Lecture 2: OS Interfaces
cs5460/6460 Operating Systems

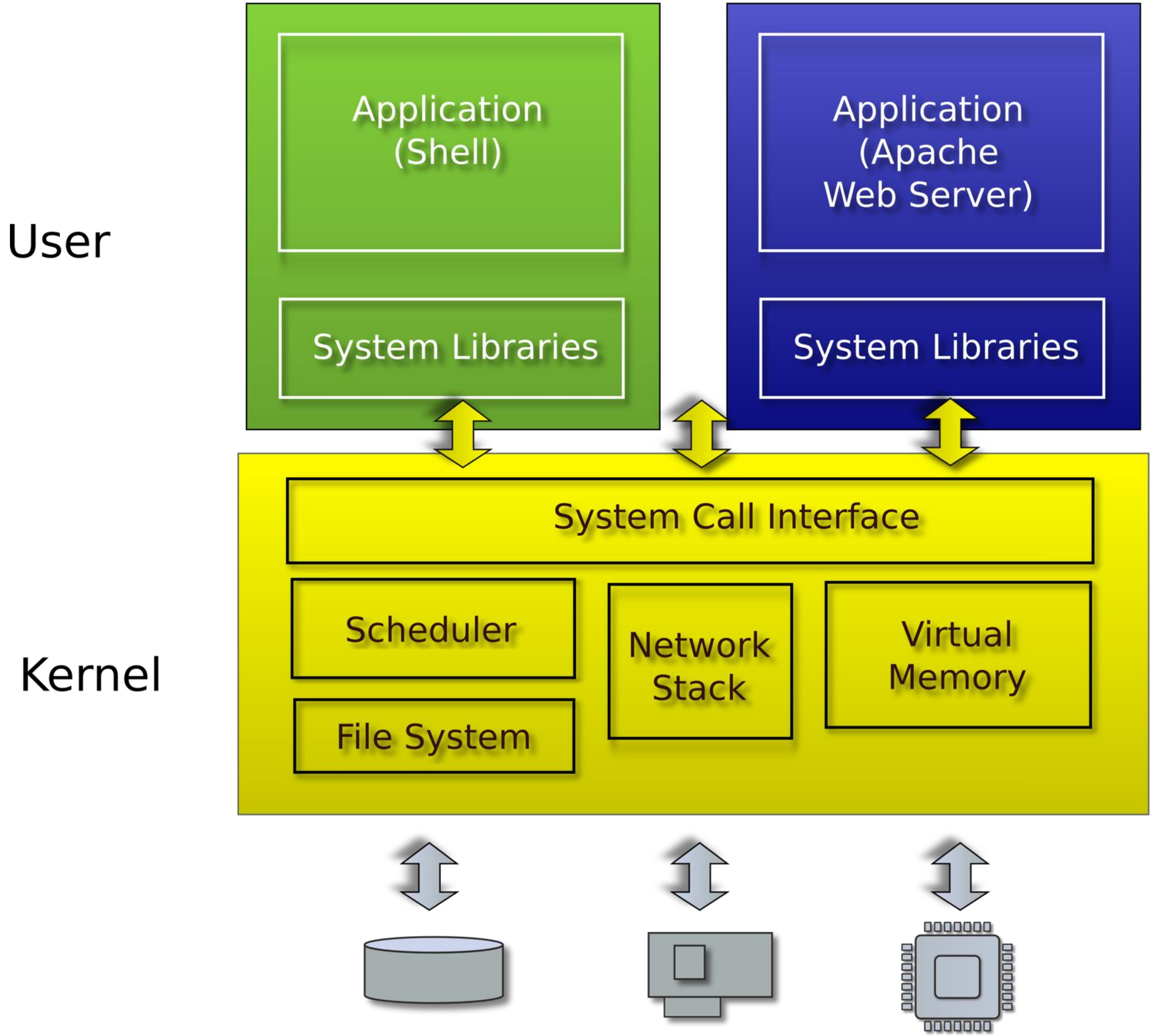
Anton Burtsev

January, 2025

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 implement the interface of the OS

Which system calls do we need?

System calls, interface for...

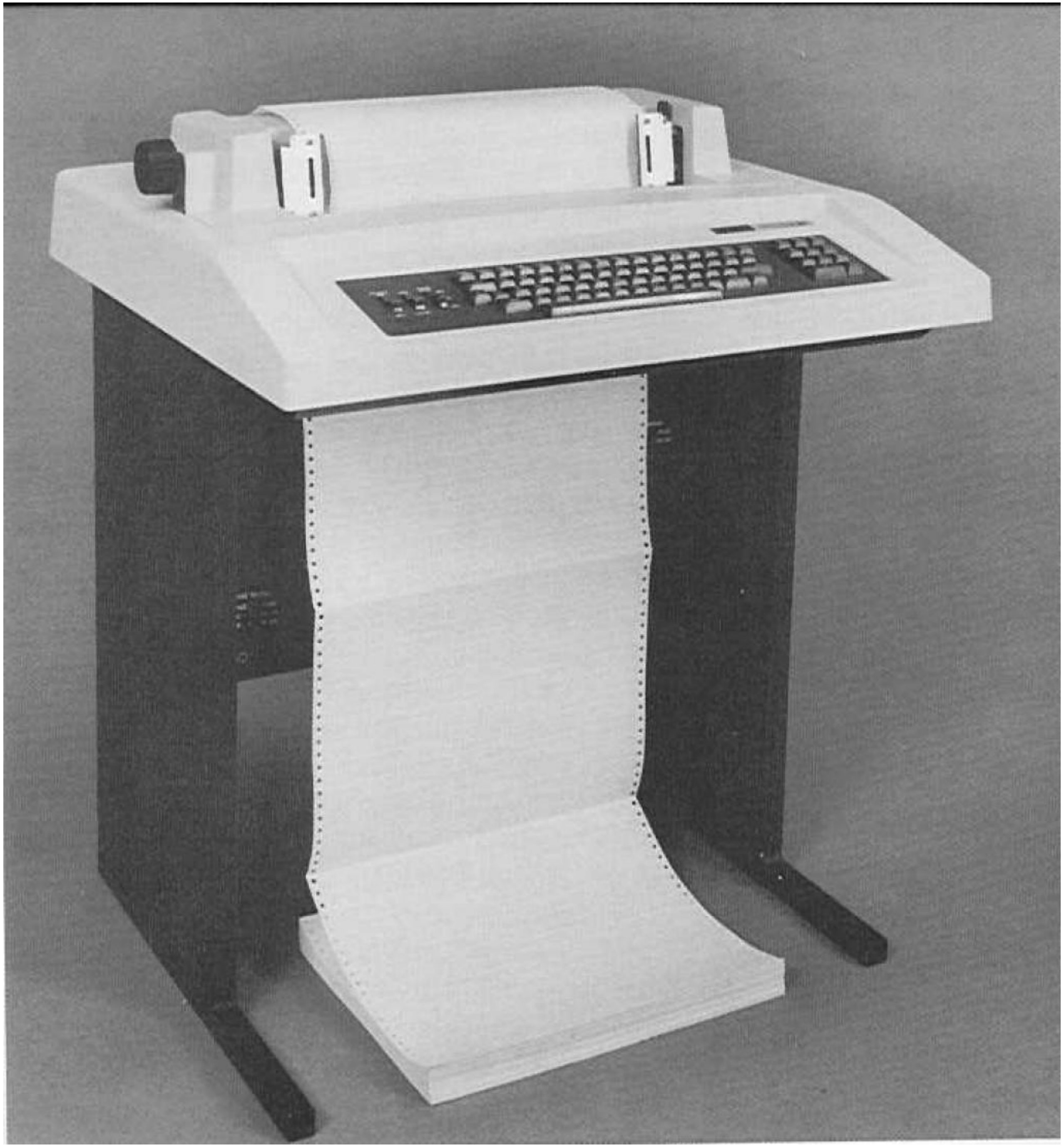
- Processes
  - Creating, exiting, waiting, terminating
- Memory
  - Allocation, deallocation
- Files and folders
  - Opening, reading, writing, closing
- Inter-process communication
  - Pipes

UNIX (and xv6) system calls are designed around 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

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 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

\>

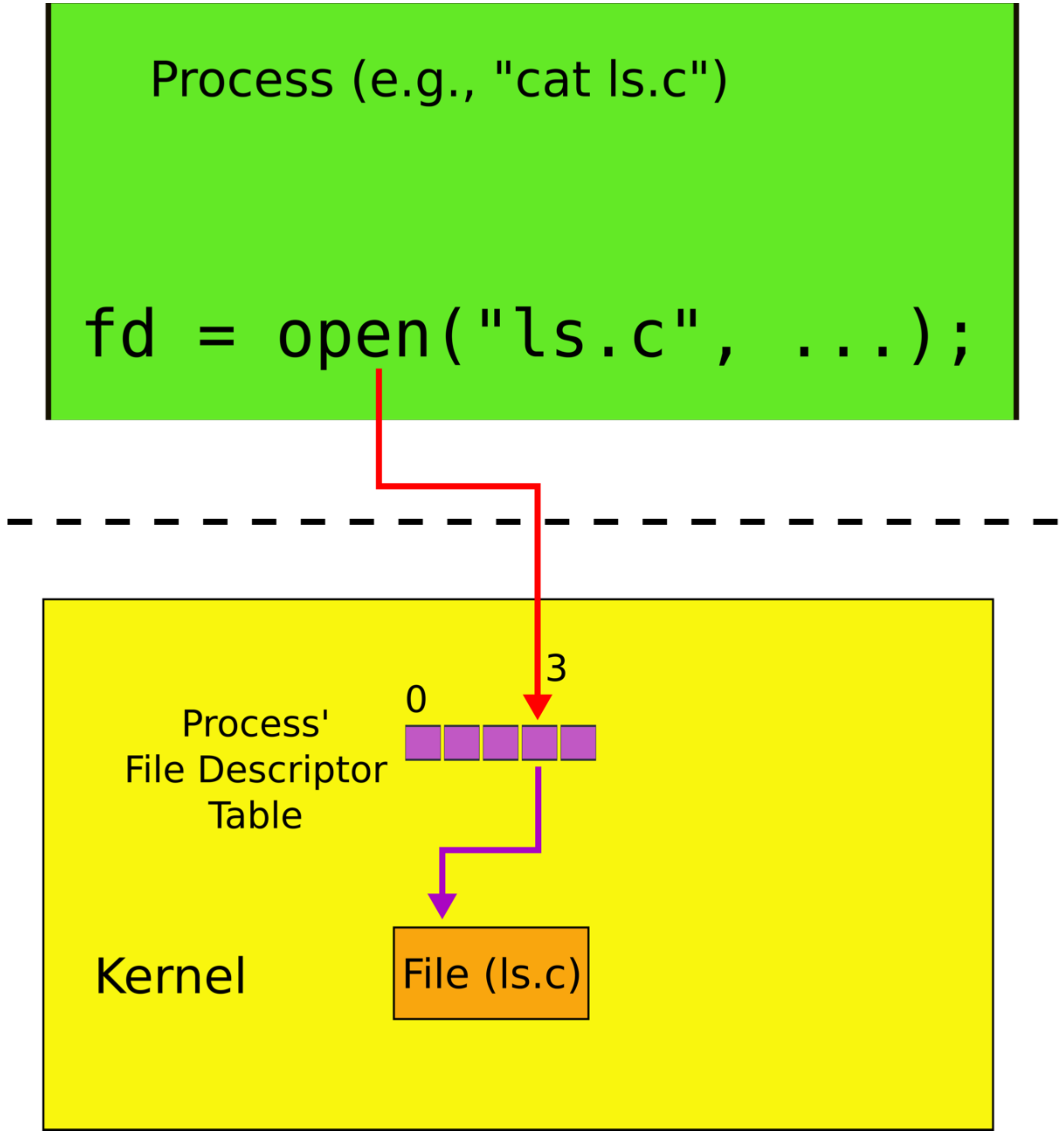
- Shell starts wc
  - Creates a new process to run wc
  - Passes the arguments (-l and ls.c)
- wc sends its output to the terminal (console)
  - Exits when done with exit()
- Shell detects that wc is done (wait())
  - Prints (to the same terminal) its command prompt
  - Ready to execute the next command

