# signals 2 / processes API

## last time

signals : [hardware] exceptions :: OS : hardware

signal types
- SIGINT (control-C), SIGSEGV (segfault), SIGUSR1, ...

OS calling signal handlers in middle of your program

“forwarding” exceptions as signals

sigaction, registering signal handlers

## anonymous feedback (1)

“i feel like there are excessive questions during lecture that prevent us from covering new material in enough time—would it be possible to have a question limit or maybe submit questions anonymously through PollEverywhere or something?...”

## anonymous feedback (2)

“for what it’s worth, I think the information given in lecture was sufficient to answer the quiz correctly....I think people in general get it and everyone here just likes to complain and freak out over nothing.”

“Regarding the feedback we were shown in class, I want to say that I heavily agree that there is a disconnect between the lectures/readings and the quizzes. Even the lab we were given is a length, involved assignment for something we were given a cursory glance at yesterday. Specifically, I want to encourage you to include at least 1-2 example questions in lecture that directly mirror the questions we will be given on the quiz.....Especially since we are not allowed to ask questions about the quiz, this would allow us to clear up any miscommunication of the relevant material before the quiz while not spoiling the quiz’s questions.”

“Right now, the learning environment in class is not positive. It feels like this course was designed for us to fail...”

## on signals lab length

signals lab seems a bit more time consuming than I want it to be

took some measures to make simpler this semester, but not quite enough

## signal handler unsafety (0)

```
void foo() {
    /* SIGINT might happen while foo() is running */
    char *p = malloc(1024);
    ...
}

/* signal handler for SIGINT
   (registered elsewhere with sigaction() */
void handle_sigint() {
    printf("You pressed control-C.\n");
}
```

## signal handler unsafety (1)

```
void *malloc(size_t size) {
    ...
    to_return = next_to_return;
    /* SIGNAL HAPPENS HERE */
    next_to_return += size;
    return to_return;
}

void foo() {
    /* This malloc() call interrupted */
    char *p = malloc(1024);
    p[0] = 'x';
}

void handle_sigint() {
    // printf might use malloc()
    printf("You pressed control-C.\n");
}
```

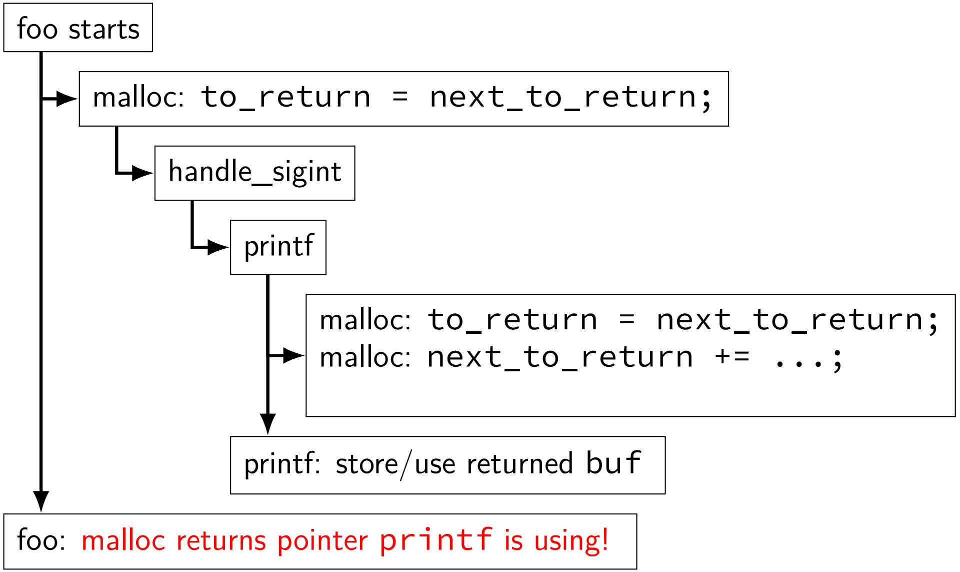
## signal handler unsafety (1)

```
void *malloc(size_t size) {
    ...
    to_return = next_to_return;
    /* SIGNAL HAPPENS HERE */
    next_to_return += size;
    return to_return;
}

void foo() {
    /* This malloc() call interrupted */
    char *p = malloc(1024);
    p[0] = 'x';
}

void handle_sigint() {
    // printf might use malloc()
    printf("You pressed control-C.\n");
}
```

## signal handler unsafety (2)

```
void handle_sigint() {
    printf("You pressed control-C.\n");
}

int printf(...) {
    static char *buf;
    ...
    buf = malloc()
    ...
}
```

# signal handler unsafety: timeline


foo starts
malloc: `to_return = next_to_return;`
handle_sigint
printf
malloc: `to_return = next_to_return;`
malloc: `next_to_return += ...;`
printf: store/use returned `buf`
foo: malloc returns pointer `printf` is using!

## signal handler unsafety (3)

```
foo() {
  char *p = malloc(1024)... {
    to_return = next_to_return;
    handle_sigint() { /* signal delivered here */
      printf("You pressed control-C.\n") {
        buf = malloc(...) {
          to_return = next_to_return;
          next_to_return += size;
          return to_return;
        }
        ...
      }
    }
    next_to_return += size;
    return to_return;
  }
  /* now p points to buf used by printf! */
}
```

## signal handler unsafety (3)

```
foo() {
  char *p = malloc(1024)... {
    to_return = next_to_return;
    handle_sigint() { /* signal delivered here */
      printf("You pressed control-C.\n") {
        buf = malloc(...) {
          to_return = next_to_return;
          next_to_return += size;
          return to_return;
        }
        ...
      }
    }
    next_to_return += size;
    return to_return;
  }
  /* now p points to buf used by printf! */
}
```

## signal handler safety

POSIX (standard that Linux follows) defines “async-signal-safe” functions

these must work correctly no matter what they interrupt

...and no matter how they are interrupted

includes: `write`, `_exit`

does not include: `printf`, `malloc`, `exit`

## blocking signals

avoid having signal handlers anywhere:

can instead block signals

- `sigprocmask()`, `pthread_sigmask()`

blocked = signal handled doesn't run

- signal not *delivered*

instead, signal becomes *pending*

- delivered if unblocked

## blocking signals

avoid having signal handlers anywhere:

can instead block signals

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blocked = signal handled doesn't run

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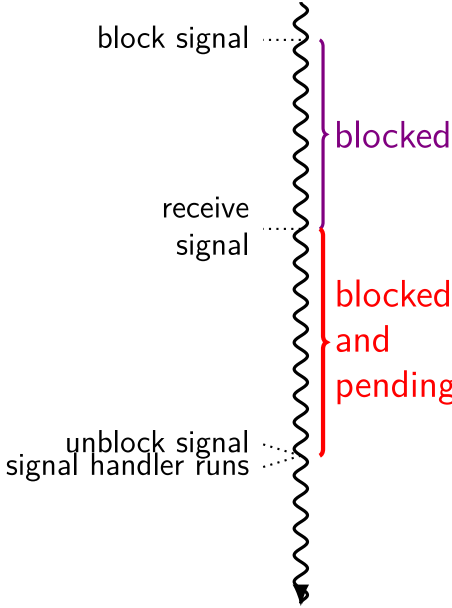


## controlling when signals are handled

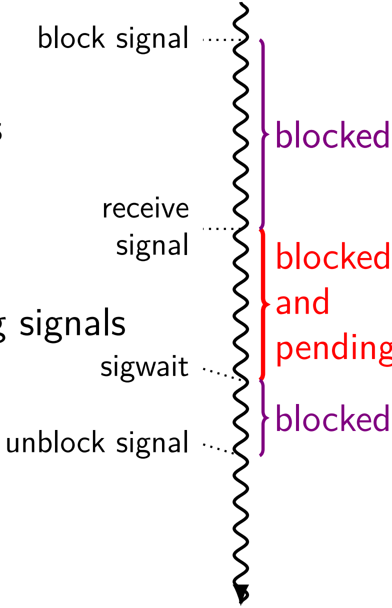
first, block a signal

then either unblock signals only at certain times

- some special functions to help:
- `sigsuspend` (unblock until handler runs),
- `pselect` (unblock while checking for I/O), ...

and/or use API for inspecting/changing pending signals

- example: `sigwait`
- typically instead of having signal handler



## controlling when signals are handled

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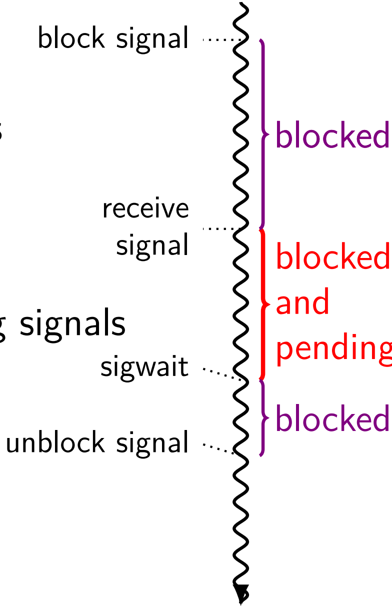

## synchronous signal handling

```
int main(void) {
    sigset_t set;
    sigemptyset(&set);
    sigaddset(&set, SIGINT);
    sigprocmask(SIG_BLOCK, &set, NULL);

    printf("Waiting for SIGINT (control-C)\n");
    int num;
    if (sigwait(&set, &num) != 0) {
        printf("sigwait failed!\n");
    }
    if (num == SIGINT);
        printf("Got SIGINT\n");
    }
}
```

## timing HW

## 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`

## POSIX process management

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# `fork`

`pid_t fork()` — copy the current process

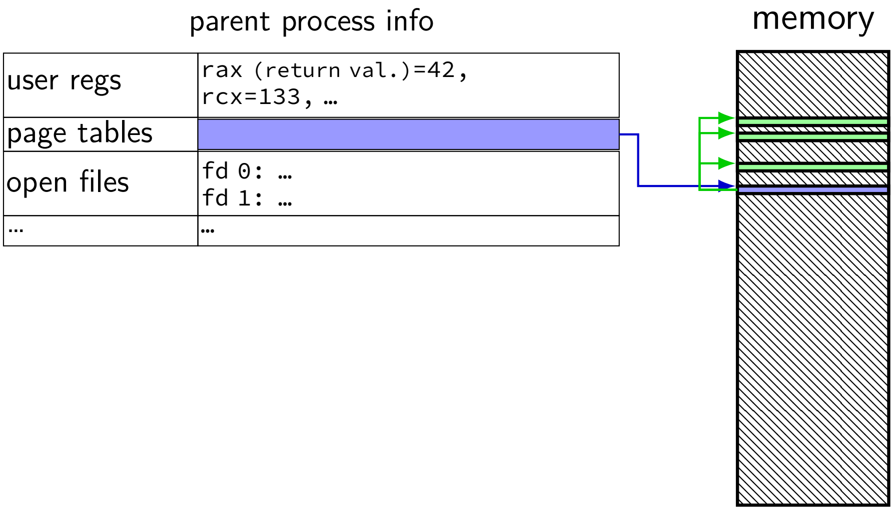
returns twice:

- in *parent* (original process): pid of new *child* process
- in *child* (new process): `0`

everything (but pid) duplicated in parent, child:

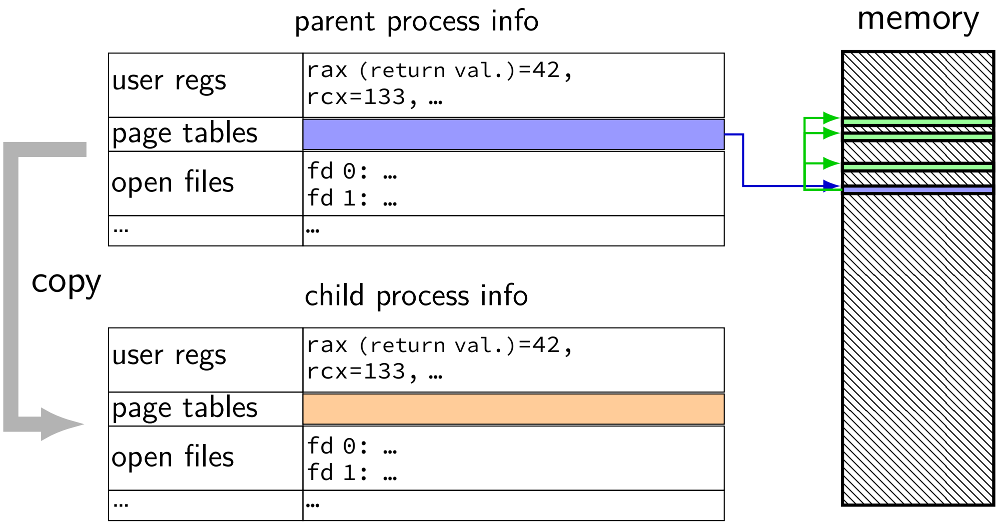
- memory
- file descriptors (later)
- registers

# fork and process info (w/o copy-on-write)

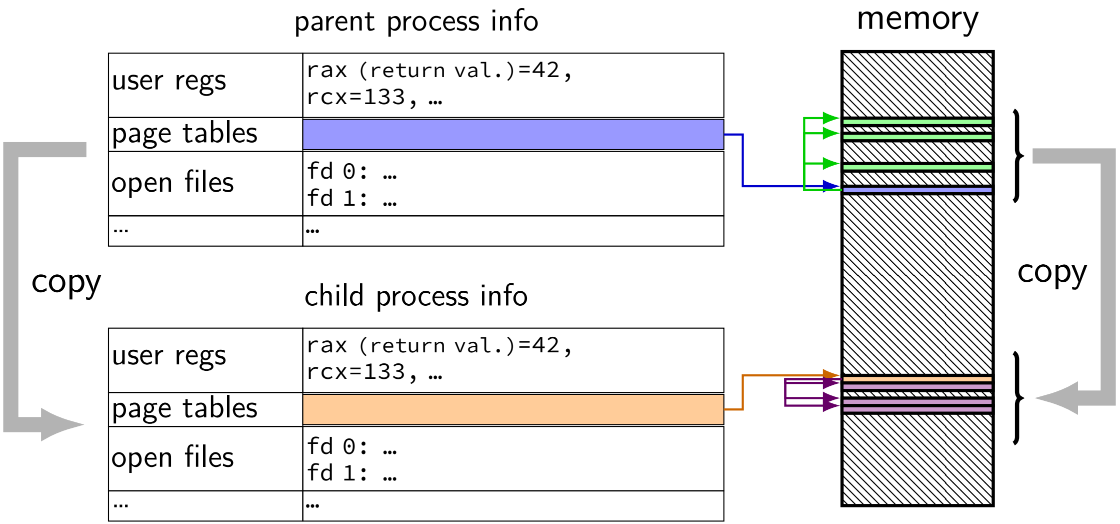


|  |  |
|---|---|
| user regs | `rax (return val.)=42,` `rcx=133, …` |
| page tables |  |
| open files | `fd 0: …` `fd 1: …` |
| … | … |

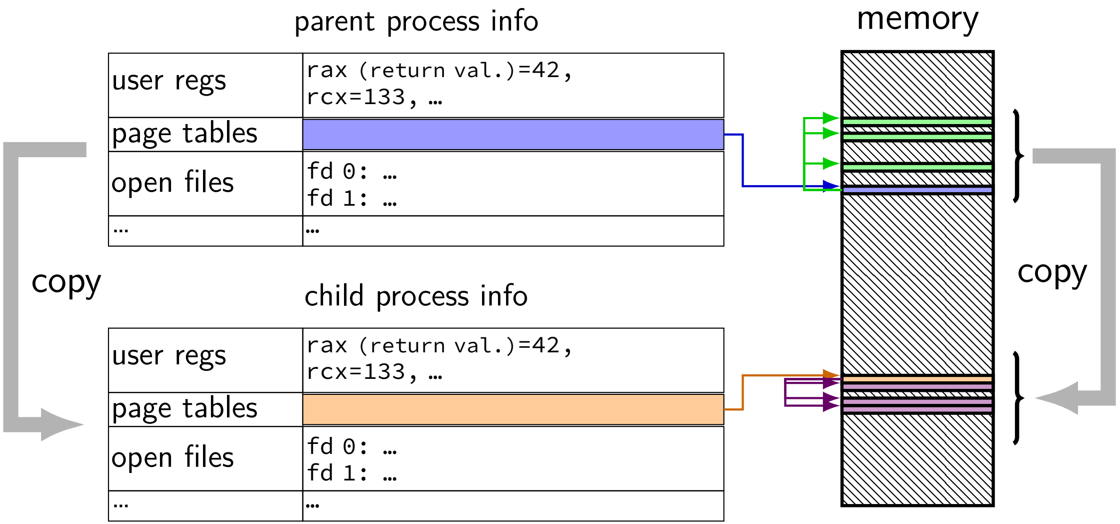
# fork and process info (w/o copy-on-write)



