# OS Interface

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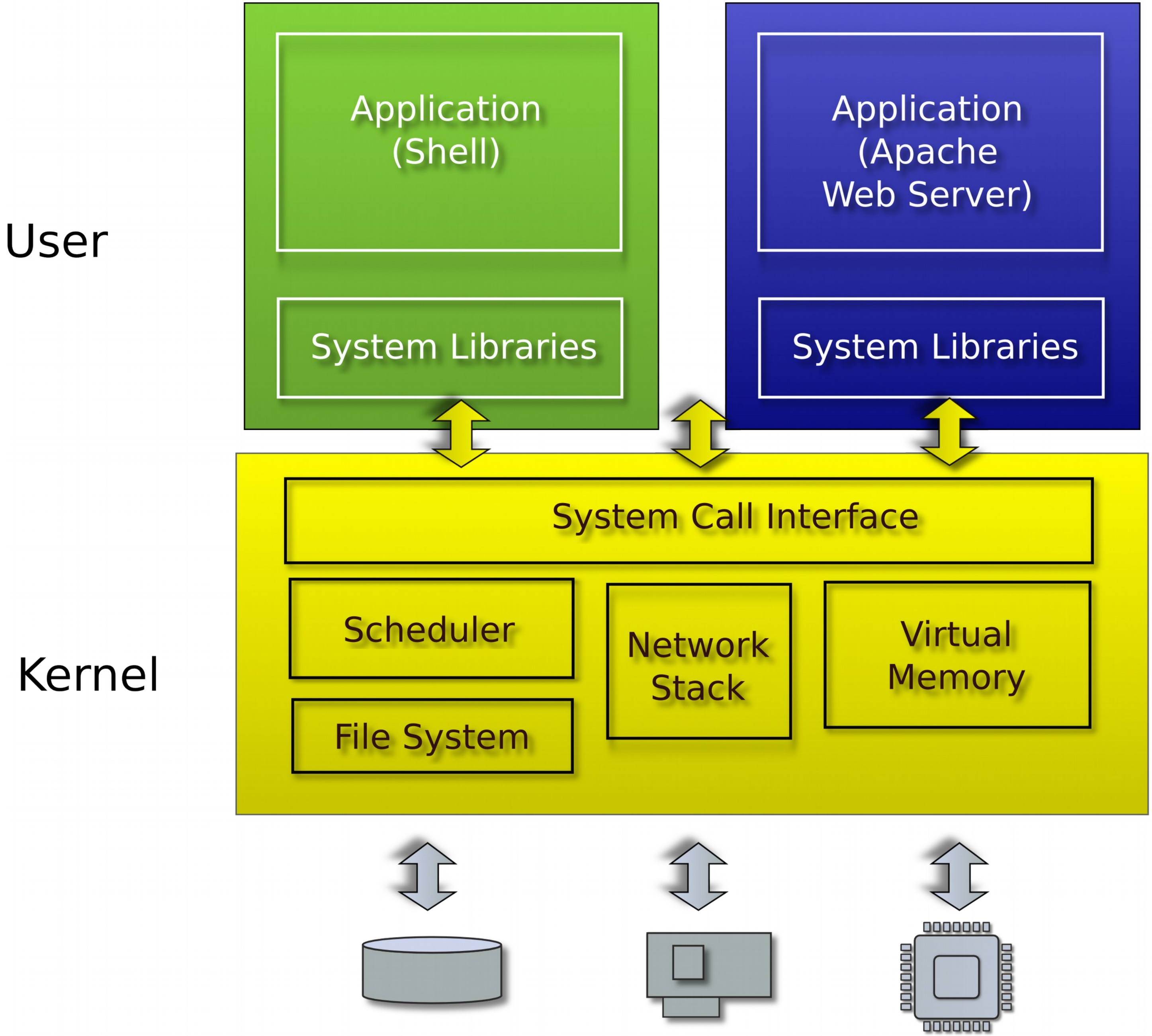
# Recap: role of the operating system

- Share hardware across multiple processes
  - Illusion of private CPU, private memory
- Abstract hardware
  - Hide details of specific hardware devices
- Provide services
  - Serve as a library for applications
- Security
  - Isolation of processes
  - Controlled ways to communicate (in a secure manner)

# Typical UNIX OS

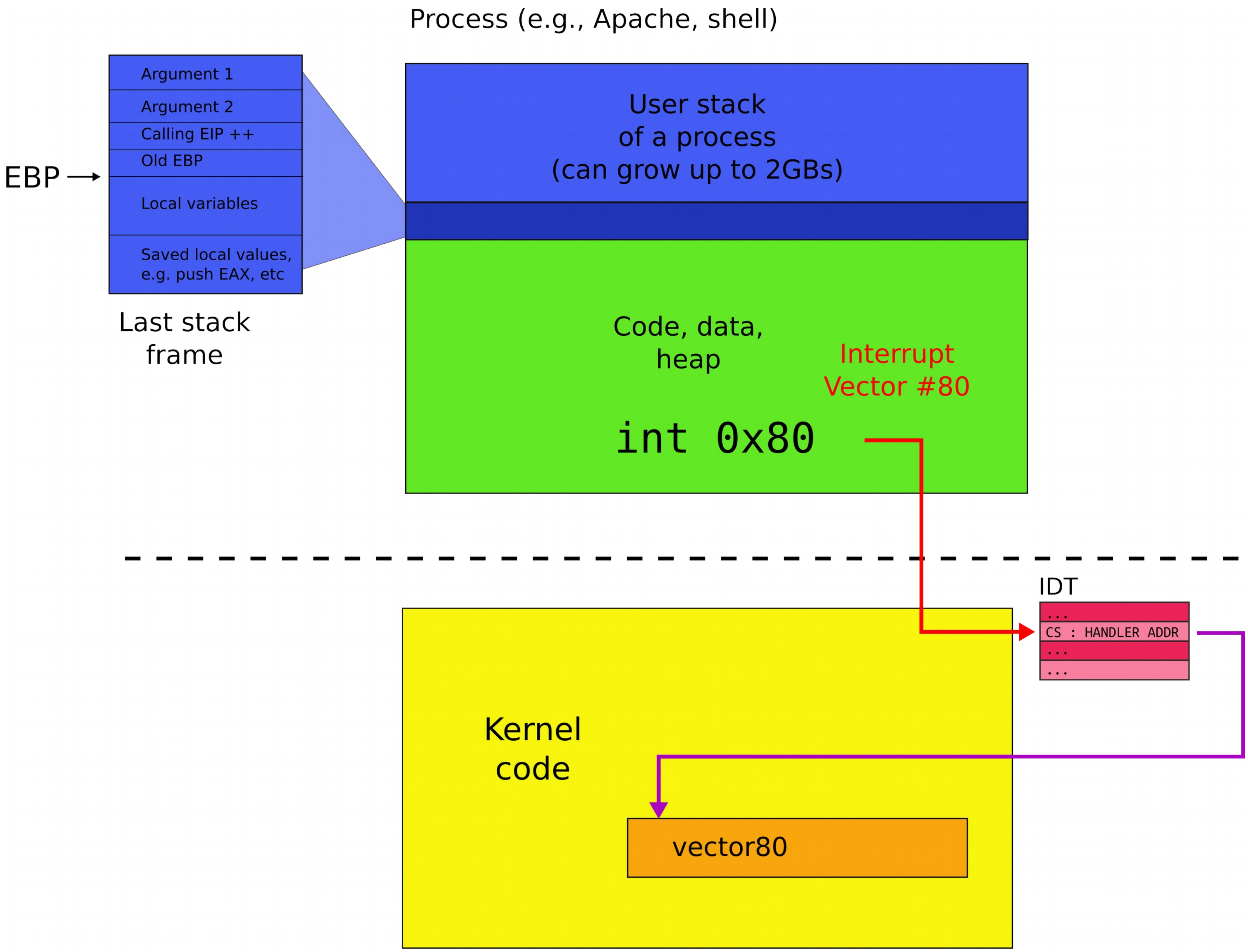


# System calls

- Provide user to kernel communication
  - Effectively an invocation of a kernel function

- *System calls are the interface of the OS*

# System call



Process (e.g., Apache, shell)

Argument 1

Argument 2

Calling EIP ++

Old EBP

Local variables

Saved local values, e.g. push EAX, etc

EBP

Last stack frame

User stack of a process (can grow up to 2GBs)

Code, data, heap

Interrupt Vector #80

`int 0x80`

IDT

...

CS : HANDLER ADDR

...

...

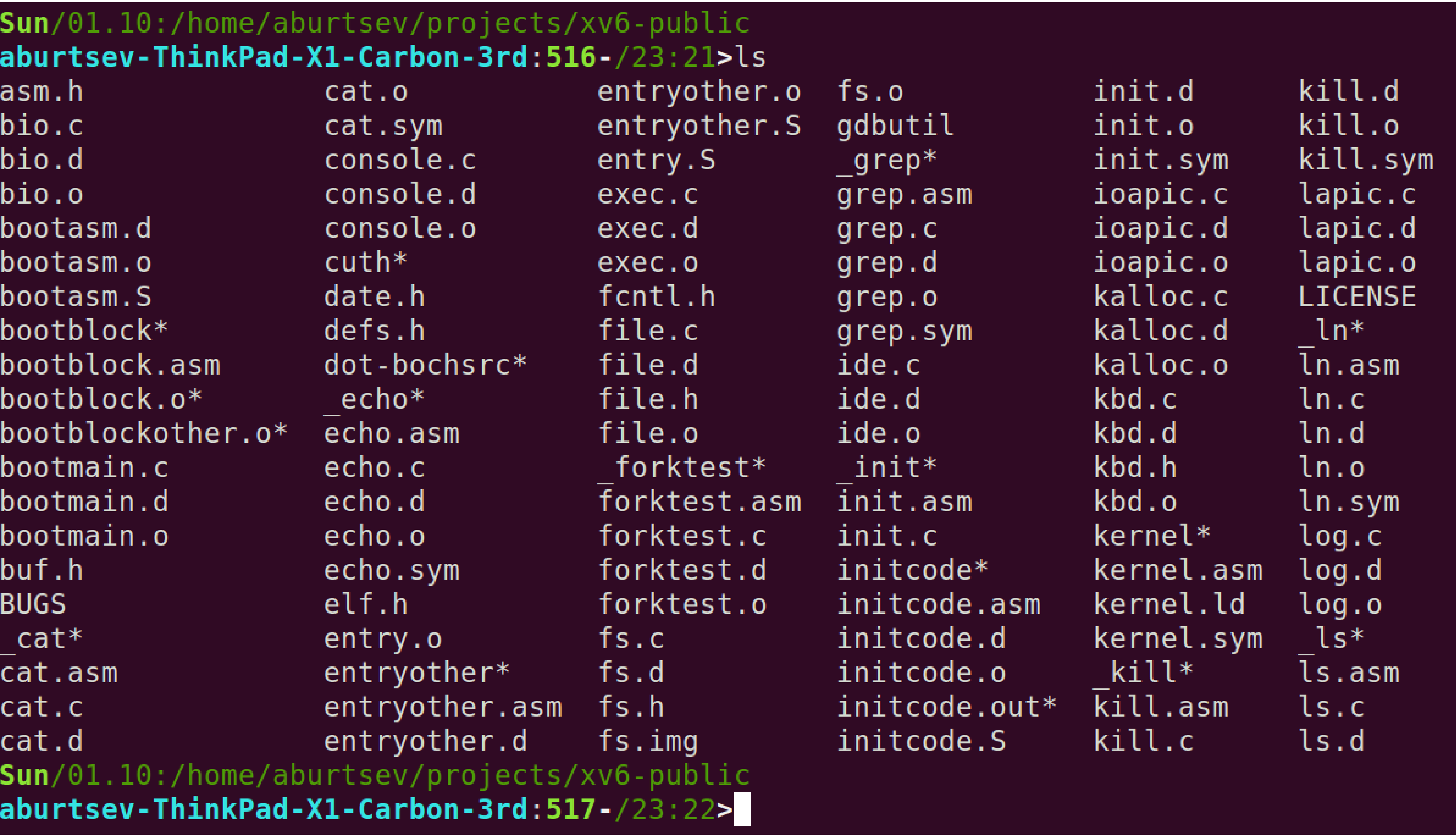
Kernel code

vector80

# System calls, interface for...

- Processes
  - Creating, exiting, waiting, terminating
- Memory
  - Allocation, deallocation
- Files and folders
  - Opening, reading, writing, closing
- Inter-process communication
  - Pipes

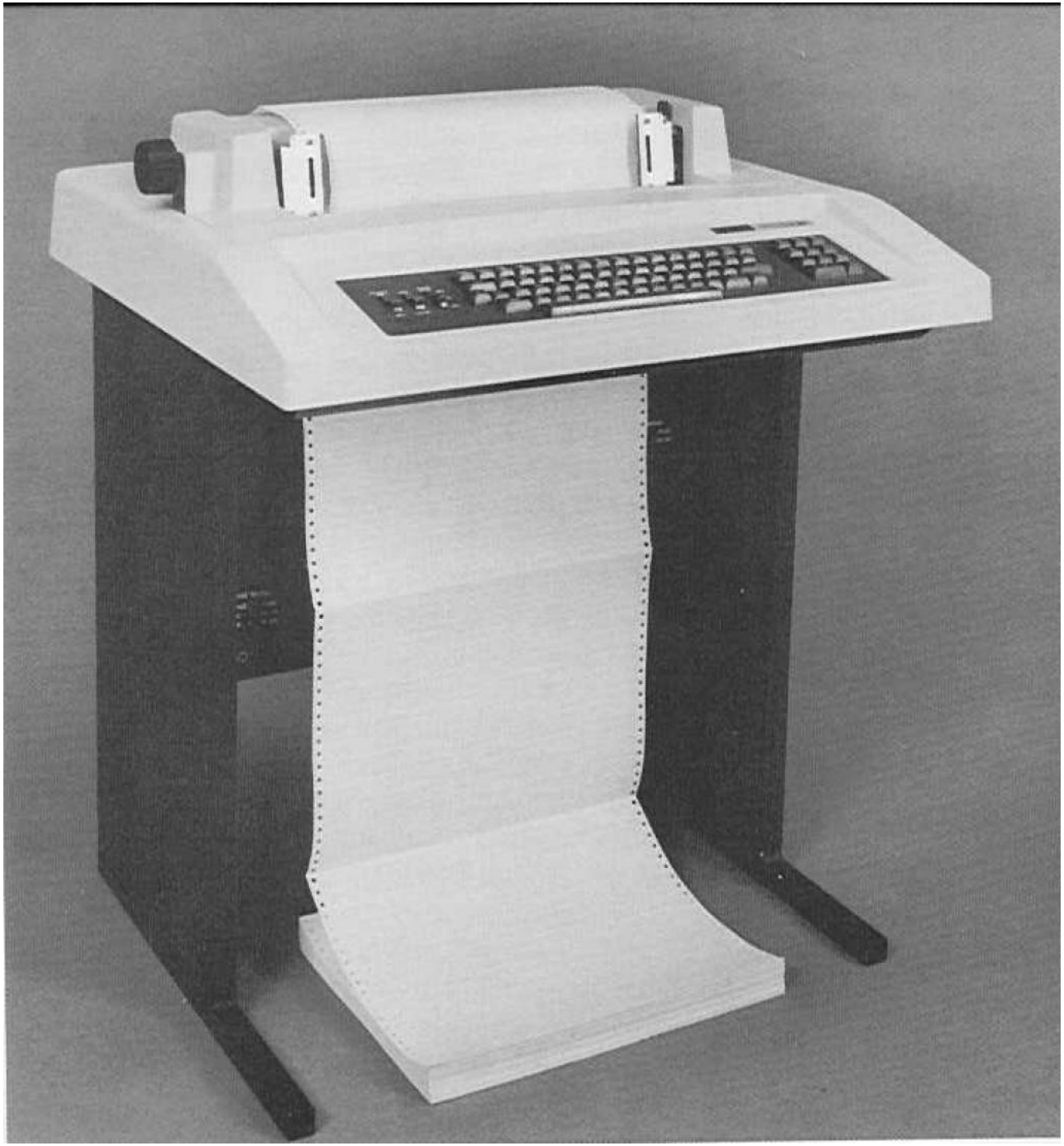
# UNIX (xv6) system calls are designed around the **shell**



