Changelog

Changes made in this version not seen in first lecture:

6 September: fix stray @s on 'implementing file descriptors in xv6 slide'
6 September: typical pattern with redirection: hilite parts of code more sensibly
6 September: exec preserves open files: add slide
6 September: dup2 example: clarify comment, note overall purpose at top
6 September: read'ing one byte at a time: missing)
6 September: layering: annotate to indicate read/write are system calls, kernel buffers in layers, user buffers in layers

Unix API 2: files

last time

POSIX — standardized Unix

process control blocks

fork, exec, waitpid

post-quizzes

starting this week, post-quizzes

link off course website

same software as CS 3330

- box around question turns green: answer recorded

no time limits, due before Tuesday's class

released Friday morning

- or possibly earlier (e.g. Thursday evening)

shell

allow user (= person at keyborad) to run applications

user's wrapper around process-management functions

upcoming homework — make a simple shell

aside: shell forms

POSIX: command line you have used before

also: graphical shells

e.g. OS X Finder, Windows explorer

other types of command lines?

completely different interfaces?

some POSIX command-line features

searching for programs (not in assignment)

```
    ls -l ≈ /bin/ls -l
    make ≈ /usr/bin/make
```

running in background (not in assignment)

```
    ./someprogram &
```

redirection:

```
    ./someprogram >output.txt
    ./someprogram <input.txt
```

pipelines:

```
    ./someprogram | ./somefilter
```

some POSIX command-line features

searching for programs (not in assignment)

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    ./someprogram &
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```

searching for programs

POSIX convention: PATH environment variable

- example: `/home/cr4bd/bin:/usr/bin:/bin`
- checked in order

one way to implement: [pseudocode]

```
for (directory in path) {
    execv(directory + "/" + program_name, argv);
}
```

some POSIX command-line features

searching for programs (not in assignment)

```
ls -l ≈ /bin/ls -l
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running in background (not in assignment)

```
./someprogram &
```

redirection:

```
./someprogram >output.txt
./someprogram <input.txt
```

pipelines:

```
./someprogram | ./somefilter
```

running in background

```
$ ./long_computation >tmp.txt &
[1] 4049
$ ...
[1]+    Done        ./long_computation > tmp.txt
$ cat tmp.txt
the result is ...
```

& — run a program in “background”

initially output PID (above: 4049)

print out after terminated

- one way: use `waitpid` with option saying “don’t wait”

some POSIX command-line features

searching for programs (not in assignment)

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    ls -l ≈ /bin/ls -l
    make ≈ /usr/bin/make
```

running in background (not in assignment)

```
    ./someprogram &
```

redirection:

```
    ./someprogram >output.txt
    ./someprogram <input.txt
```

pipelines:

```
    ./someprogram | ./somefilter
```

shell redirection

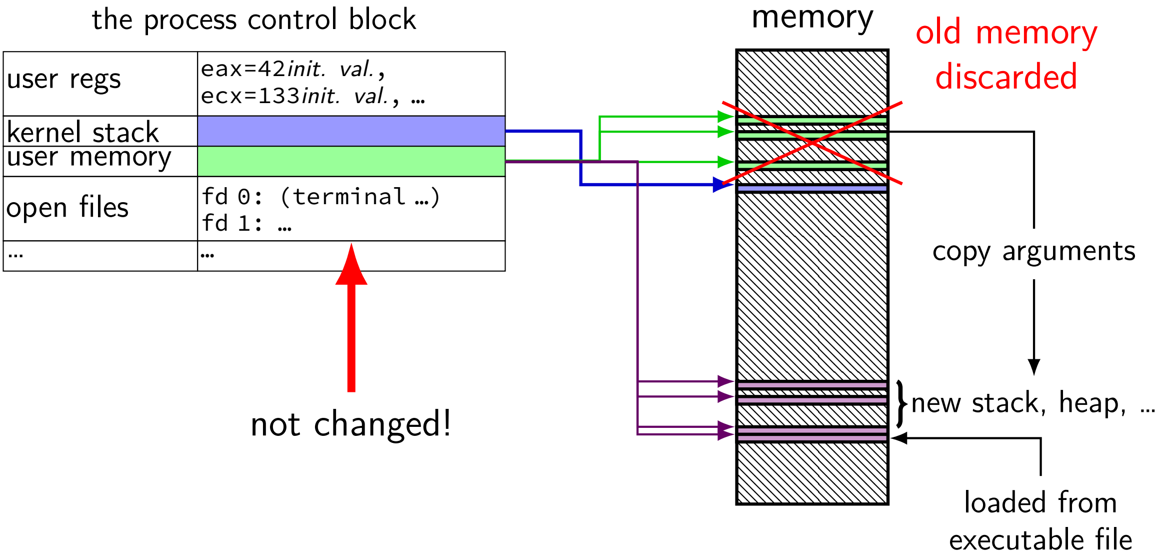
`./my_program ... <input.txt`:

- run `./my_program ...` but use `input.txt` as input
- like we copied and pasted the file into the terminal

`echo foo >output.txt`:

- runs `echo foo`, sends output to `output.txt`
- like we copied and pasted the output into that file (as it was written)

exec preserves open files



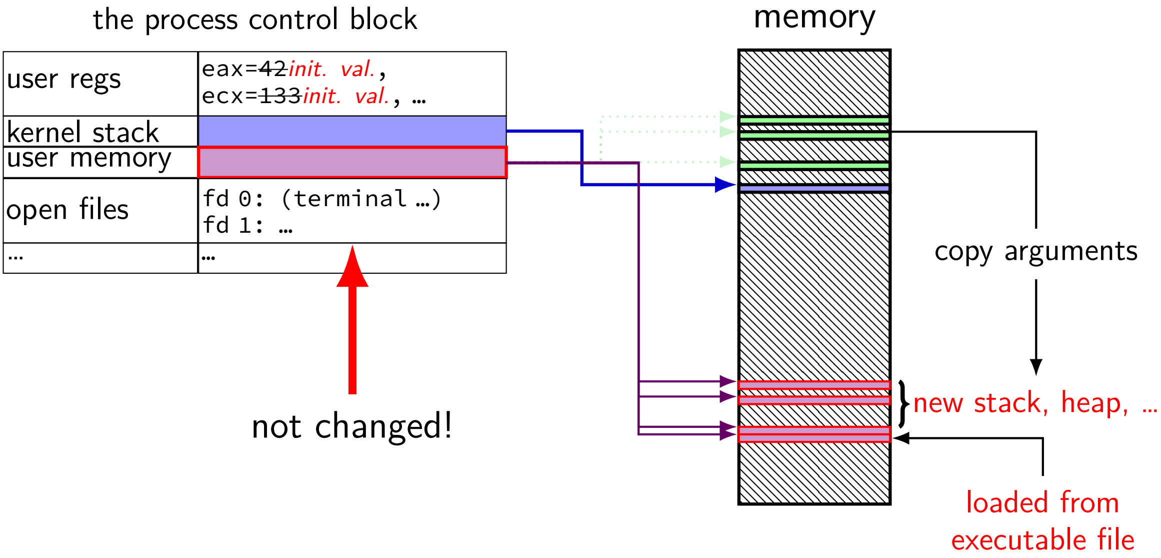
the process control block

user regs	eax=42*init. val.*,
	ecx=133*init. val.*, …

kernel stack	
user memory	
open files	fd 0: (terminal …) fd 1: …
…	…

not changed!

