1.3 A Simple OS

- *OS Structure*
- Processes, Address Spaces, & Threads
- Managing Processes
- Loading Program Into Processes
- Files

A Simple OS

- The main focus of this class is on how to ***build an OS***
  - since this is an intro class, we will focus on the fundamentals
    - occasionally, we will talk about the more advanced topics
  - this is not a "tech" class

- Sixth-Edition Unix
  - source license available to universities in 1975 from Bell Labs
  - had major influence on modern OSes
    - Solaris
    - Linux
    - MacOS X
    - Windows

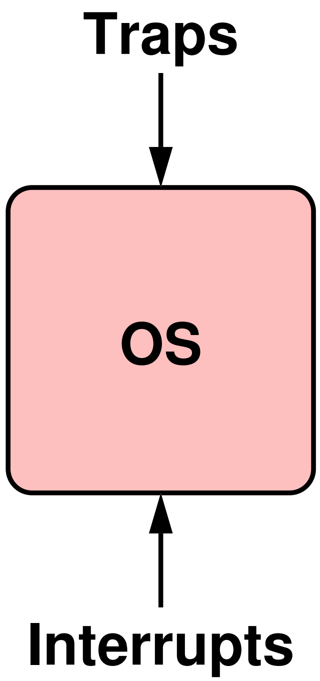
- Fits into 64KB of momory
  - single executable, completely stored in a ***single file***
  - ***loaded*** into memory as the OS boots
  - ***monolithic OS***

Hardware Support - User vs. Privileged Modes

- *Processor modes:* part of the processor state (recall from your computer organization/architecture class regarding "processor")
  - most computers have at least two modes of execution
    - *user mode:* fewest privileges
    - *privileged mode:* most privileges
      - the only code that runs in this mode is part of the OS
- For Sixth-Edition Unix
  - the whole OS run in the privileged mode
  - everything else is an application and run in the user mode
- For other systems
  - major subsystems providing OS functionality may run in the user mode
- We use the word *"kernel"* to mean the portion of the OS that runs in privileged mode
  - sometimes, a subset of this

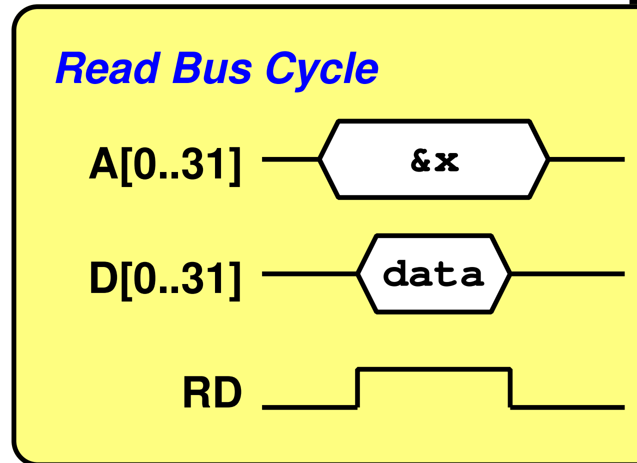
A Simple OS Structure

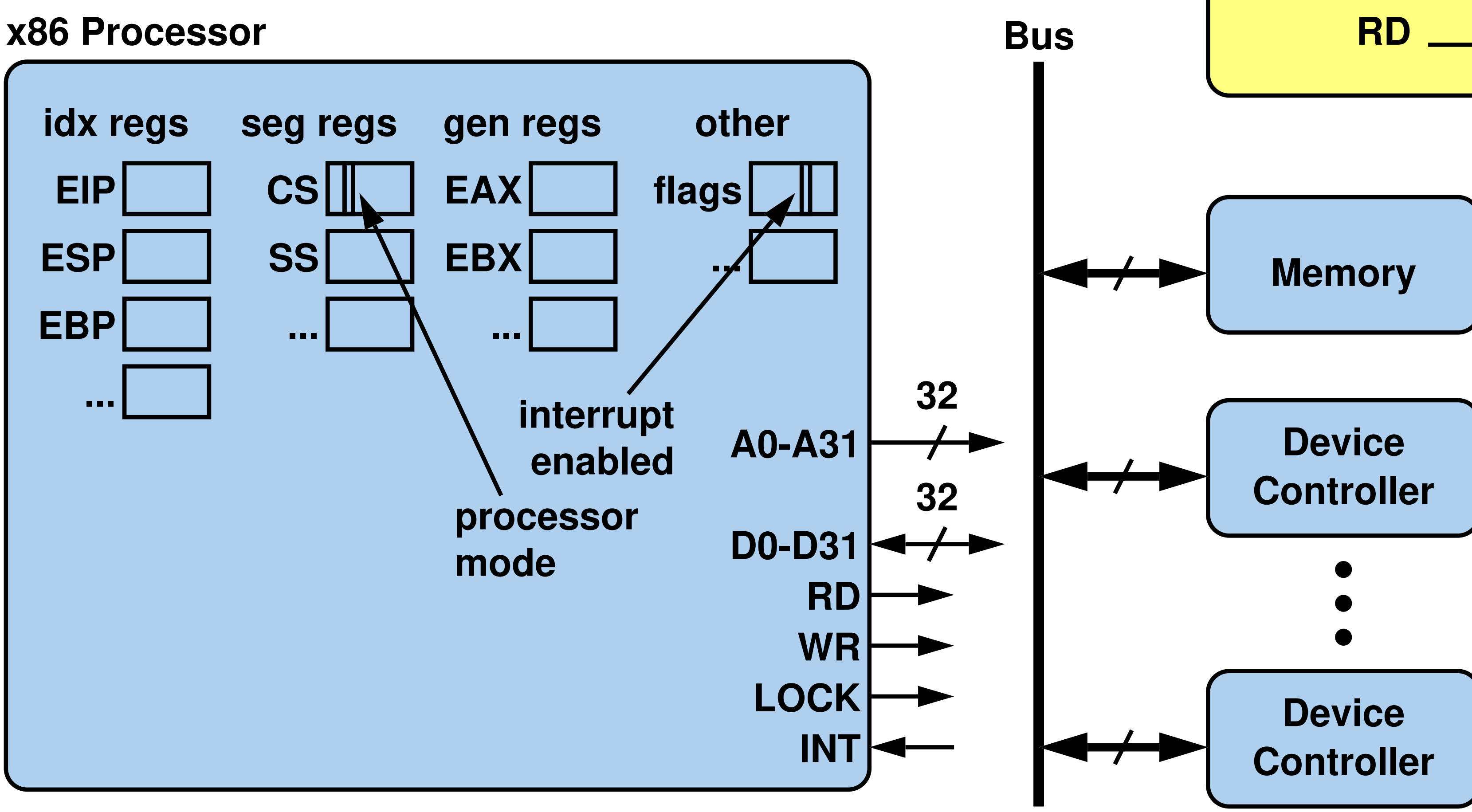
- Application programs call upon the OS via ***traps***
- External devices call upon the OS via ***interrupts***
  - I/O completion interrupt
    - executes ***interrupt service routine***



A Simple OS Structure

- Review of "Computer Organization"
  - bus architecture





A Simple OS Structure

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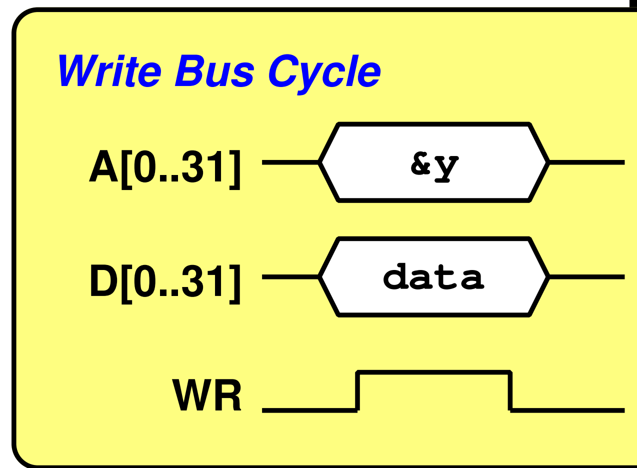

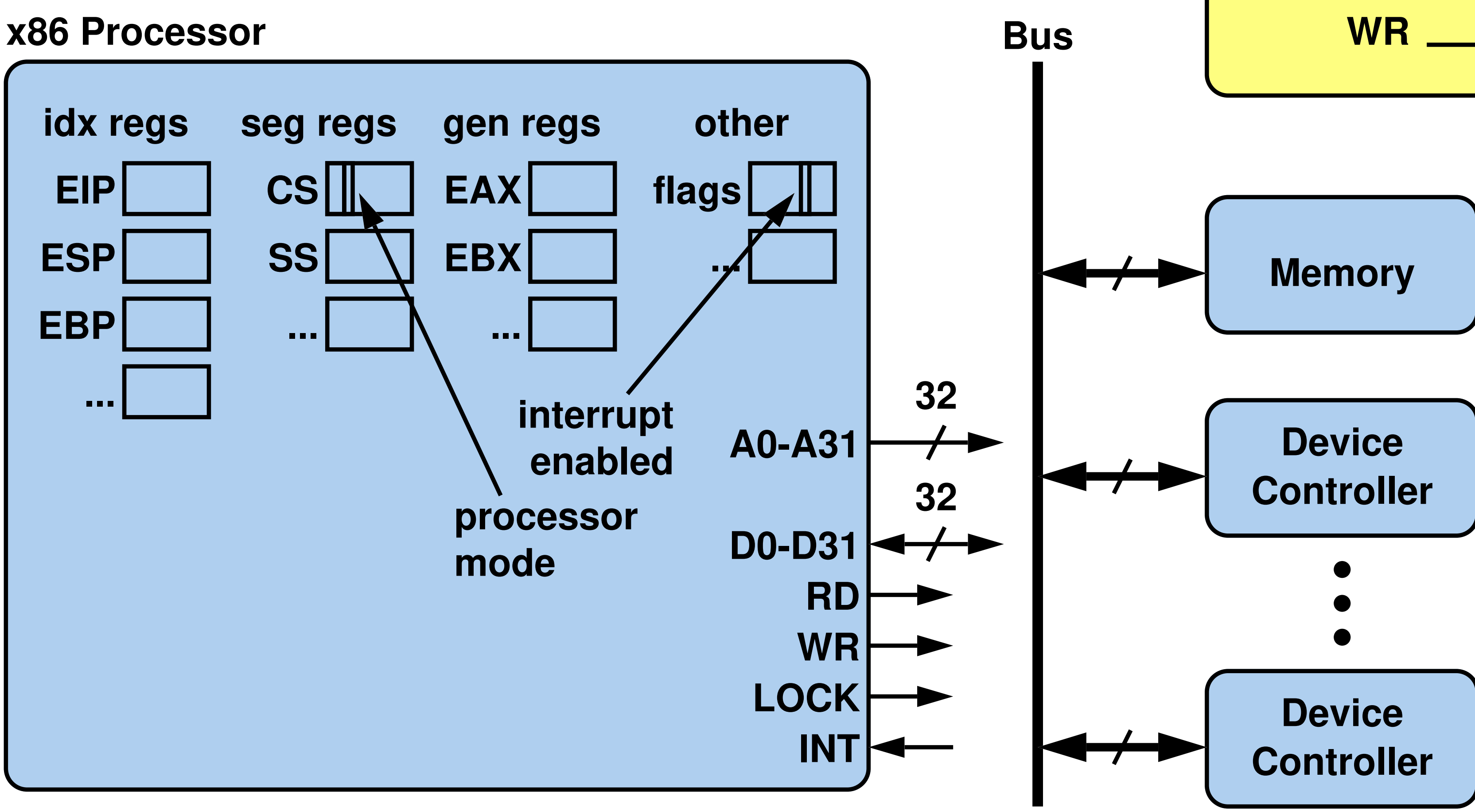

A Simple OS Structure

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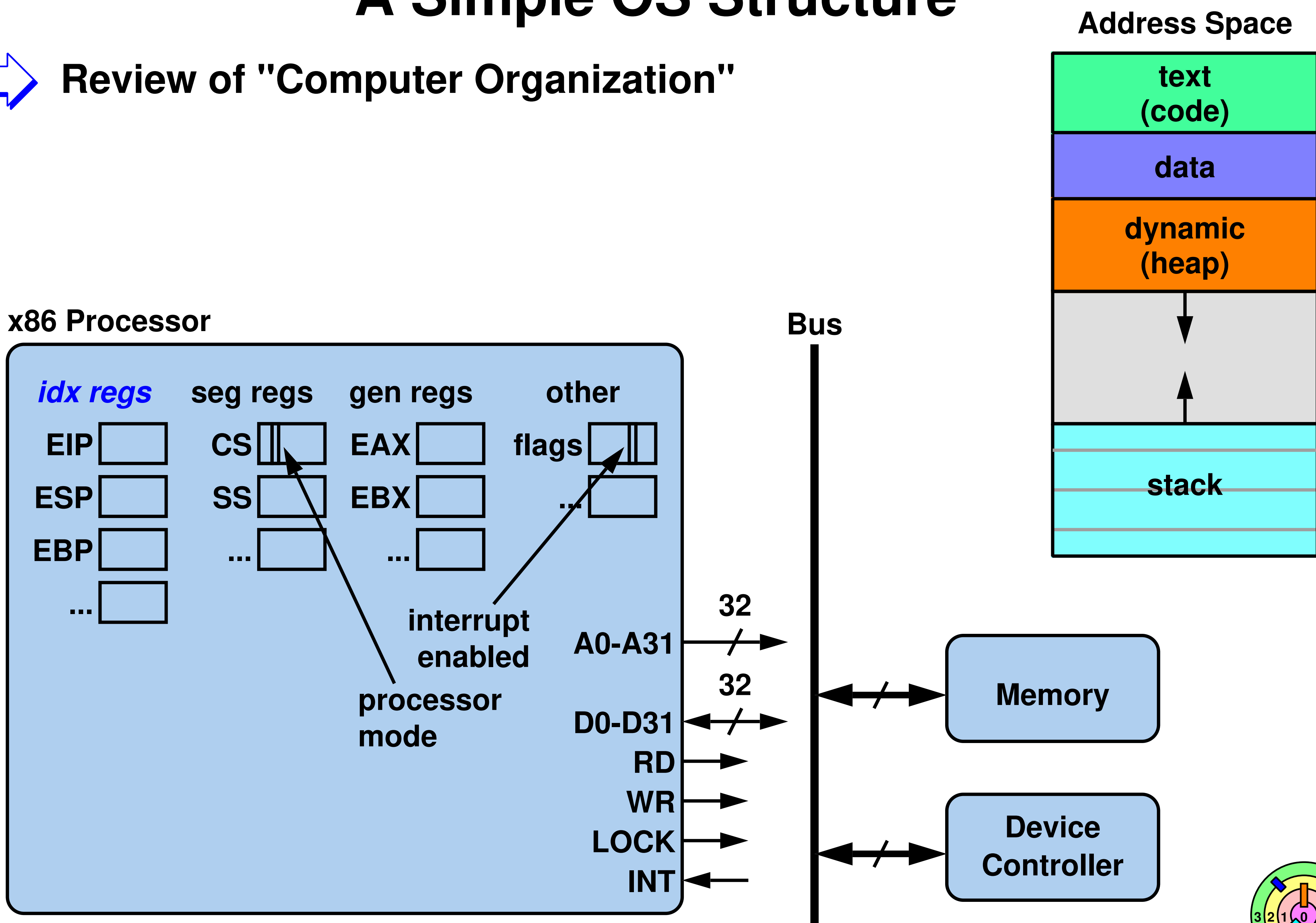

A Simple OS Structure

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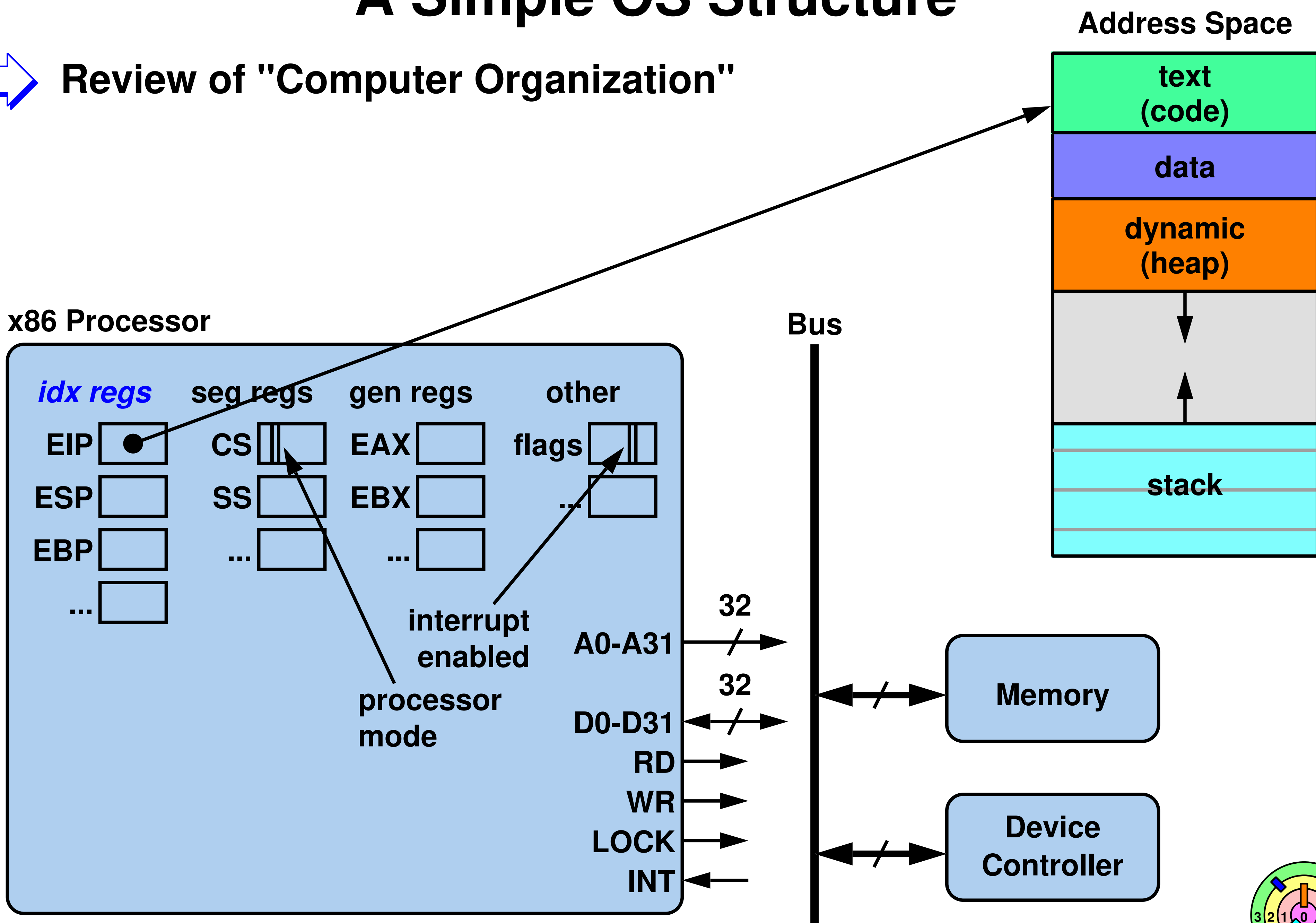

A Simple OS Structure

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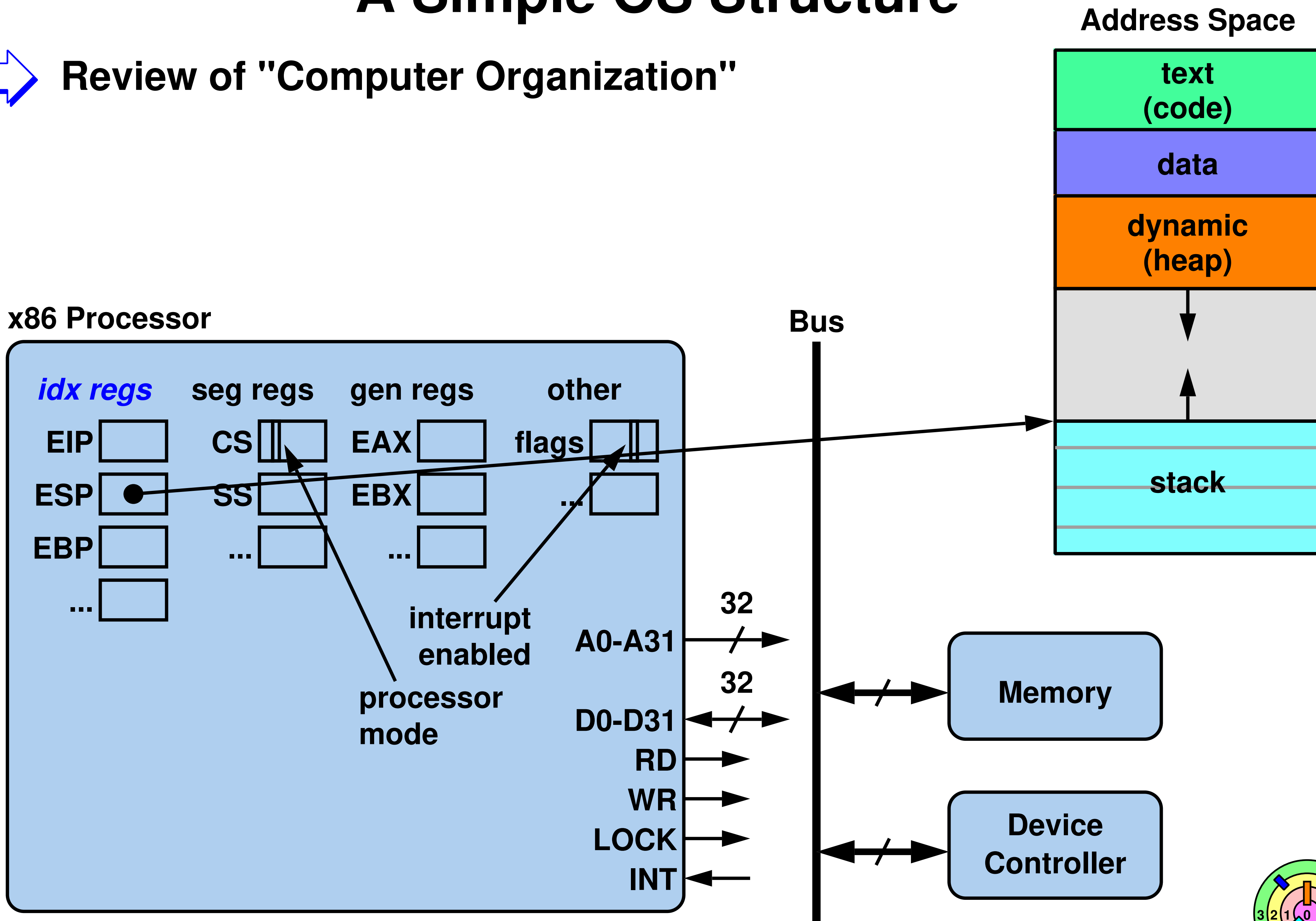