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

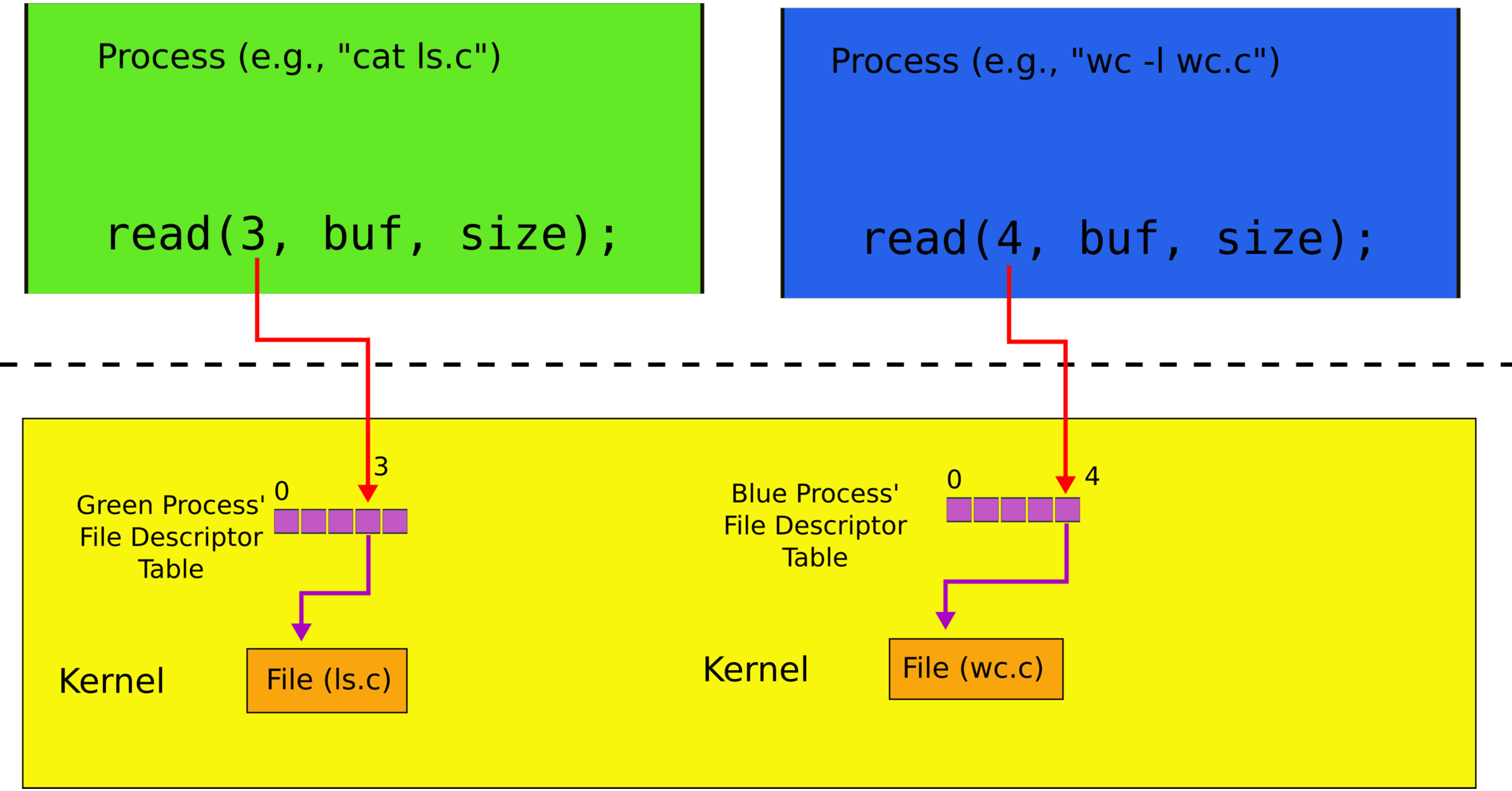
- An index into a table, i.e., just an integer
- The table maintains pointers to “file” objects
  - Abstracts files, devices, pipes
  - In UNIX everything is a file – all objects provide file interface
- Process may obtain file descriptors through
  - Opening a file, directory, device
  - By creating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