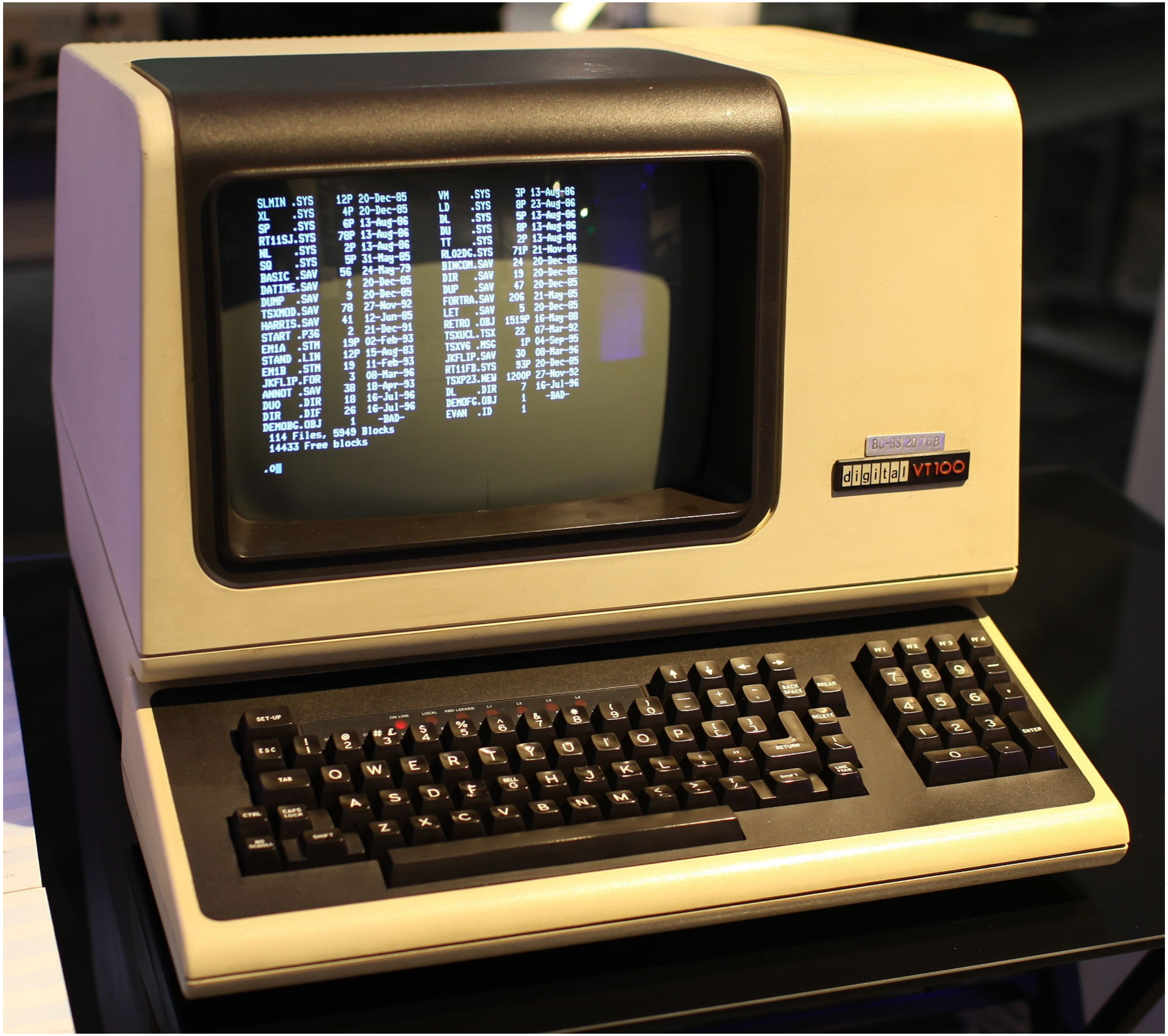
```
Sun/01.10:/home/aburtsev/projects/xv6-public
aburtsev-ThinkPad-X1-Carbon-3rd:516-/23:21>ls
asm.h              cat.o           entryother.o  fs.o           init.d      kill.d
bio.c              cat.sym         entryother.S  gdbutil        init.o      kill.o
bio.d              console.c       entry.S       _grep*         init.sym    kill.sym
bio.o              console.d       exec.c        grep.asm       ioapic.c    lapic.c
bootasm.d          console.o       exec.d        grep.c         ioapic.d    lapic.d
bootasm.o          cuth*           exec.o        grep.d         ioapic.o    lapic.o
bootasm.S          date.h          fcntl.h       grep.o         kalloc.c    LICENSE
bootblock*         defs.h          file.c        grep.sym       kalloc.d    _ln*
bootblock.asm      dot-bochsrc*    file.d        ide.c          kalloc.o    ln.asm
bootblock.o*       _echo*          file.h        ide.d          kbd.c       ln.c
bootblockother.o*  echo.asm        file.o        ide.o          kbd.d       ln.d
bootmain.c         echo.c          _forktest*    _init*         kbd.h       ln.o
bootmain.d         echo.d          forktest.asm  init.asm       kbd.o       ln.sym
bootmain.o         echo.o          forktest.c    init.c         kernel*     log.c
buf.h              echo.sym        forktest.d    initcode*      kernel.asm  log.d
BUGS               elf.h           forktest.o    initcode.asm   kernel.ld   log.o
_cat*              entry.o         fs.c          initcode.d     kernel.sym  _ls*
cat.asm            entryother*     fs.d          initcode.o     _kill*      ls.asm
cat.c              entryother.asm  fs.h          initcode.out*  kill.asm    ls.c
cat.d              entryother.d    fs.img        initcode.S     kill.c      ls.d
Sun/01.10:/home/aburtsev/projects/xv6-public
aburtsev-ThinkPad-X1-Carbon-3rd:517-/23:22>
```

# Why shell?

Ken Thompson (sitting) and Dennis Ritchie (standing) are working together on a PDP-11 (around 1970). They are using Teletype Model 33 terminals.



DEC LA36 DECwriter II Terminal



```
SLMIN .SYS    12P 20-Dec-85     VM    .SYS     3P 13-Aug-86
XL    .SYS     4P 20-Dec-85     LD    .SYS     8P 23-Aug-86
SP    .SYS     6P 13-Aug-86     DL    .SYS     5P 13-Aug-86
RT11SJ.SYS    78P 13-Aug-86     DU    .SYS     8P 13-Aug-86
NL    .SYS     2P 13-Aug-86     TT    .SYS     2P 13-Aug-86
SQ    .SYS     5P 31-May-85     RL02DG.SYS    71P 21-Nov-84
BASIC .SAV    56  24-May-79     BINCOM.SAV    24  20-Dec-85
DATIME.SAV     4  20-Dec-85     DIR   .SAV    19  20-Dec-85
DUMP  .SAV     9  20-Dec-85     DUP   .SAV    47  20-Dec-85
TSXMOD.SAV    78  27-Nov-92     FORTRA.SAV   206  21-May-85
HARRIS.SAV    41  12-Jun-85     LET   .SAV     5  20-Dec-85
START .P36     2  21-Dec-91     RETRO .OBJ  1519P 16-May-88
EM1A  .STM    19P 02-Feb-93     TSXUCL.TSX    22  07-Mar-92
STAND .LIN    12P 15-Aug-83     TSXV6 .MSG     1P 04-Sep-95
EM1B  .STM    19  11-Feb-93     JKFLIP.SAV    30  08-Mar-96
JKFLIP.FOR     3  08-Mar-96     RT11FB.SYS    93P 20-Dec-85
ANNOT .SAV    38  18-Apr-93     TSXP23.NEW  1200P 27-Nov-92
DUO   .DIR    18  16-Jul-96     DL    .DIR     7  16-Jul-96
DIR   .DIF    26  16-Jul-96     DEMOFG.OBJ     1    -BAD-
DEMOBG.OBJ     1    -BAD-       EVAN  .ID      1
 114 Files, 5949 Blocks
 14433 Free blocks

.o
```

DEC VT100 terminal, 1980

# Suddenly this makes sense

- List all files

```
\> ls
total 9212
drwxrwxr-x  3 aburtsev aburtsev   12288 Oct  1 08:27 ./
drwxrwxr-x 43 aburtsev aburtsev    4096 Oct  1 08:25 ../
-rw-rw-r--  1 aburtsev aburtsev     936 Oct  1 08:26 asm.h
-rw-rw-r--  1 aburtsev aburtsev    3397 Oct  1 08:26 bio.c
-rw-rw-r--  1 aburtsev aburtsev     100 Oct  1 08:26 bio.d
-rw-rw-r--  1 aburtsev aburtsev    6416 Oct  1 08:26 bio.o
…
```

- Count number of lines in a file (ls.c imlements ls)

```
\> wc -l ls.c
85 ls.c
```

# But what is shell?

# But what is shell?

- Normal process
  - Kernel starts it for each user that logs in into the system
  - In xv6 shell is created after the kernel boots
- Shell interacts with the kernel through system calls
  - E.g., starts other processes

# What happens underneath?

```
\> wc -l ls.c
85 ls.c
\>
```

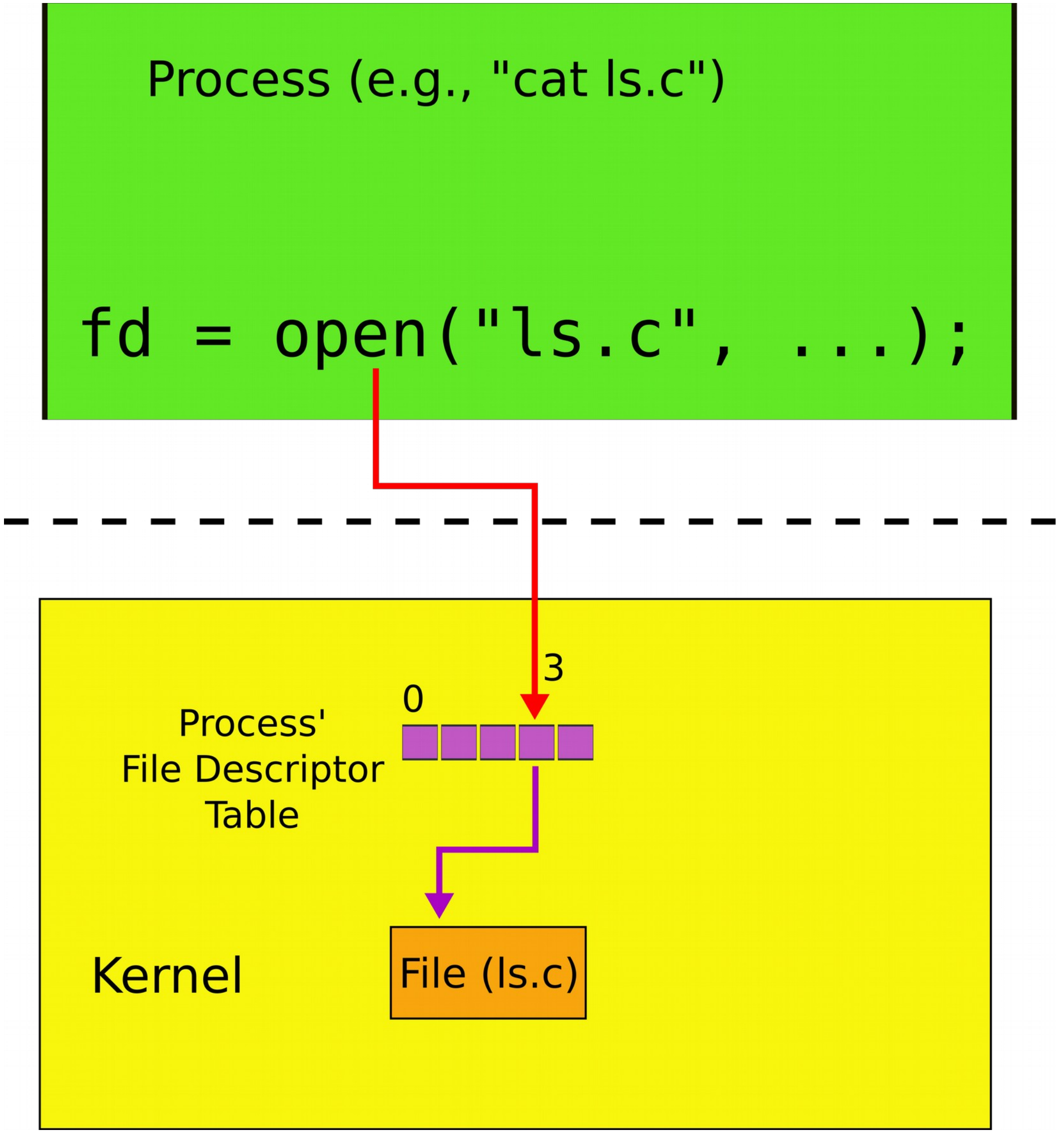
- Shell invokes `wc`
  - Creates a new process to run `wc`
  - Passes the arguments (-l and ls.c)
- `wc` sends its output to the terminal (console)
  - Exits when done with `exit()`
- Shell detects that `wc` is done (`wait()`)
  - Prints (to the same terminal) its command prompt
  - Ready to execute the next command

# Console and file I/O

# File open

- `fd = open("ls.c", O_READONLY)` – open a file
  - Operating system returns a file descriptor

