Lecture: Introduction

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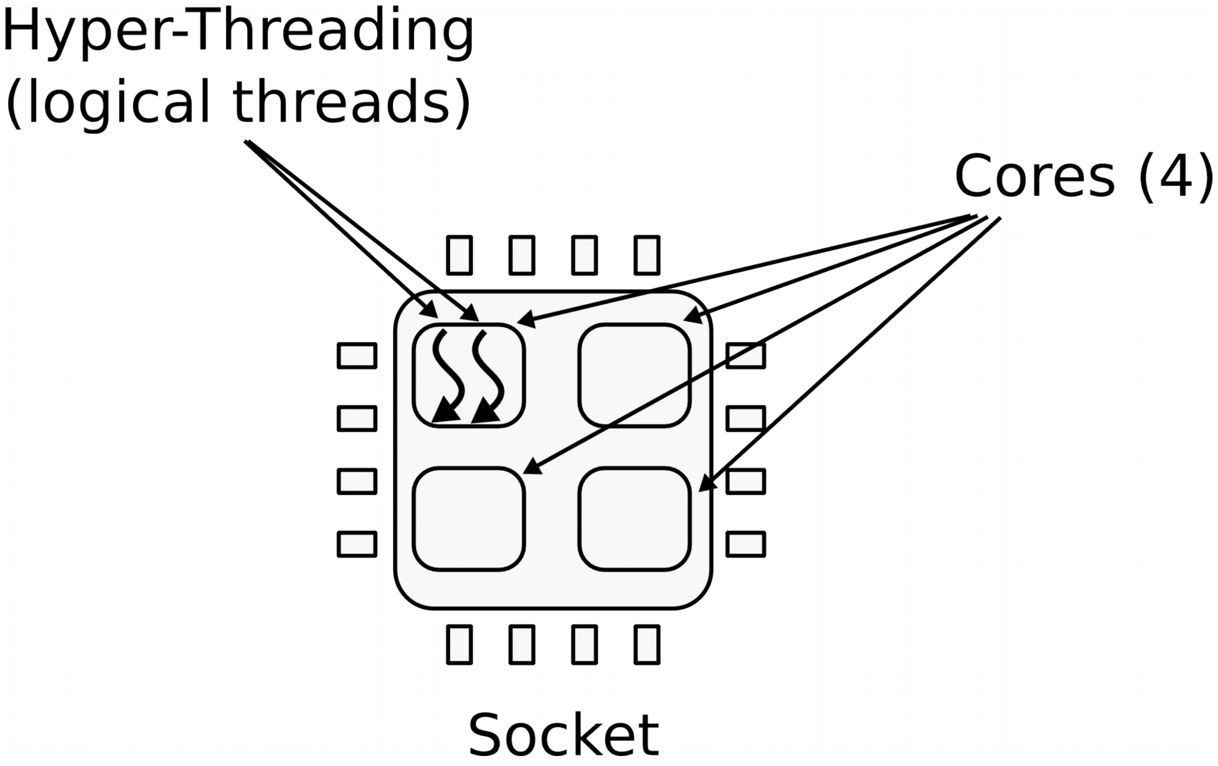
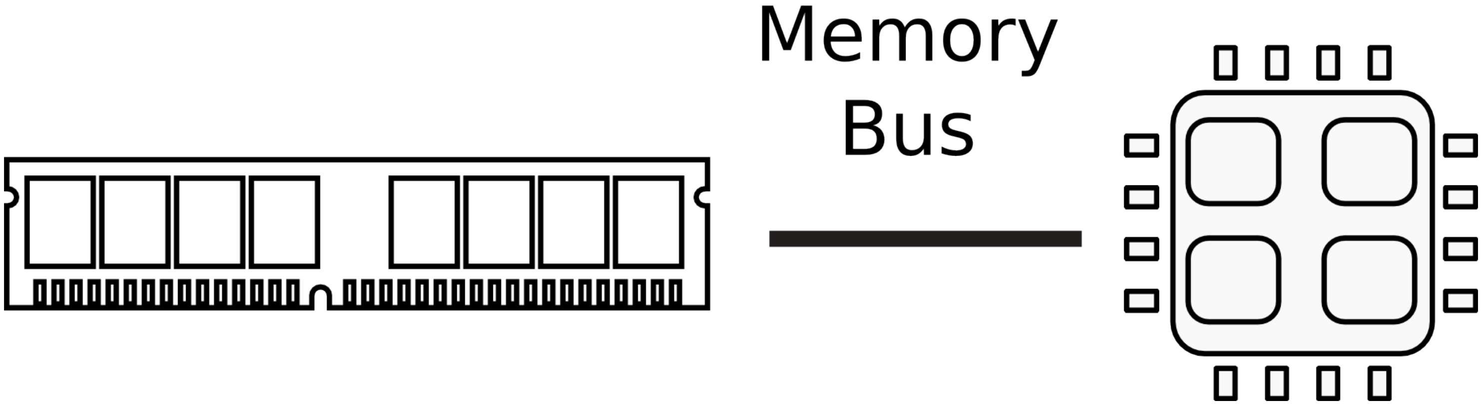
Lets take a brief look at how computers work