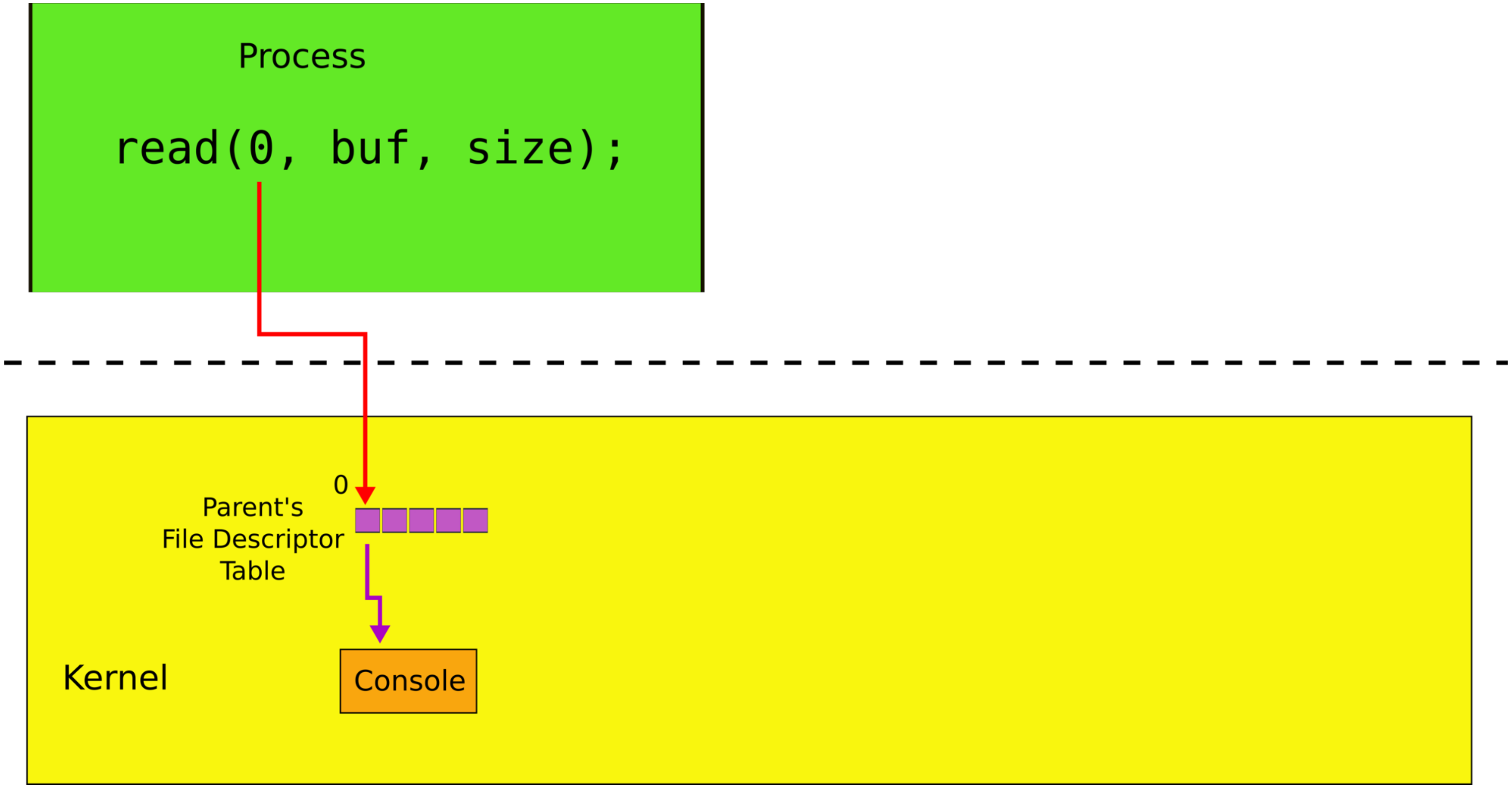


Console I/O

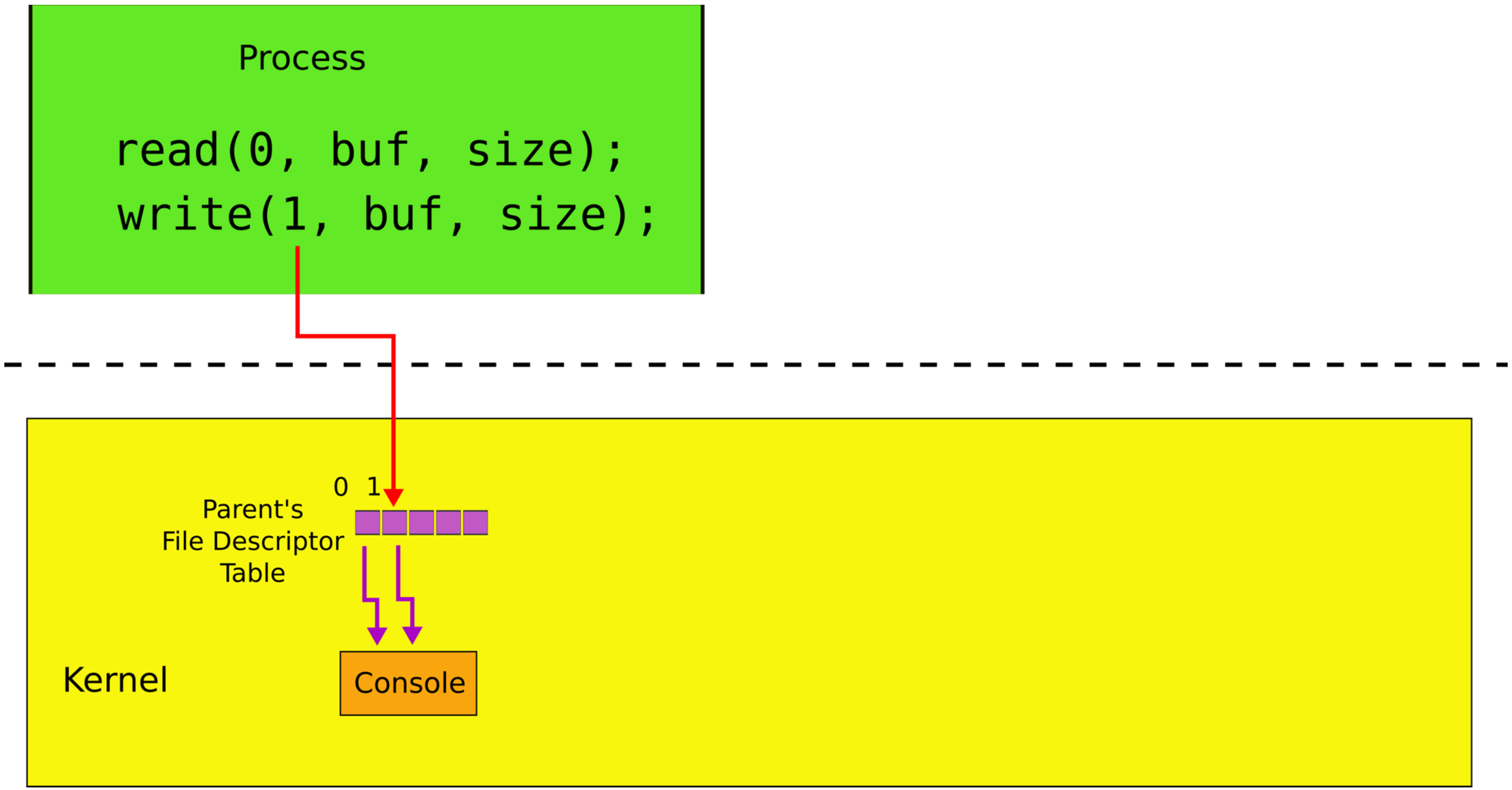
Each process has standard file descriptors

- 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)

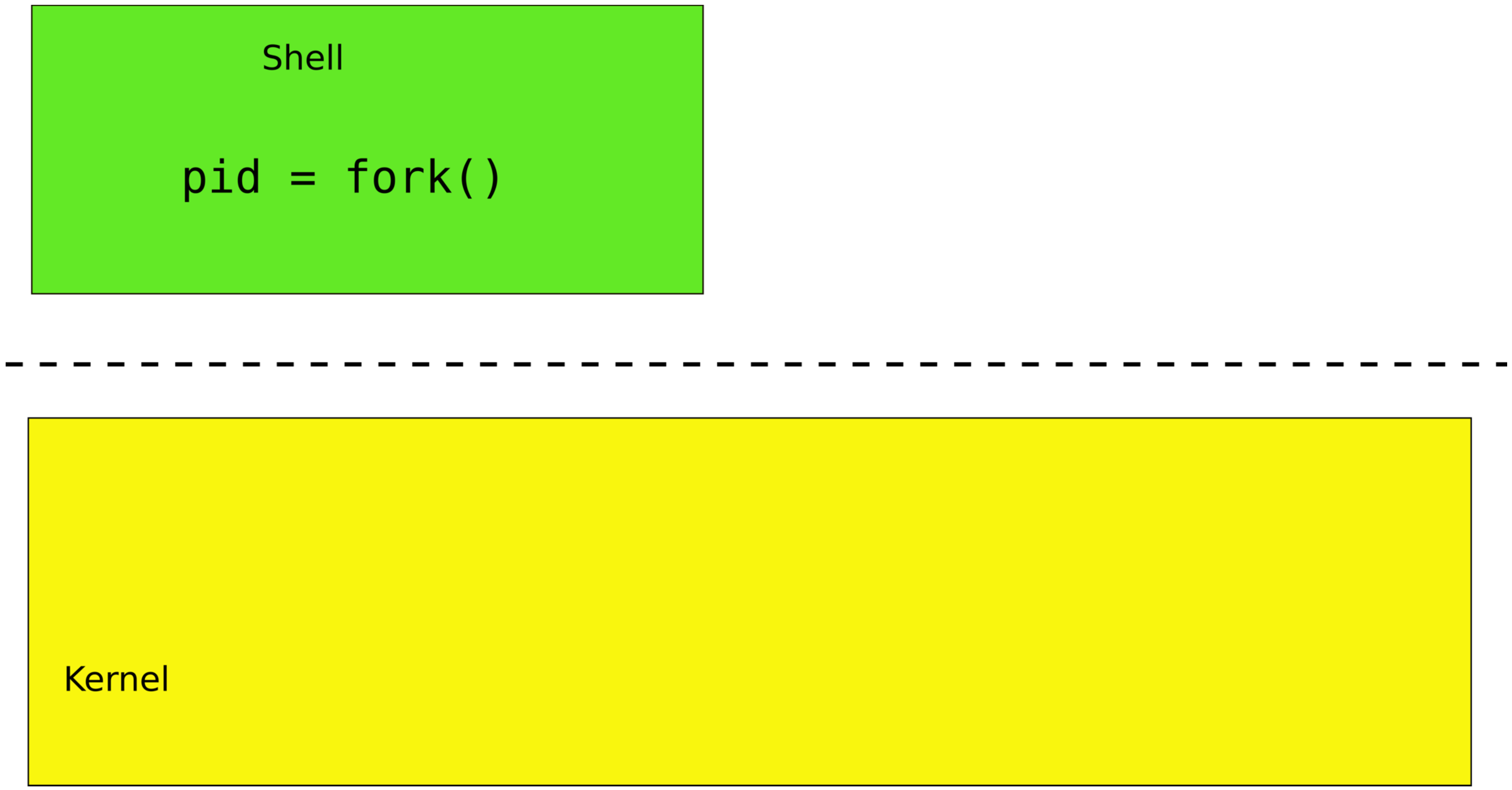


Example: cat

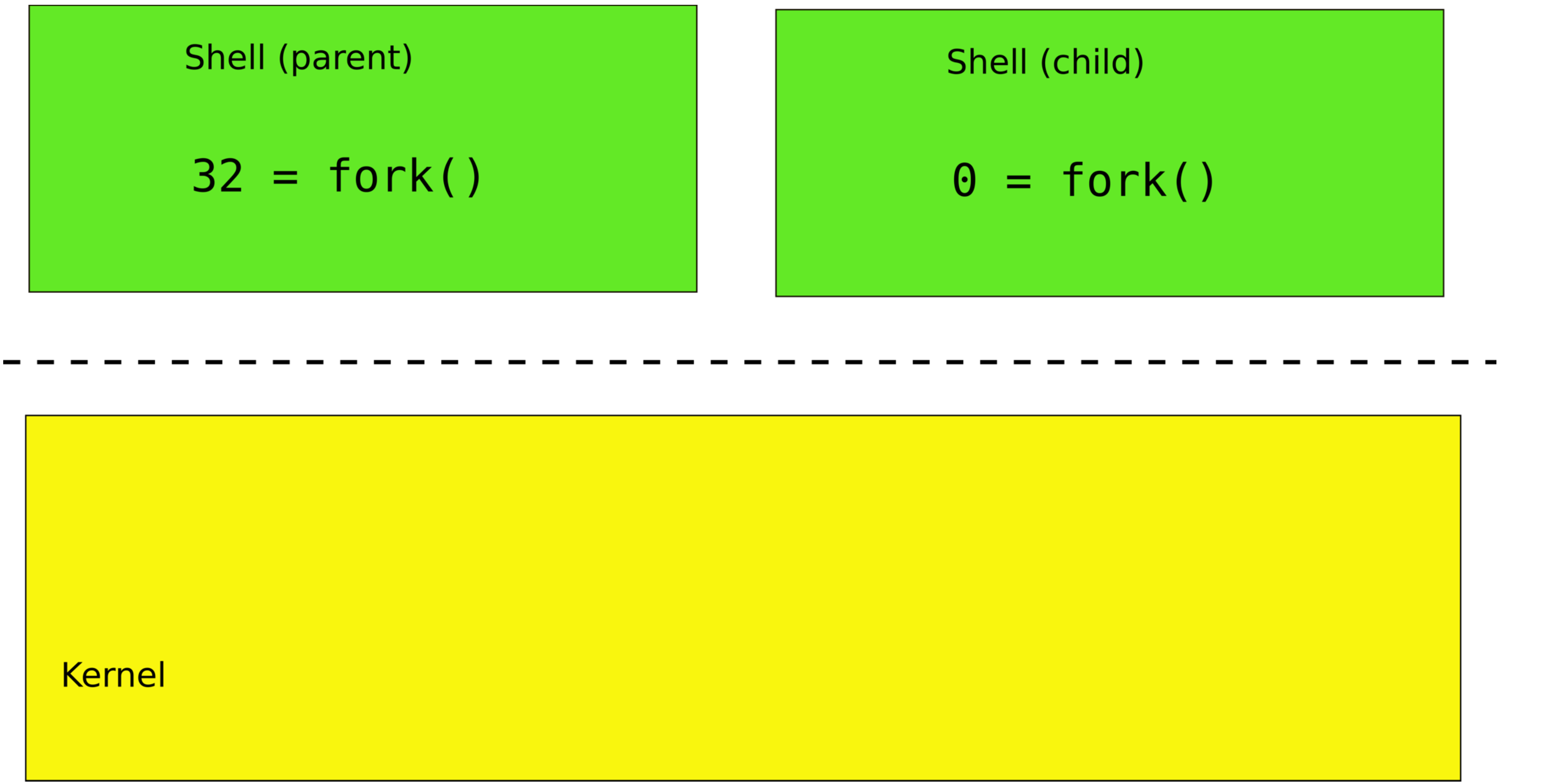
```
char buf[512];
int n;
for(;;) {
    n = read(0, buf, sizeof buf);
    if(n == 0)
        break;
    if(n < 0) {
        fprintf(2, "read error\n");
        exit(); }
    if(write(1, buf, n) != n) {
        fprintf(2, "write error\n");
        exit();
    }
}
```

