143A: Principles of Operating Systems

Lecture 2: OS Interfaces

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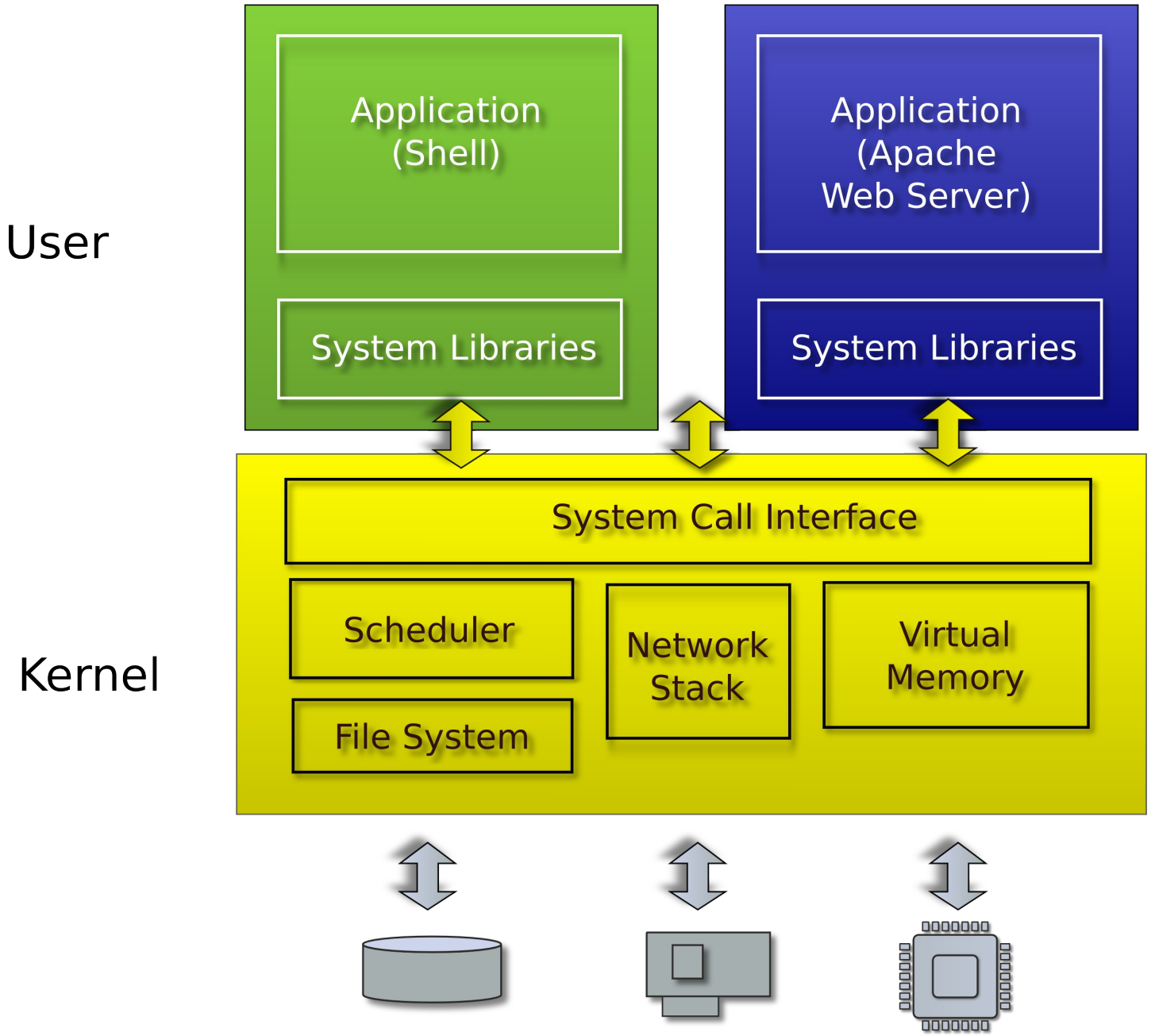
Recap from last time: role of the operating system

- 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...

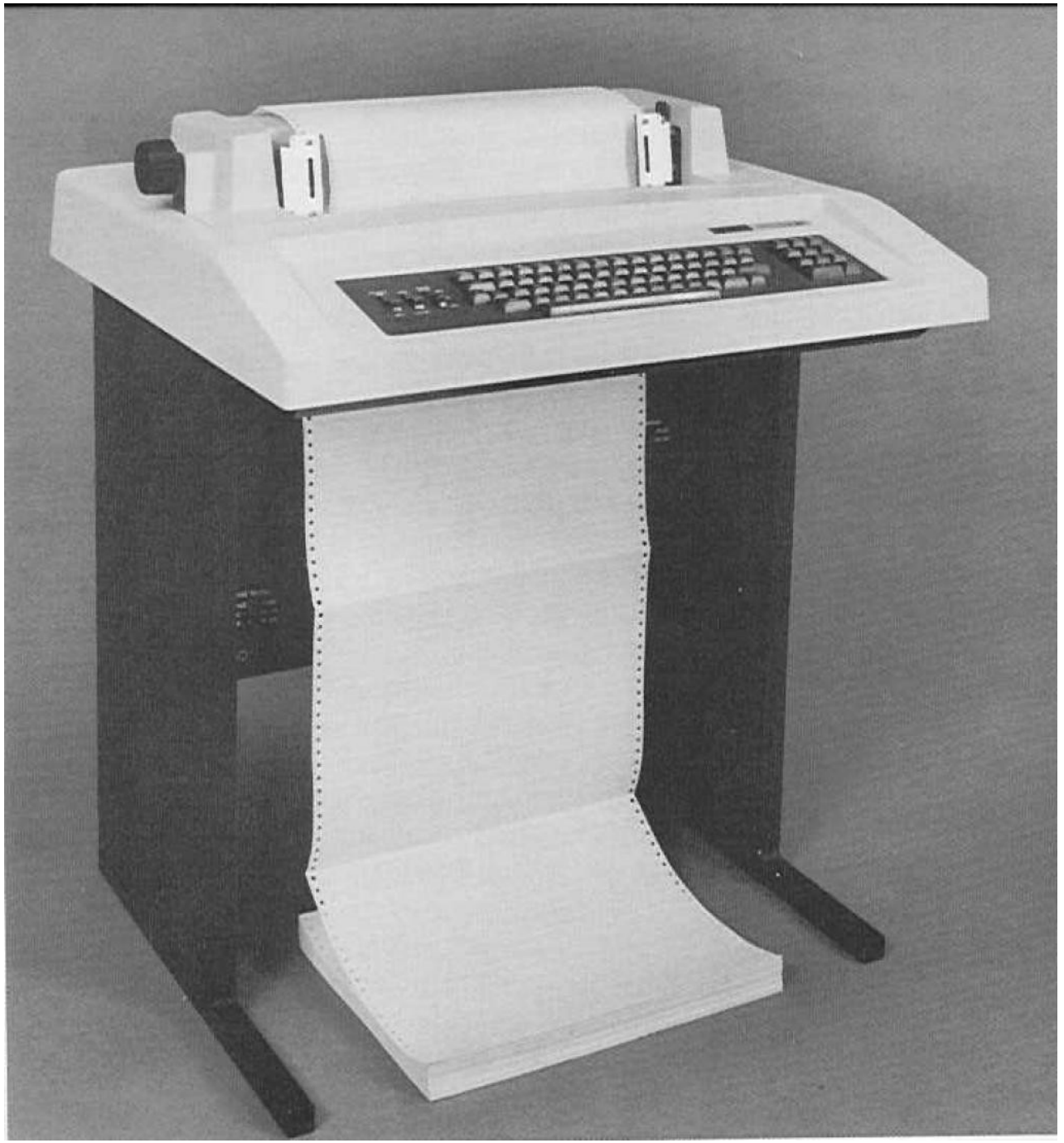
- Processes
  - Creating, exiting, waiting, terminating
- Memory
  - Allocation, deallocation
- Files and folders
  - Opening, reading, writing, closing
- Inter-process communication
  - Pipes