A Simple OS Structure

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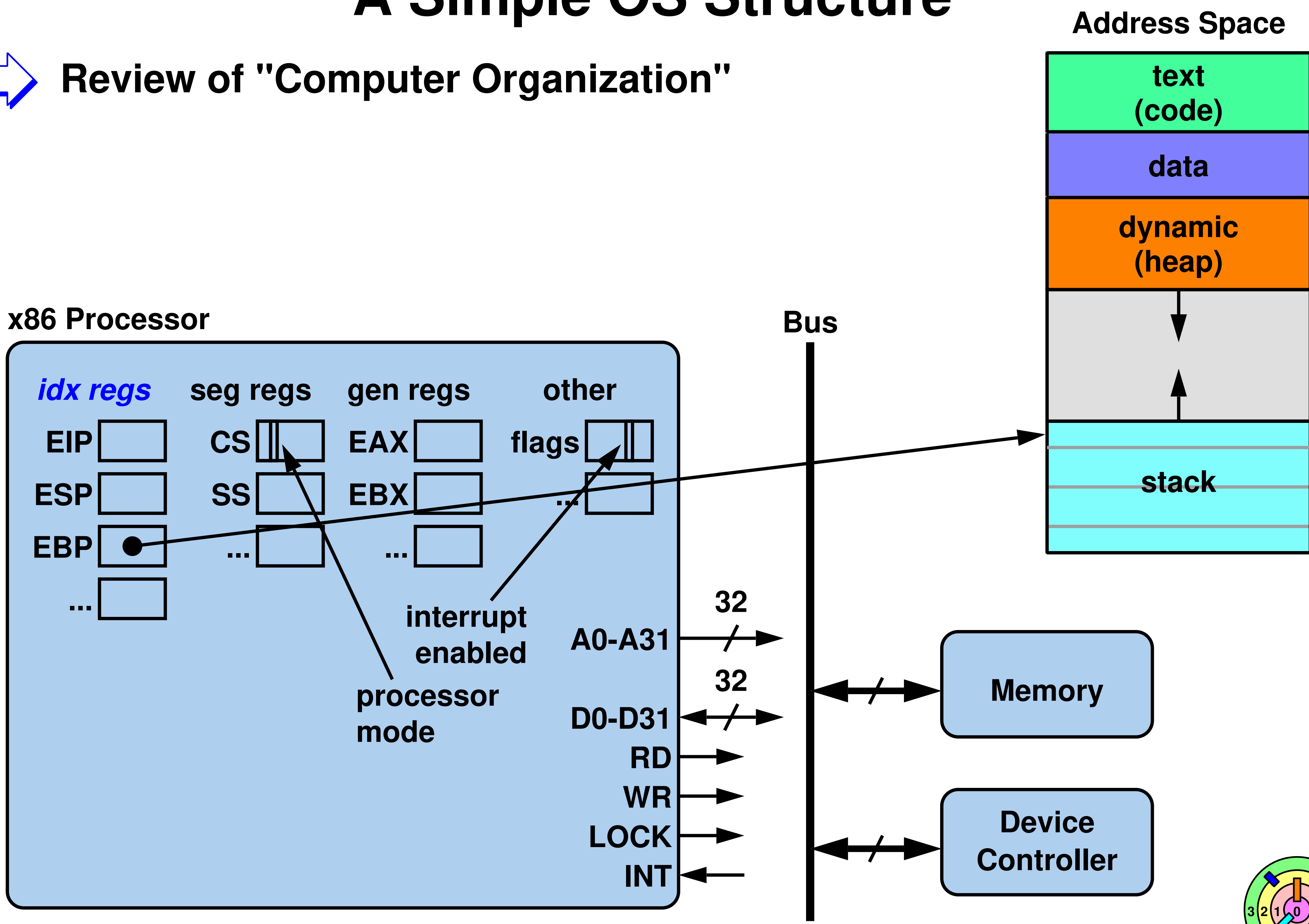
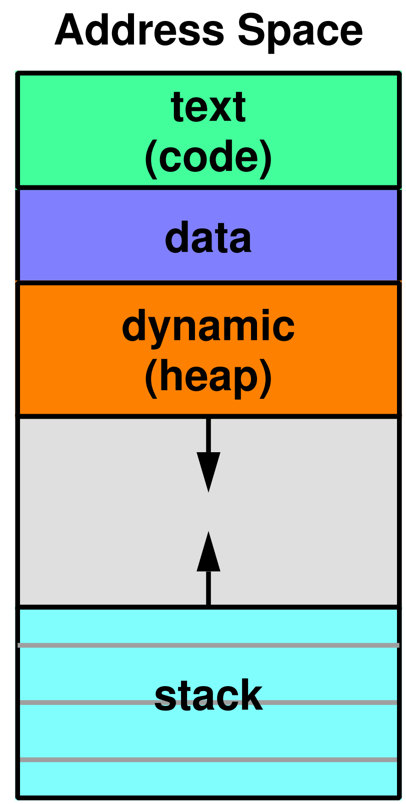


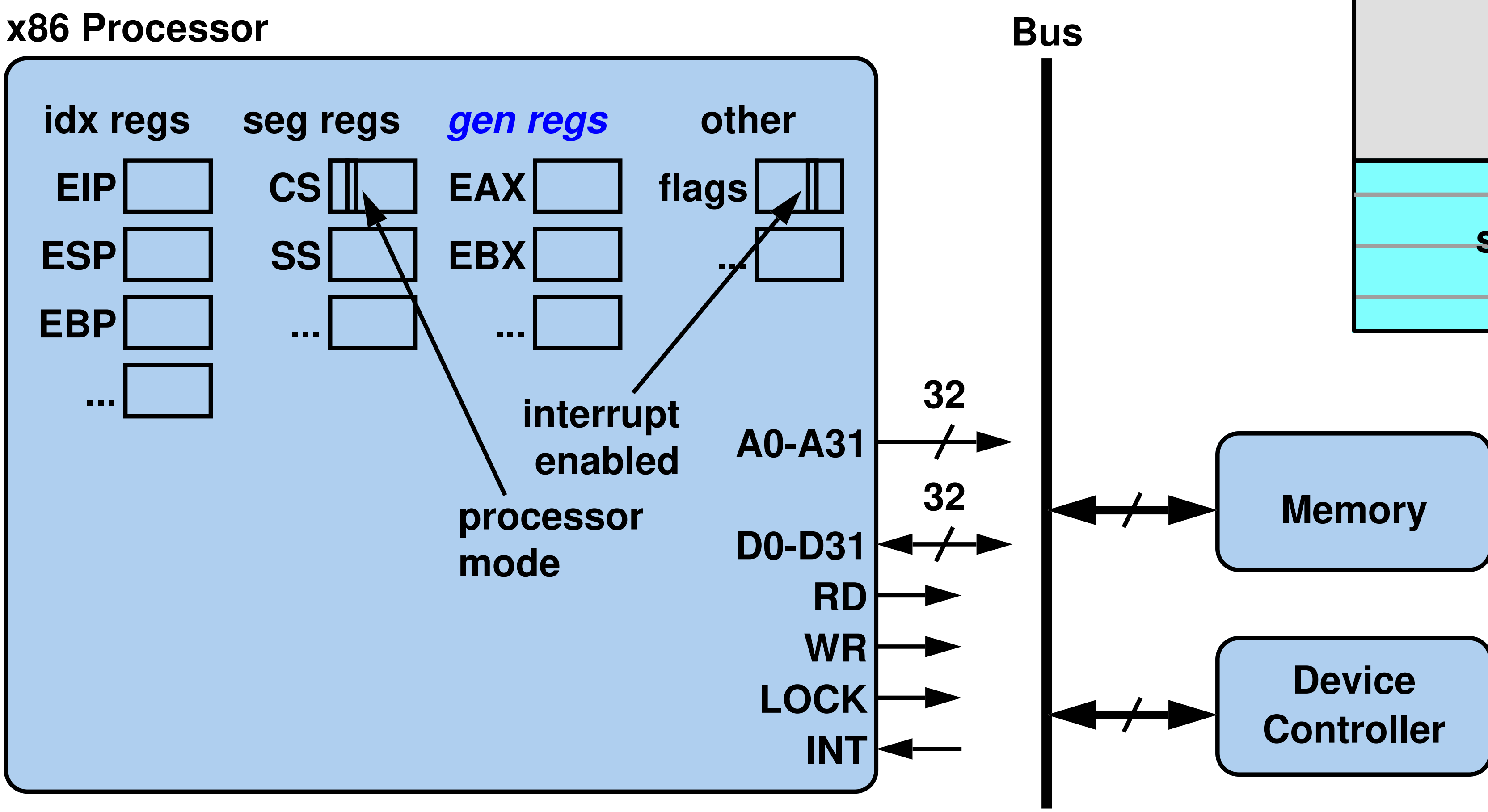
A Simple OS Structure

Review of "Computer Organization"

$z = x + y$ ⇨

```
mov &x → eax
mov &y → ebx
add(eax,ebx)
mov eax → &z
```





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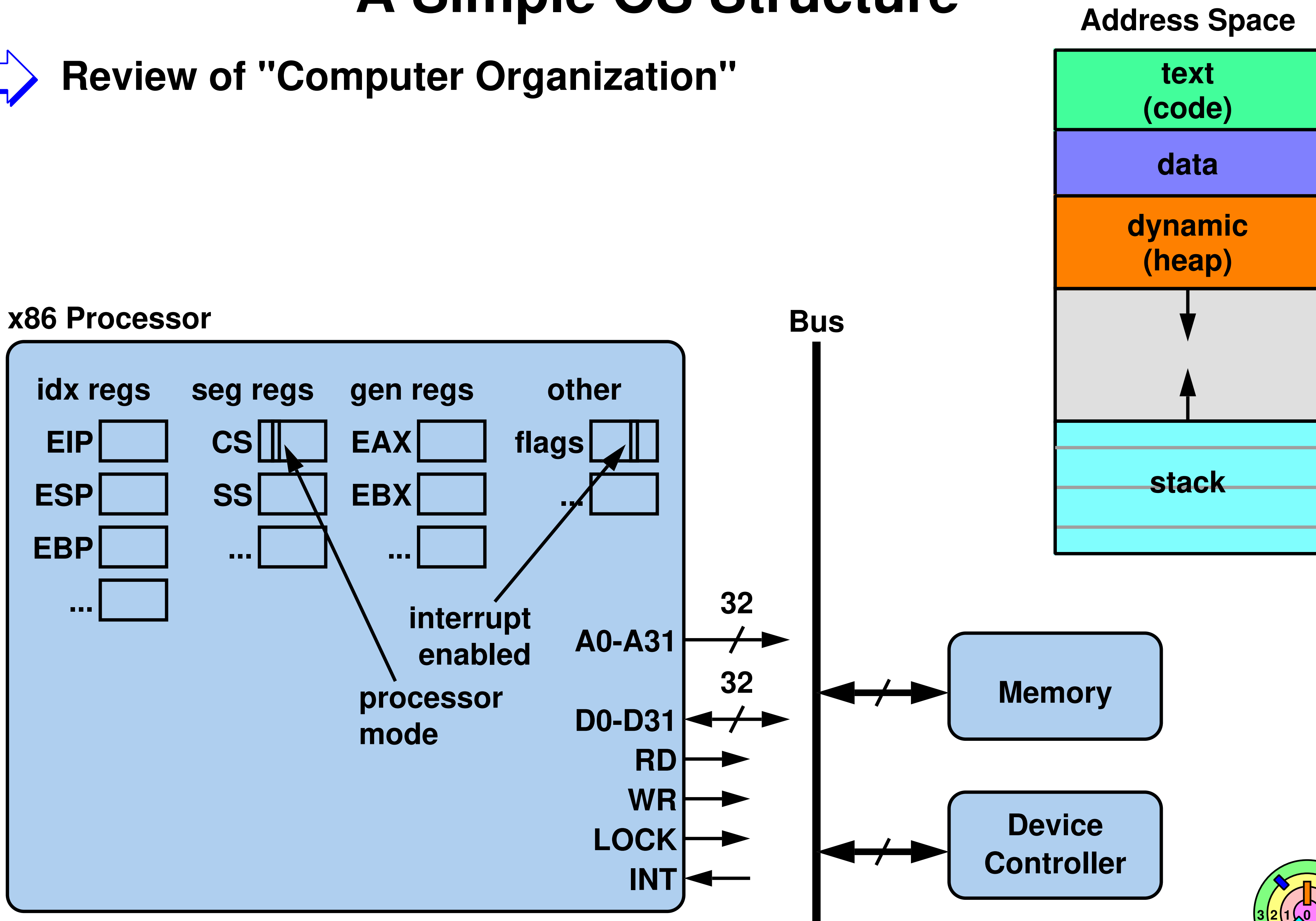
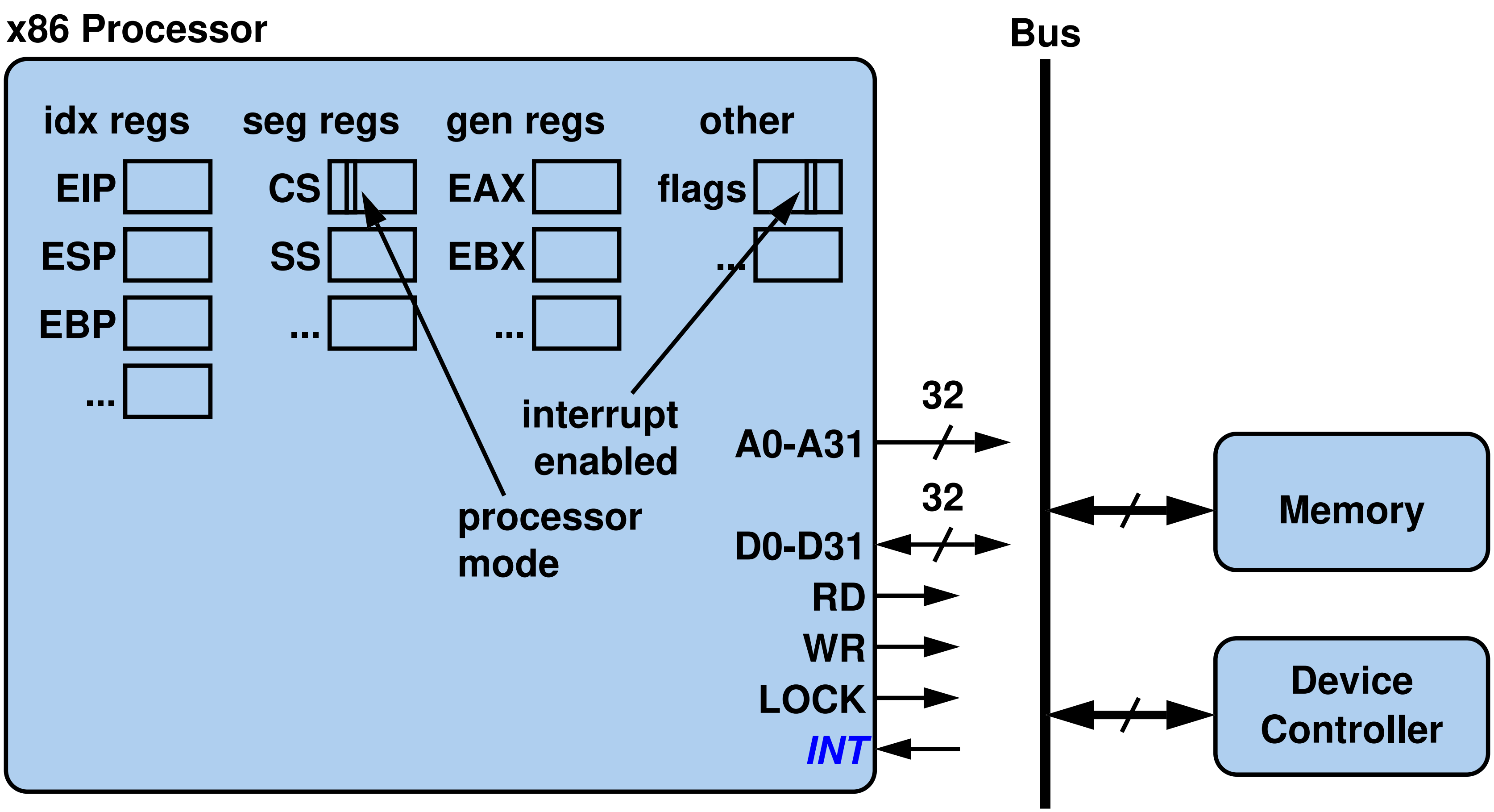
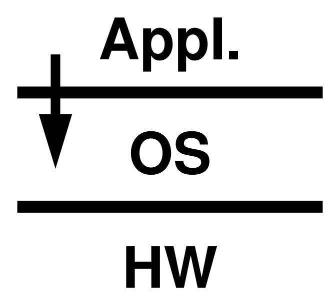


A Simple OS Structure

- Some important terms:
  - *interrupt pending*
  - *interrupt delivery*
  - *interrupt context*
  - *thread context*



Traps



- ***Traps*** **are the general means for invoking the kernel from user code**
  - **although we usually think of traps as *errors***
    - **divide by zero, segmentation fault, bus error, etc.**
  - **but they don't have to be**
    - ***system calls*, *page fault*, etc.**

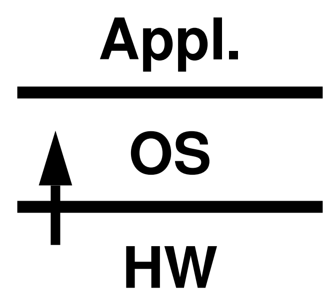
- **Traps always elicit some sort of response**
  - **for programming errors, the default action is to *terminate* the user program**
  - **for system calls, the OS is asked to perform some service**
  - **for page faults, the OS need to fix the virtual memory map**

A Special Kind Of Trap - System Calls

- Invoking OS functionality in the kernel is more complex
  - but we want to make it look simple to applications
  - must be done carefully and correctly
    - really cannot trust the application programmers to do the right thing every time

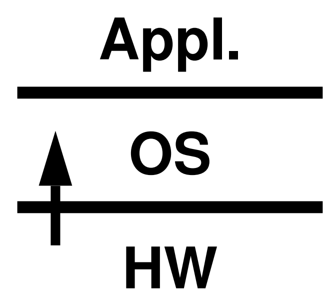
- Provide *system calls* through which user code can access the kernel *in a controlled manner*
  - any necessary checking on whether the request should be permitted can be done in the system call
    - all done in user mode
  - if all goes well
    - sets things up
    - *traps* into the kernel by executing a special machine instruction, i.e., the "trap" machine instruction
    - the kernel figures out why it was invoked and handles the trap
  - more in Ch 3

Interrupts



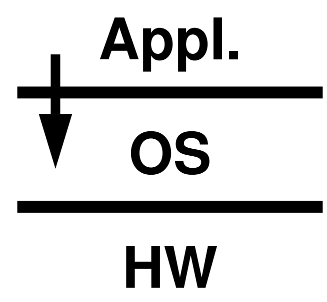
- An *interrupt* is a request from an *external device* for a response from the *processor*
  - most *hardware interrupts* are *I/O completion interrupts*
    - an I/O device is telling the CPU, "I am done" (and "what do you want me to do next?")
    - I/O devices are also hardware, they can run in parallel with the CPU, don’t keep them idle unless you have nothing for them to work on
  - *interrupts* are handled *independently of any user program*
    - unlike a *trap*, which is handled *as part of the program* that caused the trap where response to a trap directly affects that program
  - response to an interrupt may or may not indirectly affect the currently running program
    - often has *no direct effect* on the currently running program