Creating processes

fork()



fork()



fork() -- creates a 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");
}
```

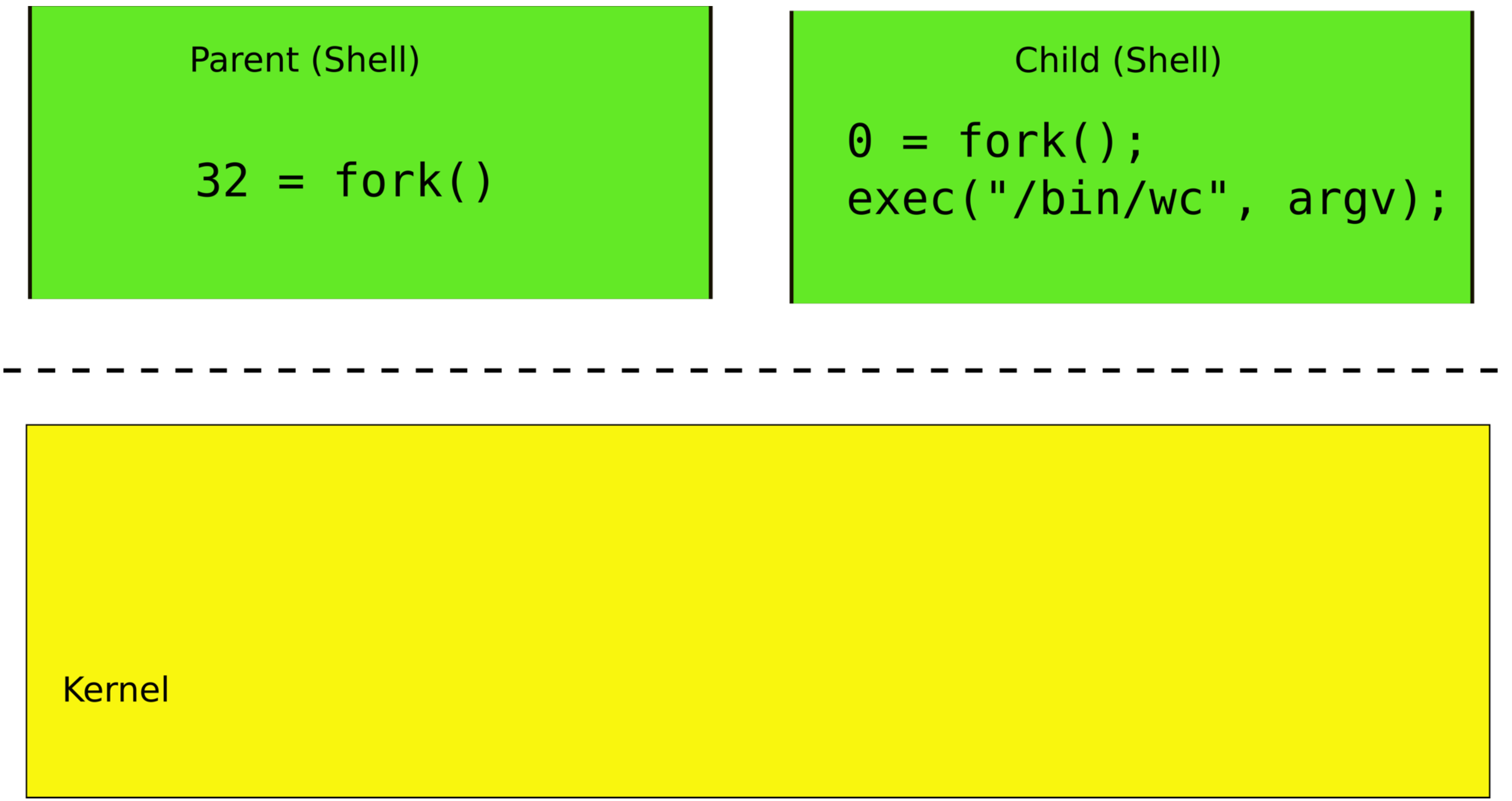
This is weird... fork() creates copies of the same process, why?

fork() is used together with exec()

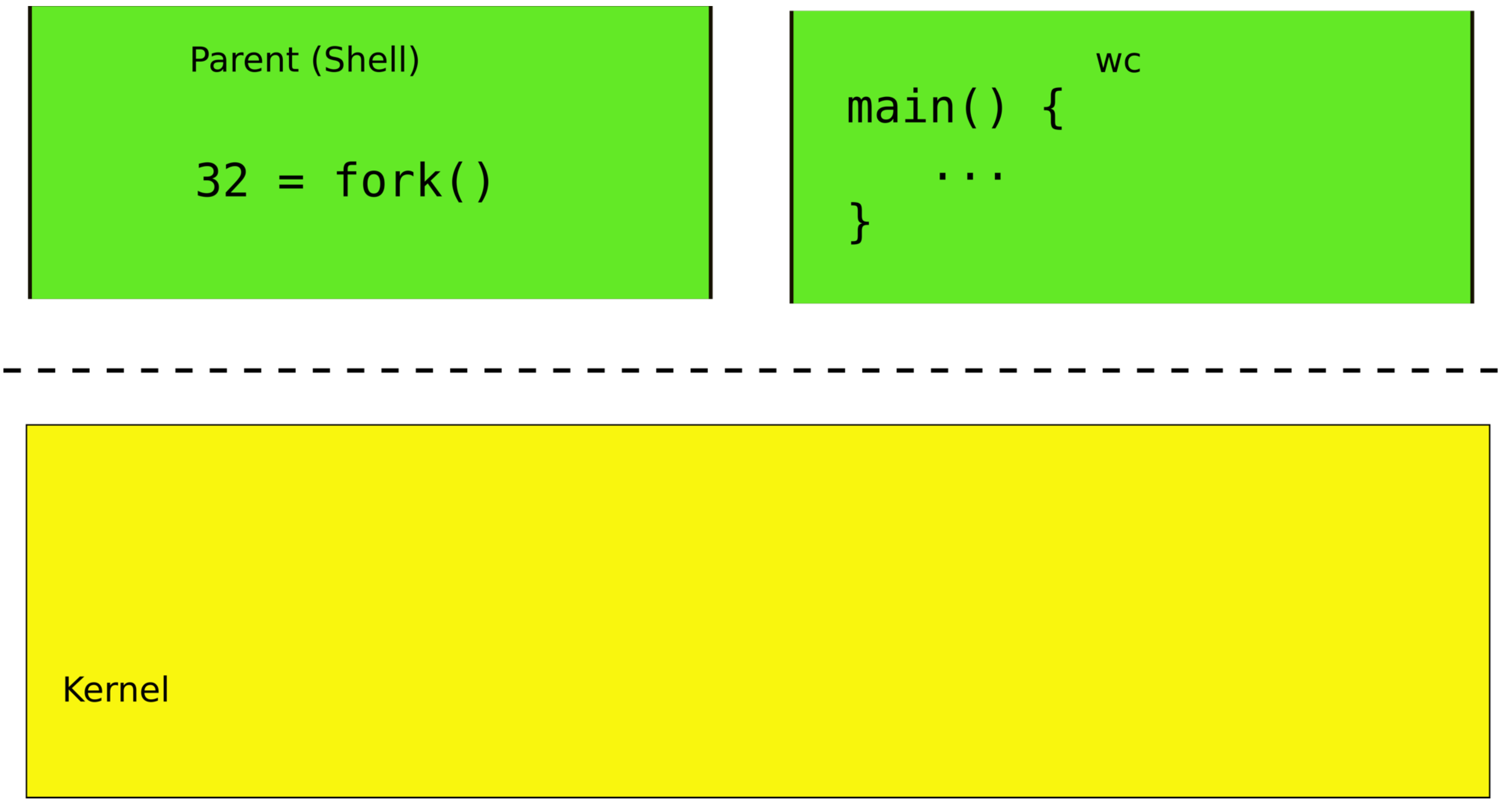
- exec() -- replaces memory of a current process with a memory image (of a program) loaded from a file

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

fork() and exec()



fork() and exec()



- 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

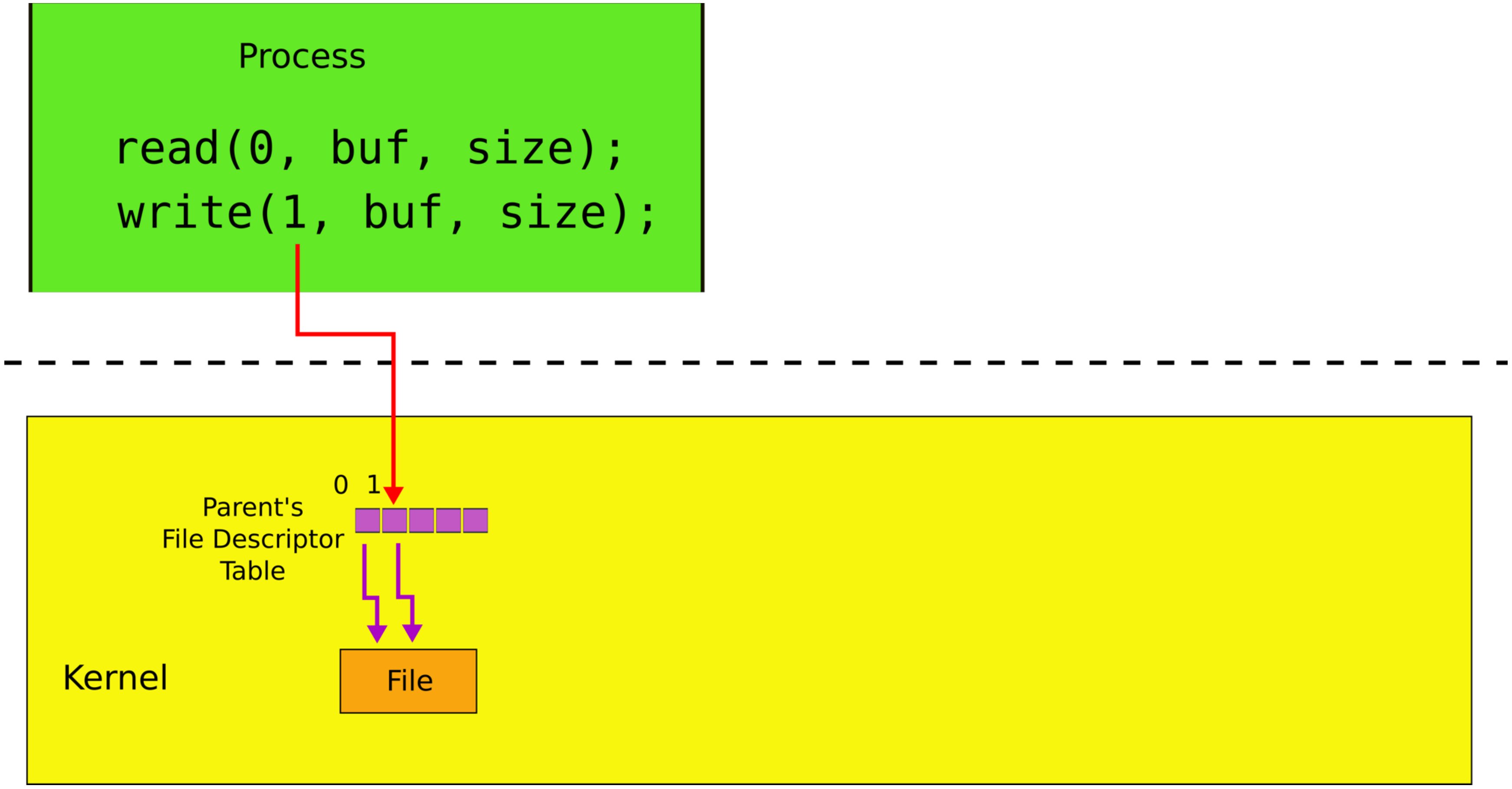
\> wc -l < ls.c

\> cat < ls.c

- You can redirect both

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