CPU

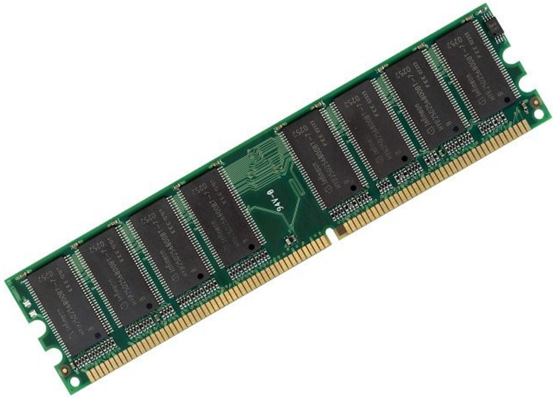
- 1 CPU
  - 4 cores
  - 2 logical (HT) threads each



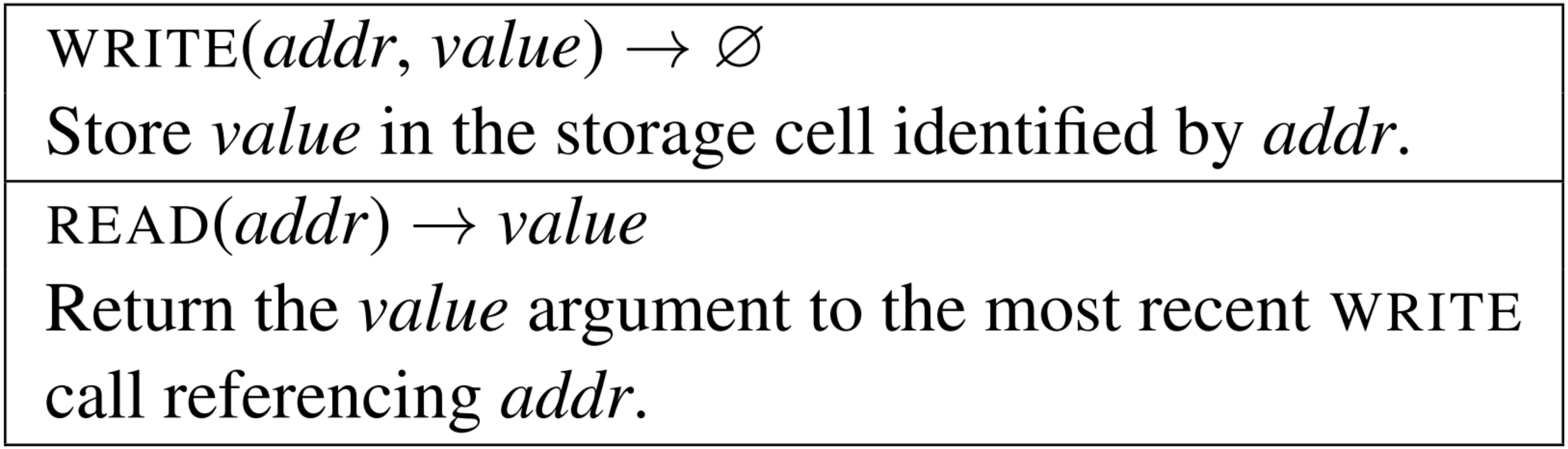
Memory



Memory Bus

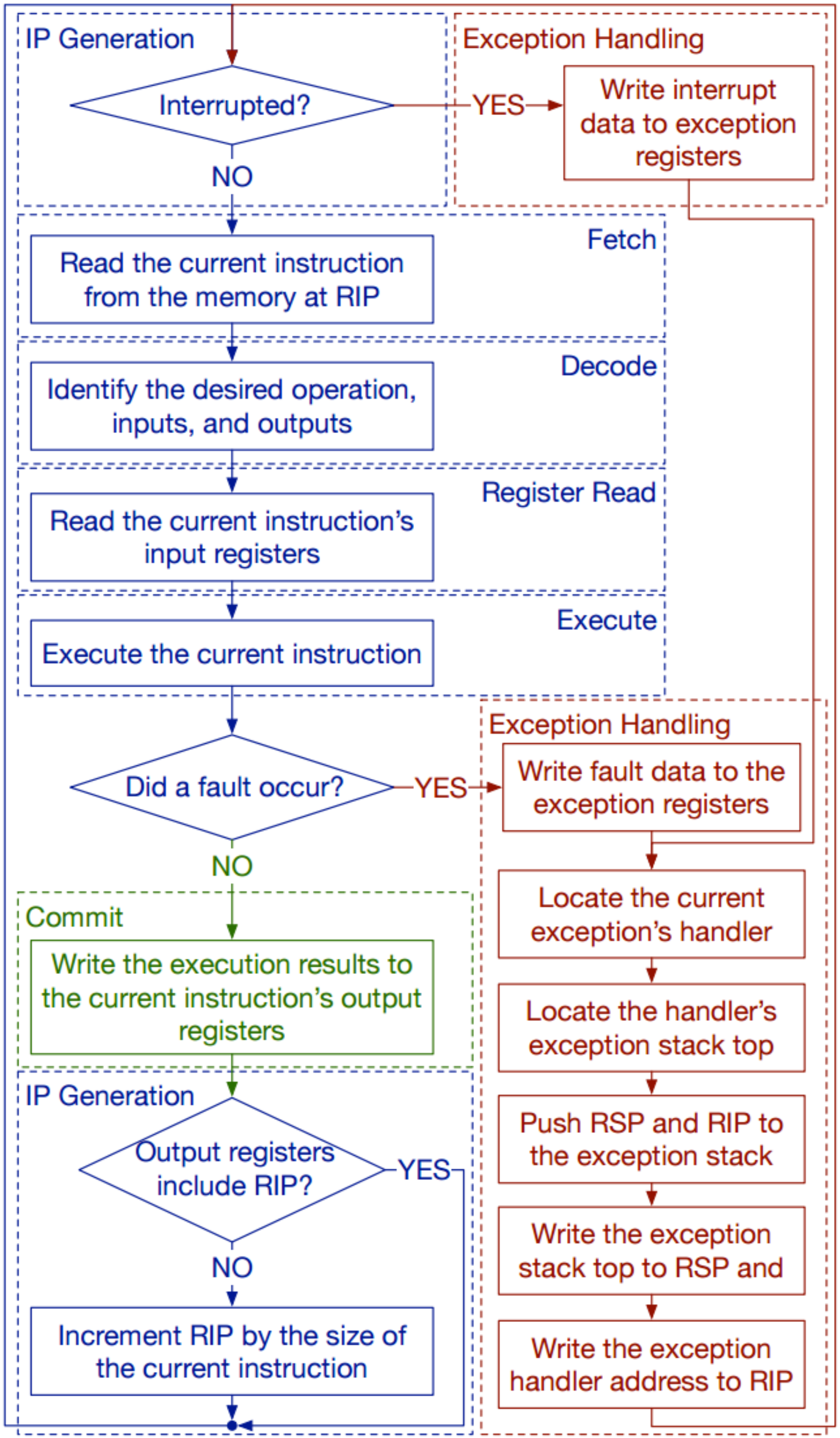


Memory abstraction



WRITE(*addr*, *value*) → ∅ Store *value* in the storage cell identified by *addr*.	
READ(*addr*) → *value* Return the *value* argument to the most recent WRITE call referencing *addr*.	

What does CPU do internally?

