Unix API 2 — shells / file descriptors

last time

context switch in xv6 (finish)

POSIX standard — source compatibility

fork — *copy* current process
- return value in copy (“child”) is 0
- return value in original (“parent”) is copy’s process ID (PID)

exec — *replace* program in current process
- specify new program to load + arguments (+ environment variables)
- keep same process ID, open files, current directory, etc.

waitpid — get status of and/or wait for child process(es)
- can wait for specific process or all child processes
- status int — encodes exit code or other termination reason
- terminated child process’s pid reserved until it’s waited for (“zombie”)
- parent exits without waiting? process’s new parent is pid 1

POSIX process management

essential operations

process information: `getpid`

process creation: `fork`

running programs: `exec*`

also `posix_spawn` (not widely supported), …

waiting for processes to finish: `waitpid` (or `wait`)

process destruction, 'signaling': `exit`, `kill`

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`

redirection:

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

pipelines:

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

some POSIX command-line features

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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)

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redirection:

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some POSIX command-line features

searching for programs (not in assignment)

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

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

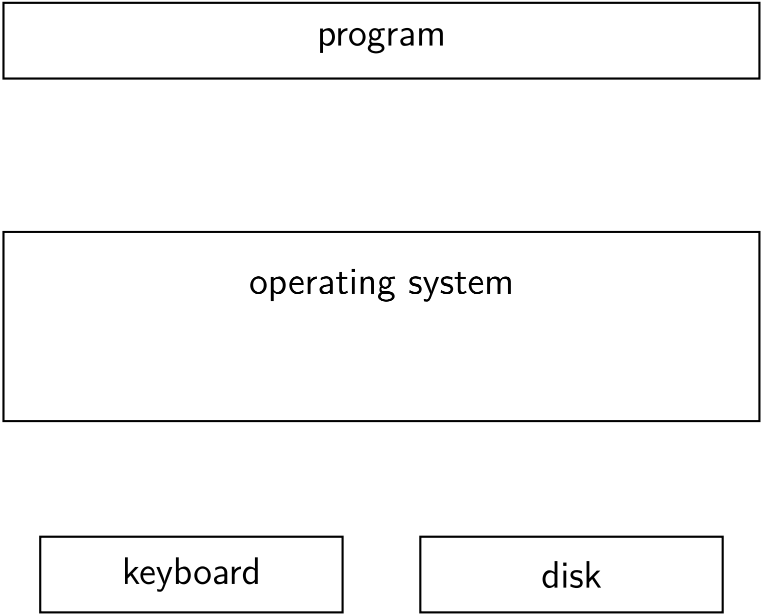
- setup, access control happens here

byte-oriented

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

explicit close

kernel buffering (reads)