Standard output is now a 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:

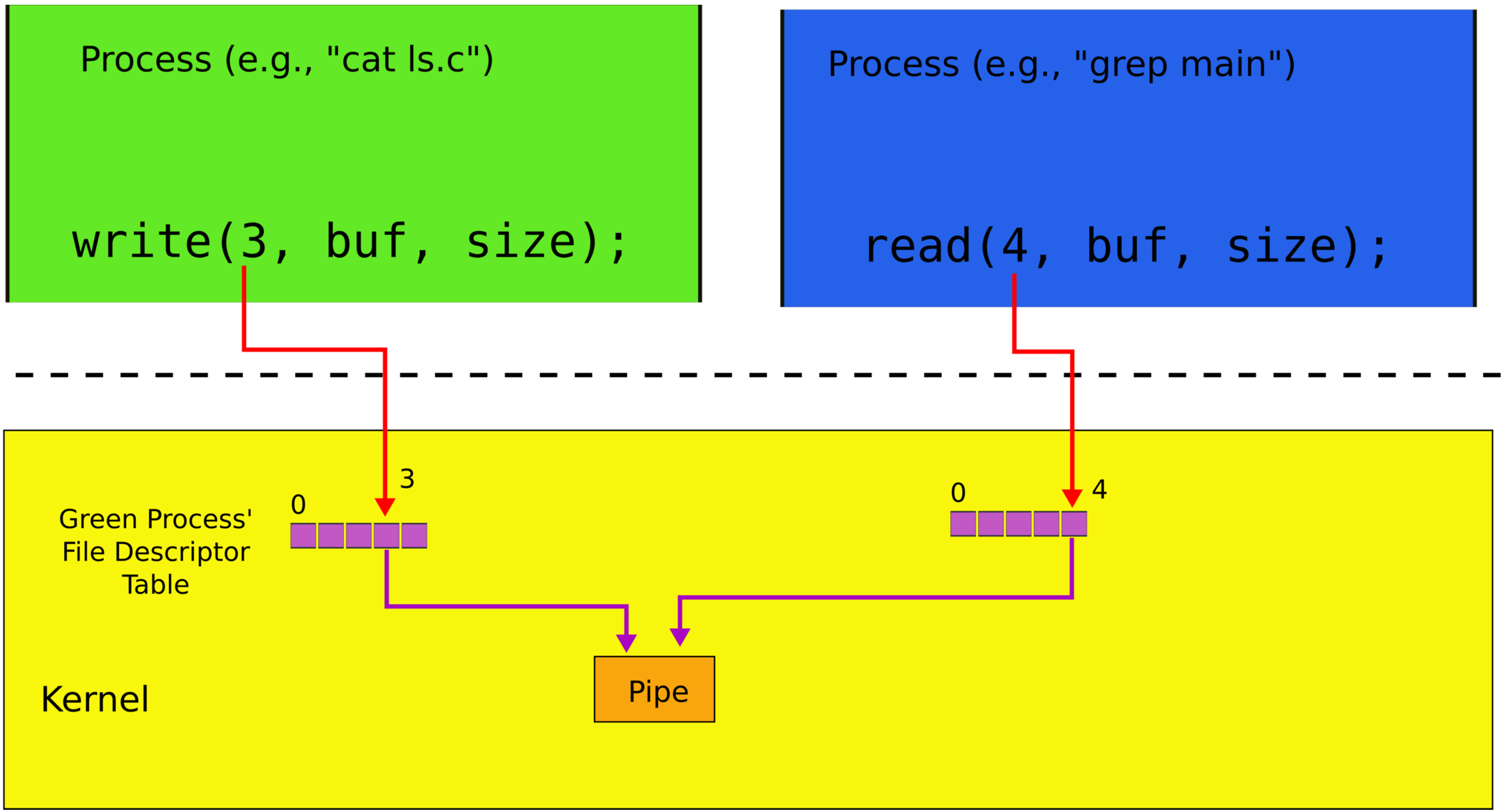
  \> cat ls.c | grep main

- 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 - inter-process 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



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:

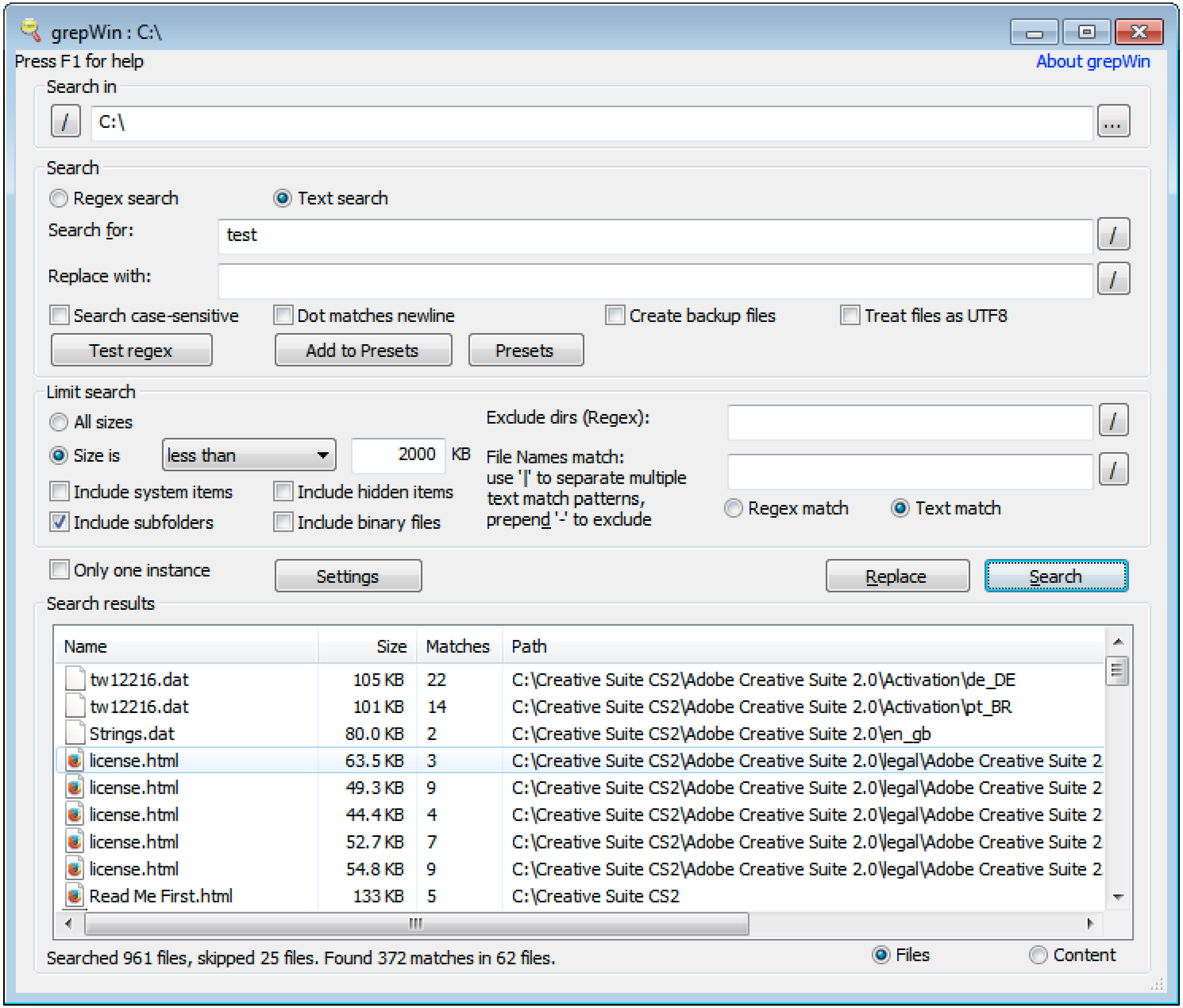
```
\> cat ls.c | grep main | wc -l
1
```

- .. 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...



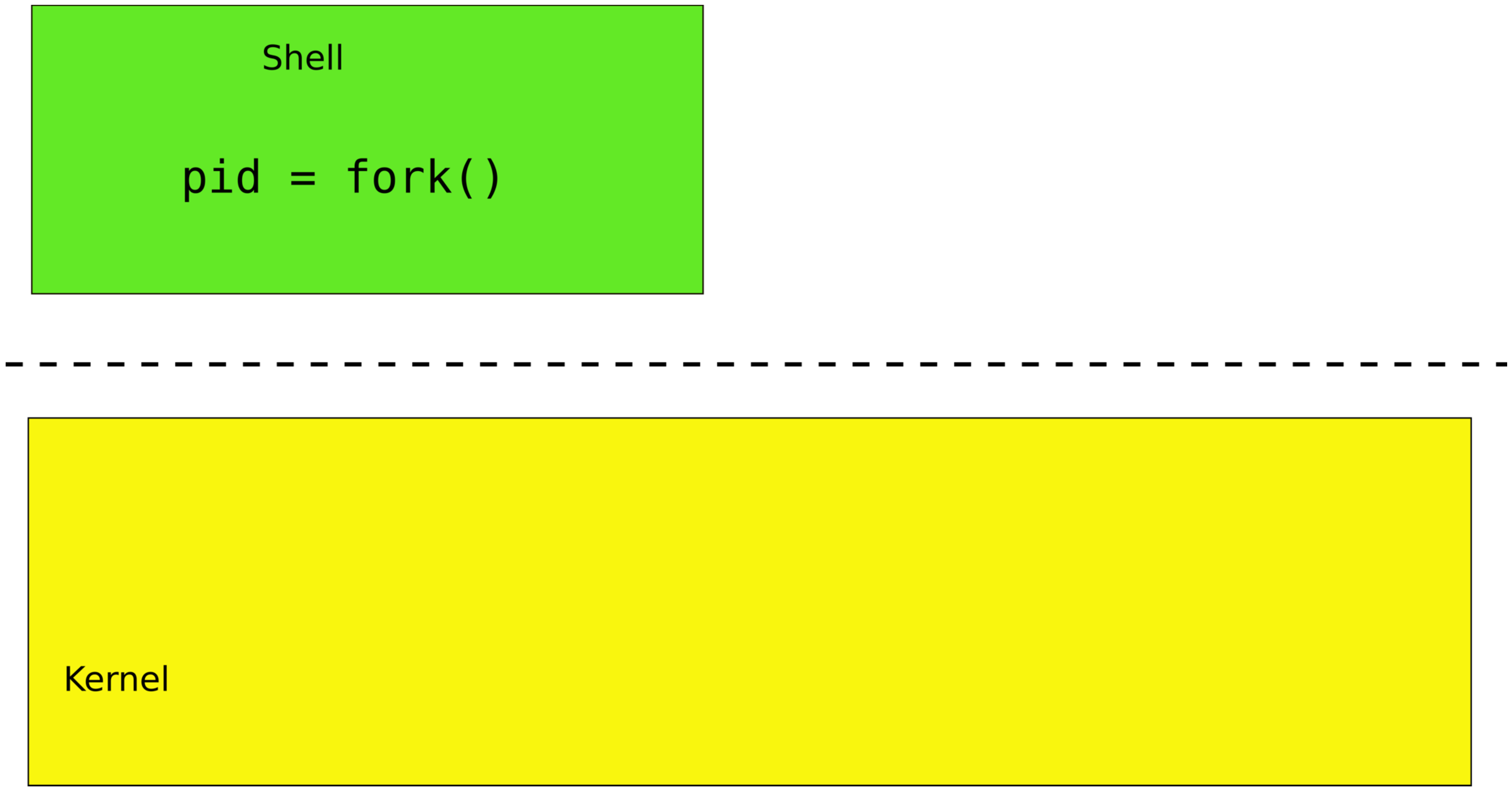
Building I/O redirection

How can we build this?

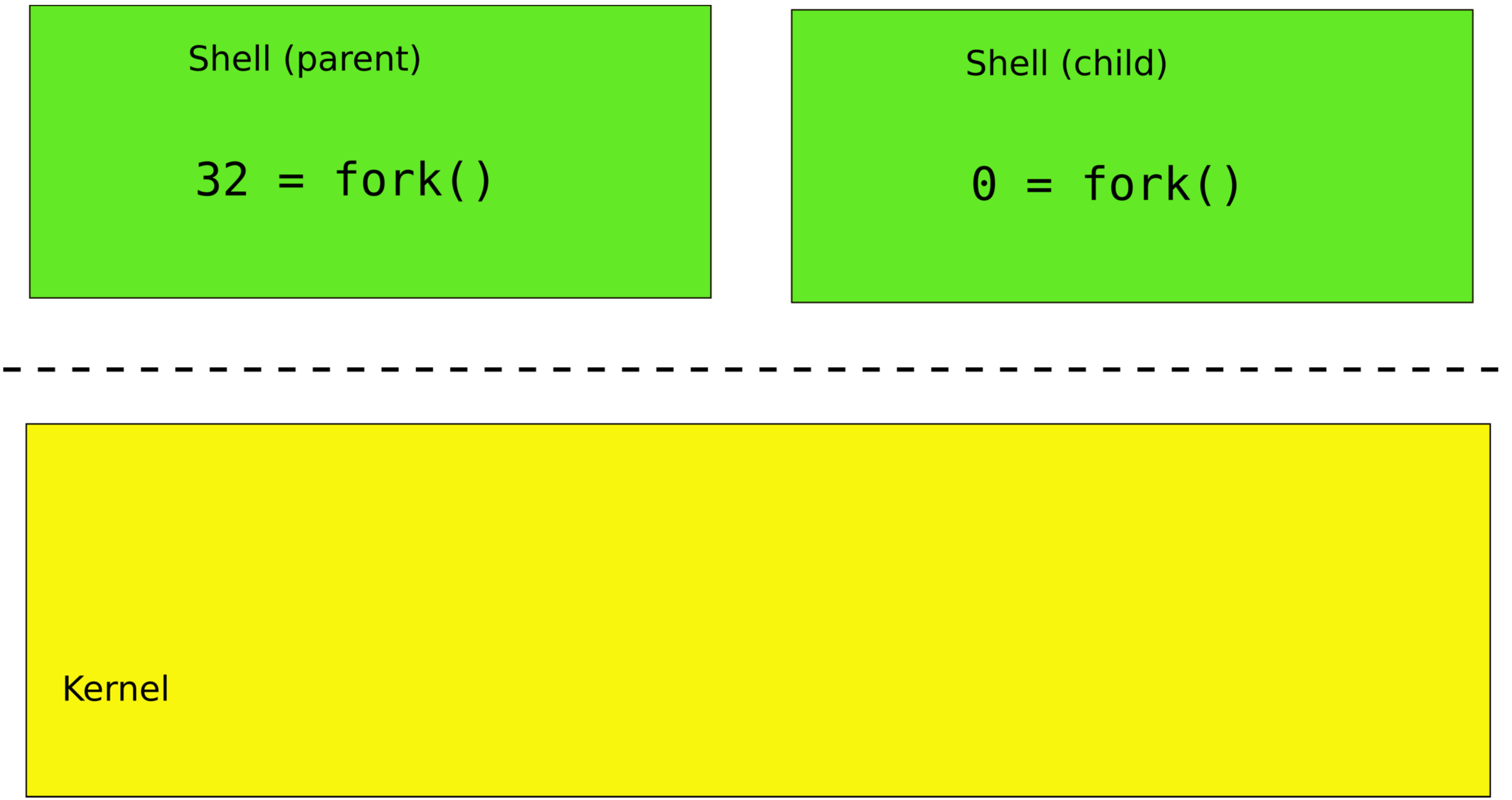
\> cat ls.c | grep main | wc -l

