143A: Principles of Operating Systems

Lecture 2: OS Interfaces

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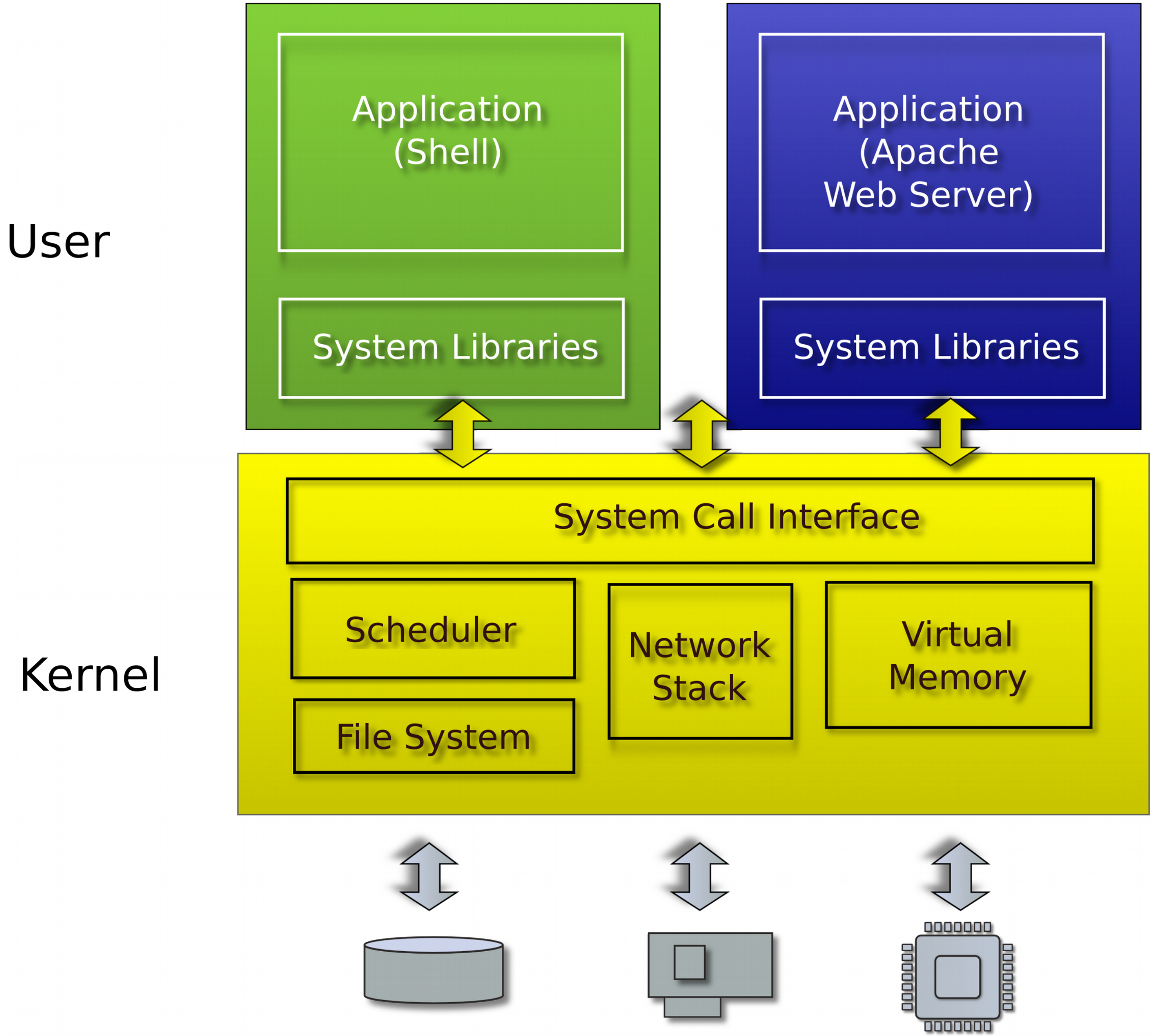
September, 2018

Recap from last time: 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, users, namesapces
  - 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 calls, interface for...

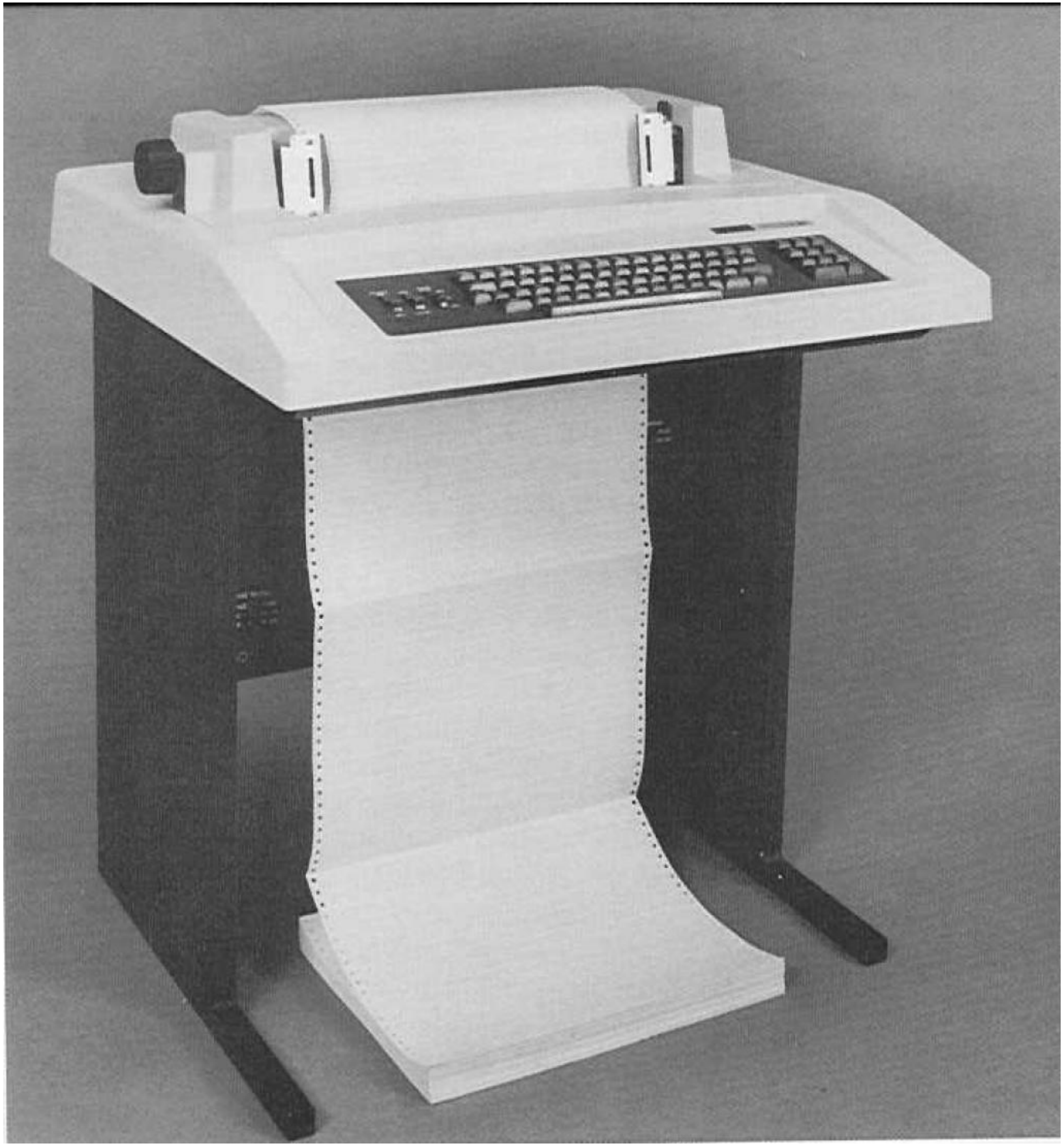
- Processes
  - Creating, exiting, waiting, terminating
- Memory
  - Allocation, deallocation
- Files and folders
  - Opening, reading, writing, closing
- Inter-process communication
  - Pipes

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 working together at a PDP-11



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 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