Interrupts



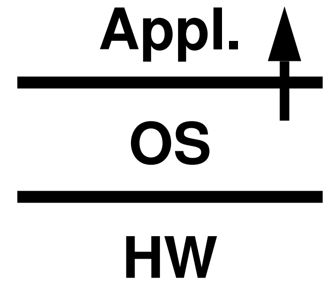
- An *interrupt* is an *asynchronous* event
  - it's asynchronous with respect to the executing entity (threads or OS)
- A *trap* occurs *synchronously* with respect to the executing entity
  - when your thread executes a divide-by-zero instruction, we know exactly where it happens and we know when it will happen

Software Interrupt



- There's also something called ***software interrupt***
  - generated programmatically (i.e., not by a device) when executing a machine instruction
    - e.g., executing an "interrupt" machine instruction
    - x86 CPU uses a software interrupt (i.e., "`int 0x2e`") to implement the "trap" machine instruction
      - other CPUs may have a separate "trap" machine instruction
  - this is very different from a hardware interrupt
    - although the mechanisms of handling interrupts are all very similar as we will see in Ch 3

Upcall



- A program may establish a handler *(i.e., a* ***signal handler****)* to be invoked in response to the error
  - the handler might clean up after the error and then terminate the program, or it might perform corrective action and continue with normal execution
  - more in Ch 2
- The ***upcall*** mechanism
  - ***signals*** allow the kernel to invoke code that's part of user program
    - for example, you can set a timer to expire at a certain time, when it expires, the OS can use the upcall mechanism to call a specified user function on behalf of the user program

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Program Execution

- Fundamental *abstraction* of *program execution*
  - memory
    - address space
      - things that are addressable by the program are kept together here
    - in Sixth-Edition Unix, processes do not share address space
    - recall that *process* is an abstraction of *memory*
  - processor(s)
    - recall that *thread* is an abstraction of *processor*
  - "execution context"
    - which represents the *state* of a process and its threads
    - represents exactly "where you are" in the program
    - a thread needs some sort of a context to execute

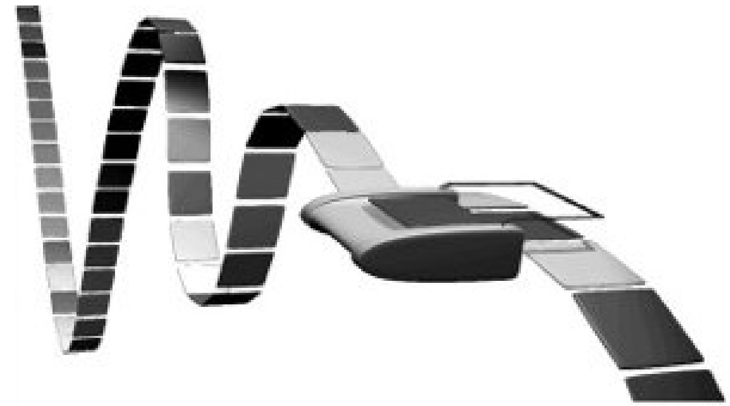
- Note: multiple meanings of the word "context" in this class
  - *save (execution) context* and *restore (execution) context*
  - *thread context* vs. *interrupt context*

A Program

```
const int nprimes = 100;
int prime[nprimes];
int main() {
  int i;
  int current = 2;
  prime[0] = current;
  for (i=1; i<nprimes; i++) {
     int j;
  NewCandidate:
     current++;
     for (j=0; prime[j]*prime[j] <= current; j++) {
        if (current % prime[j] == 0)
           goto NewCandidate;
     }
     prime[i] = current;
  }
  return(0);
}
```

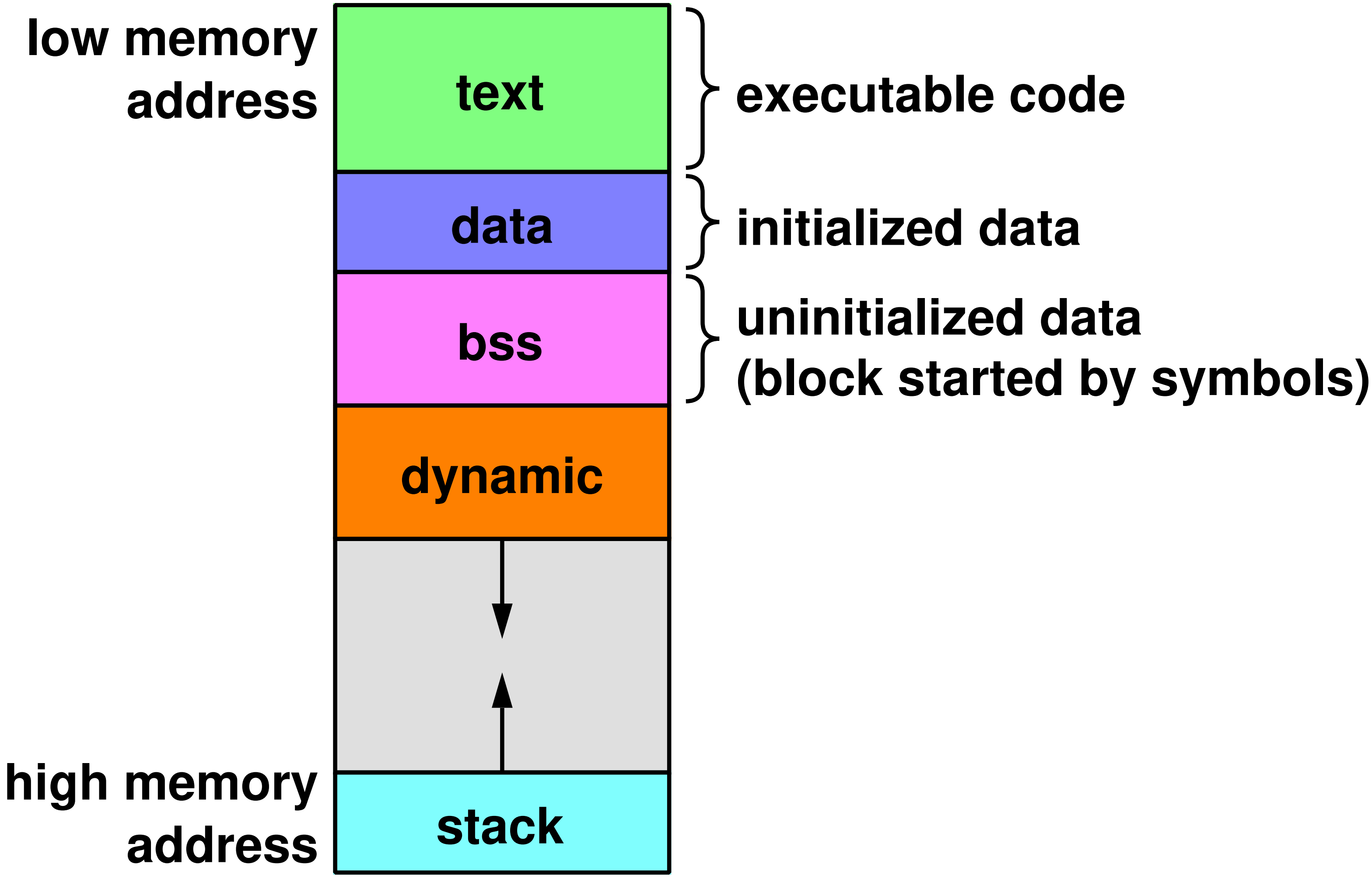
- My color codes for code
  - reserved words at in blue
  - numeric and string constants are in red
  - comments in green
  - black otherwise

Turing Machine Model of Computation



- A *Turing Machine* consists of
  - an infinite tape which is divided into cells, one next to the other *(i.e., infinite storage)*
    - one symbol in each cell (or can be a blank symbol)
  - a head that can read and write symbols on the tape and move the tape left and right one (and only one) cell at a time
  - a state register that stores the state of the Turing machine, one of finitely many *(i,e., finite state)*
  - a *finite* table of instructions that, given the state the machine is currently in and the symbol it is reading on the tape tells the machine to do the following in sequence
    - either erase or write a symbol
    - move the head
    - assume the same or a new state as prescribed

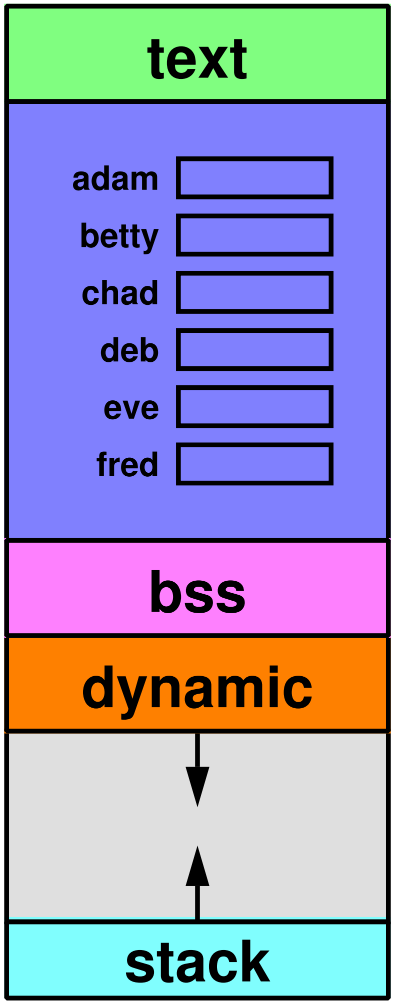
The Unix Address Space



- This is part of the *tape* of the Turing Machine
  - the rest of the *tape* of the Turing Machine can be reached by using the "*extended address space*"

Note About Naming Objects

- How do you name objects in an address space
  - *"objects"* is the word we use to mean *any* data types (primitive, data structures, pointers)
- Variables
  - name each object
  - a *variable* refers to a *memory location*



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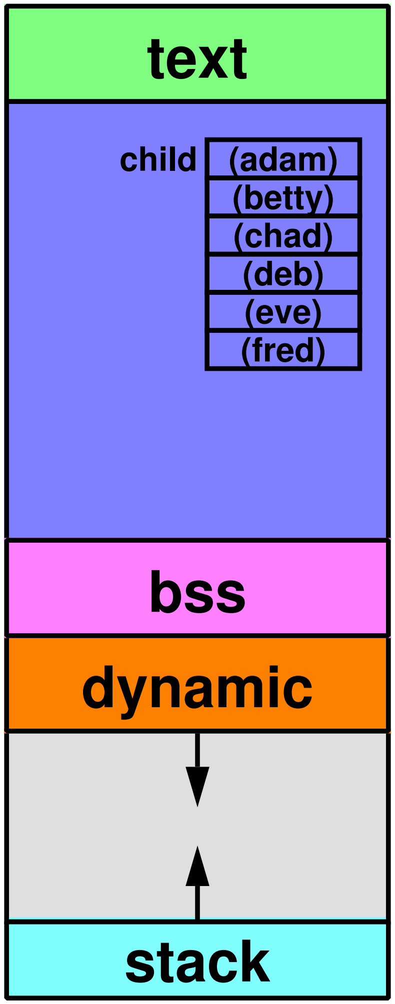
- Variables
  - name each object
  - a *variable* refers to a *memory location*
- Arrays
  - name an object with a *base* and an *index*
- Dynamically create objects do not have names
  - no variable can have a "heap address"
  - need *pointers*



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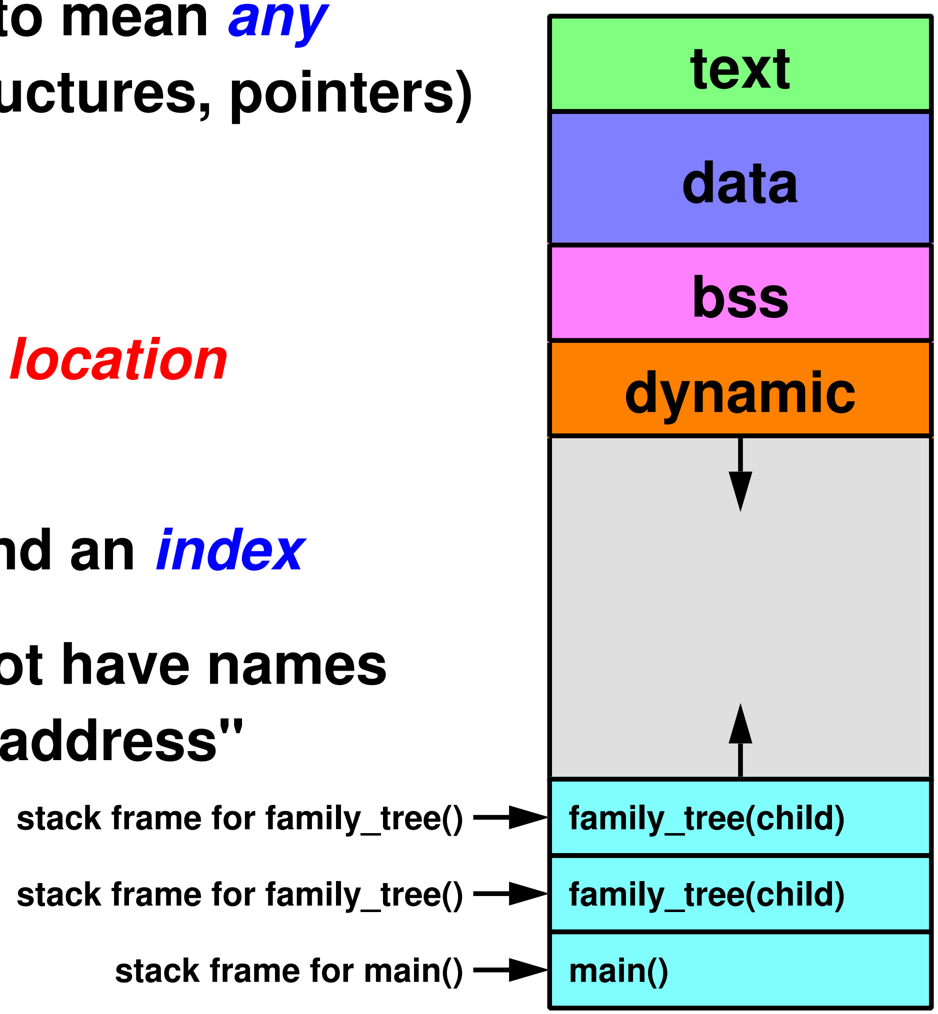
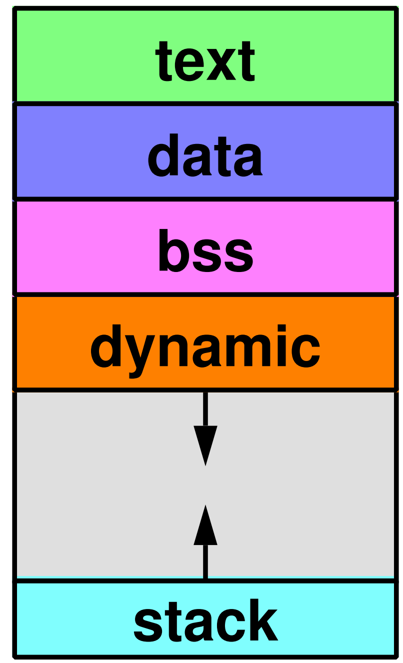
- Dynamically create objects do not have names
  - no variable can have a "heap address"
  - need *pointers*
- For objects that lives in the stack, same name is used for different object instances
  - *function arguments* and *local variables*



Modified Program

```
int nprimes;                    // in bss region
int *prime;                     // in bss region
int main(int argc, char *argv[]) { // in stack
  int i;                        // in stack
  int current = 2;              // in stack
  nprimes = atoi(argv[1]);
  prime = (int*)malloc(nprimes*sizeof(int));
  prime[0] = current;
  for (i=1; i<nprimes; i++) {
     ...
  }
  return(0);
}
```



- where do all the variables reside?
- what is `argv[1]` and why `atoi()`?
- what is `sizeof()`?
- what does `malloc()` do?

1.3 A Simple OS

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- ***Managing Processes***
- Loading Program Into Processes
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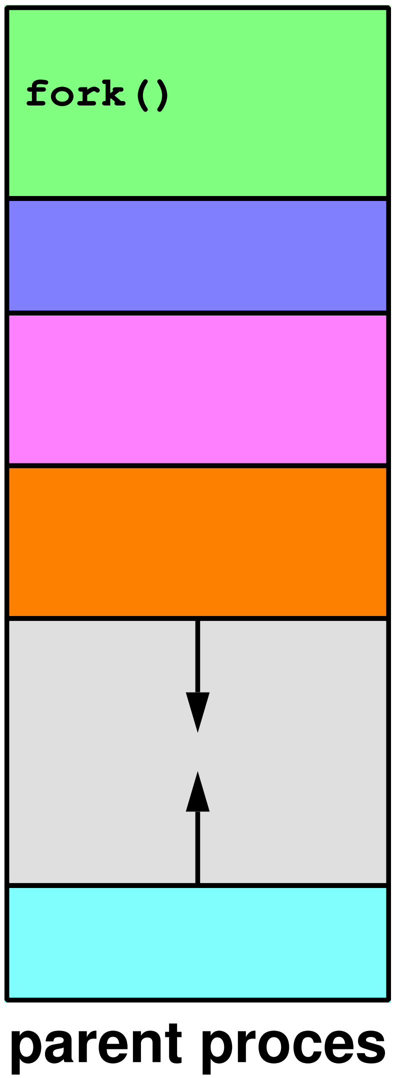
Program Execution

- With abstraction, comes an interface / API
  - for processes
    - `fork()`, `exit()`, `wait()`, `exec()`
      - it's very important to understand ***what they do exactly*** because you will implement them in kernel assignments

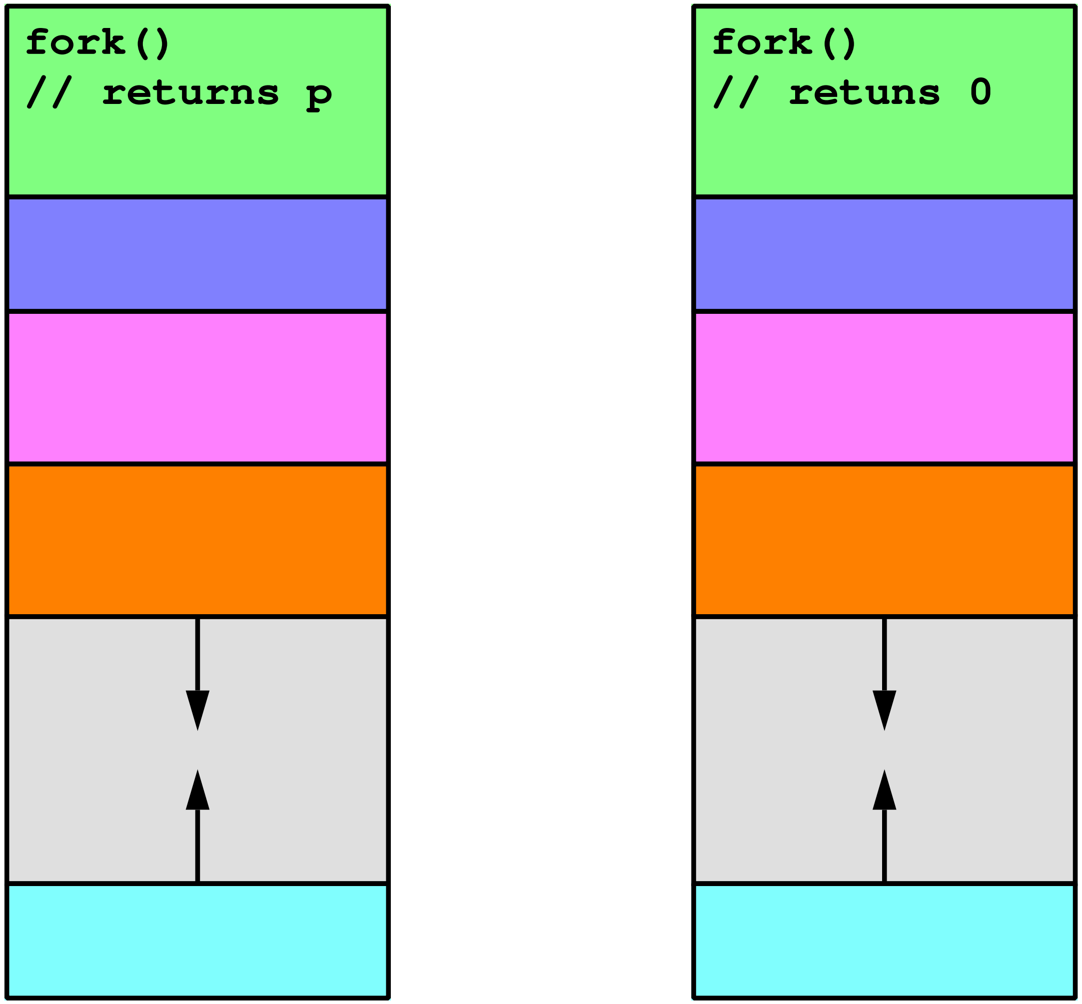
Creating a Process

- Creating a process is deceptively simple
  - make a copy of a process (the parent process)
    - `pid_t fork(void)`
    - the process where `fork()` is called is the *parent* process
    - the copy is the *child* process
    - in a way, `fork()` returns twice
      - once in the parent, the returned value is the *process ID (PID)* of the child process
      - once in the child, the returned value is 0
      - a PID is 16-bit long
  - this is the *only* way to create a process
- Making a copy of the entire address space can be expensive
  - Ch 7 shows speed up tricks
  - e.g., text segment is read-only so parent and child can share it
- Example: relationship between a shell (i.e., a command interpreter, such as `/bin/tcsh`) and `/bin/ls`

