POSIX files /pipe

last time

creating new threads for swtch

- trick: write what would be on stack during call to swtch

POSIX and Unix

`fork` — copy process to create child process

`exec` — replace program being run by current process

`waitpid` — wait for child process

typical pattern: `fork; if (child) exec; else wait`

exercise (1)

```
int main() {
    pid_t pids[2]; const char *args[] = {"echo", "ARG", NULL};
    const char *extra[] = {"L1", "L2"};
    for (int i = 0; i < 2; ++i) {
        pids[i] = fork();
        if (pids[i] == 0) {
            args[1] = extra[i];
            execv("/bin/echo", args);
        }
    }
    for (int i = 0; i < 2; ++i) {
        waitpid(pids[i], NULL, 0);
    }
}
```

Assuming fork and execv do not fail, which are possible outputs?

A. L1 `(newline)` L2

B. L1 `(newline)` L2 `(newline)` L2

C. L2 `(newline)` L1

D. A and B

E. A and C

F. all of the above

G. something else

exercise (2)

```
int main() {
    pid_t pids[2];
    const char *args[] = {"echo", "0", NULL};
    for (int i = 0; i < 2; ++i) {
        pids[i] = fork();
        if (pids[i] == 0) {
            execv("/bin/echo", args);
        }
    }
    printf("1\n"); fflush(stdout);
    for (int i = 0; i < 2; ++i) {
        waitpid(pids[i], NULL, 0);
    }
    printf("2\n"); fflush(stdout);
}
```

Assuming fork and execv do not fail, which are possible outputs?

A. 0 (newline) 0 (newline) 1 (newline) 2

B. 0 (newline) 1 (newline) 0 (newline) 2

C. 1 (newline) 0 (newline) 0 (newline) 2

D. 1 (newline) 0 (newline) 2 (newline) 0

E. A, B, and C

F. C and D

G. all of the above

H. something else

shell

allow user (= person at keyboard) 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

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```

pipelines:

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

searching for programs

POSIX convention: PATH *environment variable*

- example: `/home/cr4bd/bin:/usr/bin:/bin`
- list of directories to check in order

environment variables = key/value pairs stored with process

- by default, left unchanged on execve, fork, etc.

one way to implement: [pseudocode]

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

some POSIX command-line features

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```
ls -l ≈ /bin/ls -l
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some POSIX command-line features