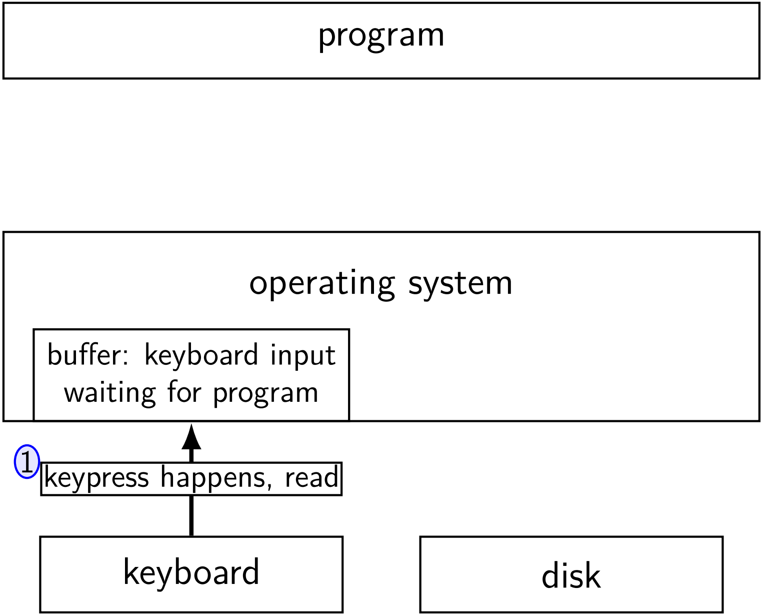
program

operating system

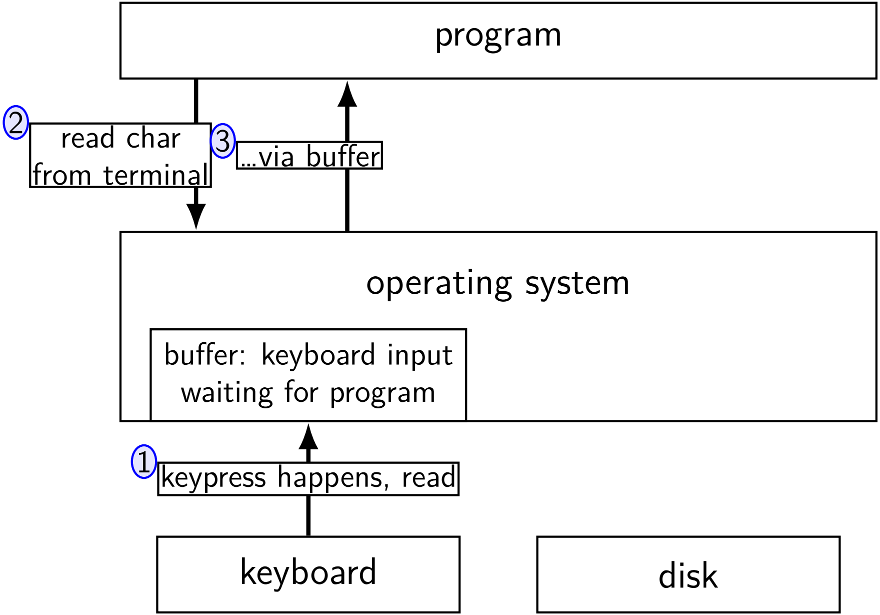
keyboard

disk

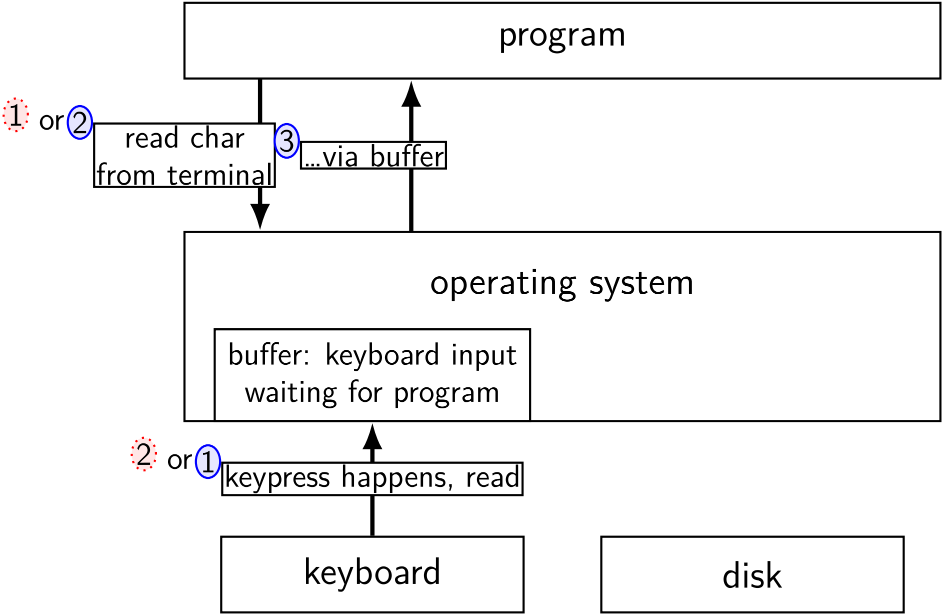
kernel buffering (reads)



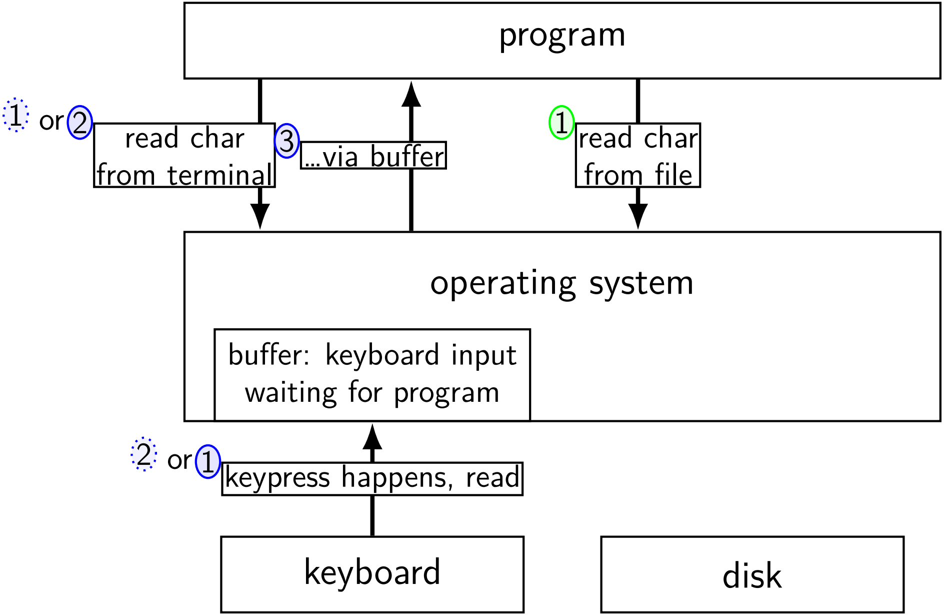
kernel buffering (reads)



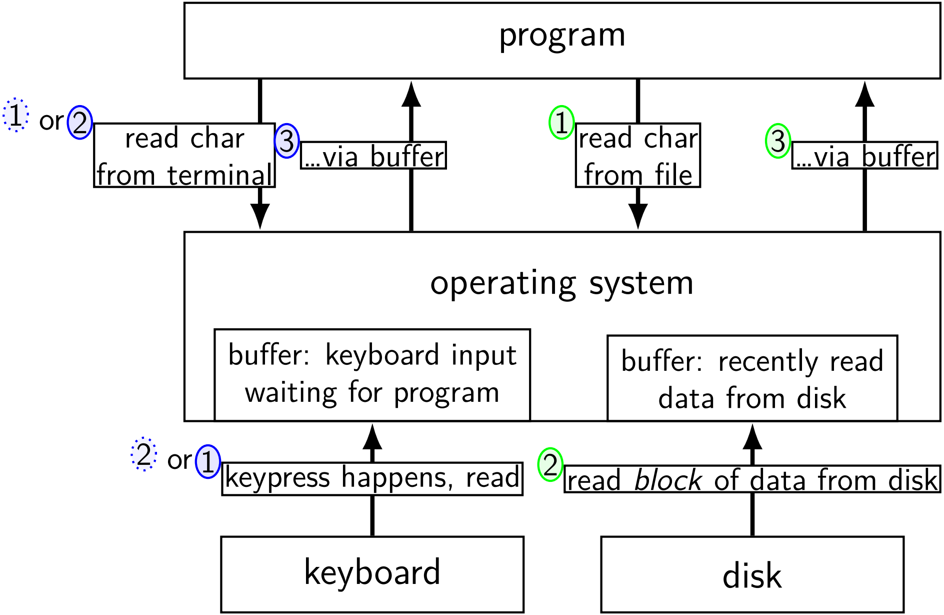
kernel buffering (reads)



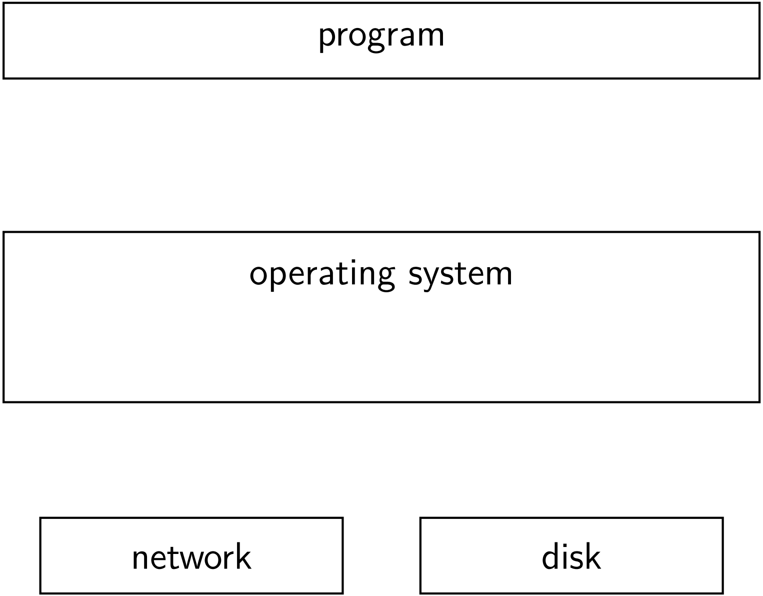
kernel buffering (reads)



kernel buffering (reads)



kernel buffering (writes)