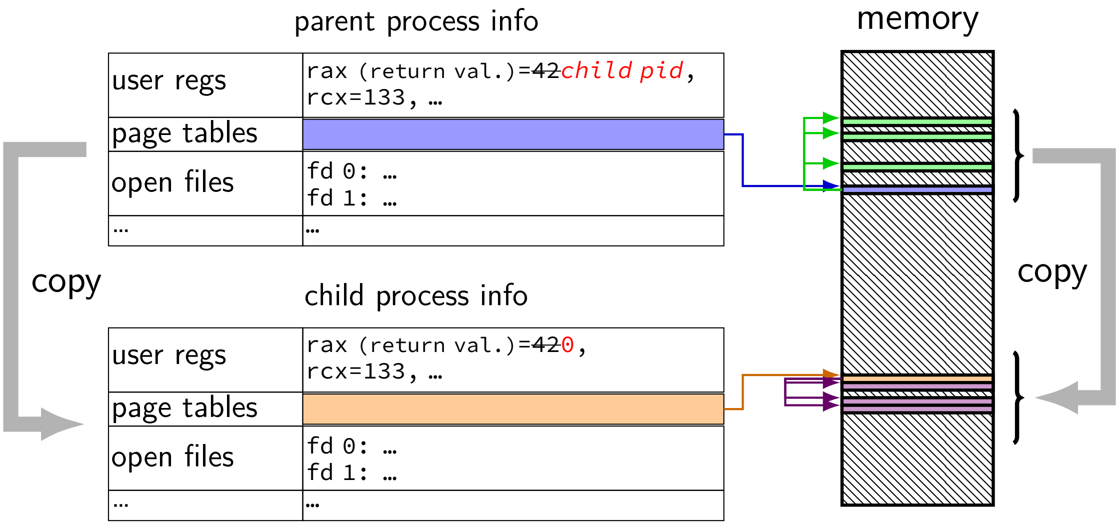
# fork and process info (w/o copy-on-write)



# fork and process info (w/o copy-on-write)



# fork and process info (w/o copy-on-write)



parent process info

| | |
|---|---|
| user regs | `rax (return val.)=`~~`42`~~*`child pid`*`,` `rcx=133, …` |
| page tables | |
| open files | `fd 0: …` `fd 1: …` |
| … | … |

child process info

| | |
|---|---|
| user regs | `rax (return val.)=`~~`42`~~`0,` `rcx=133, …` |
| page tables | |
| open files | `fd 0: …` `fd 1: …` |
| … | … |

# fork example

```
// not shown: #include various headers
int main(int argc, char *argv[]) {
    pid_t pid = getpid();
    printf("Parent pid: %d\n", (int) pid);
    pid_t child_pid = fork();
    if (child_pid > 0) {
        /* Parent Process */
        pid_t my_pid = getpid();
        printf("[%d] parent of [%d]\n",
               (int) my_pid,
               (int) child_pid);
    } else if (child_pid == 0) {
        /* Child Process */
        pid_t my_pid = getpid();
        printf("[%d] child\n",
               (int) my_pid);
    } else {
        perror("Fork failed");
    }
    return 0;
}
```

## fork example

```
// not shown: #include various headers
int main(int argc, char *argv[]) {
    pid_t pid = getpid();
    printf("Parent pid: %d\n",
    pid_t child_pid = fork();
    if (child_pid > 0) {
        /* Parent Process */
        pid_t my_pid = getpid();
        printf("[%d] parent of [%d]\n",
               (int) my_pid,
               (int) child_pid);
    } else if (child_pid == 0) {
        /* Child Process */
        pid_t my_pid = getpid();
        printf("[%d] child\n",
               (int) my_pid);
    } else {
        perror("Fork failed");
    }
    return 0;
}
```

`getpid` — returns current process pid

# fork example

```
// not shown: #include various headers
int main(int argc, char *argv[]) {
    pid_t pid
    printf("Pa
    pid_t chil
    if (child_
        /* Par
        pid_t my_pid = getpid();
        printf("[%d] parent of [%d]\n",
                   (int) my_pid,
                   (int) child_pid);
    } else if (child_pid == 0) {
        /* Child Process */
        pid_t my_pid = getpid();
        printf("[%d] child\n",
                   (int) my_pid);
    } else {
        perror("Fork failed");
    }
    return 0;
}
```

cast in case `pid_t` isn't int

POSIX doesn't specify (some systems it is, some not...)

(not necessary if you were using C++'s cout, etc.)

# fork example

```
// not shown: #include various headers
int main(int argc, char *argv[]) {
    pid_
    prin
    pid_
    if (
        pid_t my_pid = getpid();
        printf("[%d] parent of [%d]\n",
               (int) my_pid,
               (int) child_pid);
    } else if (child_pid == 0) {
        /* Child Process */
        pid_t my_pid = getpid();
        printf("[%d] child\n",
               (int) my_pid);
    } else {
        perror("Fork failed");
    }
    return 0;
}
```

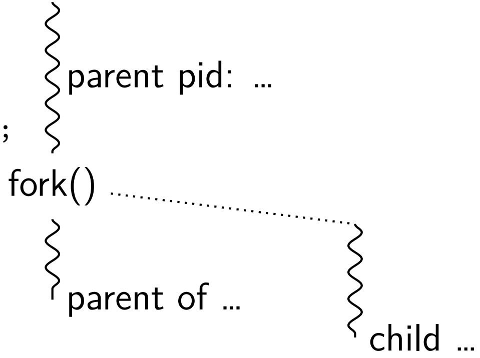
prints out `Fork failed: `*`error message`*

(example *error message*: “Resource temporarily unavailable”)

from error number stored in special global variable `errno`

# fork example

```
// not shown: #include various headers
int main(int argc, char *argv[]) {
    pid_t pid = getpid();
    printf("Parent pid: %d\n", (int) pid);
    pid_t child_pid = fork();
    if (child_pid > 0) {
        /* Parent Process */
        pid_t my_pid = getpid();
        printf("[%d] parent of [%d]\n",
               (int) my_pid,
               (int) child_pid);
    } else if (child_pid == 0) {
        /* Child Process */
        pid_t my_pid = getpid();
        printf("[%d] child\n",
               (int) my_pid);
    } else {
        perror("Fork failed");
    }
    return 0;
}
```



Example output:

```
Parent pid: 100
[100] parent of [432]
[432] child
```

## a fork question

```
int main() {
    pid_t pid = fork();
    if (pid == 0) {
        printf("In child\n");
    } else {
        printf("Child %d\n", pid);
    }
    printf("Done!\n");
}
```

Exercise: Suppose the pid of the parent process is `99` and child is `100`. Give **two** possible outputs. (Assume no crashes, etc.)

## a fork question (2)

```
int x = 0;
int main() {
    pid_t pid = fork();
    int y = 0;
    if (pid == 0) {
        x += 1;
        y += 2;
    } else {
        x += 3;
        y += 4;
    }
    printf("%d %d\n", x, y);
}
```

Exercise: which (possibly multiple) are possible outputs?

A. 1 2 (newline) 3 4 B. 1 2 (newline) 4 4 C. 1 2 (newline) 4 6
D. 3 4 (newline) 1 2 E. 3 4 (newline) 4 6 F. 4 6 (newline) 4 6

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also `posix_spawn` (not widely supported), …

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## exec*

exec* — replace current program with new program

- * — multiple variants
- same pid, new process image

```
int execv(const char *path, const char **argv)
```

- path: new program to run
- argv: array of arguments, termianted by null pointer

also other variants that take argv in different form and/or environment variables*

*environment variables = list of key-value pairs

## execv example

```
...
child_pid = fork();
if (child_pid == 0) {
  /* child process */
  char *args[] = {"ls", "-l", NULL};
  execv("/bin/ls", args);
  /* execv doesn't return when it works.
     So, if we got here, it failed. */
  perror("execv");
  exit(1);
} else if (child_pid > 0) {
  /* parent process */
  ...
}
```

## execv example

```
...
child_pid = fork();
if (child_pid == 0) {
  /* child process */
  char *args[] = {"ls", "-l", NULL};
  execv("/bin/ls",
  /* execv doesn't
     So, if we got
  perror("execv");
  exit(1);
} else if (child_pid > 0) {
  /* parent process */
  ...
}
```

used to compute argv, argc
when program's `main` is run

convention: first argument is program name

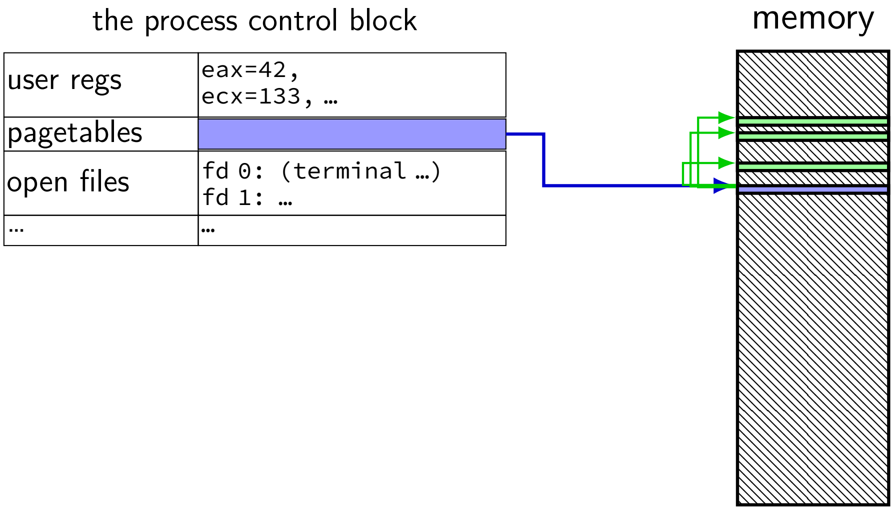
## execv example

```
...
child_pid = fork();
if (child_pid == 0) {
  /* child process */
  char *args[] = {"ls", "-l", NULL};
  execv("/bin/ls", args)
  /* execv doesn't retur
     So, if we got here,
  perror("execv");
  exit(1);
} else if (child_pid > 0
  /* parent process */
  ...
}
```

path of executable to run
need not match first argument
(but probably should match it)

on Unix /bin is a directory
containing many common programs,
including `ls` ('list directory')

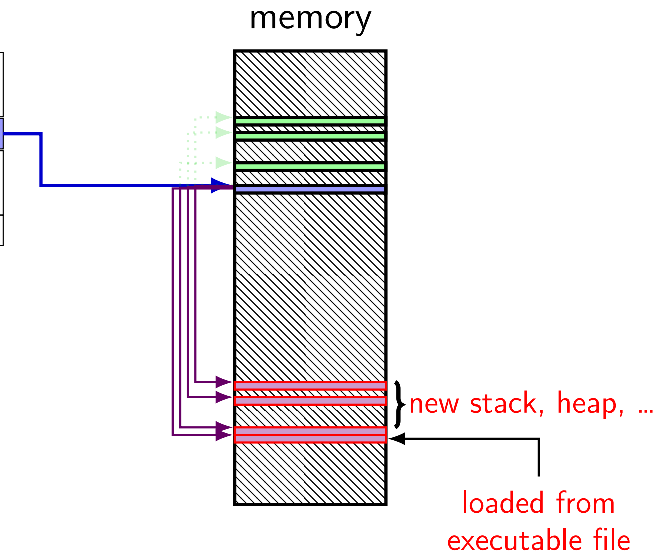
# exec in the kernel



# exec in the kernel

the process control block

| | |
|---|---|
| user regs | `eax=`~~`42`~~*init. val.*, `ecx=`~~`133`~~*init. val.*, … |
| pagetables | 🟦 |
| open files | `fd 0: (terminal …)` `fd 1: …` |
| … | … |



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the process control block

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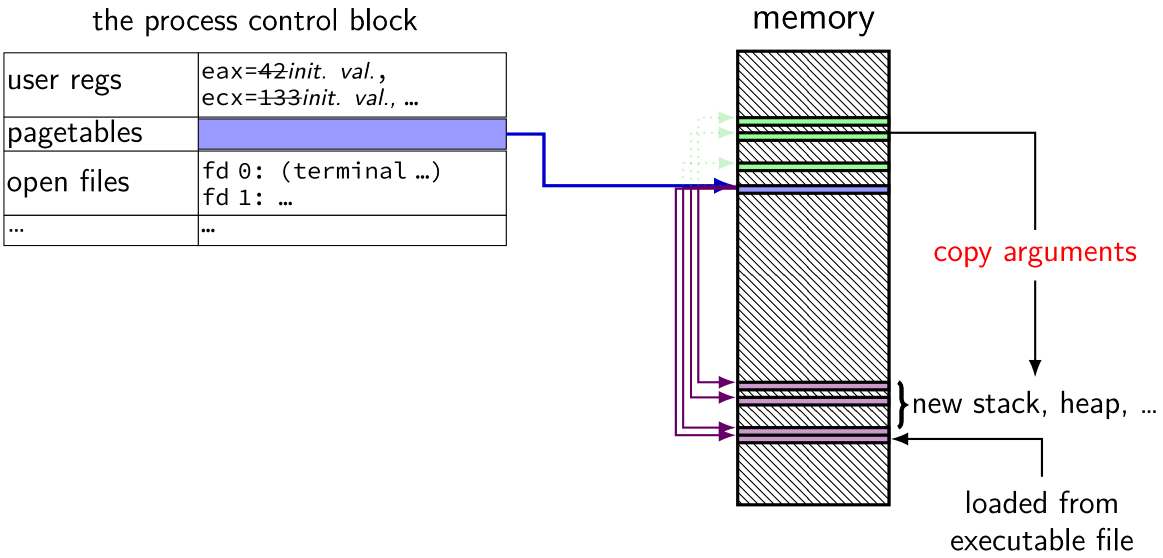
| open files | `fd 0: (terminal …)` `fd 1: …` |
| … | … |



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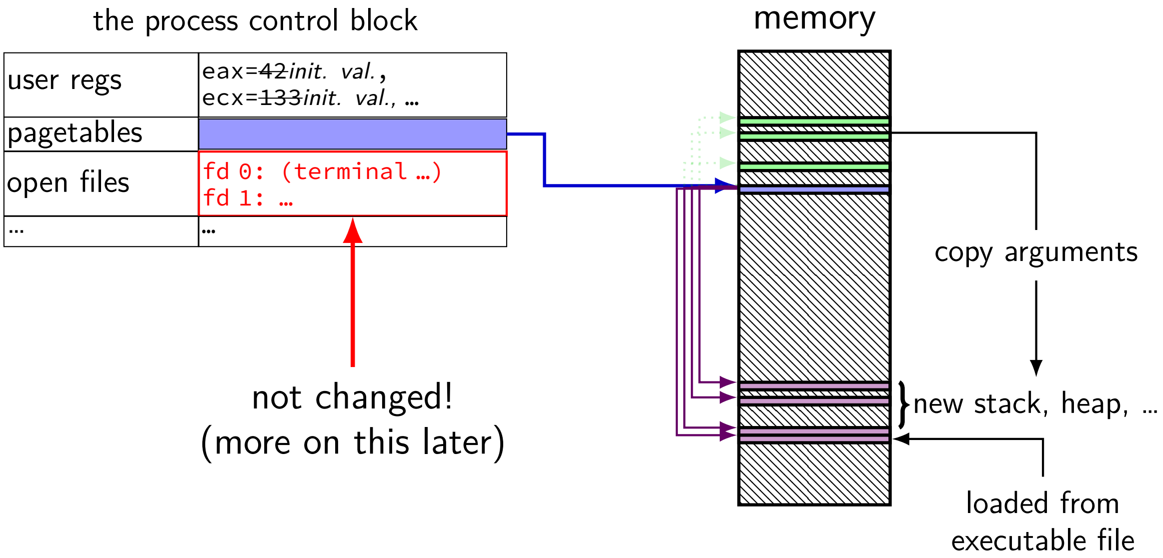

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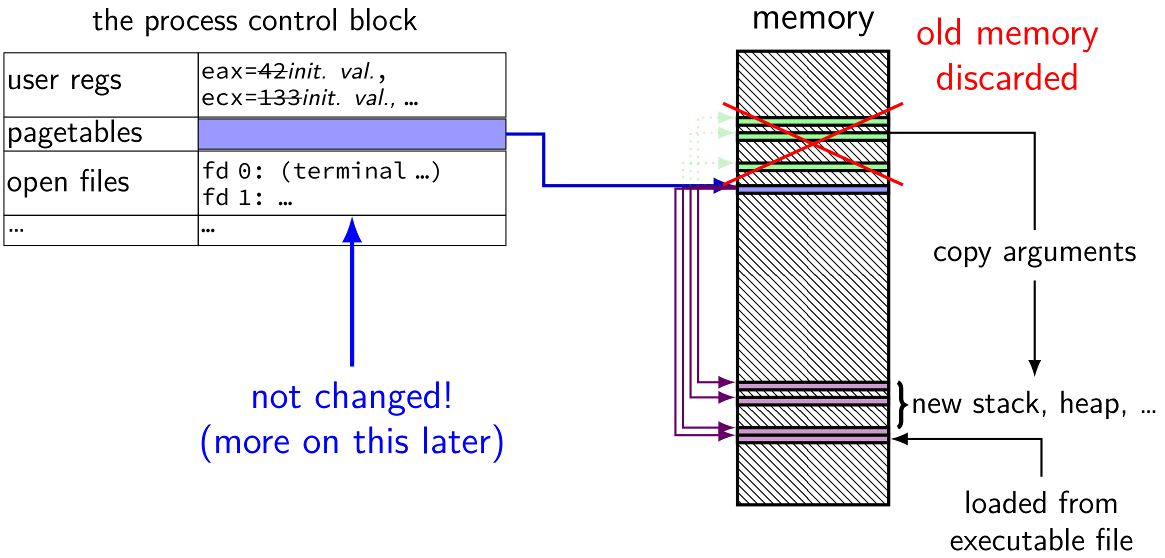