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
```

Shell

- Normal process
- Interacts with the kernel through system calls
  - Creates new processes

But what happens underneath?

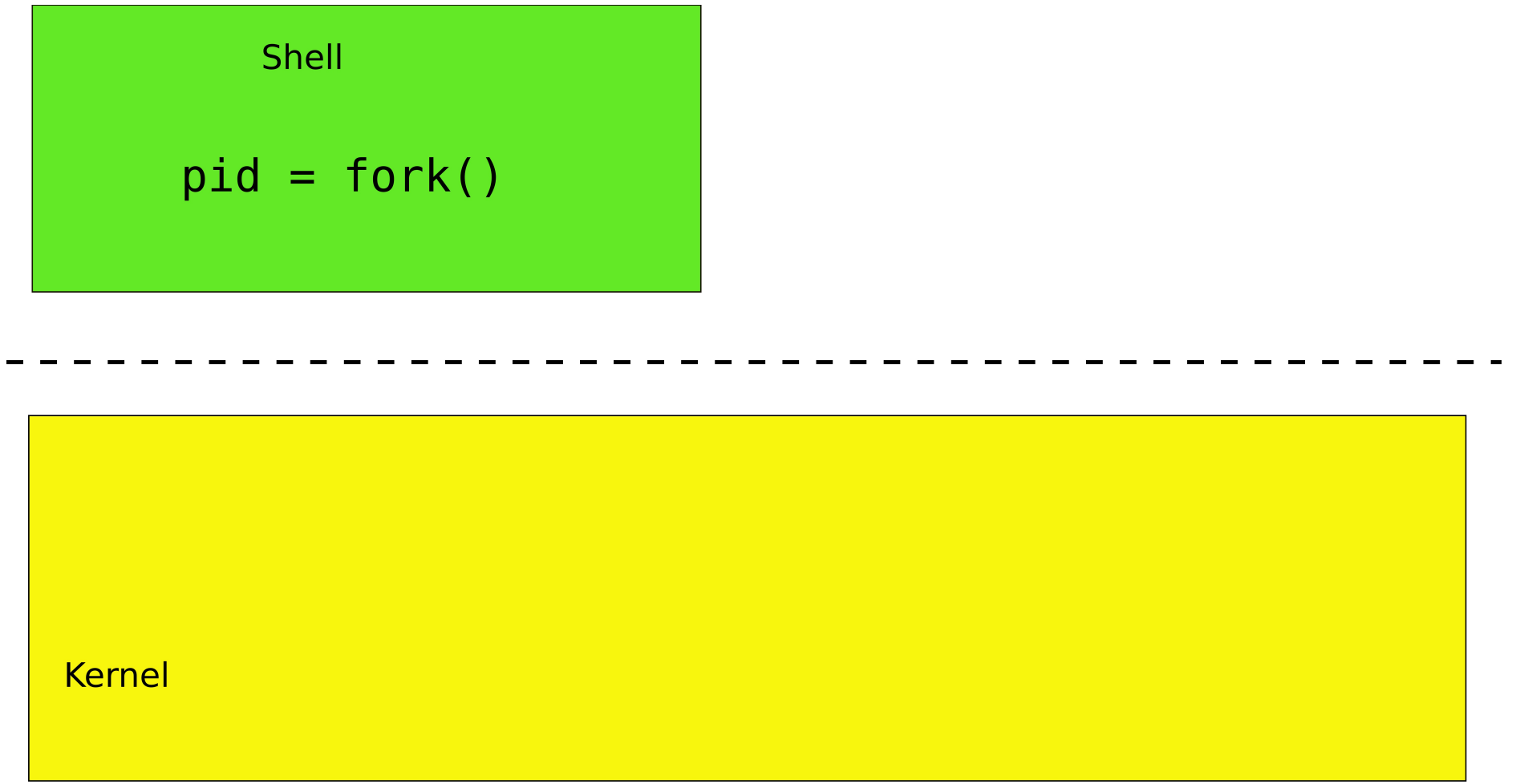
```
\> wc -l ls.c
85 ls.c
\>
```

- 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

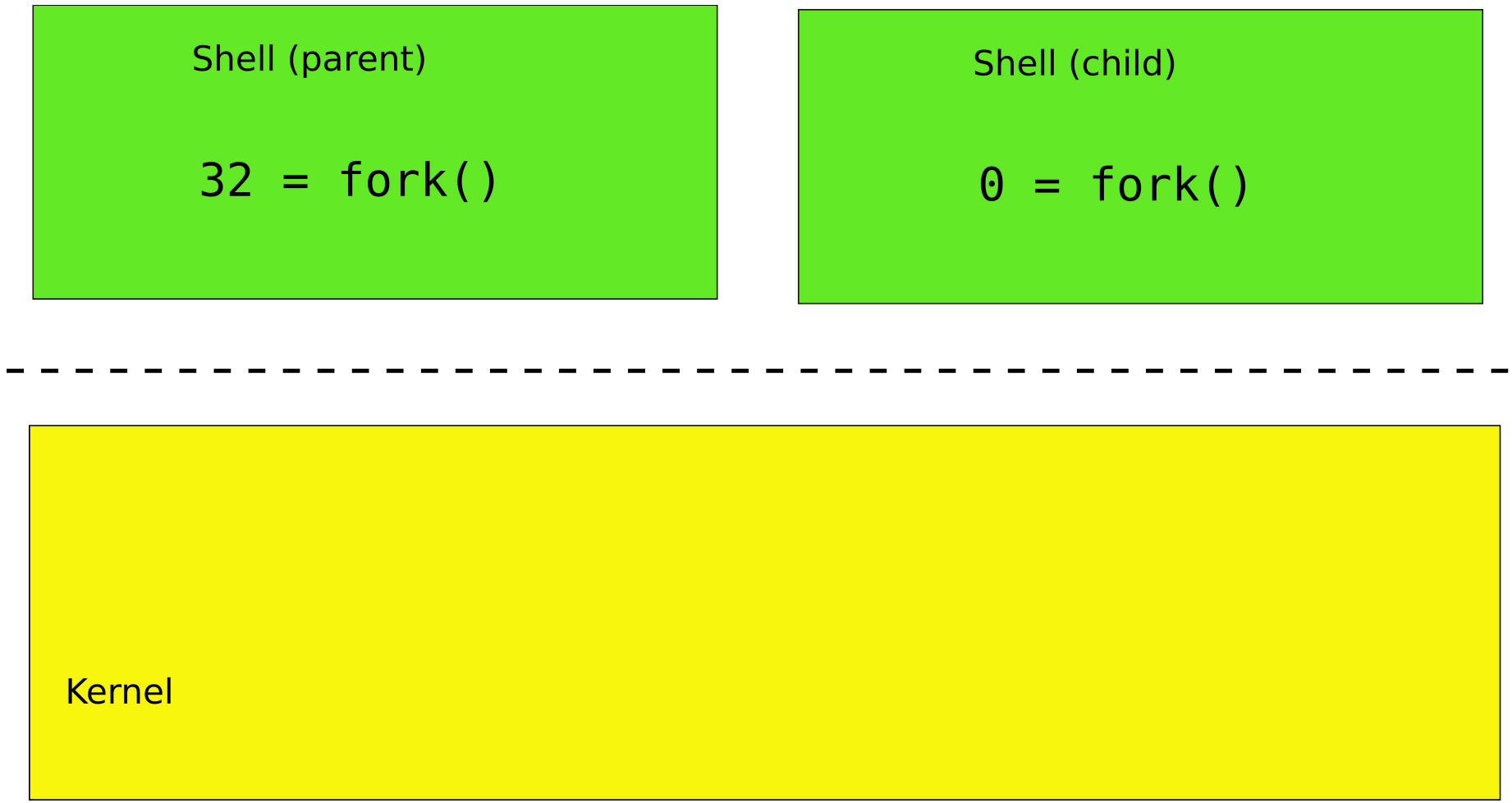
fork() -- create new process