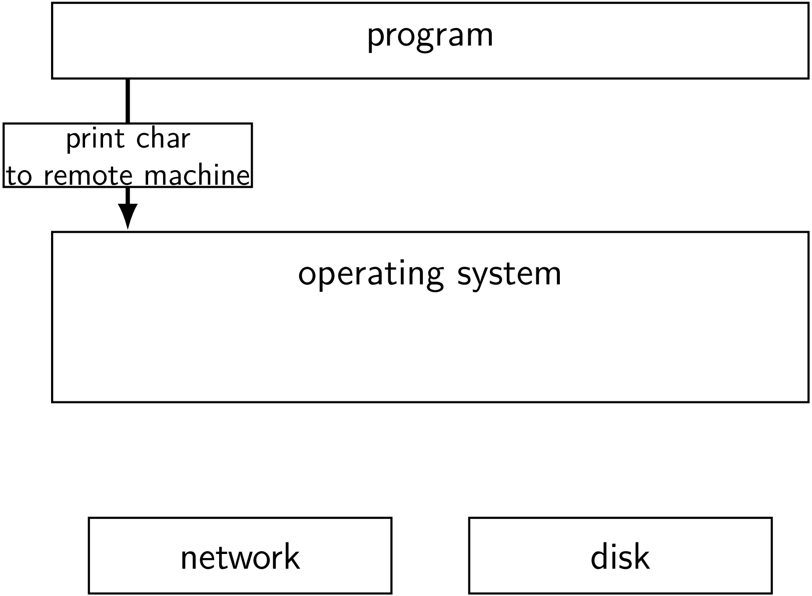
program

operating system

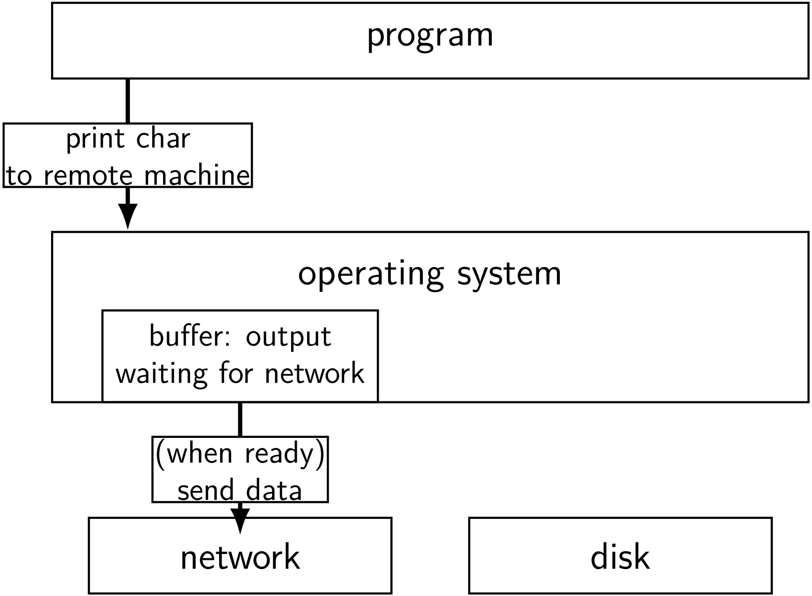
network

disk

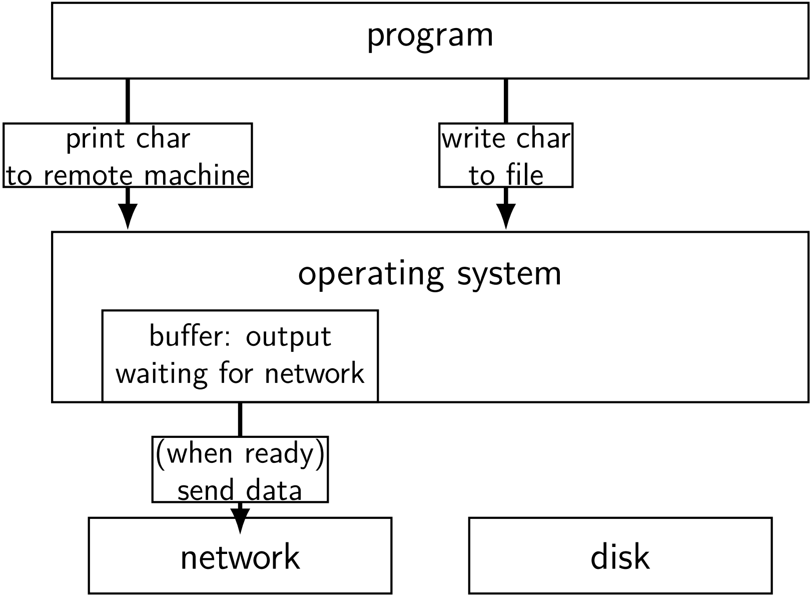
kernel buffering (writes)



kernel buffering (writes)



kernel buffering (writes)



program

print char to remote machine

write char to file

operating system

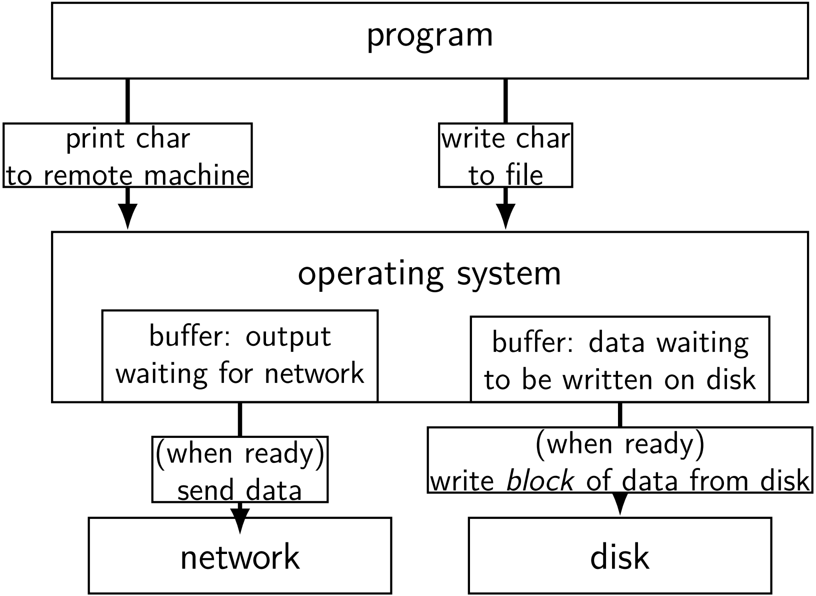
buffer: output waiting for network

(when ready) send data

network

disk

kernel buffering (writes)