# why fork/exec?

could just have a function to spawn a new program

- Windows `CreateProcess()`; POSIX's (rarely used) `posix_spawn`

some other OSs do this (e.g. Windows)

needs to include API to set new program's state

- e.g. without fork: either:
- need function to set new program's current directory, *or*
- need to change your directory, then start program, then change back
- e.g. with fork: just change your current directory before exec

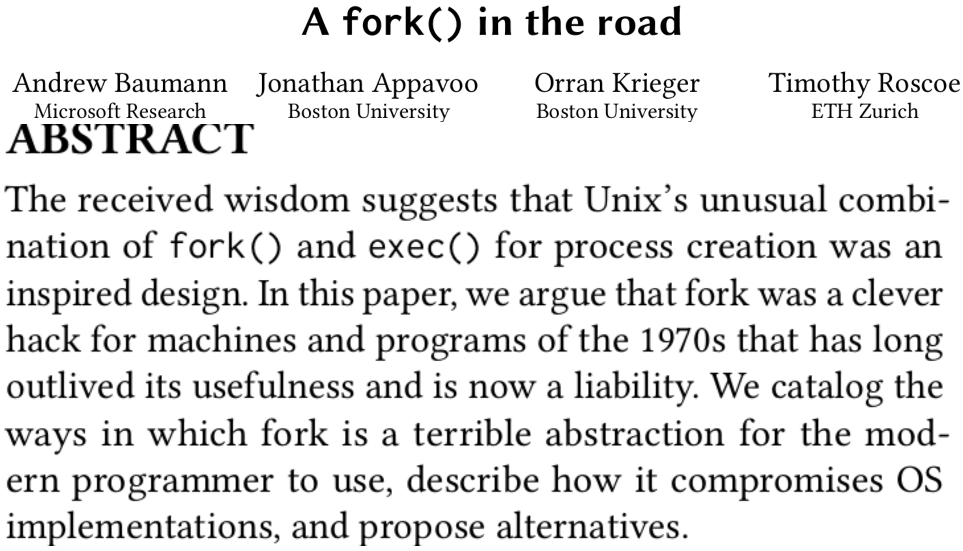
but allows OS to avoid 'copy everything' code

- probably makes OS implementation easier

## posix_spawn

```
pid_t new_pid;
const char argv[] = { "ls", "-l", NULL };
int error_code = posix_spawn(
    &new_pid,
    "/bin/ls",
    NULL /* null = copy current process's open files;
            if not null, do something else */,
    NULL /* null = no special settings for new process */,
    argv,
    NULL /* null = copy current "environment variables",
            if not null, do something else */
);
if (error_code == 0) {
    /* handle error */
}
```

## some opinions (via HotOS '19)



**A fork() in the road**

Andrew Baumann
Microsoft Research

Jonathan Appavoo
Boston University

Orran Krieger
Boston University

Timothy Roscoe
ETH Zurich

**ABSTRACT**

The received wisdom suggests that Unix's unusual combination of `fork()` and `exec()` for process creation was an inspired design. In this paper, we argue that fork was a clever hack for machines and programs of the 1970s that has long outlived its usefulness and is now a liability. We catalog the ways in which fork is a terrible abstraction for the modern programmer to use, describe how it compromises OS implementations, and propose alternatives.

## 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

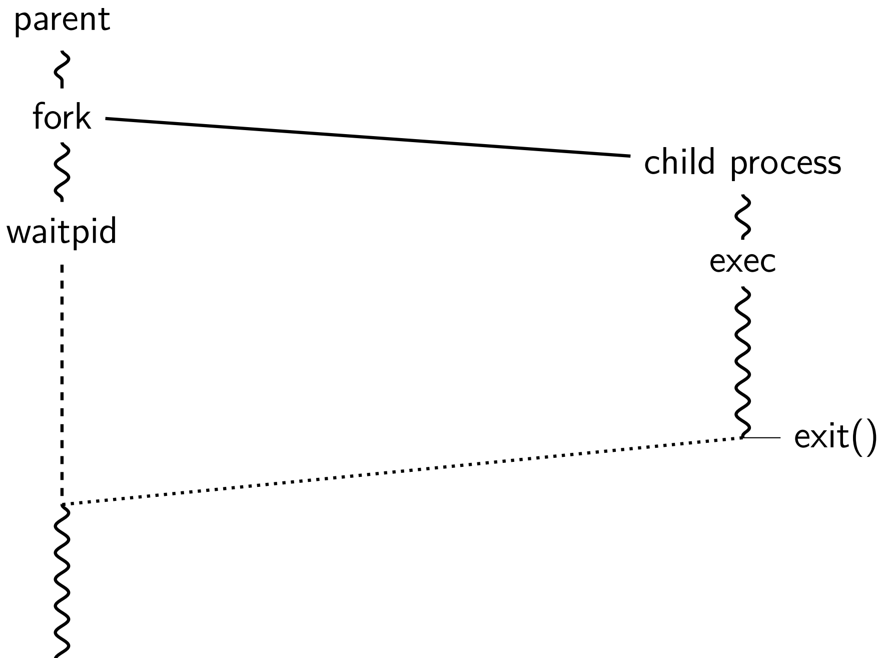
options? see manual page (command `man waitpid`)

- `0` — no options

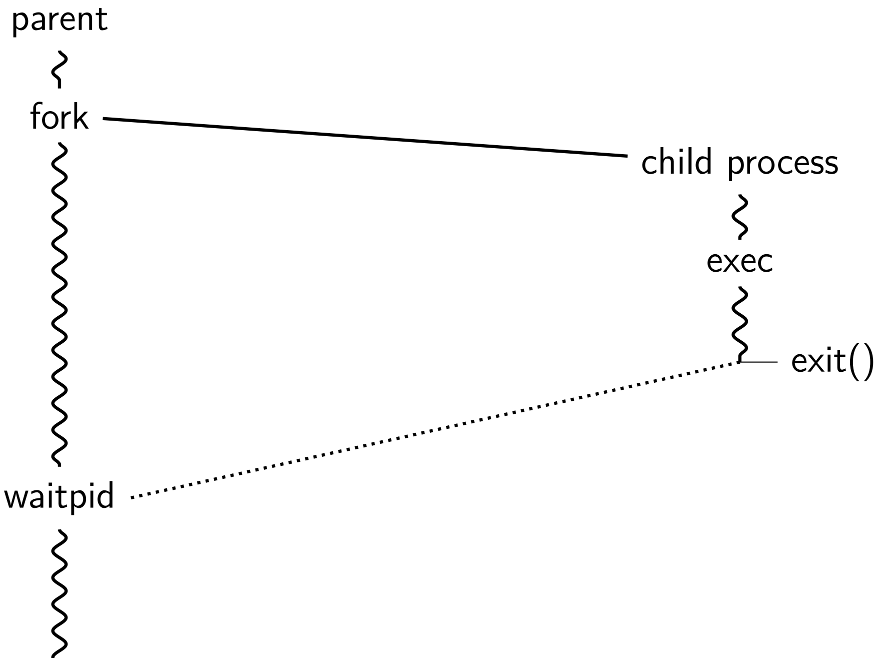
## waitpid example

```
#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 */
      ...
```

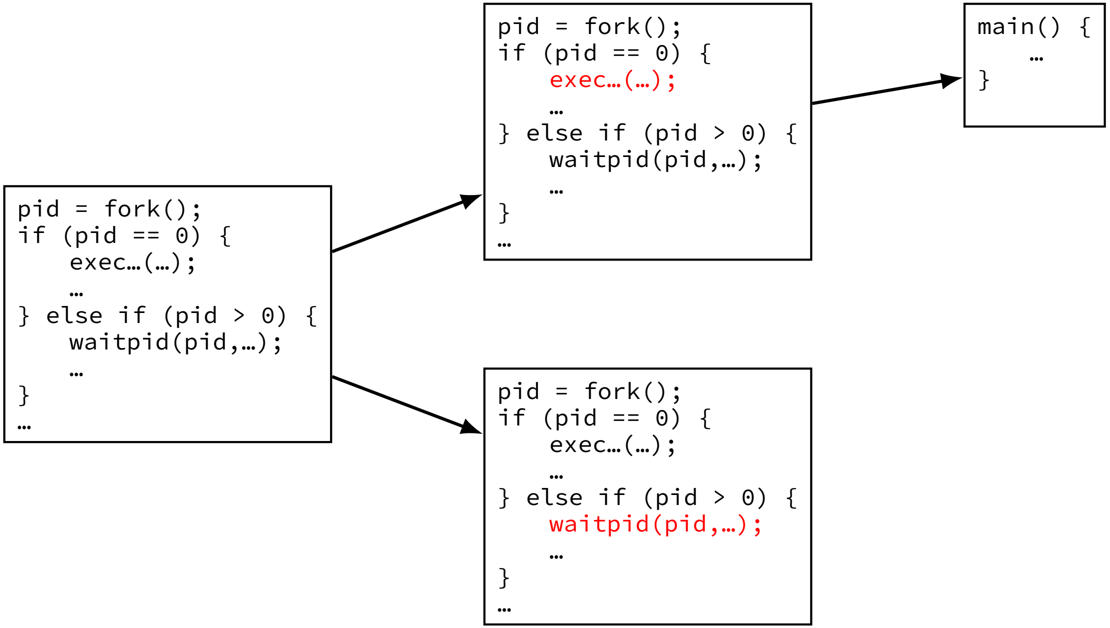
## typical pattern



## typical pattern (alt)



# 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,…);
    …
}
…
```

# POSIX process management

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## 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

## some POSIX command-line features

searching for programs

`ls -l` ≈ `/bin/ls -l`

`make` ≈ `/usr/bin/make`

running in background

```
./someprogram &
```

redirection:

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

pipelines:

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

## some POSIX command-line features

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`ls -l` ≈ `/bin/ls -l`

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running in background

```
./someprogram &
```

redirection:

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

pipelines:

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

## some POSIX command-line features

searching for programs

`ls -l` ≈ `/bin/ls -l`

`make` ≈ `/usr/bin/make`

running in background

```
./someprogram &
```

redirection:

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

pipelines:

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

## file descriptors

```
struct process_info {  /* <-- in the kernel somewhere */
    ...
    struct open_file_description *files[SIZE};
    ...
};
...
process->files[file_descriptor]
```

Unix: every process has
array (or similar) of *open file descriptions*

“open file”: terminal · socket · regular file · pipe

file descriptor = index into array

- usually what’s used with system calls
- stdio.h FILE*s usually have file descriptor + buffer

## 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

## getting file descriptors

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

used internally by fopen(), etc.

also for files without normal filenames...:

```
int fd = shm_open("/shared_memory", O_RDWR, 0666); // shared memory
int socket_fd = socket(AF_INET, SOCK_STREAM, 0); // TCP socket
int term_fd = posix_openpt(O_RDWR); // pseudo-terminal
int pipe_fds[2]; pipe(pipefds); // "pipes" (later)
...
```

## 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

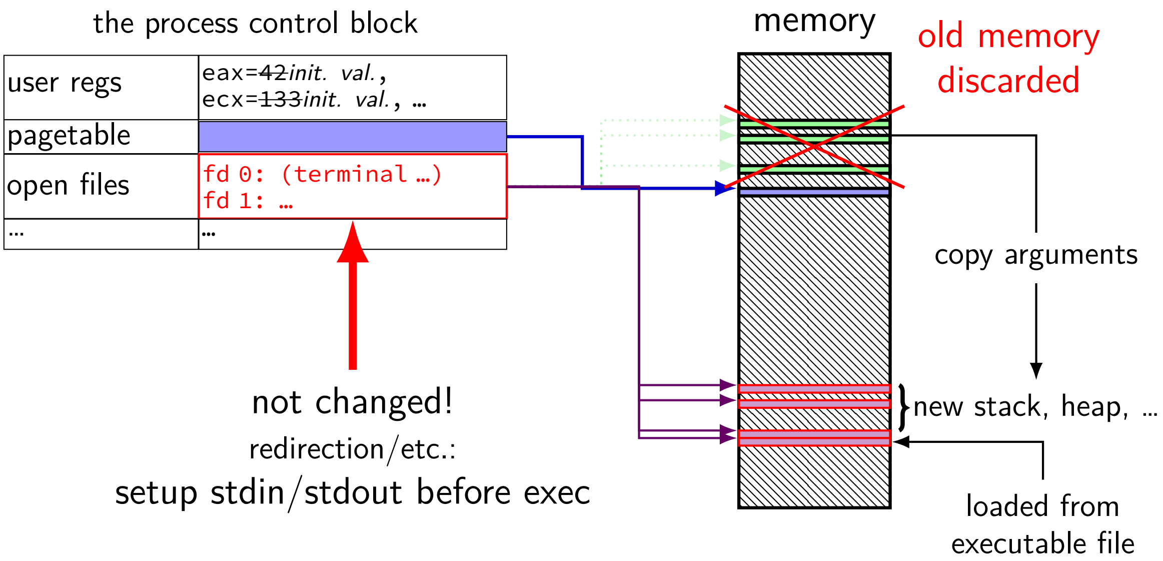
`echo foo > output.txt`:

runs `echo foo`, sends output to `output.txt`

like we copied and pasted the output into that file

(as it was written)

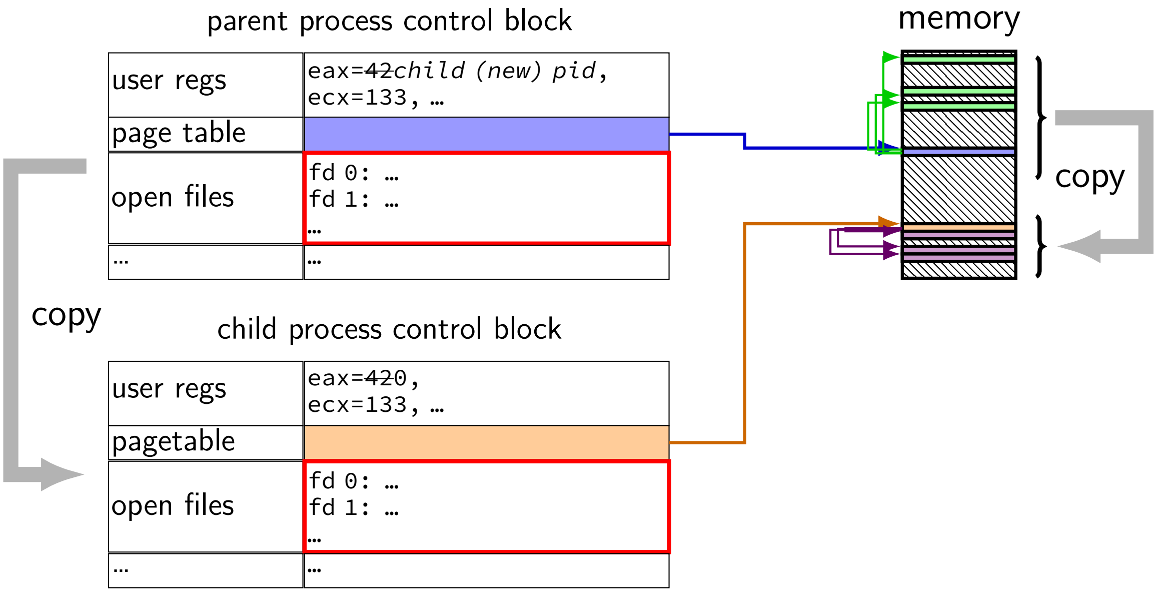
# exec preserves open files



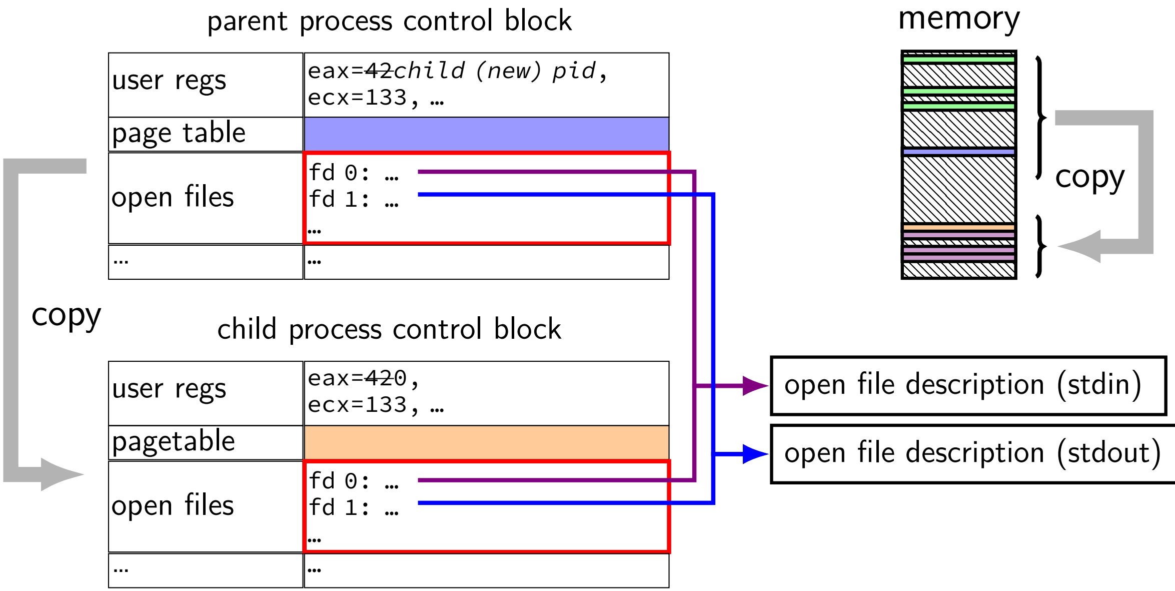
redirection/etc.:

setup stdin/stdout before exec

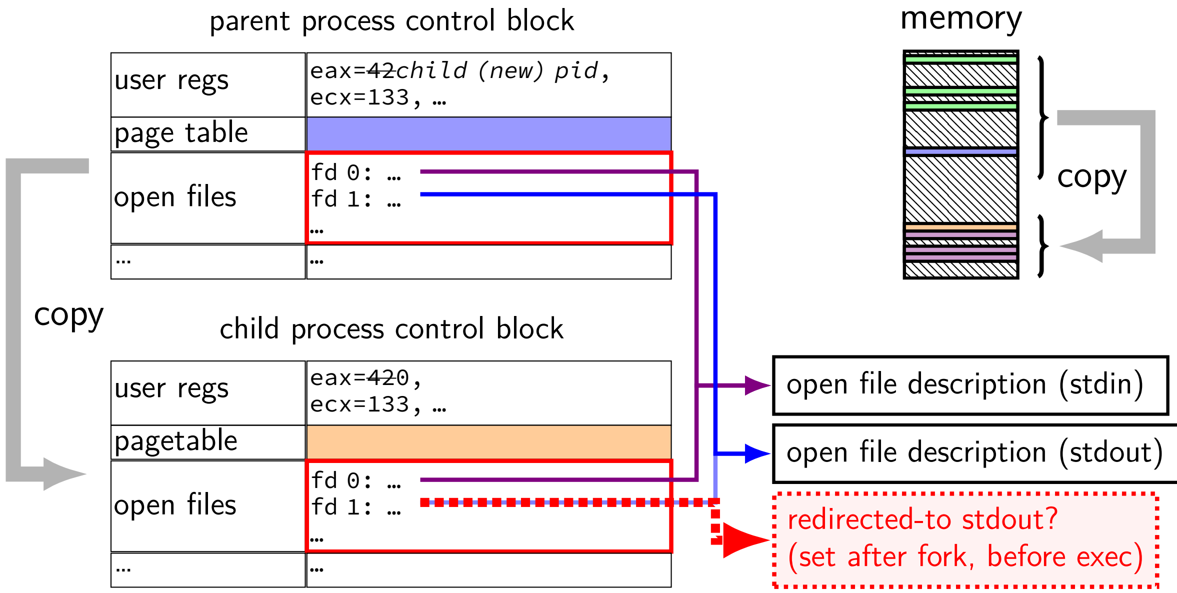
# fork copies open file list



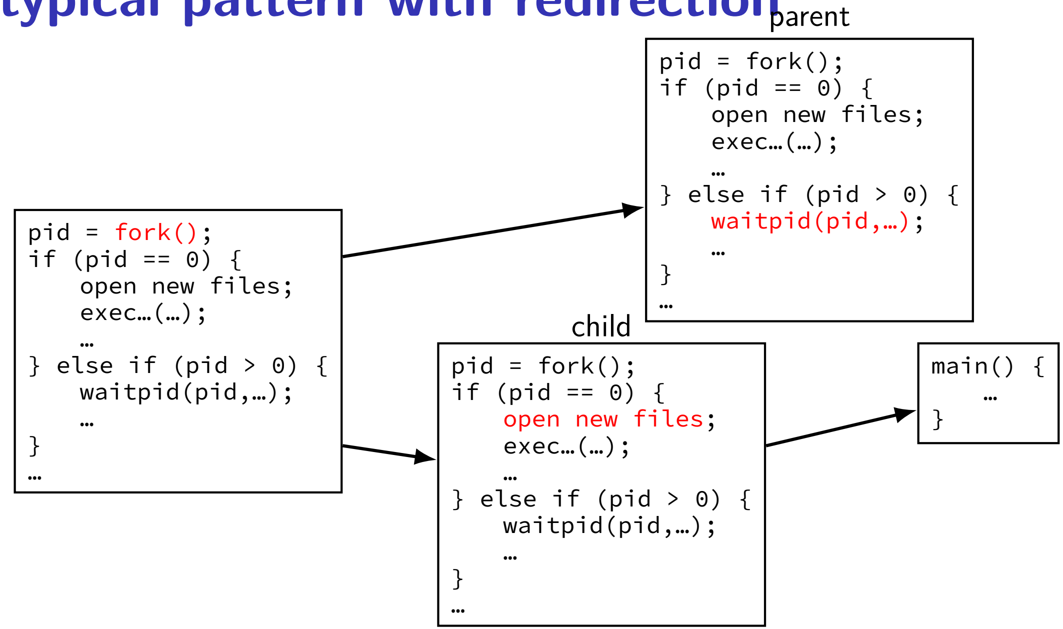
# fork copies open file list


parent process control block
user regs
eax=~~42~~child (new) pid,
ecx=133, …
page table
open files
fd 0: …
fd 1: …
…
…
…
copy
child process control block
user regs
eax=~~42~~0,
ecx=133, …
pagetable
open files
fd 0: …
fd 1: …
…
…
…
memory
copy
open file description (stdin)
open file description (stdout)

# fork copies open file list


parent process control block
user regs
eax=~~42~~*child (new) pid*,
ecx=133, …
page table
open files
fd 0: …
fd 1: …
…
…
…
memory
copy
copy
child process control block
user regs
eax=~~42~~0,
ecx=133, …
pagetable
open files
fd 0: …
fd 1: …
…
…
…
open file description (stdin)
open file description (stdout)
redirected-to stdout?
(set after fork, before exec)

# 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)

(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

```
// something like this in OS code
struct process_info {
    ...
    struct open_file_description *files[SIZE];
    ....
};
...
process->files[STDOUT_FILENO] = process->files[opened-fd];
```

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

## 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

```
// something like this in OS code
struct process_info {
  ...
  struct open_file_description *files[NUM];
};
```

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

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

close: `files[fd] = NULL;`

fork:

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

(plus extra work to avoid leaking memory)

## 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 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
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 fi
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 */ }
```

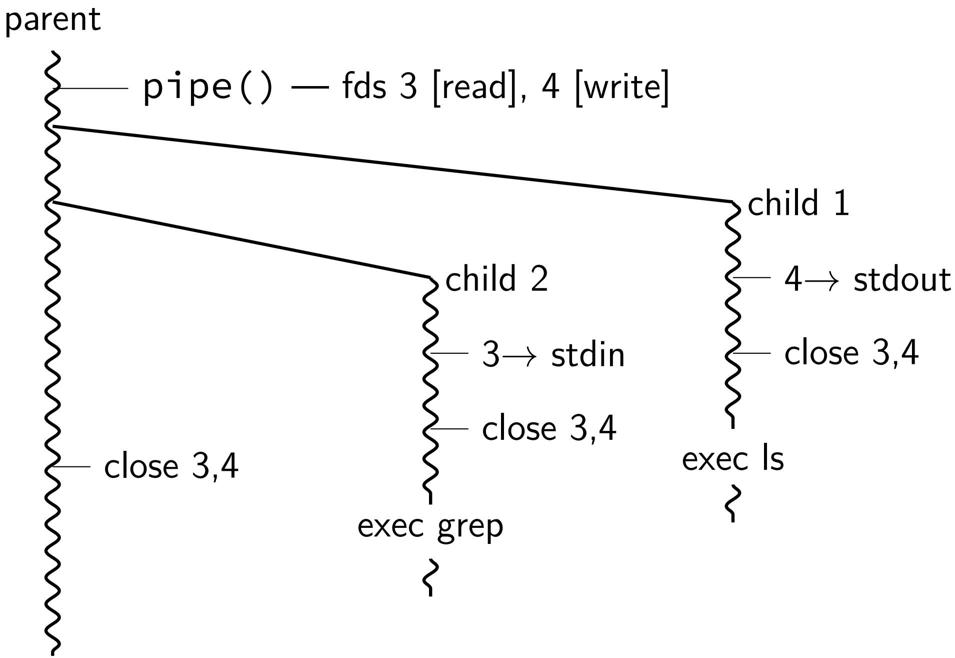
have habit of closing
to avoid 'leaking' file descriptors
you can run out

## 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 the above code outputs `read 0 bytes` instead of `read 1 bytes`. What happened?

## exercise solution

## 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

- one interface for 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

redirection/pipelines

- open() or pipe() to create new file descriptors
- dup2 in child to assign file descriptor to index 0, 1

## backup slides

## output of this?

pid 1000

```
void handle_usr1(int num) {
    write(1, "X", 1);
    kill(2000, SIGUSR1);
    _exit(0);
}

int main() {
    struct sigaction act;
    ...
    act.sa_handler = &handle_usr1;
    sigaction(SIGUSR1, &act, NULL);
    kill(1000, SIGUSR1);
}
```

pid 2000

```
void handle_usr1(int num) {
    write(1, "Y", 1);
    _exit(0);
}

int main() {
    struct sigaction act;
    ...
    act.sa_handler = &handle_usr1;
    sigaction(SIGUSR1, &act, NULL);
}
```

If these run at same time, expected output?

A. XY
B. X
C. Y
D. YX
E. X or XY, depending on timing
F. crash
G. (nothing)
H. something else

# output of this? (v2)

pid 1000

```
void handle_usr1(int num) {
    write(1, "X", 1);
    kill(2000, SIGUSR1);
    _exit(0);
}

int main() {
    struct sigaction act;
    ...
    act.sa_handler = &handle_usr1;
    sigaction(SIGUSR1, &act);
    kill(1000, SIGUSR1);
    while (1) pause();
}
```

pid 2000

```
void handle_usr1(int num) {
    write(1, "Y", 1);
    _exit(0);
}

int main() {
    struct sigaction act;
    ...
    act.sa_handler = &handle_usr1;
    sigaction(SIGUSR1, &act);
    while (1) pause();
}
```

If these run at same time, expected output?

A. XY
B. X
C. Y
D. YX
E. X or XY, depending on timing
F. crash
G. (nothing)
H. something else

## sending signals (1)

pid 1000

```
void handle_usr1(int num) {
    write(1, "Y", 1);
    kill(2000, SIGUSR2);
}

int main() {
    struct sigaction act;
    ... // initialize act
    act.sa_handler = &handle_usr1;
    sigaction(SIGUSR1, &act, NULL);
    sleep(60); // wait for pid 2000 to start
    kill(2000, SIGUSR1);
    while (1) pause();
}
```

## sending signals (2)

pid 1000

```
void handle_usr1(int num) {
    write(1, "Y", 1);
    kill(2000, SIGUSR2);
}

int main() {
    struct sigaction act;
    ... // initialize act
    act.sa_handler = &handle_usr1;
    sigaction(SIGUSR1, &act, NULL);
    sleep(60); // wait for pid 2000 to start
    kill(2000, SIGUSR1);
    while (1) pause();
}
```

pid 2000

```
void handle_usr1(int num) {
    write(1, "X", 1);
    kill(1000, SIGUSR1);
}

void handle_usr2(int num) {
    write(1, "Z", 1);
    kill(1000, SIGTERM);
    _exit(0);
}

int main() {
    struct sigaction act;
    ... // initialize act
    act.sa_handler = &handle_usr1;
    sigaction(SIGUSR1, &act, NULL);
    act.sa_handler = &handle_usr2;
    sigaction(SIGUSR2, &act, NULL);
    while (1) pause();
}
```

## sending signals (2)

pid 1000

```
void handle_usr1(int num) {
    write(1, "Y", 1);
    kill(2000, SIGUSR2);
}

int main() {
    struct sigaction act;
    ... // initialize act
    act.sa_handler = &handle_usr1;
    sigaction(SIGUSR1, &act, NULL);
    sleep(60); // wait for pid 2000 to start
    kill(2000, SIGUSR1);
    while (1) pause();
}
```

pid 2000

```
void handle_usr1(int num) {
    write(1, "X", 1);
    kill(1000, SIGUSR1);
}

void handle_usr2(int num) {
    write(1, "Z", 1);
    kill(1000, SIGTERM);
    _exit(0);
}

int main() {
    struct sigaction act;
    ... // initialize act
    act.sa_handler = &handle_usr1;
    sigaction(SIGUSR1, &act, NULL);
    act.sa_handler = &handle_usr2;
    sigaction(SIGUSR2, &act, NULL);
    while (1) pause();
}
```

## sending signals (2)

pid 1000

```
void handle_usr1(int num) {
    write(1, "Y", 1);
    kill(2000, SIGUSR2);
}

int main() {
    struct sigaction act;
    ... // initialize act
    act.sa_handler = &handle_usr1;
    sigaction(SIGUSR1, &act, NULL);
    sleep(60); // wait for pid 2000 to start
    kill(2000, SIGUSR1);
    while (1) pause();
}
```

pid 2000

```
void handle_usr1(int num) {
    write(1, "X", 1);
    kill(1000, SIGUSR1);
}

void handle_usr2(int num) {
    write(1, "Z", 1);
    kill(1000, SIGTERM);
    _exit(0);
}

int main() {
    struct sigaction act;
    ... // initialize act
    act.sa_handler = &handle_usr1;
    sigaction(SIGUSR1, &act, NULL);
    act.sa_handler = &handle_usr2;
    sigaction(SIGUSR2, &act, NULL);
    while (1) pause();
}
```

# sending signals (2)

pid 1000

```c
void handle_usr1(int num) {
    write(1, "Y", 1);
    kill(2000, SIGUSR2);
}

int main() {
    struct sigaction act;
    ... // initialize act
    act.sa_handler = &handle_usr1;
    sigaction(SIGUSR1, &act, NULL);
    sleep(60); // wait for pid 2000 to start
    kill(2000, SIGUSR1);
    while (1) pause();
}
```

pid 2000

```c
void handle_usr1(int num) {
    write(1, "X", 1);
    kill(1000, SIGUSR1);
}

void handle_usr2(int num) {
    write(1, "Z", 1);
    kill(1000, SIGTERM);
    _exit(0);
}

int main() {
    struct sigaction act;
    ... // initialize act
    act.sa_handler = &handle_usr1;
    sigaction(SIGUSR1, &act, NULL);
    act.sa_handler = &handle_usr2;
    sigaction(SIGUSR2, &act, NULL);
    while (1) pause();
}
```

## sending signals (2)

pid 1000

```
void handle_usr1(int num) {
    write(1, "Y", 1);
    kill(2000, SIGUSR2);
}

int main() {
    struct sigaction act;
    ... // initialize act
    act.sa_handler = &handle_usr1;
    sigaction(SIGUSR1, &act, NULL);
    sleep(60); // wait for pid 2000 to start
    kill(2000, SIGUSR1);
    while (1) pause();
}
```

pid 2000

```
void handle_usr1(int num) {
    write(1, "X", 1);
    kill(1000, SIGUSR1);
}

void handle_usr2(int num) {
    write(1, "Z", 1);
    kill(1000, SIGTERM);
    _exit(0);
}

int main() {
    struct sigaction act;
    ... // initialize act
    act.sa_handler = &handle_usr1;
    sigaction(SIGUSR1, &act, NULL);
    act.sa_handler = &handle_usr2;
    sigaction(SIGUSR2, &act, NULL);
    while (1) pause();
}
```

# sending signals (2)

pid 1000

```
void handle_usr1(int num) {
    write(1, "Y", 1);
    kill(2000, SIGUSR2);
}

int main() {
    struct sigaction act;
    ... // initialize act
    act.sa_handler = &handle_usr1;
    sigaction(SIGUSR1, &act, NULL);
    sleep(60); // wait for pid 2000 to start
    kill(2000, SIGUSR1);
    while (1) pause();
}
```

pid 2000

```
void handle_usr1(int num) {
    write(1, "X", 1);
    kill(1000, SIGUSR1);
}

void handle_usr2(int num) {
    write(1, "Z", 1);
    kill(1000, SIGTERM);
    _exit(0);
}

int main() {
    struct sigaction act;
    ... // initialize act
    act.sa_handler = &handle_usr1;
    sigaction(SIGUSR1, &act, NULL);
    act.sa_handler = &handle_usr2;
    sigaction(SIGUSR2, &act, NULL);
    while (1) pause();
}
```