```
1.  int pid;
2.  pid = fork();
3.  if(pid > 0){
4.      printf("parent: child=%d\n", pid);
5.      pid = wait();
6.      printf("child %d is done\n", pid);
7.  } else if(pid == 0){
8.      printf("child: exiting\n");
9.      exit();
10. } else {
11.      printf("fork error\n");
12. }
```

fork()



fork()



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

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

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

1
```

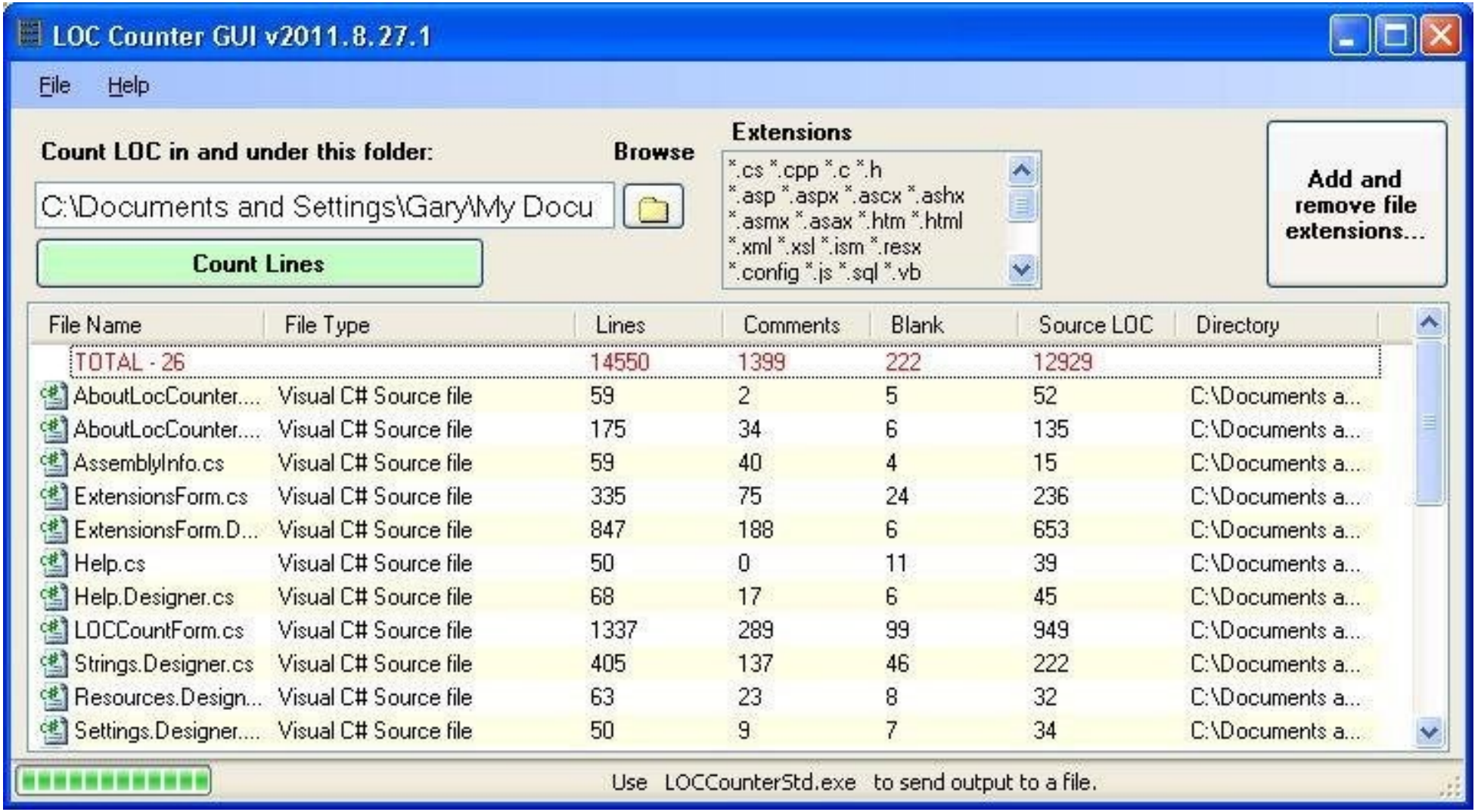
- .. or contain “a”