# File descriptors



# File descriptors

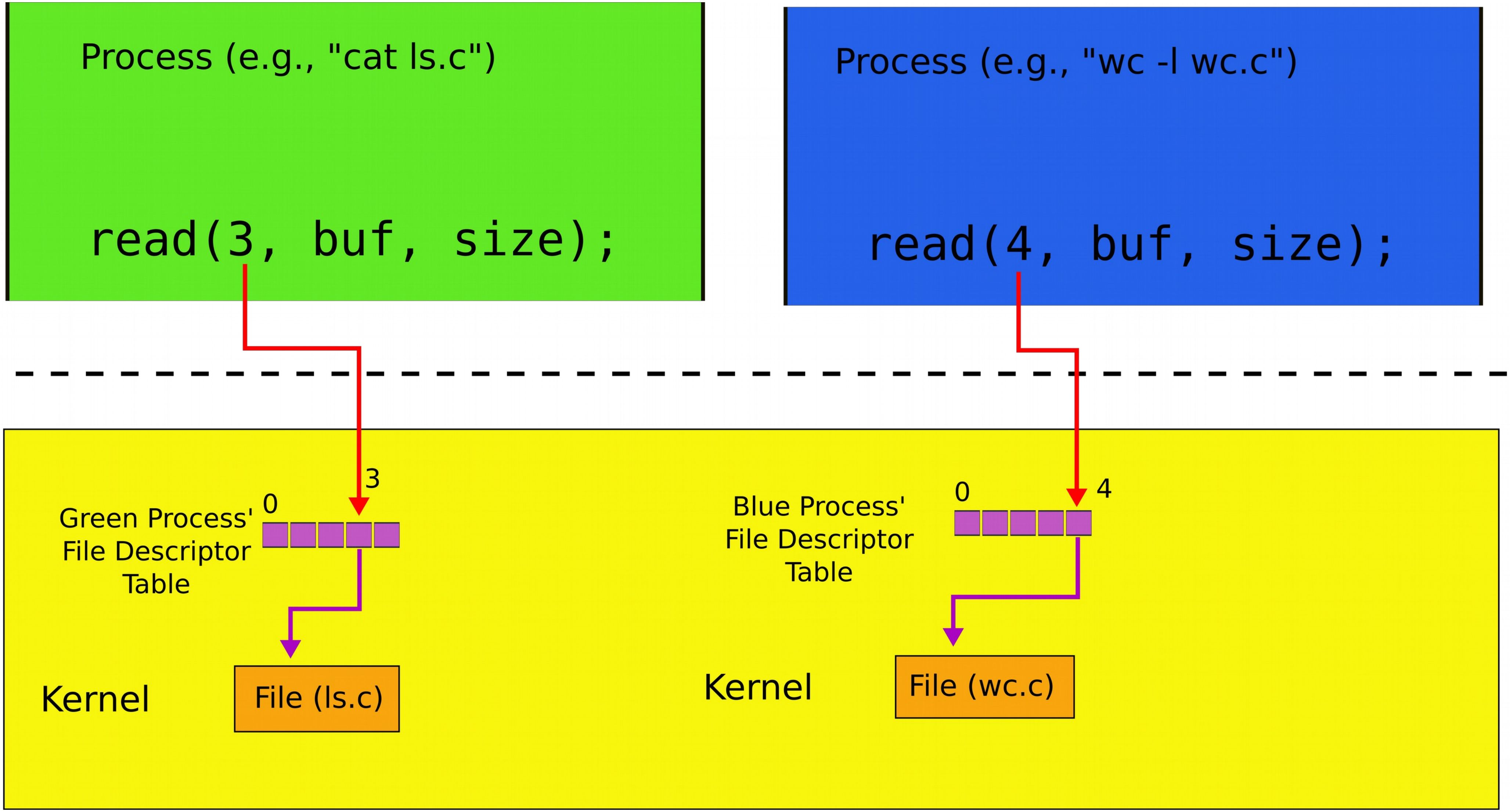
- An index into a table, i.e., just an integer
- The table maintains pointers to “file” objects
  - Abstracts files, devices, pipes
  - In UNIX everything is a file – all objects provide file interface
- Process may obtain file descriptors through
  - Opening a file, directory, device
  - By creating a pipe
  - Duplicating an existing descriptor

# File I/O

- `fd = open("foobar.txt", O_READONLY)` – open a file
  - Operating system returns a file desciptor

- `read(fd, buf, n)` – read `n` bytes from `fd` into `buf`
- `write(fd, buf, n)` – write `n` bytes from `buf` into `fd`

# File descriptors: two processes

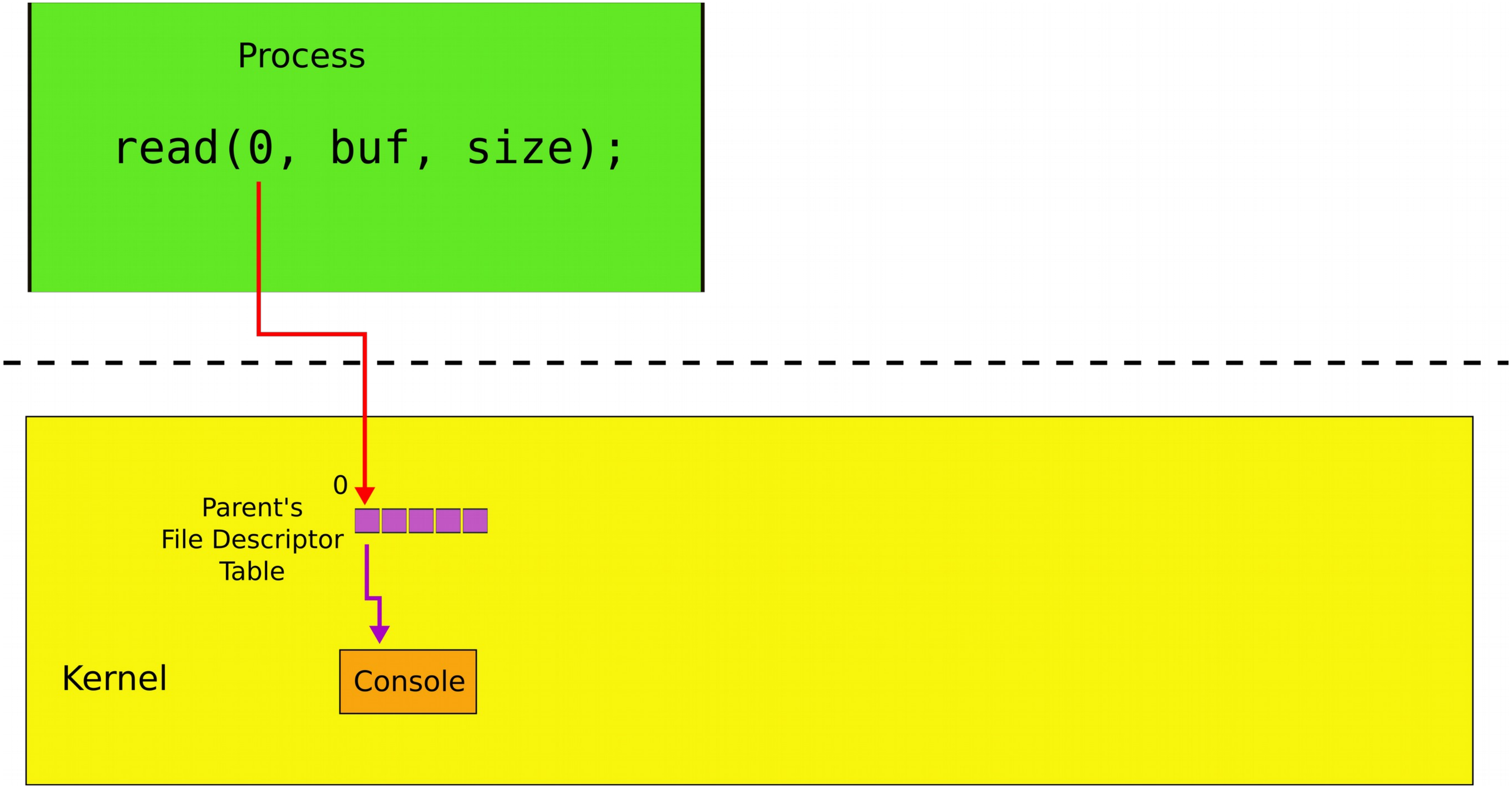

Process (e.g., "cat ls.c")
read(3, buf, size);
Process (e.g., "wc -l wc.c")
read(4, buf, size);
3
0
Green Process' File Descriptor Table
Kernel
File (ls.c)
0
4
Blue Process' File Descriptor Table
Kernel
File (wc.c)

# Console I/O

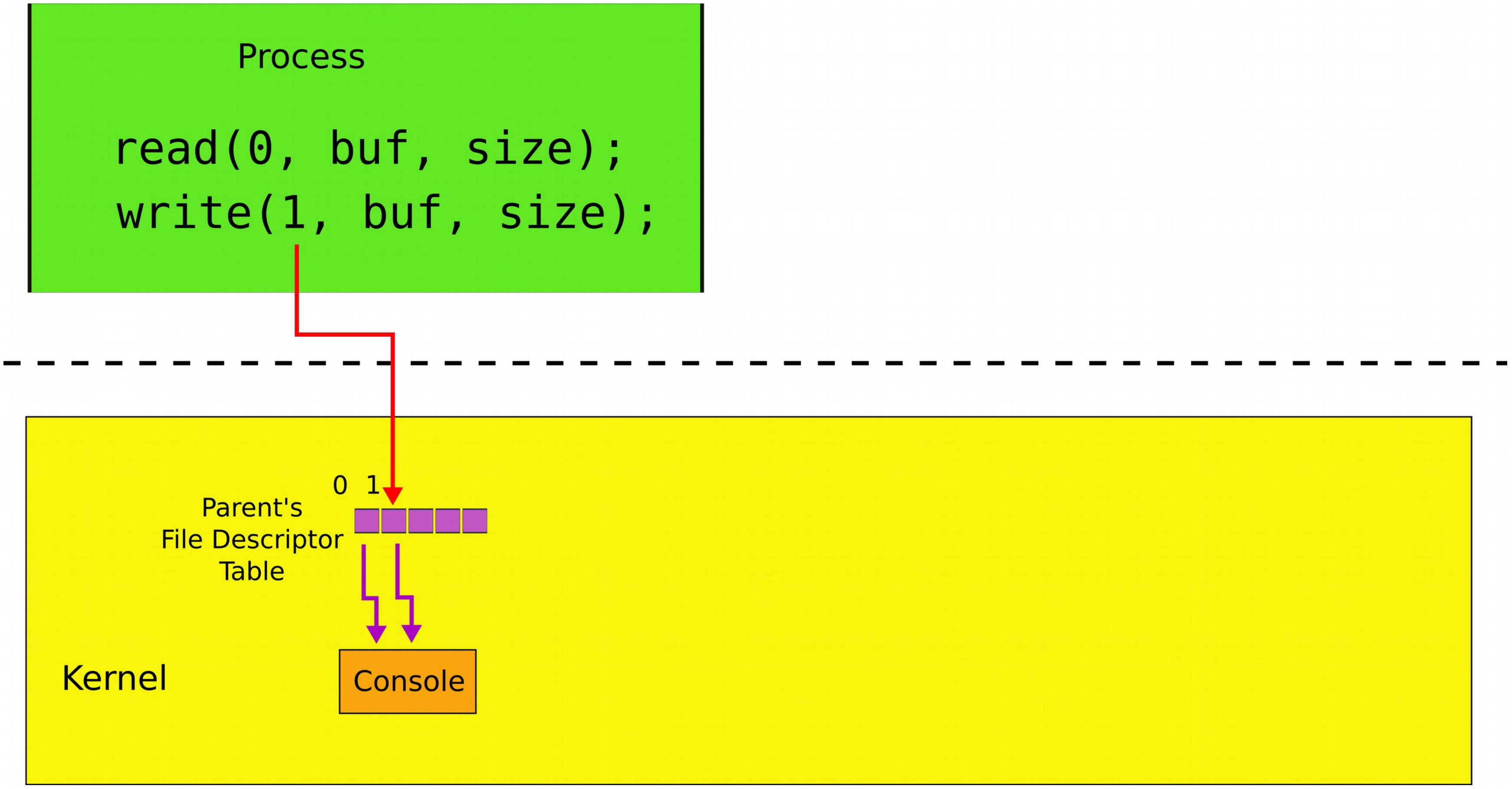
# Each process has standard file descriptors

- Numbers are just a convention
  - 0 – standard input
  - 1 – standard output
  - 2 – standard error
- This convention is used by the shell to implement I/O redirection and pipes

# Console read (read of standard intput)



# Console write (write of standard output)



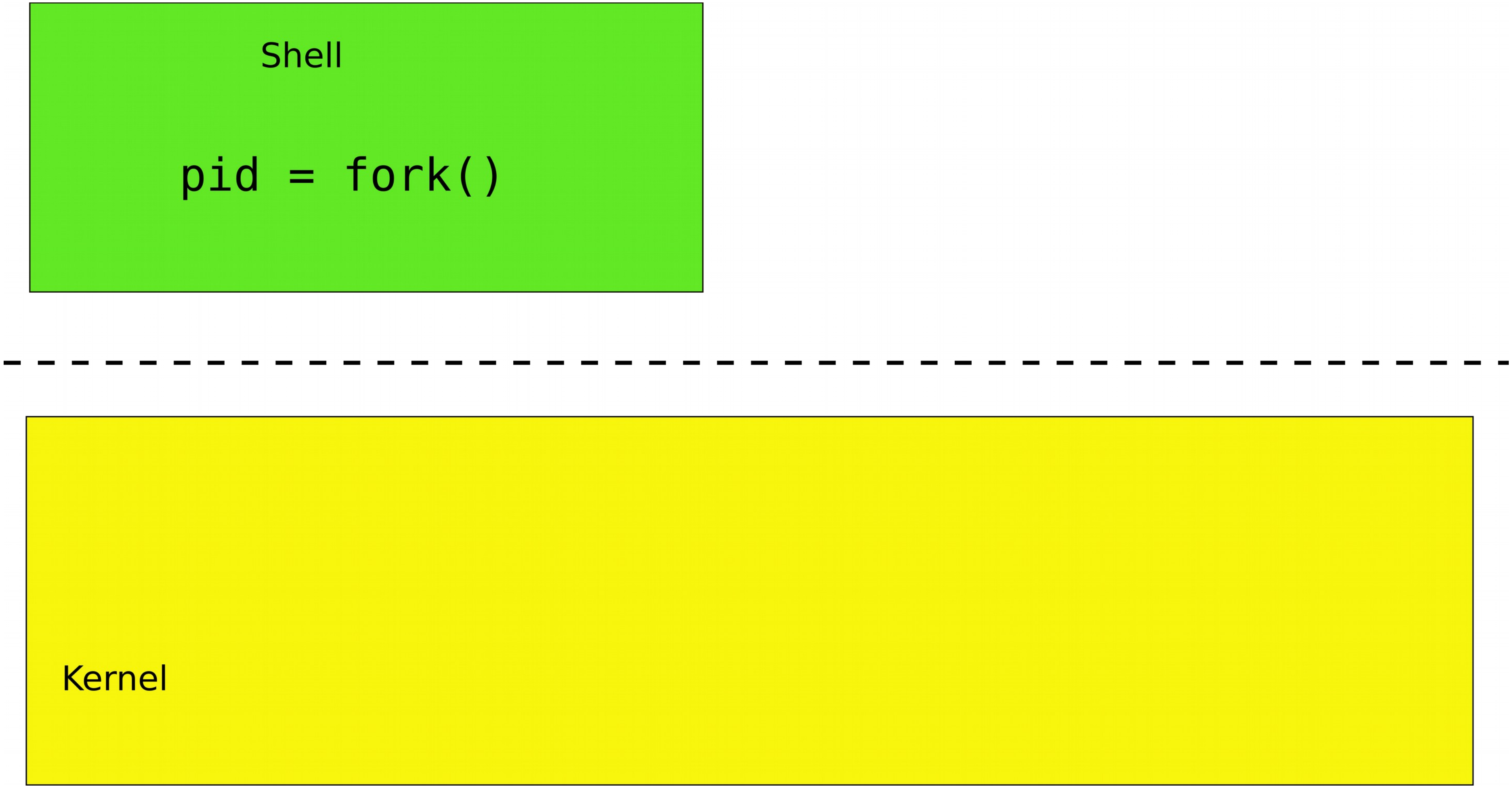
```
read(0, buf, size);
write(1, buf, size);
```

# Example: cat

```
char buf[512]; int n;
for(;;) {
    n = read(0, buf, sizeof buf);
    if(n == 0)
        break;
    if(n < 0) {
        fprintf(2, "read error\n");
        exit(); }
    if(write(1, buf, n) != n) {
        fprintf(2, "write error\n");
        exit();
    }
}
```