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

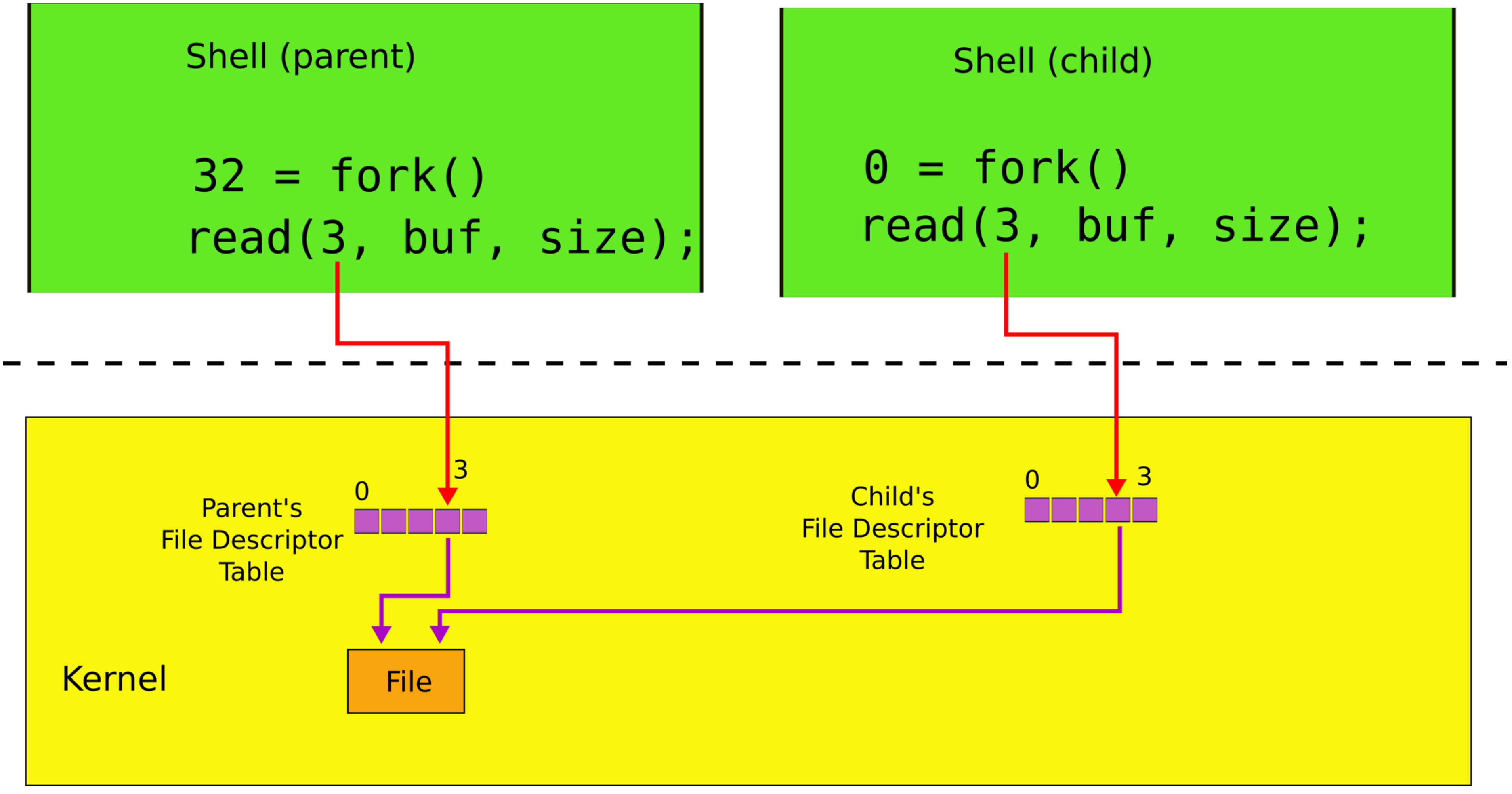
Back to fork()



fork()



File descriptors after fork()

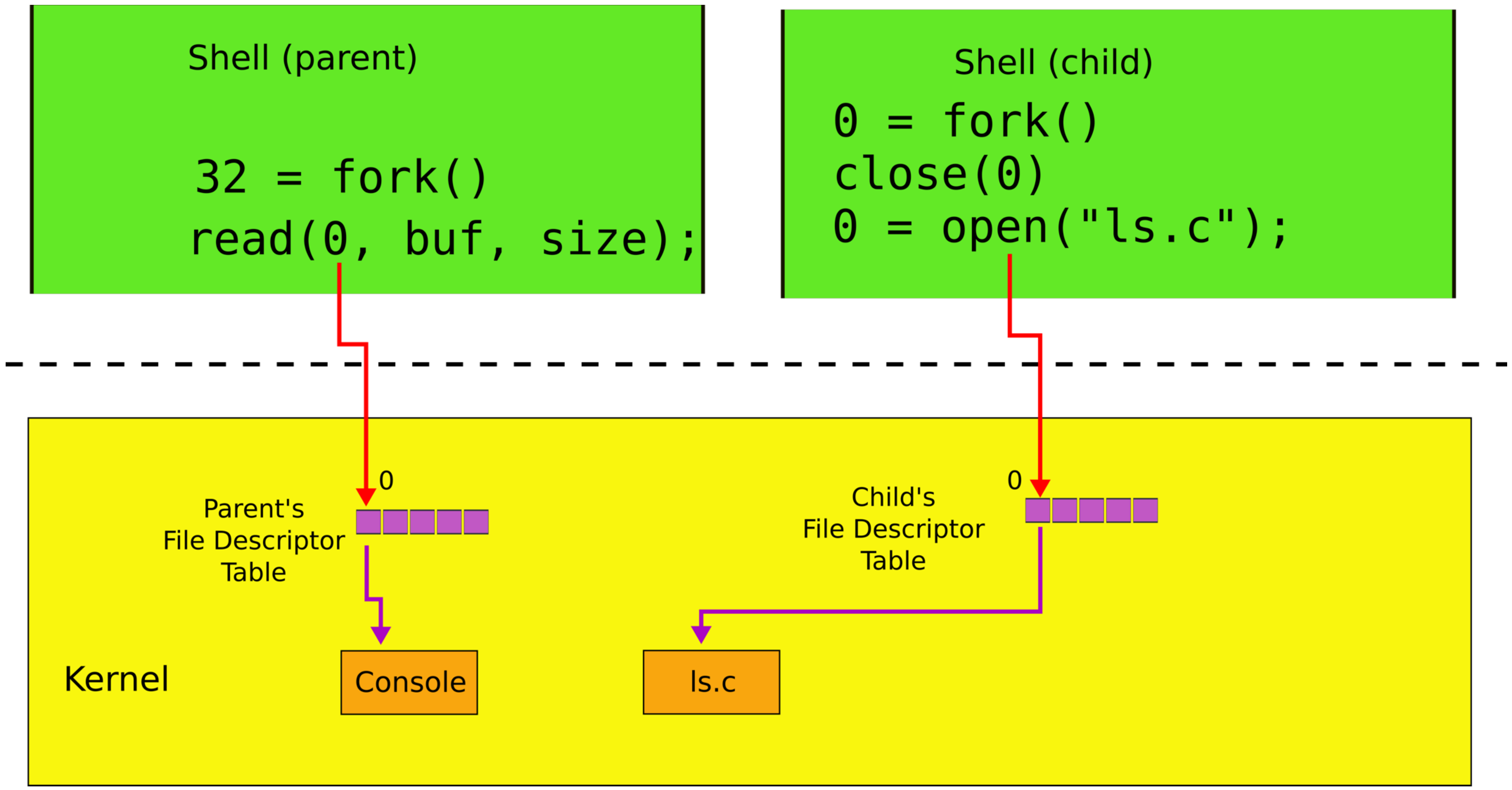


Two system calls for I/O redirection

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

File descriptors after close()/open()

Example: \> cat < ls.c

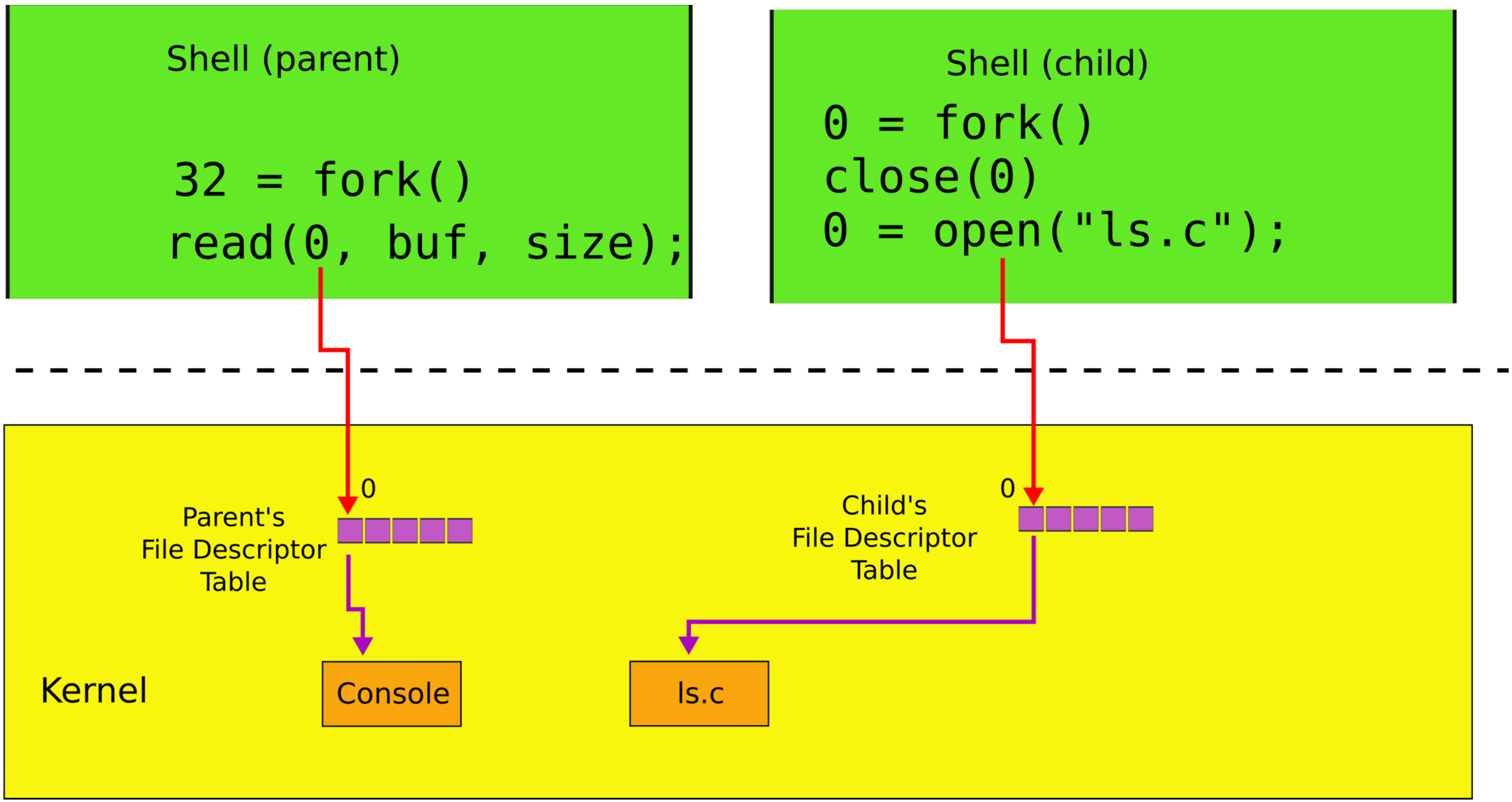


Two system calls for I/O redirection

- close(fd) – closes file descriptor
  - **The next opened file descriptor will have the lowest number**
- exec() replaces process memory, but
  - **leaves its file descriptor table intact**
  - 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



Example: \> cat < ls.c