read/write operations

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

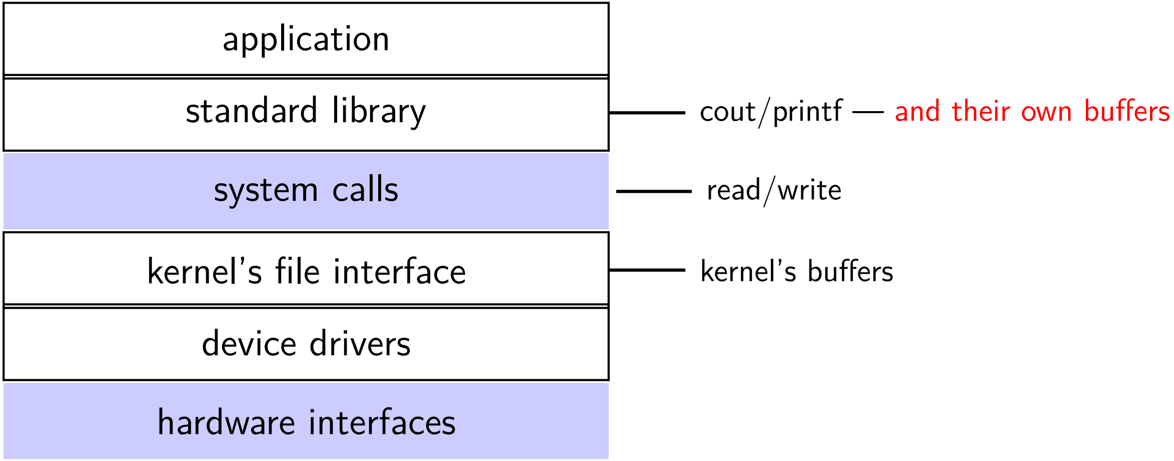
block (make process wait) if buffer is empty (read)/full (write)

- (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 — cout/printf — and their own buffers

system calls — read/write

kernel's file interface — kernel's buffers

device drivers

hardware interfaces

why layering?

better (?) interface — “read line”, etc.

less system calls (bigger reads/writes) sometimes faster

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)
- ...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)

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

shell redirection

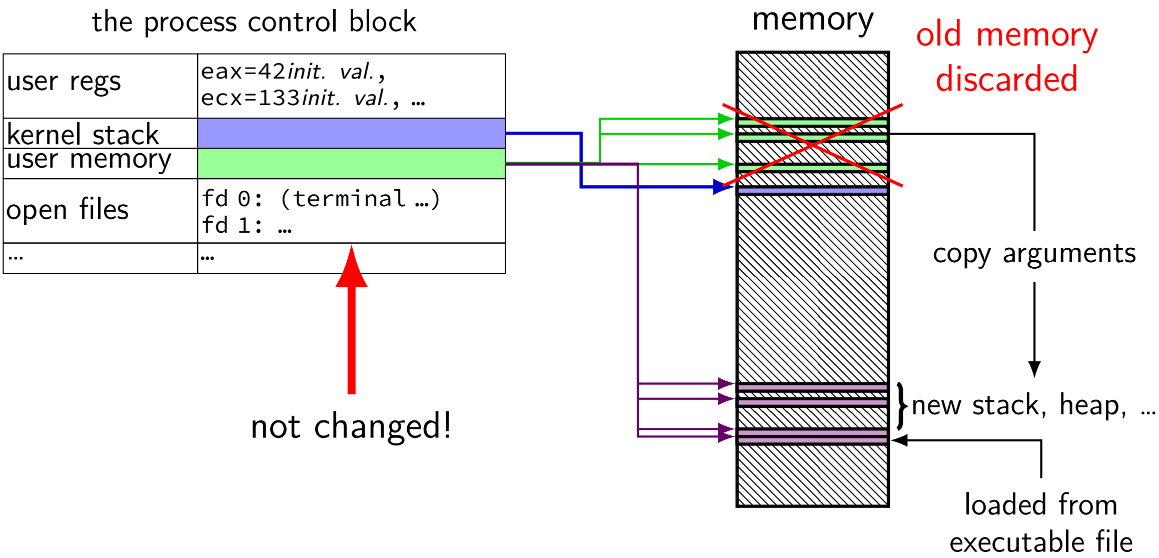
`./my_program ... <input.txt`:

- 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



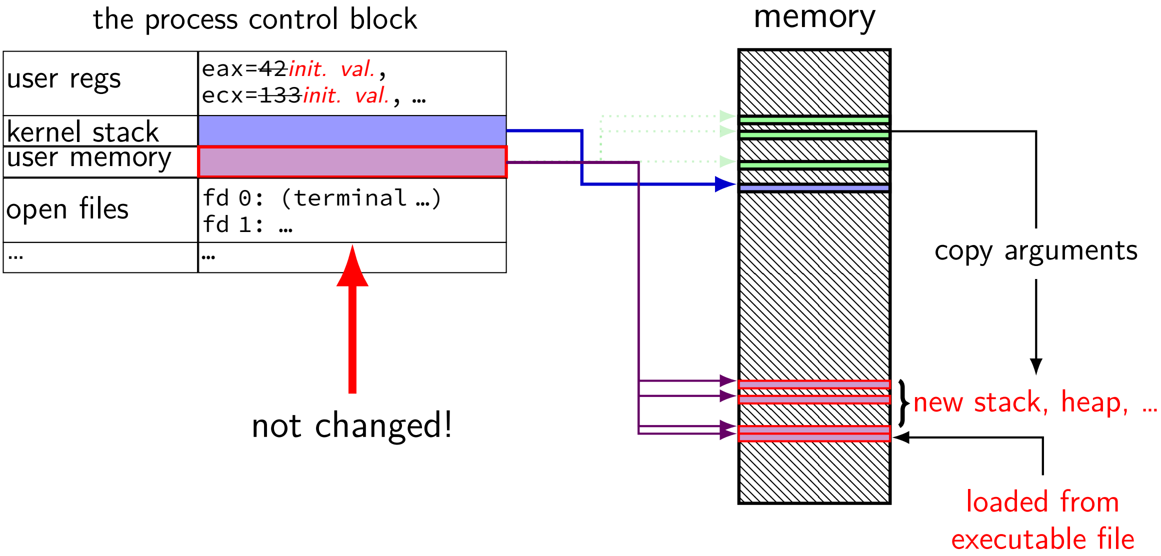
the process control block

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!