## exit statuses

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

## 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\n", WTERMSIG(status));
  } 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\n", WTERMSIG(status));
  } else {
      ...
  }
```

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

W* macros to decode it

## shell

allow user (= person at keyboard) to run applications

user's wrapper around process-management functions

## 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?

## searching for programs

POSIX convention: PATH *environment variable*

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

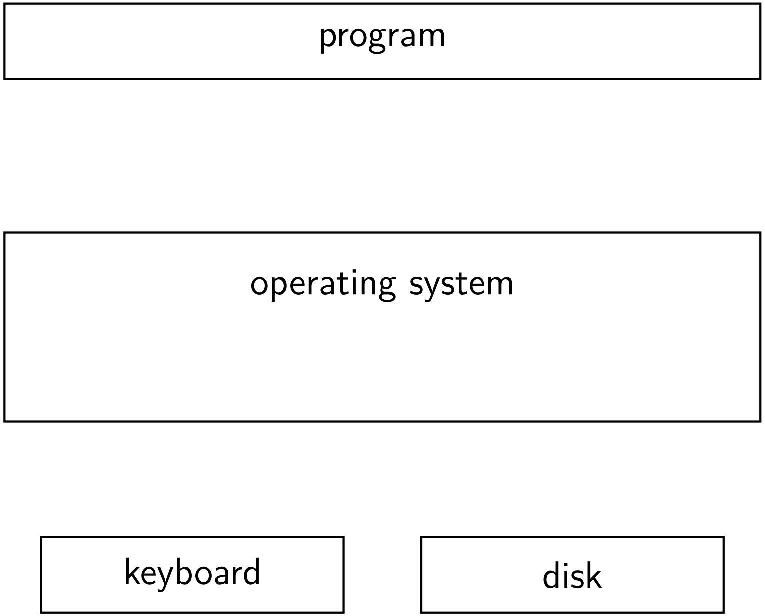
environment variables = key/value pairs stored with process

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

one way to implement: [pseudocode]

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

## kernel buffering (reads)



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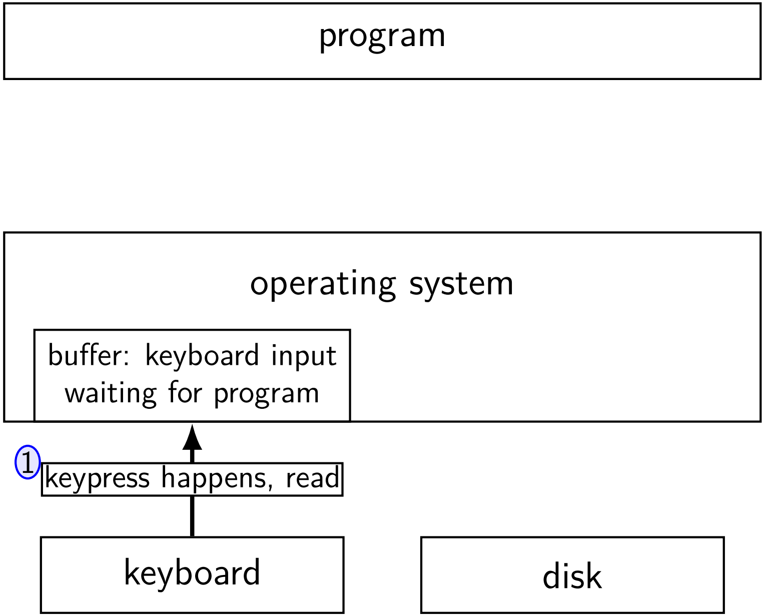

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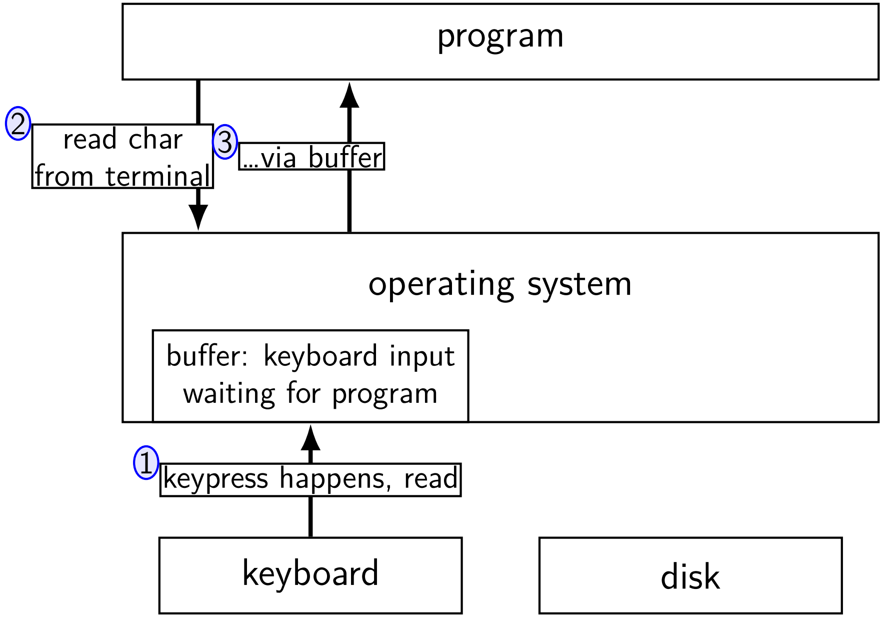

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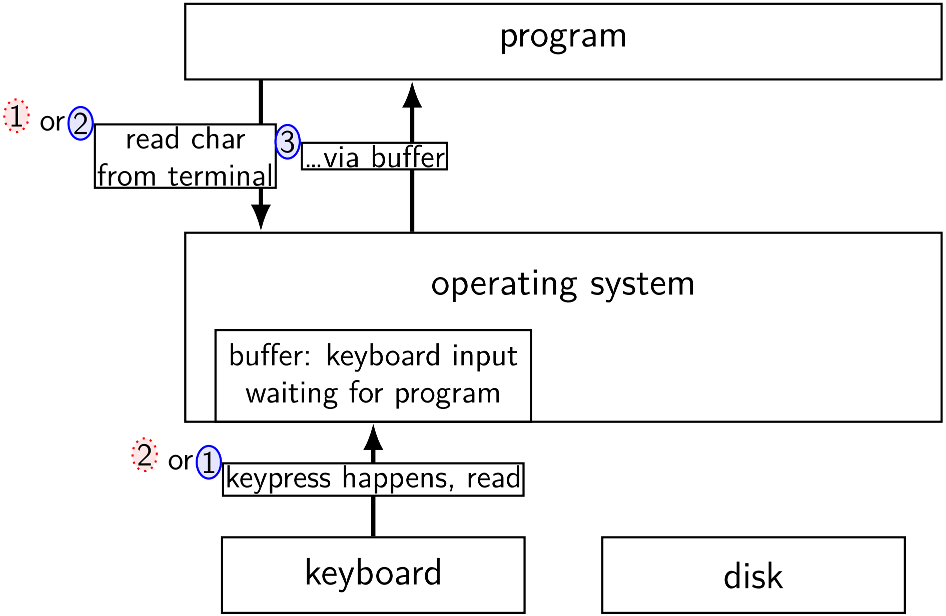

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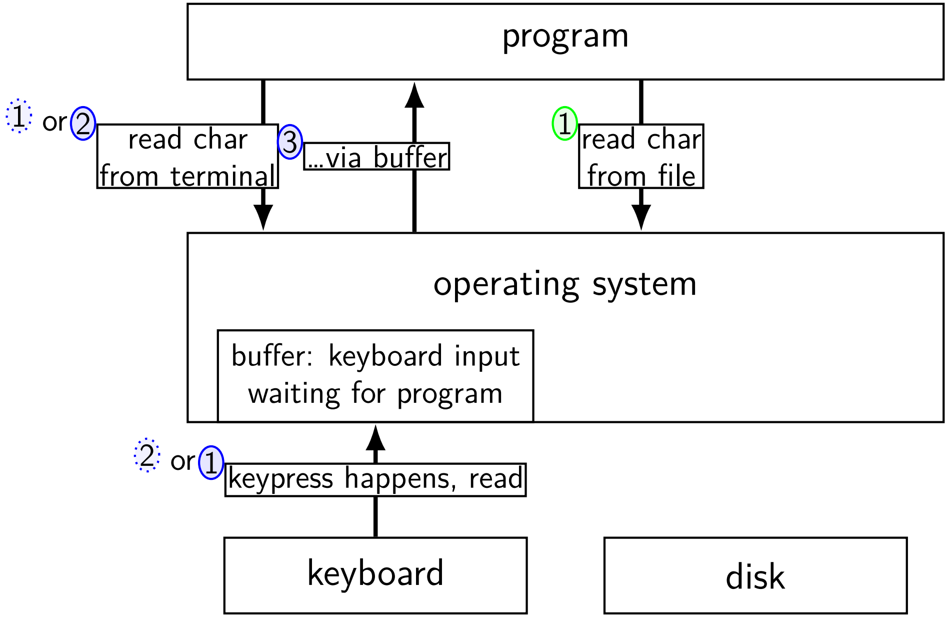

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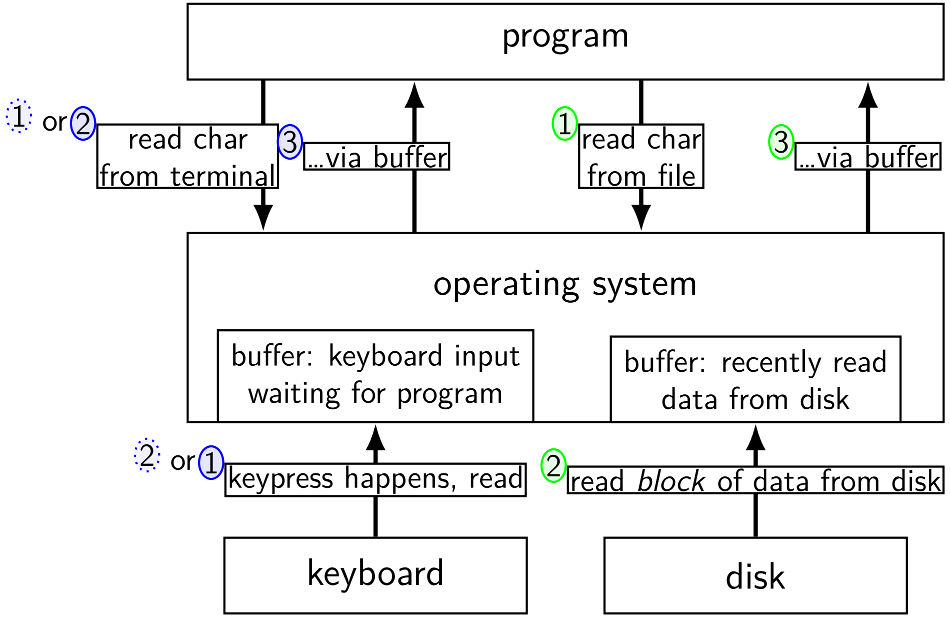

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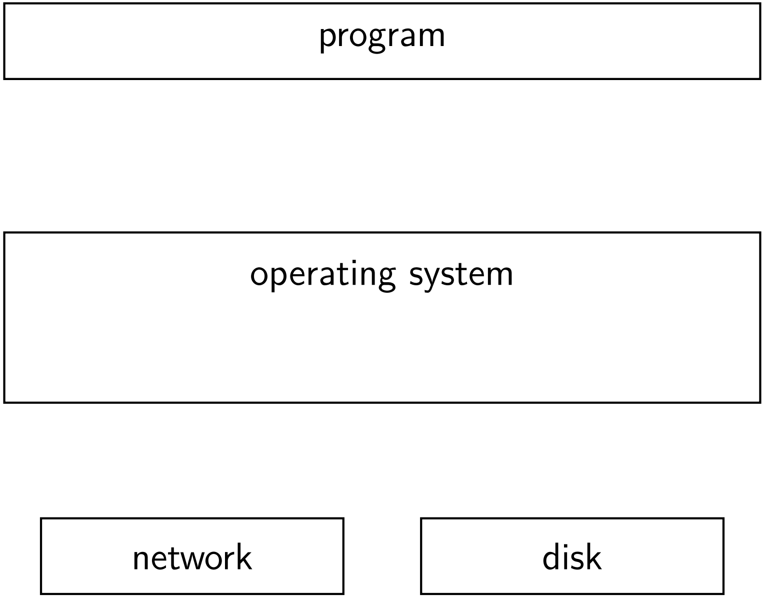

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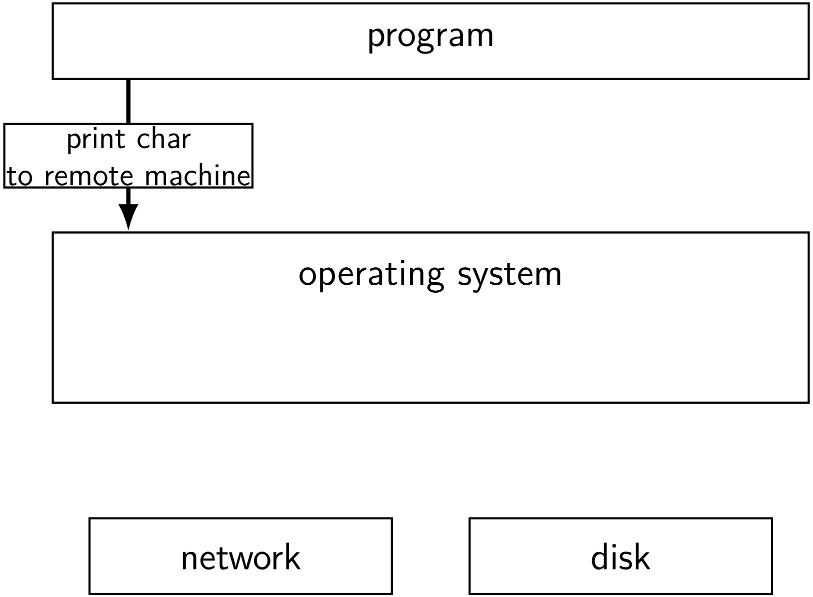

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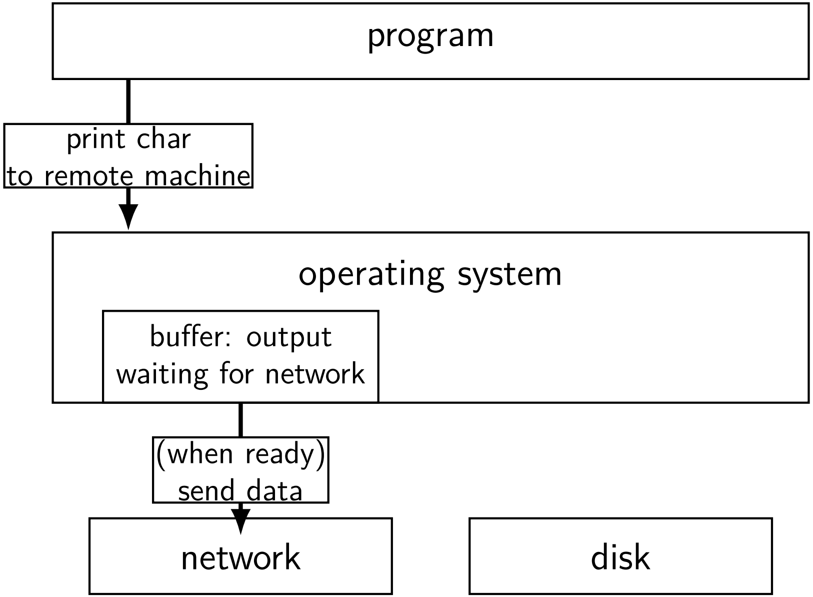

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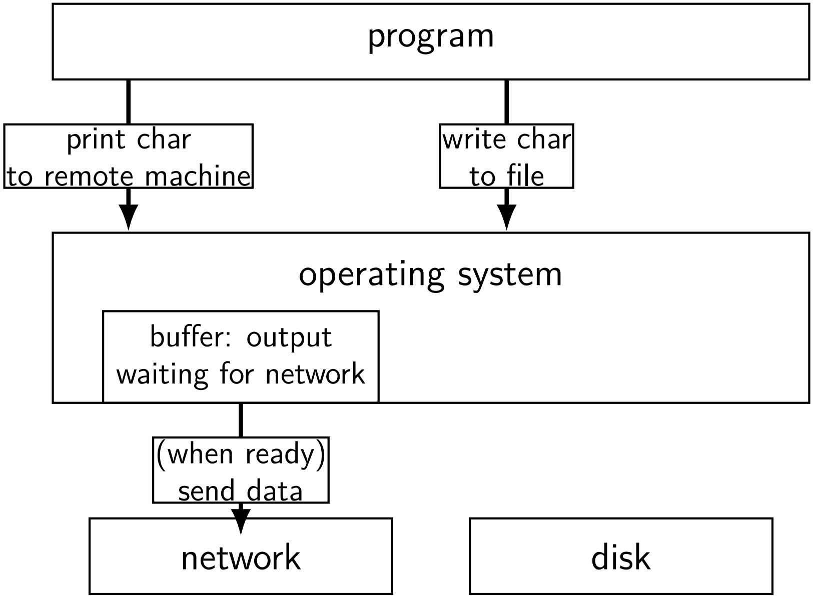
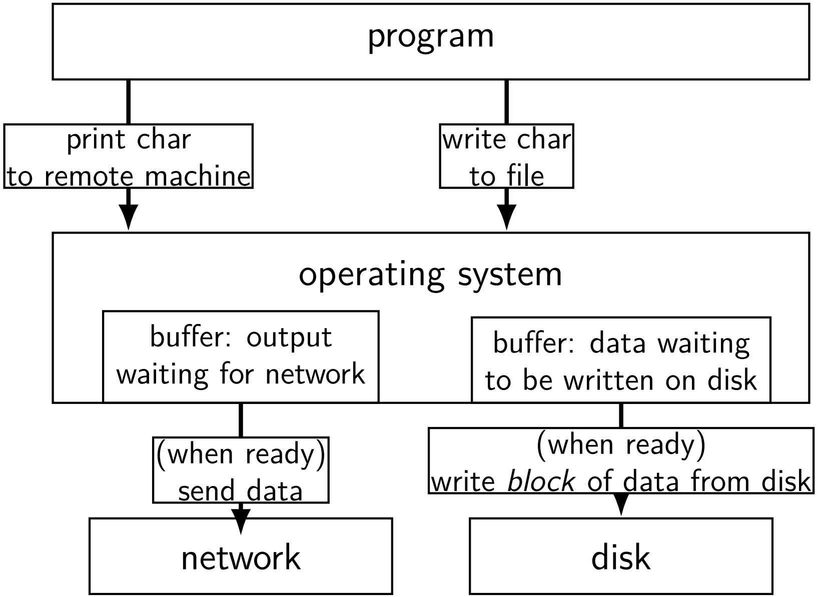


## kernel buffering (writes)


program
print char to remote machine
write char to file
operating system
buffer: output waiting for network
buffer: data waiting to be written on disk
(when ready) send data
(when ready) write *block* of data from disk
network
disk

## read/write operations

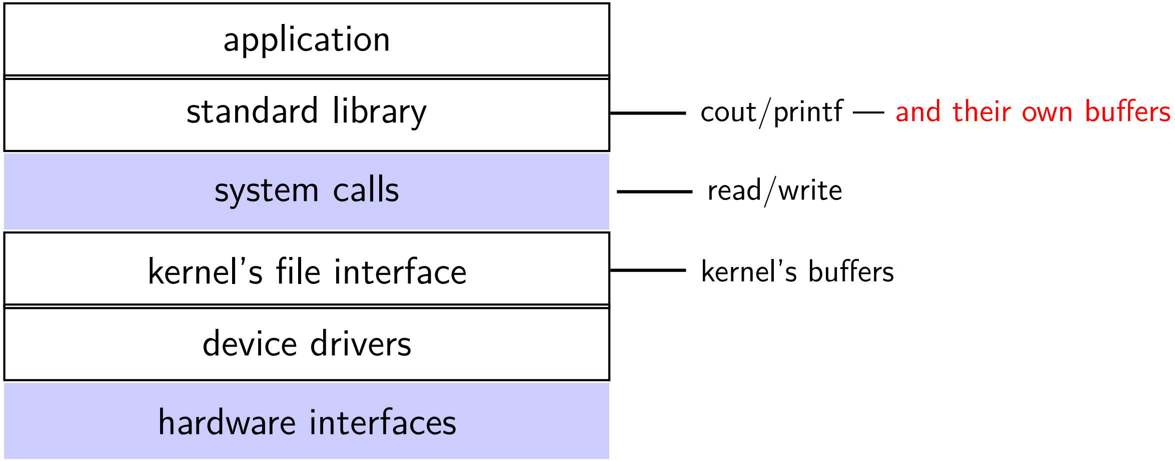
read()/write(): move data into/out of buffer

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

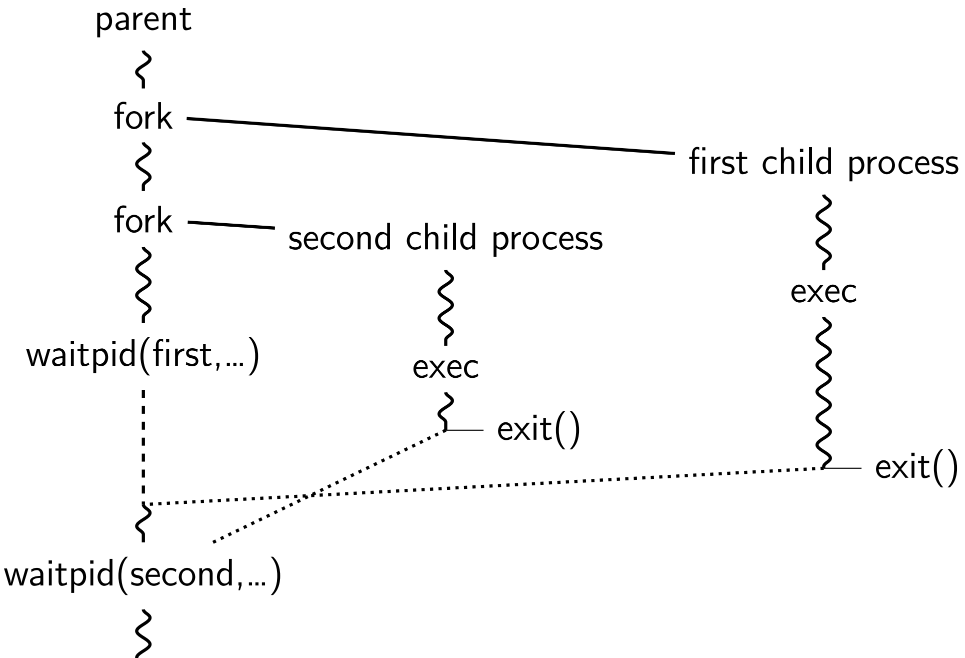
## pipe() and blocking

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?

## pattern with multiple?



## this class: focus on Unix

Unix-like OSes will be our focus

we have source code

used to from 2150, etc.?

have been around for a while

xv6 imitates Unix

# Unix history

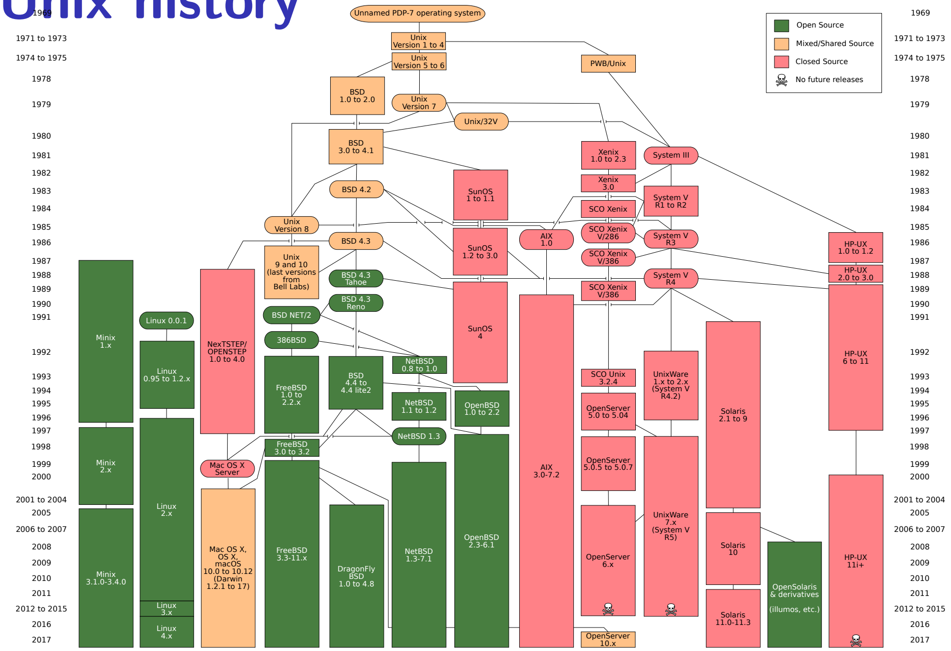


image: Wikpedia/Eraserhead1+Infinity0+Sav_vas

## POSIX: standardized Unix

Portable Operating System Interface (POSIX)

“standard for Unix”

current version online:
https://pubs.opengroup.org/onlinepubs/9699919799/

(almost) followed by most current Unix-like OSes

…but OSes add extra features

…and POSIX doesn’t specify everything

## what POSIX defines

POSIX specifies the library and shell interface

- source code compatibility

doesn't care what is/is not a system call...

doesn't specify binary formats...

idea: write applications for POSIX, recompile and run on all implementations

- this was a very important goal in the 80s/90s
- at the time, no dominant Unix-like OS (Linux was very immature)

## getpid