exec preserves open files



the process control block

user regs	eax=~~42~~*init. val.*,
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…	…

not changed!

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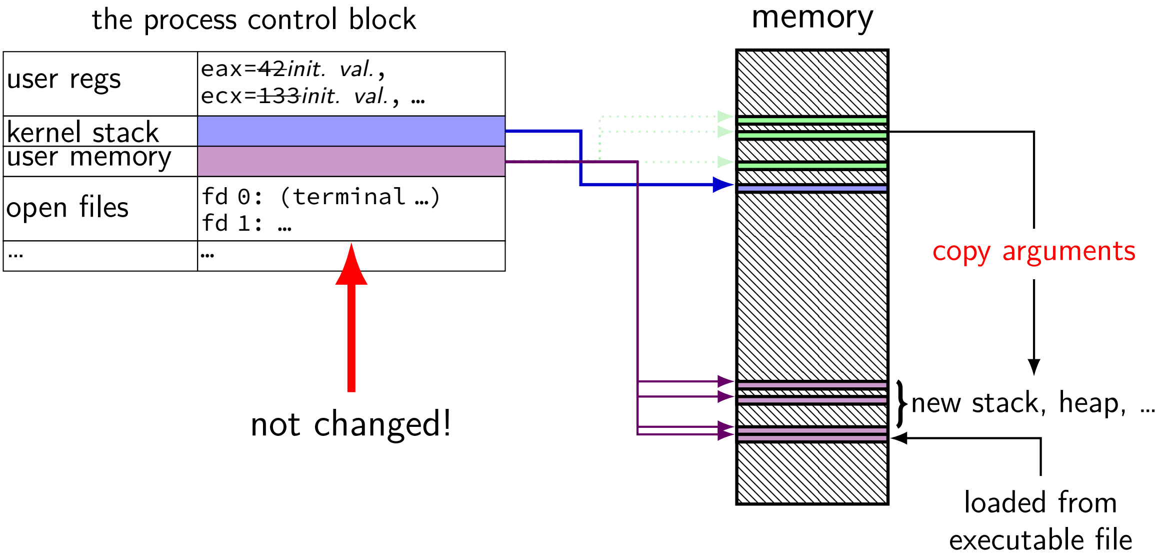


the process control block

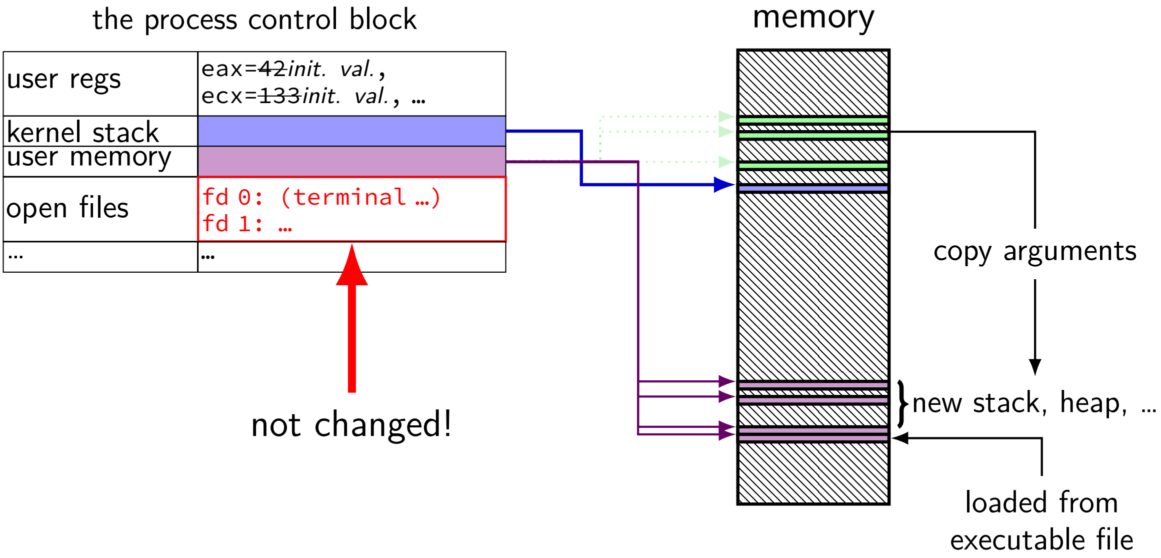
user regs	eax=~~42~~*init. val.*,
	ecx=~~133~~*init. val.*, …