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./someprogram &
```

redirection:

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

pipelines:

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

shell assignment

implement a simple shell that supports redirection and pipeline

(for Linux or another POSIX system — not xv6)

...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

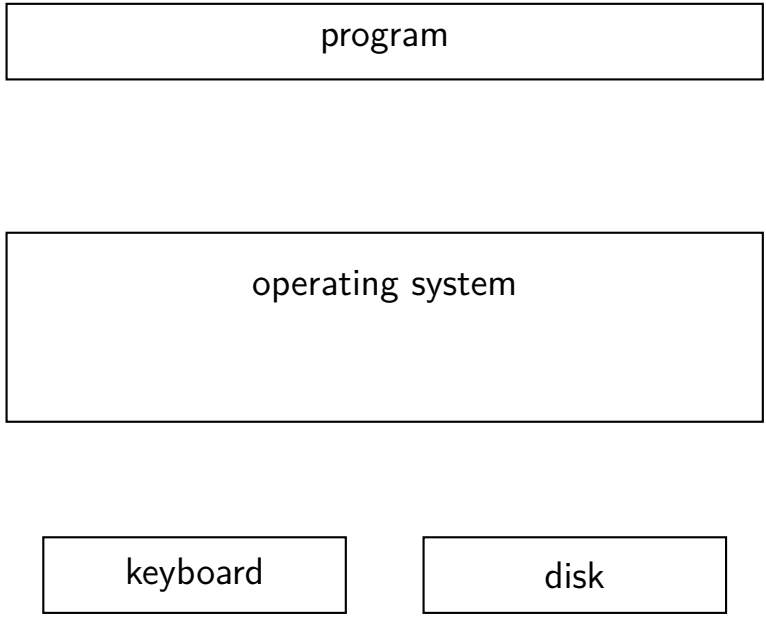
- setup, access control happens here

byte-oriented

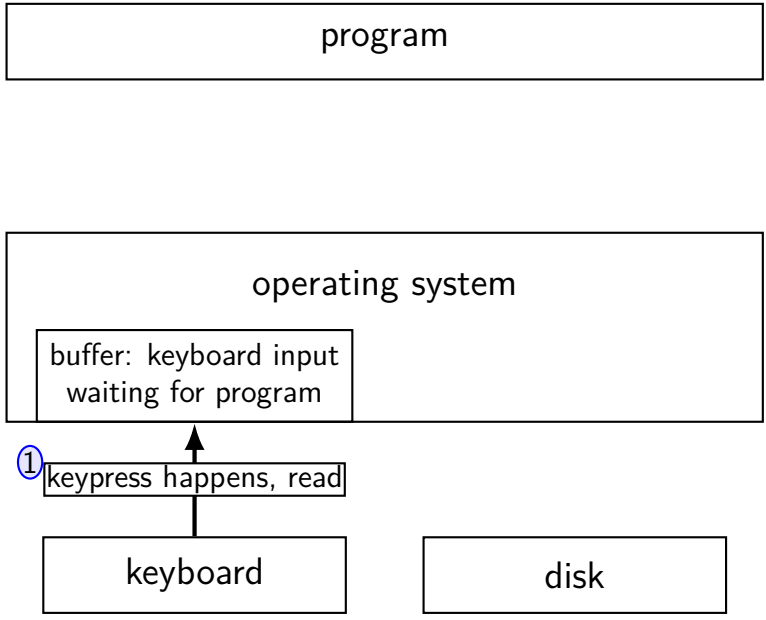
- real device isn't? operating system needs to hide that

explicit close

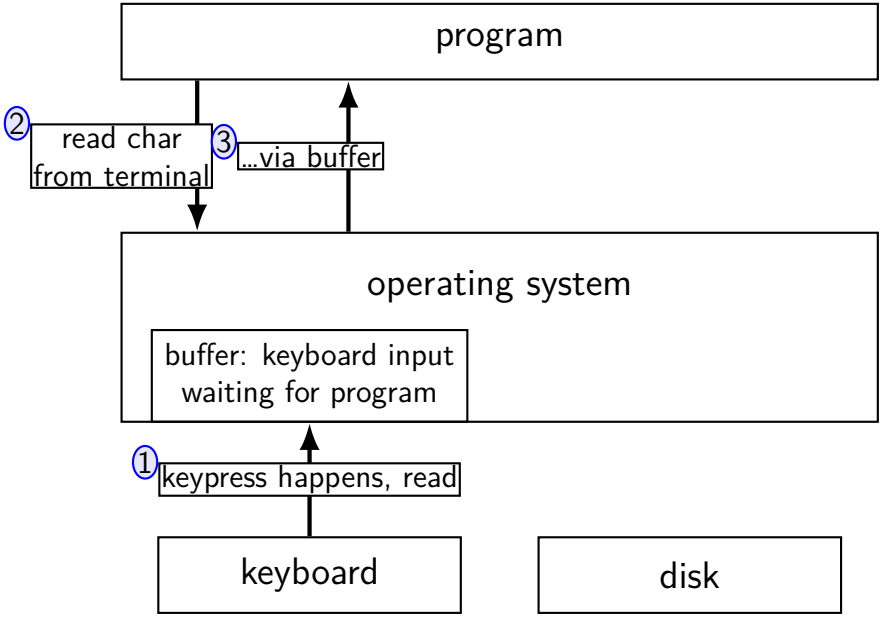
kernel buffering (reads)