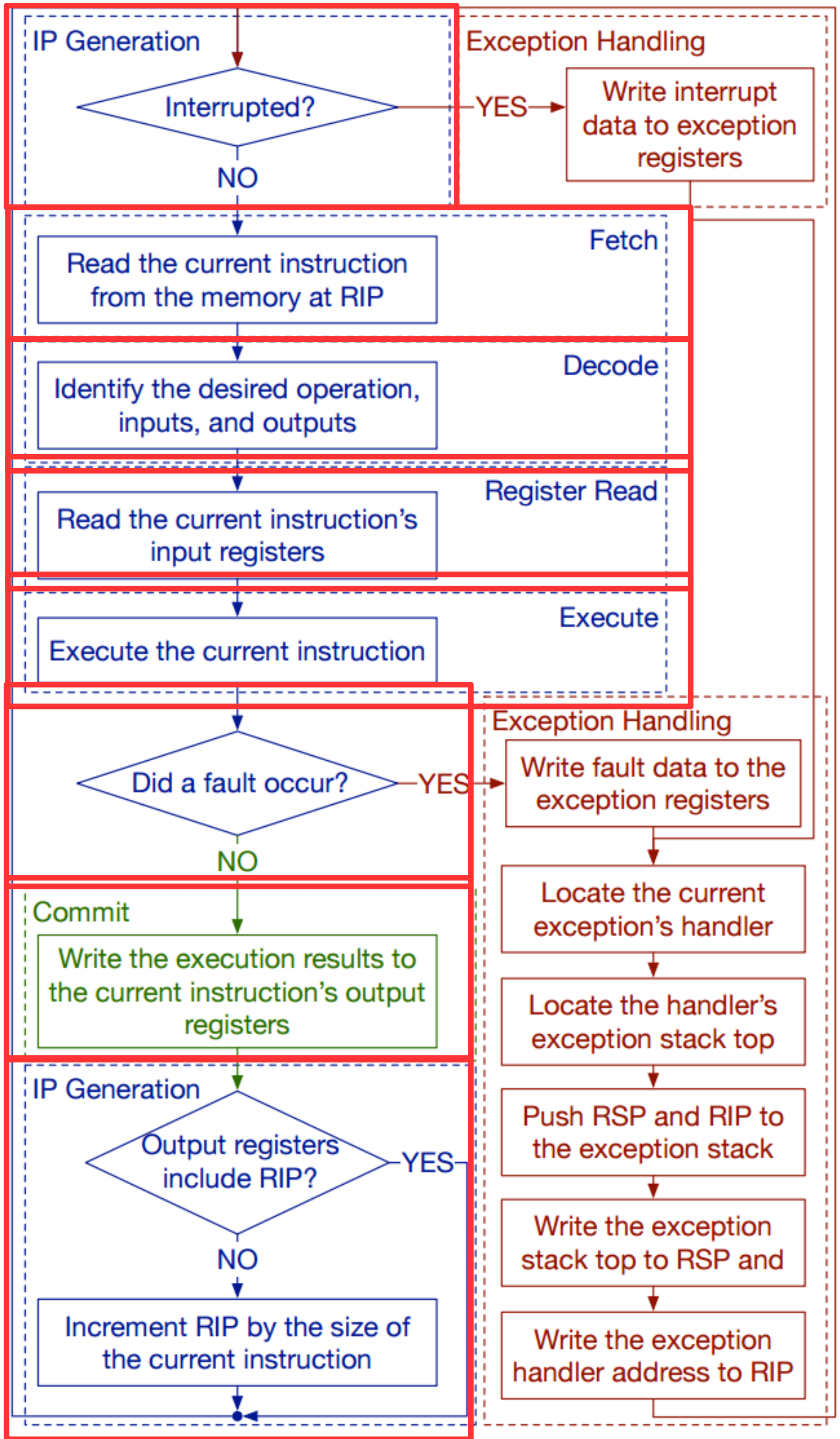


CPU execution loop

- CPU repeatedly reads instructions from memory
- Executes them
- Example

```
ADD EDX, EAX, EBX

// EDX = EAX + EBX
```



IP Generation

Interrupted?

YES

NO

Exception Handling

Write interrupt data to exception registers

Fetch

Read the current instruction from the memory at RIP

Decode

Identify the desired operation, inputs, and outputs

Register Read

Read the current instruction's input registers

Execute

Execute the current instruction

Did a fault occur?