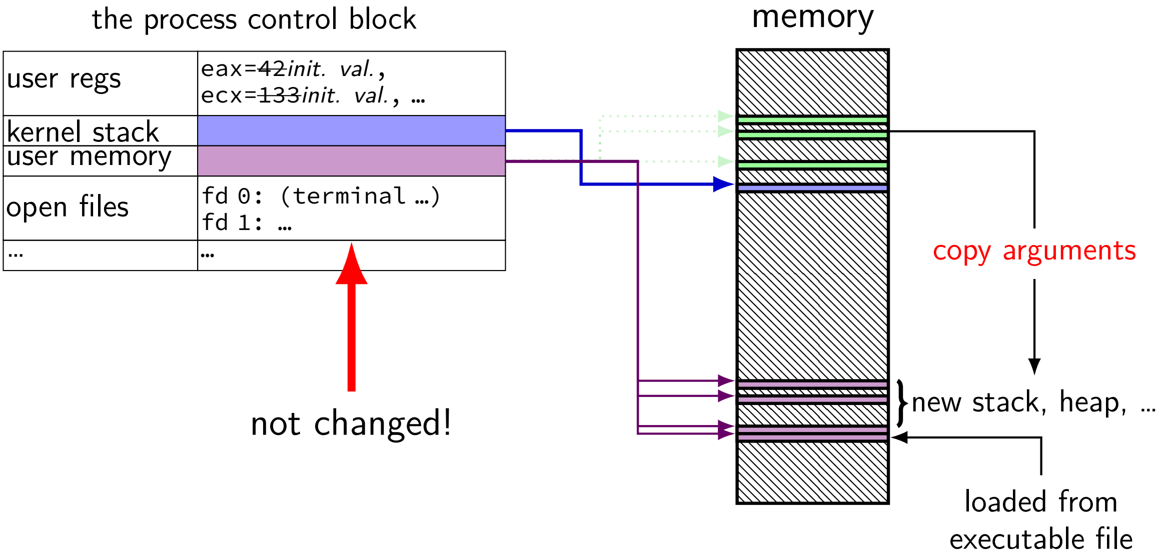
memory

copy arguments

new stack, heap, …

loaded from executable file

exec preserves open files



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

…	…

not changed!