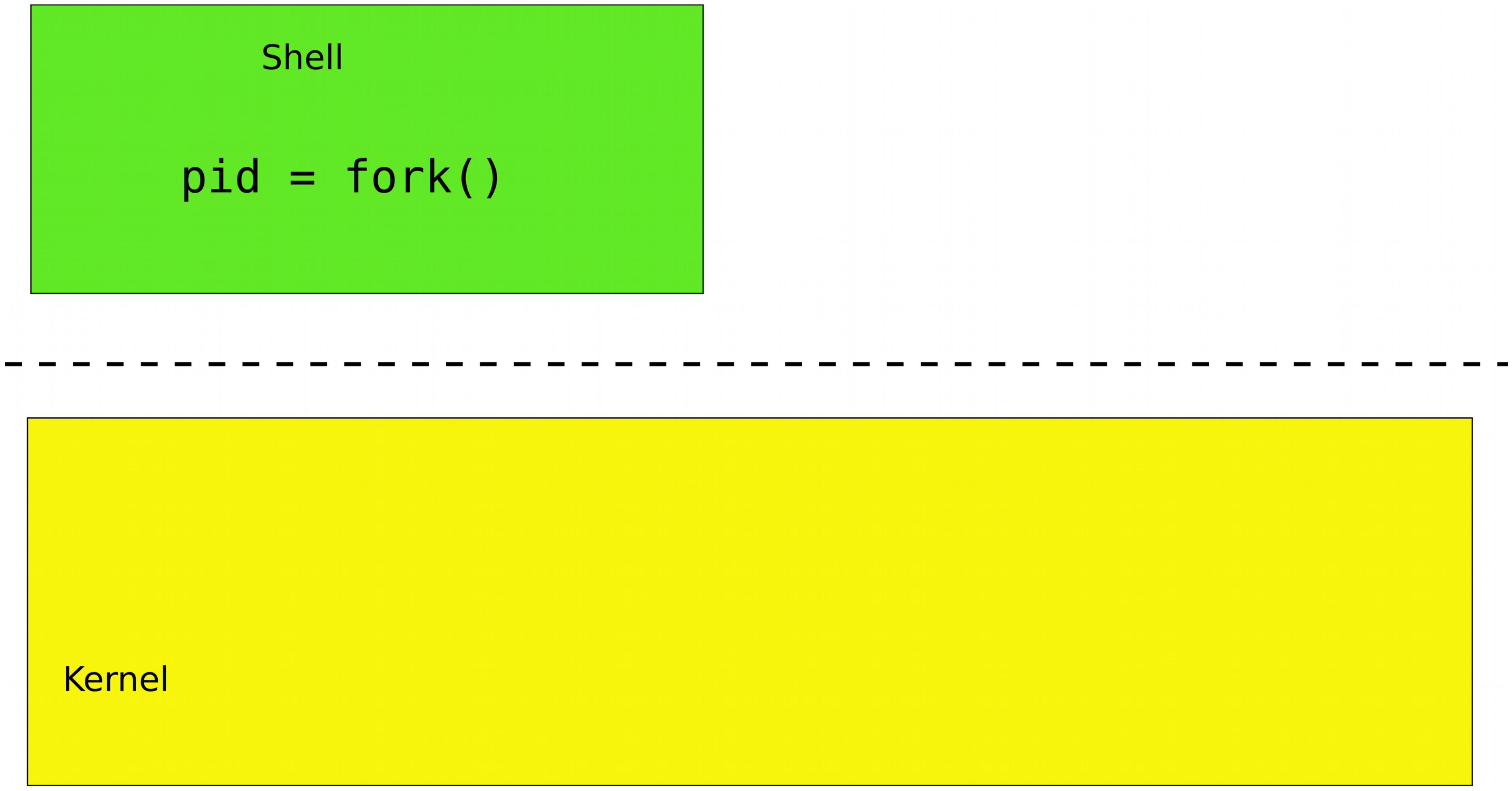
But what happens underneath?

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

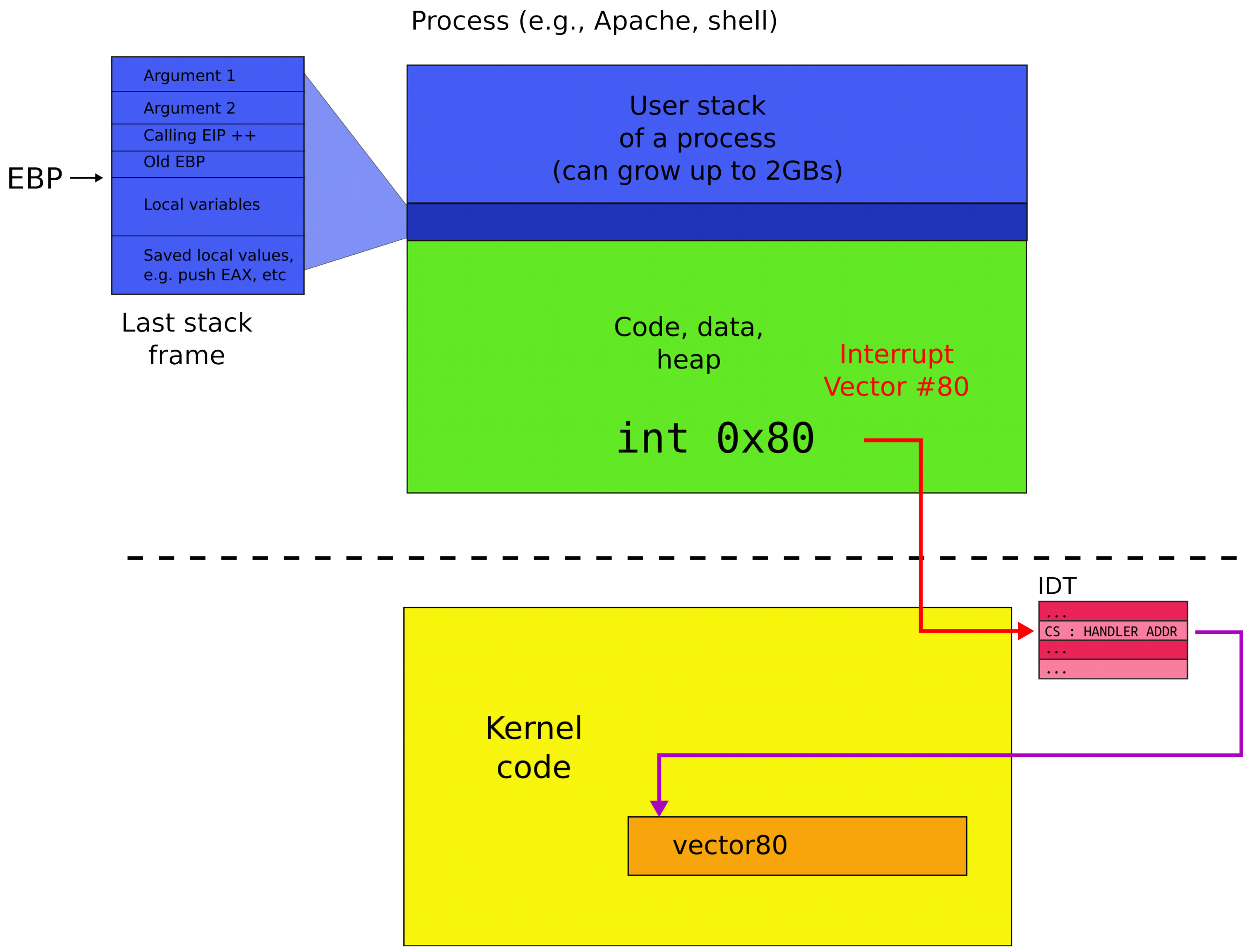
- Shell invokes `wc`
  - Creates a new process to run `wc`
  - Passes the arguments (-l and ls.c)
- `wc` sends its output to the terminal (console)
  - Exits when done with `exit()`
- Shell detects that `wc` is done
  - Prints (to the same terminal) its command prompt
  - Ready to execute the next command

How do we create a process?

fork()