```
pid_t my_pid = getpid();
printf("my pid is %ld\n", (long) my_pid);
```

## process ids in ps

```
cr4bd@machine:~$ ps
  PID TTY          TIME CMD
14777 pts/3    00:00:00 bash
14798 pts/3    00:00:00 ps
```

## 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;
/* cast to void * not needed in C */
while ((amount_read = read(STDIN_FILENO, (void*) &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 */
}
```

## write example

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

## aside: environment variables (1)

key=value pairs associated with every process:

```
$ printenv
MODULE_VERSION_STACK=3.2.10
MANPATH=:/opt/puppetlabs/puppet/share/man
XDG_SESSION_ID=754
HOSTNAME=labsrv01
SELINUX_ROLE_REQUESTED=
TERM=screen
SHELL=/bin/bash
HISTSIZE=1000
SSH_CLIENT=128.143.67.91 58432 22
SELINUX_USE_CURRENT_RANGE=
QTDIR=/usr/lib64/qt-3.3
OLDPWD=/zf14/cr4bd
QTINC=/usr/lib64/qt-3.3/include
SSH_TTY=/dev/pts/0
QT_GRAPHICSSYSTEM_CHECKED=1
USER=cr4bd
LS_COLORS=rs=0:di=01;34:ln=01;36:mh=00:pi=40;33:so=01;35:do=01;35:bd=40;33;01:cd=40;33;01:or
MODULE_VERSION=3.2.10
MAIL=/var/spool/mail/cr4bd
PATH=/zf14/cr4bd/.cargo/bin:/zf14/cr4bd/bin:/usr/lib64/qt-3.3/bin:/usr/local/bin:/usr/bin:/u
PWD=/zf14/cr4bd
LANG=en_US.UTF-8
MODULEPATH=/sw/centos/Modules/modulefiles:/sw/linux-any/Modules/modulefiles
LOADEDMODULES=
KDEDIRS=/usr
```

## aside: environment variables (2)

environment variable library functions:

`getenv("KEY")` → *value*
`putenv("KEY=`*value*`")` (sets KEY to *value*)
`setenv("KEY", "value")` (sets KEY to *value*)

```
int execve(char *path, char **argv, char **envp)
```

```
    char *envp[] = { "KEY1=value1", "KEY2=value2", NULL };
    char *argv[] = { "somecommand", "some arg", NULL };
    execve("/path/to/somecommand", argv, envp);
```

normal exec versions — keep same environment variables

## aside: environment variables (3)

interpretation up to programs, but common ones…

`PATH=/bin:/usr/bin`

> to run a program 'foo', look for an executable in `/bin/foo`, then `/usr/bin/foo`

`HOME=/zf14/cr4bd`

> current user's home directory is '/zf14/cr4bd'

`TERM=screen-256color`

> your output goes to a 'screen-256color'-style terminal

…

## 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, ...);
    ...
}
```

## 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 */
  }
```

## 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);
}
```

## ‘waiting’ without waiting

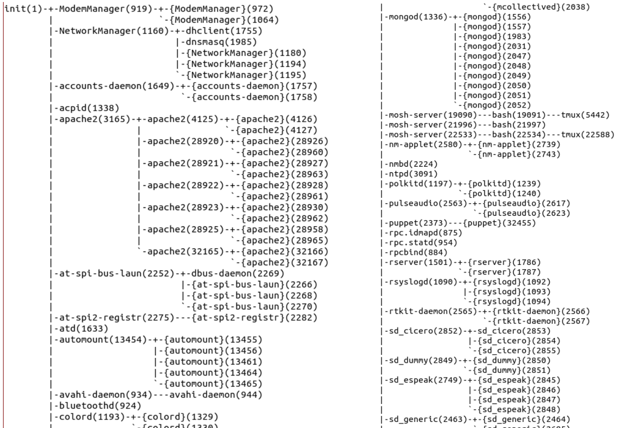
```
#include <sys/wait.h>
...
  pid_t return_value = waitpid(child_pid, &status, WNOHANG);
  if (return_value == (pid_t) 0) {
    /* child process not done yet */
  } else if (child_pid == (pid_t) -1) {
    /* error */
  } else {
    /* handle child_pid exiting */
  }
```

## 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 (Linux `pstree` command):