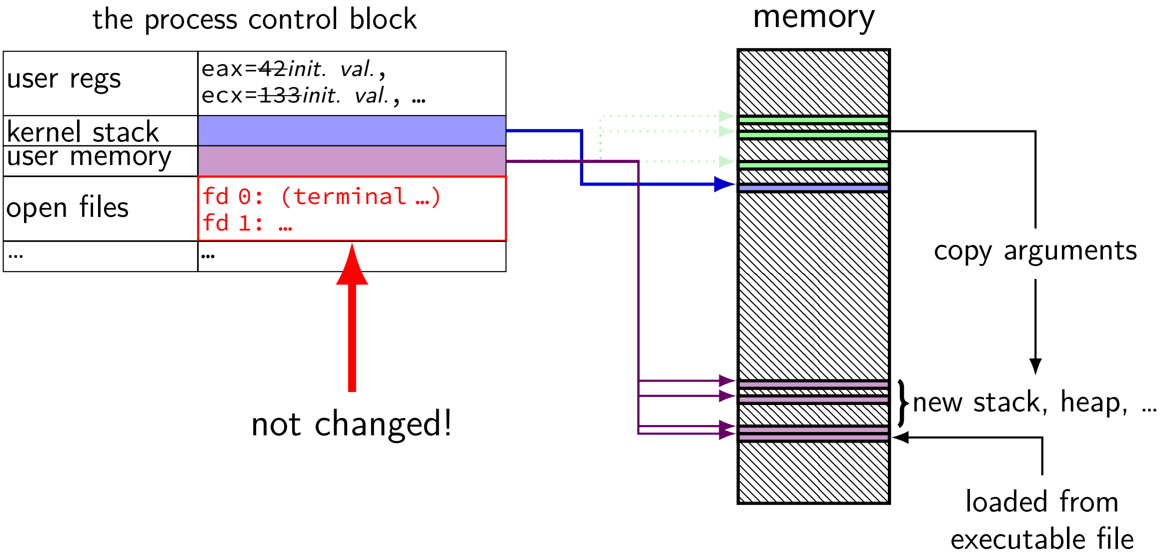
memory

copy arguments

}new stack, heap, …

loaded from
executable file

exec preserves open files



the process control block

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

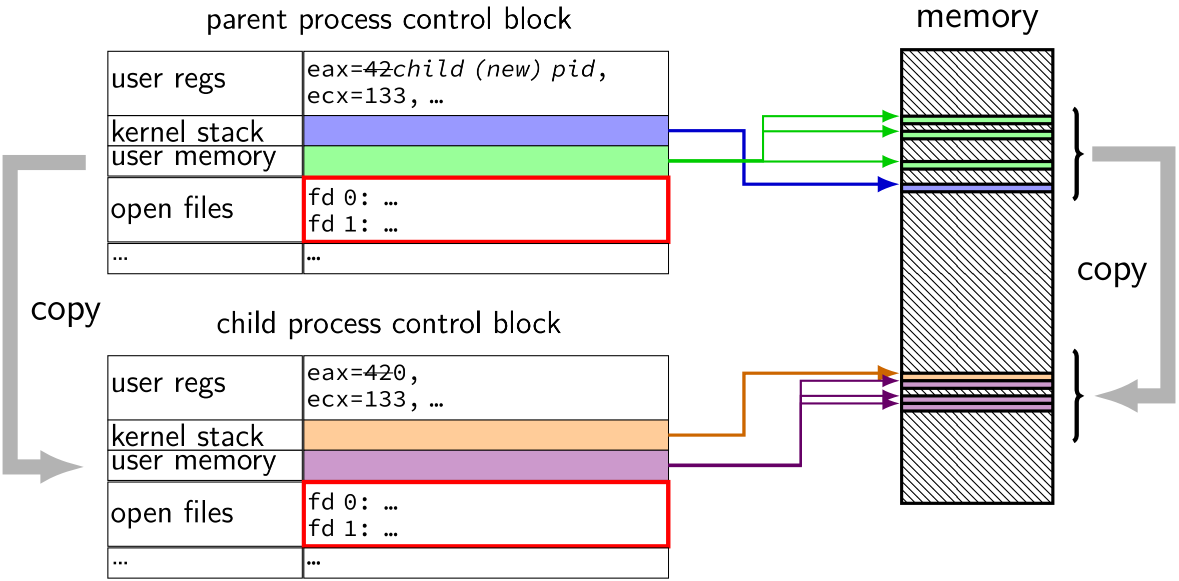
kernel stack	
user memory	

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, …

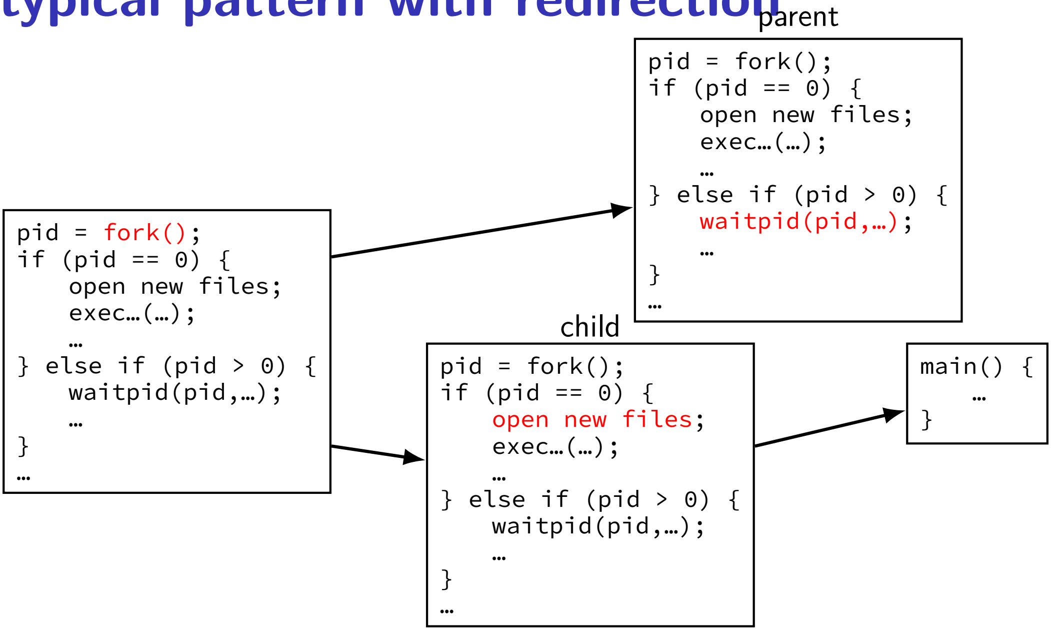
kernel stack	
user memory	
open files	fd 0: … fd 1: …
…	…

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,…);
    …
}
…
```

parent

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

child

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

```
main() {
    …
}
```

redirecting with exec

standard output/error/input are files

- (C stdout/stderr/stdin; C++ cout/cerr/cin)
- yes, your terminal is a file
- more on this later

after forking, open files to redirect

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

- typically using `dup2()`

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`*`)`

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 = ...)
        new_process->ofile[i] = old_process->ofile
```

(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: 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?

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)

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)
    handle_error(); /* e.g. out of file d
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 */ }
```

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 */ }
```

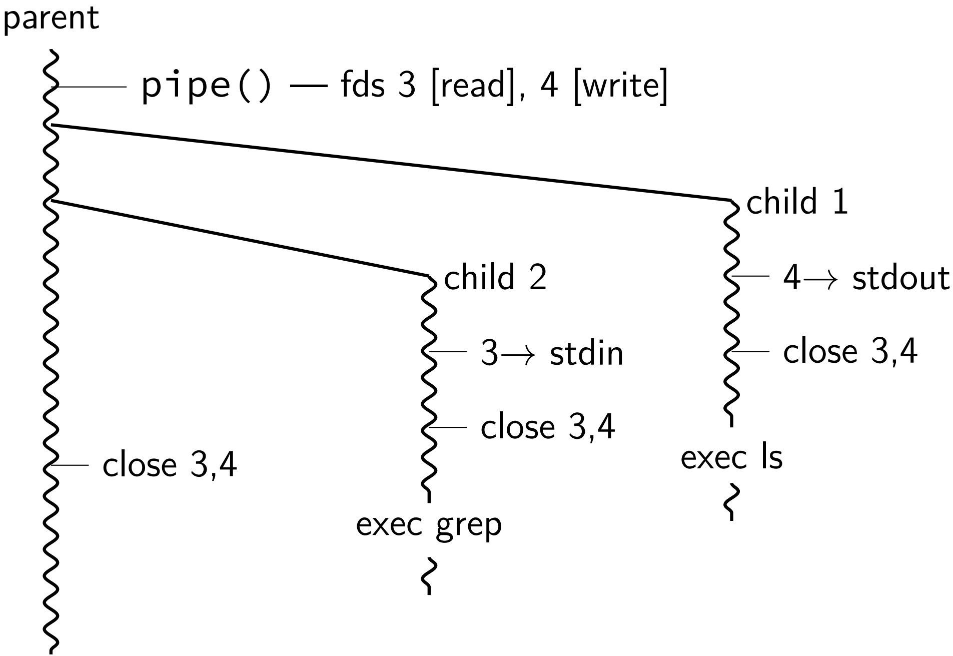
have habit of closing
to avoid ‘leaking’ file descriptors
you can run out

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

```c
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();
} 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 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();
}
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 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

backup slides

POSIX process management

essential operations

process information: `getpid`

process creation: `fork`

running programs: `exec*`

- also `posix_spawn` (not widely supported), …

waiting for processes to finish: `waitpid` (or `wait`)

process destruction, 'signaling': `exit`, `kill`

wait/waitpid

```
pid_t waitpid(pid_t pid, int *status,
                int options)
```

wait for a child process (with pid=`pid`) to finish

sets `*status` to its “status information”

`pid=-1` → wait for any child process instead

options? see manual page (command `man waitpid`)

- `0` — no options
- `WNOHANG` — return 0 rather than hanging if process not yet done

wait/waitpid

```
pid_t waitpid(pid_t pid, int *status,
                  int options)
```

wait for a child process (with pid=`pid`) to finish

sets `*status` to its “status information”

`pid=-1` → wait for any child process instead

options? see manual page (command `man waitpid`)

- `0` — no options
- `WNOHANG` — return 0 rather than hanging if process not yet done

exit statuses

