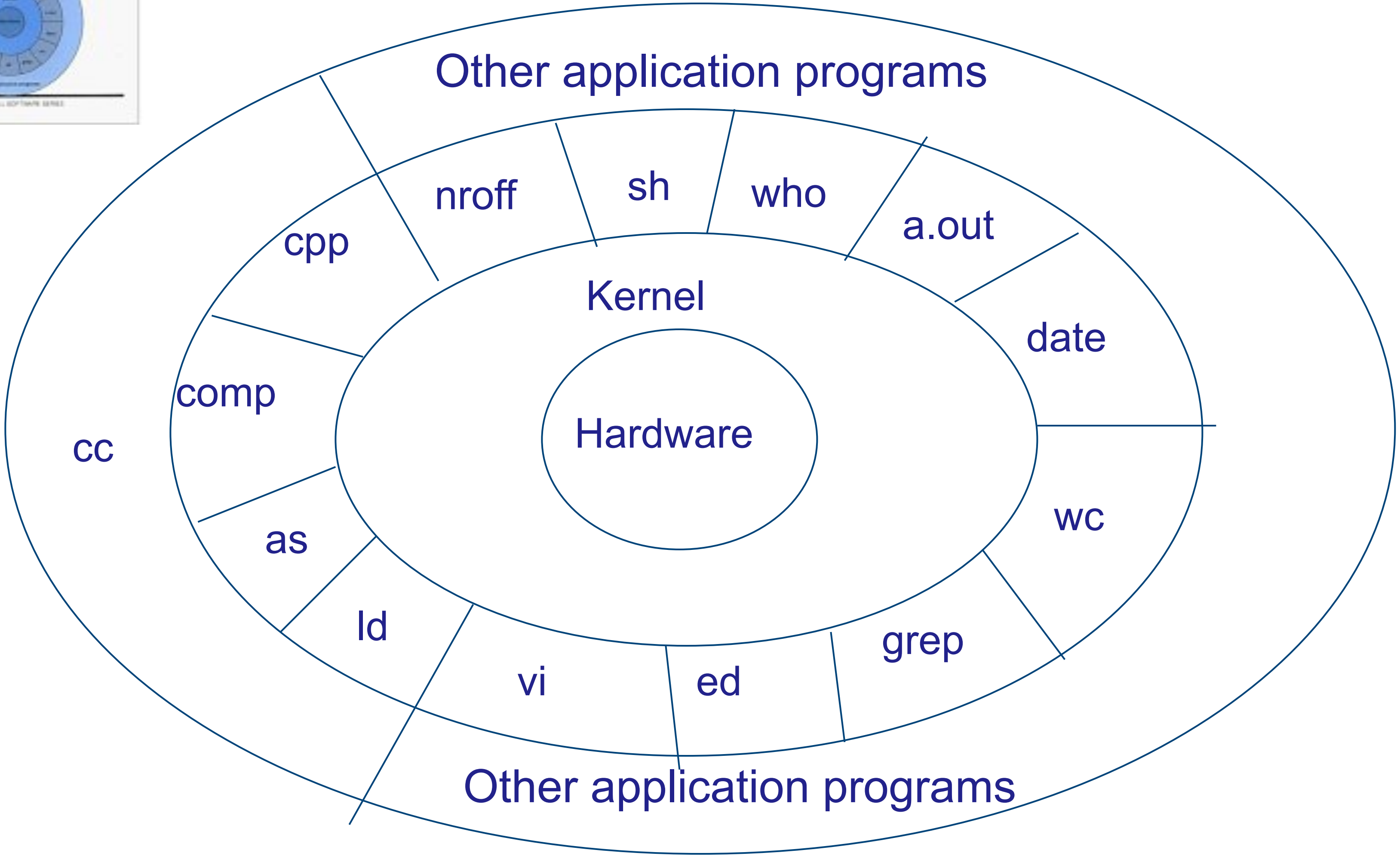


Child process inherits standard I/O channels to the terminal (tty).

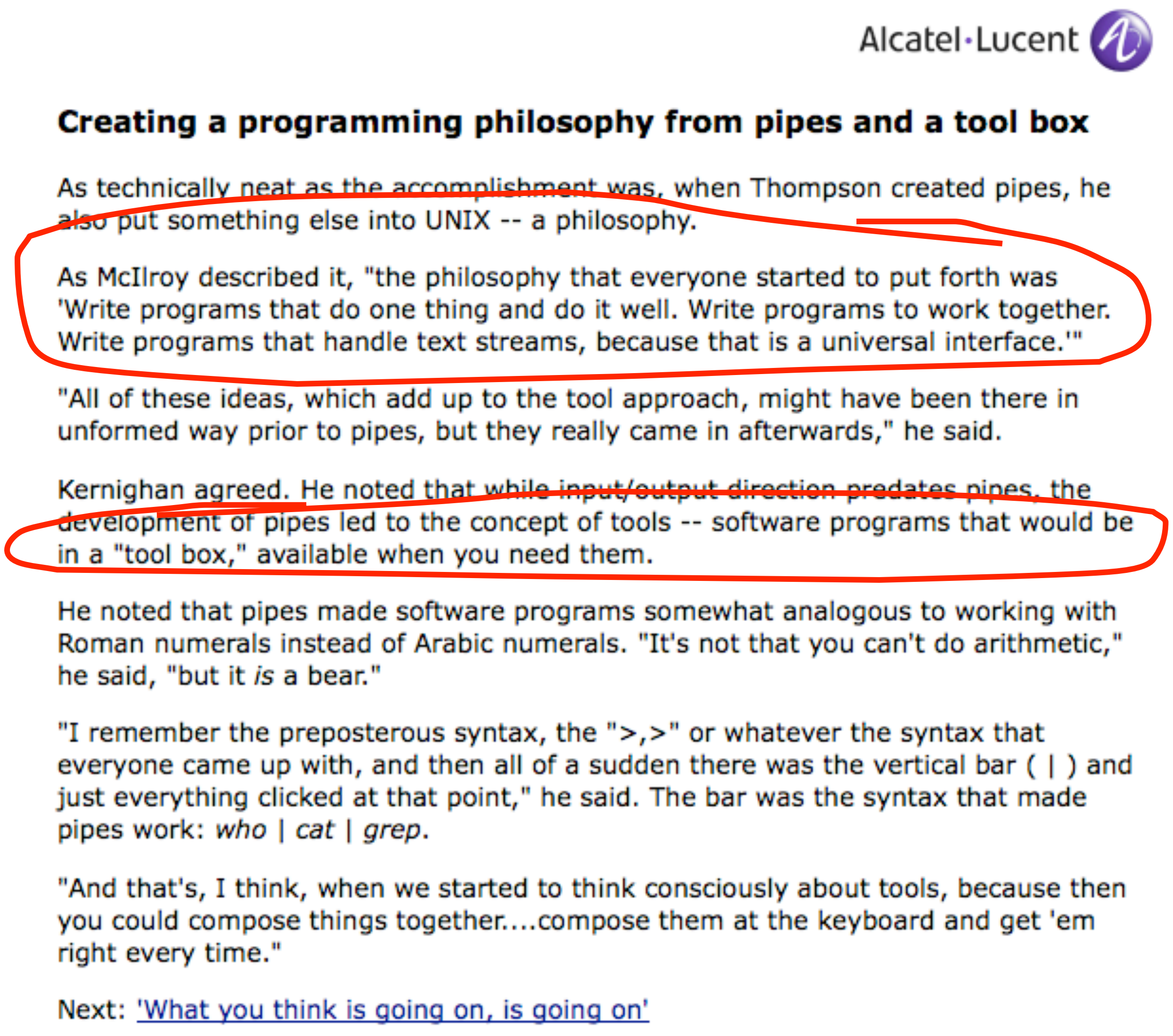
If child is to run in the **foreground**:
Child receives/takes control of the terminal (tty) input (tcsetpgrp).
The foreground process receives all tty input until it stops or exits.
The parent **waits** for a foreground child to stop or exit.



Unix defines uniform, modular ways to combine programs to build up more complex functionality.



A key idea: Unix pipes



Alcatel·Lucent

Creating a programming philosophy from pipes and a tool box

As technically neat as the accomplishment was, when Thompson created pipes, he also put something else into UNIX -- a philosophy.