# Creating processes

# fork()

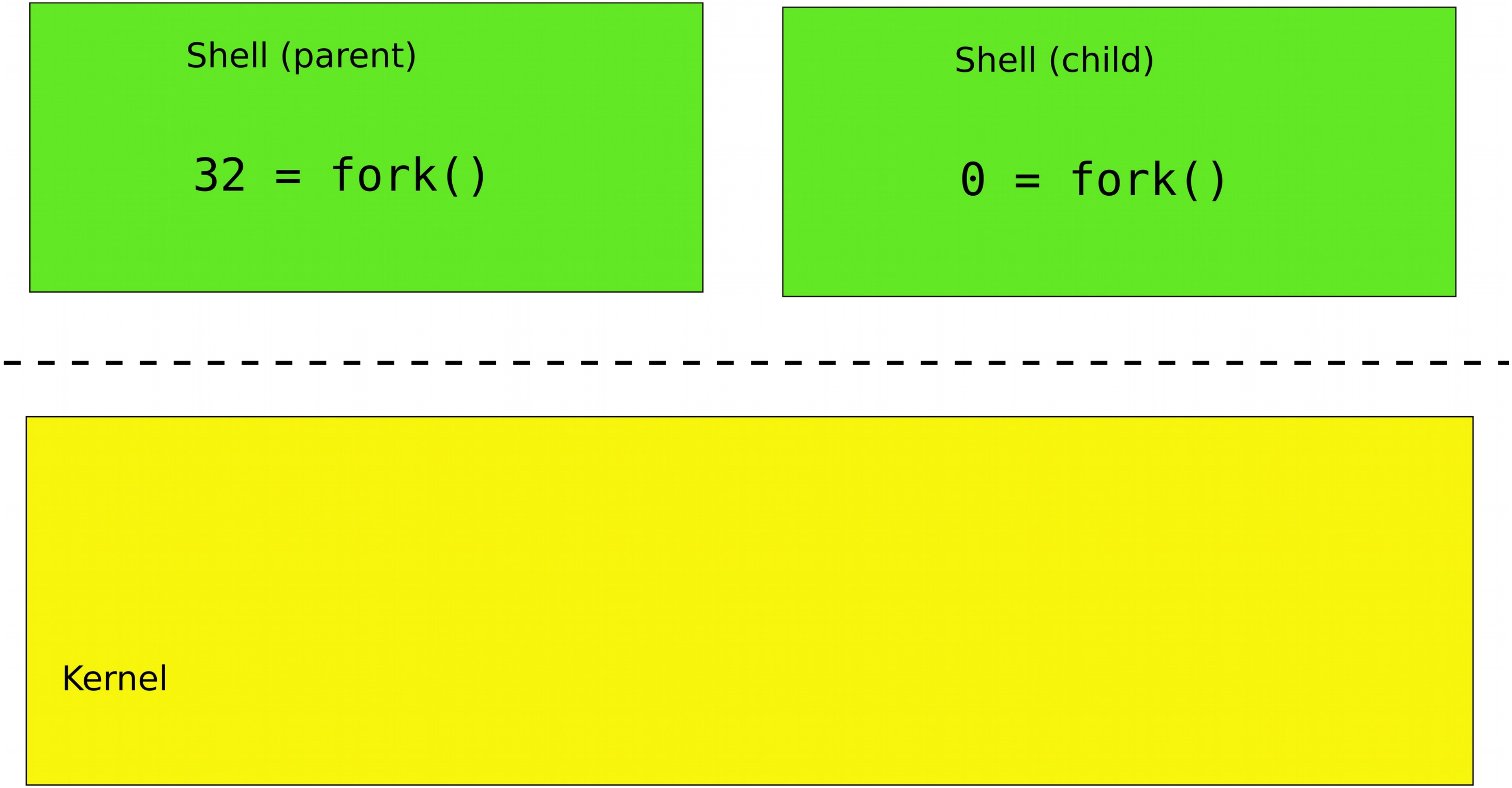


Shell

```
pid = fork()
```

Kernel

# fork()



Shell (parent)

32 = fork()

Shell (child)

0 = fork()

Kernel

# fork() -- create new process

```c
int pid;
pid = fork();
if(pid > 0){
    printf("parent: child=%d\n", pid);
    pid = wait();
    printf("child %d is done\n", pid);
} else if(pid == 0){
    printf("child: exiting\n");
    exit();
} else {
     printf("fork error\n");
}
```

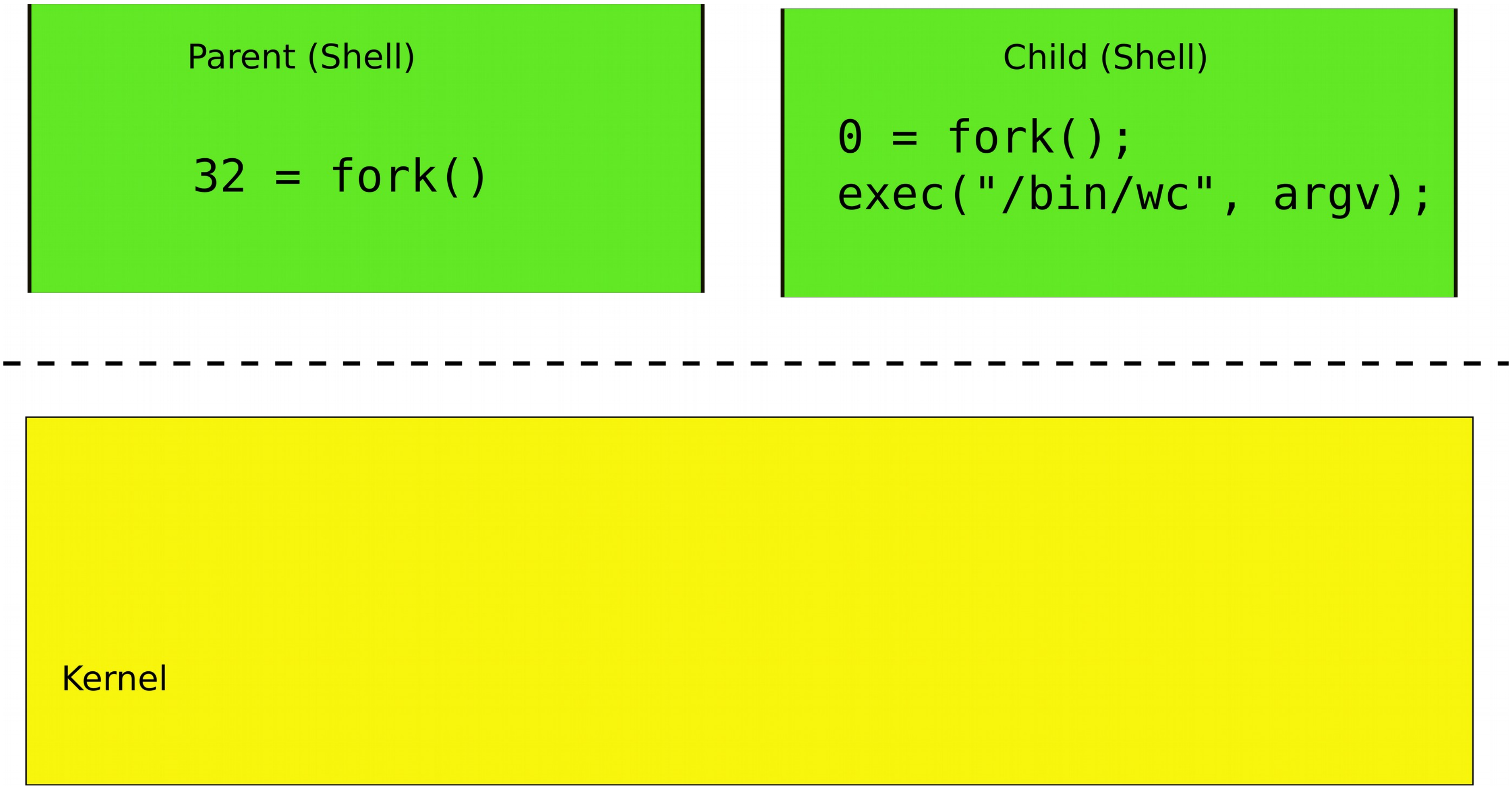
# This is weird... `fork()` creates copies of the same process, why?

# `fork()` is used together with `exec()`

- `exec()` -- replaces memory of a current process with a memory image (of a program) loaded from a file

```
char *argv[3];
argv[0] = "echo";
argv[1] = "hello";
argv[2] = 0;
exec("/bin/echo", argv);
printf("exec error\n");
```

# fork() and exec()



Parent (Shell)

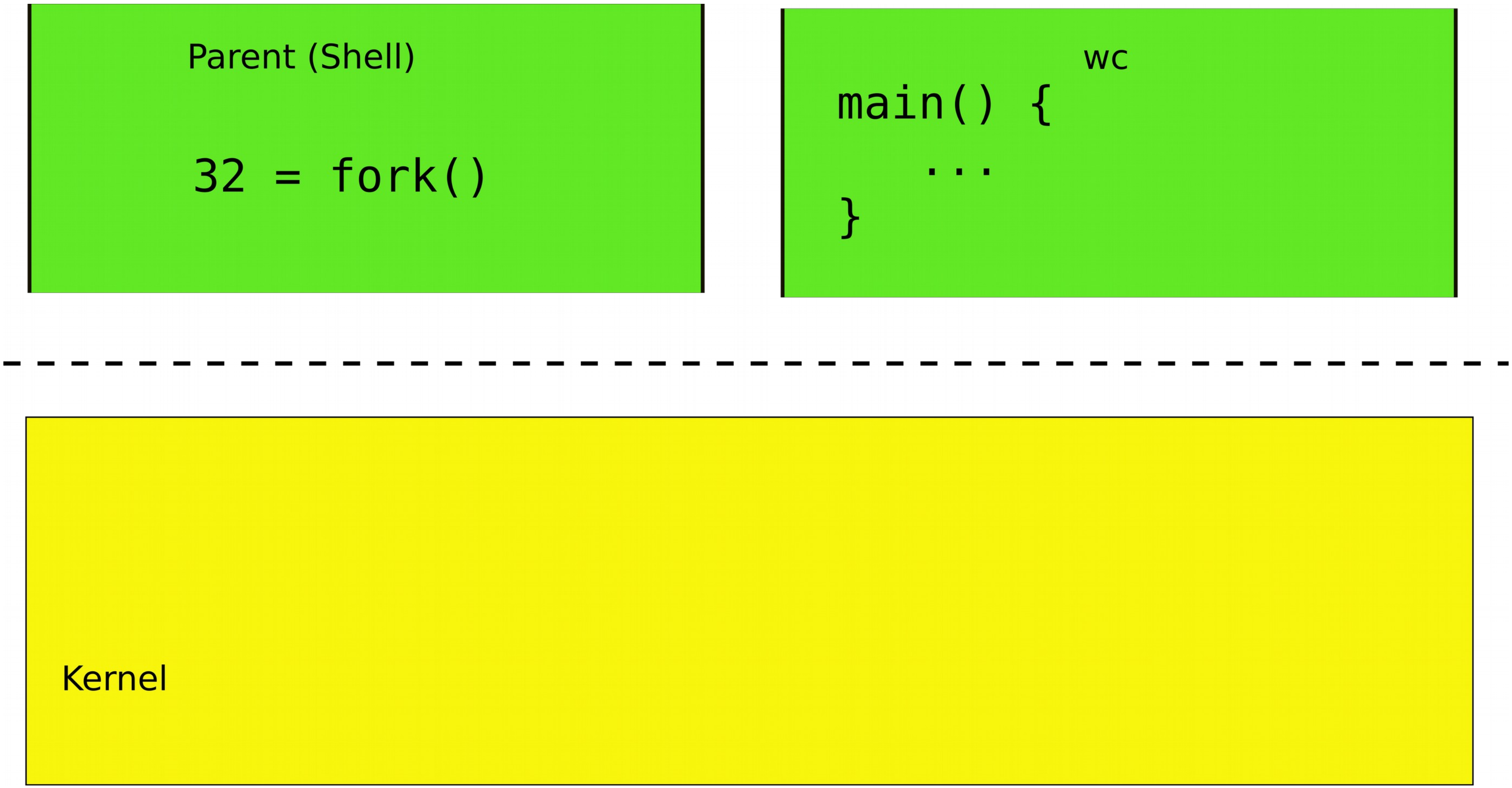
```
32 = fork()
```

Child (Shell)

```
0 = fork();
exec("/bin/wc", argv);
```

Kernel

# fork() and exec()



Parent (Shell)

```
32 = fork()
```

wc

```
main() {
    ...
}
```

Kernel

- Still weird... why first `fork()` and then `exec()`?
- Why not `exec()` directly?

# I/O Redirection

# Motivating example #1

- Normally `wc` sends its output to the console (screen)
  - Count the number of lines in `ls.c`

```
\> wc -l ls.c
85 ls.c
```

- What if we want to save the number of lines into a file?

# Motivating example #1

- Normally `wc` sends its output to the console (screen)
  - Count the number of lines in `ls.c`

```
\> wc -l ls.c
85 ls.c
```

- What if we want to save the number of lines into a file?
  - We can add an argument

```
\> wc -l ls.c -o foobar.txt
```

# Motivating example #1

```
\> wc -l ls.c -o foobar.txt
```

- But there is a better way

```
\> wc -l ls.c > foobar.txt
```

# I/O redirection

- **>** redirect output
  - Redirect output of a command into a file

```
\> wc -l ls.c > foobar.txt
\> cat ls.c > ls-new.c
```

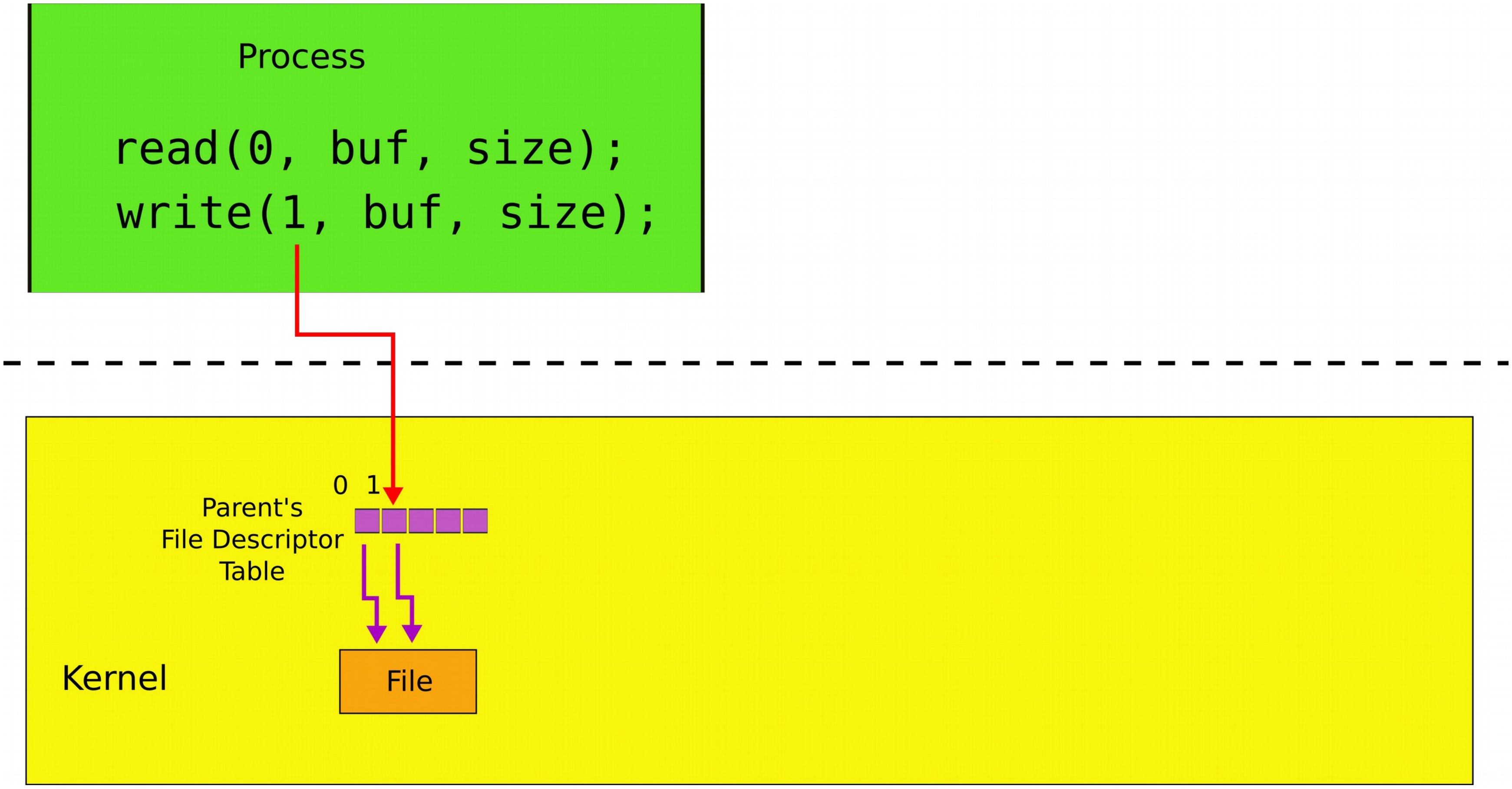
- **<** redirect input
  - Redirect input to read from a file

```
\> wc -l < ls.c
\> cat < ls.c
```