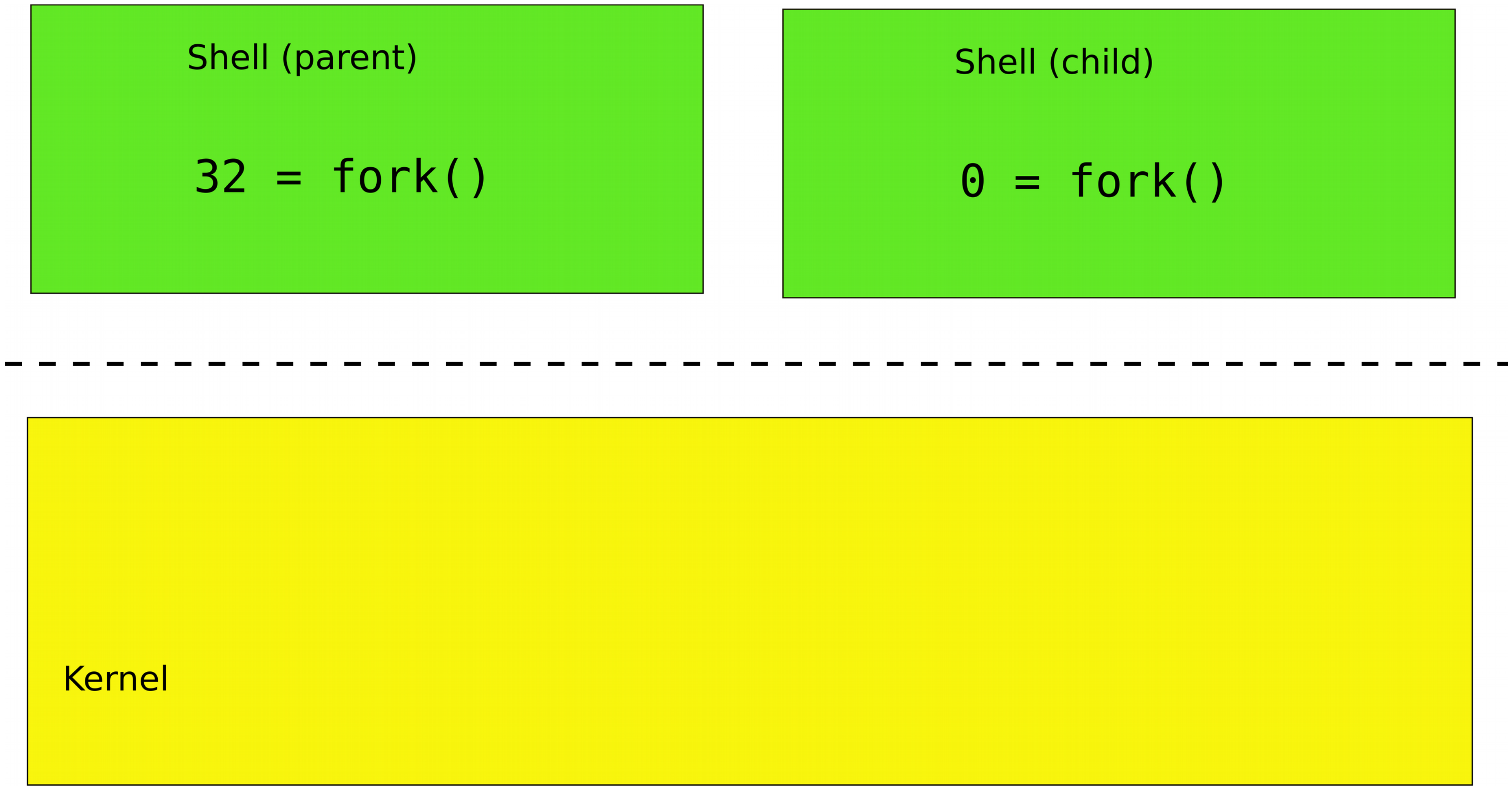


System call



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

fork()



`fork()` -- create new process

```
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?

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?

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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
```

What! Why do we need this?

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
```

- `|` (or 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”

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
```

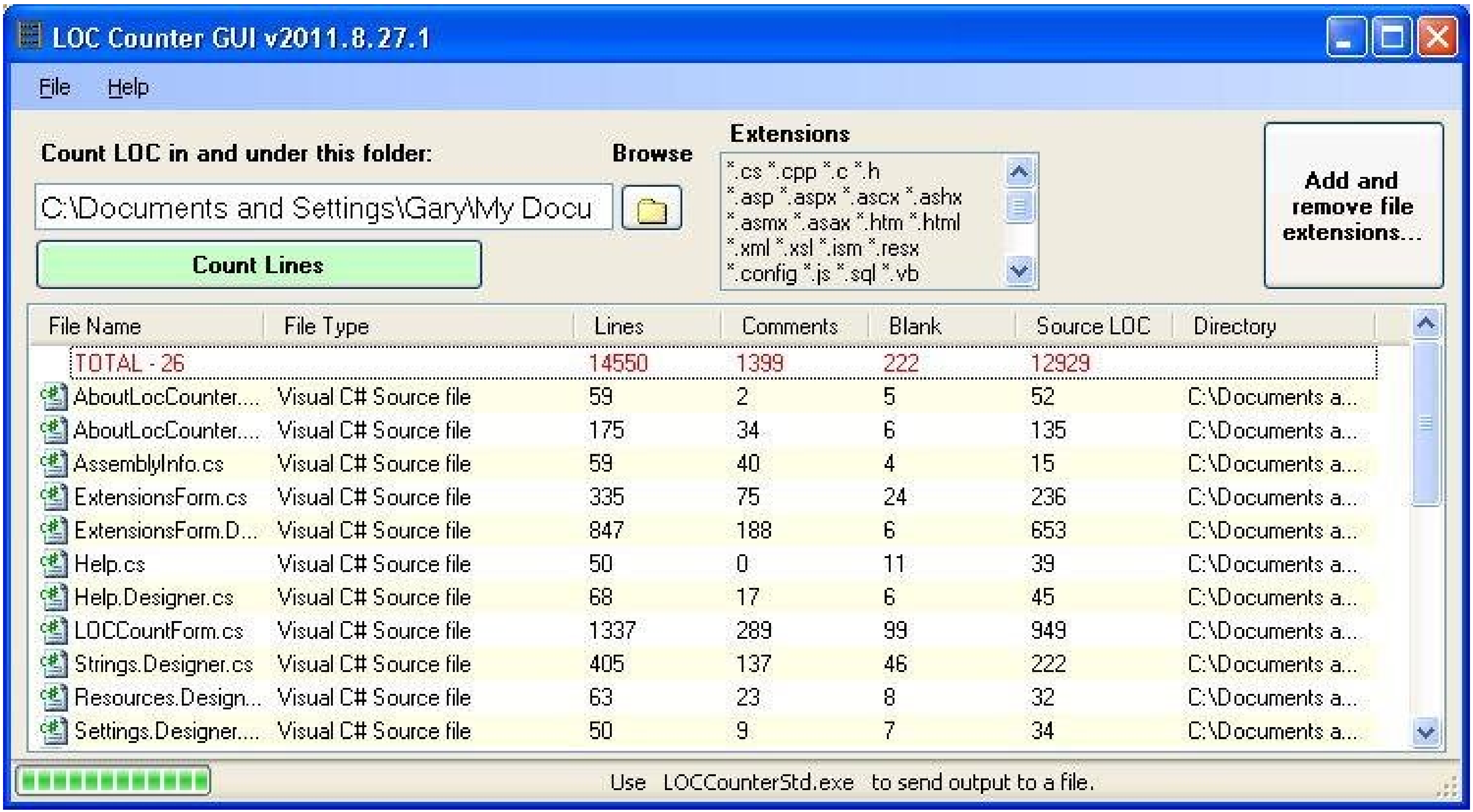
- .. but if we want to count the once that contain “a”:

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

33
```

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

Better than this...



Inside I/O redirection

How can we build this?

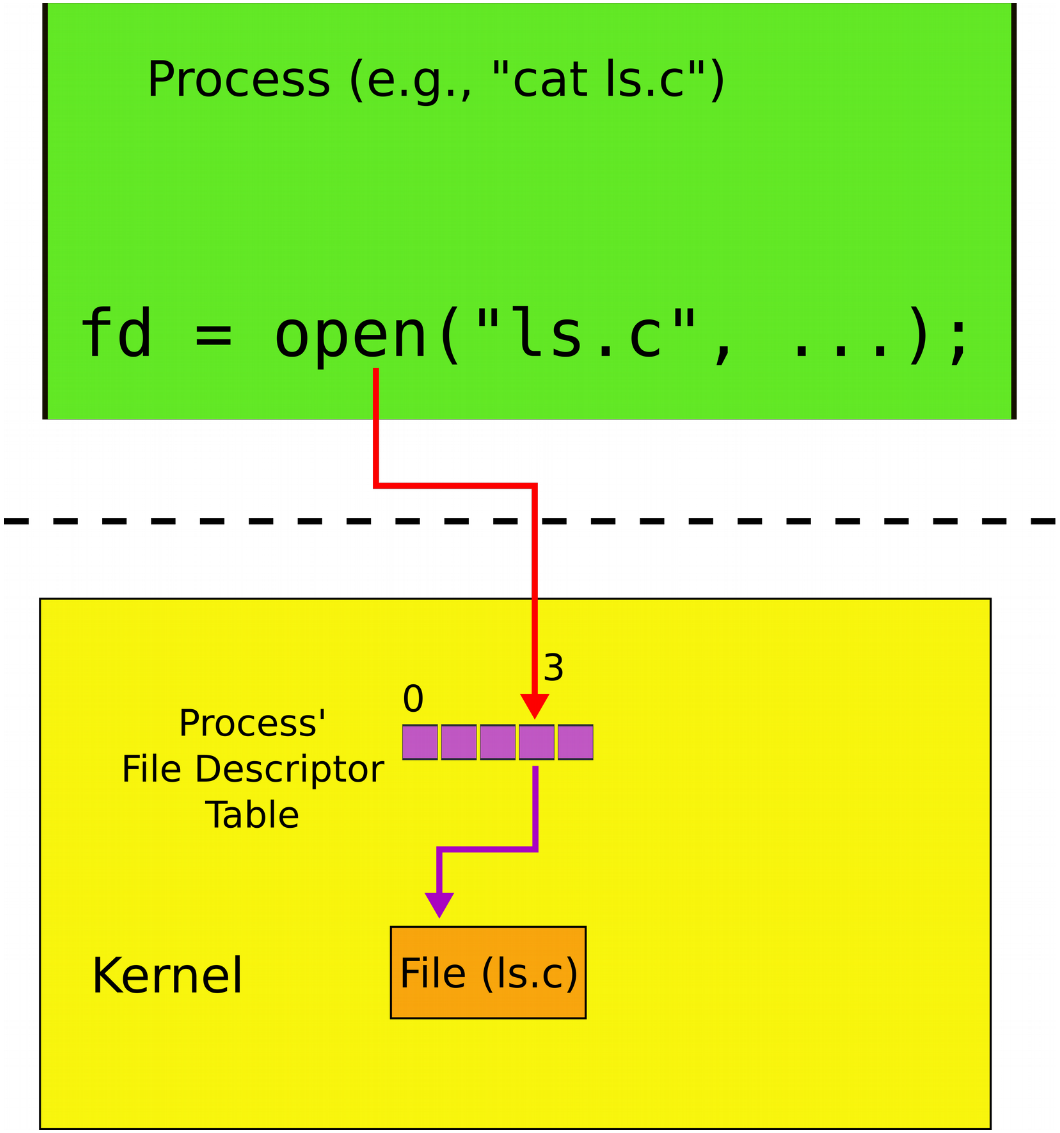
```
\> cat ls.c | grep main | wc -l
1
```

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

Lets look at file I/O

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

File descriptors



File descriptors

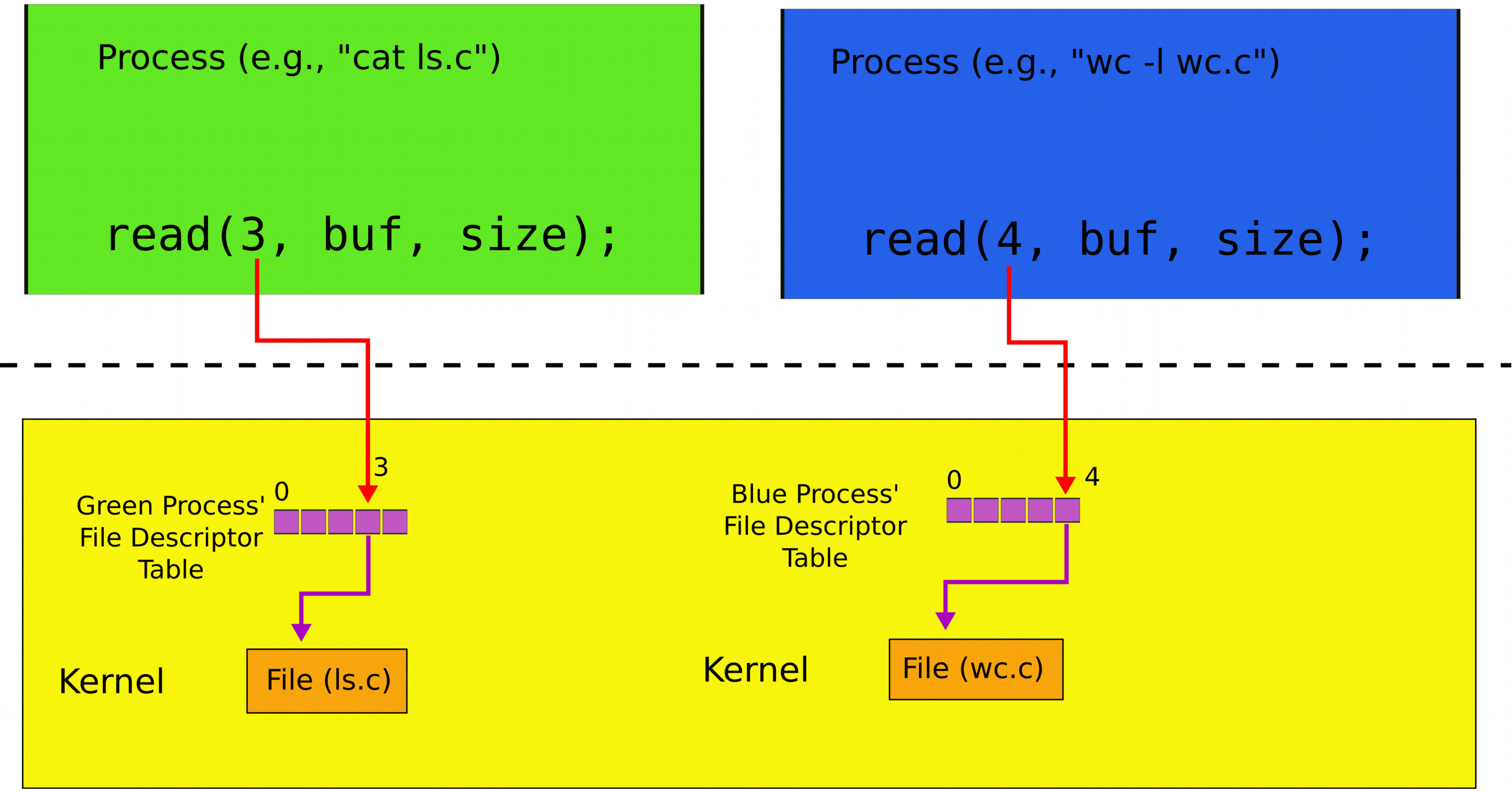
- An index into a table, i.e., just an integer
- The table maintains pointers to “file” objects
  - Abstracts files, devices, pipes
  - In UNIX everything is a pipe – all objects provide file interface
- Process may obtain file descriptors through
  - Opening a file, directory, device
  - By creating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

Lets look at 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



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

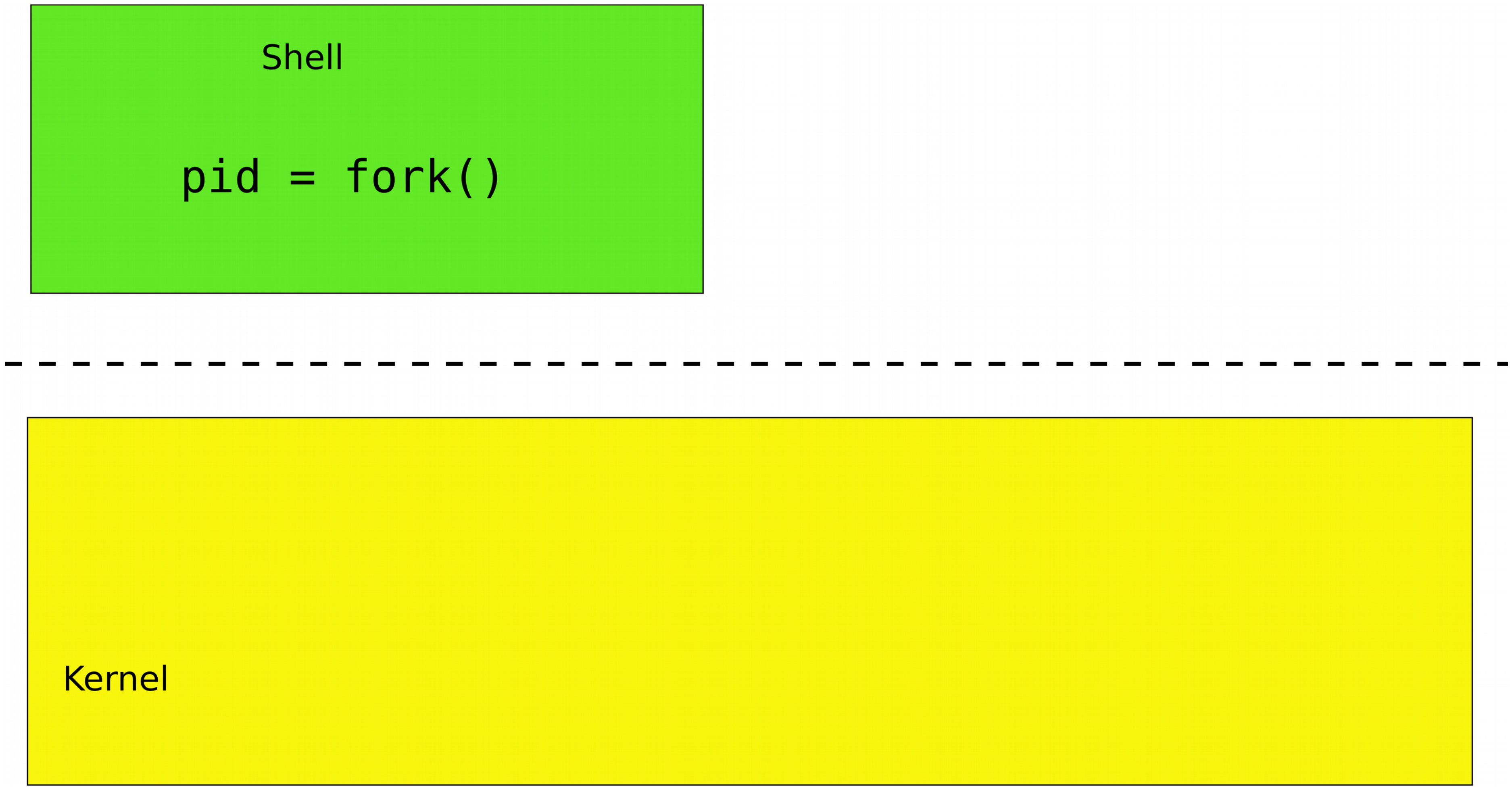
Example: cat