```
1.    char *argv[2];
2.    argv[0] = "cat";
3.    argv[1] = 0;
4.    if(fork() == 0) {
5.        close(0);
6.        open("ls.c", O_RDONLY);
7.        exec("cat", argv);
8.    }
9.    …
```

- Poll time
  - Inside the cat process which file file descriptor 0 points to?
  - Do we reach line 9?

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

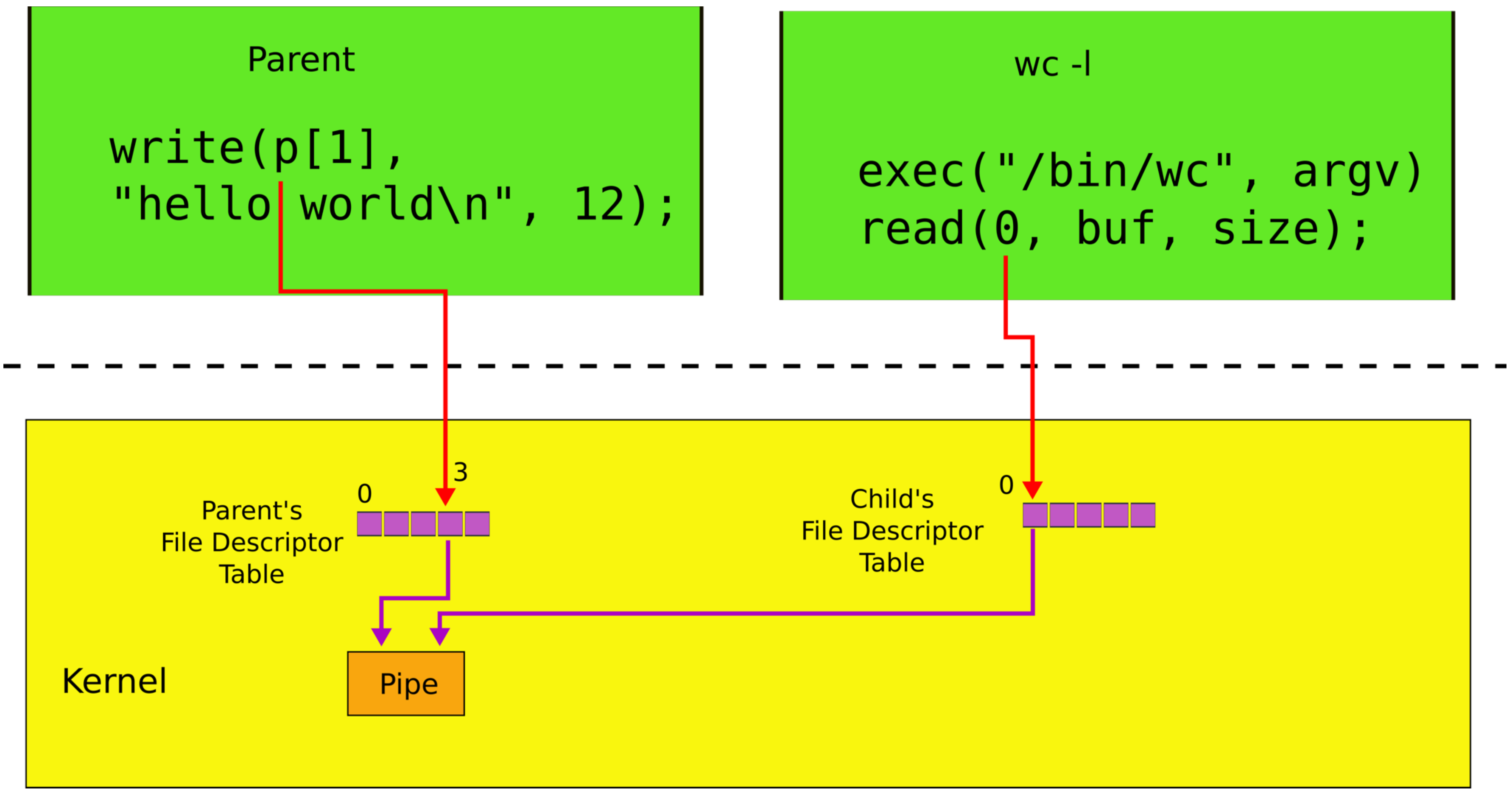
(\> cat ls.c | grep main | wc -l)

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);
0
3
Parent's File Descriptor Table
0
Child's File Descriptor Table
Kernel
Pipe

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
  - Any child (can be multiple)
  - Return it's process id (pid)

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

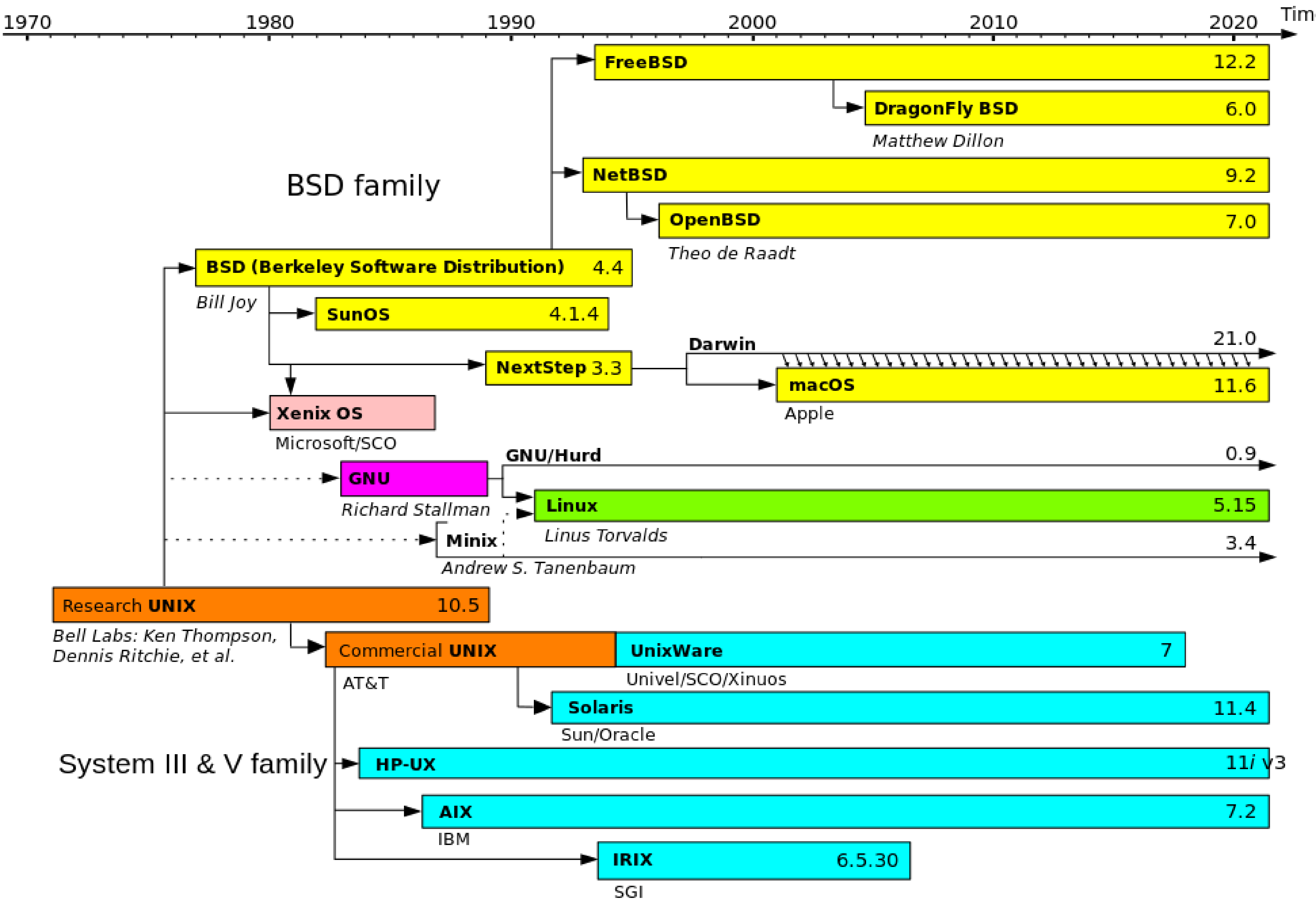
- Same file can have multiple names – links
  - But unique inode number
- link() – create a link
- unlink() – delete file
- Example, create a temporary file