- Redirect both

```
\> wc -l < ls.c > foobar.txt
```

# Standard output is now a file



Process

```
read(0, buf, size);
write(1, buf, size);
```

0 1

Parent's
File Descriptor
Table

Kernel

File

# Powerful design choice

- File descriptors don't have to point to files *only*
  - Any object with the same read/write interface is ok
  - Files
  - Devices
    - Console
  - Pipes

# Example: cat

```
char buf[512]; int n;
for(;;) {
    n = read(0, buf, sizeof buf);
    if(n == 0)
        break;
    if(n < 0) {
        fprintf(2, "read error\n");
        exit(); }
    if(write(1, buf, n) != n) {
         fprintf(2, "write error\n");
         exit();
     }
 }
```

# Why do we need I/O redirection?

# Motivating example #2

- We want to see how many strings in ls.c contain “main”

# Motivating example #2

- We want to see how many strings in ls.c contain “main”
  - Imagine we have `grep`
    - `grep` filters strings matching a pattern

```
\>grep "main" ls.c

main(int argc, char *argv[])
```

  - Or the same written differently

```
\>grep "main" < ls.c

main(int argc, char *argv[])
```

# Motivating example #2

- Now we have
  - `grep`
    - Filters strings matching a pattern
  - `wc -l`
    - Counts lines

- Can we combine them?

# Pipes

- Imagine we have a way to redirect output of one process into input of another

```
\> cat ls.c | grep main
```

- `|` (a “pipe”) does redirection

# Pipes

- In our example:

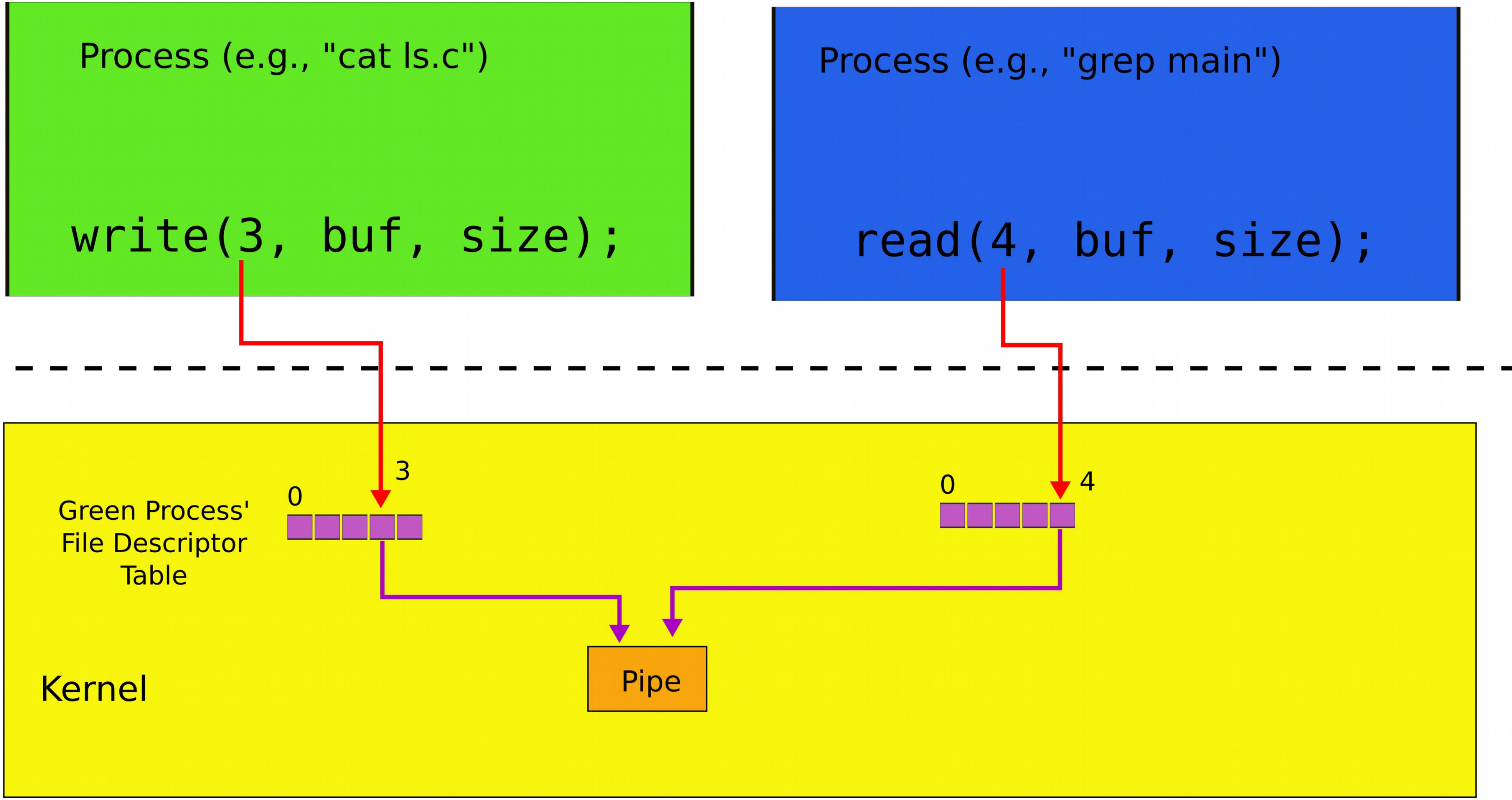
```
\> cat ls.c | grep main
```

- cat outputs ls.c to its output
  - cat's output is connected to grep's input with the pipe
  - grep filters lines that match a specific criteria, i.e., once that have “main”

# `pipe` - interprocess communication

- Pipe is a kernel buffer exposed as a pair of file descriptors
  - One for reading, one for writing
- Pipes allow processes to communicate
  - Send messages to each other

# Two file descriptors pointing to a pipe


Process (e.g., "cat ls.c")
write(3, buf, size);
Process (e.g., "grep main")
read(4, buf, size);
0
3
Green Process' File Descriptor Table
0
4
Pipe
Kernel

Pipes allow us to connect programs,
i.e., the output of one program to the input of another

# Composability

- Now if we want to see how many strings in ls.c contain “main”  we do:

```
\> cat ls.c | grep main | wc -l

1
```

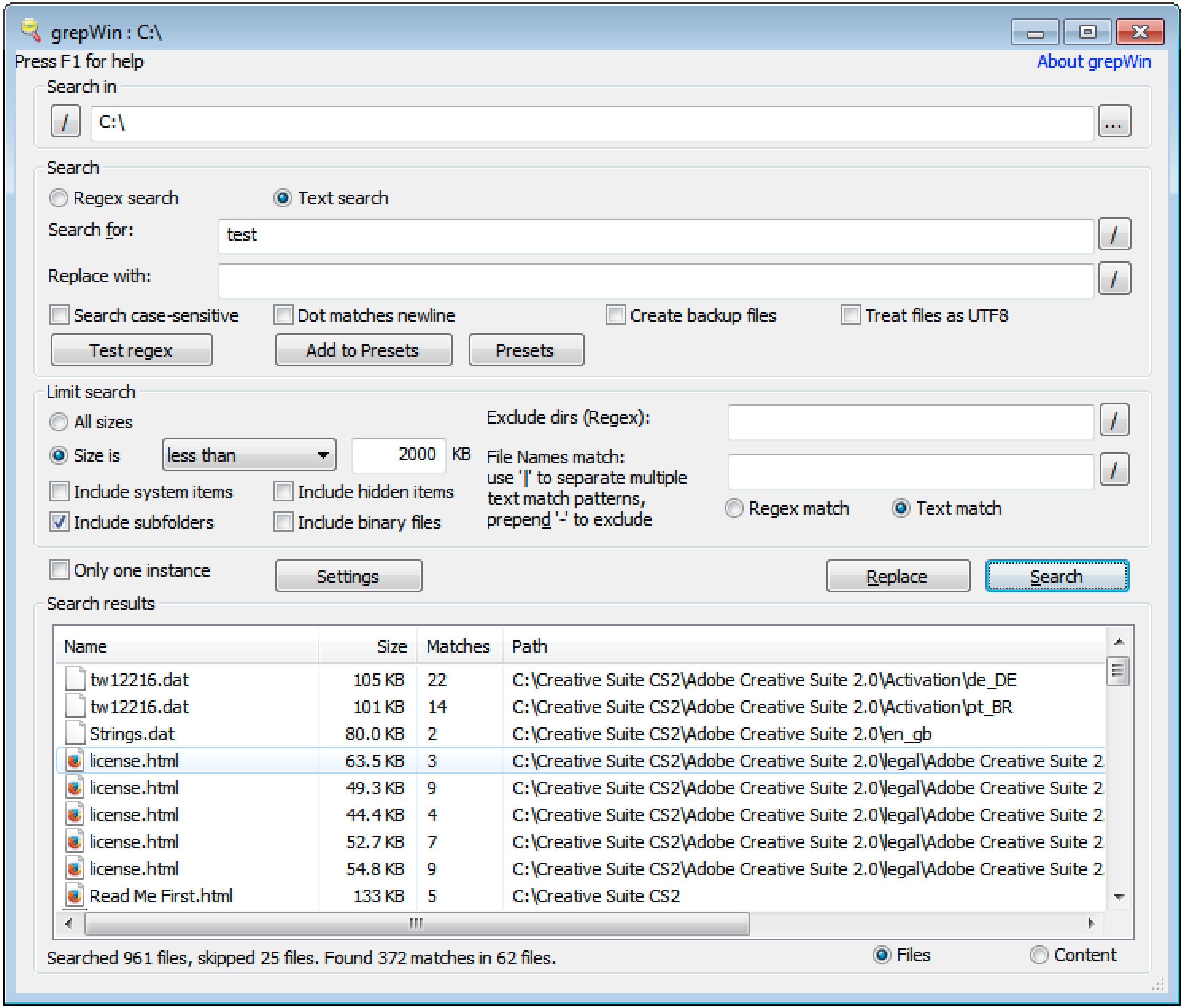
- .. but if we want to count the once that contain “a”:

```
cat ls.c | grep a | wc -l

33
```

- We change only input to grep!
  - Small set of tools (ls, grep, wc) compose into complex workflows

# Better than this...



Search in: C:\

Search

○ Regex search ● Text search

Search for: test

Replace with:

□ Search case-sensitive □ Dot matches newline □ Create backup files □ Treat files as UTF8

Limit search

○ All sizes

● Size is less than 2000 KB

□ Include system items □ Include hidden items

☑ Include subfolders □ Include binary files

Exclude dirs (Regex):

File Names match:
use '|' to separate multiple
text match patterns,
prepend '-' to exclude

○ Regex match ● Text match

□ Only one instance

Search results

| Name | Size | Matches | Path |
|---|---|---|---|
| tw12216.dat | 105 KB | 22 | C:\Creative Suite CS2\Adobe Creative Suite 2.0\Activation\de_DE |
| tw12216.dat | 101 KB | 14 | C:\Creative Suite CS2\Adobe Creative Suite 2.0\Activation\pt_BR |
| Strings.dat | 80.0 KB | 2 | C:\Creative Suite CS2\Adobe Creative Suite 2.0\en_gb |
| license.html | 63.5 KB | 3 | C:\Creative Suite CS2\Adobe Creative Suite 2.0\legal\Adobe Creative Suite 2 |
| license.html | 49.3 KB | 9 | C:\Creative Suite CS2\Adobe Creative Suite 2.0\legal\Adobe Creative Suite 2 |
| license.html | 44.4 KB | 4 | C:\Creative Suite CS2\Adobe Creative Suite 2.0\legal\Adobe Creative Suite 2 |
| license.html | 52.7 KB | 7 | C:\Creative Suite CS2\Adobe Creative Suite 2.0\legal\Adobe Creative Suite 2 |
| license.html | 54.8 KB | 9 | C:\Creative Suite CS2\Adobe Creative Suite 2.0\legal\Adobe Creative Suite 2 |
| Read Me First.html | 133 KB | 5 | C:\Creative Suite CS2 |

Searched 961 files, skipped 25 files. Found 372 matches in 62 files.