As McIlroy described it, "the philosophy that everyone started to put forth was 'Write programs that do one thing and do it well. Write programs to work together. Write programs that handle text streams, because that is a universal interface.'"

"All of these ideas, which add up to the tool approach, might have been there in unformed way prior to pipes, but they really came in afterwards," he said.

Kernighan agreed. He noted that while input/output direction predates pipes, the development of pipes led to the concept of tools -- software programs that would be in a "tool box," available when you need them.

He noted that pipes made software programs somewhat analogous to working with Roman numerals instead of Arabic numerals. "It's not that you can't do arithmetic," he said, "but it *is* a bear."

"I remember the preposterous syntax, the ">,>" or whatever the syntax that everyone came up with, and then all of a sudden there was the vertical bar (|) and just everything clicked at that point," he said. The bar was the syntax that made pipes work: *who* | *cat* | *grep*.

"And that's, I think, when we started to think consciously about tools, because then you could compose things together....compose them at the keyboard and get 'em right every time."

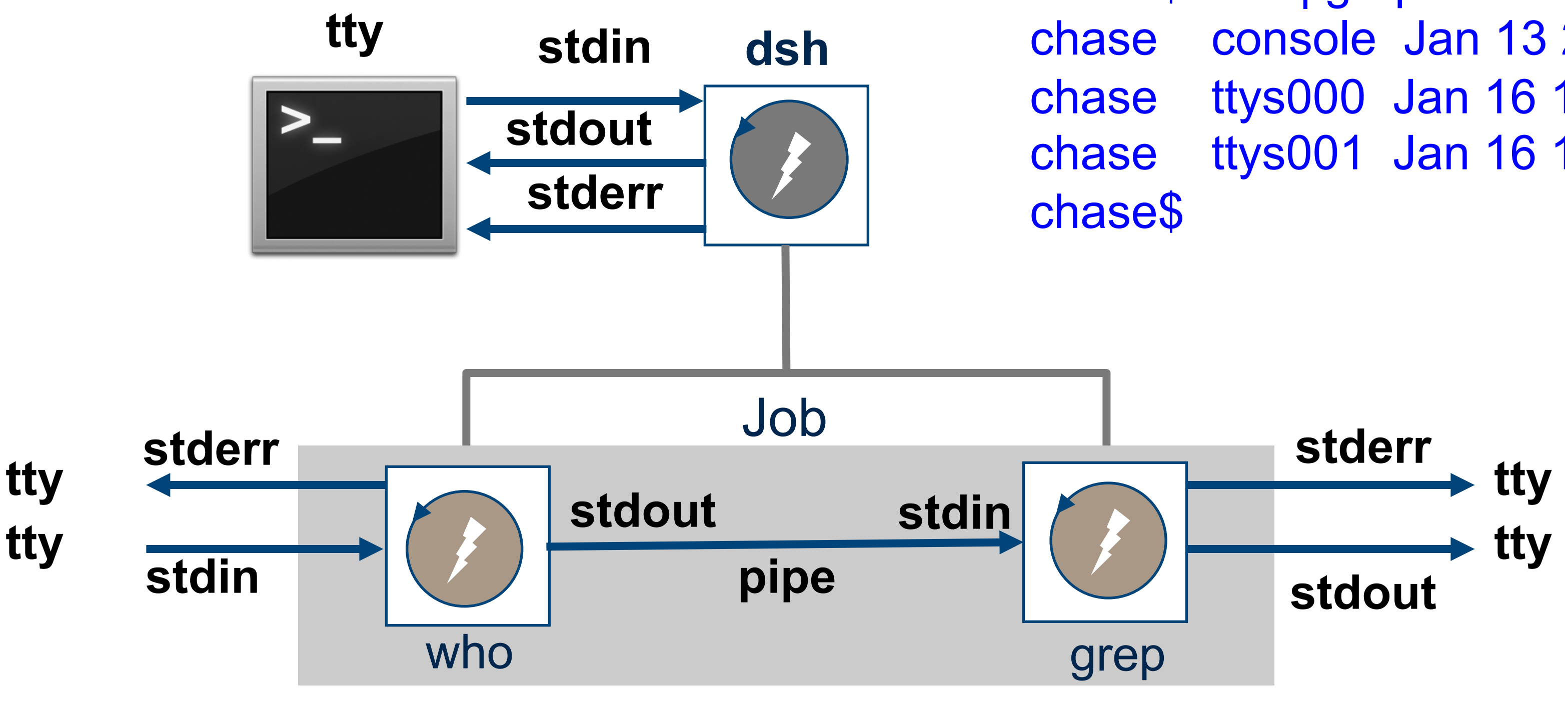
Next: 'What you think is going on, is going on'

The shell offers an intuitive syntax for pipes. That makes it possible to combine programs interactively from the shell. They each operate on a data **stream** flowing through them.

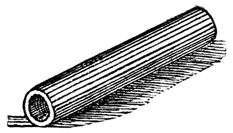
source | filter | sink

[http://www.bell-labs.com/history/unix/philosophy.html]

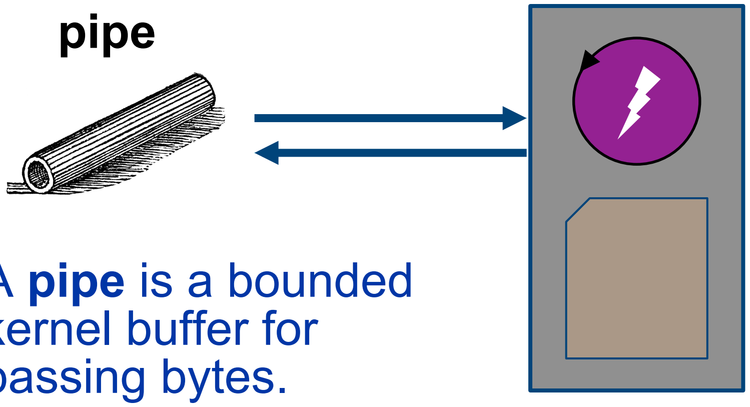
Shell pipeline example



```
chase$ who | grep chase
chase    console  Jan 13 21:08
chase    ttys000  Jan 16 11:37
chase    ttys001  Jan 16 15:00
chase$
```



Pipes



A **pipe** is a bounded kernel buffer for passing bytes.

```
int pfd[2] = {0, 0};
pipe(pfd);
/*pfd[0] is read, pfd[1] is write */

b = write(pfd[1], "12345\n", 6);
b = read(pfd[0], buf, b);
b = write(1, buf, b);
```