```
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)
```

## 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()`s (or equivalent) 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

## 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 (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

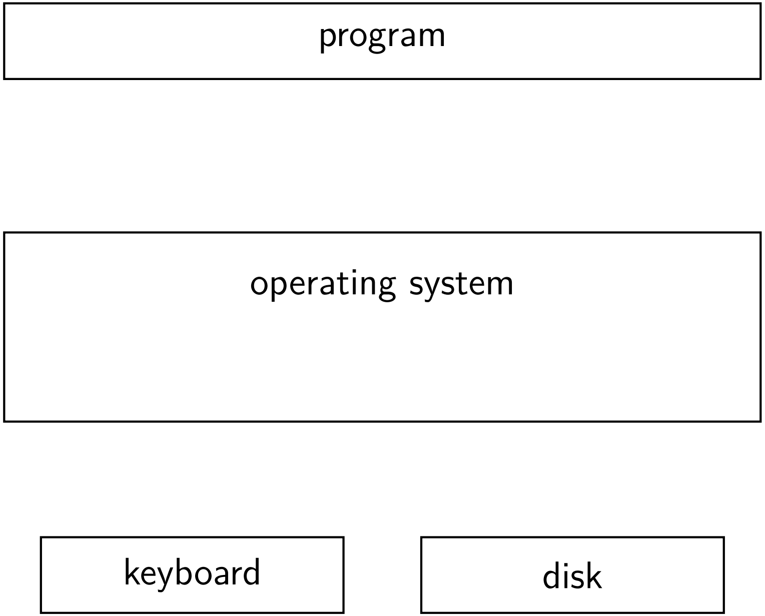
usually only happen on error or interruption

- 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.

## kernel buffering (reads)



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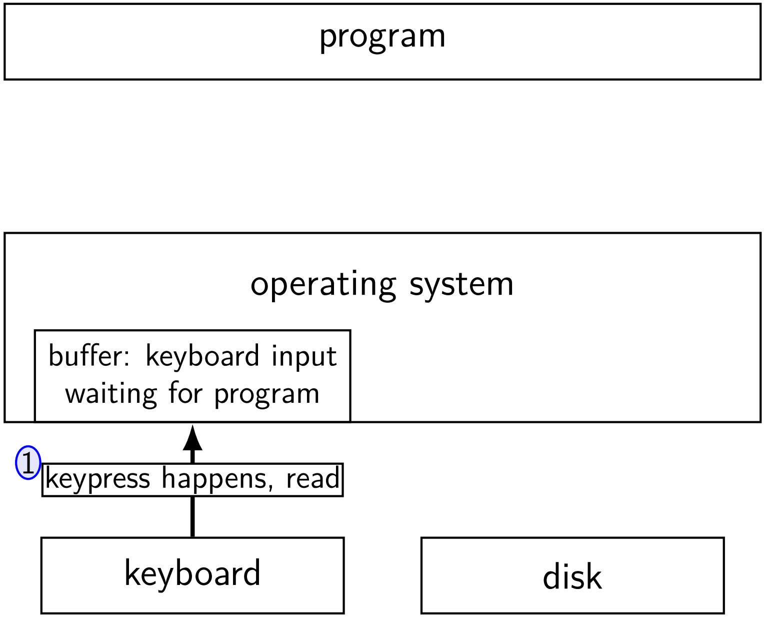

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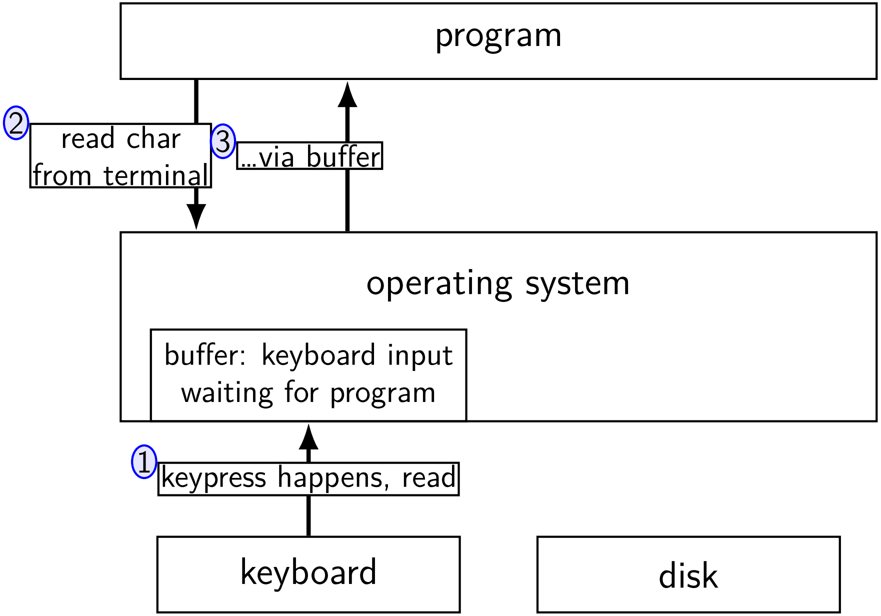

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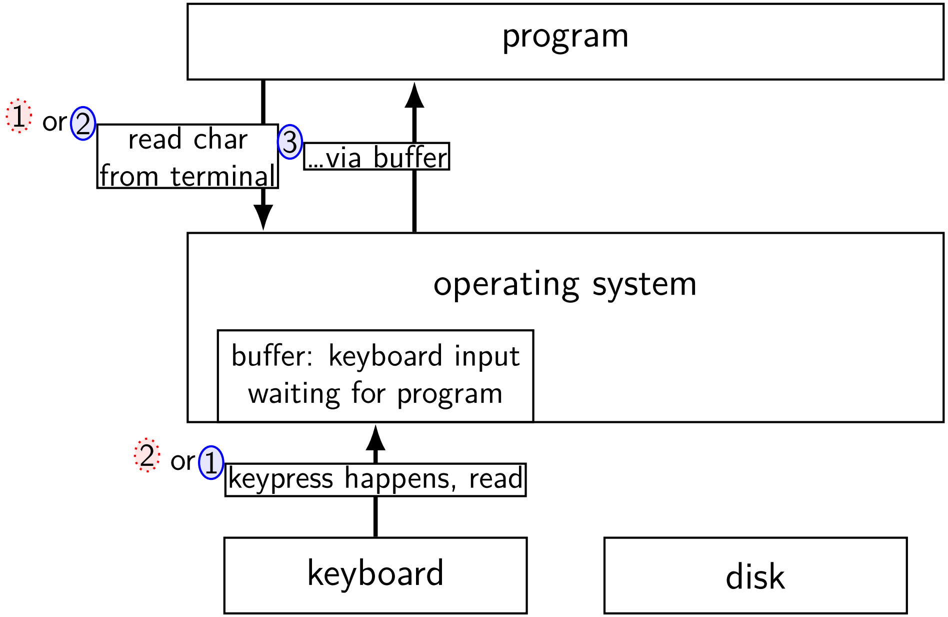

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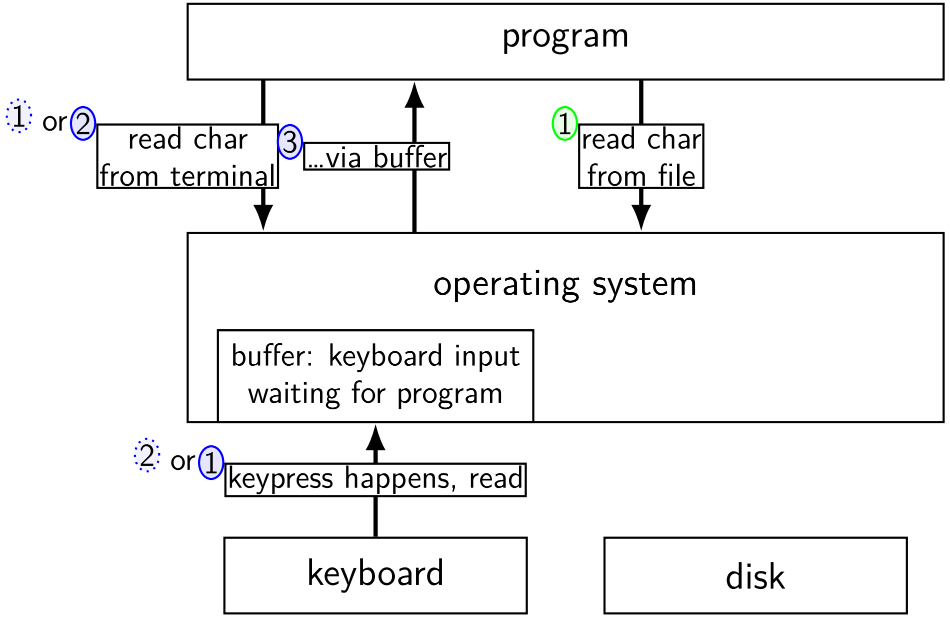

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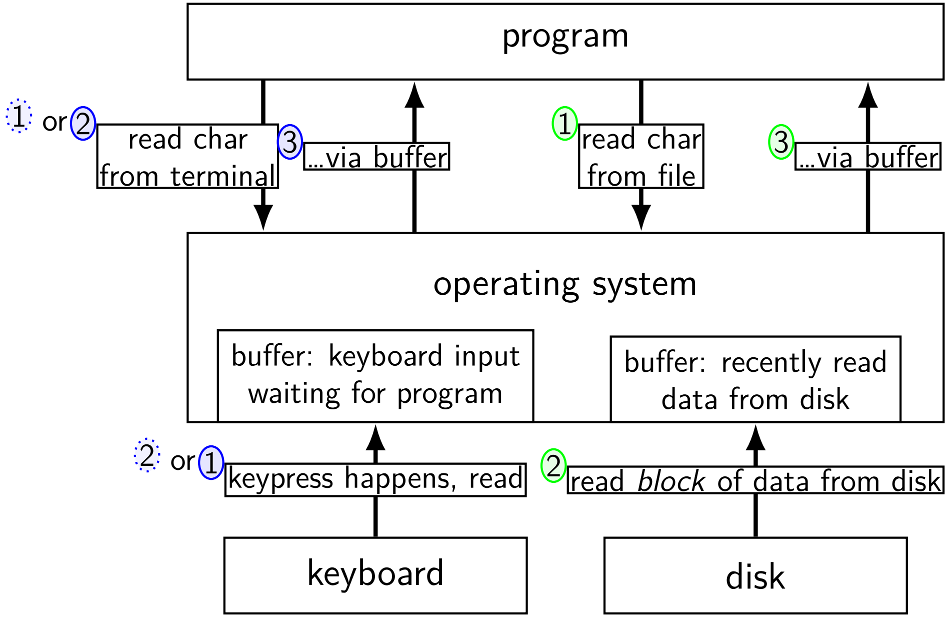

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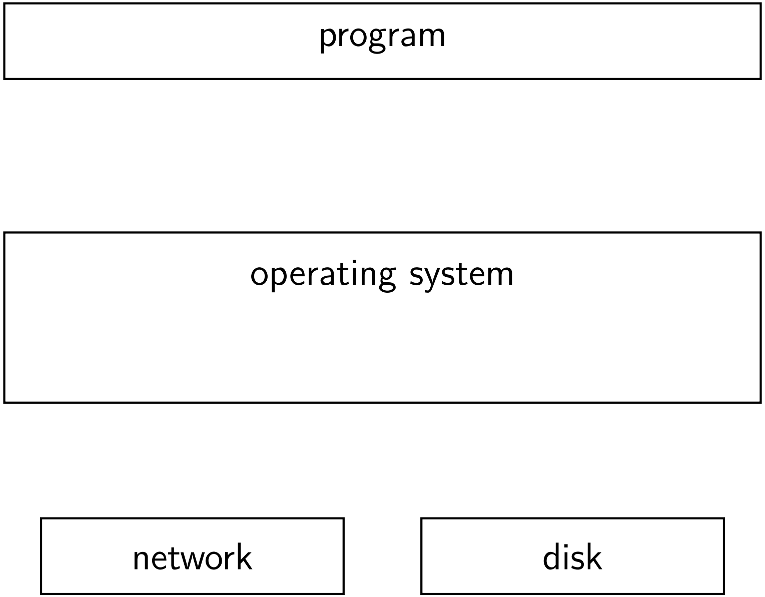

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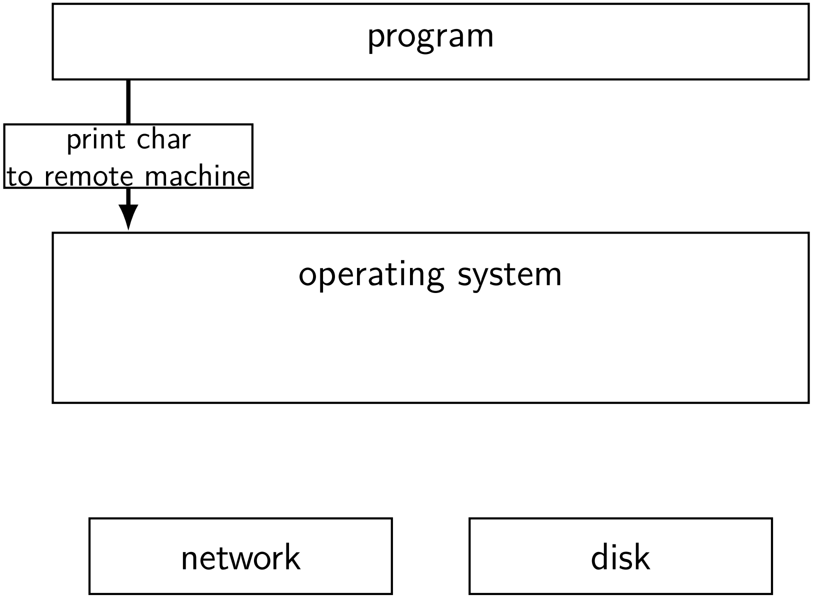

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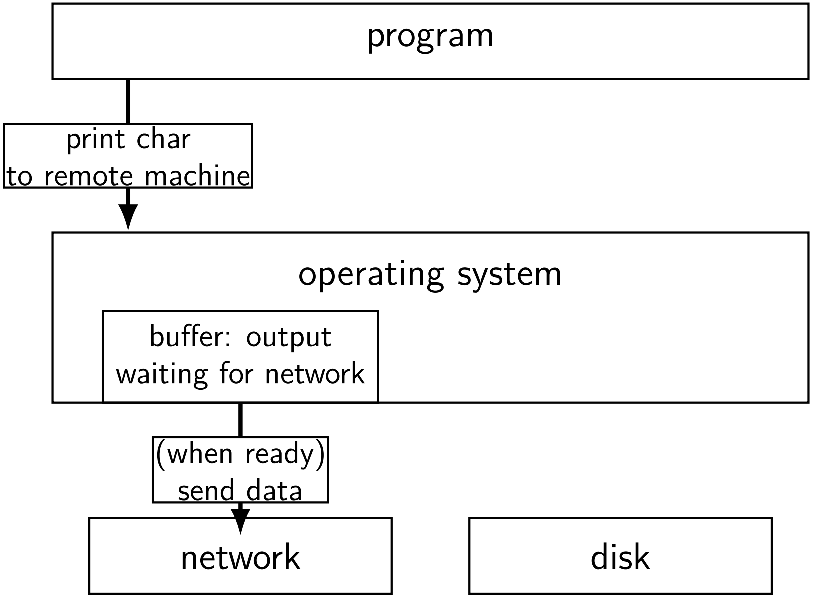

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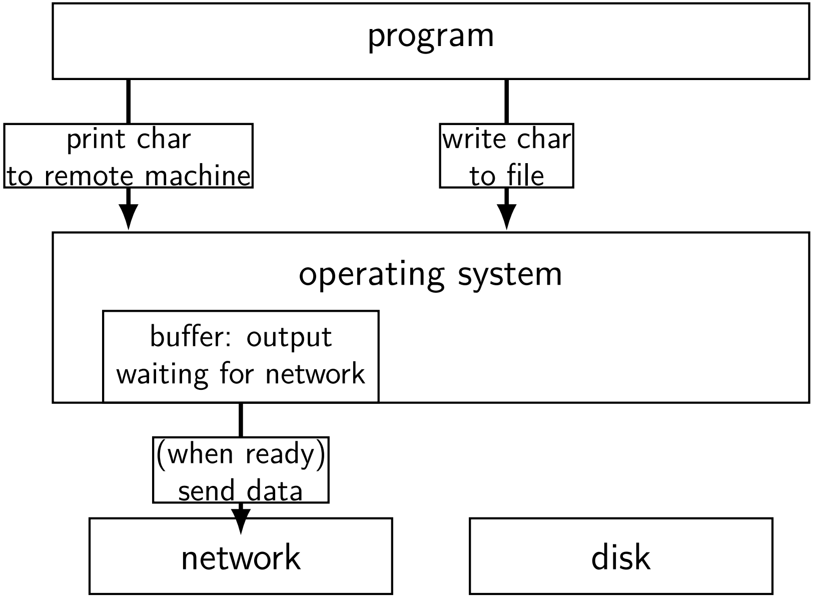

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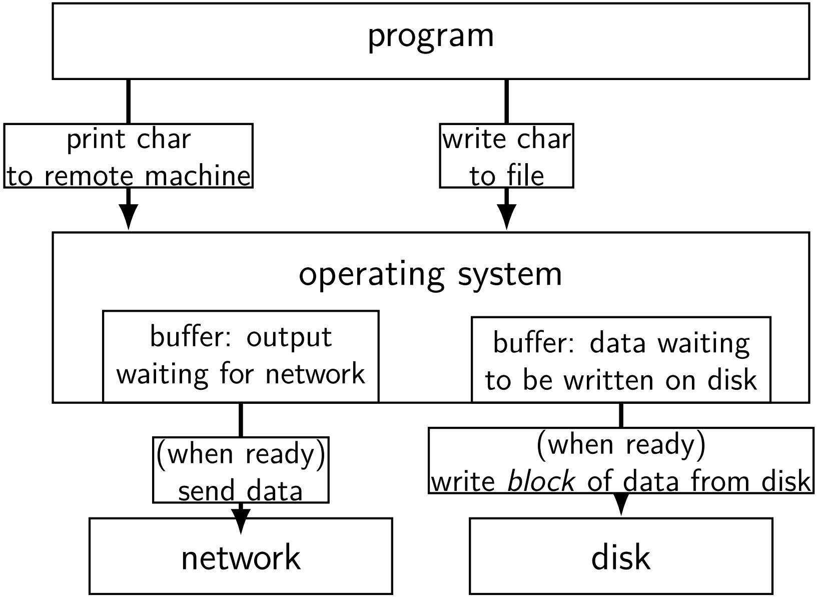


## read/write operations

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

## 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

## 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()

## 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

## pipe: closing?

if all write ends of pipe are closed

- can get end-of-file (read() returning 0) on read end
- exit()ing closes them

→ close write end when not using

generally: limited number of file descriptors per process

→ good habit to close file descriptors not being used

(but probably didn't matter for read end of pipes in example)

## dup2 exercise

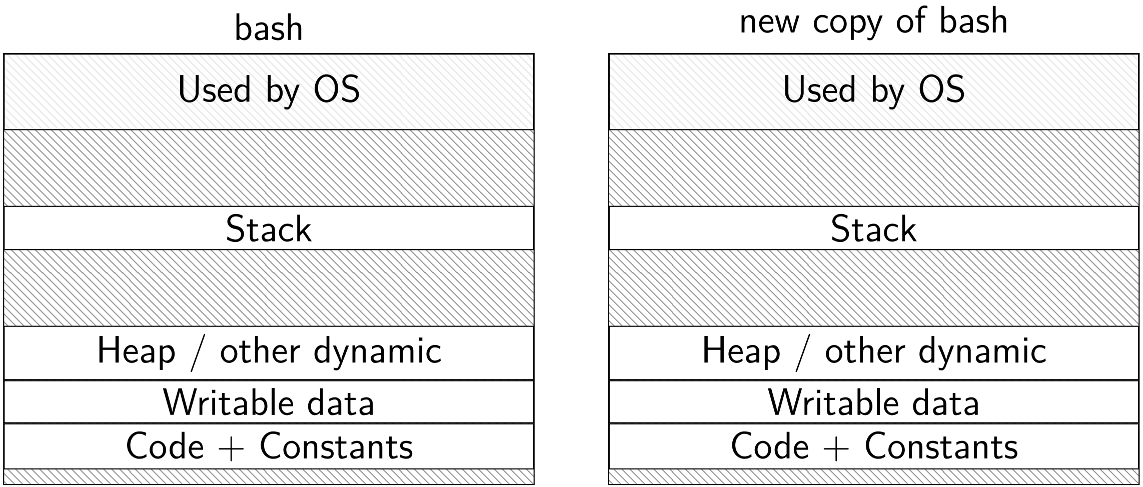
recall: `dup2(old_fd, new_fd)`