● Files ○ Content

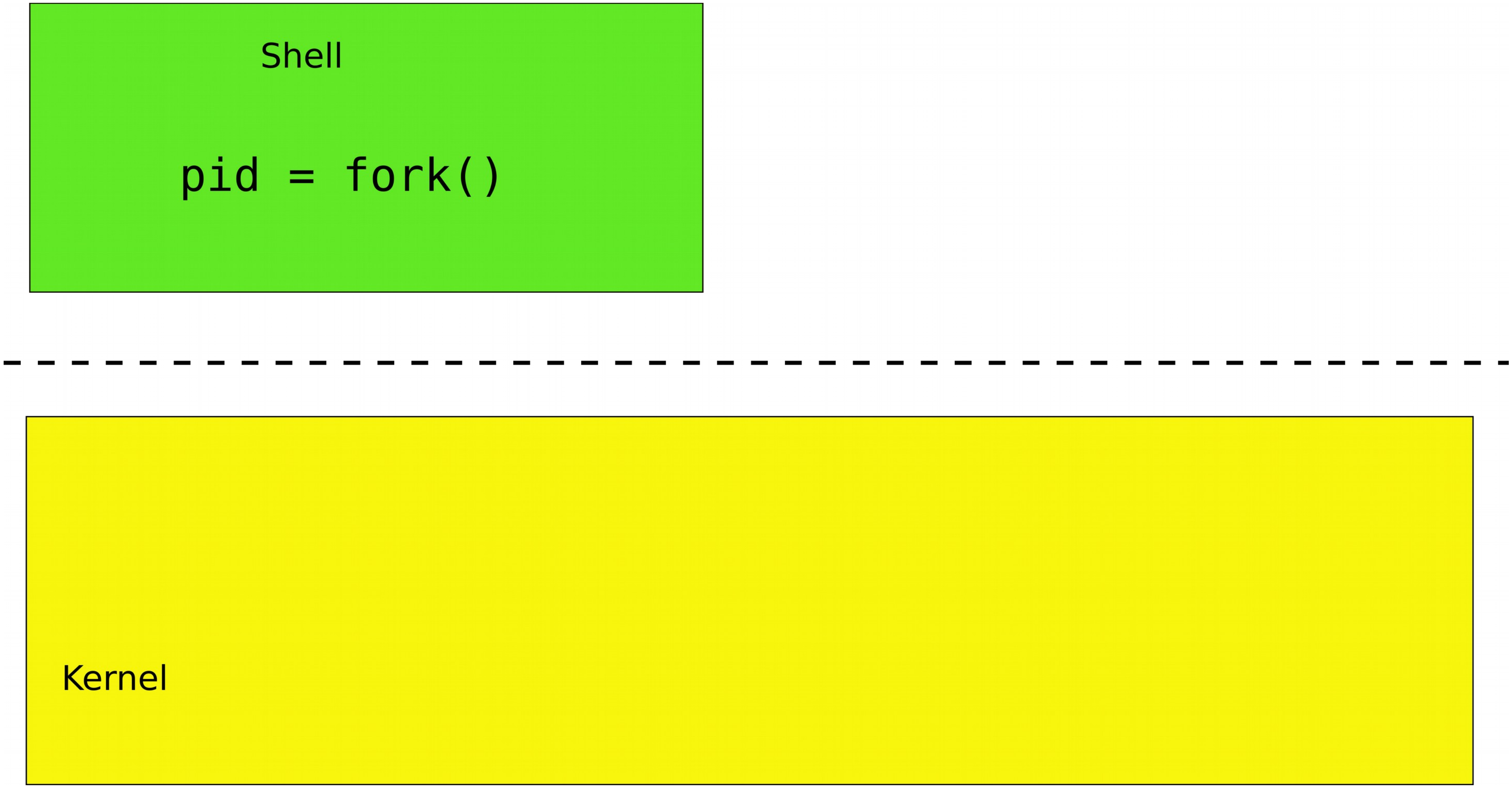
# Building I/O redirection

# How can we build this?

```
\> cat ls.c | grep main | wc -l
1
```

- `wc` has to operate on the output of `grep`
- `grep` operates on the output of `cat`

# Back to `fork()`

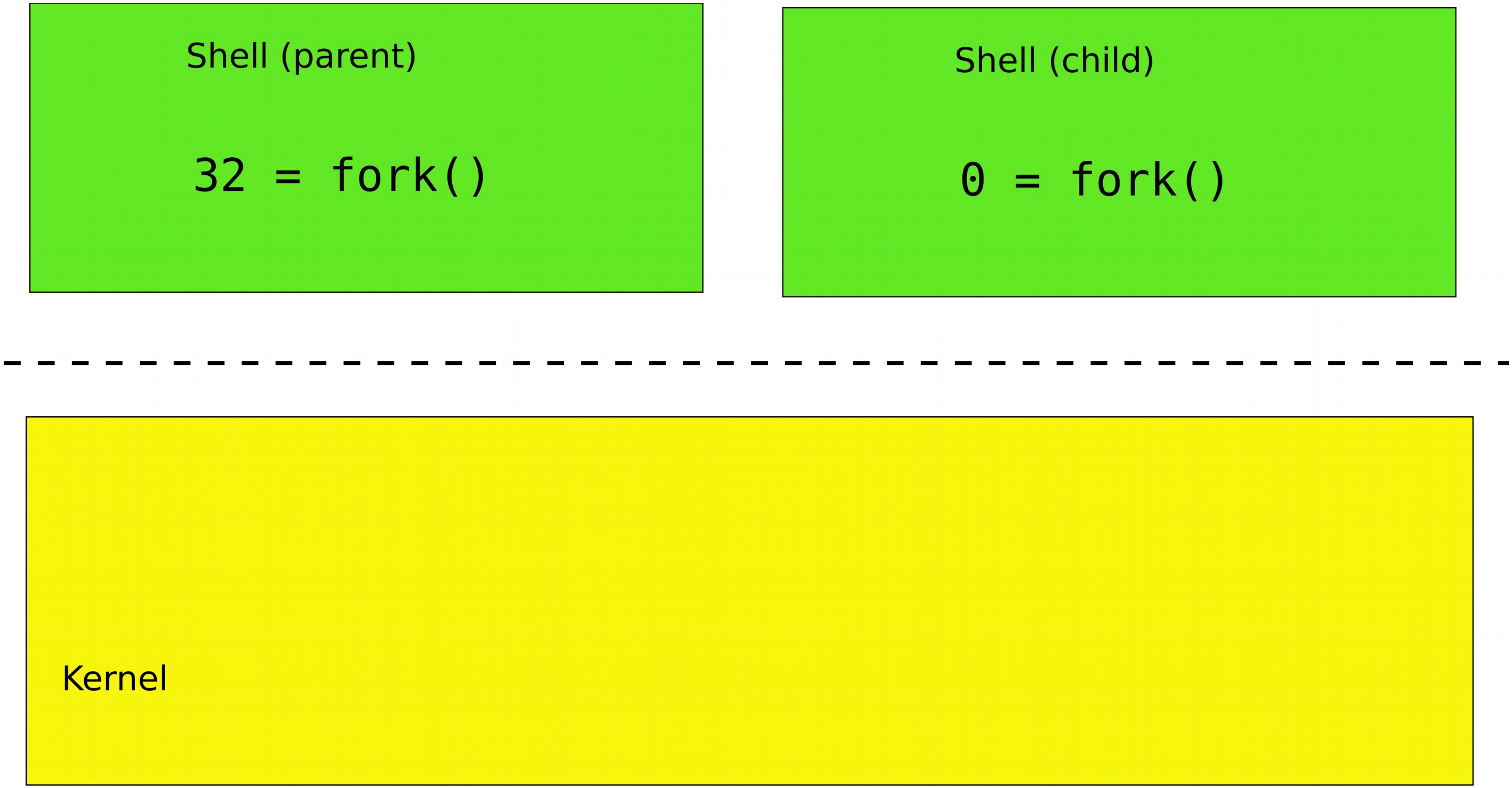


Shell

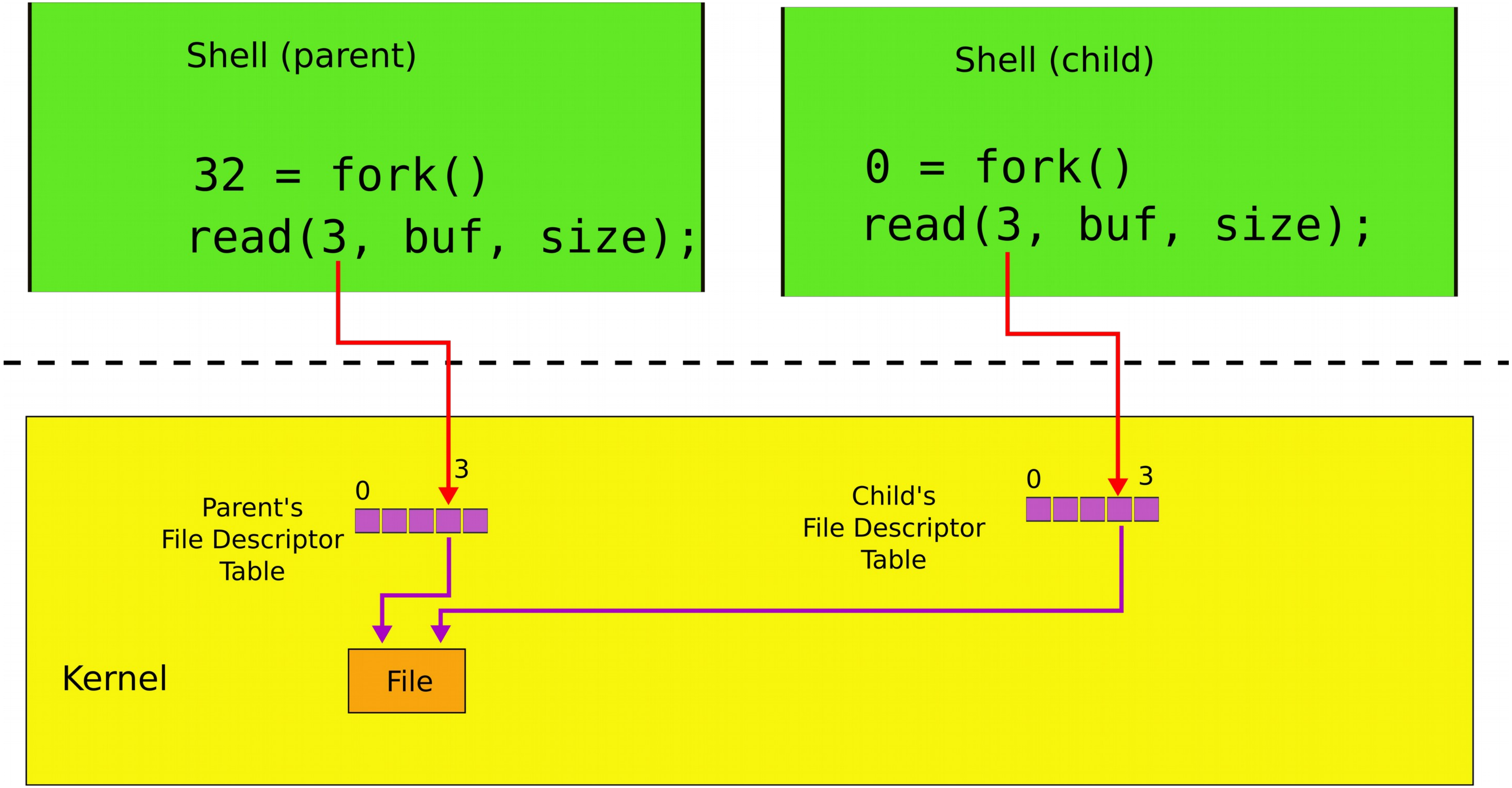
```
pid = fork()
```

Kernel

# fork()



# File descriptors after `fork()`



Shell (parent)

```
32 = fork()
read(3, buf, size);
```

Shell (child)

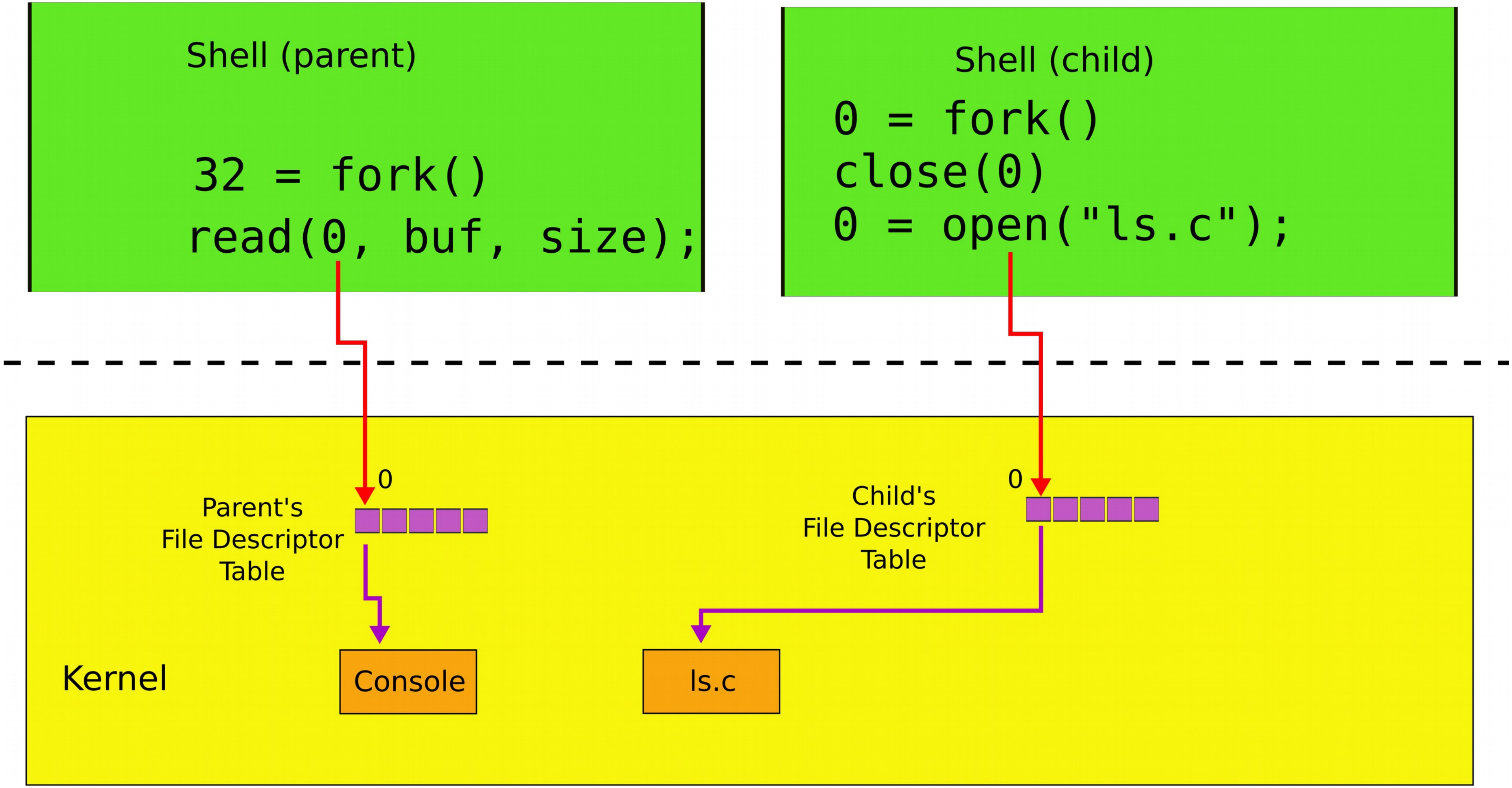
```
0 = fork()
read(3, buf, size);
```

# Two system calls for I/O redirection

- `close(fd)` – closes file descriptor
  - **The next opened file descriptor will have the lowest number**

# File descriptors after `close()/open()`

Example: \> cat < ls.c



Shell (parent)

```
32 = fork()
read(0, buf, size);
```

Shell (child)