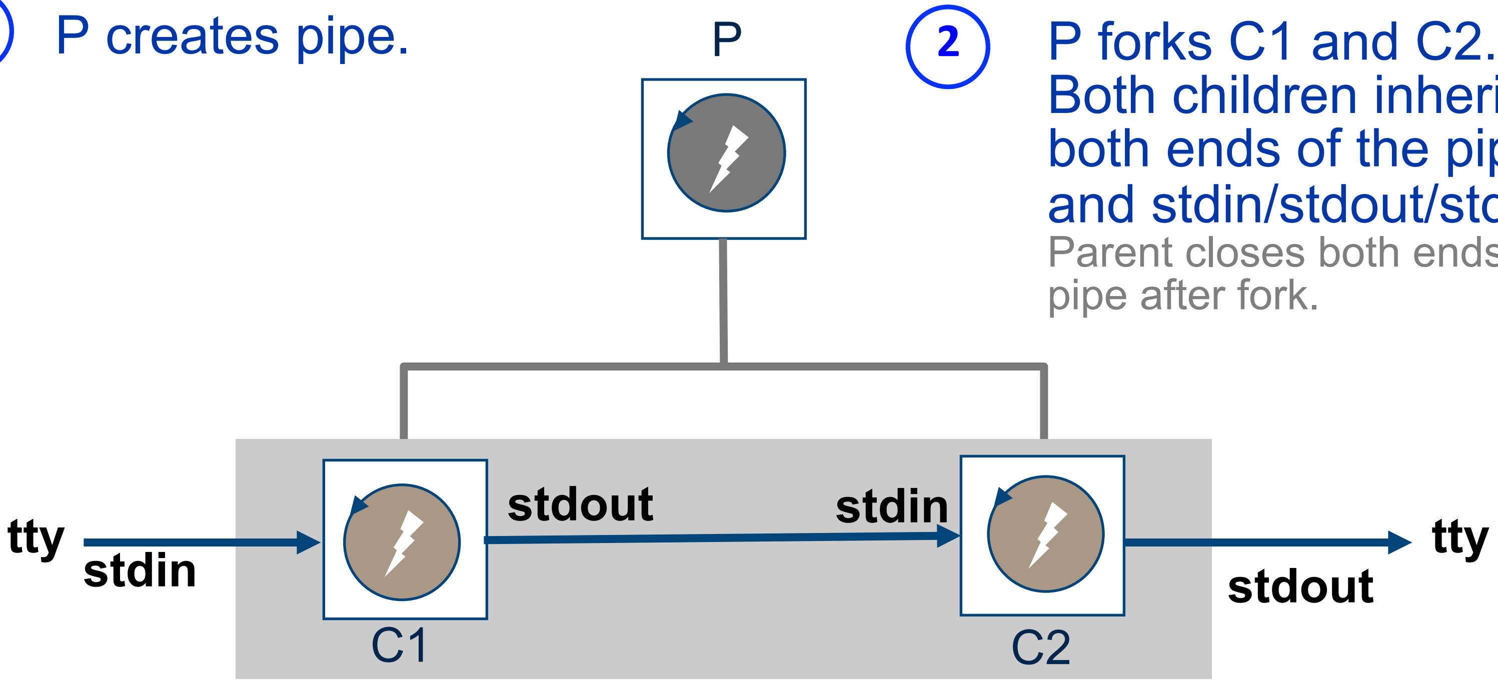
```
12345
```

- The **pipe**() system call creates a **pipe** object.
- A pipe has one read end and one write end: **unidirectional**.
- Bytes placed in the pipe with **write** are returned by **read** in order.
- The **read** syscall blocks if the pipe is empty.
- The **write** syscall blocks if the pipe is full.
- **Write** fails (SIGPIPE) if no process has the read end open.
- **Read** returns EOF if the pipe is empty and all writers close the pipe.

How to plumb the pipe?

1 P creates pipe.

2 P forks C1 and C2. Both children inherit both ends of the pipe, and stdin/stdout/stderr. Parent closes both ends of pipe after fork.



3A C1 closes the read end of the pipe, closes its stdout, "dups" the write end onto stdout, and execs.

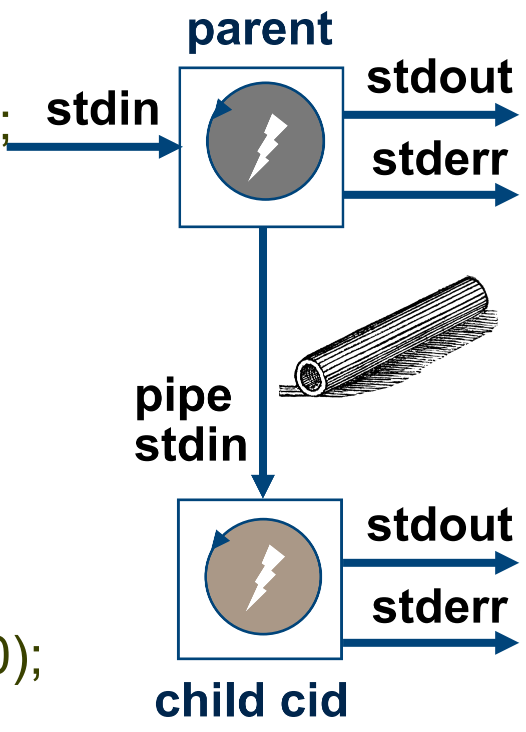
3B C2 closes the write end of the pipe, closes its stdin, "dups" the read end onto stdin, and execs.

Simpler example

Feeding a child through a pipe

Parent

```
int ifd[2] = {0, 0};
pipe(ifd);
cid = fork();
```



Parent

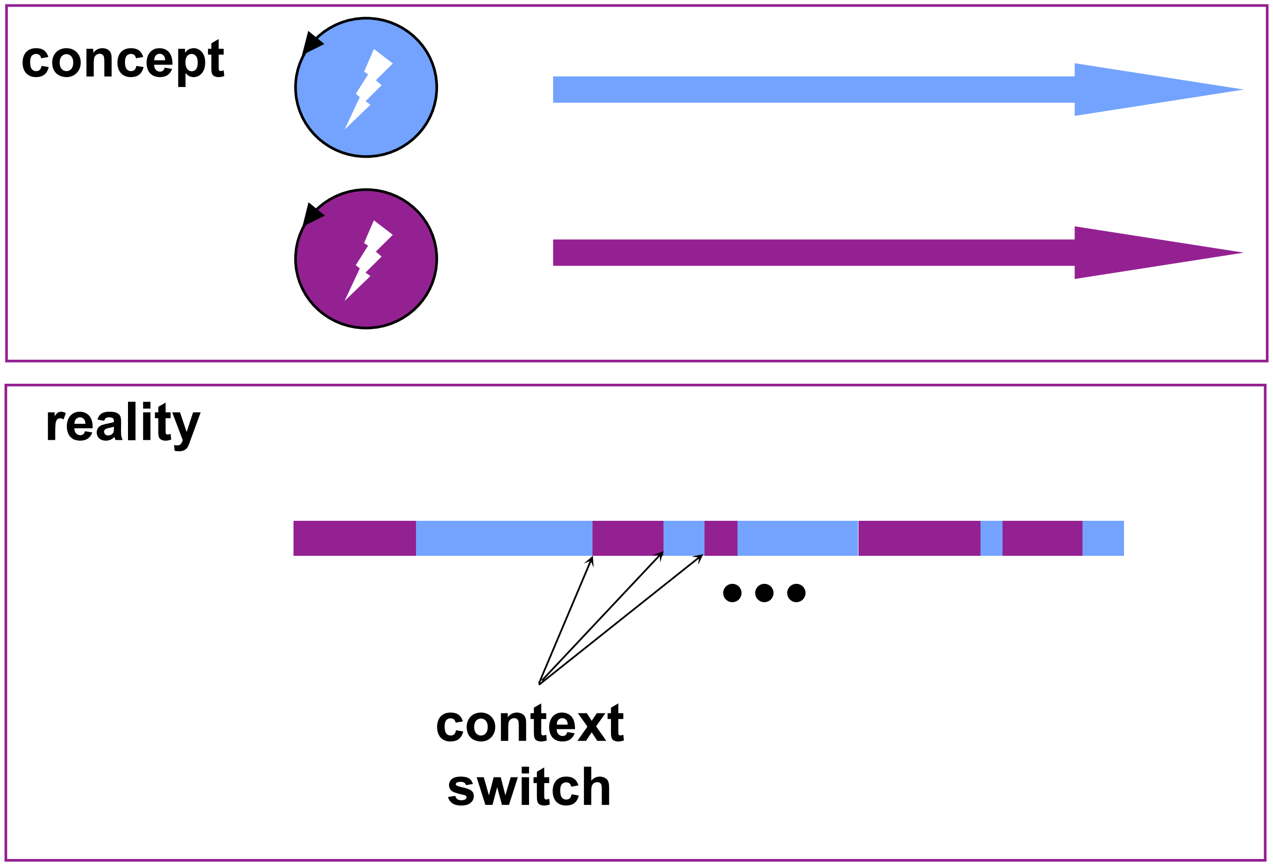
```
close(ifd[0]);
count = read(0, buf, 5);
count = write(ifd[1], buf, 5);
waitpid(cid, &status, 0);
printf("child %d exited…");
```

Child

```
close(0);
close(ifd[1]);
dup2(ifd[0],0);
close(ifd[0]);
execve(…);
```

```
chase$ man dup2
chase$ cc -o childin childin.c
chase$ ./childin cat5
12345
12345
5 bytes moved
child 23185 exited with status 0
chase$
```

Pipe reader and writer run concurrently



Context switch occurs when one process is forced to sleep because the pipe is full or empty, and maybe at other times.