kernel stack	
user memory	

open files	`fd 0: (terminal …)`
	`fd 1: …`

…	…

exec preserves open files



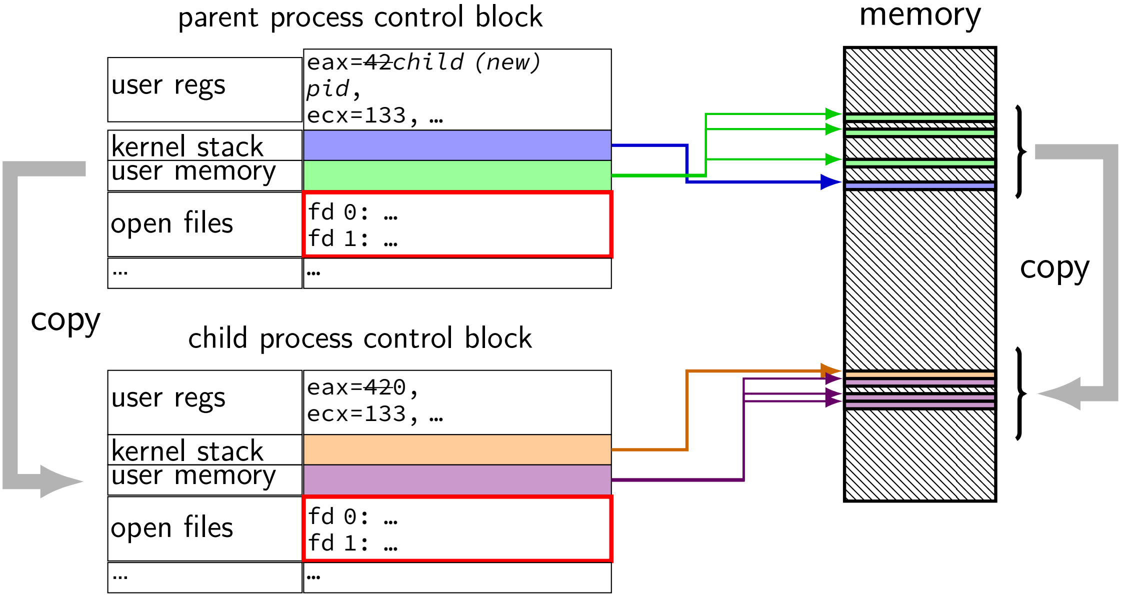
the process control block

user regs	eax=~~42~~*init. val.*,
	ecx=~~133~~*init. val.*, …

kernel stack	
user memory	
open files	fd 0: (terminal …) fd 1: …
…	…

not changed!

fork copies open files



parent process control block

user regs	eax=~~42~~*child (new) pid*, ecx=133, …
kernel stack	
user memory	
open files	fd 0: … fd 1: …
…	…

memory

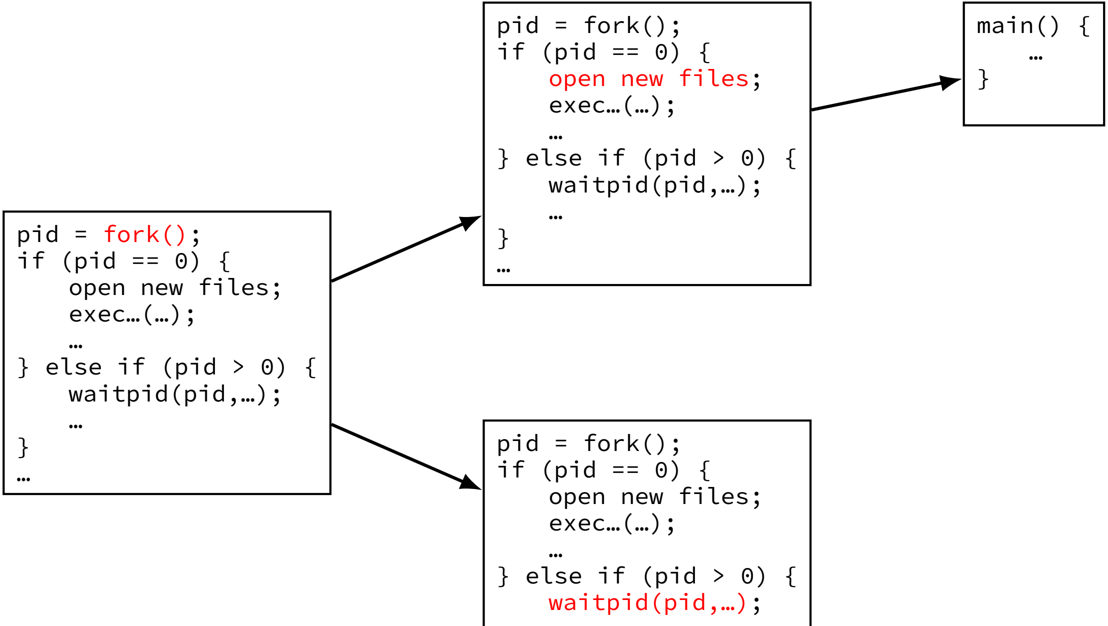
copy

copy

child process control block

user regs	eax=~~42~~0, ecx=133, …
kernel stack	
user memory	
open files	fd 0: … fd 1: …
…	…

typical pattern with redirection



```
pid = fork();
if (pid == 0) {
    open new files;
    exec…(…);
    …
} else if (pid > 0) {
    waitpid(pid,…);
    …
}
…
```

```
pid = fork();
if (pid == 0) {
    open new files;
    exec…(…);
    …
} else if (pid > 0) {
    waitpid(pid,…);
    …
}
…
```

```
main() {
    …
}
```

```
pid = fork();
if (pid == 0) {
    open new files;
    exec…(…);
    …
} else if (pid > 0) {
    waitpid(pid,…);
```

redirecting with exec

std output, std error are files

- yes, your terminal is a file
- more on this later

after forking, open files to redirect

...and make them be standard output/error

missing pieces:

- how open files becomes default output/input

some POSIX command-line features

searching for programs (not in assignment)

```
    ls -l ≈ /bin/ls -l
    make ≈ /usr/bin/make
```

running in background (not in assignment)

```
    ./someprogram &
```

redirection:

```
    ./someprogram >output.txt
    ./someprogram <input.txt
```

pipelines:

```
    ./someprogram | ./somefilter
```

shell assignment

implement a simple shell that supports redirection and pipeline

...and prints the exit code of program in the pipeline

simplified parsing: space-seperated:

okay: `/bin/ls␣-1␣>␣tmp.txt`
not okay: `/bin/ls␣-l␣>tmp.txt`
okay: `/bin/ls␣-1␣|␣/bin/grep␣foo␣>␣tmp.txt`
not okay: `/bin/ls␣-1␣|/bin/grep␣foo␣>tmp.txt`