kernel buffering (reads)



kernel buffering (reads)



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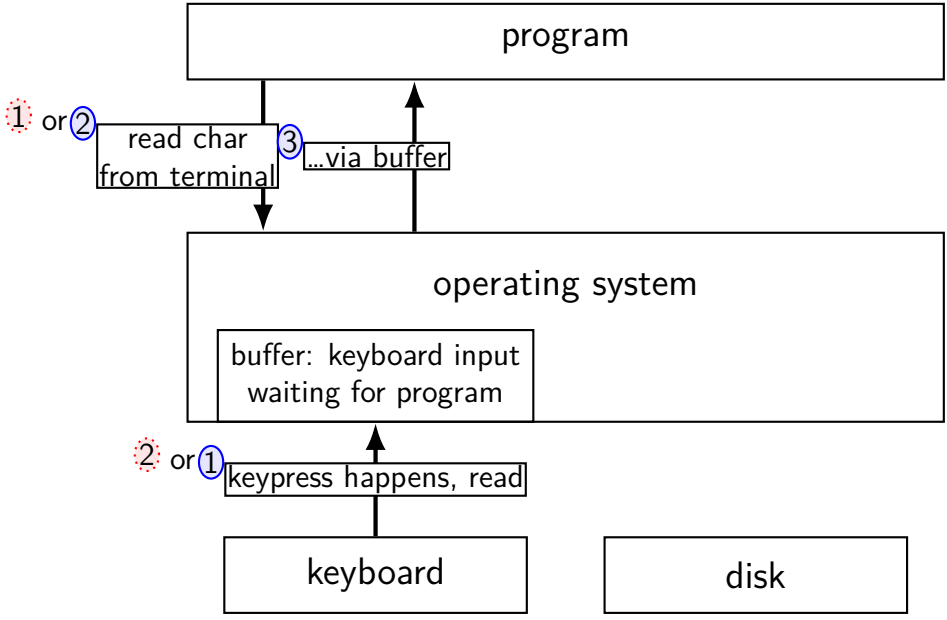
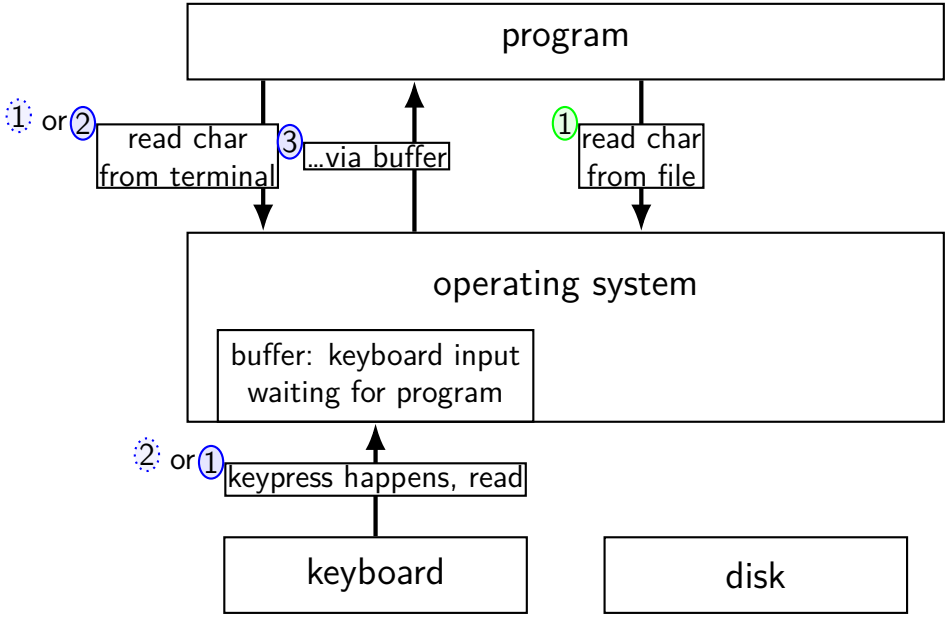
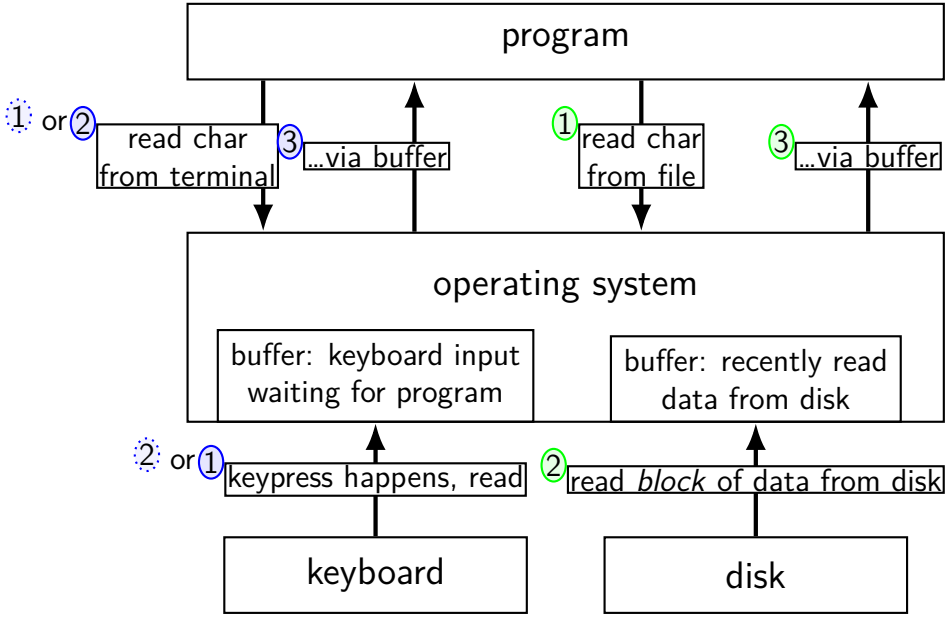


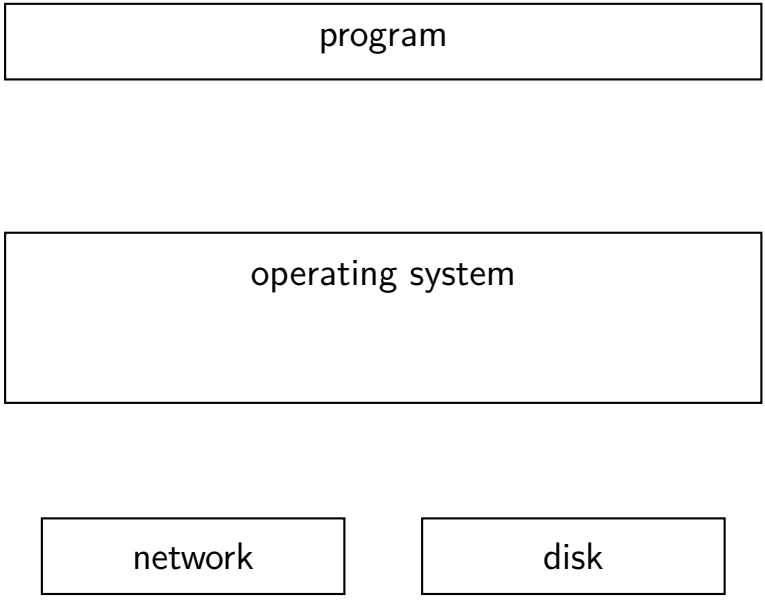
kernel buffering (reads)



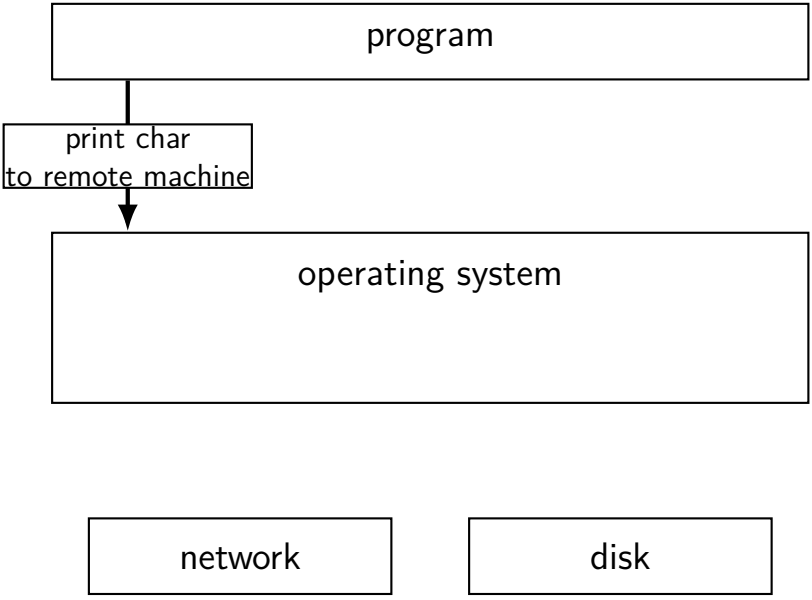
kernel buffering (reads)



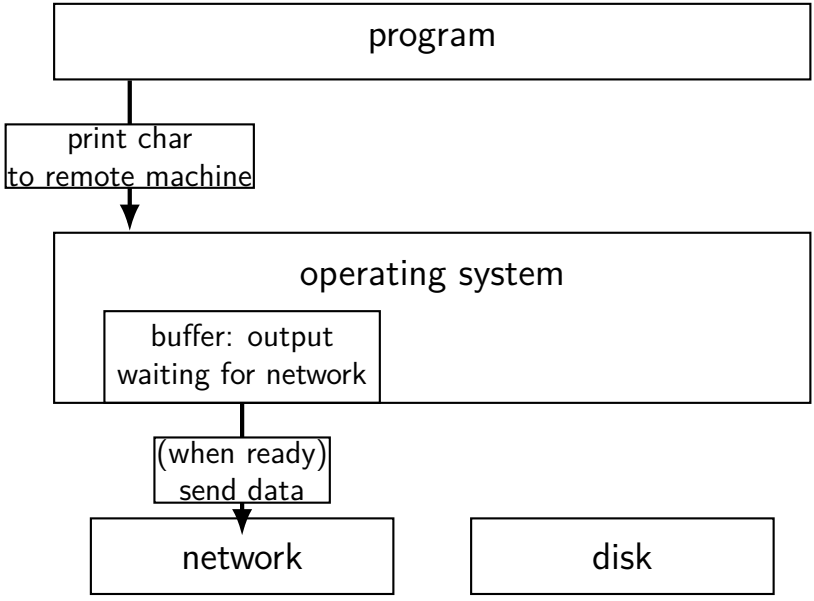
kernel buffering (writes)



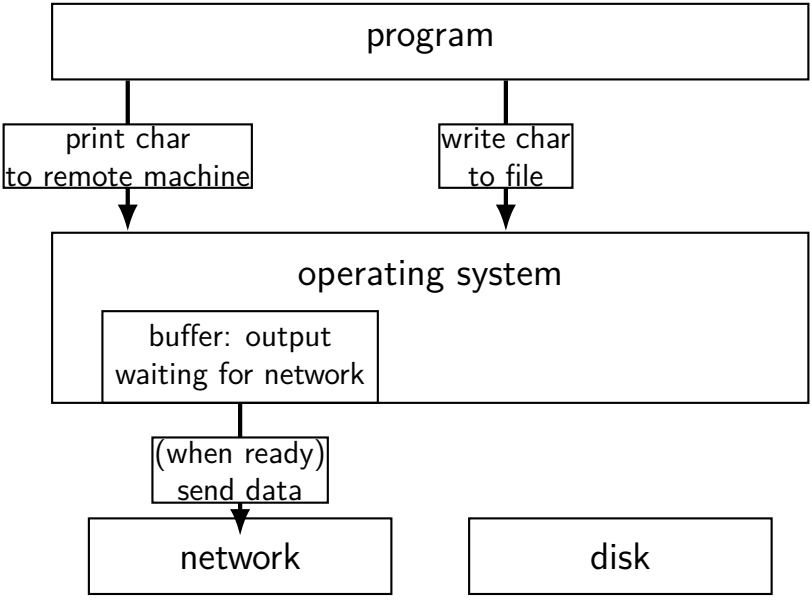
kernel buffering (writes)



kernel buffering (writes)



kernel buffering (writes)



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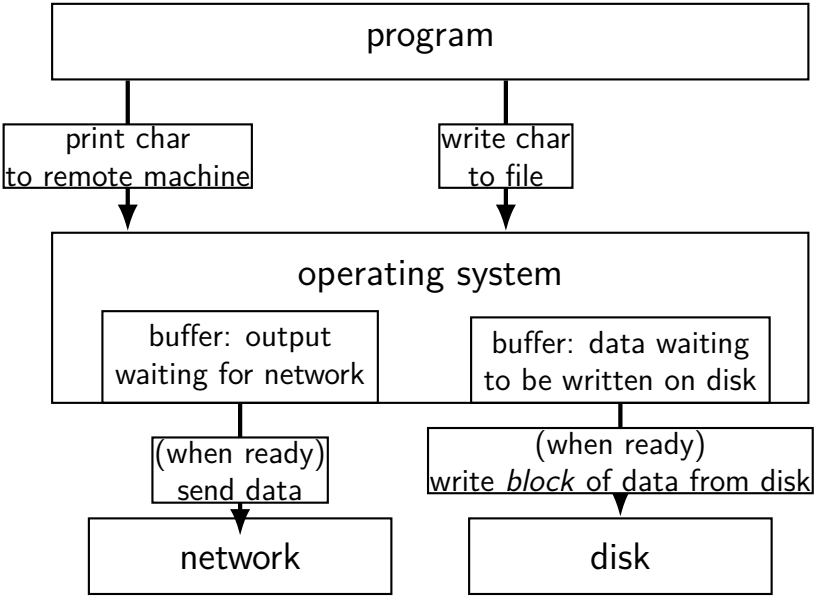