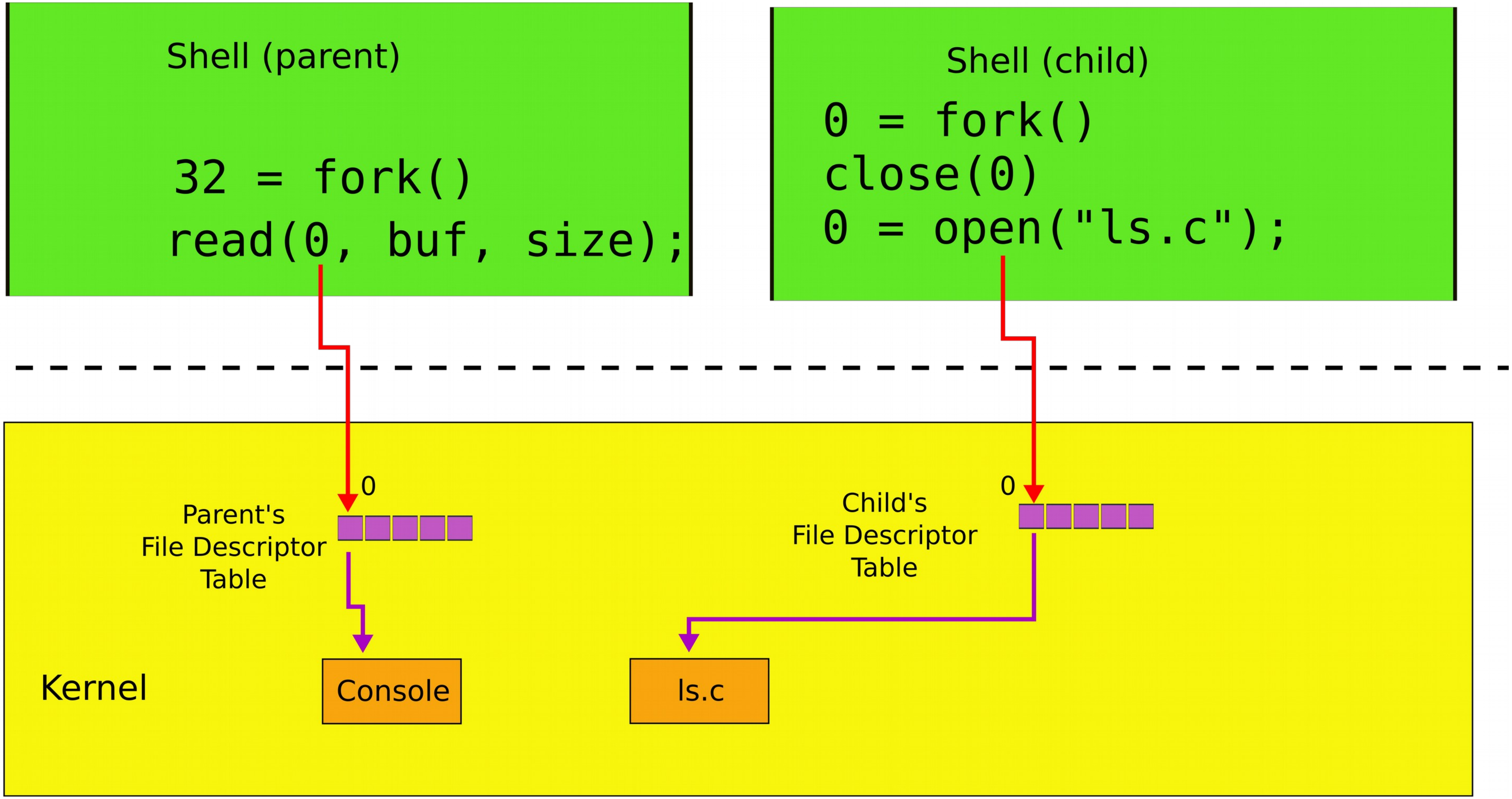
```
0 = fork()
close(0)
0 = open("ls.c");
```

# Two system calls for I/O redirection

- `close(fd)` – closes file descriptor
  - **The next opened file descriptor will have the lowest number**
- `exec()` replaces process memory, but
  - **leaves its file table (table of the file descriptors untouched)**
  - A process can create a copy of itself with `fork()`
  - Change the file descriptors for the next program it is about to run
  - And then execute the program with `exec()`

# File descriptors after `exec()`

Example: \> cat < ls.c



Shell (parent)

```
32 = fork()
read(0, buf, size);
```

Shell (child)

```
0 = fork()
close(0)
0 = open("ls.c");
```

# Example: \> cat < ls.c

```
char *argv[2];
argv[0] = "cat";
argv[1] = 0;
if(fork() == 0) {
    close(0);
    open("ls.c", O_RDONLY);
    exec("cat", argv);
}
```

# Why `fork()` not just `exec()`

- The reason for the pair of `fork()`/`exec()`
    - Shell can manipulate the new process (the copy created by `fork()`)
    - Before running it with `exec()`

# Back to Motivating example #2

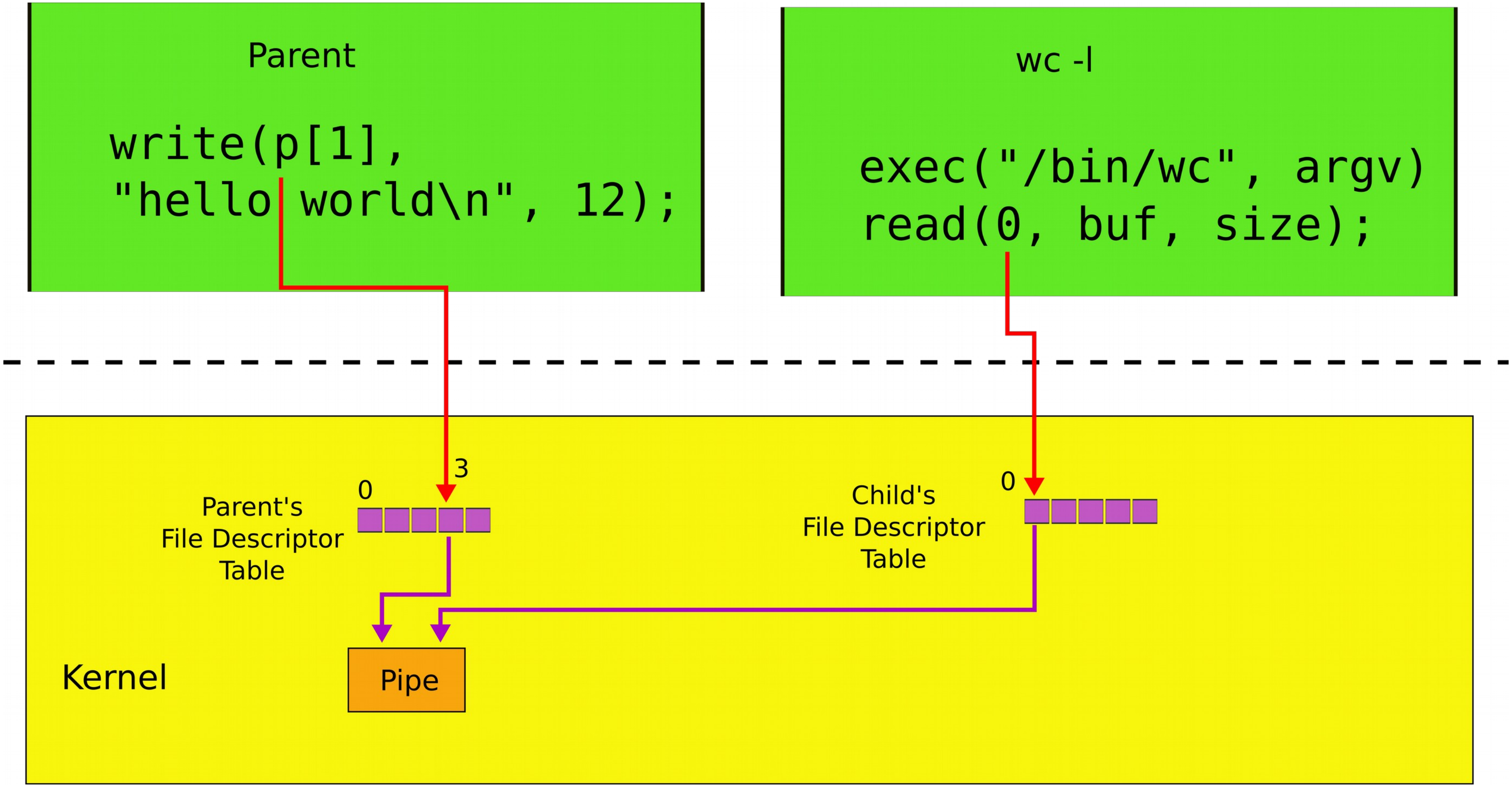
(`\> cat ls.c | grep main | wc -l`)

# Pipes

- We now understand how to use a pipe to connect two programs
  - Create a pipe
  - Fork
  - Attach one end to standard output
    - of the left side of “|”
  - Another to the standard input
    - of the right side of “|”

```
int p[2];
char *argv[2]; argv[0] = "wc"; argv[1] = 0;
pipe(p);
if(fork() == 0) {
   close(0);
   dup(p[0]);
   close(p[0]);
   close(p[1]);
   exec("/bin/wc", argv);
} else {
   write(p[1], "hello world\n", 12);
   close(p[0]);
   close(p[1]);
}
```

wc on the read end of the pipe



Parent

```
write(p[1],
"hello world\n", 12);
```

wc -l

```
exec("/bin/wc", argv)
read(0, buf, size);
```

Parent's
File Descriptor
Table

Child's
File Descriptor
Table

Kernel

Pipe

```
cat ls.c | grep main | wc -l
```

# Powerful conclusion

- `fork()`, standard file descriptors, `pipes` and `exec()` allow complex programs out of simple tools
- They form the core of the UNIX interface

# More system calls

# Process management

- `exit()` -- terminate current process
- `wait()` -- wait for the child to exit

# Creating files

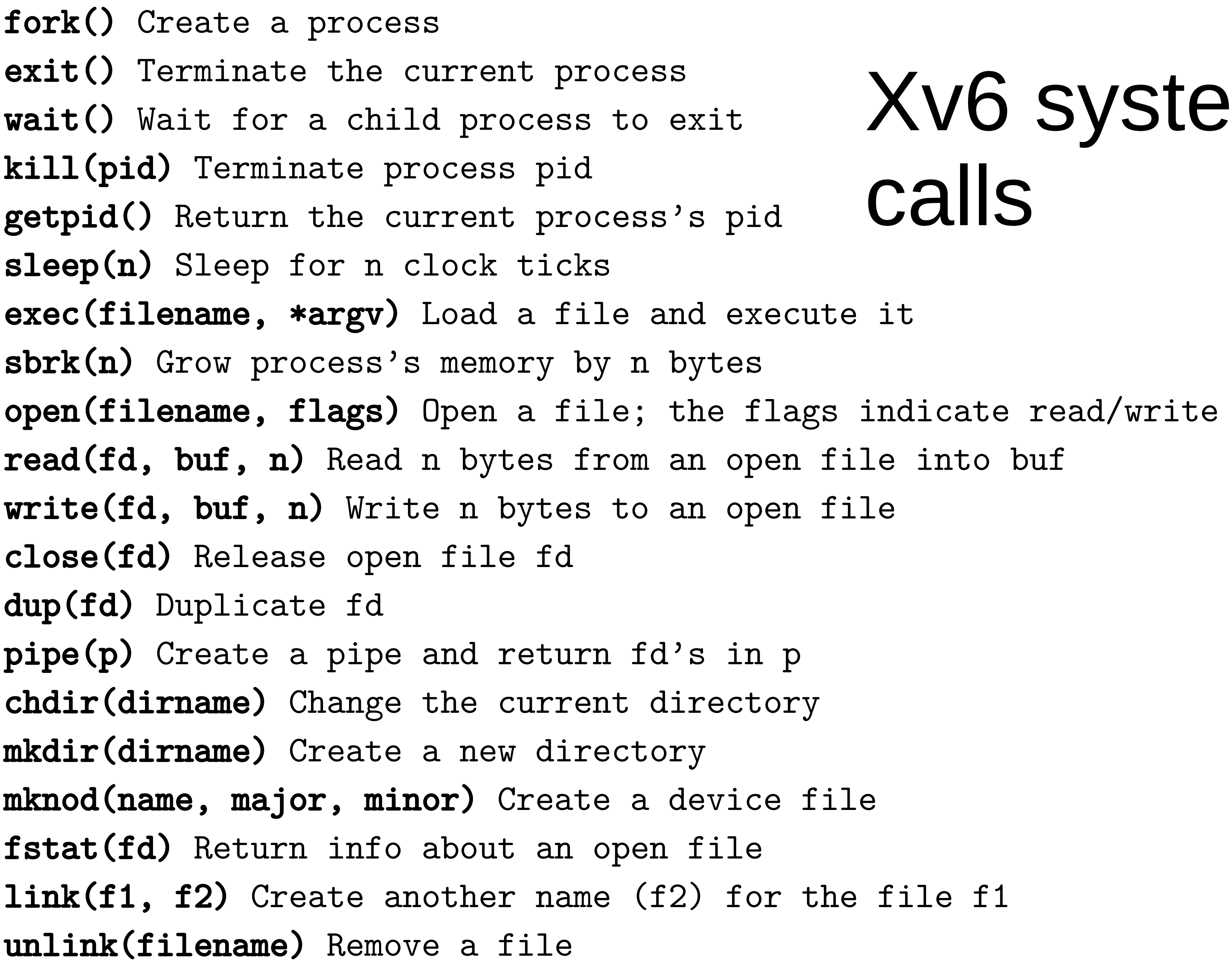
- `mkdir()` – creates a directory
- `open(O_CREATE)` – creates a file
- `mknod()` – creates an empty file marked as device
  - Major and minor numbers uniquely identify the device in the kernel
- `fstat()` – retrieve information about a file

# Links, inodes

- Same file can have multiple names – links
  - But unique inode number
- `link()` – create a link
- `unlink()` – delete file
- Example, create a temporary file

```
fd = open("/tmp/xyz", O_CREATE|O_RDWR);
unlink("/tmp/xyz");
```

# Xv6 system calls



**fork()** Create a process

**exit()** Terminate the current process

**wait()** Wait for a child process to exit

**kill(pid)** Terminate process pid

**getpid()** Return the current process's pid

**sleep(n)** Sleep for n clock ticks

**exec(filename, *argv)** Load a file and execute it

**sbrk(n)** Grow process's memory by n bytes

**open(filename, flags)** Open a file; the flags indicate read/write

**read(fd, buf, n)** Read n bytes from an open file into buf

**write(fd, buf, n)** Write n bytes to an open file

**close(fd)** Release open file fd

**dup(fd)** Duplicate fd

**pipe(p)** Create a pipe and return fd's in p

**chdir(dirname)** Change the current directory

**mkdir(dirname)** Create a new directory

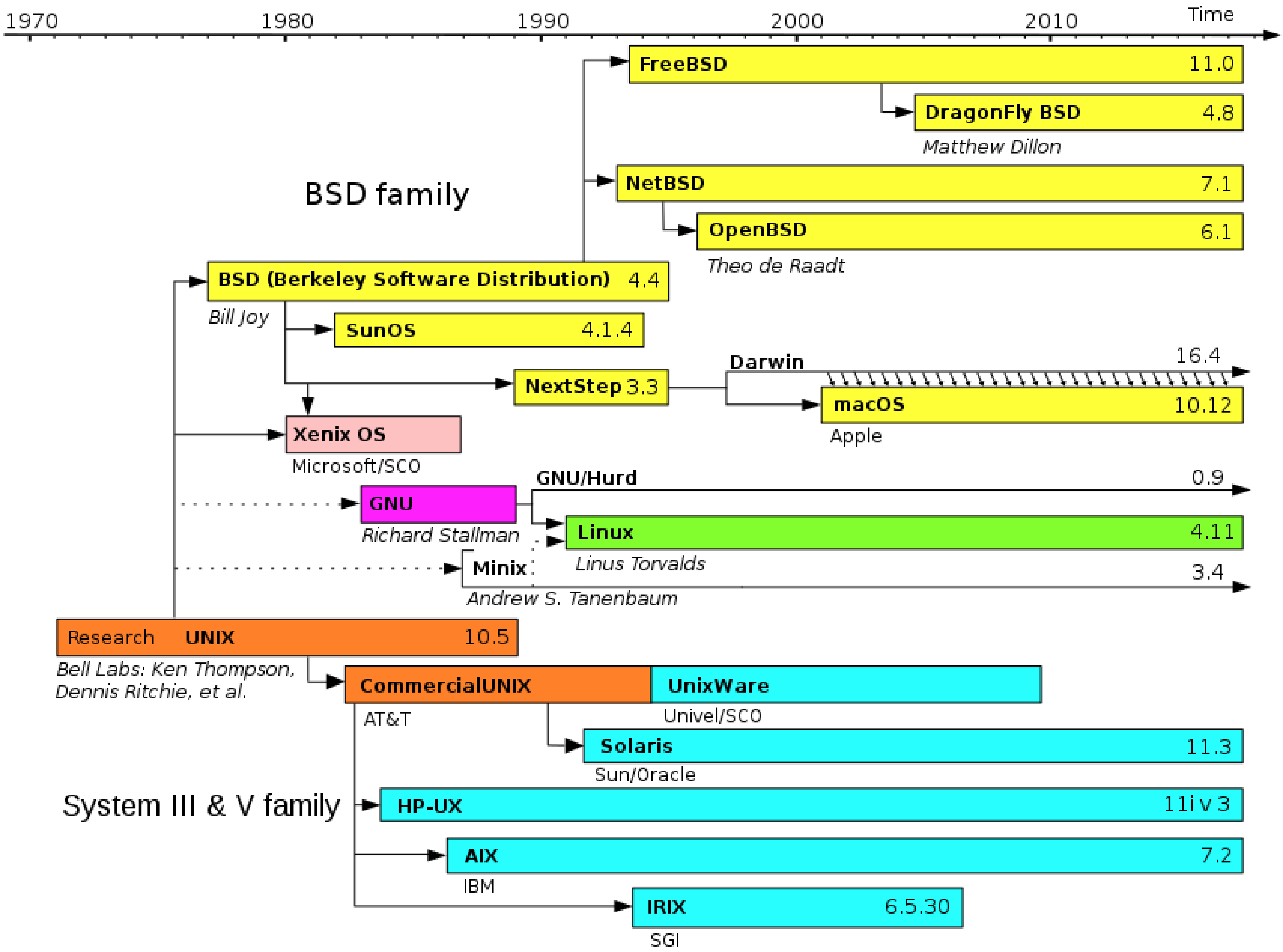
**mknod(name, major, minor)** Create a device file