Notes on pipes

- All the processes in a pipeline run **concurrently**. The order in which they run is not defined. They may execute at the same time on multiple cores. They do **NOT** execute in sequence (necessarily).
- Their execution is "synchronized by producer/consumer bounded buffer". (More about this next month.) It means that a writer blocks if there is no space to **write**, and a reader blocks if there are no bytes to **read**. Otherwise they may both run: they might not, but they could.
- They do **NOT** read all the input before passing it downstream.
- The **pipe** itself must be created by a common parent. The children inherit the pipe's file descriptors from the parent on **fork**. Unix has no other way to pass a file descriptor to another process.
- How does a reader "know" that it has read all the data coming to it through a pipe? **Answer**: there are no bytes in the pipe, and no process has the write side open. Then the **read** syscall returns EOF.

C1/C2 user pseudocode

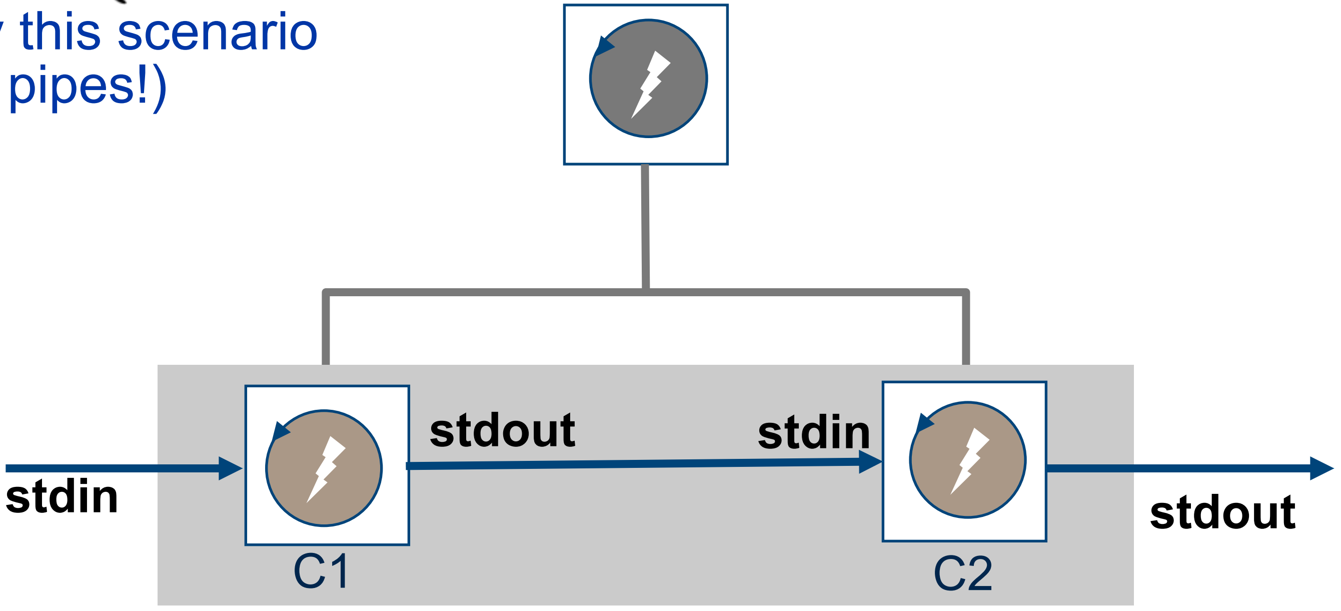
```
while(until EOF) {
    read(0, buf, count);
    compute/transform data in buf;
    write(1, buf, count);
}
```

Kernel pseudocode for pipes:
Producer/consumer bounded buffer

Pipe write: copy in bytes from user buffer to in-kernel pipe buffer, blocking if k-buffer is full.

Pipe read: copy bytes from pipe's k-buffer out to u-buffer. Block while k-buffer is empty, or return EOF if empty and pipe has no writer.

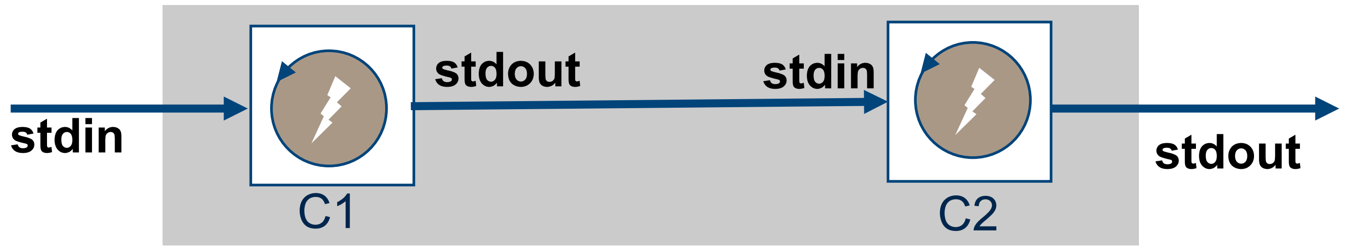
cat | cat
(Note: try this scenario to debug pipes!)



Pipes

Kernel-space pseudocode
System call internals to read/write N bytes for buffer size B.

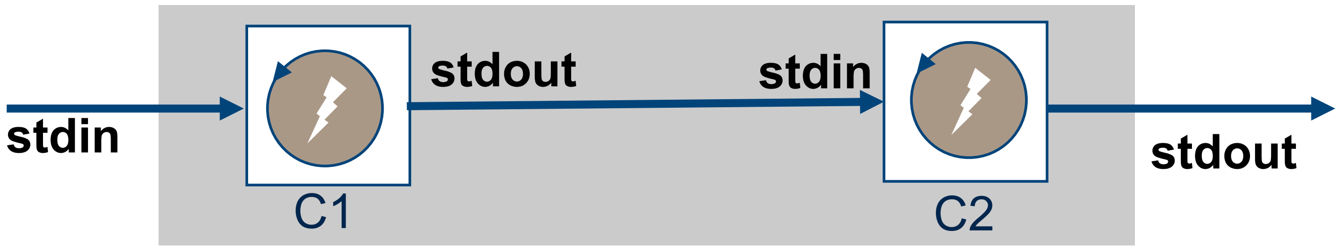
```
read(buf, N)
{
    for (i = 0; i++; i<N) {
        move one byte into buf[i];
    }
}
```



Pipes

```
read(buf, N)
{
    pipeMx.lock();
    for (i = 0; i++; i<N) {
        while (no bytes in pipe)
            dataCv.wait();
        move one byte from pipe into buf[i];
        spaceCV.signal();
    }
    pipeMx.unlock();
}
```

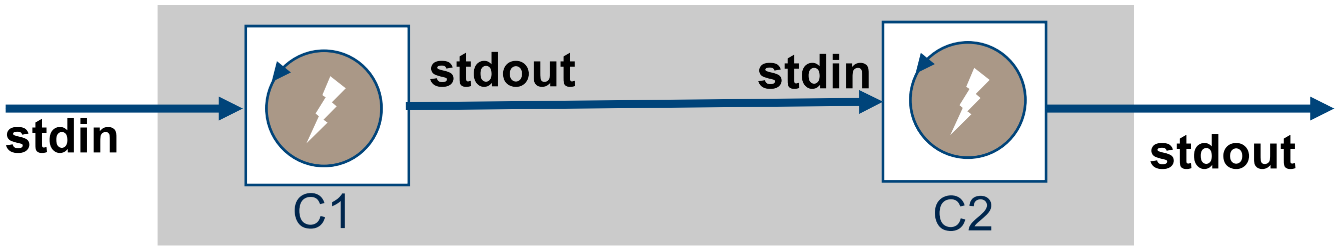
Read N bytes from the pipe into the user buffer named by **buf**. Think of this code as deep inside the implementation of the **read** system call on a pipe. The **write** implementation is similar.



Pipes

```
read(buf, N)
{
    readerMx.lock();
    pipeMx.lock();
    for (i = 0; i++; i<N) {
        while (no bytes in pipe)
            dataCv.wait();
        move one byte from pipe into buf[i];
        spaceCV.signal();
    }
    pipeMx.unlock();
    readerMx.unlock();
}
```

In Unix, the **read/write** system calls are "atomic" in the following sense: no **read** sees interleaved data from multiple **writes**. The extra lock here ensures that all read operations occur in a serial order, even if any given operation blocks/ waits while in progress.