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

33
```

- Composability is great
  - Small set of tools (ls, grep, wc) compose into more complex programs

Better than this...



How to assemble this pipeline?

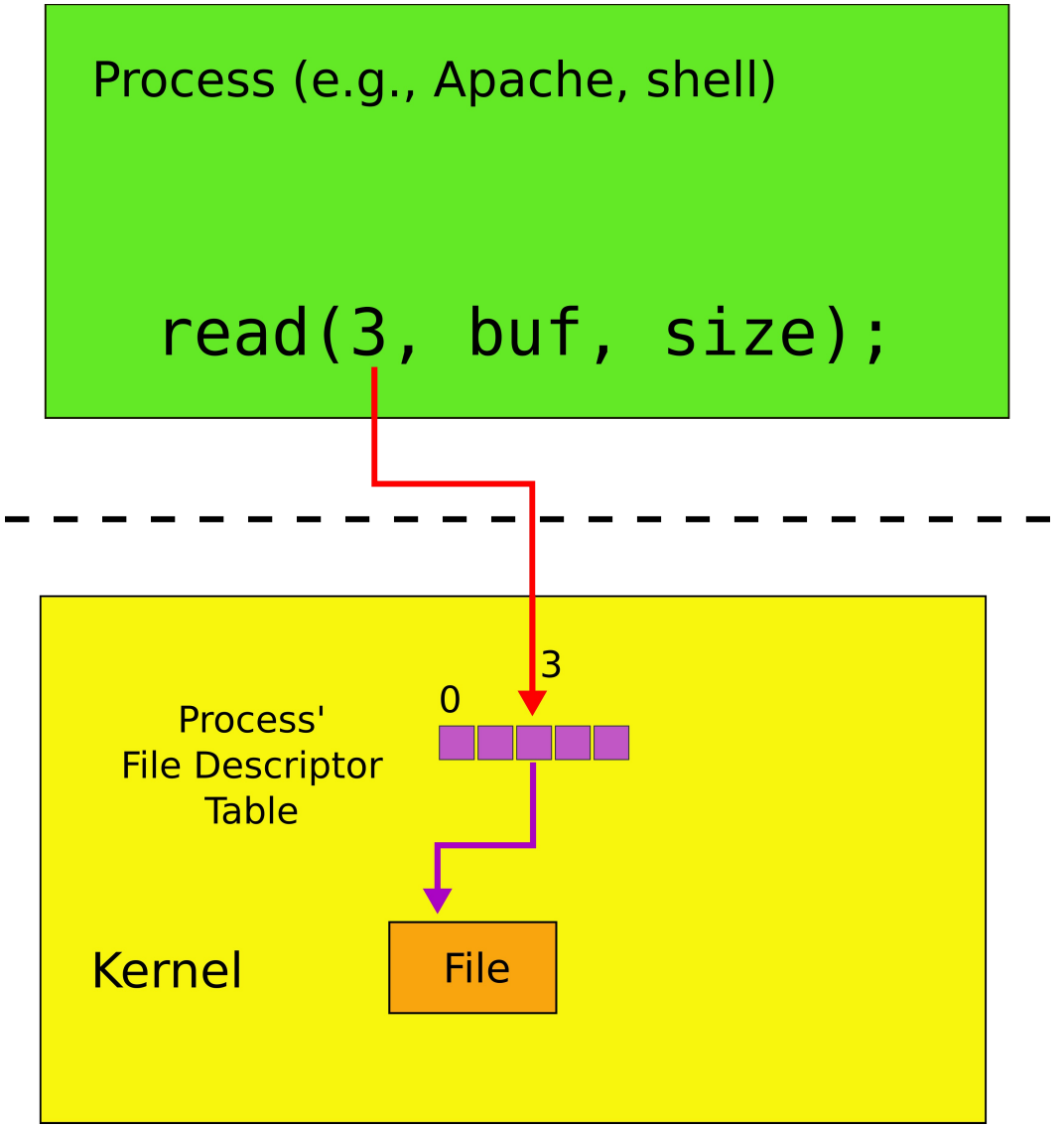
```
\> cat ls.c | grep main | wc -l
1
```

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

Lets look at file I/O

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

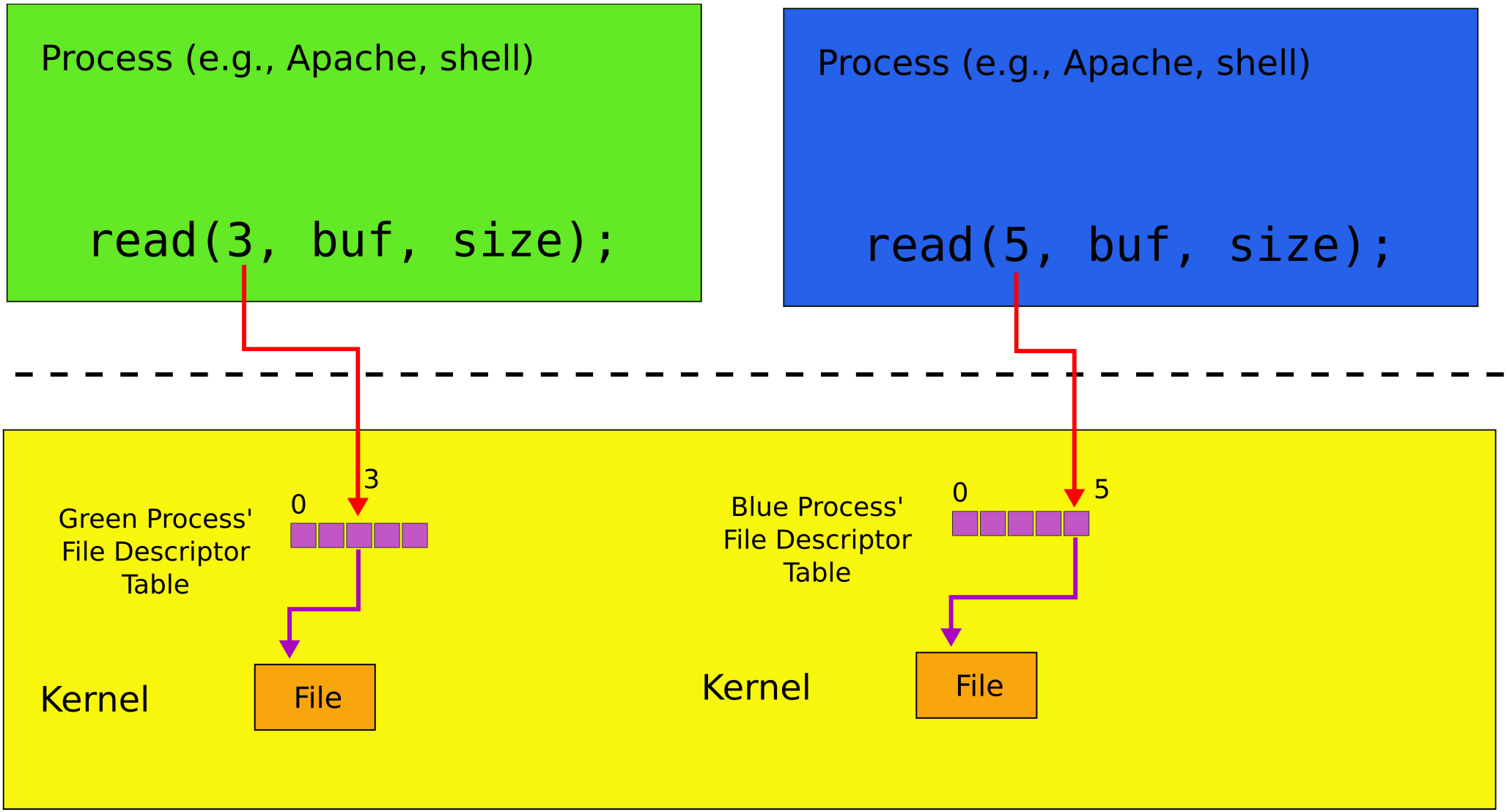
File descriptors