read/write operations

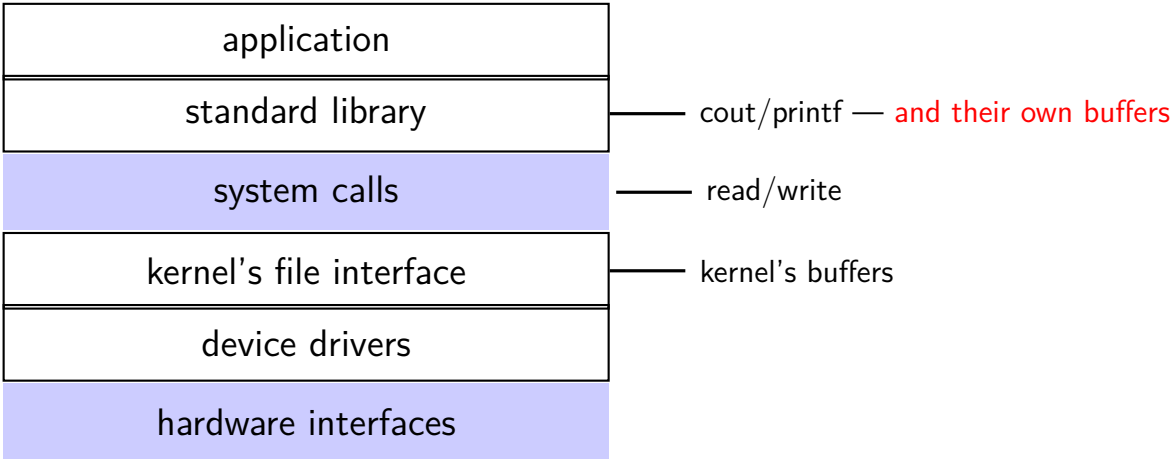
read()/write(): move data into/out of buffer

possibly wait if buffer is empty (read)/full (write)

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

why the extra layer

better (but more complex to implement) interface:

- read line
- formatted input (scanf, cin into integer, etc.)
- formatted output

less system calls (bigger reads/writes) sometimes faster

- buffering can combine multiple in/out library calls into one system call

more portable interface

- cin, printf, etc. defined by C and C++ standards

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

e.g. after `fork` same pointer