```
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();
    }
}
```

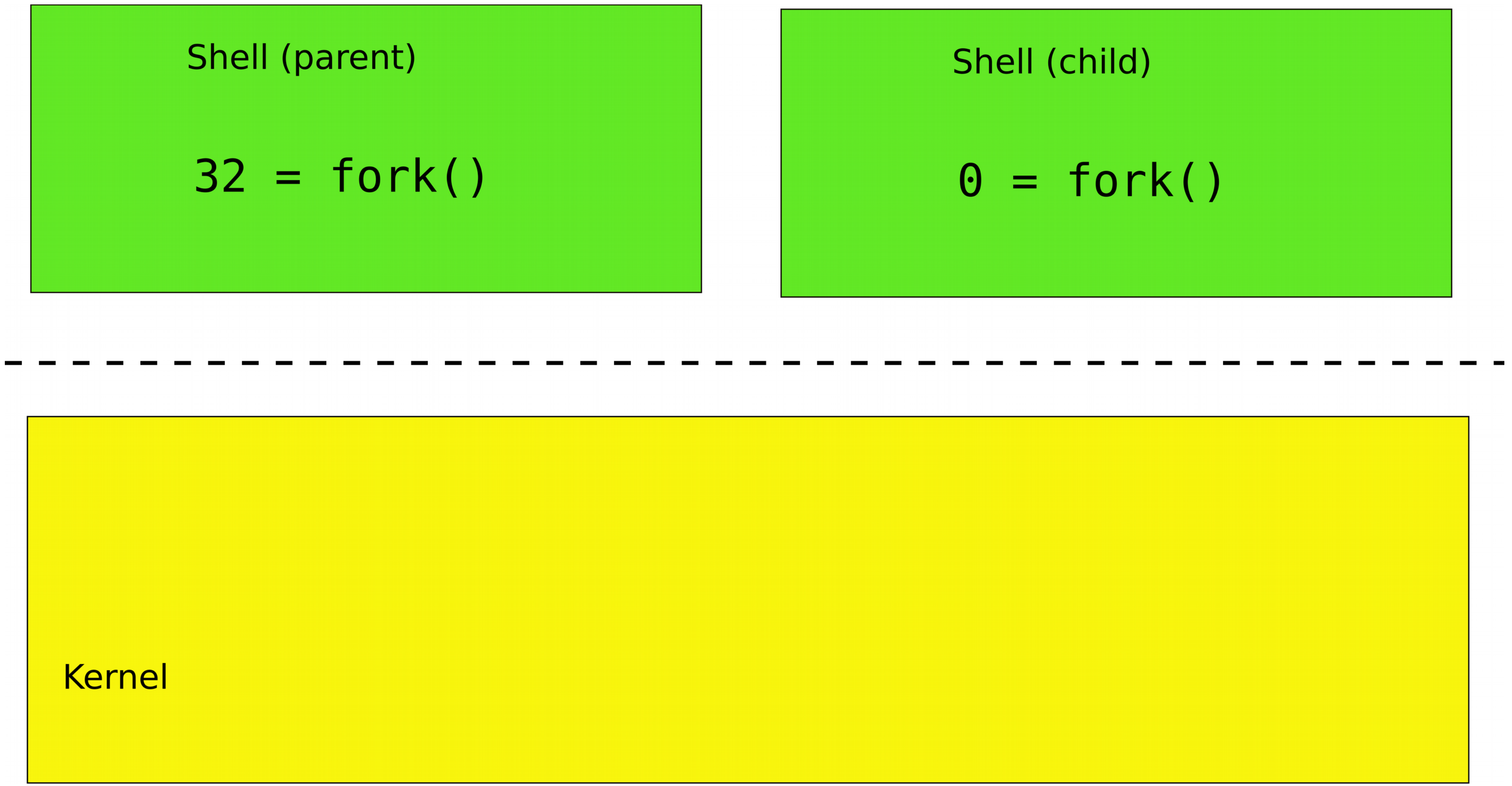
Now we can redirect standard input and output

Remember fork()?

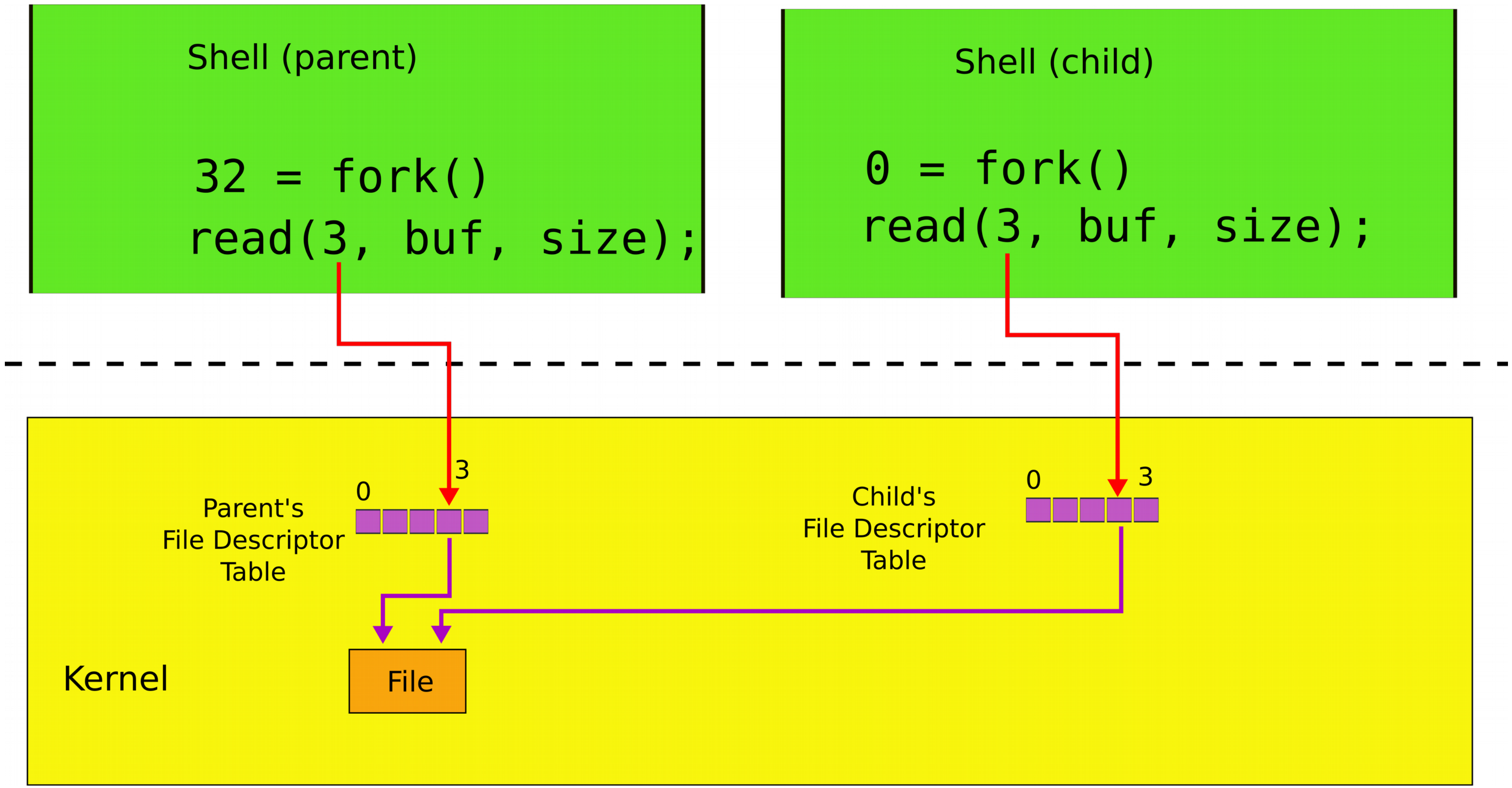
fork()



fork()



File descriptors after fork()



fork() is used together with exec()

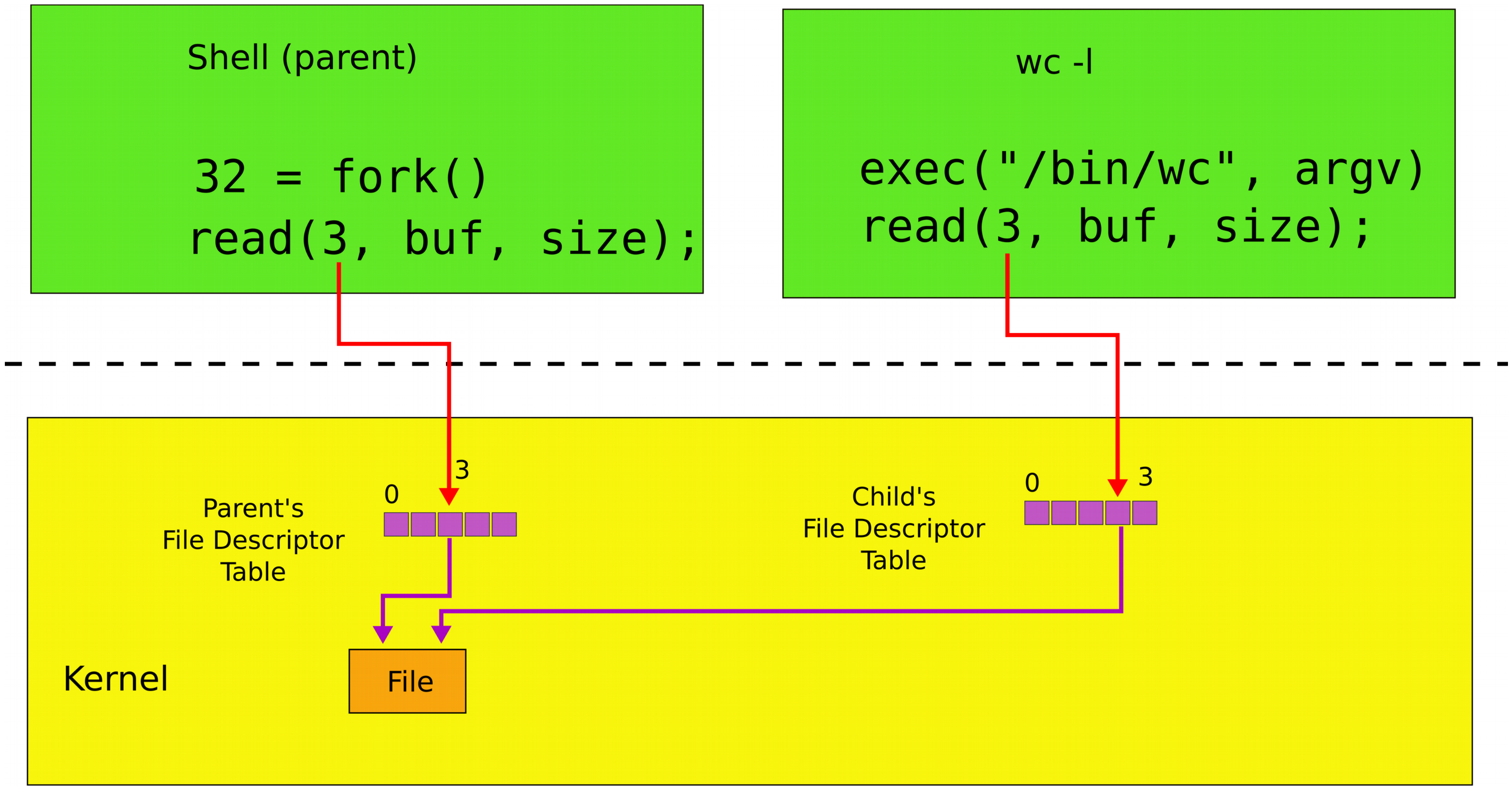
- `exec()` -- replaces memory of a current process with a memory image (of a program) loaded from a file

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

Two system calls for I/O redirection

- `close(fd)` – closes file descriptor
  - **The next opened file descriptor will have the lowest number**
- `exec()` preplace process memory, but
  - **leaves its file table (table of the file descriptors untouched)**

File descriptors after exec()



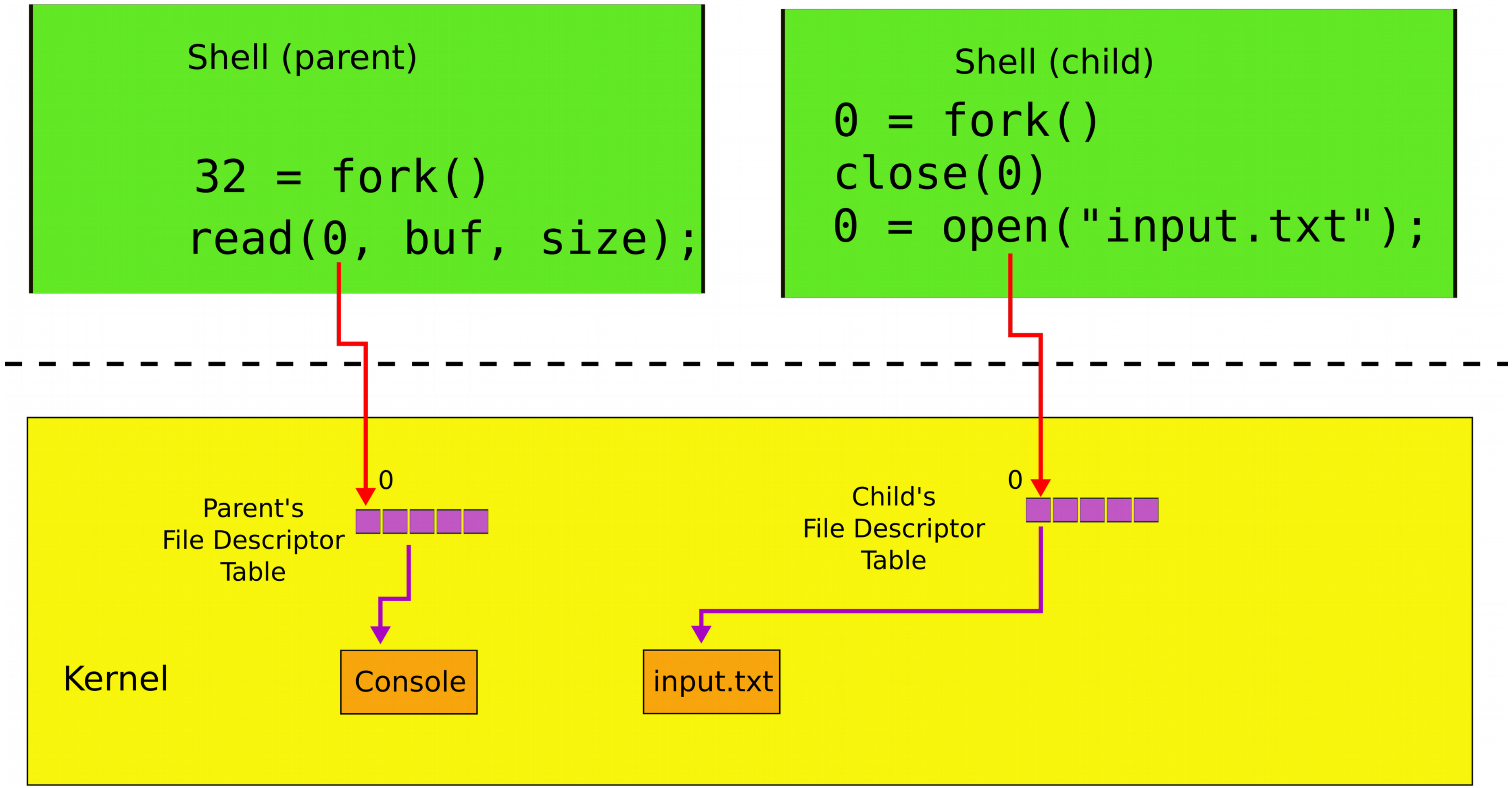
File I/O redirection