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

File descriptors: two processes

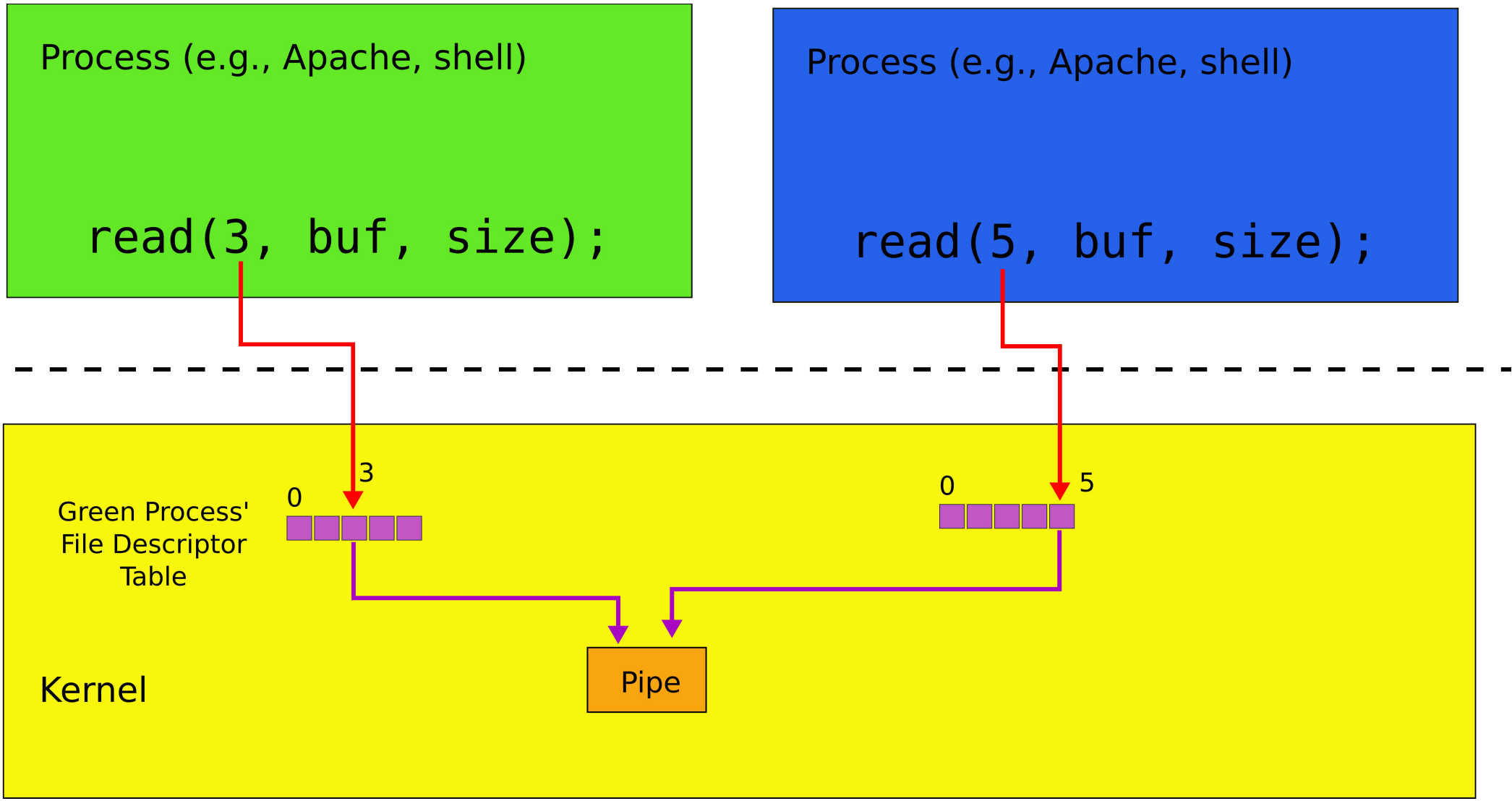


- File descriptors don't have to point only to files
  - Any object with the same read/write interface is ok
  - Network channel
  - Pipe

`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



Now we're ready to build the pipelines

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

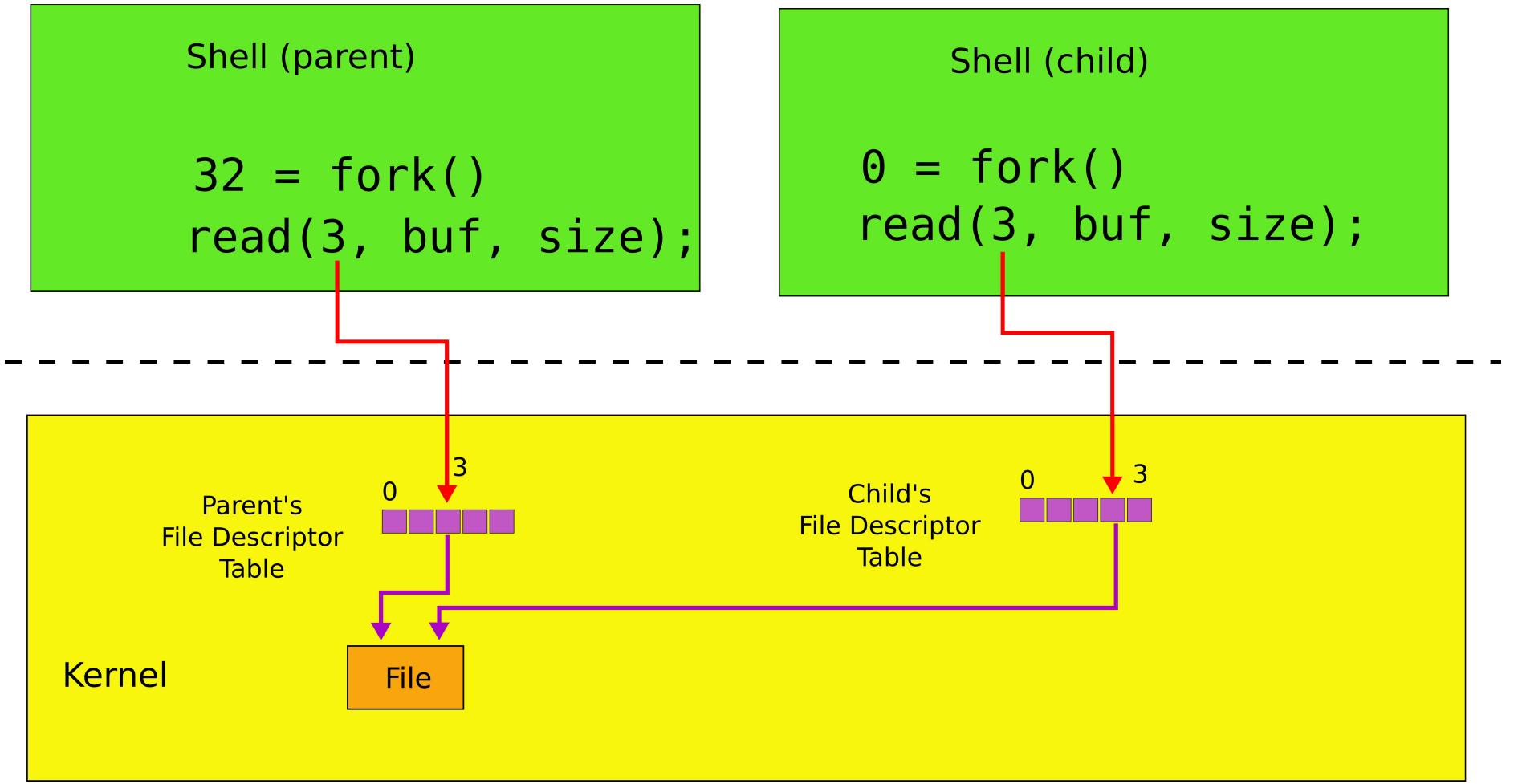
Example: cat