shared in parent, child

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)
- ...and more

`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)

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 or created via (later) `dup2`)

if last file descriptor for open file description, resources deallocated

returns 0 on success

returns -1 on error

- e.g. ran out of disk space while finishing saving file

shell redirection

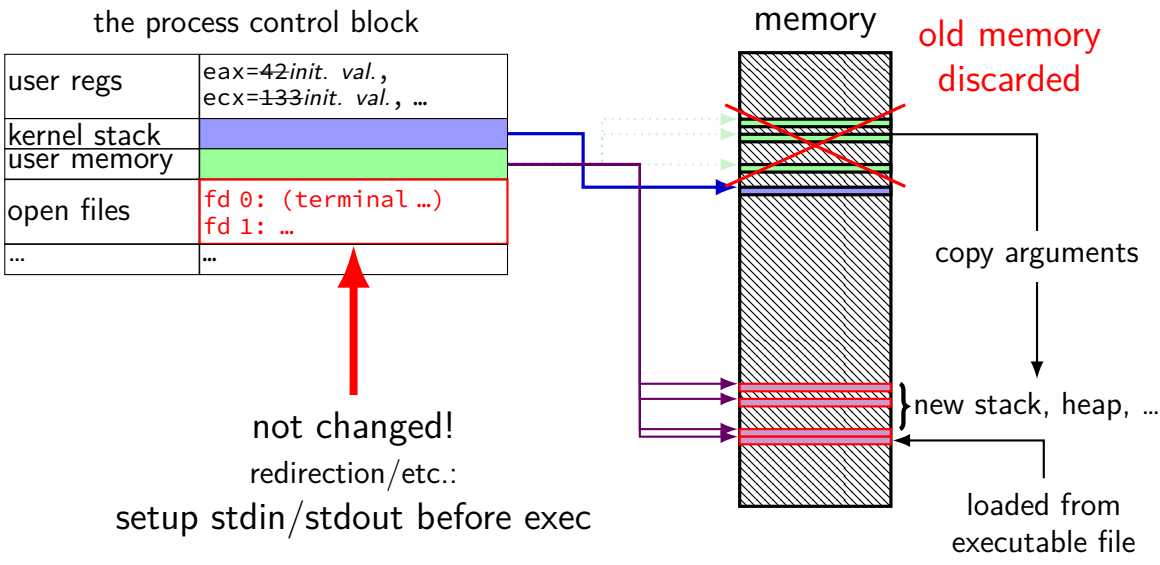
`./my_program ... < input.txt`:

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

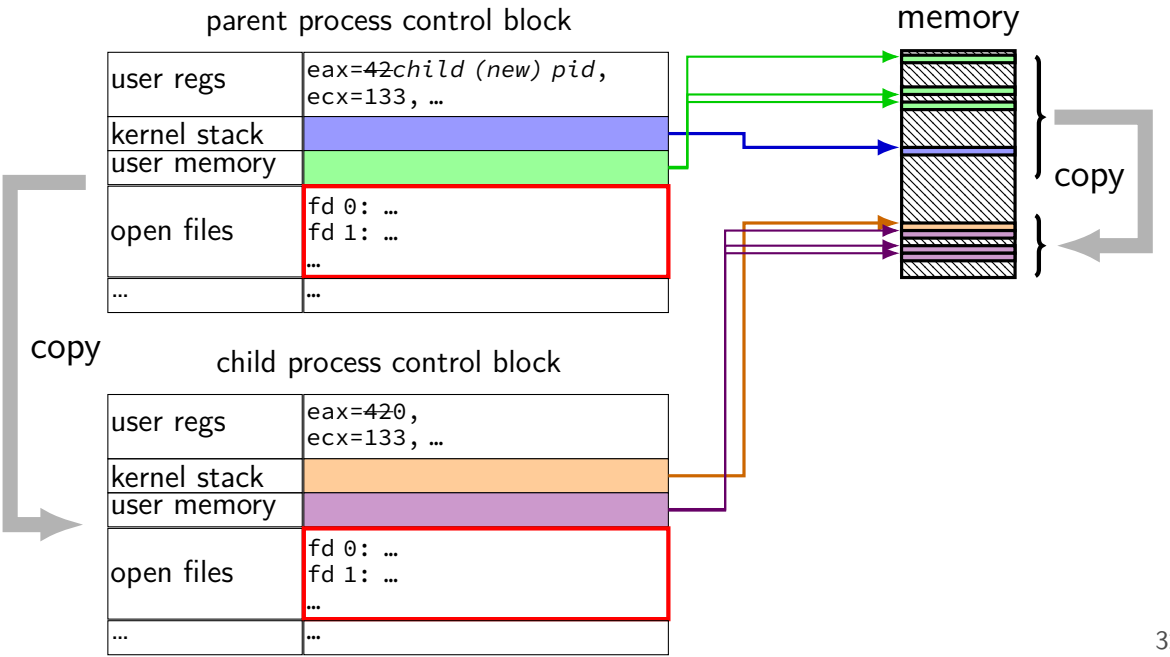
`echo foo > output.txt`:

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