Creating a Process: Before



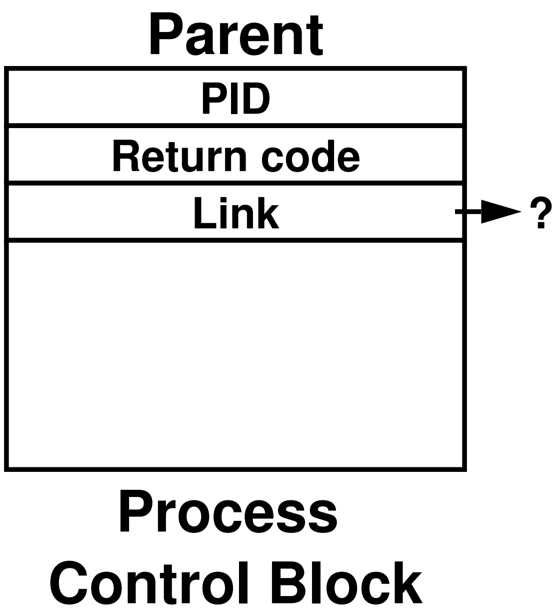
Creating a Process: After



parent proces

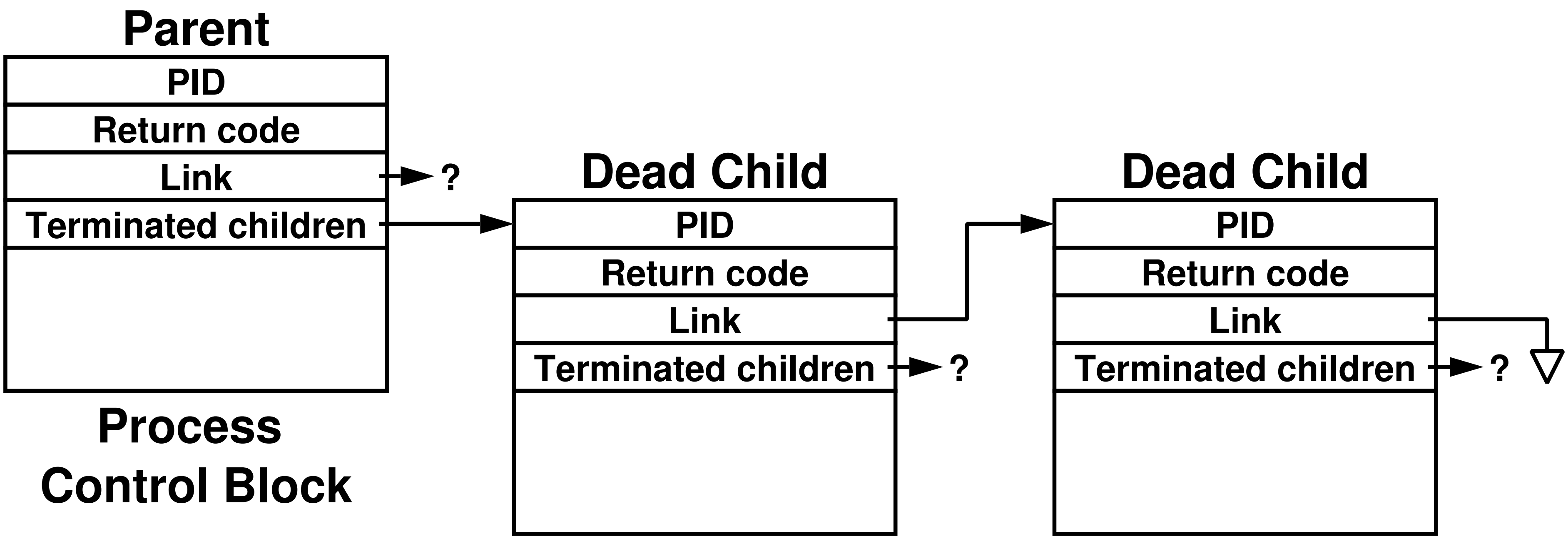
child proces
(pid = p)

Process Control Blocks



- ***Process Control Block (PCB)*** **is a kernel data structure**
  - **pretty much every field is unsigned**
  - **return code (when a process dies) is 8-bit long**
    - **so that the parent process can know what happened to child**
  - **the "Link" field points to the next PCB**
    - **but, the next PCB in what list?**

Process Control Blocks



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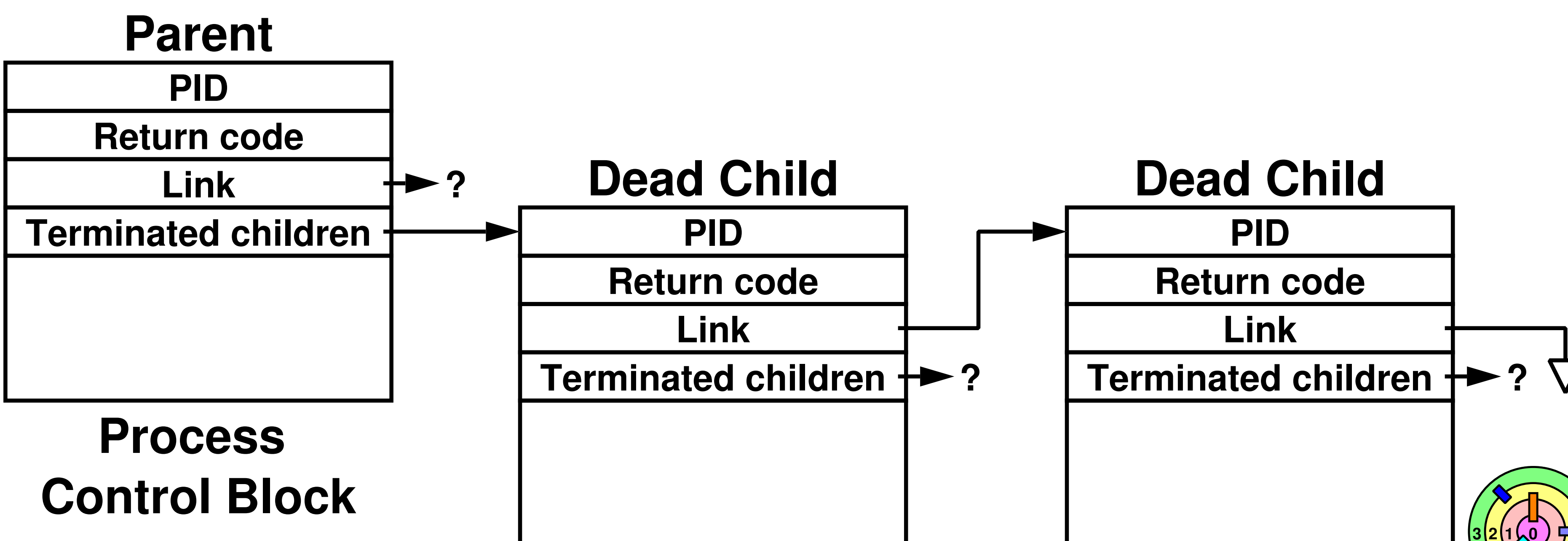
  - the "Link" field points to the next PCB
    - but, the next PCB in what list?
- **Above is *not* a real implementation (just an example)**

The `exit()` System Calls

- The `exit()` system call

```
void exit(int status)
```

  - your process can call `exit(n)` to self-terminate
    - set `n` to be the "exit/return code" of this process
    - this sytem call does not return (your process will die inside the kernel)



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- Where does the "primes" program go after it executes the "`return(0)`"?
  - it returns to a "startup" function
  - the code of the "startup" function is simply:

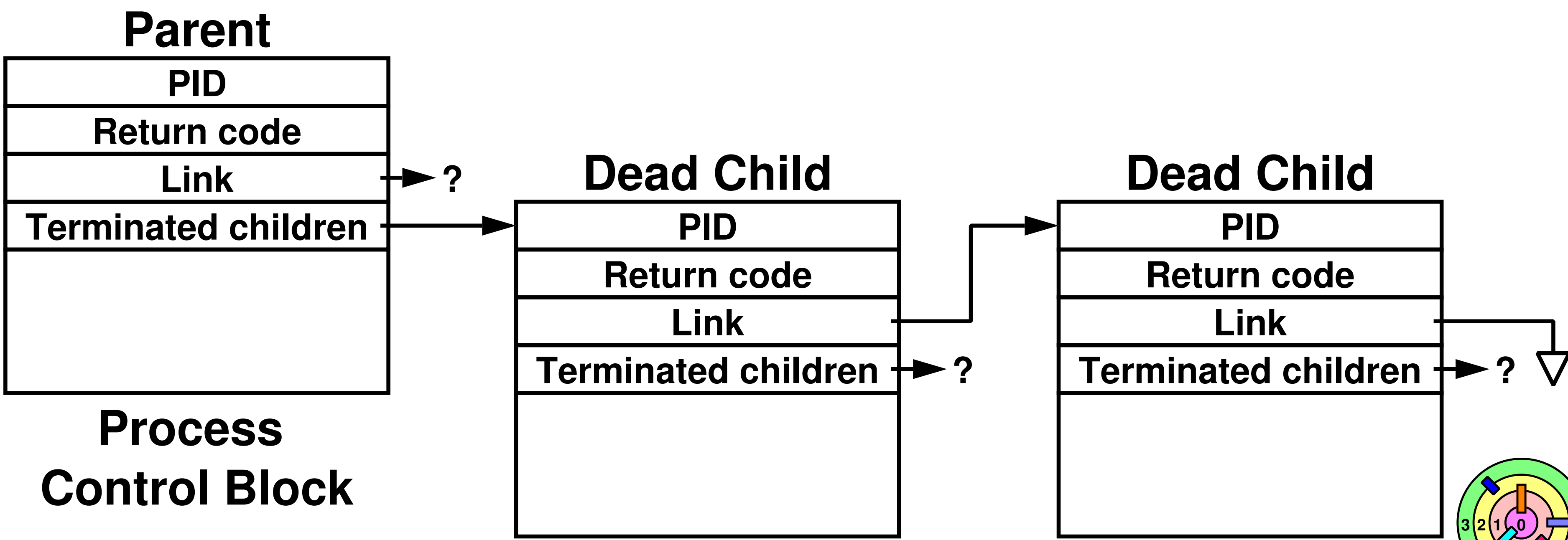
```
exit(main());
```

The `wait()` System Calls

- The `wait()` system call

```
pid_t wait(int *status)
```

  - your process can call `wait()` to wait for *any* child process to die
    - returns the PID of a dead child process where `(*status)` is the exit/return code of the corresponding child process
      - if there are more than one dead child processes, one of them will be *chosen at random*



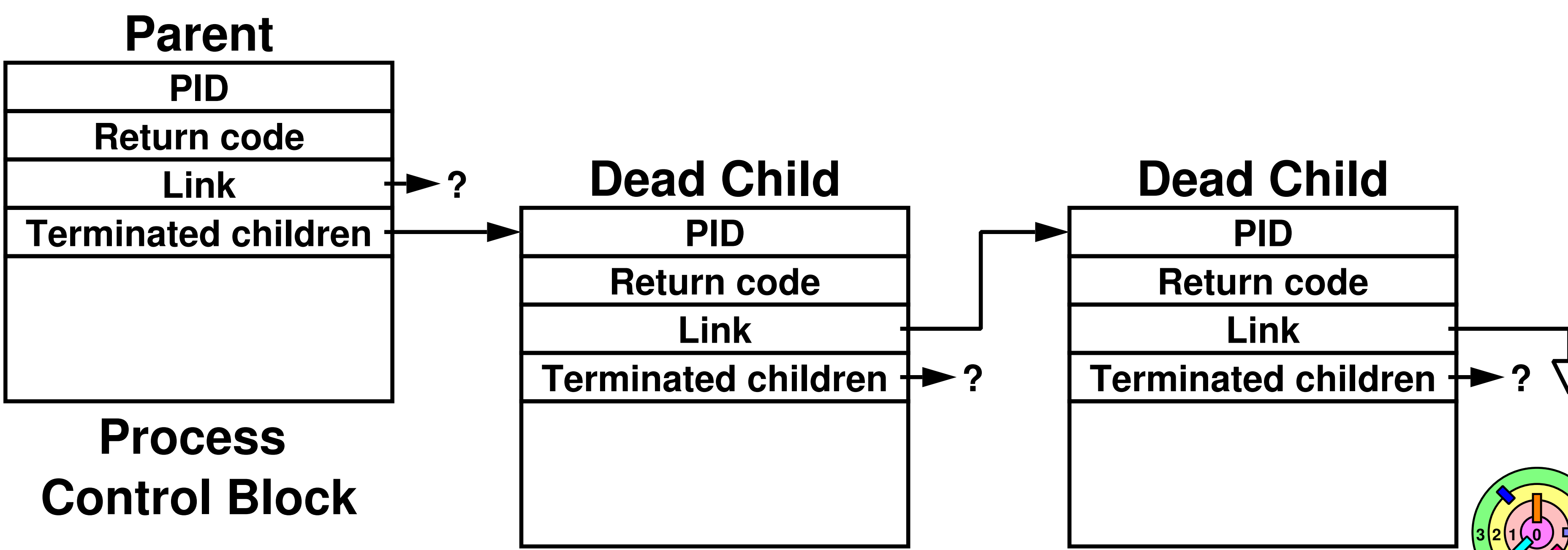
Process Control Block

The `wait()` System Calls

- The `wait()` system call

```
pid_t wait(int *status)
```

  - your process can call `wait()` to wait for *any* child process to die
    - it's a *blocking call*, i.e., the calling process gets suspended inside the kernel if this call cannot return yet



Fork and Wait

```
short pid;
if ((pid = fork()) == 0) {
  /* some code is here for the child to execute */
  exit(n);
} else {
  int ReturnCode;
  while(pid != wait(&ReturnCode))
     ;
  /* the child has terminated with ReturnCode as
     its return code */
}
```

- e.g., this is the first step when `/bin/tcsh` forks `/bin/ls`
- what does `exit(n)` do other than copying `n` into PCB?
  - least significant 8-bits of `n`
- what happens when `main()` calls `return(n)`?
  - eventually, `exit(n)` will be invoked
- `pid_t wait(int *status)` is a ***blocking call***
  - it reaps dead child processes ***one at a time***
- parent and child are the same "program" here!

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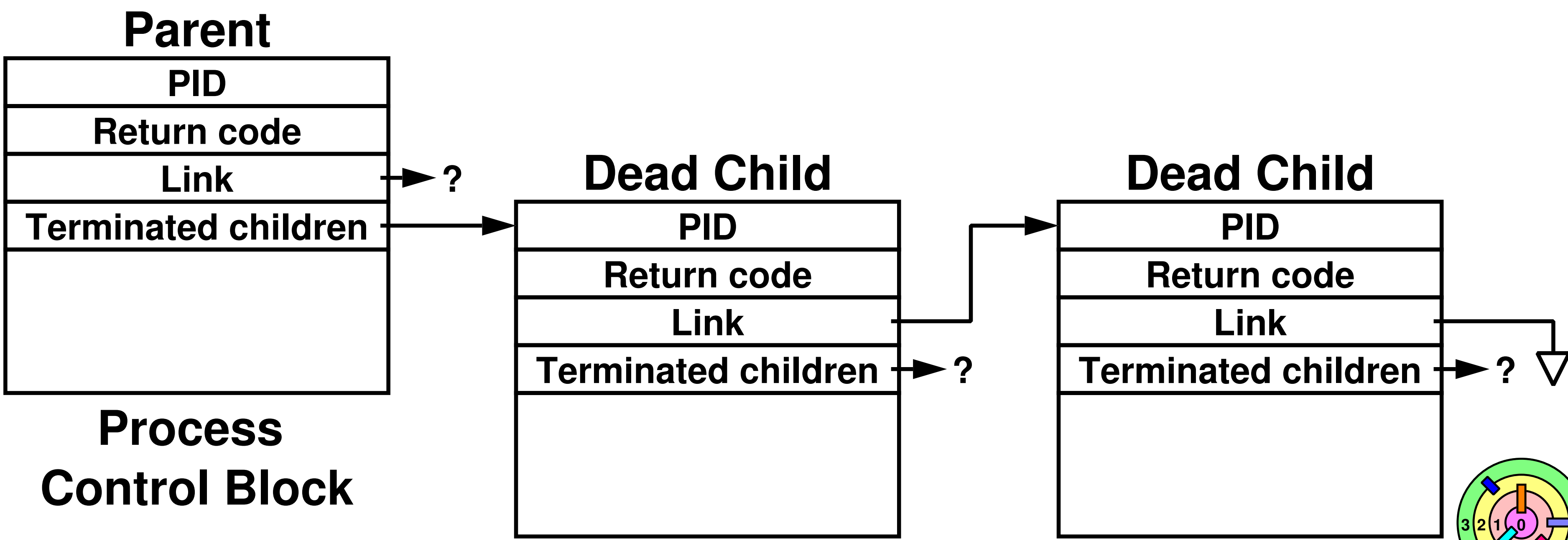