```
1.    char buf[512]; int n;
2.    for(;;) {
3.        n = read(0, buf, sizeof buf);
4.        if(n == 0)
5.            break;
6.        if(n < 0) {
7.            fprintf(2, "read error\n");
8.            exit(); }
9.        if(write(1, buf, n) != n) {
10.           fprintf(2, "write error\n");
11.           exit();
12.       }
13.   }
```

File I/O redirection

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

`fork()` leaves file descriptors untouched



File I/O redirection

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

Exec

- `exec()` -- replace 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");
```

Example: \> cat < input.txt

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

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 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 “|”

```
1. int p[2];
2. char *argv[2]; argv[0] = "wc"; argv[1] = 0;
3. pipe(p);
4. if(fork() == 0) {
5.     close(0);
6.     dup(p[0]);
7.     close(p[0]);
8.     close(p[1]);
9.     exec("/bin/wc", argv);
10. } else {
11.     write(p[1], "hello world\n", 12);
12.     close(p[0]);
13.     close(p[1]);
14. }
```

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

Fstat

- `fstat()` – retrieve information about a file

```
#define T_DIR 1 // Directory
#define T_FILE 2 // File
#define T_DEV 3 // Device
struct stat {
      short type; // Type of file
      int dev; // File system's disk device
      uint ino; // Inode number
      short nlink; // Number of links to file
      uint size; // Size of file in bytes
};
```