fork copies open file list



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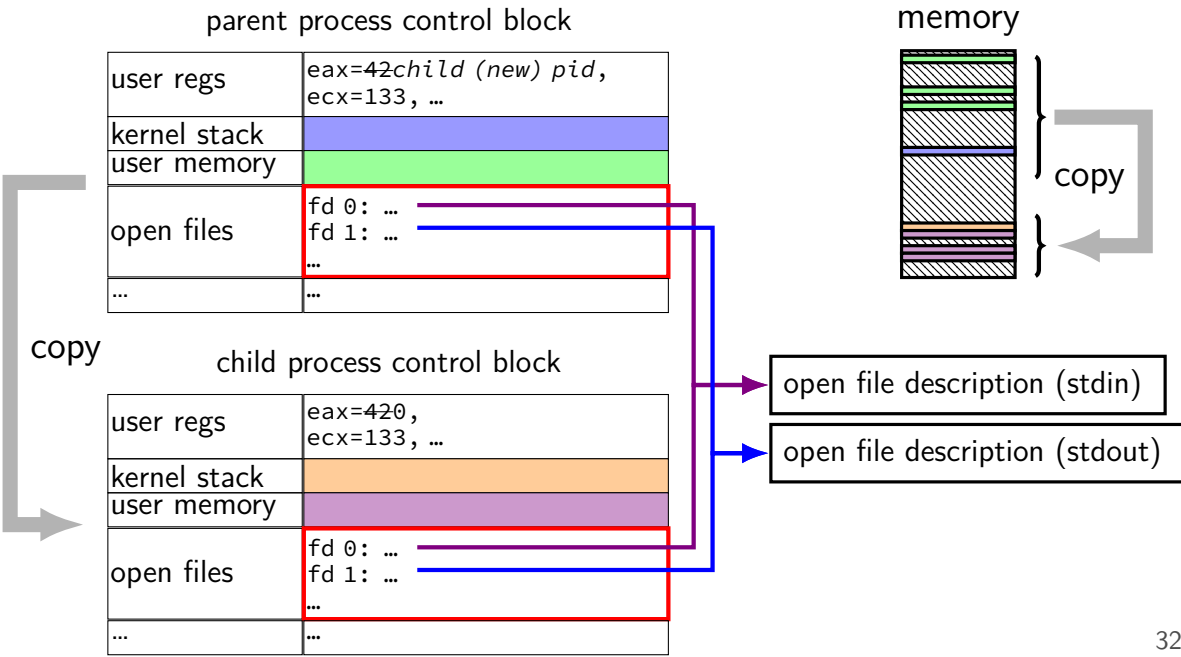

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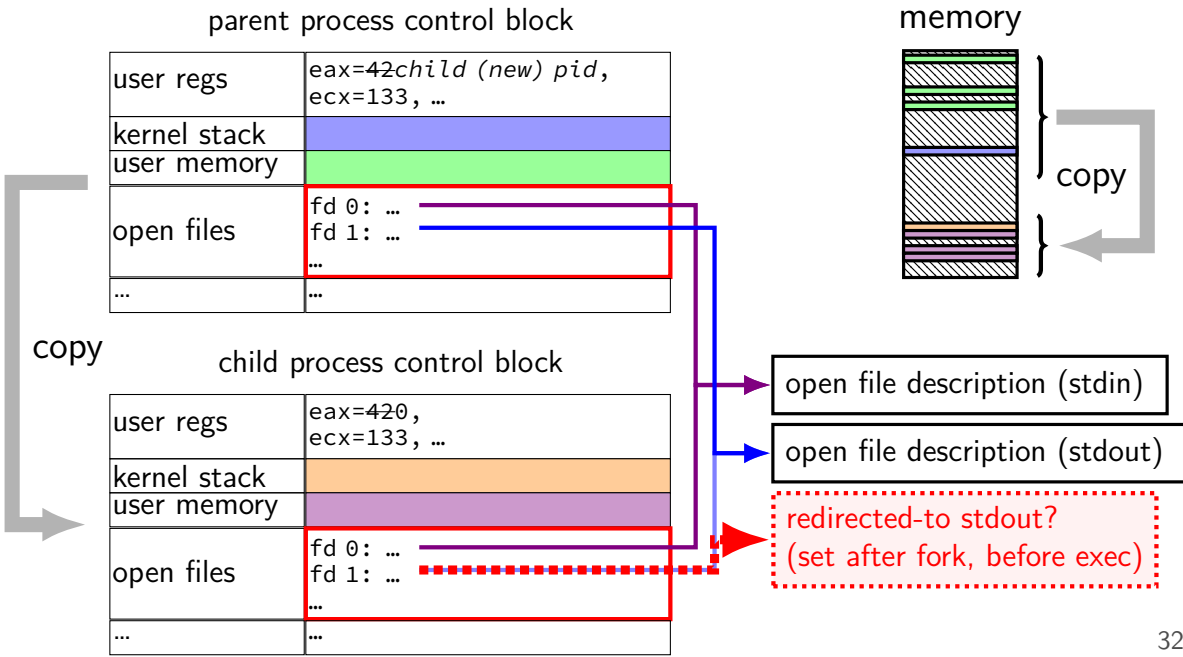
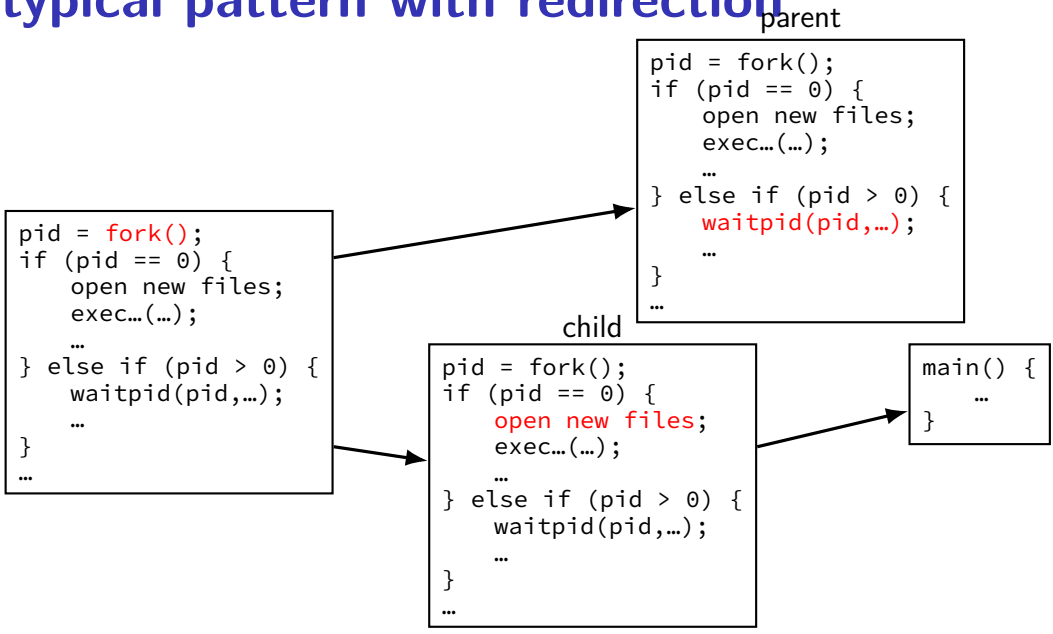


typical pattern with redirection



redirecting with exec

standard output/error/input are files

(C stdout/stderr/stdin; C++ cout/cerr/cin)

(probably after forking) open files to redirect

...and make them be standard output/error/input

using `dup2()` library call

then exec, preserving new standard output/etc.

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");
```