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      ;
  /* the child has terminated with ReturnCode as
      its return code */
}
```

- What if you don’t want to write your code this way?
  - you can write any code you want, you just shouldn’t expect your code to work if you write weird code
  - you need to understand exactly what these system calls do and use them appropriately
    - if you do something weird, the OS will try to satisfy your request, but may end up with results you don’t expect

Process Termination Issues

- PID is only 16-bits long
  - OS must not reuse PID too quickly or there may be ambiguity
- When `exit()` is called, the OS must not free up PCB too quickly
  - parent needs to get the return code
  - it's okay to free up everything else (such as address space)
- Solutions for both is for the terminated child process to go into a *zombie* state
  - only after `wait()` returned with the child's PID can the PID be reused and the PCB can be freed up
  - but what if the parent calls `exit()` while the child is in the zombie state?
    - process 1 (the process with PID=1) inherits all the children of this parent process
      - this is known as *"reparenting"*
    - process 1 keeps calling `wait()` to reap the zombies

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Loading Programs Into Processes

- How do you run a program?
  - make a copy of a process
    - any process
  - replace the child process with a new one
    - wipe out the child process
      - not everything, some stuff survives this (i.e., won't get destroyed)
      - definitely need a *new address space* since we will be running a different program
    - using a family of system calls known as *exec*
  - kind of a waste to make a copy in the first place
    - but it's the only way
    - also, the OS does not know if the reason the parent process calls `fork()` is to run a new program or not

Exec

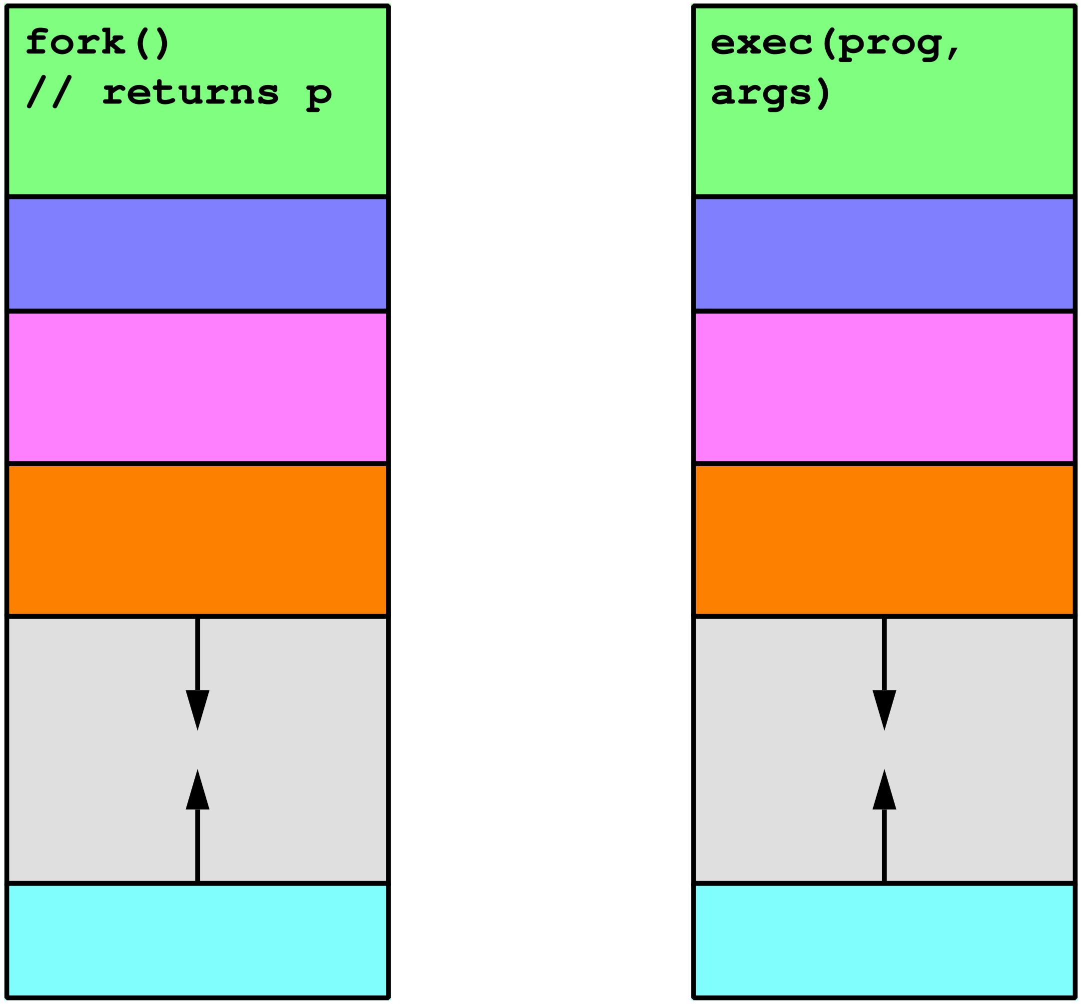
```
int pid;
if ((pid = fork()) == 0) {
  /* we'll discuss what might take place before
     exec is called */
  execl("/home/bc/bin/primes", "primes", "300", 0);
  exit(1);
}
/* parent continues here */
while(pid != wait(0)) /* ignore the return code */
  ;
```

- what does `execl()` do?
  - "man execl" says:

    ```
    int execl(const char *path,
              const char *arg, ...);
    ```

  - isn't "primes" in the 2nd argument kind of redundent?
  - what's up with "..."?
    - this is called *"varargs"* (similar to `printf()`)

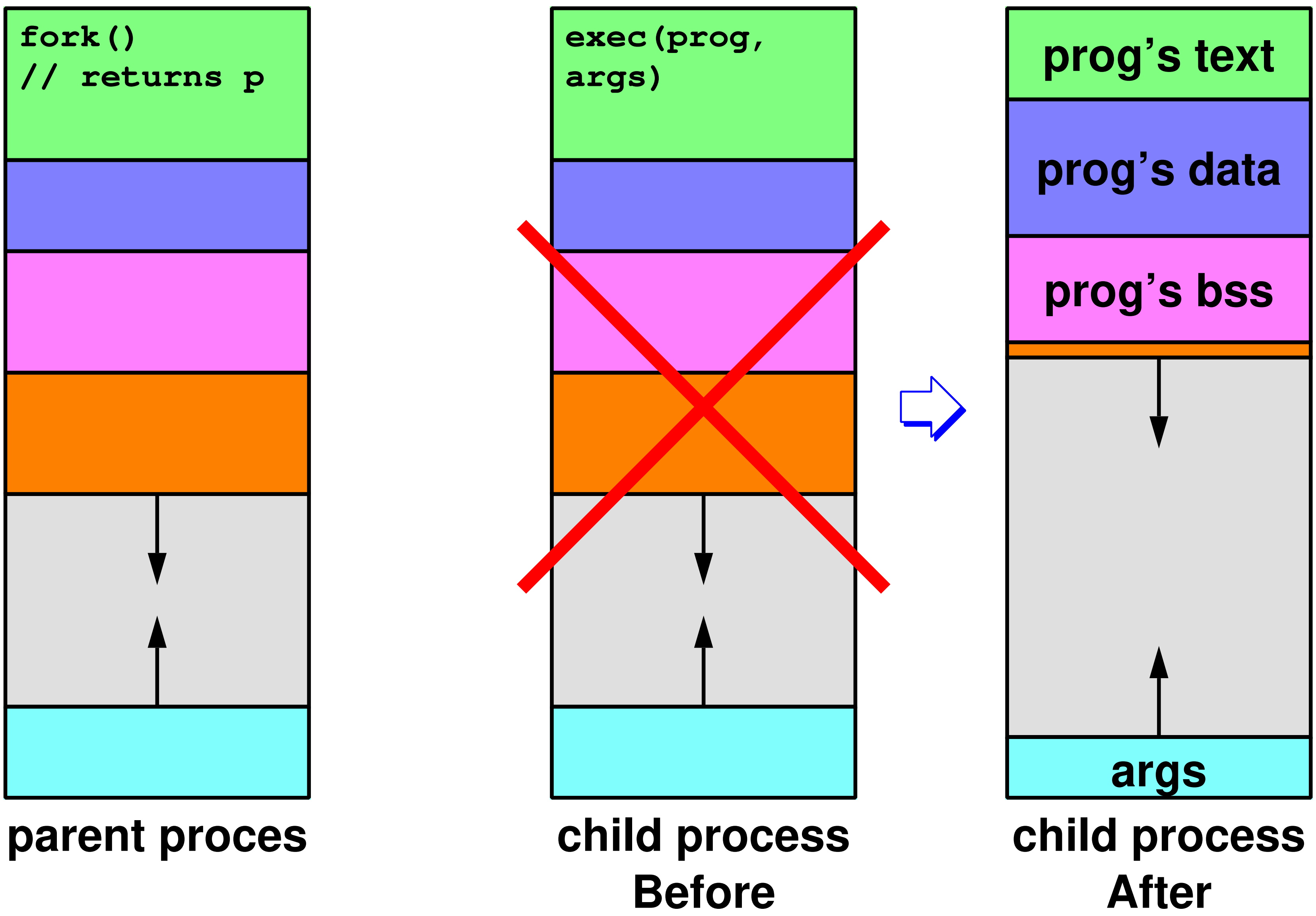
Loading a New Image



parent proces

child process
Before

Loading a New Image



Exec

```
int pid;
if ((pid = fork()) == 0) {
  execl("/home/bc/bin/primes", "primes", "300", 0);
  exit(1);
}
while(pid != wait(0)) /* ignore the return code */
  ;
```

```
% primes 300
```

- Your login shell forks off a child process, load the primes program on top of it, wait for the child to terminate
  - the same code as before
  - `exit(1)` would get called if somehow `execl()` returned
    - if `execl()` is successful, it cannot return since the code is *gone* (i.e., the code segment has been replaced by the code segment of "`primes`")

Put It All Together

Parent
(shell)

```
fork()
```

```
int pid;
if ((pid = fork()) == 0) {
  execl("/home/bc/bin/primes",
        "primes", "300", 0);
  exit(1);
}
while(pid != wait(0))
  ;
```

Applications

OS

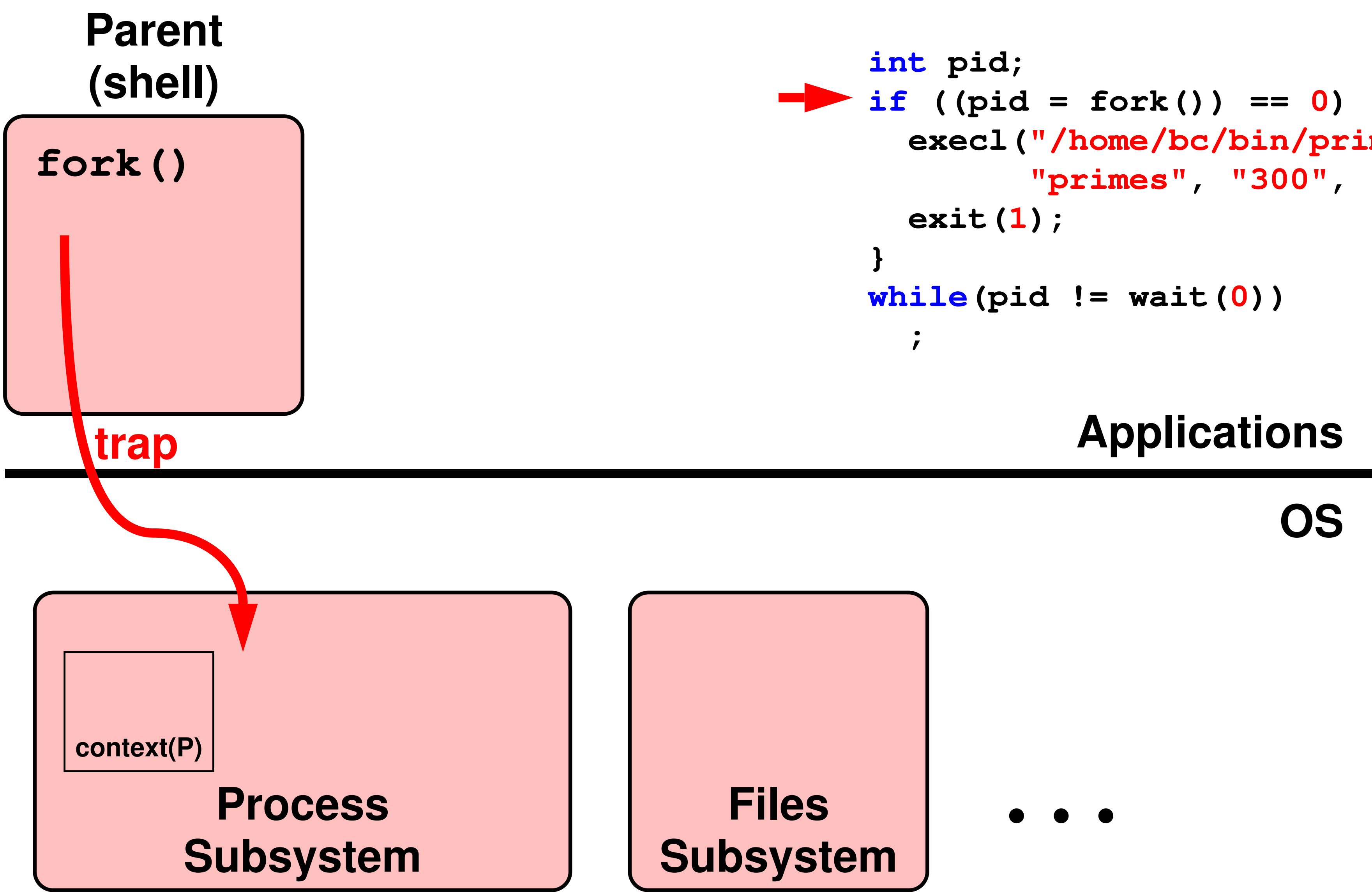
Process Subsystem

Files Subsystem

. . .

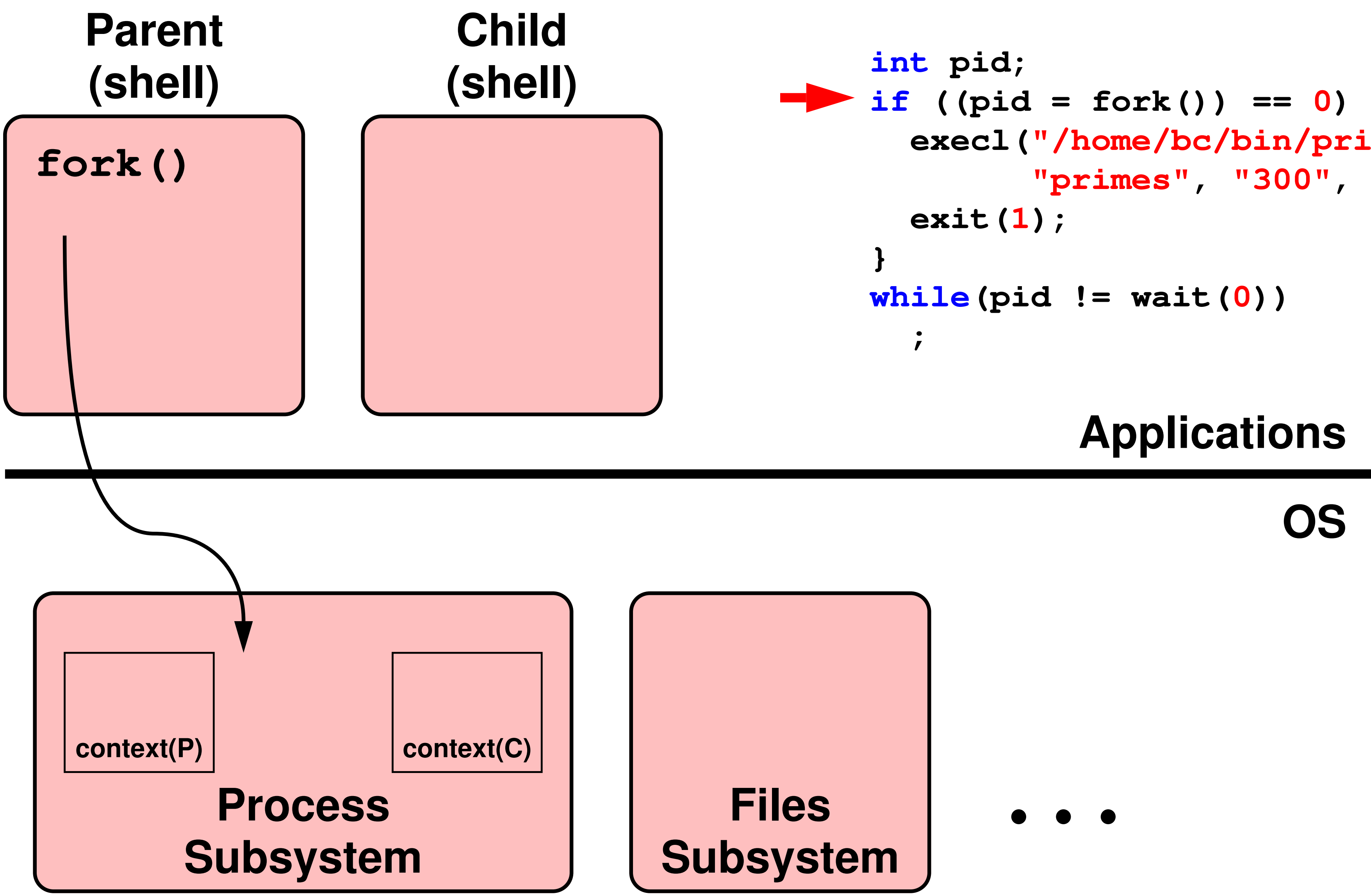
Put It All Together

```
int pid;
if ((pid = fork()) == 0) {
  execl("/home/bc/bin/primes",
        "primes", "300", 0);
  exit(1);
}
while(pid != wait(0))
  ;
```



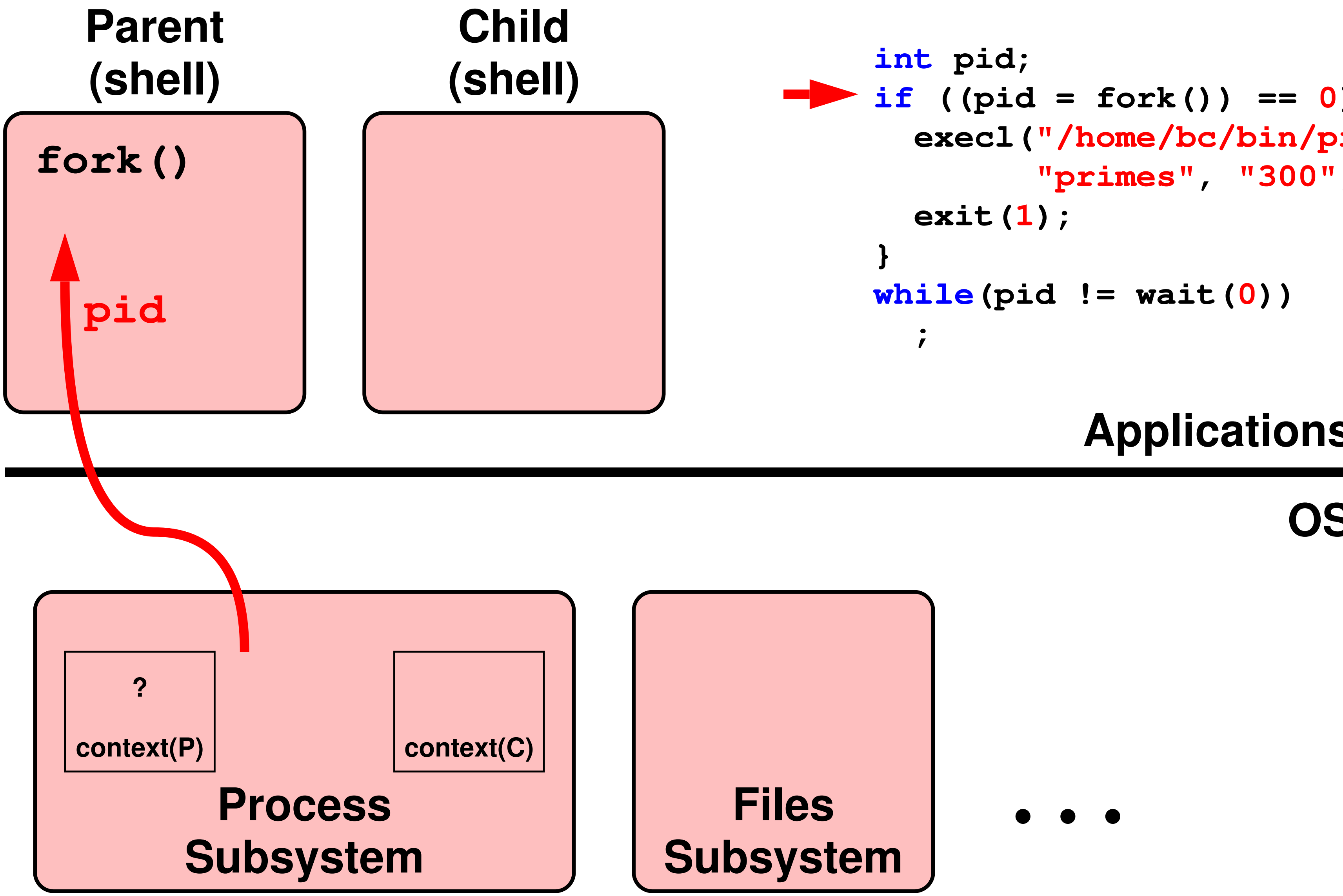
- Where do you keep "context"?

Put It All Together




```
int pid;
if ((pid = fork()) == 0) {
  execl("/home/bc/bin/primes",
        "primes", "300", 0);
  exit(1);
}
while(pid != wait(0))
  ;
```

Put It All Together