```
int fd = open("output.txt", O_WRONLY | O_CREAT, 0666);
write(STDOUT_FILENO, "A", 1);
dup2(fd, STDOUT_FILENO);
pid_t pid = fork();
if (pid == 0) { /* child: */
    dup2(STDOUT_FILENO, fd); write(fd, "B", 1);
} else {
    write(STDOUT_FILENO, "C", 1);
}
```

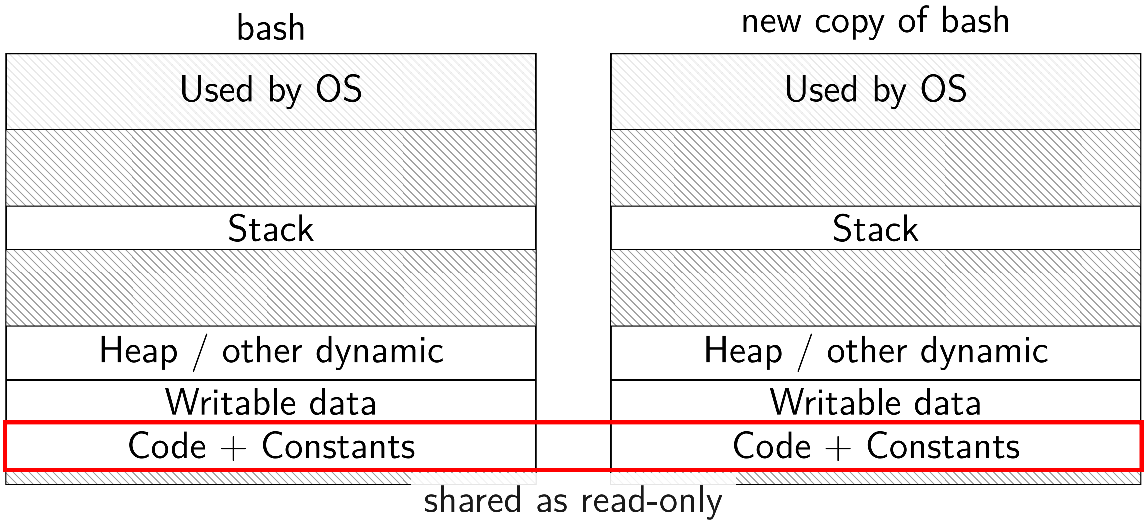
Which outputs are possible?

A. stdout: ABC ; output.txt: empty
B. stdout: AC ; output.txt: B
C. stdout: A ; output.txt: CB
D. stdout: A ; output.txt: BC
E. more?

## do we really need a complete copy?



## do we really need a complete copy?



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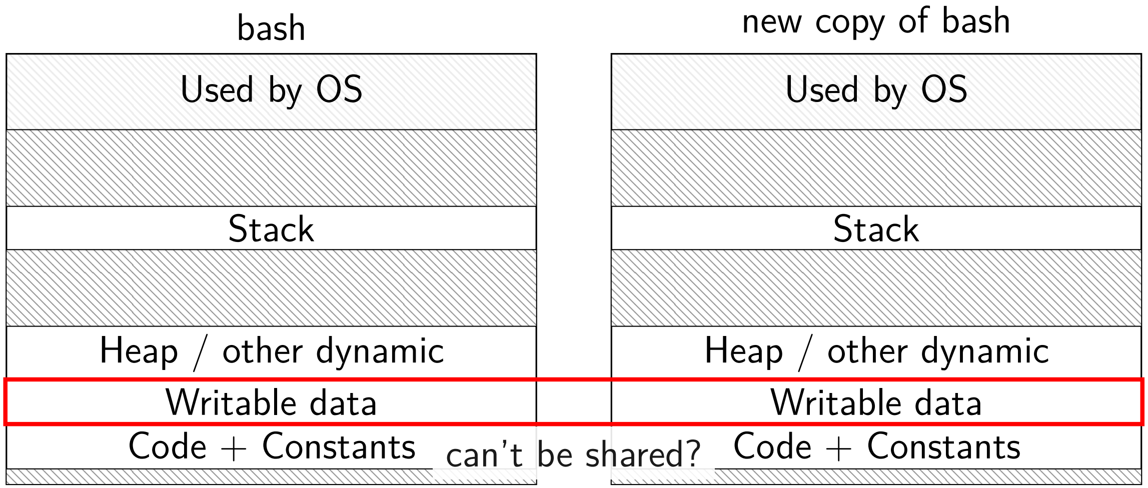

## trick for extra sharing

sharing writeable data is fine — until either process modifies it

- example: default value of global variables
- might typically not change
- (or OS might have preloaded executable's data anyways)

can we detect modifications?

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can we detect modifications?

trick: tell CPU (via page table) shared part is read-only

processor will trigger a fault when it's written

## copy-on-write and page tables

| VPN | valid? | write? | physical page |
|---|---|---|---|
| … | … | … | … |
| 0x00601 | 1 | 1 | 0x12345 |
| 0x00602 | 1 | 1 | 0x12347 |
| 0x00603 | 1 | 1 | 0x12340 |
| 0x00604 | 1 | 1 | 0x200DF |
| 0x00605 | 1 | 1 | 0x200AF |
| … | … | … | … |

# copy-on-write and page tables

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| 0x00605 | 1 | 0 | 0x200AF |
| … | … | … | … |

copy operation actually duplicates page table
both processes share all physical pages
but marks pages in both copies as read-only

# copy-on-write and page tables

| VPN | valid? | write? | physical page |
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| … | … | … | … |

when either process tries to write read-only page
triggers a fault — OS actually copies the page

# copy-on-write and page tables

| VPN | valid? | write? | physical page |
|---|---|---|---|
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| 0x00603 | 1 | 0 | 0x12340 |
| 0x00604 | 1 | 0 | 0x200DF |
| 0x00605 | 1 | 0 | 0x200AF |
| … | … | … | … |

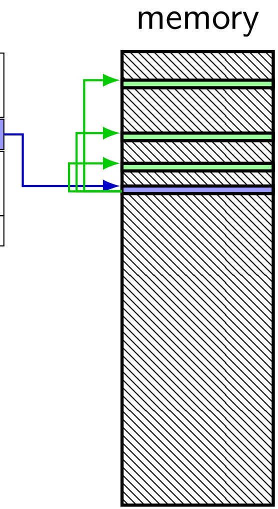
| VPN | valid? | write? | physical page |
|---|---|---|---|
| … | … | … | … |
| 0x00601 | 1 | 0 | 0x12345 |
| 0x00602 | 1 | 0 | 0x12347 |
| 0x00603 | 1 | 0 | 0x12340 |
| 0x00604 | 1 | 0 | 0x200DF |
| 0x00605 | 1 | 1 | 0x300FD |
| … | … | … | … |

after allocating a copy, OS reruns the write instruction

## fork (w/ copy-on-write, if parent writes first)

parent process info

|  |  |
|---|---|
| user regs | `rax (return val.)=~~42~~`*`child pid`*`,`<br>`rcx=133, …` |
| page tables | ▨ |
| open files | `fd 0: …`<br>`fd 1: …` |
| … | … |



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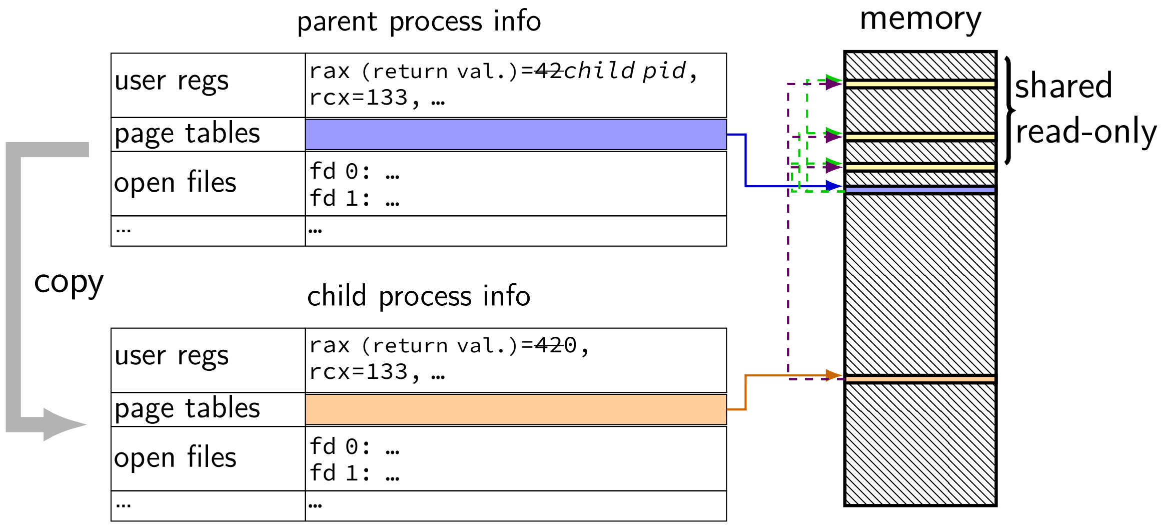

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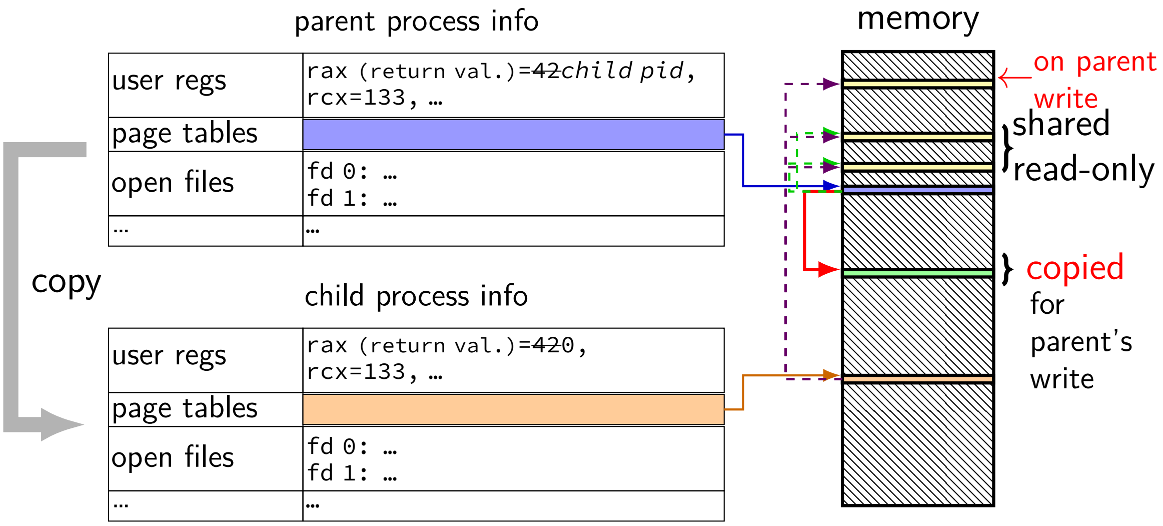

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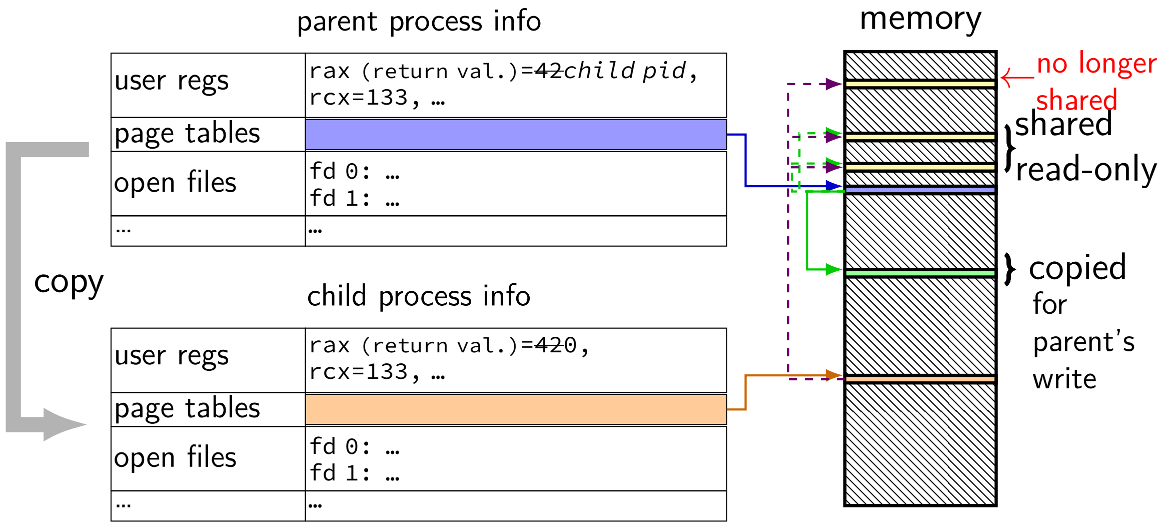
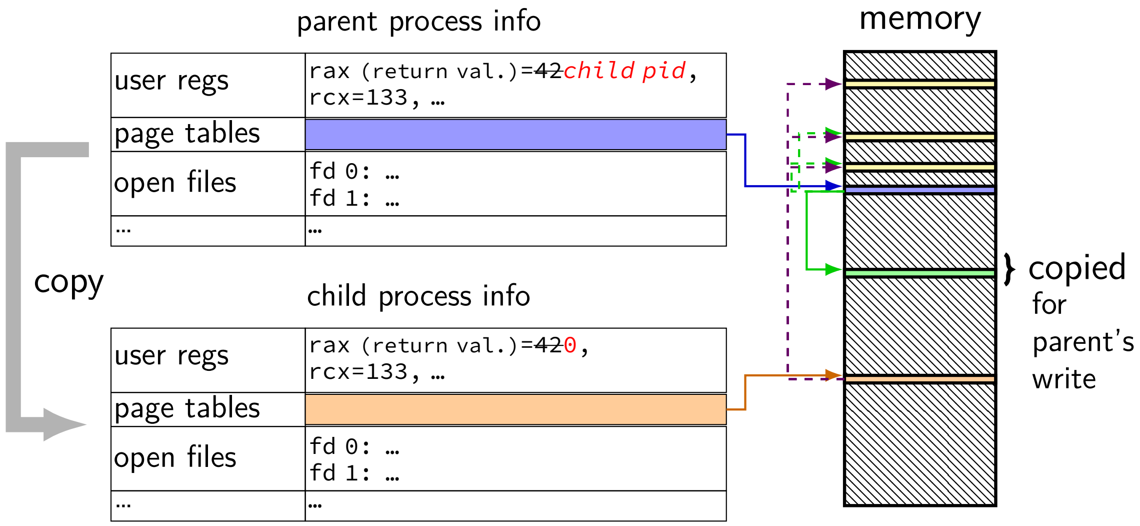
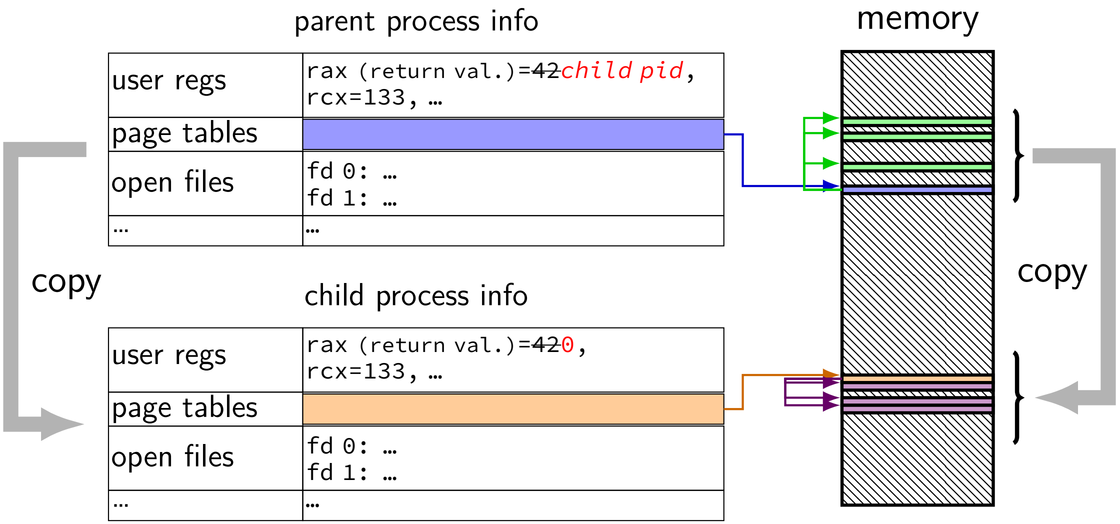


# fork (w/ copy-on-write, if parent writes first)



# fork and process info (w/o copy-on-write)



parent process info

| | |
|---|---|
| user regs | `rax (return val.)=`~~`42`~~*child pid*`,`<br>`rcx=133, …` |
| page tables | 🟦 |
| open files | `fd 0: …`<br>`fd 1: …` |
| … | … |

child process info

| | |
|---|---|
| user regs | `rax (return val.)=`~~`42`~~`0,`<br>`rcx=133, …` |
| page tables | 🟧 |
| open files | `fd 0: …`<br>`fd 1: …` |
| … | … |