Why exactly does Pipe (bounded buffer) require a nested lock?

First: remember that this is the exception that proves the rule. Nested locks are generally not *necessary*, although they may be useful for performance. Correctness first: always start with a single lock.

Second: the nested lock is not necessary even for Pipe if there is at most one reader and at most one writer, as would be the case for your typical garden-variety Unix pipe.

The issue is what happens if there are multiple readers and/or multiple writers. The nested lock is needed to meet a requirement that read/write calls are **atomic**. Understanding this requirement is half the battle.

Consider an example. Suppose three different writers {A, B, C} write 10 bytes each, each with a single write operation, and a reader reads 30 bytes with a single read operation. The read returns the 30 bytes, so the read will "see" data from multiple writes. That's OK. The atomicity requirement is that the reader does not observe bytes from different writes that are **interleaved** (mixed together).

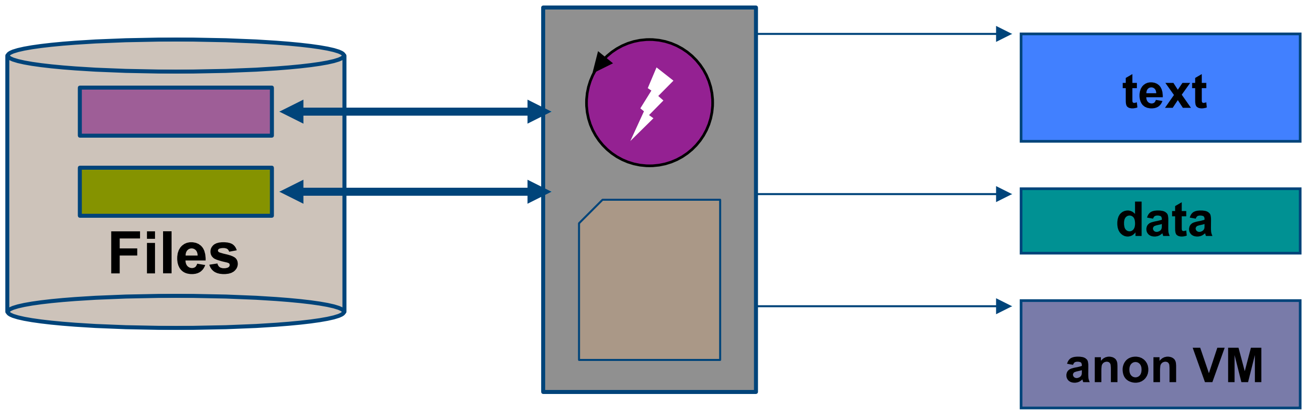
A necessary condition for atomicity is that the writes are **serialized**: the system chooses some order for the writes by A, B, and C, even if they request their writes "at the same time". The data returned by the read reflects this ordering. Under no circumstances does a read see an interleaving, e.g.: 5 bytes from A, then 5 bytes from B, then 5 more bytes from A,… (Note: if you think about it, you can see that a correct implementation must also serialize the reads.)

This atomicity requirement exists because applications may depend on it: e.g., if the writers are writing records to the pipe, then a violation of atomicity would cause a record to be "split".

This is particularly important when the size of a read or write (N) exceeds the size of the bounded buffer (B), i.e., N>B. A read or write with N>B is legal. But such an operation can't be satisfied with a single buffer's worth of data, so it can't be satisfied without alternating execution of a reader and a writer ("ping-pong style"). On a single core, the reader or writer is always forced to block at least once to wait for its counterparty to place more bytes in the buffer (if the operation is a read) or to drain more bytes out of the buffer (if the operation is a write). In this case, it is crucial to block any other readers or writers from starting a competing operation. Otherwise, atomicity is violated and at least one of the readers will observe an interleaving of data.

The nested lock ensures that at most one reader and at most one writer are moving data in the "inner loop" at any given time.

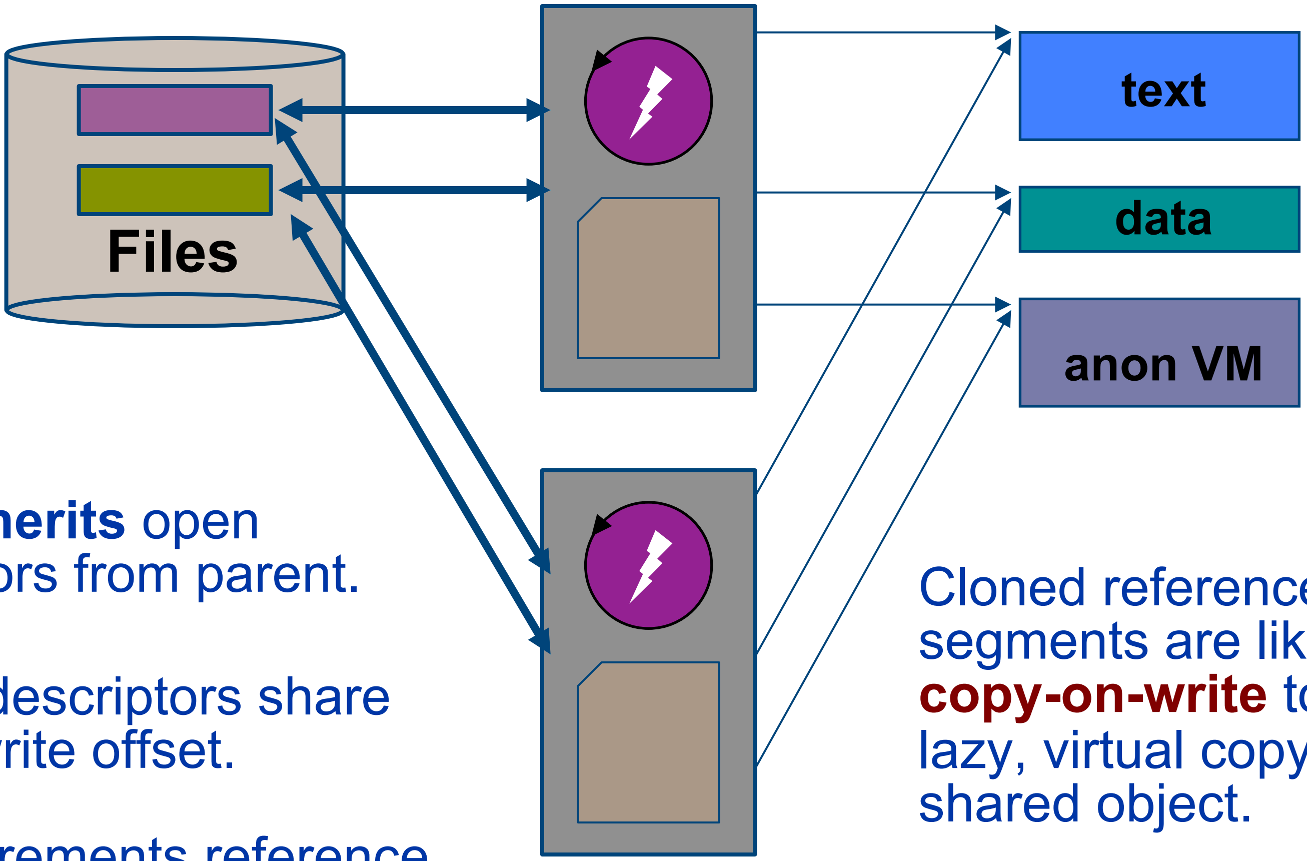
Processes reference objects



The kernel objects referenced by a process have **reference counts**. They may be destroyed after the last ref is released, but not before.

What operations release ref counts?

Fork clones all references



Child **inherits** open descriptors from parent.