POSIX: everything is a file

the file: one interface for

- devices (terminals, printers, …)
- regular files on disk
- networking (sockets)
- local interprocess communication (pipes, sockets)

basic operations: open(), read(), write(), close()

the file interface

open before use

- setup, access control happens here

byte-oriented

- real device isn't? operating system needs to hide that

explicit close

the file interface

open before use

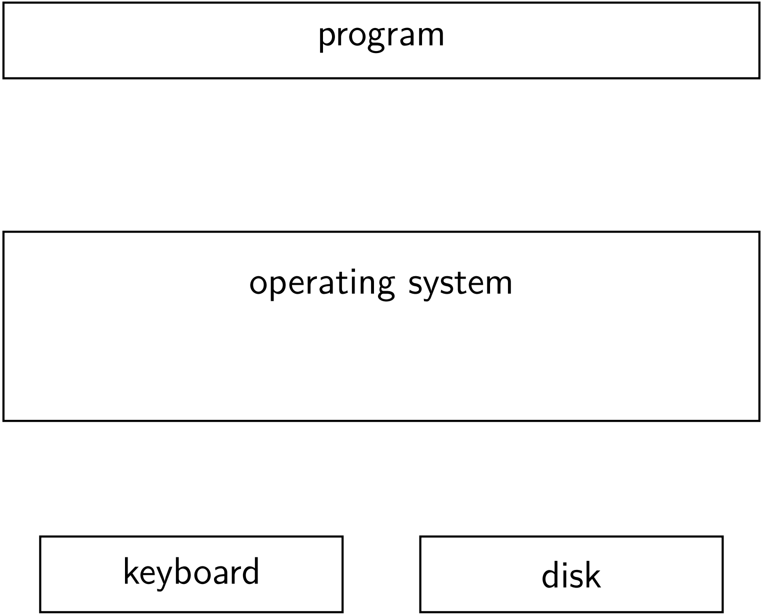
setup, access control happens here

byte-oriented

real device isn't? operating system needs to hide that

explicit close

kernel buffering (reads)



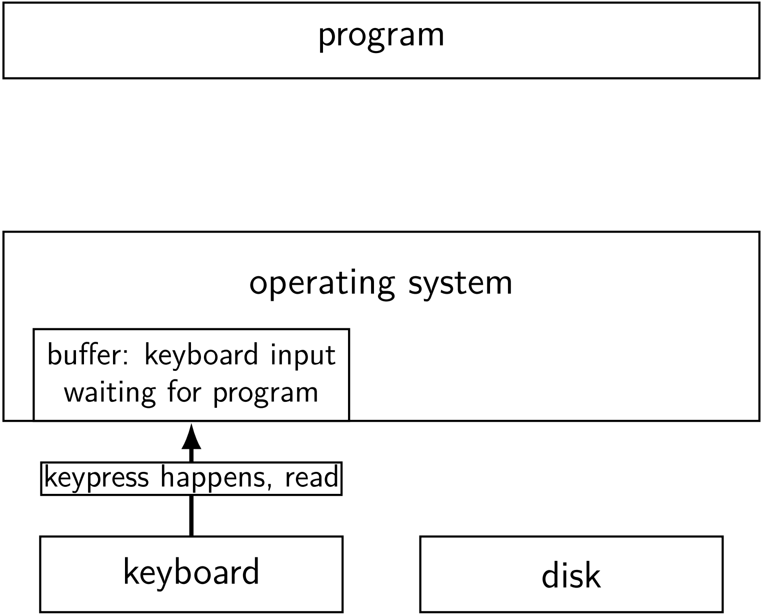
program

operating system

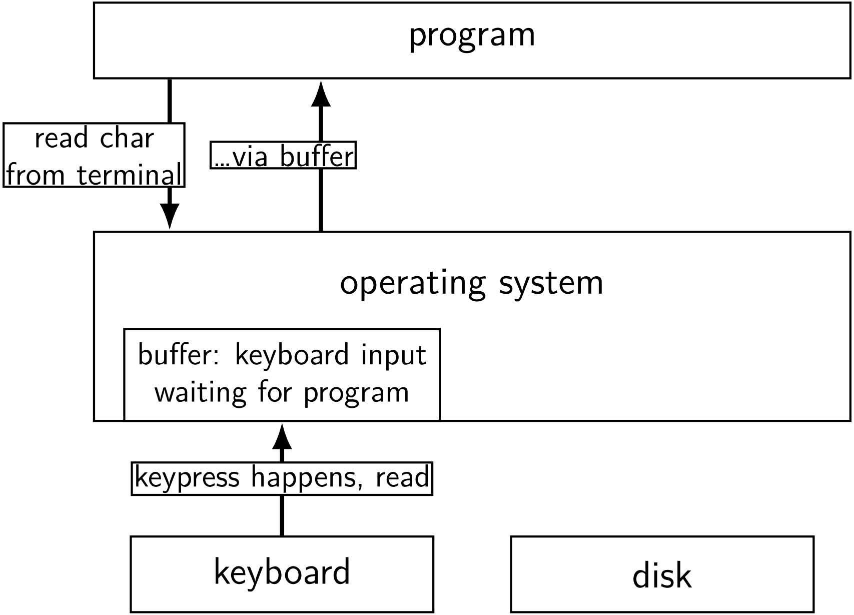
keyboard

disk

kernel buffering (reads)



kernel buffering (reads)