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

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

Backup slides

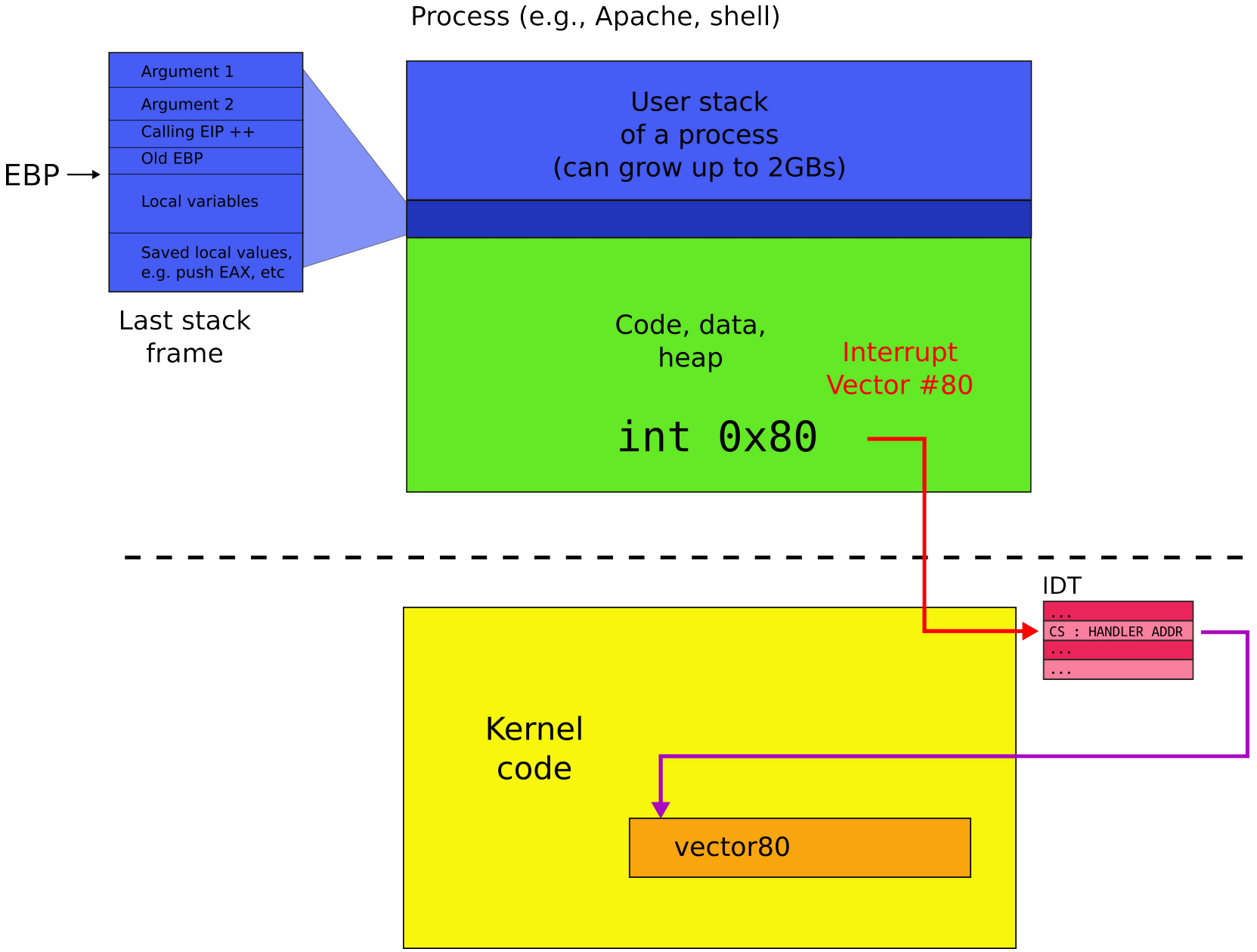
Pipes

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

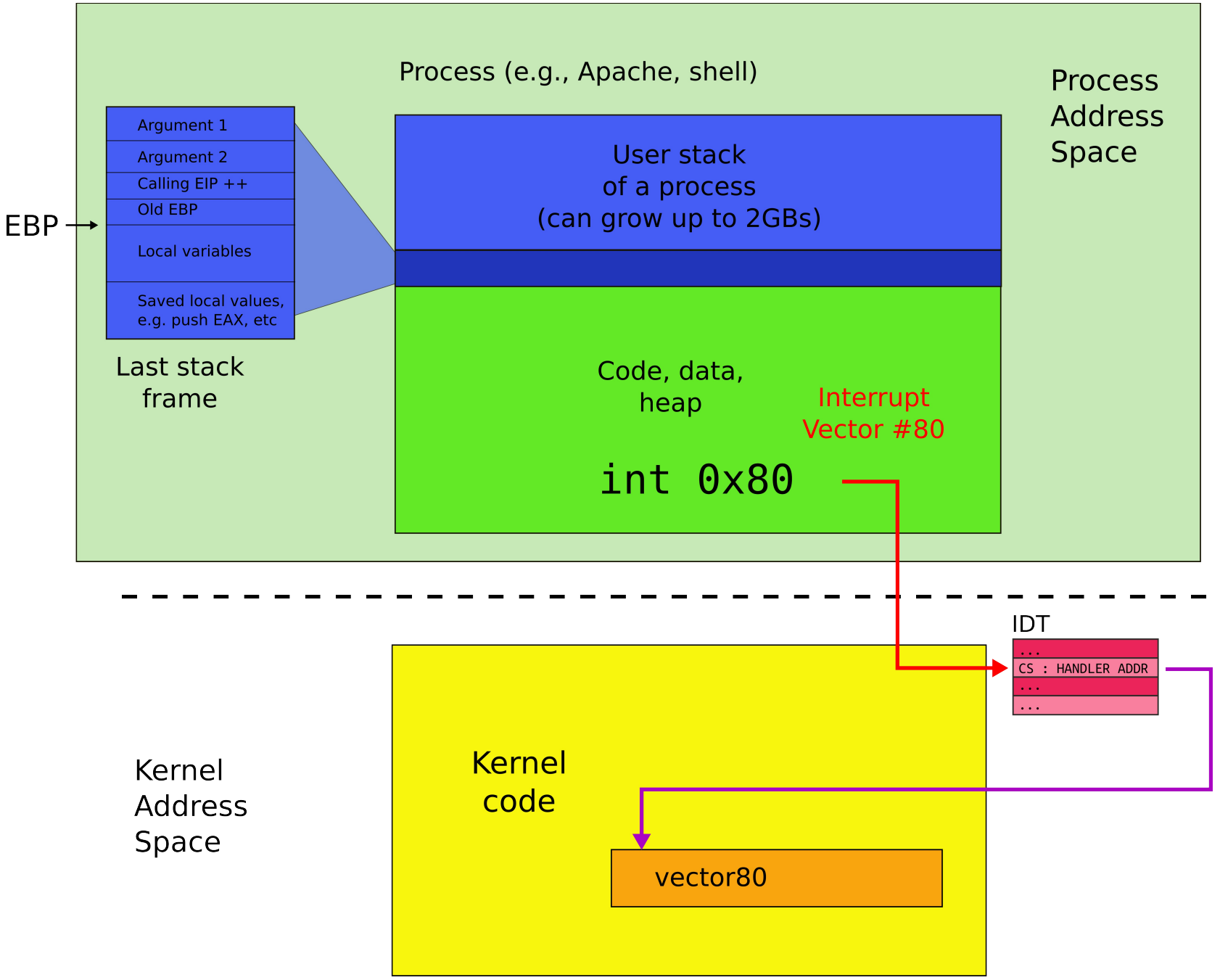
```
grep FORK sh.c | wc -l