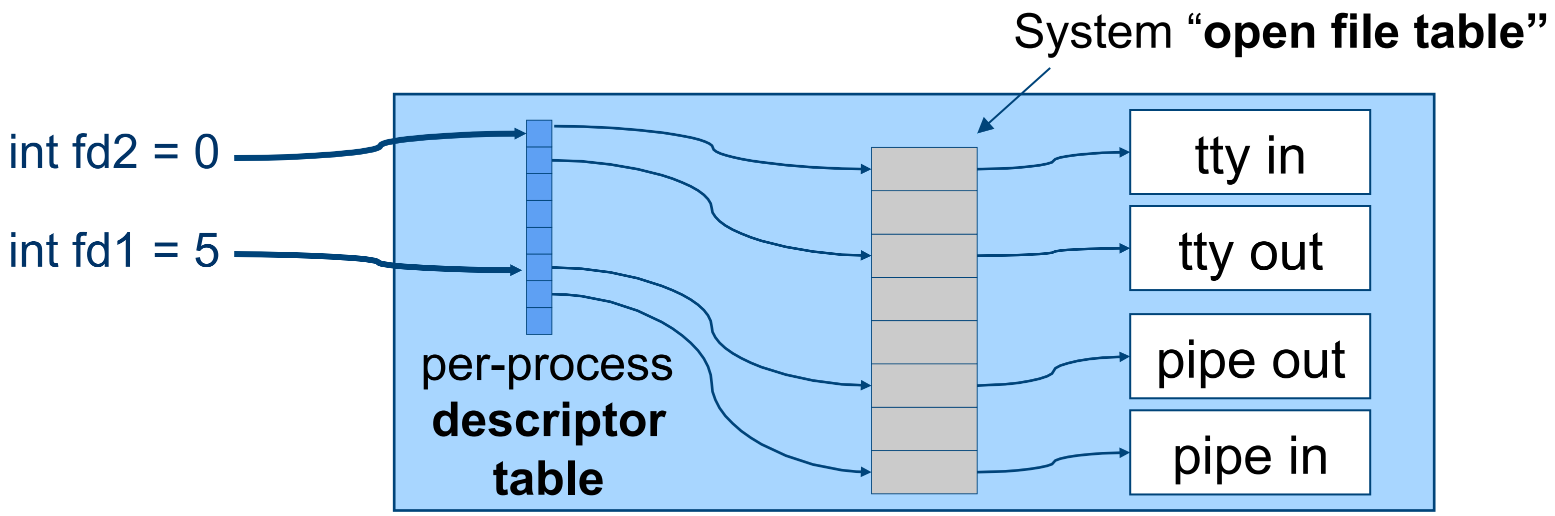
Cloned descriptors share a read/write offset.

Fork increments reference counts on shared objects.

Cloned references to VM segments are likely to be **copy-on-write** to create a lazy, virtual copy of the shared object.

What operations release ref counts?

Unix dup* syscall



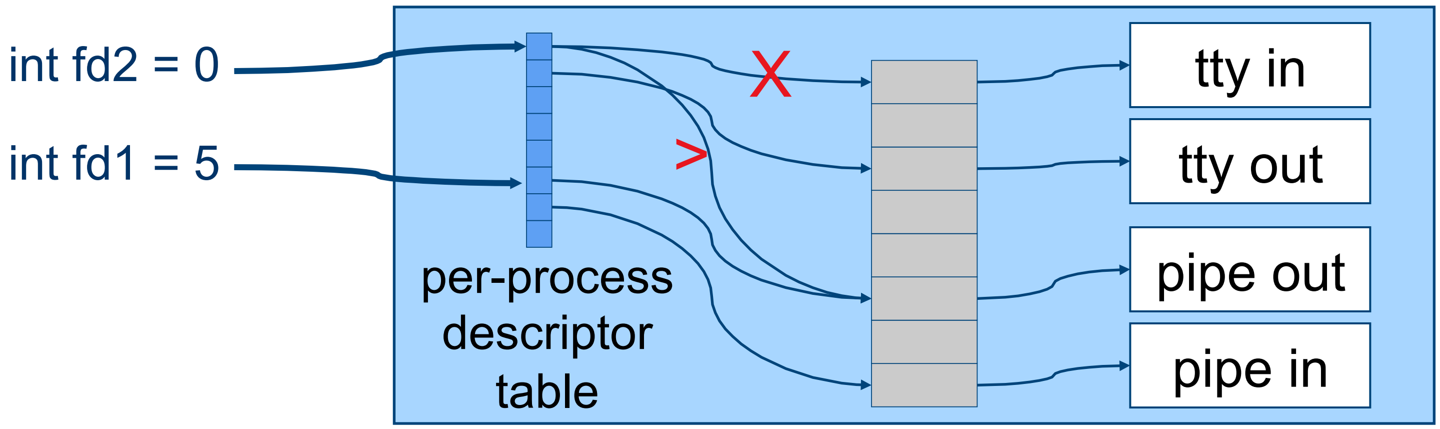
Hypothetical initial state before **dup2(fd1, fd2)** syscall.

dup2(old**fd1,** new**fd2)**. **What does it mean?**

Yes, fd1 and fd2 are integer variables. But let's use "fd" as shorthand for "the file descriptor whose number is the value of the variable fd".

Then fd1 and fd2 denote entries in the file **descriptor table** of the calling process. The **dup2** syscall is asking the kernel to operate on those entries in a kernel data structure. It doesn't affect the values in the variables fd1 and fd2 at all! And it doesn't affect the I/O objects themselves (e.g., the pipe) at all.

Unix dup* syscall



Final state after **dup2(fd1, fd2)** syscall.

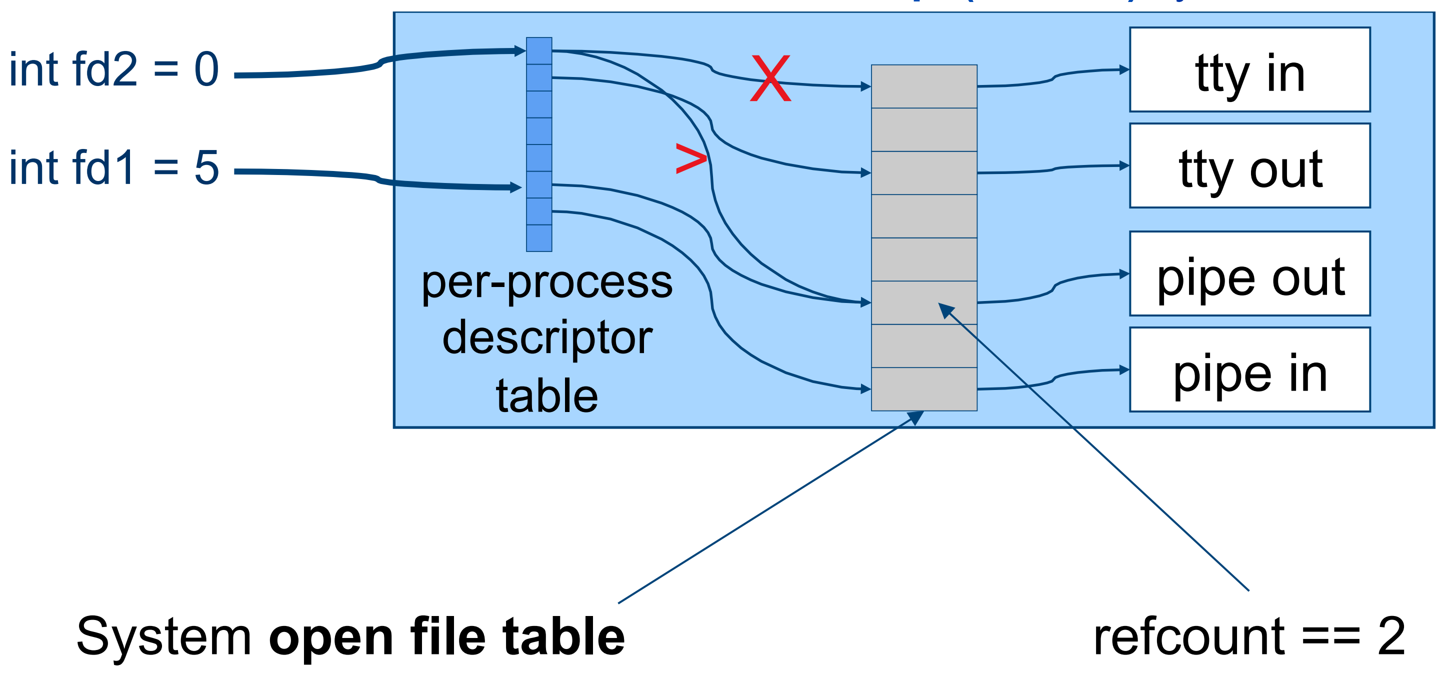
Then **dup2(**old**fd1,** new**fd2)** means: “close(fd2) (if it was open) then set fd2 to refer to the same underlying I/O object as fd1.”