open/dup/close/etc. and fd array

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

open: `ofile[new_fd] = ...;`

dup2(from, to): `ofile[to] = ofile[from];`

close: `ofile[fd] = NULL;`

fork:

```
for (int i = ...)
    child->ofile[i] = parent->ofile[i];
```

(plus extra work to avoid leaking memory)

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

```
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 && amount_read != 0);
```

partial reads

on regular file: read reads what you request

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

- after waiting for something to be available

partial reads

on regular file: read reads what you request

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

after waiting for something 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

- but can request "non-blocking"
- (interruption: via *signal*)

usually: write waits until it completes

- = until remaining part fits in buffer in kernel
- does not mean data was sent on network, shown to user yet, etc.

exercise

```
int fd = open("output.txt", O_WRONLY|O_CREAT|O_TRUNC, 0666);
write(fd, "A", 1);
dup2(STDOUT_FILENO, 100);
dup2(fd, STDOUT_FILENO);
write(STDOUT_FILENO, "B", 1);
write(fd, "C", 1);
close(fd);
write(STDOUT_FILENO, "D", 1);
write(100, "E", 1);
```

Assume `open()` and `dup2()` *do not fail*, `write()` does not fail as long as the fd it writes to is open, fd `100` was closed and is not what open returns, and `STDOUT_FILENO` is initially open. What is written to `output.txt`?