```
int pid;
if ((pid = fork()) == 0) {
  execl("/home/bc/bin/primes",
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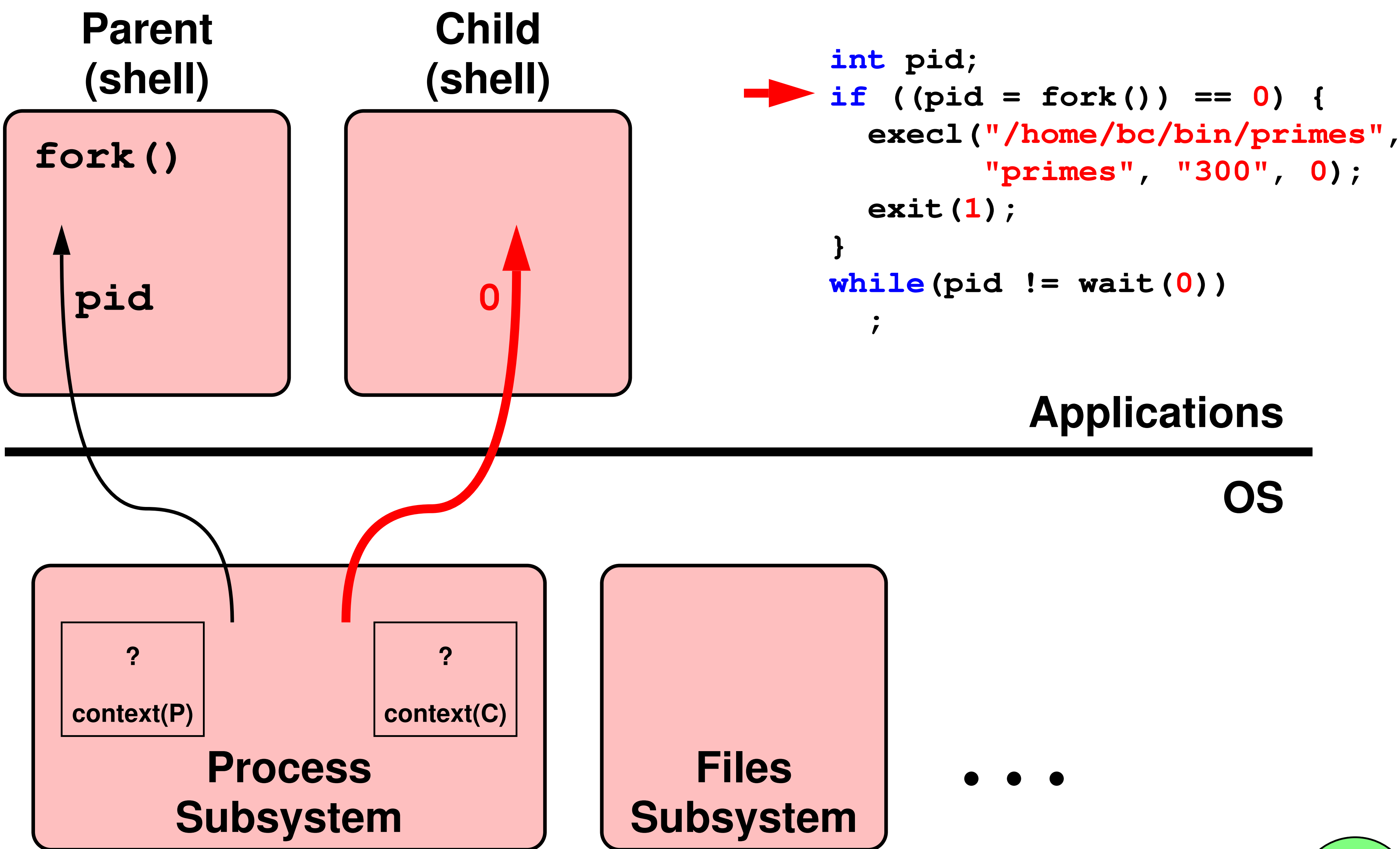
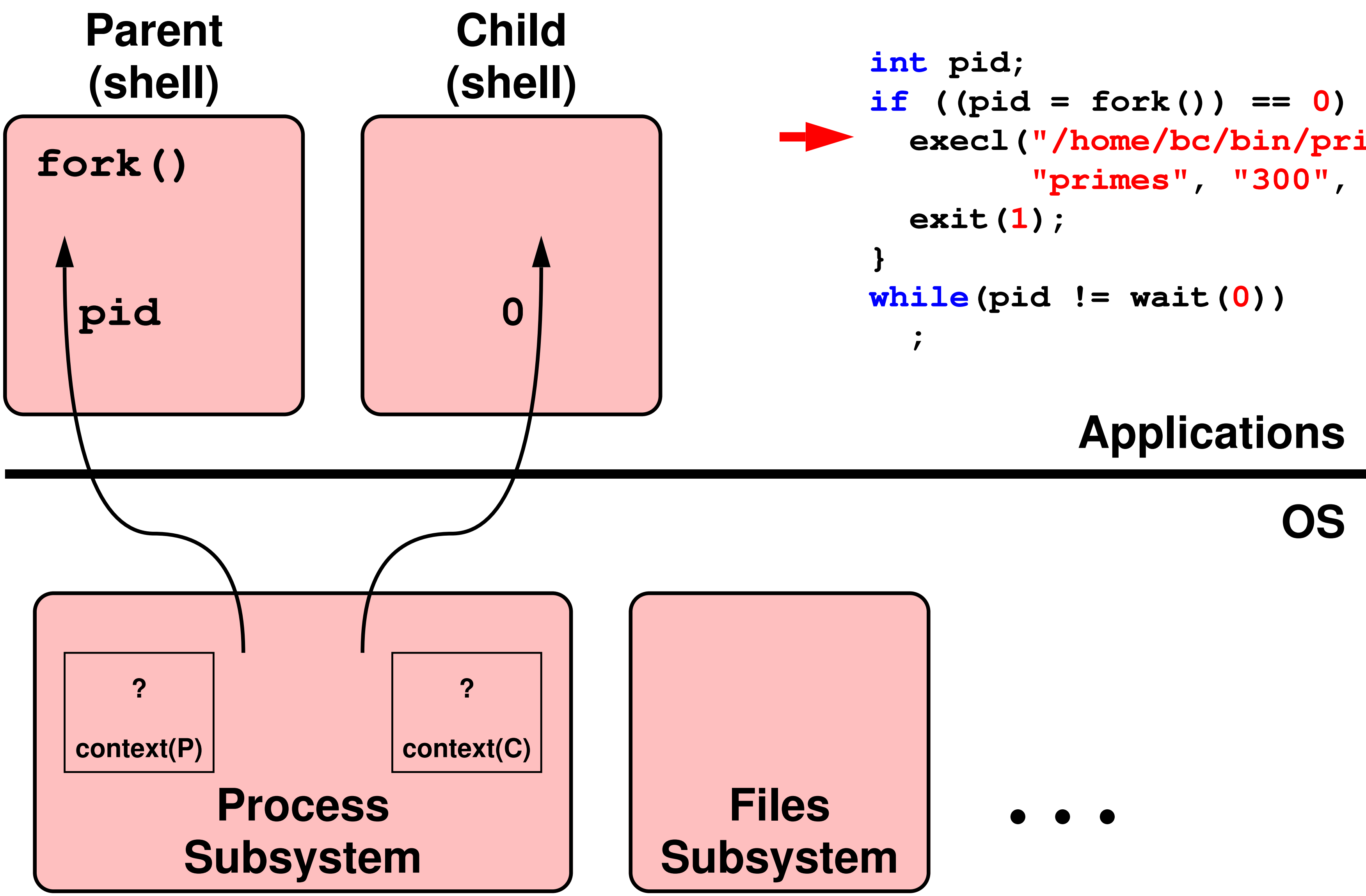
  exit(1);
}
while(pid != wait(0))
  ;
```

Put It All Together




```
int pid;
if ((pid = fork()) == 0) {
  execl("/home/bc/bin/primes",
        "primes", "300", 0);
  exit(1);
}
while(pid != wait(0))
  ;
```

Put It All Together




```c
int pid;
if ((pid = fork()) == 0) {
  execl("/home/bc/bin/primes",
        "primes", "300", 0);
  exit(1);
}
while(pid != wait(0))
  ;
```

Put It All Together

Parent (shell)

`fork()`

Child (shell)

`execl()`

```
int pid;
if ((pid = fork()) == 0) {
  execl("/home/bc/bin/primes",
        "primes", "300", 0);
  exit(1);
}
while(pid != wait(0))
  ;
```

Applications

OS

?

context(P)

?

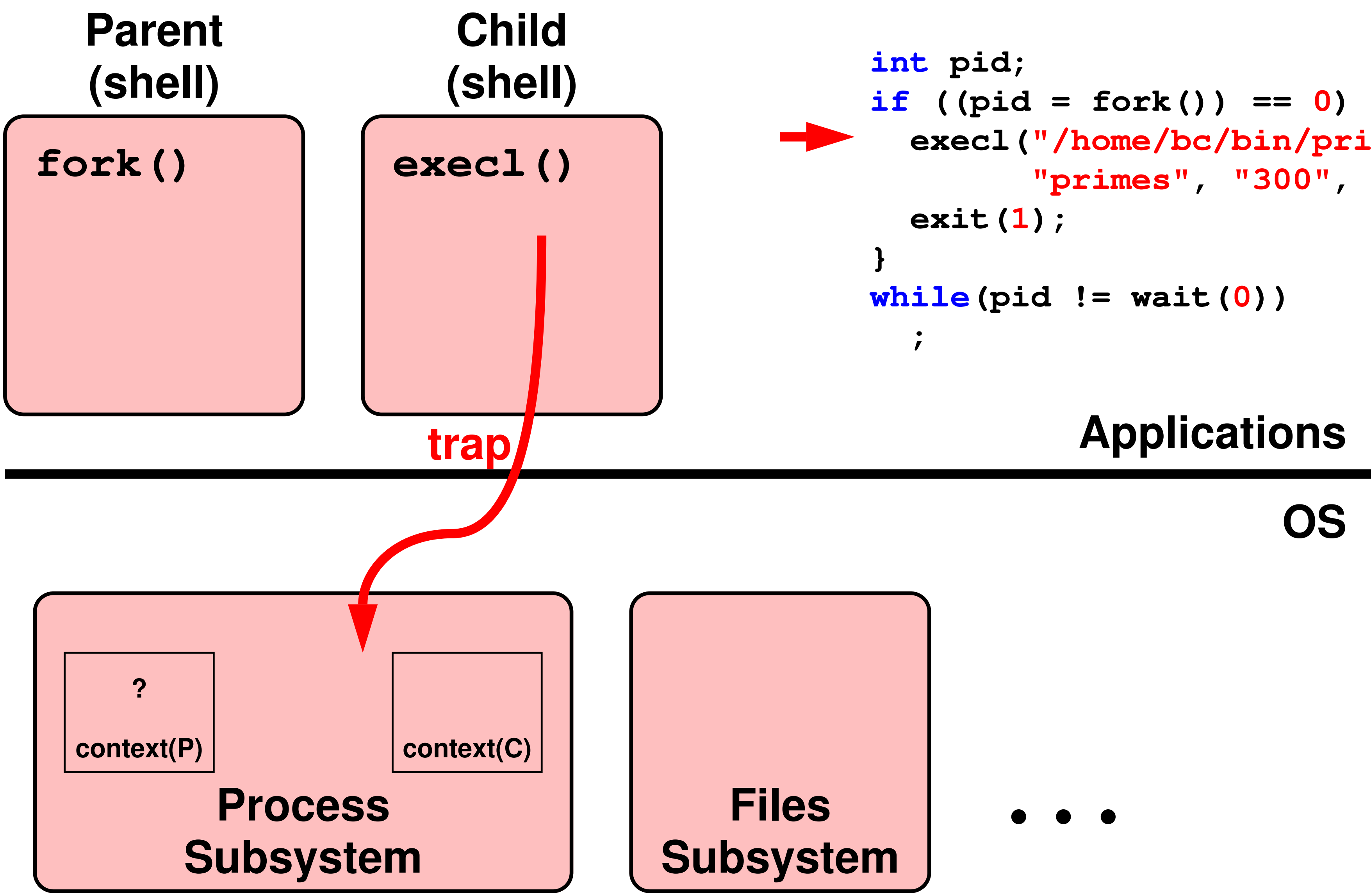
context(C)

Process Subsystem

Files Subsystem

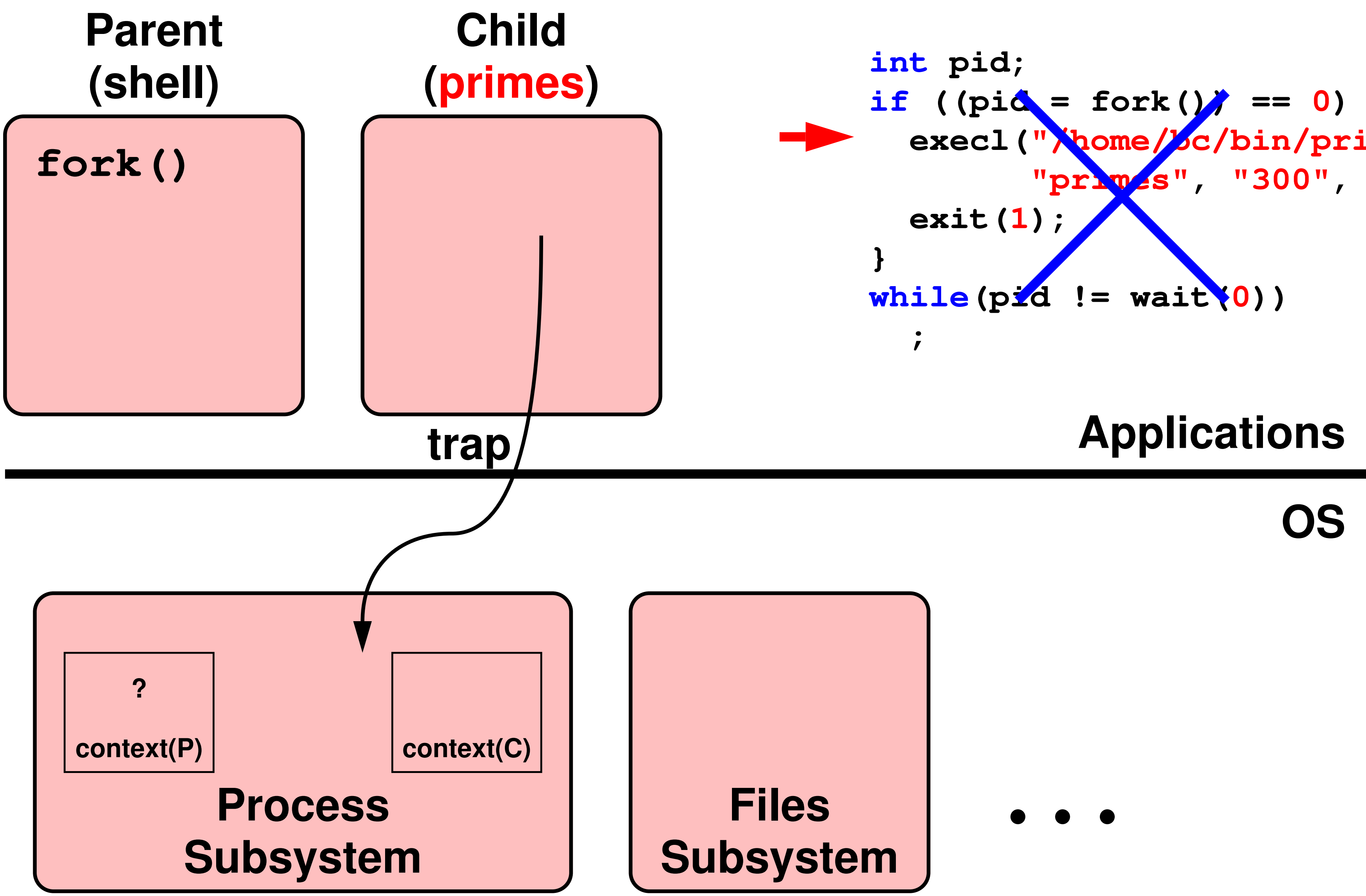
. . .

Put It All Together




```
int pid;
if ((pid = fork()) == 0) {
  execl("/home/bc/bin/primes",
        "primes", "300", 0);
  exit(1);
}
while(pid != wait(0))
  ;
```

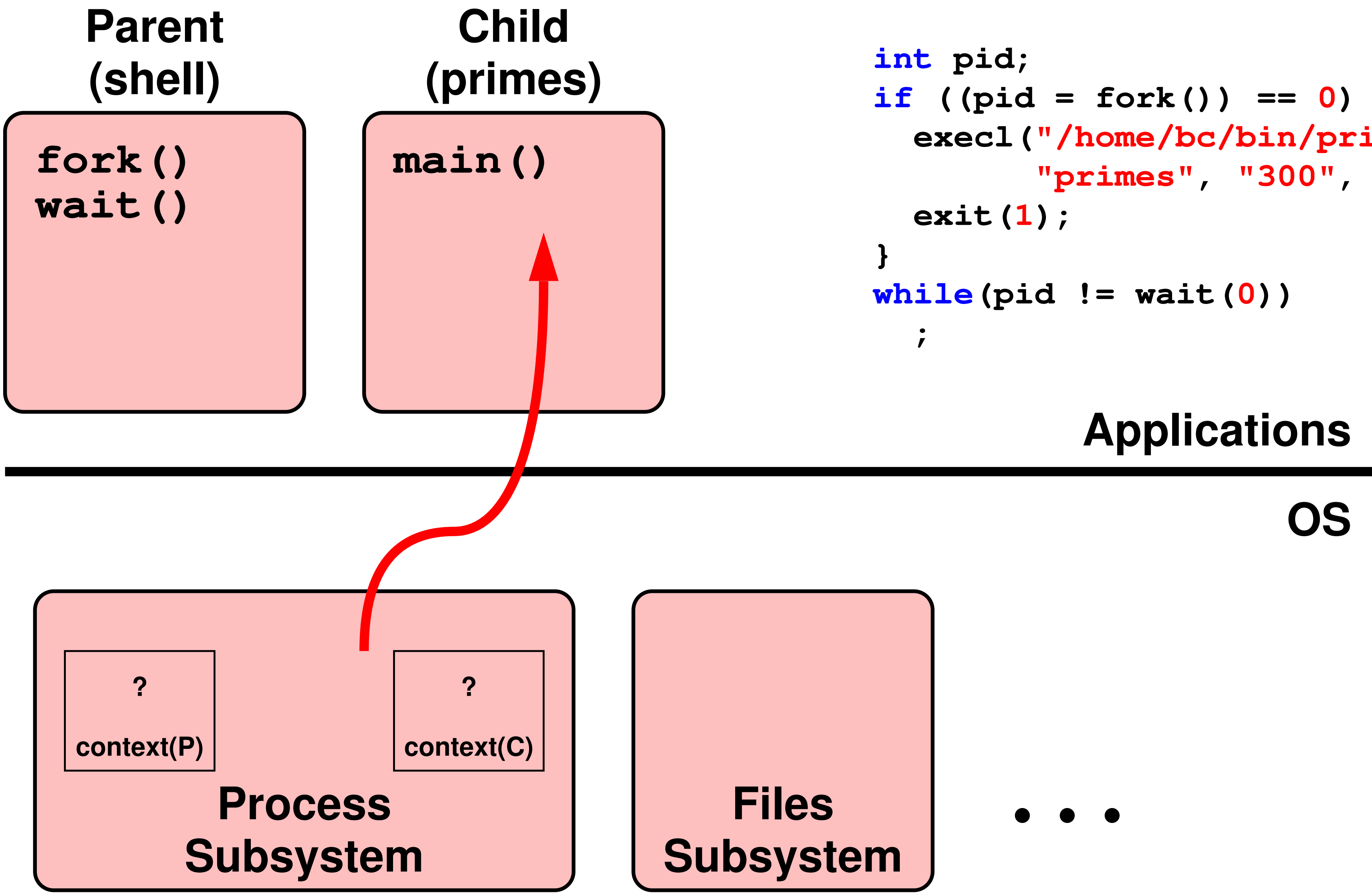
Put It All Together




```
int pid;
if ((pid = fork()) == 0) {
  execl("/home/bc/bin/primes",
        "primes", "300", 0);
  exit(1);
}
while(pid != wait(0))
  ;
```

Put It All Together

```
int pid;
if ((pid = fork()) == 0) {
  execl("/home/bc/bin/primes",
        "primes", "300", 0);
  exit(1);
}
while(pid != wait(0))
  ;
```



Put It All Together

Parent (shell)

```
fork()
wait()
```

Child (primes)

```
int pid;
if ((pid = fork()) == 0) {
  execl("/home/bc/bin/primes",
        "primes", "300", 0);
  exit(1);
}
while(pid != wait(0))
  ;
```

Applications

OS

? context(P)

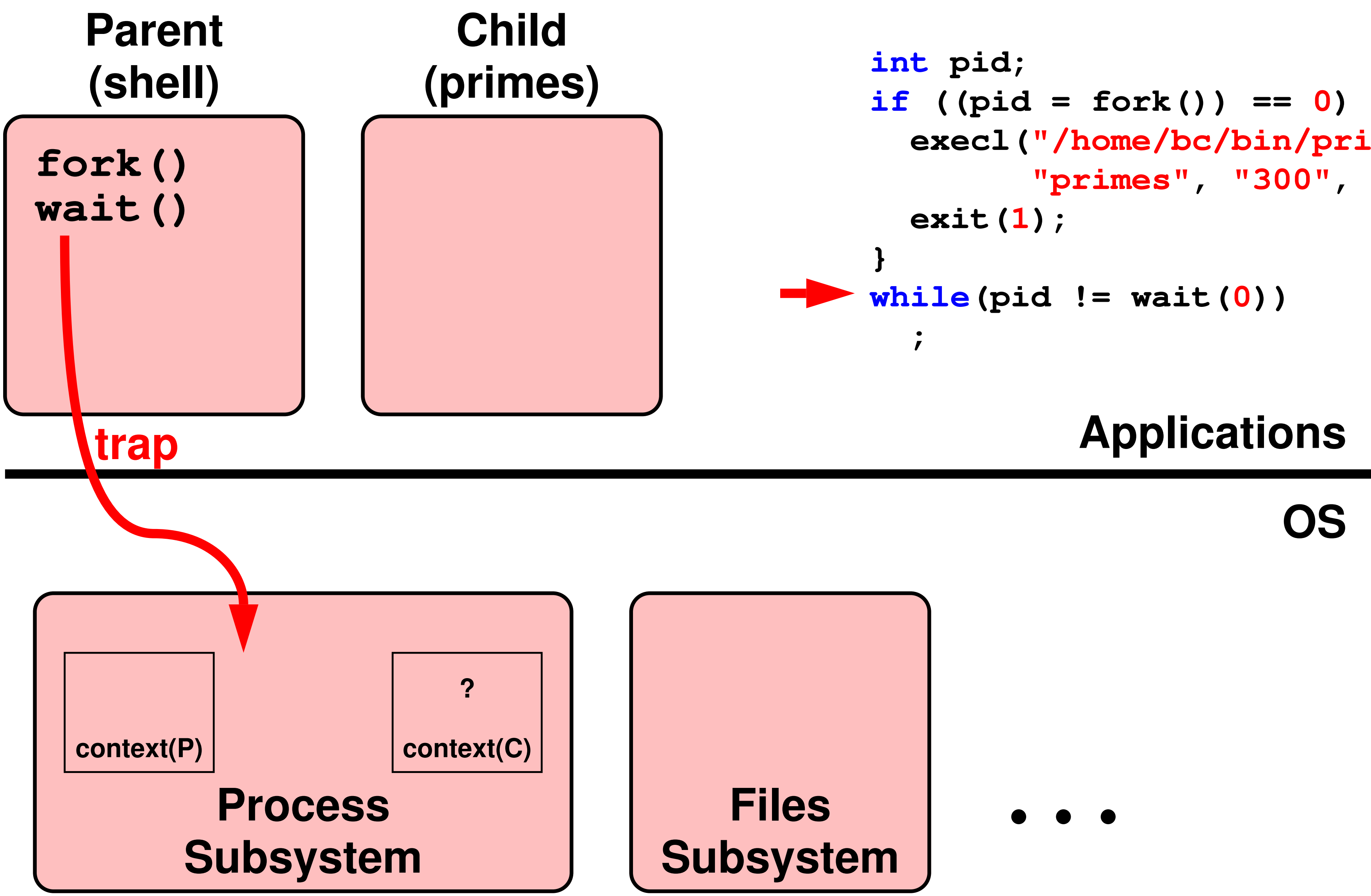
? context(C)

Process Subsystem

Files Subsystem

• • •

Put It All Together




```
int pid;
if ((pid = fork()) == 0) {
  execl("/home/bc/bin/primes",
        "primes", "300", 0);
  exit(1);
}
while(pid != wait(0))
  ;
```

Put It All Together

Parent (shell)

`fork()`
`wait()`

Child (primes)

`exit()`