It results in two file descriptors referencing the same underlying I/O object. You can use either of them to **read/write**: they are equivalent.

But you should probably just **close(fd1)**.

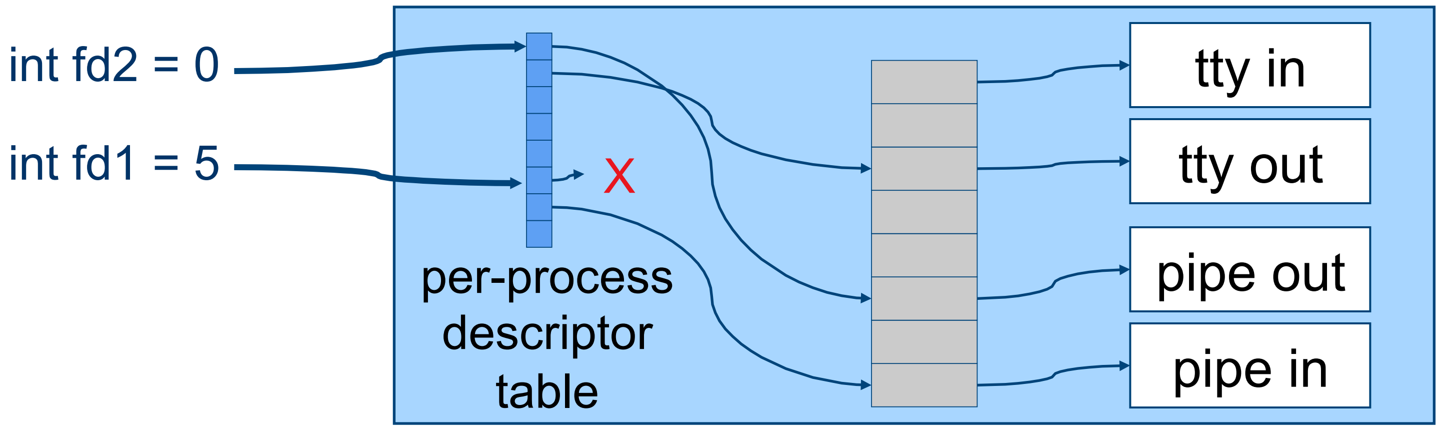
Unix dup* syscall

Final state after **dup2(fd1, fd2)** syscall.



Why should you close(fd1) after **dup2**(fd1, fd2)? Because the kernel uses **reference counting** to track open file descriptors. Resources associated with an I/O object are not released until all of the open descriptors on the object are closed. They are closed automatically on exit, but you should always close any descriptors that you don't need.

Unix dup* syscall



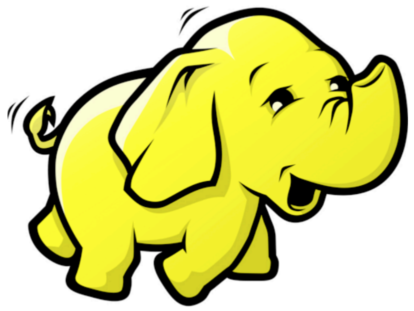
Final state after **dup2(fd1, fd2)** syscall.

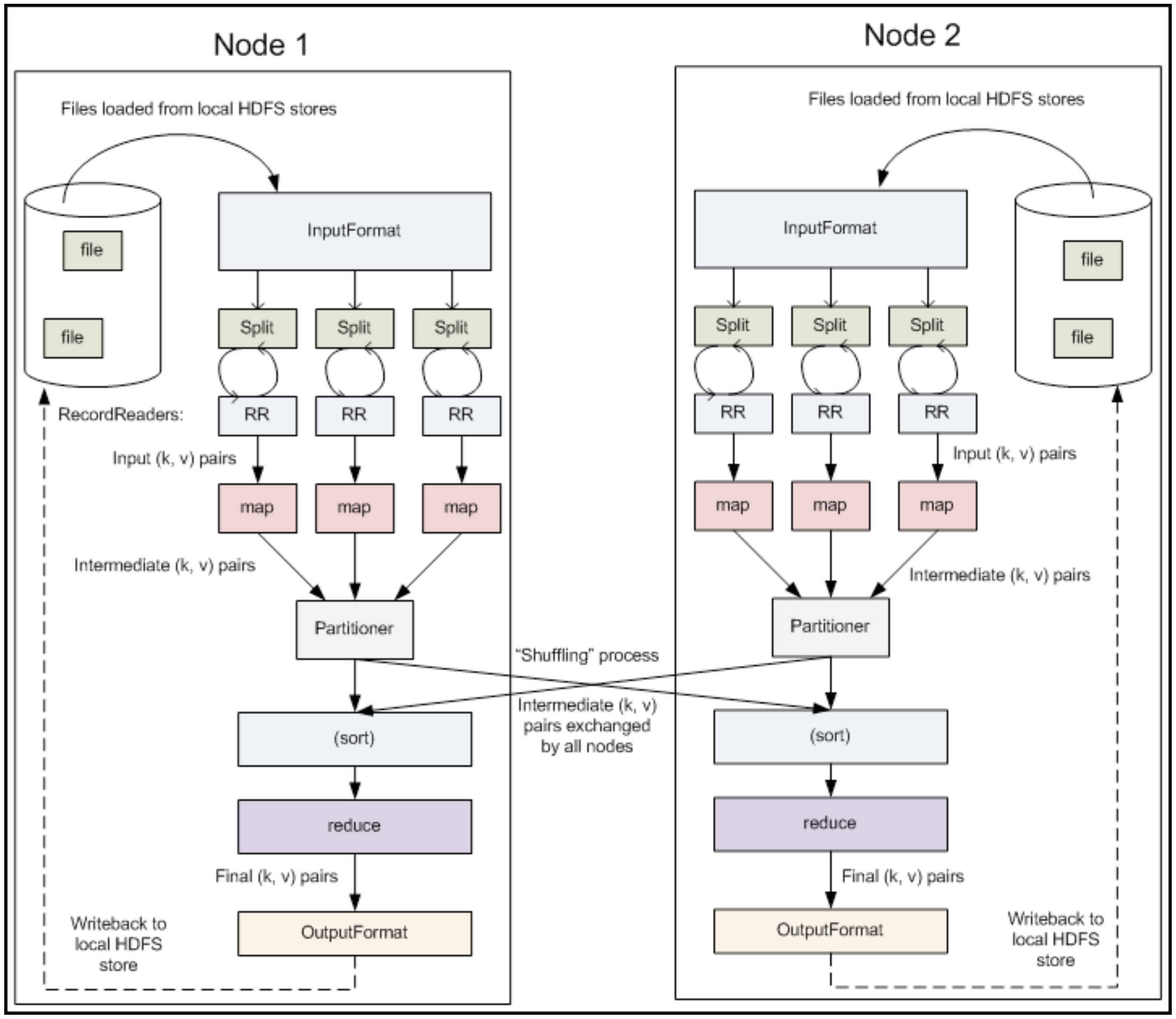
Then **dup2(fd1,fd2); close(fd1)** means: "remap the object referenced by file descriptor fd1 to fd2 instead".

It is convenient for remapping descriptors onto **stdin, stdout, stderr**, so that some program will use them "by default" after **exec***.

Note that we still have not changed the values in fd1 or fd2. Also, changing the values in fd1 and fd2 can never affect the state of the entries in the file descriptor table. Only the kernel can do that.

MapReduce/ Hadoop





Dataflow programming

MapReduce is a filter-and-pipe model for **data-intensive cluster computing**. Its programming model is "like" Unix pipes. It adds "parallel pipes" (my term) that split streams among multiple downstream children.

Unix: simple abstractions?