A. ABCDE **C.** ABC **E.** something else
B. ABCD **D.** ACD

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)

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)

```
int pipe_fd[2];
if (pipe(pipe_fd) < 0)
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if (child_pid  == 0) {
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} 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 */ }
```

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

pipe example (1)

```
int pipe_fd[2];
if (pipe(pipe_fd) < 0)
    handle_error(); /* e.g. out of fil
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 */ }
```

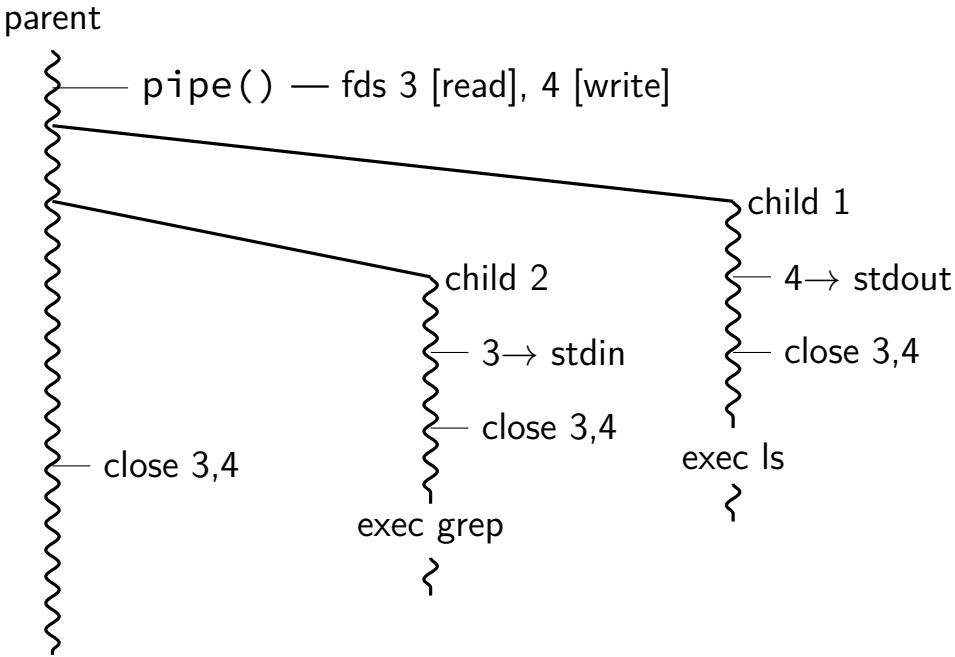
have habit of closing
to avoid 'leaking' file descriptors
you can run out

pipe and pipelines

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

```
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);
}
close(pipe_fd[0]); close(pipe_fd[1]);
/* wait for processes, etc. */
```

example execution



exercise

```
pid_t p = fork();
int pipe_fds[2];
pipe(pipe_fds);
if (p == 0) { /* child */
  close(pipe_fds[0]);
  char c = 'A';
  write(pipe_fds[1], &c, 1);
  exit(0);
} else { /* parent */
  close(pipe_fds[1]);
  char c;
  int count = read(pipe_fds[0], &c, 1);
  printf("read %d bytes\n", count);
}
```

The child is trying to send the character A to the parent, but it has a (subtle) bug.

But the above code outputs `read 0 bytes` instead of `read 1 bytes`.

What happened?

exercise solution

pipe() is after fork — two pipes, one in child, one in parent

exercise

```
int pipe_fds[2]; pipe(pipe_fds);
pid_t p = fork();
if (p == 0) {
  close(pipe_fds[0]);
  for (int i = 0; i < 10; ++i) {
    char c = '0' + i;
    write(pipe_fds[1], &c, 1);
  }
  exit(0);
}
close(pipe_fds[1]);
char buffer[10];
ssize_t count = read(pipe_fds[0], buffer, 10);
for (int i = 0; i < count; ++i) {
  printf("%c", buffer[i]);
}
```

Which of these are possible outputs (if pipe, read, write, fork don't fail)?

A. `0123456789` B. `0` C. (nothing)

D. A and B E. A and C F. A, B, and C

exercise

```
int pipe_fds[2]; pipe(pipe_fds);
pid_t p = fork();
if (p == 0) {
  close(pipe_fds[0]);
  for (int i = 0; i < 10; ++i) {
    char c = '0' + i;
    write(pipe_fds[1], &c, 1);
  }
  exit(0);
}
close(pipe_fds[1]);
char buffer[10];
ssize_t count = read(pipe_fds[0], buffer, 10);
for (int i = 0; i < count; ++i) {
  printf("%c", buffer[i]);
}
```

Which of these are possible outputs (if pipe, read, write, fork don't fail)?

A. `0123456789` B. `0` C. (nothing)

D. A and B E. A and C F. A, B, and C

partial reads

read returning 0 always means end-of-file

- by default, read always waits *if no input available yet*
- but can set read to return *error* instead of waiting

read can return less than requested if not available

- e.g. child hasn't gotten far enough

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