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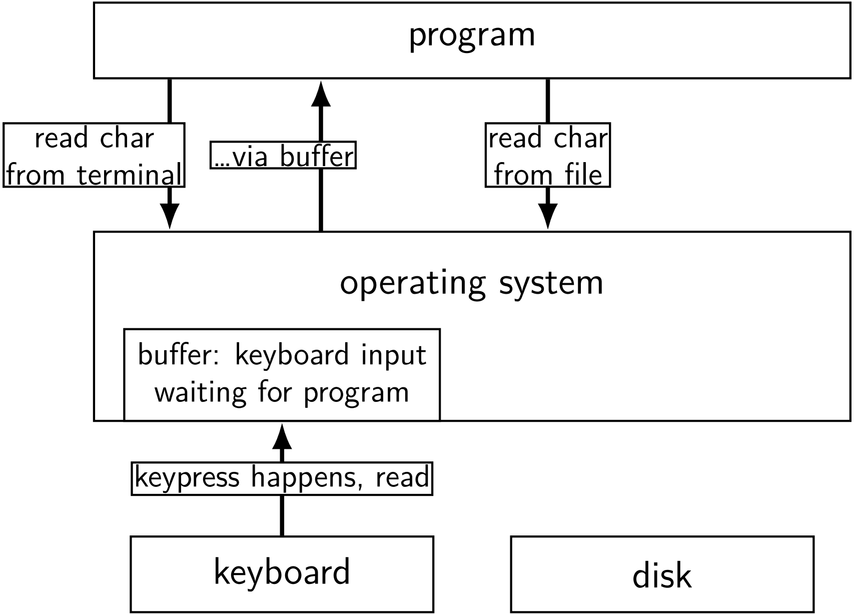
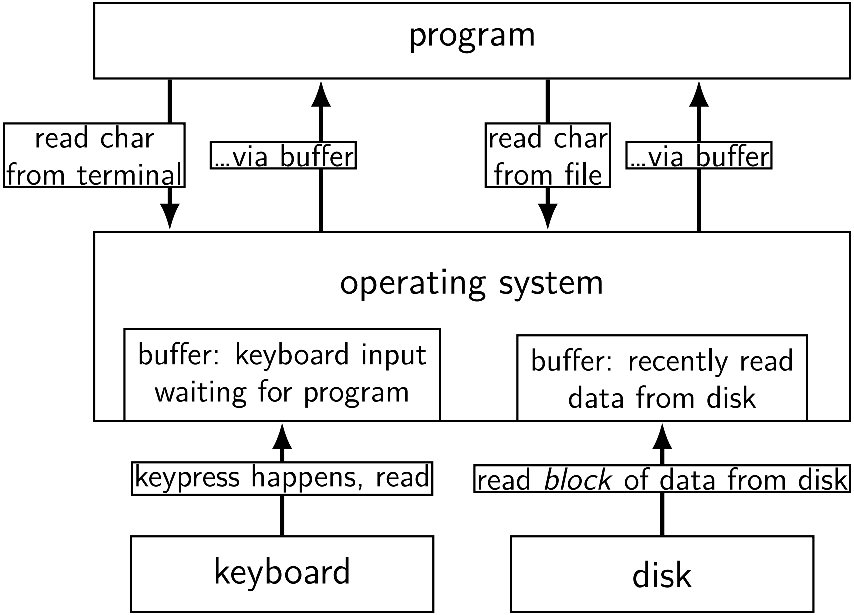
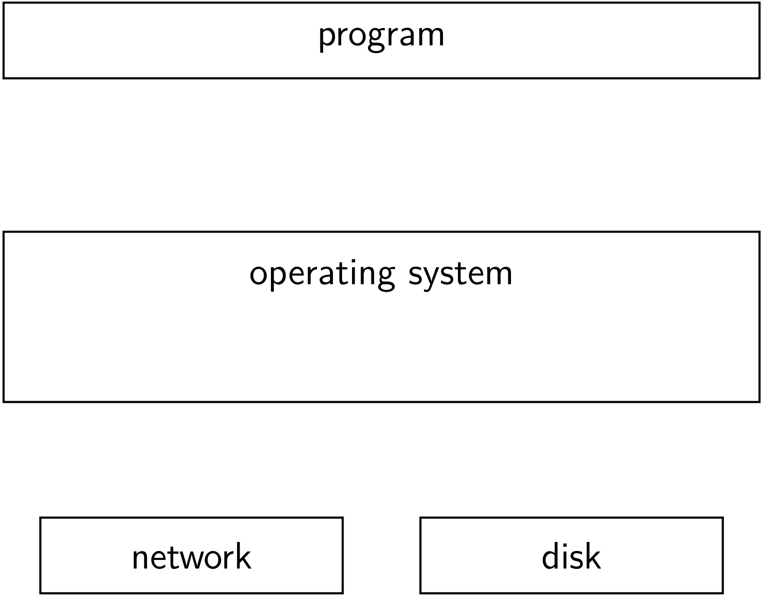


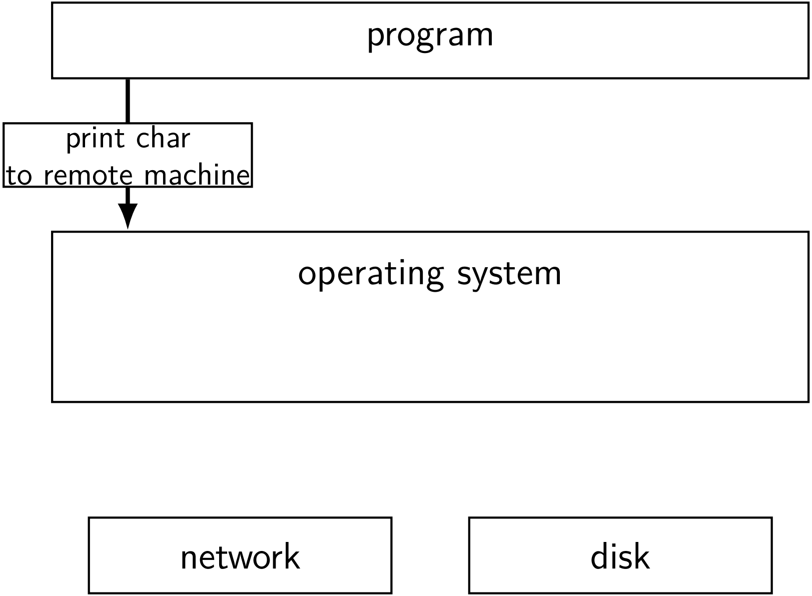
kernel buffering (reads)



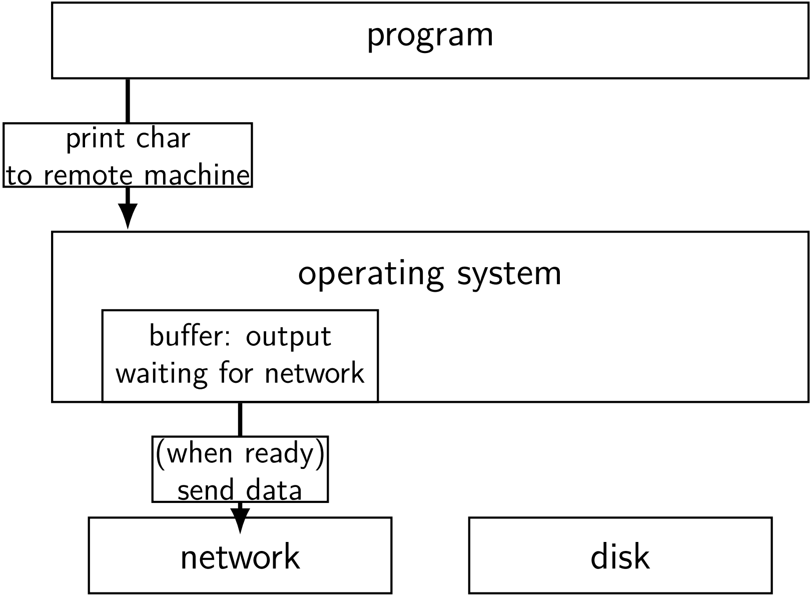
kernel buffering (writes)