```
int main() {
    return 0;  /* or exit(0);   */
}
```

waitpid example

```
#include <sys/wait.h>
...
  child_pid = fork();
  if (child_pid > 0) {
      /* Parent process */
      int status;
      waitpid(child_pid, &status, 0);
  } else if (child_pid == 0) {
      /* Child process */
      ...
```

the status

```
#include <sys/wait.h>
...
  waitpid(child_pid, &status, 0);
  if (WIFEXITED(status)) {
    printf("main returned or exit called with %d\n",
           WEXITSTATUS(status));
  } else if (WIFSIGNALED(status)) {
    printf("killed by signal %d (control-C causes signal %d)\n",
           WTERMSIG(status), SIGINT);
  } else {
      ...
  }
```

“status code” encodes both return value and if exit was abnormal

W* macros to decode it

the status

```
#include <sys/wait.h>
...
  waitpid(child_pid, &status, 0);
  if (WIFEXITED(status)) {
    printf("main returned or exit called with %d\n",
            WEXITSTATUS(status));
  } else if (WIFSIGNALED(status)) {
    printf("killed by signal %d (control-C causes signal %d)\n",
            WTERMSIG(status), SIGINT);
  } else {
      ...
  }
```

“status code” encodes both return value and if exit was abnormal

W* macros to decode it

aside: signals

signals are a way of communicating between processes

they are also how abnormal termination happens

wait's status will tell you when and what signal killed a program

- constants in signal.h
- SIGINT — control-C
- SIGTERM — `kill` command (by default)
- SIGSEGV — segmentation fault
- SIGBUS — bus error
- SIGABRT — `abort()` library function
- …

waiting for all children

```
#include <sys/wait.h>
...
  while (true) {
    pid_t child_pid = waitpid(-1, &status, 0);
    if (child_pid == (pid_t) -1) {
      if (errno == ECHILD) {
        /* no child process to wait for */
        break;
      } else {
        /* some other error */
      }
    }
    /* handle child_pid exiting */
  }
```

‘waiting’ without waiting

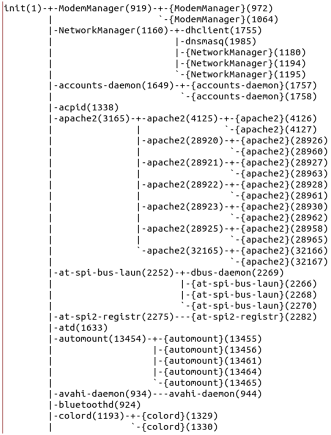
```
#include <sys/wait.h>
...
  pid_t return_value = waitpid(child_pid, &status, WNOHANG);
  if (return_value == (pid_t) 0) {
    /* child process not done yet */
  } else if (child_pid == (pid_t) −1) {
    /* error */
  } else {
    /* handle child_pid exiting */
  }
```

parent and child processes

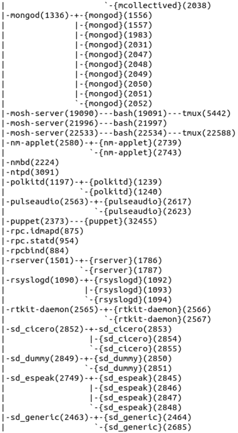
every process (but process id 1) has a *parent process* (`getppid()`)

this is the process that can wait for it

creates tree of processes:



```
init(1)-+-ModemManager(919)-+-{ModemManager}(972)
        |                   `-{ModemManager}(1064)
        |-NetworkManager(1160)-+-dhclient(1755)
        |                      |-dnsmasq(1985)
        |                      |-{NetworkManager}(1180)
        |                      |-{NetworkManager}(1194)
        |                      `-{NetworkManager}(1195)
        |-accounts-daemon(1649)-+-{accounts-daemon}(1757)
        |                       `-{accounts-daemon}(1758)
        |-acpid(1338)
        |-apache2(3165)-+-apache2(4125)-+-{apache2}(4126)
        |               |              `-{apache2}(4127)
        |               |-apache2(28920)-+-{apache2}(28926)
        |               |               `-{apache2}(28960)
        |               |-apache2(28921)-+-{apache2}(28927)
        |               |               `-{apache2}(28963)
        |               |-apache2(28922)-+-{apache2}(28928)
        |               |               `-{apache2}(28961)
        |               |-apache2(28923)-+-{apache2}(28930)
        |               |               `-{apache2}(28962)
        |               |-apache2(28925)-+-{apache2}(28958)
        |               |               `-{apache2}(28965)
        |               `-apache2(32165)-+-{apache2}(32166)
        |                               `-{apache2}(32167)
        |-at-spi-bus-laun(2252)-+-dbus-daemon(2269)
        |                       |-{at-spi-bus-laun}(2266)
        |                       |-{at-spi-bus-laun}(2268)
        |                       `-{at-spi-bus-laun}(2270)
        |-at-spi2-registr(2275)---{at-spi2-registr}(2282)
        |-atd(1633)
        |-automount(13454)-+-{automount}(13455)
        |                  |-{automount}(13456)
        |                  |-{automount}(13461)
        |                  |-{automount}(13464)
        |                  `-{automount}(13465)
        |-avahi-daemon(934)---avahi-daemon(944)
        |-bluetoothd(924)
        |-colord(1193)-+-{colord}(1329)
        |              `-{colord}(1330)
```