```
int pid;
if ((pid = fork()) == 0) {
  execl("/home/bc/bin/primes",
        "primes", "300", 0);
  exit(1);
}
while(pid != wait(0))
  ;
```

trap

Applications

OS

context(P)

?

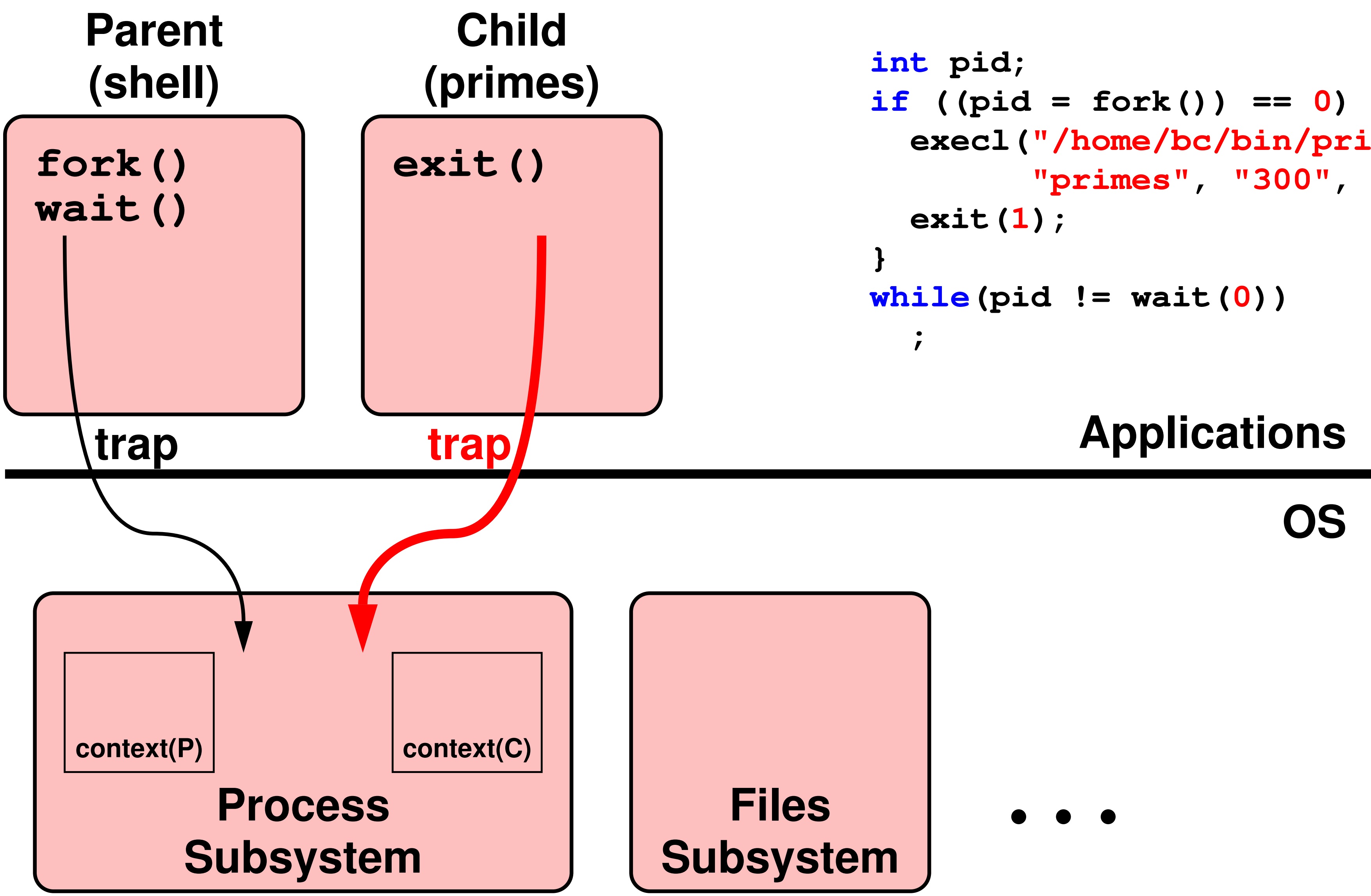
context(C)

Process Subsystem

Files Subsystem

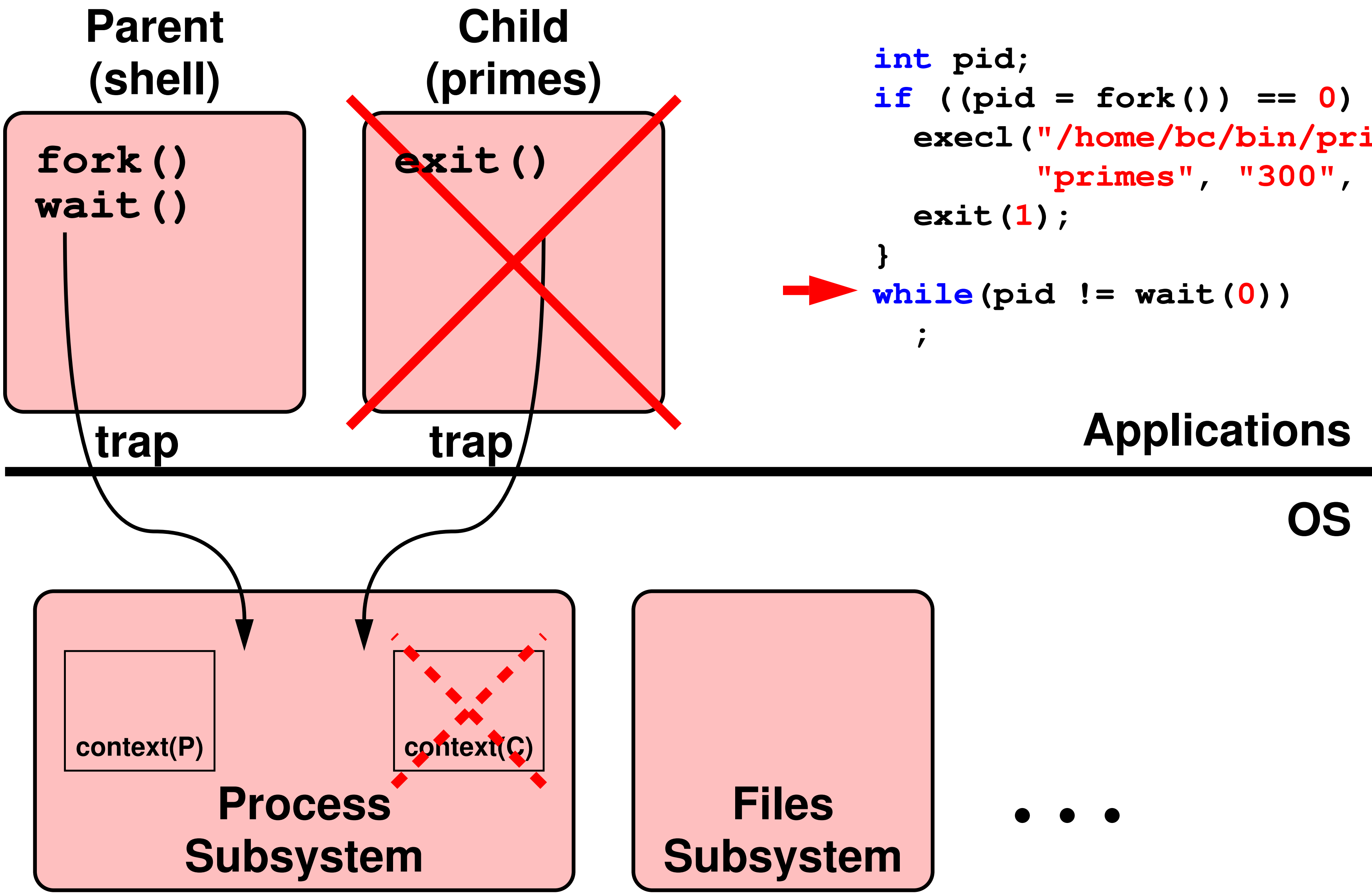
. . .

Put It All Together



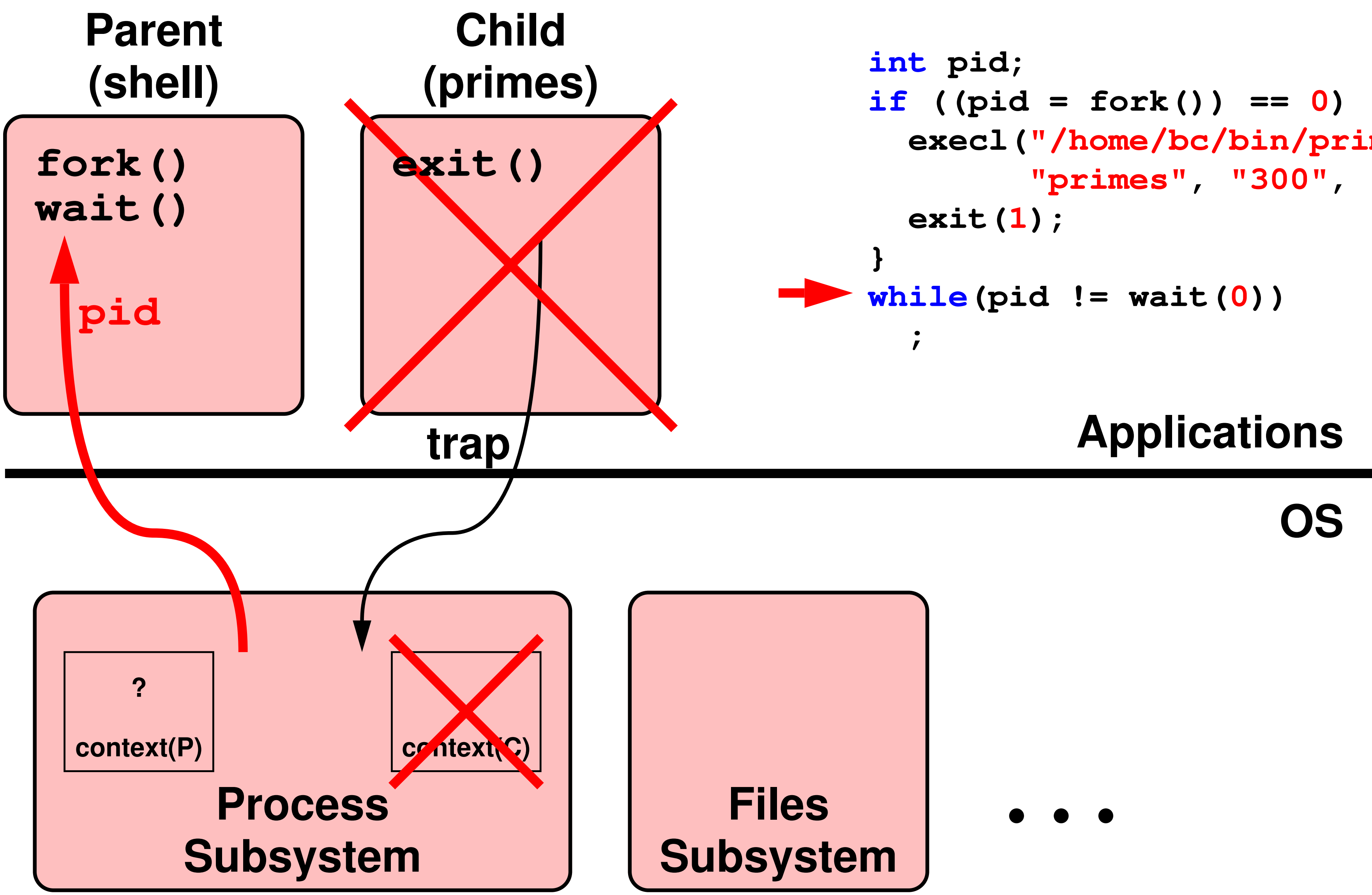

```
int pid;
if ((pid = fork()) == 0) {
  execl("/home/bc/bin/primes",
        "primes", "300", 0);
  exit(1);
}
while(pid != wait(0))
  ;
```

Put It All Together



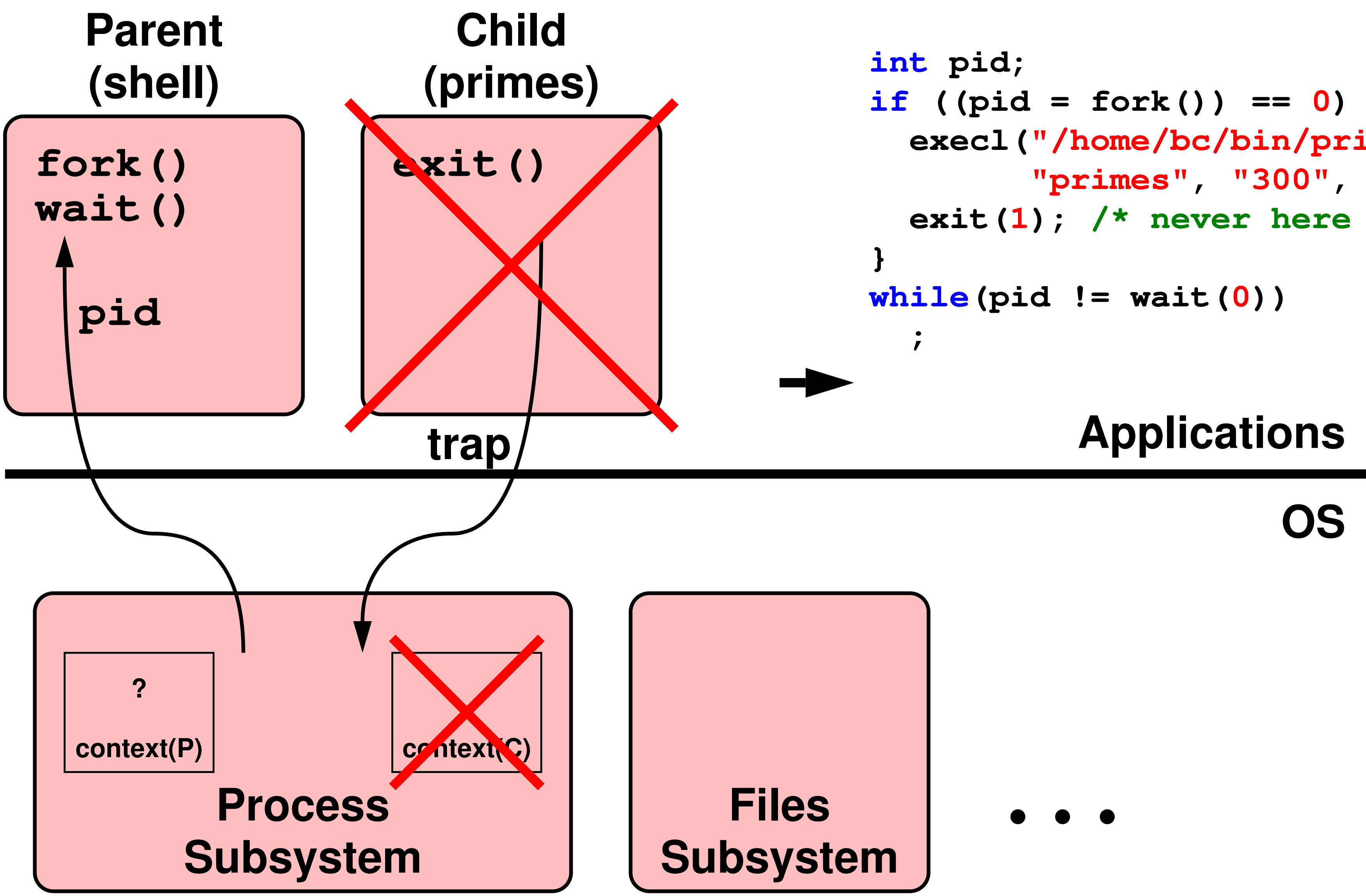

```
int pid;
if ((pid = fork()) == 0) {
  execl("/home/bc/bin/primes",
        "primes", "300", 0);
  exit(1);
}
while(pid != wait(0))
  ;
```

Put It All Together




```
int pid;
if ((pid = fork()) == 0) {
  execl("/home/bc/bin/primes",
        "primes", "300", 0);
  exit(1);
}
while(pid != wait(0))
  ;
```

Put It All Together




```
int pid;
if ((pid = fork()) == 0) {
  execl("/home/bc/bin/primes",
        "primes", "300", 0);
  exit(1); /* never here */
}
while(pid != wait(0))
  ;
```

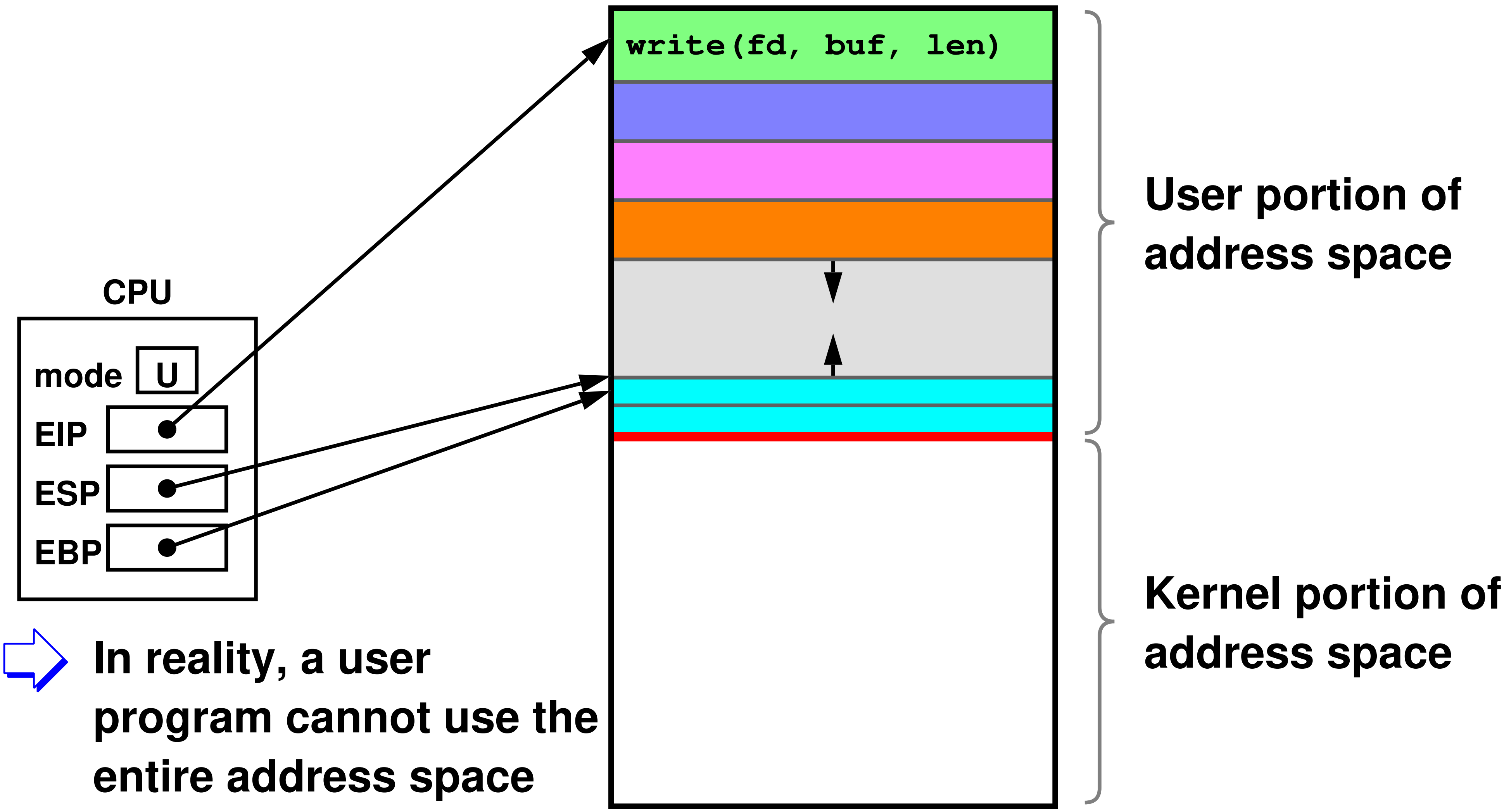
More On System Calls

- *Sole interface* between user and kernel
  - this interface (definition of system calls) is what distinguishes one OS from another
    - in this class, we focus on Sixth-Edition Unix
- Implemented as library routines that execute *"trap" machine instructions* to enter kernel
- Errors indicated by returning an invalid value
  - error code is in a global variable named `errno`