- `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)**
  - Shell 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()`

Example: \> cat < input.txt

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

File descriptors after redirect



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()`

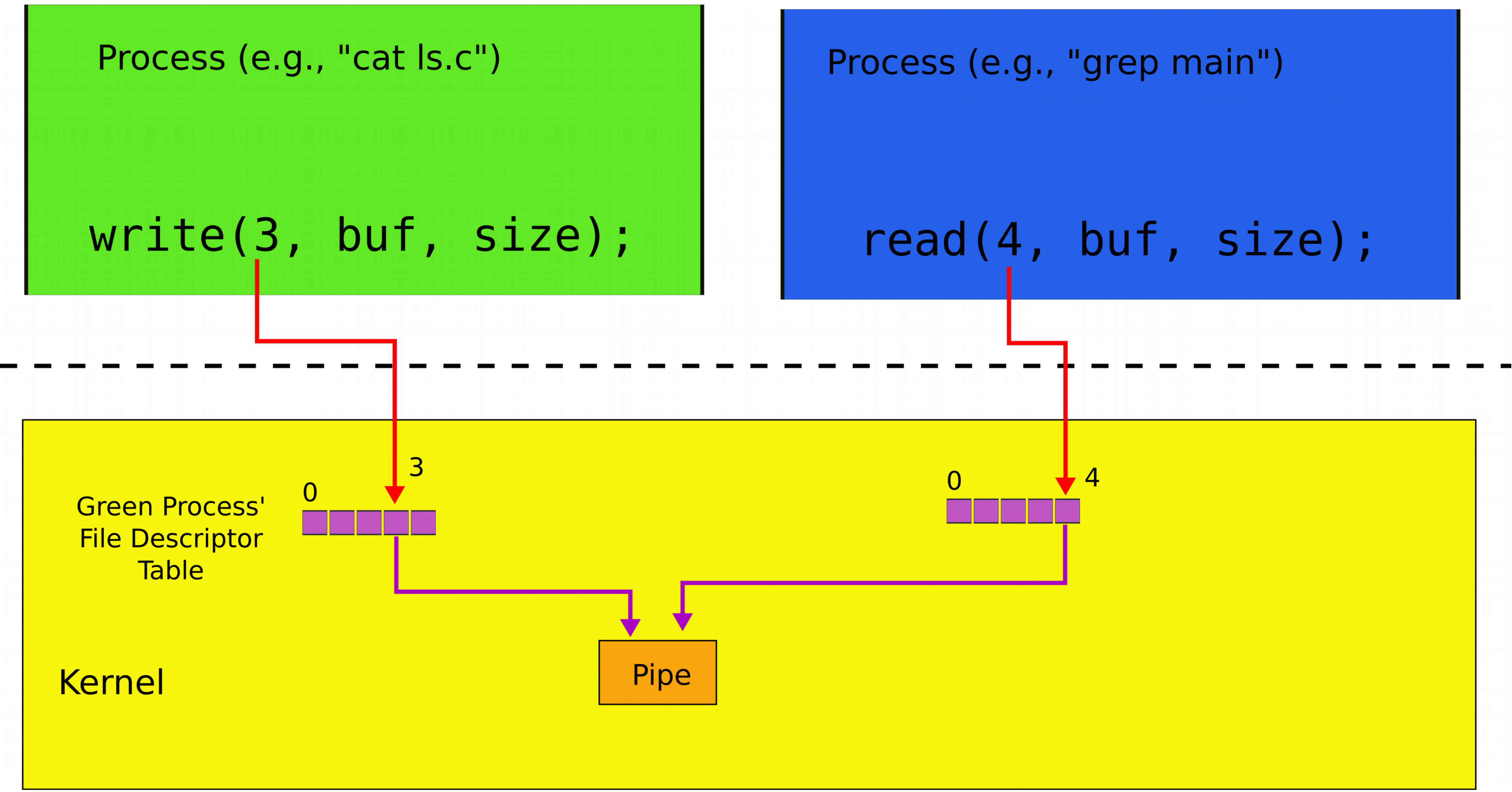
Back to Motivating example #2
(Building pipes)

- File descriptors don't have to point to files *only*
  - Any object with the same read/write interface is ok
  - Network channel
  - Pipe

`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



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

Back to pipes

- It's possible to use a pipe to connect two programs
  - Create a pipe
  - Attach one end to standard output
    - of the left side of “|”
  - Another to the standard input
    - of the right side of “|”