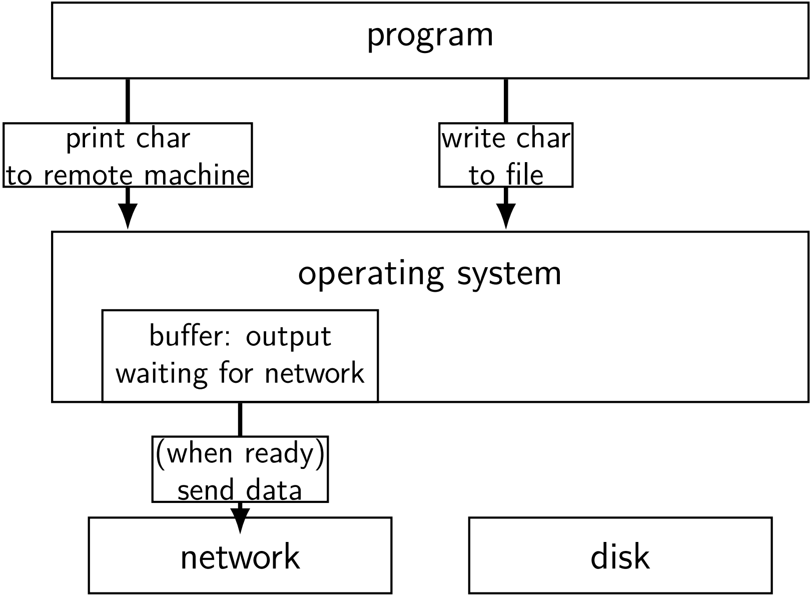
kernel buffering (writes)



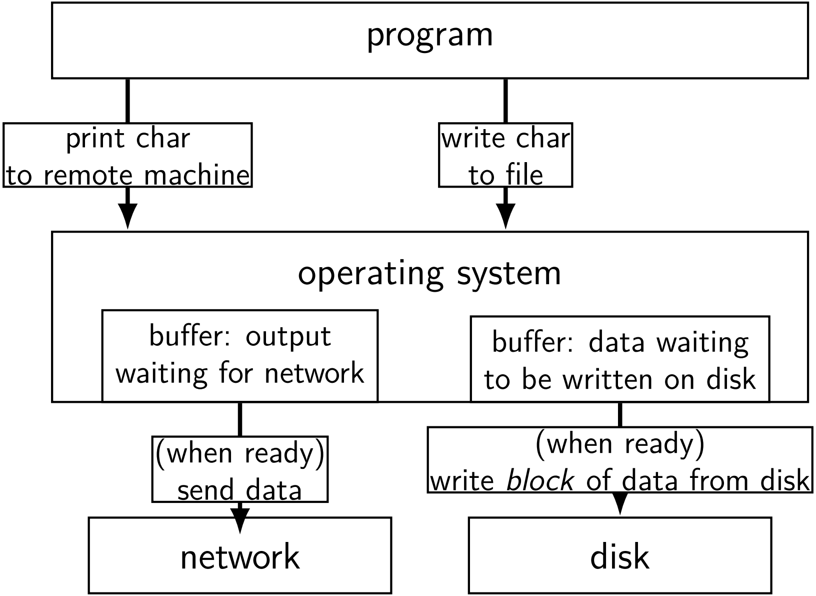
kernel buffering (writes)



kernel buffering (writes)



kernel buffering (writes)



read/write operations

read/write: move data into/out of buffer

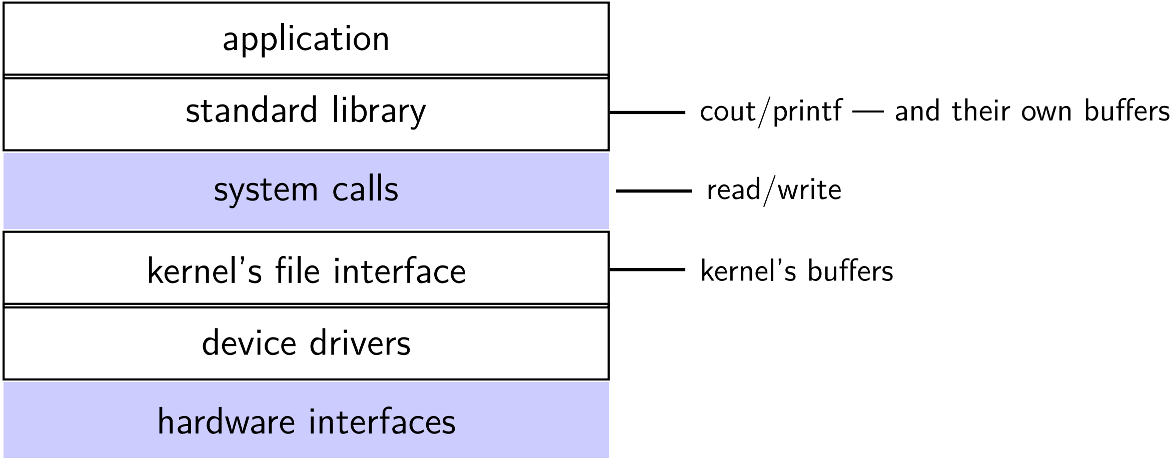
block (make process wait) if buffer is empty (read)/full (write)

- (default behavior, possibly changeable)

actual I/O operations — wait for device to be ready

- trigger process to stop waiting if needed

layering


application
standard library
system calls
kernel's file interface
device drivers
hardware interfaces
cout/printf — and their own buffers
read/write
kernel's buffers

filesystem abstraction

regular files — named collection of bytes

- also: size, modification time, owner, access control info, …

directories — folders containing files and directories

- hierarchical naming: `/net/zf14/cr4bd/fall2018/cs4414`
- *mostly* contains regular files or directories

open

```
int open(const char *path, int flags);
int open(const char *path, int flags, int mode);
...

int read_fd = open("dir/file1", O_RDONLY);
int write_fd = open("/other/file2",
        O_WRONLY | O_CREAT | O_TRUNC, 0666);
int rdwr_fd = open("file3", O_RDWR);
```

open

```
int open(const char *path, int flags);
int open(const char *path, int flags, int mode);
```

path = filename

e.g. `"/foo/bar/file.txt"`
`file.txt` in
directory `bar` in
directory `foo` in
"the root directory"

e.g. `"quux/other.txt`
`other.txt` in
directory `quux` in
"the current working directory" (set with `chdir()`)

open: file descriptors

```
int open(const char *path, int flags);
int open(const char *path, int flags, int mode);
```

return value = file descriptor (or -1 on error)

index into table of *open file descriptions* for each process

used by system calls that deal with open files

implementing file descriptors in xv6 (1)

```
struct proc {
  ...
  struct file *ofile[NOFILE];  // Open files
};
```