**fstat(fd)** Return info about an open file

**link(f1, f2)** Create another name (f2) for the file f1

**unlink(filename)** Remove a file

# In many ways xv6 is an OS you run today



BSD family

FreeBSD 11.0

DragonFly BSD 4.8

*Matthew Dillon*

NetBSD 7.1

OpenBSD 6.1

*Theo de Raadt*

BSD (Berkeley Software Distribution) 4.4

*Bill Joy*

SunOS 4.1.4

Darwin 16.4

NextStep 3.3

macOS 10.12

Apple

Xenix OS

Microsoft/SCO

GNU/Hurd 0.9

GNU

*Richard Stallman*

Linux 4.11

*Linus Torvalds*

Minix 3.4

*Andrew S. Tanenbaum*

Research UNIX 10.5

*Bell Labs: Ken Thompson, Dennis Ritchie, et al.*

CommercialUNIX

AT&T

UnixWare

Univel/SCO

Solaris 11.3

Sun/Oracle

System III & V family

HP-UX 11i v 3

AIX 7.2

IBM

IRIX 6.5.30

SGI

Evolution of Unix and Unix-like systems

# Backup slides

Speakers from the 1984 Summer Usenix Conference (Salt Lake City, UT)

# Pipes

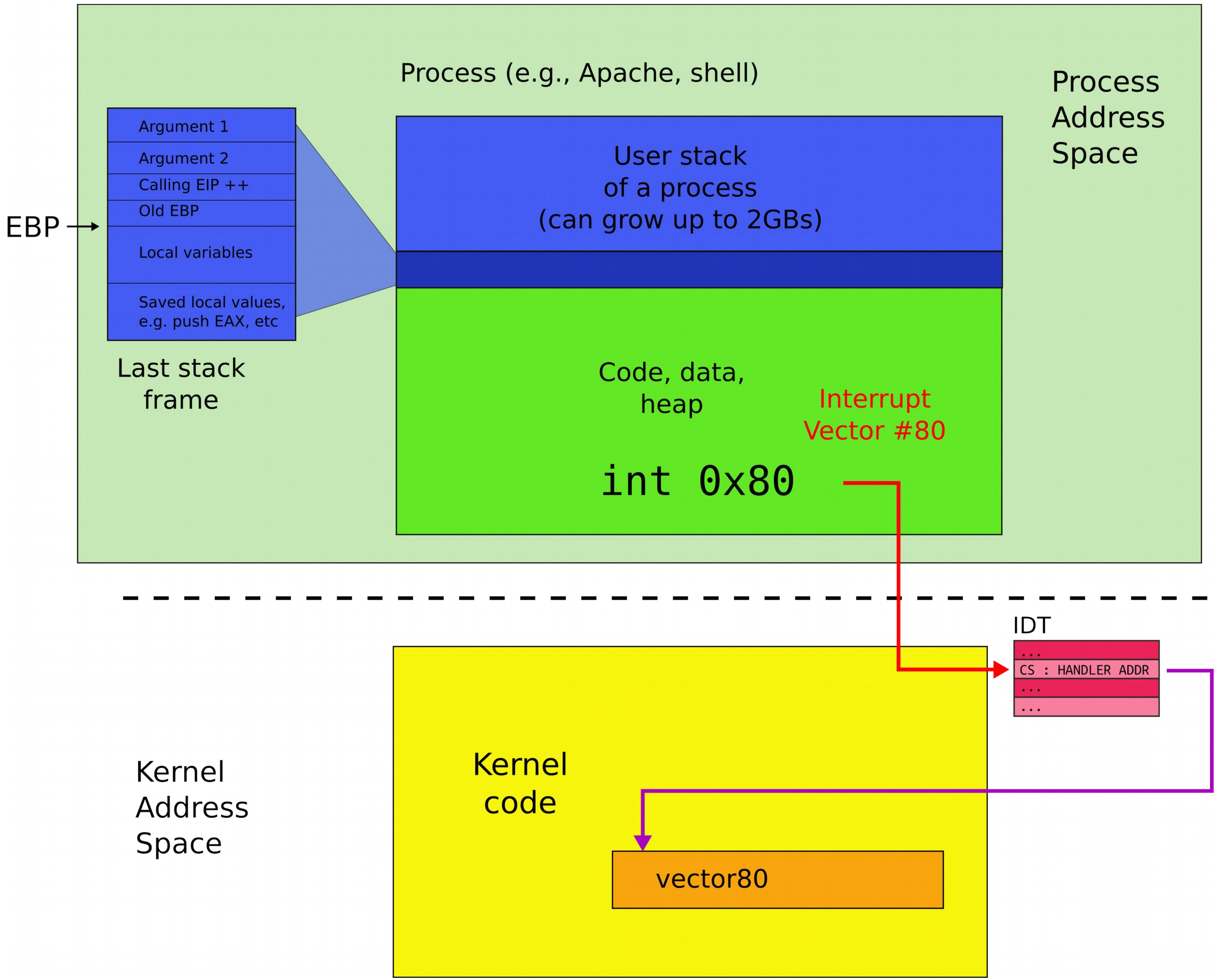
- Shell composes simple utilities into more complex actions with pipes, e.g.

```
grep FORK sh.c | wc -l
```

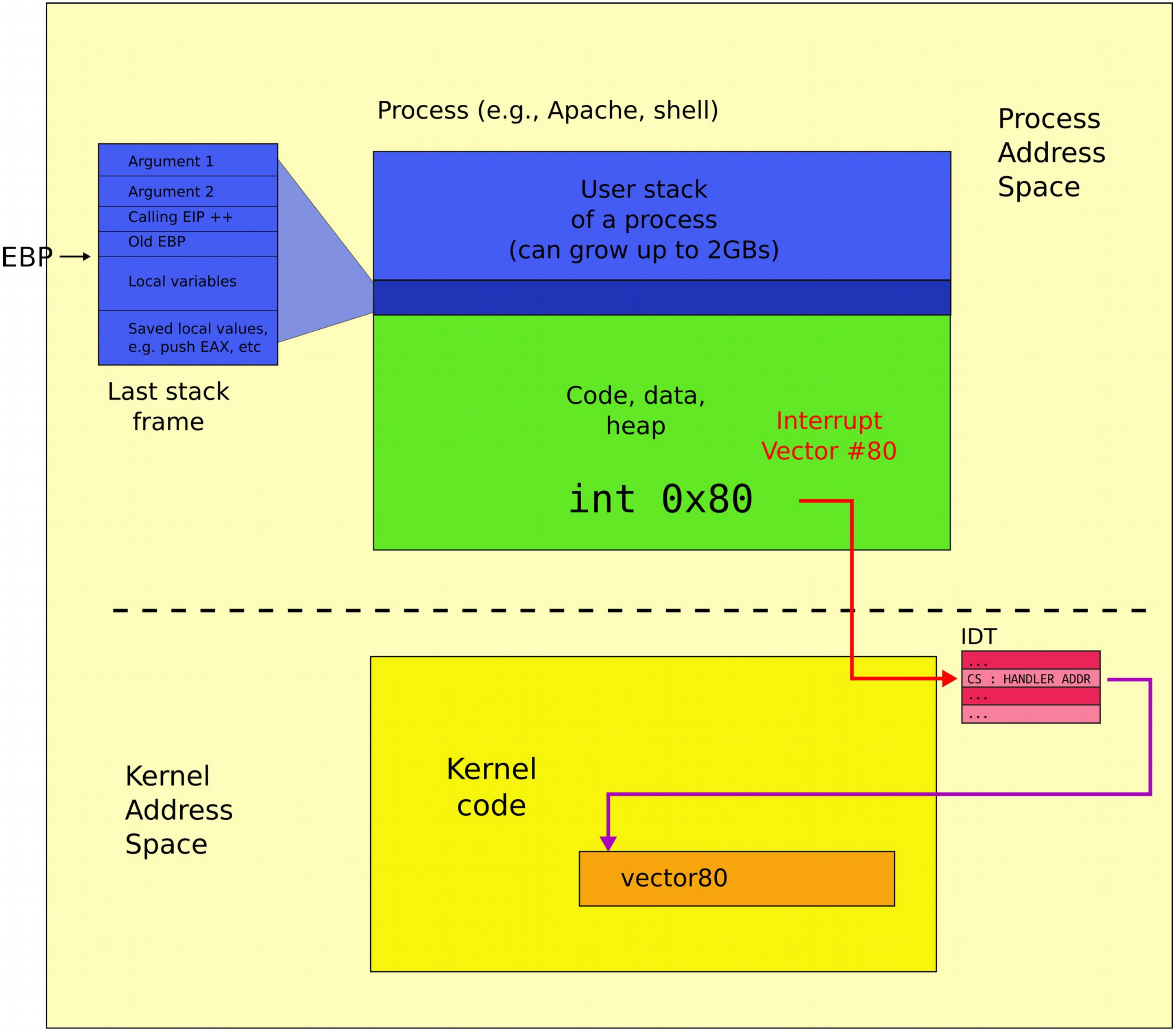
- Create a pipe and connect ends

# System call

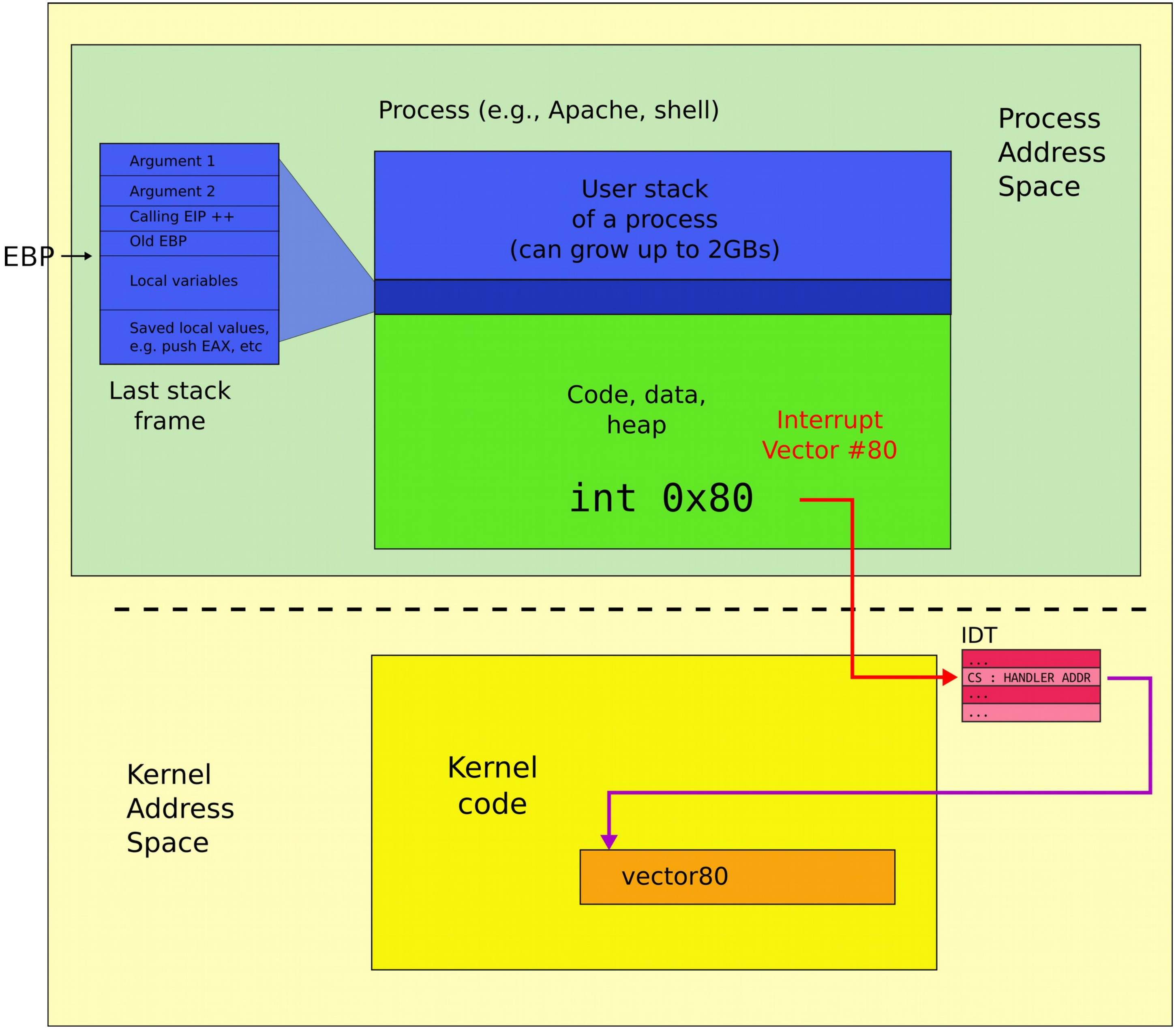
# User address space



# Kernel address space



# Kernel and user address spaces


Process (e.g., Apache, shell)
Process Address Space
Argument 1
Argument 2
Calling EIP ++
Old EBP
Local variables
Saved local values, e.g. push EAX, etc
EBP
Last stack frame
User stack of a process (can grow up to 2GBs)
Code, data, heap
Interrupt Vector #80
int 0x80
IDT
...
CS : HANDLER ADDR
...
...
Kernel Address Space
Kernel code
vector80