```c
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

More process management

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

Powerful conclusion

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

Of course there is more

You need to deal with files

- Files
  - Uninterpreted arrays of bytes
- Directories
  - Named references to other files and directories

Creating files

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

  - Named references to other files and directories

Links, inodes

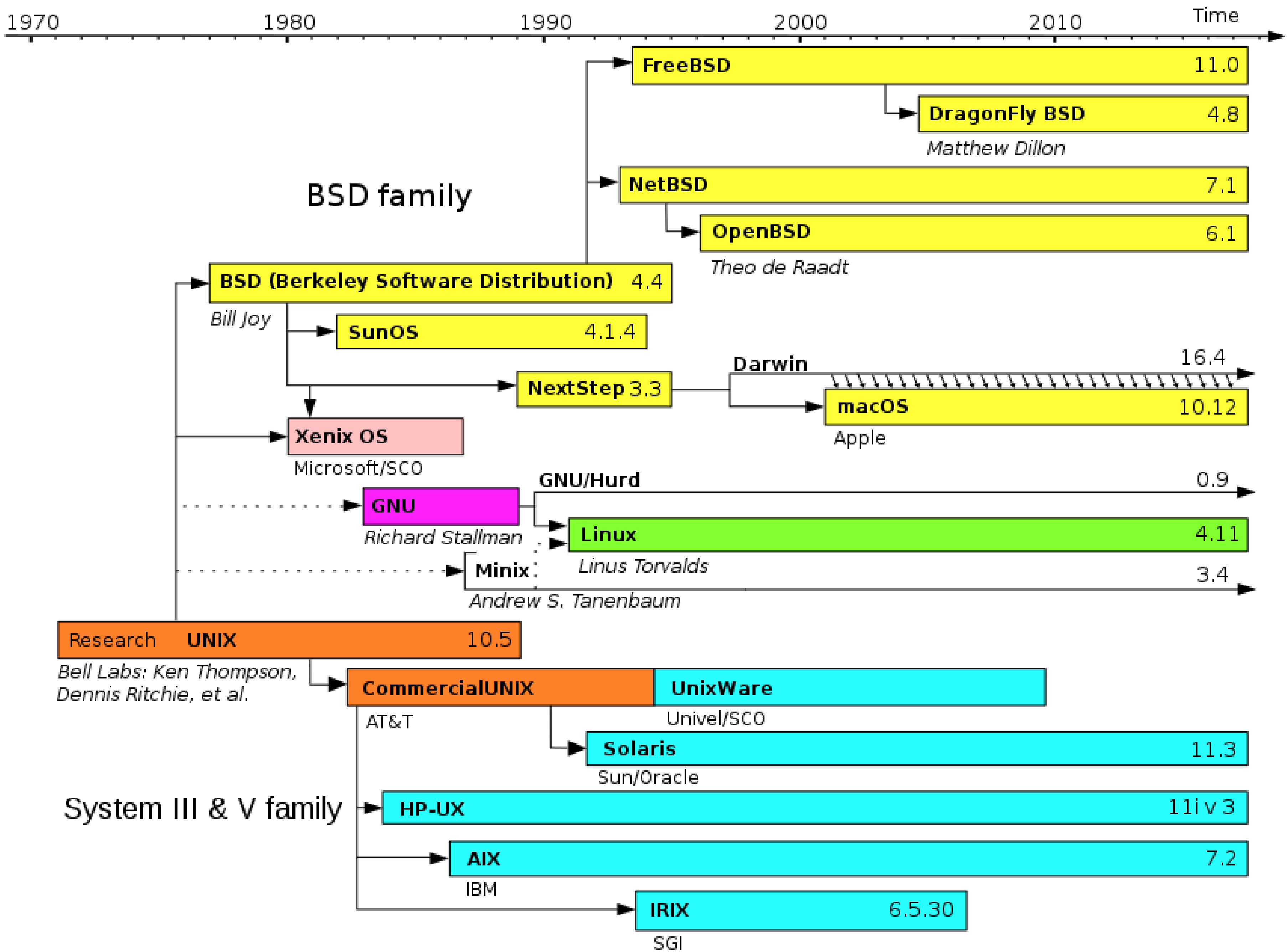
- Same file can have multiple names – links
  - But unique inode number
- `link()` – create a link
- `unlink()` – delete file
- Example, create a temporary file