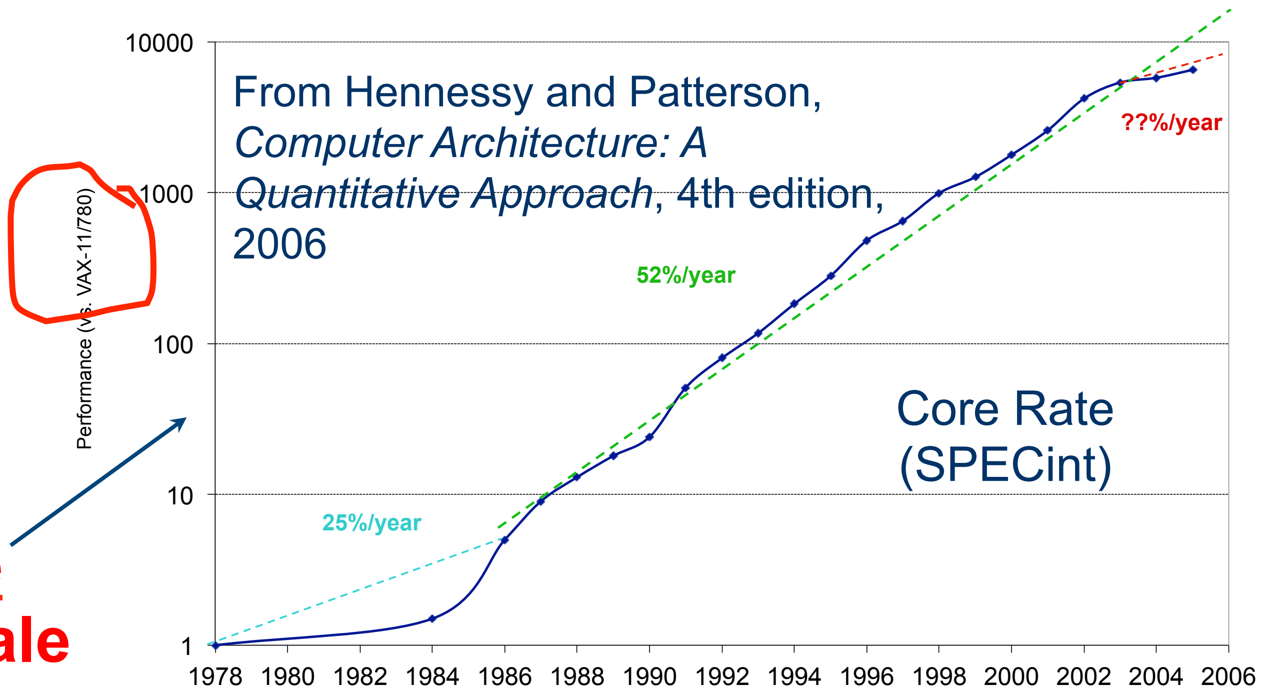
- users
- files
- processes
- pipes
  - which “look like” files

These persist across reboots. They have symbolic names (you choose it) and internal IDs (the system chooses).

These exist within a running system, and they are transient: they disappear on a crash or reboot. They have internal IDs.

Unix supports dynamic create/destroy of these objects.
It manages the various name spaces.
It has system calls to access these objects.
It checks permissions.

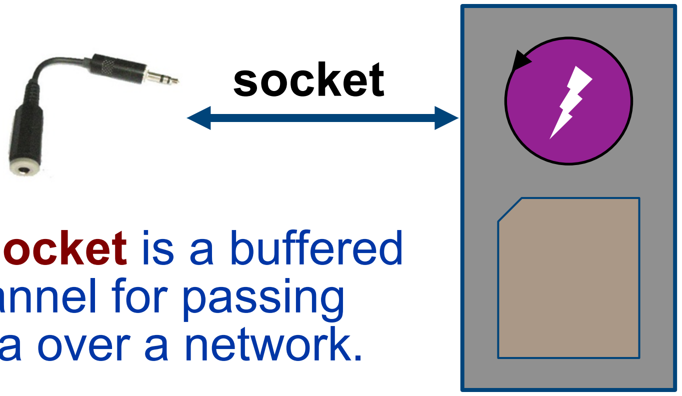
Let’s pause a moment to reflect...



Note log scale

Today Unix runs embedded in devices costing < $100.

Sockets



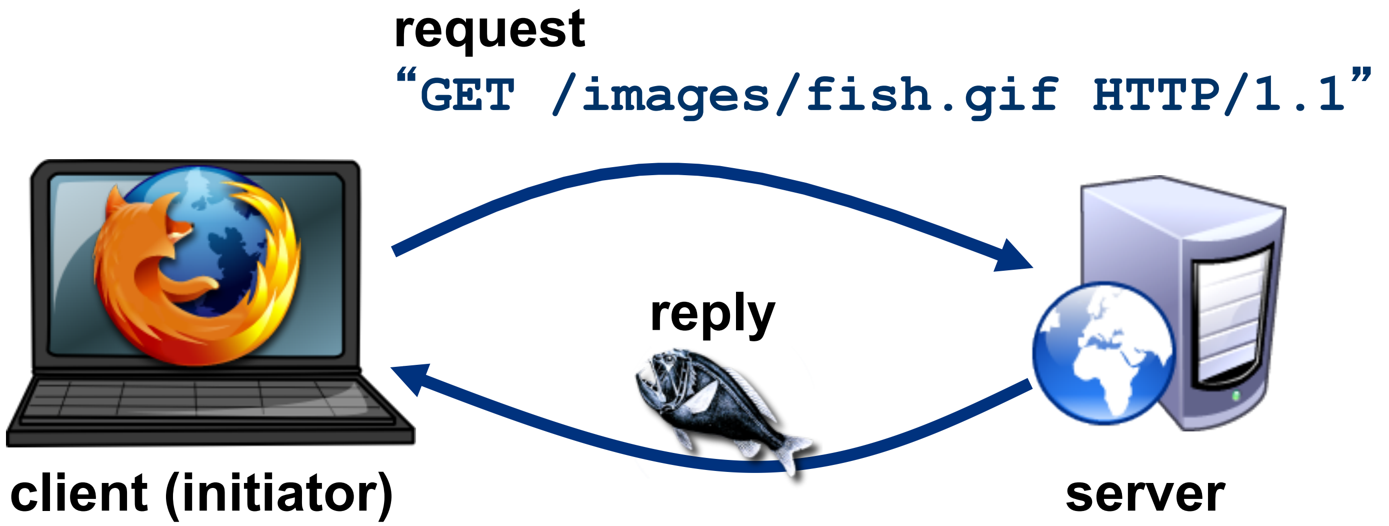
A **socket** is a buffered channel for passing data over a network.

client

```
int sd = socket(<internet stream>);
gethostbyname("www.cs.duke.edu");
<make a sockaddr_in struct>
<install host IP address and port>
connect(sd, <sockaddr_in>);
write(sd, "abcdefg", 7);
read(sd, ….);
```

- The **socket**() system call creates a **socket** object.
- Other socket syscalls establish a connection (e.g., **connect**).
- A file descriptor for a connected socket is **bidirectional**.
- Bytes placed in the socket with **write** are returned by **read** in order.
- The **read** syscall blocks if the socket is empty.
- The **write** syscall blocks if the socket is full.
- Both **read** and **write** fail if there is no valid connection.

A simple, familiar example



```
sd = socket(…);
connect(sd, name);
write(sd, request…);
read(sd, reply…);
close(sd);
```

```
s = socket(…);
bind(s, name);
sd = accept(s);
read(sd, request…);
write(sd, reply…);
close(sd);
```

catserver

```
    ...
    struct sockaddr_in socket_addr;
    sock = socket(PF_INET, SOCK_STREAM, 0);

    memset(&socket_addr, 0, sizeof socket_addr);
    socket_addr.sin_family = PF_INET;
    socket_addr.sin_port = htons(port);
    socket_addr.sin_addr.s_addr = htonl(INADDR_ANY);

    if (bind(sock, (struct sockaddr *) &socket_addr, sizeof socket_addr) < 0) {
        perror("bind failed");
        exit(1);
    }
    listen(sock, 10);

    while (1) {
        int acceptsock = accept(sock, NULL, NULL);
        forkme(acceptsock, prog, argv);
        close(acceptsock);
    }
}
```