```
if (write(fd, buffer, bufsize) == -1) {
  // error!
  printf("error %d\n", errno);
  // see perror
}
```

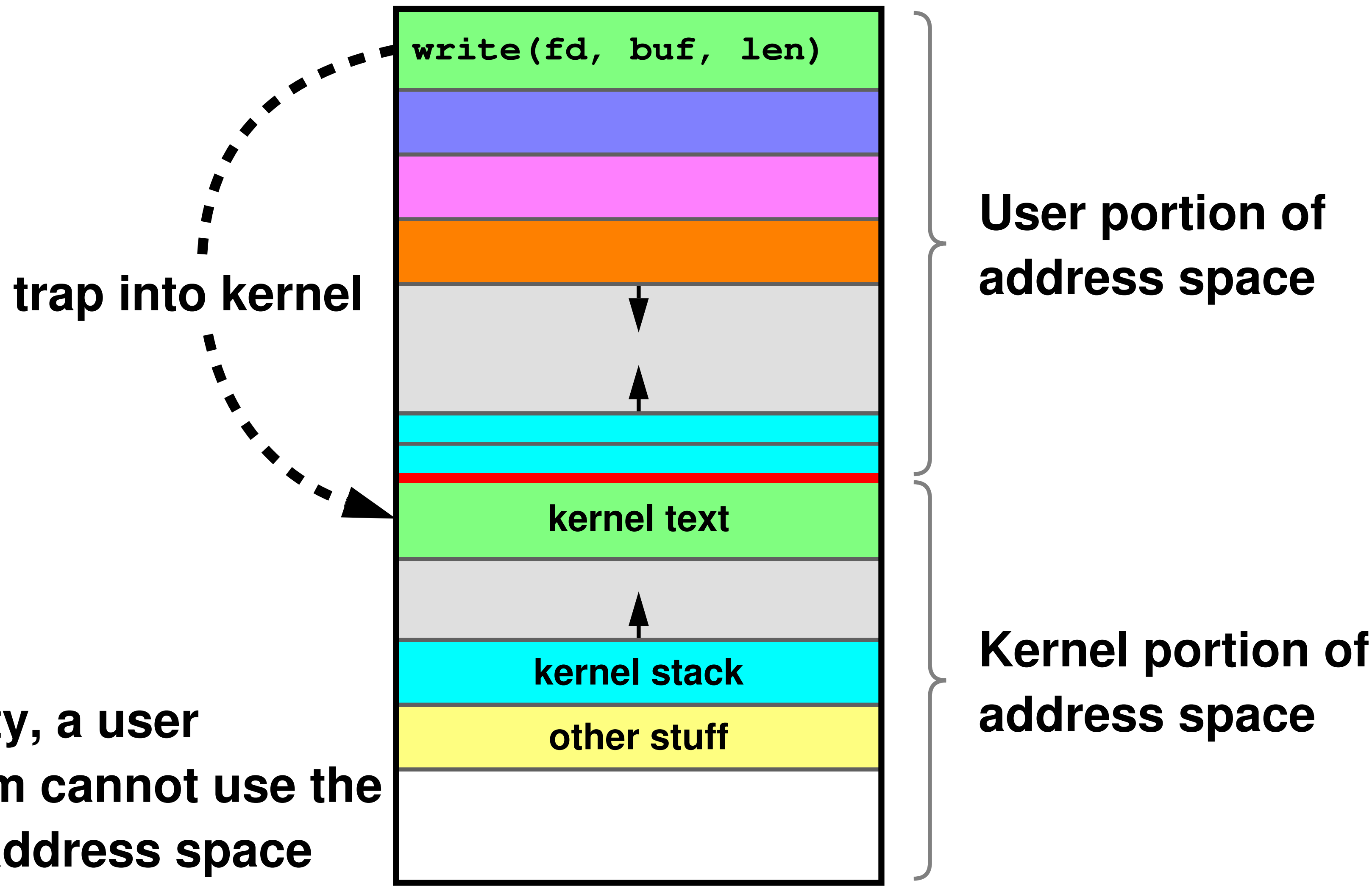
  - on Ubuntu: "`man 2 write`" or "`man -s 2 write`"
  - search man pages in all sections: "`man -k ...`"

System Calls



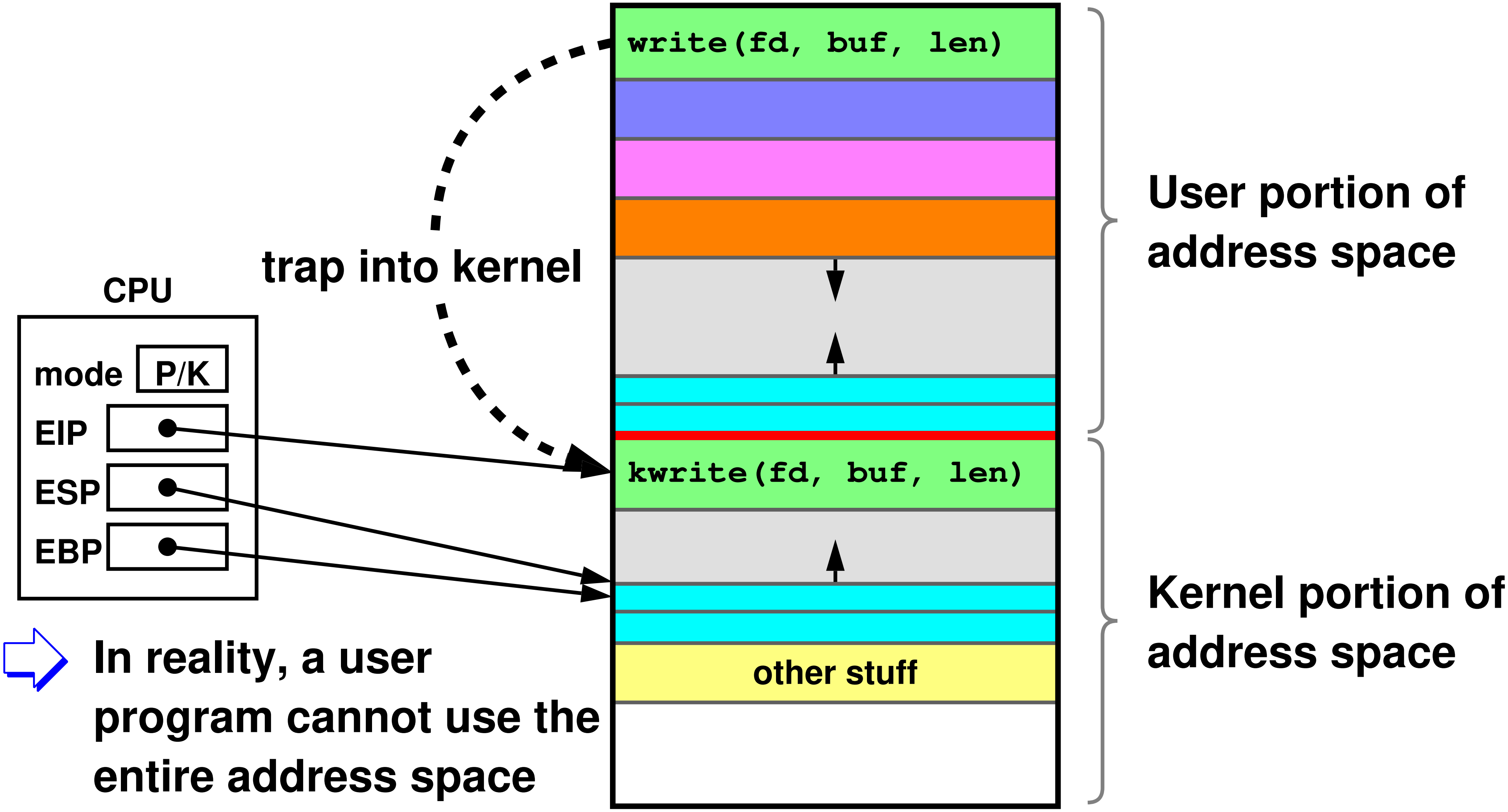
- In reality, a user program cannot use the entire address space

System Calls



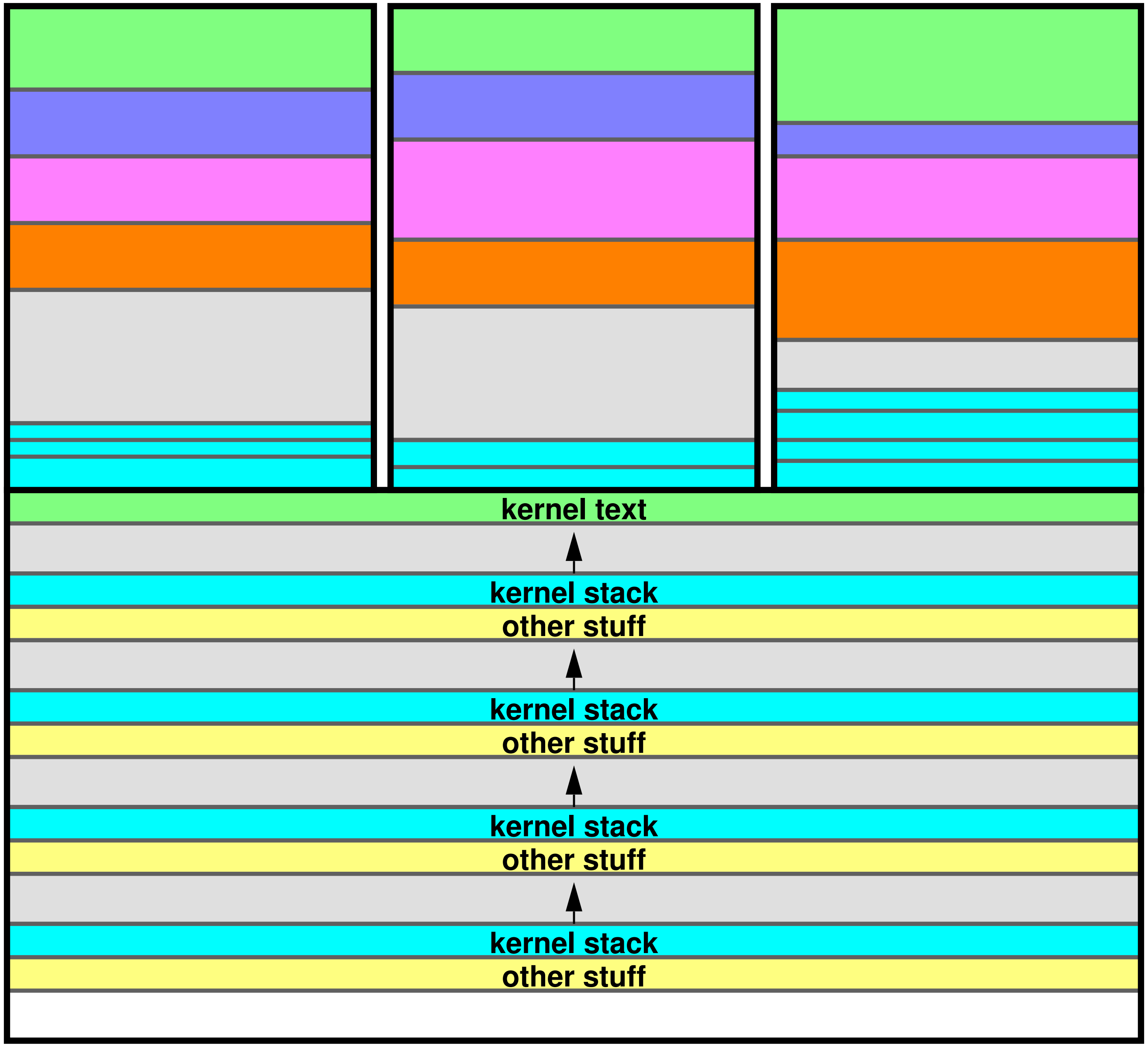
- In reality, a user program cannot use the entire address space
- Is this the same *"thread of execution"*?
  - is this the same process?

System Calls



- In reality, a user program cannot use the entire address space
- Is this the same *"thread of execution"*?
  - is this the same process?

Multiple Processes



- the same kernel spans across all user processes
  - although there are kernel-only processes as well (and they don't make system calls)
- process is just an abstraction
  - the kernel is very powerful

1.3 A Simple OS

- OS Structure
- Processes, Address Spaces, & Threads
- Managing Processes
- Loading Program Into Processes
- *Files*

Files

- Our "primes" program wasn't too interesting
  - it has no output!
  - cannot even verify that it's doing the right thing
  - other program cannot use its result
  - how does a process write to someplace *outside the process*?
- Files
  - abstraction of persistent data storage
  - means for fetching and storing data outside a process
    - including disks, another process, keyboard, display, etc.
    - need to *name* these different places
      - hierarchical naming structure
    - part of a process's *extended address space*
      - file "cursor position" is part of "execution context"
- The notion of a *file* is our Unix system's *sole abstraction* for this concept of "someplace outside the process"
  - modern Unix systems have additional abstractions

Naming Files

- Directory system
  - shared by all processes running on a computer
    - although each process can have a different view
    - Unix provides a means to restrict a process to a subtree
      - by redefining what "root" means for the process
  - name space is outside the processes
    - a user process provides the name of a file to the OS
    - the OS returns a *handle* to be used to access the file
      - after it has verified that the process is allowed *access* along the *entire path*, starting from root
    - user process uses the handle to read/write the file
      - avoid subsequent access checks

- *Using a handle* (which can be an index into a kernel array) to *refer to an object managed by the kernel* is an important concept
  - *handles* are essentially an *extension* to the process's *address space*
    - can even *survive execs!*

The File Abstraction

- A file is a simple array of bytes
- Files are made larger by writing beyond their current end
  - although you cannot *read* past the current end
- Files are named by paths in a naming tree
- File API
  - `open()`, `read()`, `write()`, `close()`
  - e.g., `cat`
- System calls on files are *synchronous* (unfortunately, Computer Science likes to use the same word to mean different things)
  - here, it means that the system call will not return until the operation is considered completed

File Handles (File Descriptors)

```
int fd;
char buffer[1024];
int count;
if ((fd = open("/home/bc/file", O_RDWR) == -1) {
  // the file couldn't be opened
  perror("/home/bc/file");
  exit(1);
}
if ((count = read(fd, buffer, 1024)) == -1) {
  // the read failed
  perror("read");
  exit(1);
}
// buffer now contains count bytes read from the file
```

- what is O_RDWR?
- what does `perror()` do?
- *cursor* position in an opened file depends on what functions/system calls you use
  - what about C++?

Standard File Descriptors

- **Standard File Descriptors**
  - 0 is `stdin` (by default, "map/connect" to the keyboard)
  - 1 is `stdout` (by default, "map/connect" to the display)
  - 2 is `stderr` (by default, "map/connect" to the display)

```
main() {
  char buf[BUFSIZE];
  int n;
  const char *note = "Write failed\n";

  while ((n = read(0, buf, sizeof(buf))) > 0)
    if (write(1, buf, n) != n) {
      (void)write(2, note, strlen(note));
      exit(EXIT_FAILURE);
    }
  return(EXIT_SUCCESS);
}
```

Back to Primes

- Have our primes program write out the solution, i.e., the `primes[]` array

```
int nprimes;
int *prime;
int main(int argc, char *argv[]) {
  ...
  for (i=1; i<nprimes; i++) {
    ...
  }
  if (write(1, prime, nprimes*sizeof(int)) == -1) {
    perror("primes output");
    exit(1);
  }
  return(0);
}
```

  - the output is not readable by human

Human-Readable Output

```
int nprimes;
int *prime;
int main(int argc, char *argv[]) {
  ...
  for (i=1; i<nprimes; i++) {
    ...
  }
  for (i=0; i<nprimes; i++) {
    fprintf(stdout, "%d\n", prime[i]);
  }
  return(0);
}
```

- `fprintf(stdout, ...)` is the same as `printf(...)`
  - `stdout` is a pre-defined *file pointer*
  - please see the *Programming FAQ* regarding the difference between a *file descriptor* and a *file pointer*

Allocation of File Descriptors

- For *each process*, the kernel maintains a *file descriptor table*, which is an array of pointers to *"file objects"*
  - a file object represents an *opened* file
  - a *file descriptor* is simply an *index* to this array
- Whenever a process requests a new file descriptor, the *lowest* numbered file descriptor not already associated with an open file is selected; thus

```
#include <fcntl.h>
#include <unistd.h>
...
close(0);
fd = open("file", O_RDONLY);
```

  - the above will always associate "file" with file descriptor 0 (assuming that `open()` succeeds)
- You will need to implement the above rule in the kernel 2 assignment

Running It

```
if (fork() == 0) {
  /* set up file descriptor 1 in the child process */
  close(1);
  if (open("/home/bc/Output", O_WRONLY) == -1) {
    perror("/home/bc/Output");
    exit(1);
  }
  execl("/home/bc/bin/primes", "primes", "300", 0);
  exit(1);
}
/* parent continues here */
while(pid != wait(0)) /* ignore the return code */
  ;
```

- `close(1)` removes file descriptor 1 from *extended address space*
- file descriptors are allocated *lowest first* on `open()`
- *extended address space* survives *execs*
- new code is same as running

```
% primes 300 > /home/bc/Output
```

I/O Redirection

```
% primes 300 > /home/bc/Output
```

- The ">" parameter in a shell command that instructs the command shell to *redirect* the output to the given file
  - If ">" weren't there, the output would go to the display

- Can also redirect input

```
% cat < /home/bc/Output
```

  - when the "`cat`" program reads from file descriptor 0, it would get the data bytes from the file "/home/bc/Output"

File Descriptor Table

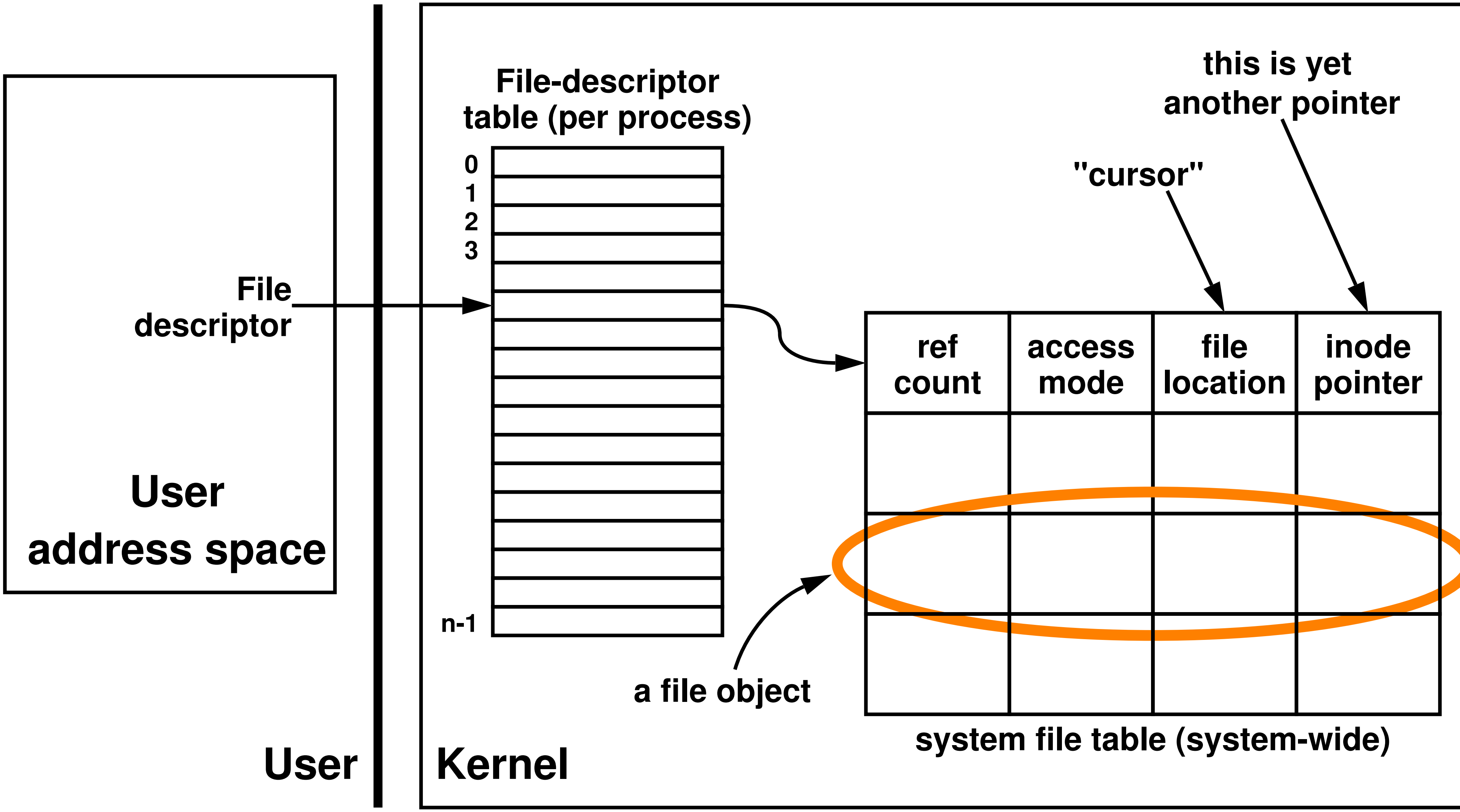
- A file descriptor refers not just to a file
  - it also refers to the *process's* current *context* for that file
    - includes how the file is to be accessed (how `open()` was invoked)
    - *cursor* position / file position
      - next location (zero-based array index) to read/write
      - initialized to 0 when a file is opened

File Object

- *Context* (or "execution context") information must be maintained by the OS and not directly by the user program
  - in this class, we will say that a *file object* is used to maintain the context information about an *opened file*
  - in addition to cursor position, a file object must also remember how a file was opened

- Let's say a user program opened a file with O_RDONLY
  - later on it calls `write()` using the opened file descriptor
  - how does the OS knows that it doesn't have write access?
    - stores O_RDONLY in context
  - if the user program can manipulate the context, it can change O_RDONLY to O_RDWR
  - therefore, user program must not have access to context!
    - all it can see is the handle
    - the file handle is an *index* into an array maintained for the process in kernel's address space

File-Descriptor Table



- *context* is not stored directly into the file-descriptor table
  - one-level of *indirection*