`ofile[0]` = file descriptor `0`

pointer — *can be shared between proceses*

  not part of deep copy fork does

null pointers — no file open with that number

implementing file descriptors in xv6 (2)

```
struct file {
  enum { FD_NONE, FD_PIPE, FD_INODE } type;
  int ref; // reference count
  char readable;
  char writable;
  struct pipe *pipe;
  struct inode *ip;
  uint off;
};
```

implementing file descriptors in xv6 (2)

```
struct file {
  enum { FD_NONE, FD_PIPE, FD_INODE } type;
  int ref; // reference count
  char readable;
  char writable;
  struct pipe *pipe;
  struct inode *ip;
  uint off;
};
```

FD_PIPE = to talk to other process
FD_INODE = other kind of file

alternate designs:

- class + subclass per type
- pointer to list of functions (Linux soln.)

implementing file descriptors in xv6 (2)

```
struct file {
  enum { FD_NONE, FD_PIPE, FD_INODE } type;
  int ref; // reference count
  char readable;
  char writable;
  struct pipe *pipe
  struct inode *ip;
  uint off;
};
```

number of pointers to this struct file

used to safely delete this struct

needs kept up-to-date (example: on `fork`)

implementing file descriptors in xv6 (2)

```
struct file {
  enum { FD_NONE, FD_PIPE, FD_INODE } type;
  int ref; // reference count
  char readable;
  char writable;
  struct pipe *pipe;
  struct inode *ip;
  uint off;
};
```

should read/write be allowed?
based on flags to open

implementing file descriptors in xv6 (2)

```
struct file {
  enum { FD_NONE, FD_PIPE, FD_INODE } type;
  int ref; // reference count
  char readable;
  char writable;
  struct pipe *pipe;
  struct inode *ip;
  uint off;
};
```

`off` = location in file
(not meaningful for all files)

special file descriptors

file descriptor 0 = standard input

file descriptor 1 = standard output

file descriptor 2 = standard error

constants in `unistd.h`

`STDIN_FILENO`, `STDOUT_FILENO`, `STDERR_FILENO`

special file descriptors

file descriptor 0 = standard input

file descriptor 1 = standard output

file descriptor 2 = standard error

constants in `unistd.h`

- `STDIN_FILENO`, `STDOUT_FILENO`, `STDERR_FILENO`

but you can't choose which number `open` assigns...?

- more on this later

open: flags

```
int open(const char *path, int flags);
int open(const char *path, int flags, int mode);
```

flags: bitwise or of:

- `O_RDWR`, `O_RDONLY`, or `O_WRONLY`
  - read/write, read-only, write-only
- `O_APPEND`
  - append to end of file
- `O_TRUNC`
  - truncate (set length to 0) file if it already exists
- `O_CREAT`
  - create a new file if one doesn't exist
  - (default: file must already exist)
- `O_EXCL`
  - fail if file already exists (be first to create it)

```
man 2 open
```

open: mode

```
int open(const char *path, int flags);
int open(const char *path, int flags, int mode);
```

mode: permissions of newly created file

- like numbers provided to `chmod` command
- filtered by a “umask”

simple advice: always use `0666`

- = readable/writeable by everyone, except where umask prohibits
- (typical umask: prohibit other/group writing)

read/write

```
ssize_t read(int fd, void *buffer, size_t count);
ssize_t write(int fd, void *buffer, size_t count);
```

read/write up to *count* bytes to/from *buffer*

returns number of bytes read/written or -1 on error

- ssize_t is a signed integer type
- error code in `errno`

read returning 0 means end-of-file (*not an error*)

- can read/write less than requested (end of file, broken I/O device, …)

read'ing one byte at a time

```
string s;
ssize_t amount_read;
char c;
while ((amount_read = read(STDIN_FILENO, &c, 1)) > 0) {
    /* amount_read must be exactly 1 */
    s += c;
}
if (amount_read == -1) {
    /* some error happened */
    perror("read"); /* print out a message about it */
} else if (amount_read == 0) {
    /* reached end of file */
}
```

read/write

```
ssize_t read(int fd, void *buffer, size_t count);
ssize_t write(int fd, void *buffer, size_t count);
```

read/write up to *count* bytes to/from *buffer*

returns number of bytes read/written or -1 on error

- ssize_t is a signed integer type
- error code in `errno`

read returning 0 means end-of-file (*not an error*)

- can read/write less than requested (end of file, broken I/O device, ...)

read'ing a fixed amount

```c
ssize_t offset = 0;
const ssize_t amount_to_read = 1024;
char result[amount_to_read];
do {
    /* cast to void * optional in C */
    ssize_t amount_read =
        read(STDIN_FILENO,
             (void *) (result + offset),
             amount_to_read - offset);
    if (amount_read < 0) {
        perror("read"); /* print error message */
        ... /* abort??? */
    } else {
        offset += amount_read;
    }
} while (offset != amount_to_read);
```

partial reads

on regular file: read reads what you request

but otherwise: gives you what's known to be available

partial reads

on regular file: read reads what you request

but otherwise: gives you what's known to be available

reading from network — what's been received

reading from keyboard — what's been typed

write example

```
/* cast to void * optional in C */
write(STDOUT_FILENO, (void *) "Hello,␣World!\n", 14);
```

write example (with error checking)

```
const char *ptr = "Hello,␣World!\n";
ssize_t remaining = 14;
while (remaining > 0) {
    /* cast to void * optional in C */
    ssize_t amount_written = write(STDOUT_FILENO,
                                   ptr,
                                   remaining);
    if (amount_written < 0) {
        perror("write"); /* print error message */
        ... /* abort??? */
    } else {
        remaining -= amount_written;
        ptr += amount_written;
    }
}
```

partial writes

usually only happen on error or interruption

- or if used another call to request “non-blocking”
- (interruption: via *signal*)

more typical: write waits until it completes

- until remaining part fits in buffer in kernel?

close

```
int close(int fd);
```

close the file descriptor, deallocating that array index

- does not affect other file descriptors that refer to same "open file description"
  (e.g. in `fork()`ed child)

returns 0 on success, -1 on error (e.g. ran out of disk space while trying to save file)

stdio and iostreams

what about `cout`, `printf`, etc.?

...implemented in terms of `read`, `write`, `open`, `close`

adds buffering in the process — faster

- read/write typically system calls
- running system call for approx. each character is slow!
- *in addition* to buffering that occurs in the kernel

more convenient

- formatted I/O, partial reads/writes handled by library, etc.

more portable

- stdio.h and iostreams defined by the C and C++ standards

mixing stdio/iostream and raw read/write

don't do it (unless you're very careful)

`cin`/`scanf` read some extra characters into a buffer?

- you call `read` — they disappear!

`cout`/`printf` has output waiting in a buffer?