```
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



Evolution of Unix and Unix-like systems

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

Backup slides

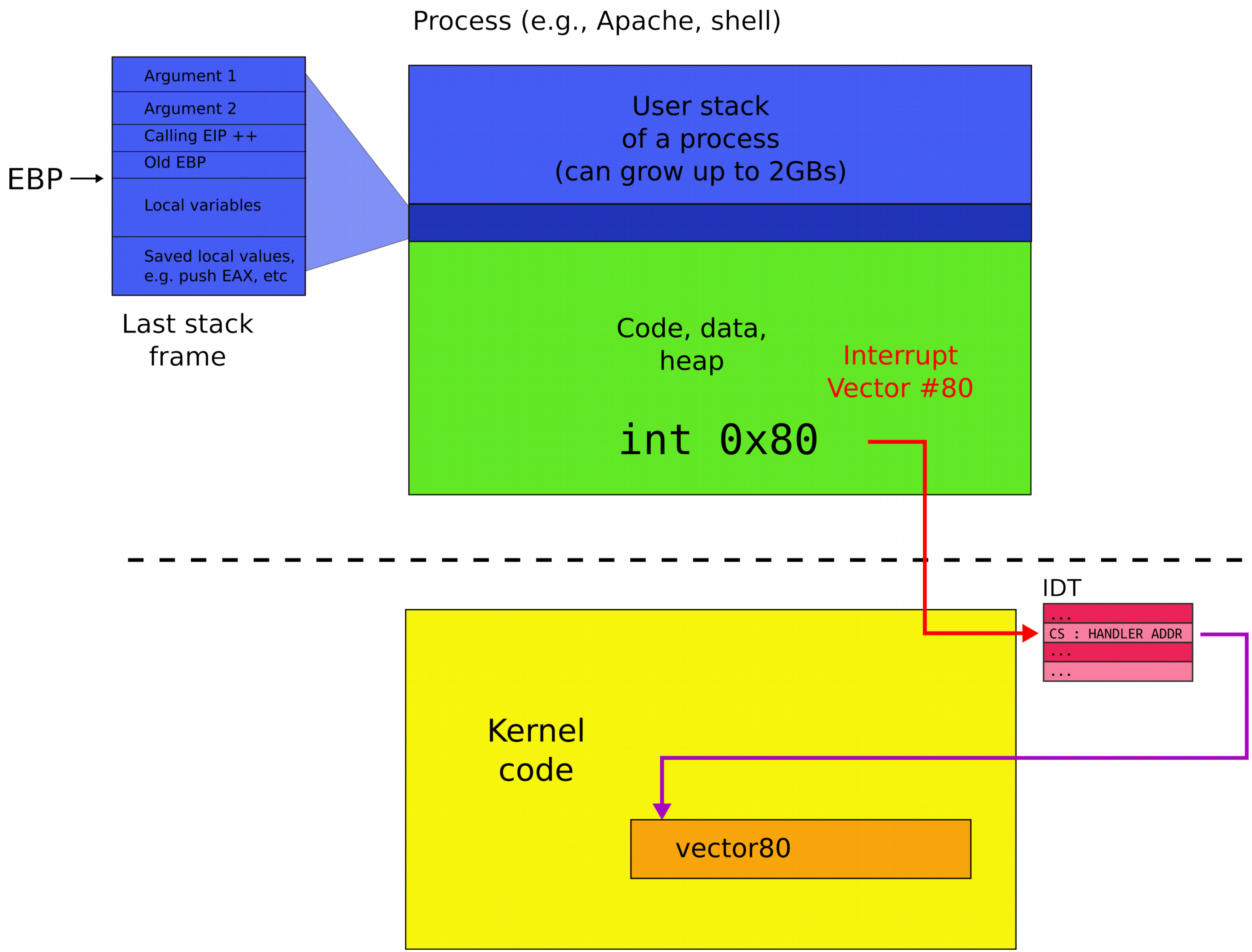
Pipes

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

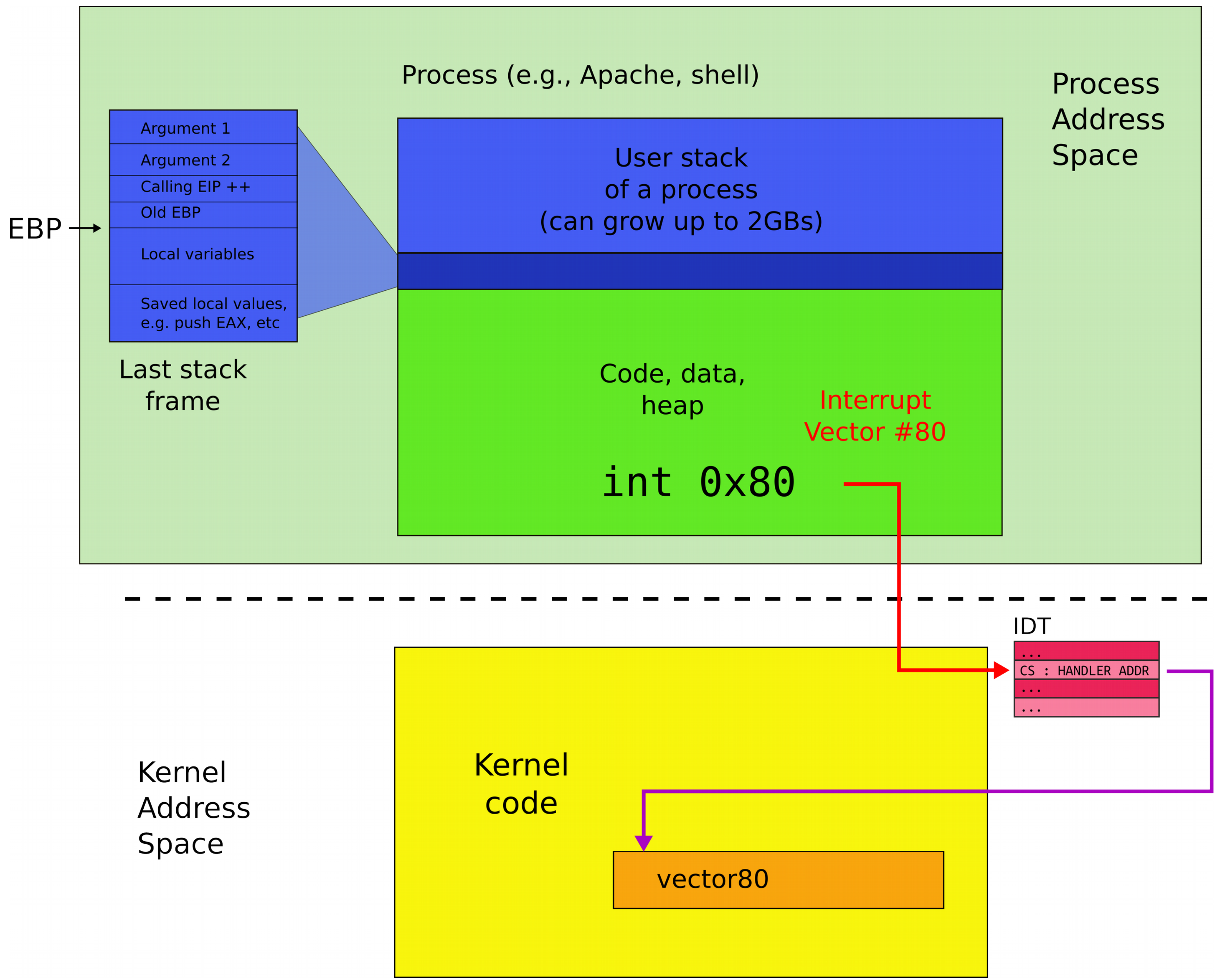
```
grep FORK sh.c | wc -l
```

- Create a pipe and connect ends

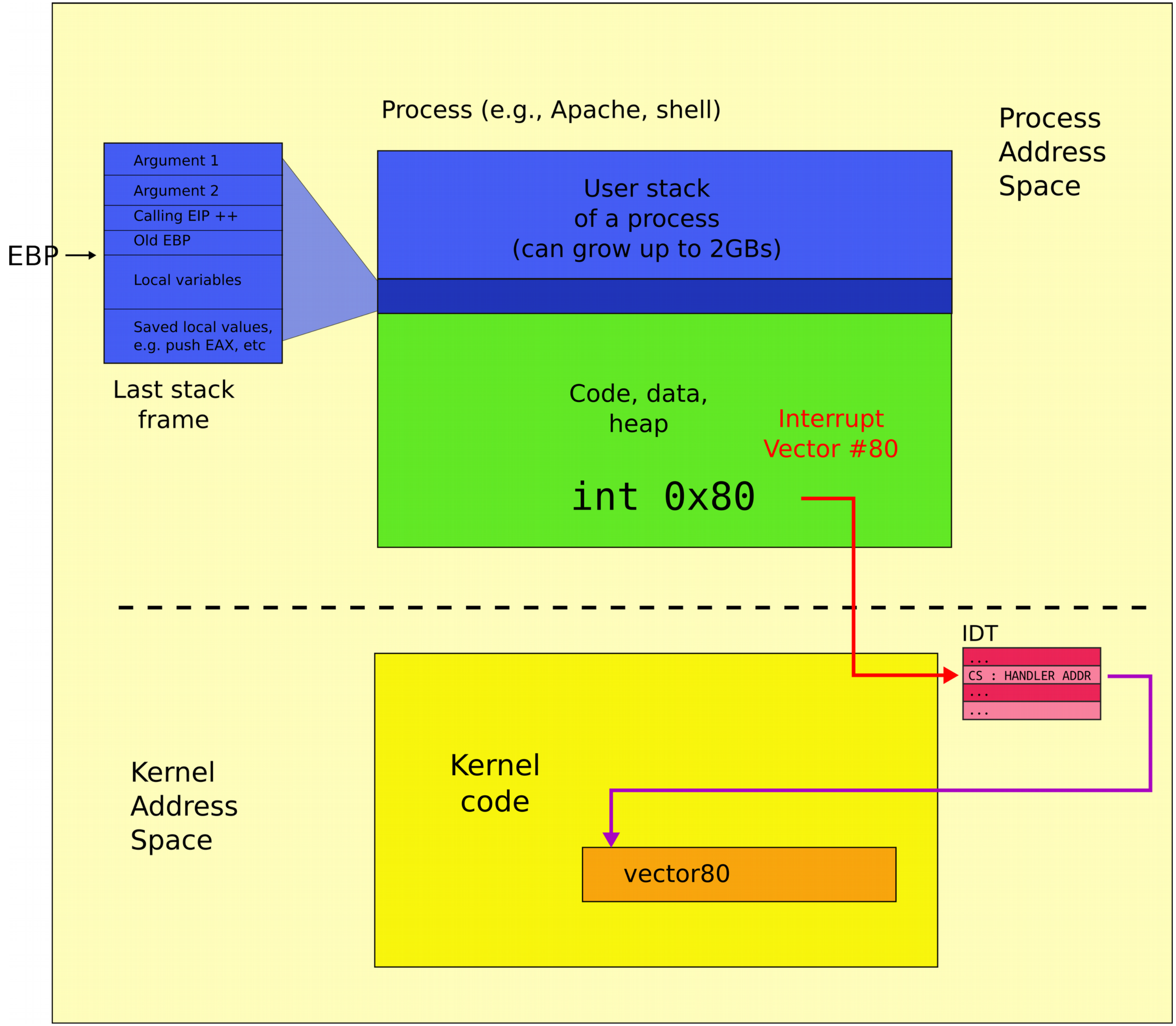
System call


Process (e.g., Apache, shell)
Argument 1
Argument 2
Calling EIP ++
Old EBP
EBP
Local variables
Saved local values, e.g. push EAX, etc
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

User address space



Kernel address space



Kernel and user address spaces