```
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 very similar to the operating systems we run today



Evolution of Unix and Unix-like systems

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

Backup slides

Pipes

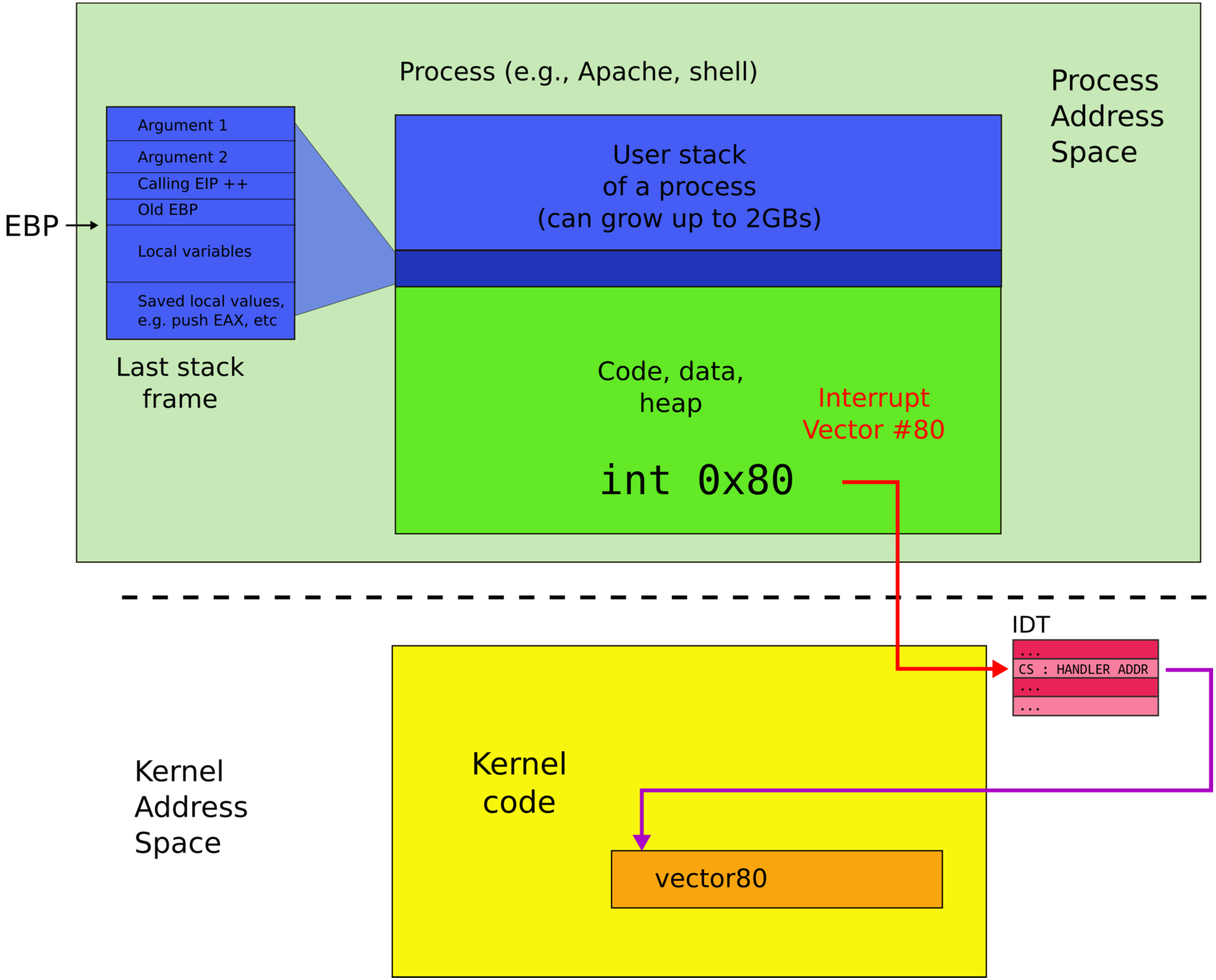
- Shell composes simple utilities into more complex actions with pipes, e.g.

  grep FORK sh.c | wc -l

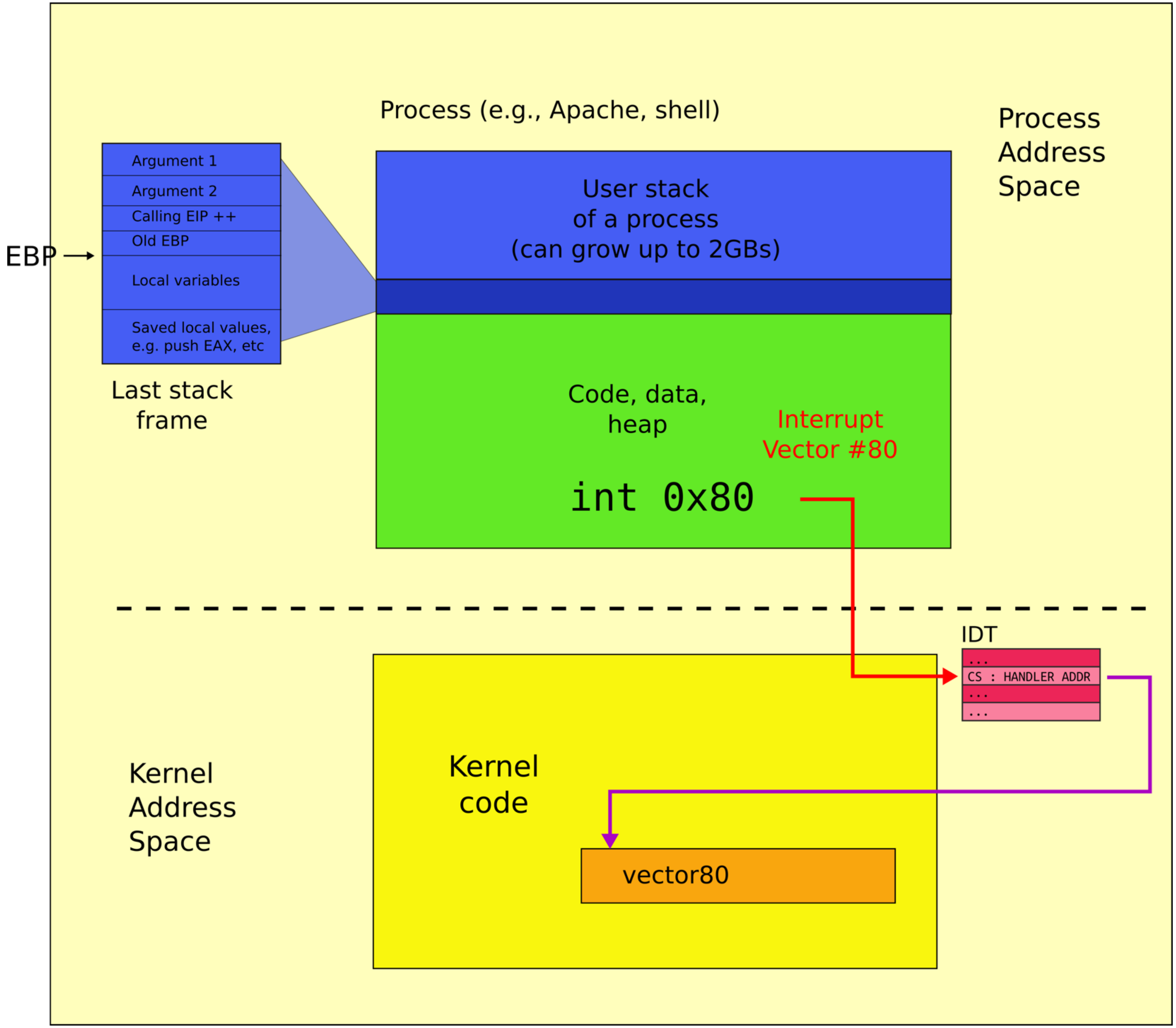
- Create a pipe and connect ends

System call

User address space



Kernel address space



Kernel and user address spaces