```
|                    `-{mcollectived}(2038)
|-mongod(1336)-+-{mongod}(1556)
|              |-{mongod}(1557)
|              |-{mongod}(1983)
|              |-{mongod}(2031)
|              |-{mongod}(2047)
|              |-{mongod}(2048)
|              |-{mongod}(2049)
|              |-{mongod}(2050)
|              |-{mongod}(2051)
|              `-{mongod}(2052)
|-mosh-server(19090)---bash(19091)---tmux(5442)
|-mosh-server(21996)---bash(21997)
|-mosh-server(22533)---bash(22534)---tmux(22588)
|-nm-applet(2580)-+-{nm-applet}(2739)
|                 `-{nm-applet}(2743)
|-nmbd(2224)
|-ntpd(3091)
|-polkitd(1197)-+-{polkitd}(1239)
|               `-{polkitd}(1240)
|-pulseaudio(2563)-+-{pulseaudio}(2617)
|                  `-{pulseaudio}(2623)
|-puppet(2373)---{puppet}(32455)
|-rpc.idmapd(875)
|-rpc.statd(954)
|-rpcbind(884)
|-rserver(1501)-+-{rserver}(1786)
|               `-{rserver}(1787)
|-rsyslogd(1090)-+-{rsyslogd}(1092)
|                |-{rsyslogd}(1093)
|                `-{rsyslogd}(1094)
|-rtkit-daemon(2565)-+-{rtkit-daemon}(2566)
|                    `-{rtkit-daemon}(2567)
|-sd_cicero(2852)-+-sd_cicero(2853)
|                 |-{sd_cicero}(2854)
|                 `-{sd_cicero}(2855)
|-sd_dummy(2849)-+-{sd_dummy}(2850)
|                `-{sd_dummy}(2851)
|-sd_espeak(2749)-+-{sd_espeak}(2845)
|                 |-{sd_espeak}(2846)
|                 |-{sd_espeak}(2847)
|                 `-{sd_espeak}(2848)
|-sd_generic(2463)-+-{sd_generic}(2464)
|                  `-{sd_generic}(2685)
```

parent and child questions...

what if parent process exits before child?

- child's parent process becomes process id 1 (typically called *init*)

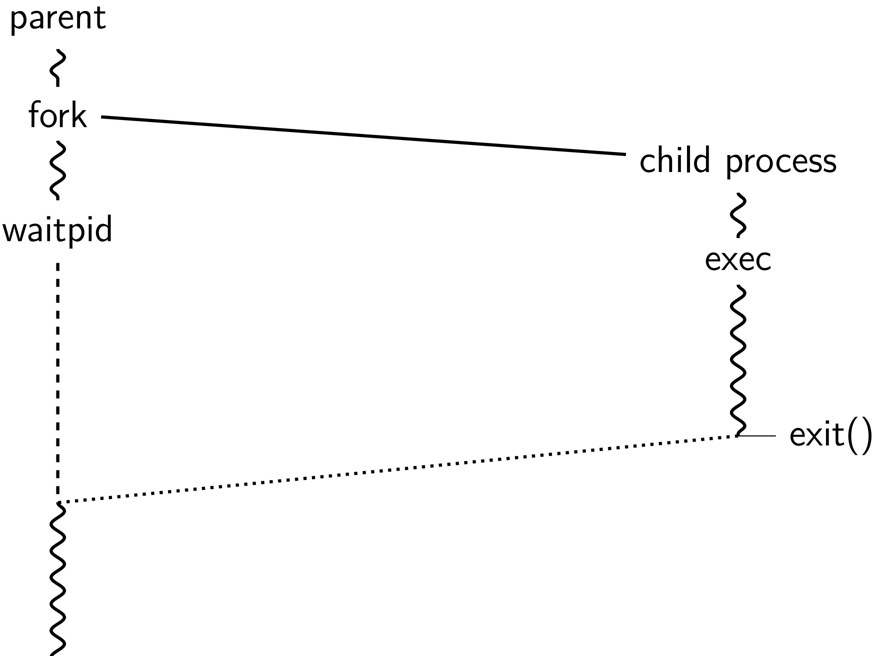
what if parent process never `waitpid()/wait()`s for child?

- child process stays around as a "zombie"
- can't reuse pid in case parent wants to use `waitpid()`

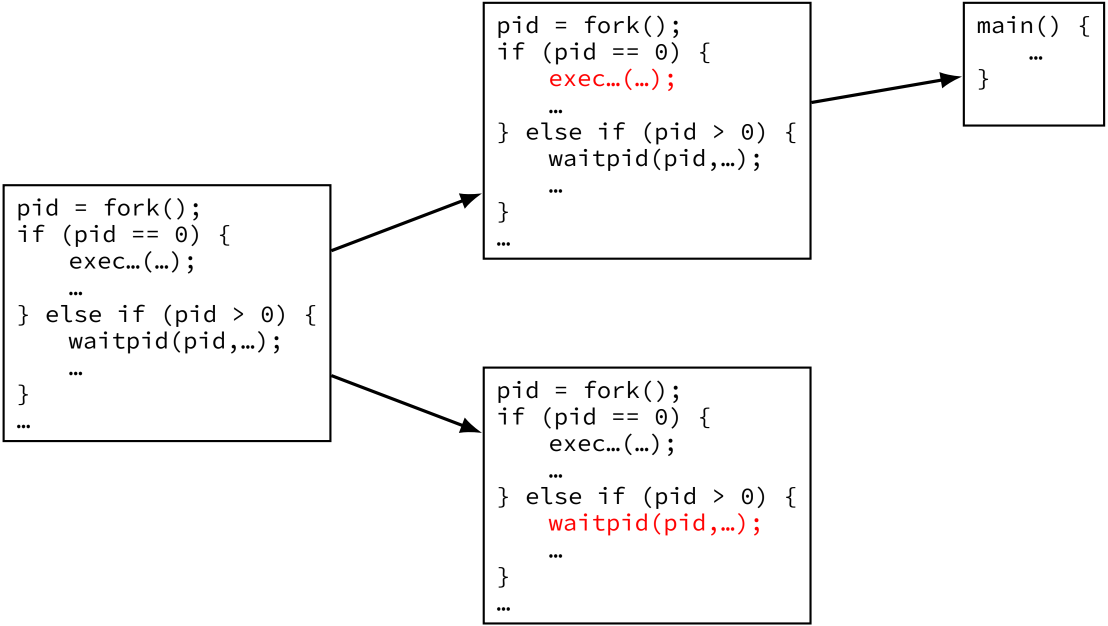
what if non-parent tries to `waitpid()` for child?

- waitpid fails

typical pattern



typical pattern (detail)



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

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

```
main() {
    …
}
```

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

multiple processes?

```
while (...) {
    pid = fork();
    if (pid == 0) {
        exec ...
    } else if (pid > 0) {
        pids.push_back(pid);
    }
}

/* retrieve exit statuses in order */
for (pid_t pid : pids) {
    waitpid(pid, ...);
    ...
}
```

multiple processes?

```
while (...) {
    pid = fork();
    if (pid == 0) {
        exec ...
    } else if (pid > 0) {
        pids.push_back(pid);
    }
}

/* retrieve exit statuses as processes finish */
while ((pid = waitpid(-1, ...)) != -1) {
    handleProcessFinishing(pid);
}
```

POSIX process management

essential operations

process information: `getpid`

process creation: `fork`

running programs: `exec*`

- also `posix_spawn` (not widely supported), …

waiting for processes to finish: `waitpid` (or `wait`)

process destruction, 'signaling': `exit`, `kill`