- you call `write` — out-of-order output!

(if you need to: some stdio calls specify that they clear out buffers)

reassigning file descriptors

redirection: `./program >output.txt`

step 1: open output.txt for writing, get new file descriptor

step 2: make that new file descriptor stdout (number 1)

reassigning and file table

```
struct proc {
  ...
  struct file *ofile[NOFILE];  // Open files
};
```

redirect stdout: want: `ofile[1] = ofile[`*opened-fd*`];`

(plus increment reference count, so nothing is deleted early)

but can't access `ofile` from userspace

so syscall: `dup2(`*opened-fd*`, 1);`

reassigning file descriptors

redirection: `./program >output.txt`

step 1: open output.txt for writing, get new file descriptor

step 2: make that new file descriptor stdout (number 1)

tool: `int dup2(int oldfd, int newfd)`
make `newfd` refer to same open file as `oldfd`

- same *open file description*
- shares the current location in the file
- (even after more reads/writes)

what if newfd already allocated — closed, then reused

dup2 example

redirects stdout to output to `output.txt`:

```
fflush(stdout);  /* clear printf's buffer */
int fd = open("output.txt",
              O_WRONLY | O_CREAT | O_TRUNC);
if (fd < 0)
    do_something_about_error();

dup2(fd, STDOUT_FILENO);
/* now both write(fd, ...) and write(STDOUT_FILENO, ...)
   write to output.txt
   */

close(fd); /* only close original, copy still works! */

printf("This␣will␣be␣sent␣to␣output.txt.\n");
```

dup

`int dup(int oldfd)`
copy oldfd to a newly chosen file descriptor

almost same as `dup2(oldfd,` *`new-fd-number`*`)`

pipes

special kind of file: pipes

bytes go in one end, come out the other — once

created with `pipe()` library call

intended use: communicate between processes

- like implementing shell pipelines

pipe()

```
int pipe_fd[2];
if (pipe(pipe_fd) < 0)
    handle_error();
/* normal case: */
int read_fd = pipe_fd[0];
int write_fd = pipe_fd[1];
```

then from one process...

```
write(write_fd, ...);
```

and from another

```
read(read_fd, ...);
```

pipe() and blocking

BROKEN example:

```
int pipe_fd[2];
if (pipe(pipe_fd) < 0)
    handle_error();
int read_fd = pipe_fd[0];
int write_fd = pipe_fd[1];
write(write_fd, some_buffer, some_big_size);
read(read_fd, some_buffer, some_big_size);
```

This is likely to not terminate. What's the problem?

pipe example (1)

```
int pipe_fd[2];
if (pipe(pipe_fd) < 0)
    handle_error(); /* e.g. out of file descriptors */
int read_fd = pipe_fd[0];
int write_fd = pipe_fd[1];
child_pid = fork();
if (child_pid  == 0) {
    /* in child process, write to pipe */
    close(read_fd);
    write_to_pipe(write_fd); /* function not shown */
    exit(EXIT_SUCCESS);
} else if (child_pid > 0) {
    /* in parent process, read from pipe */
    close(write_fd);
    read_from_pipe(read_fd); /* function not shown */
    waitpid(child_pid, NULL, 0);
    close(read_fd);
} else { /* fork error */ }
```

pipe example (1)

‘standard’ pattern with fork()

```
int pipe_fd[2];
if (pipe(pipe_fd) < 0)
    handle_error(); /* e.g. out of file descriptors */
int read_fd = pipe_fd[0];
int write_fd = pipe_fd[1];
child_pid = fork();
if (child_pid  == 0) {
    /* in child process, write to pipe */
    close(read_fd);
    write_to_pipe(write_fd); /* function not shown */
    exit(EXIT_SUCCESS);
} else if (child_pid > 0) {
    /* in parent process, read from pipe */
    close(write_fd);
    read_from_pipe(read_fd); /* function not shown */
    waitpid(child_pid, NULL, 0);
    close(read_fd);
} else { /* fork error */ }
```

pipe example (1)

read() will not indicate end-of-file if write fd is open (any copy of it)

```
int pipe_fd[2];
if (pipe(pipe_fd) < 0)
    handle_error(); /* e.g. out of file descriptors */
int read_fd = pipe_fd[0];
int write_fd = pipe_fd[1];
child_pid = fork();
if (child_pid  == 0) {
    /* in child process, write to pipe */
    close(read_fd);
    write_to_pipe(write_fd); /* function not shown */
    exit(EXIT_SUCCESS);
} else if (child_pid > 0) {
    /* in parent process, read from pipe */
    close(write_fd);
    read_from_pipe(read_fd); /* function not shown */
    waitpid(child_pid, NULL, 0);
    close(read_fd);
} else { /* fork error */ }
```

pipe example (1)

have habit of closing
to avoid ‘leaking’ file descriptors
you can run out

```
int pipe_fd[2];
if (pipe(pipe_fd) < 0)
    handle_error(); /* e.g. out of file descriptors */
int read_fd = pipe_fd[0];
int write_fd = pipe_fd[1];
child_pid = fork();
if (child_pid  == 0) {
    /* in child process, write to pipe */
    close(read_fd);
    write_to_pipe(write_fd); /* function not shown */
    exit(EXIT_SUCCESS);
} else if (child_pid > 0) {
    /* in parent process, read from pipe */
    close(write_fd);
    read_from_pipe(read_fd); /* function not shown */
    waitpid(child_pid, NULL, 0);
    close(read_fd);
} else { /* fork error */ }
```

pipe and pipelines

```
ls -1 | grep foo
```

```c
pipe(pipe_fd);
ls_pid = fork();
if (ls_pid == 0) {
    dup2(pipe_fd[1], STDOUT_FILENO);
    close(pipe_fd[0]); close(pipe_fd[1]);
    char *argv[] = {"ls", "-1", NULL};
    execv("/bin/ls", argv);
}
grep_pid = fork();
if (grep_pid == 0) {
    dup2(pipe_fd[0], STDIN_FILENO);
    close(pipe_fd[0]); close(pipe_fd[1]);
    char *argv[] = {"grep", "foo", NULL};
    execv("/bin/grep", argv);
}
/* wait for processes, etc. */
```

Unix API summary

spawn and wait for program: `fork` (copy), then

- in child: setup, then `execv`, etc. (replace copy)
- in parent: `waitpid`

files: open, read and/or write, close

- regular files, pipes, network, devices, ...

file descriptors are indices into per-process array

- index 0, 1, 2 = stdin, stdout, stderr
- `dup2` — assign one index to another
- `close` — deallocate index