```

- Create a pipe and connect ends

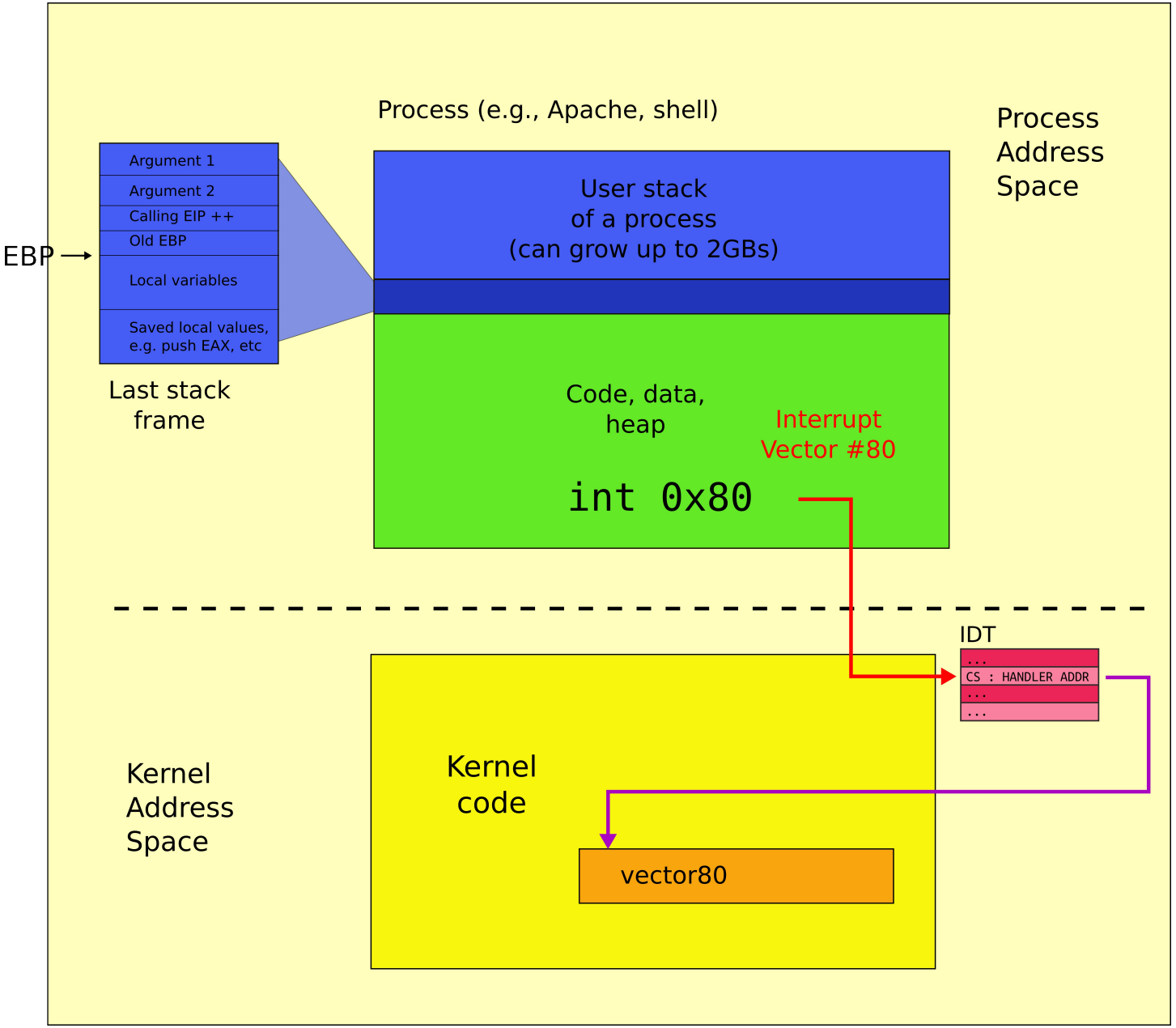
System call


Process (e.g., Apache, shell)
Argument 1
Argument 2
Calling EIP ++
Old EBP
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

User address space



Kernel address space



Kernel and user address spaces