YES

NO

Exception Handling

Write fault data to the exception registers

Locate the current exception's handler

Locate the handler's exception stack top

Push RSP and RIP to the exception stack

Write the exception stack top to RSP and

Write the exception handler address to RIP

Commit

Write the execution results to the current instruction's output registers

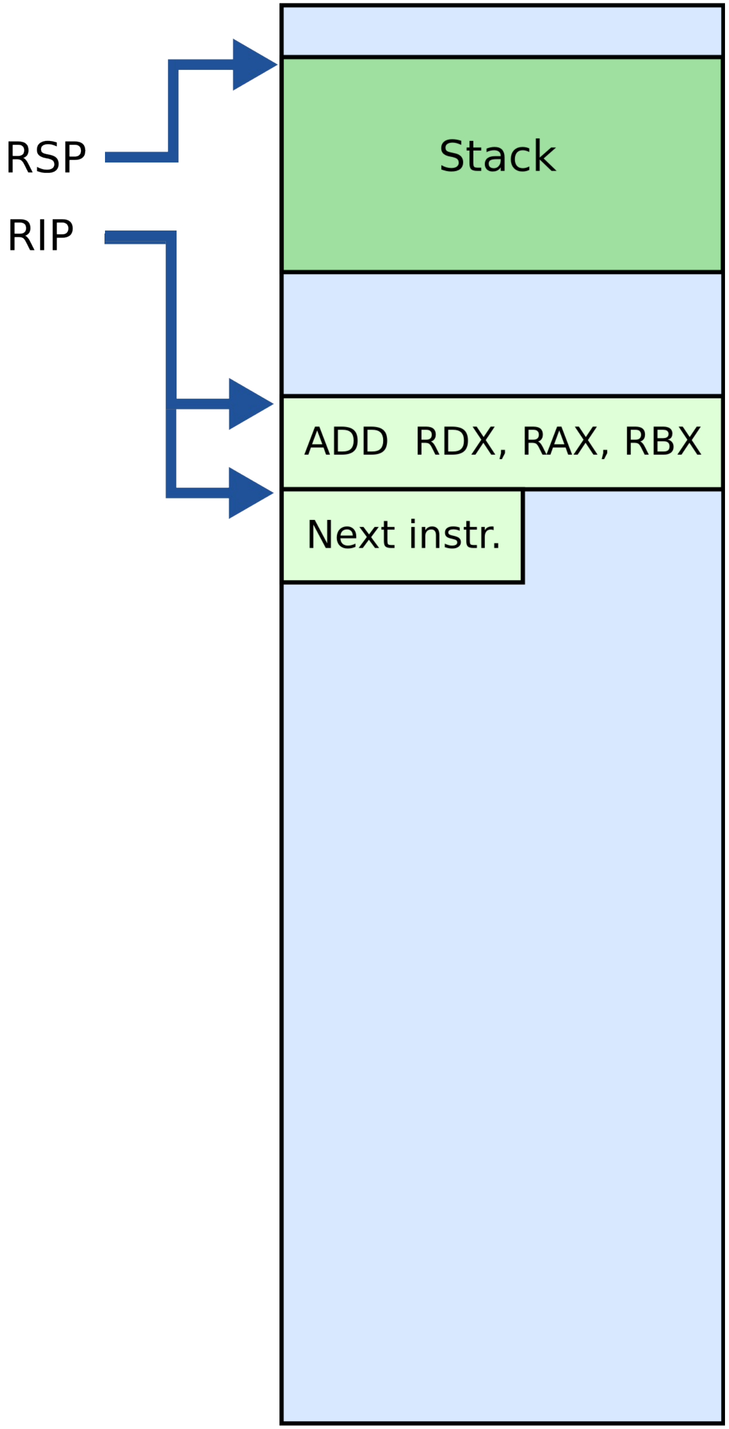
IP Generation

Output registers include RIP?

YES

NO

Increment RIP by the size of the current instruction

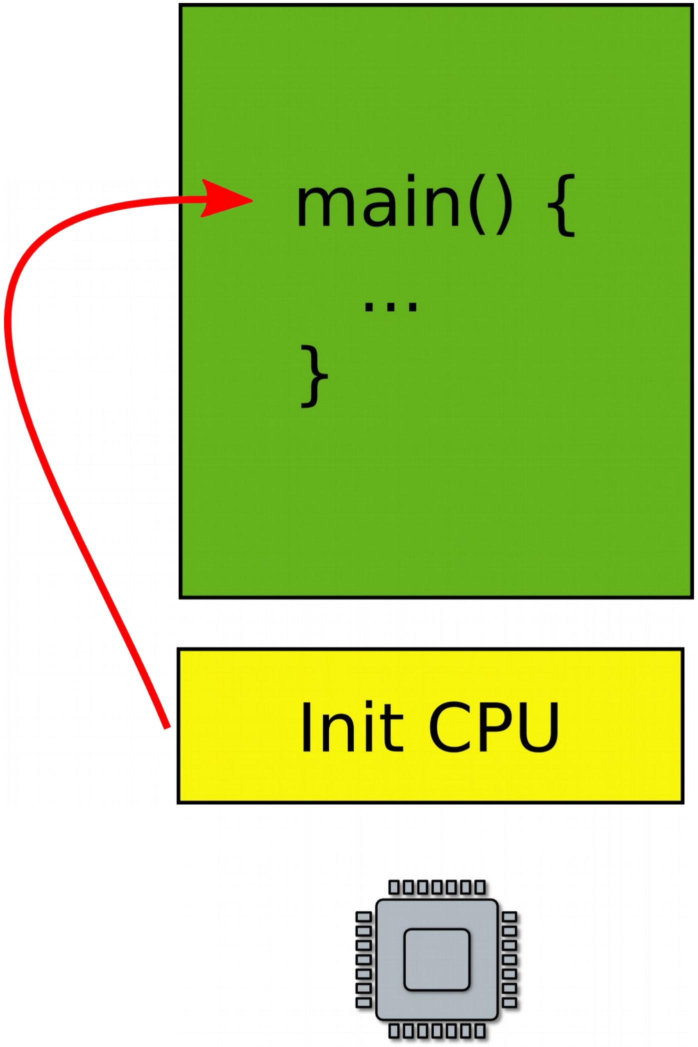


Simple observation

- Hardware executes instructions one by one

What is an operating system?

Task #1: Run your code on a piece of hardware



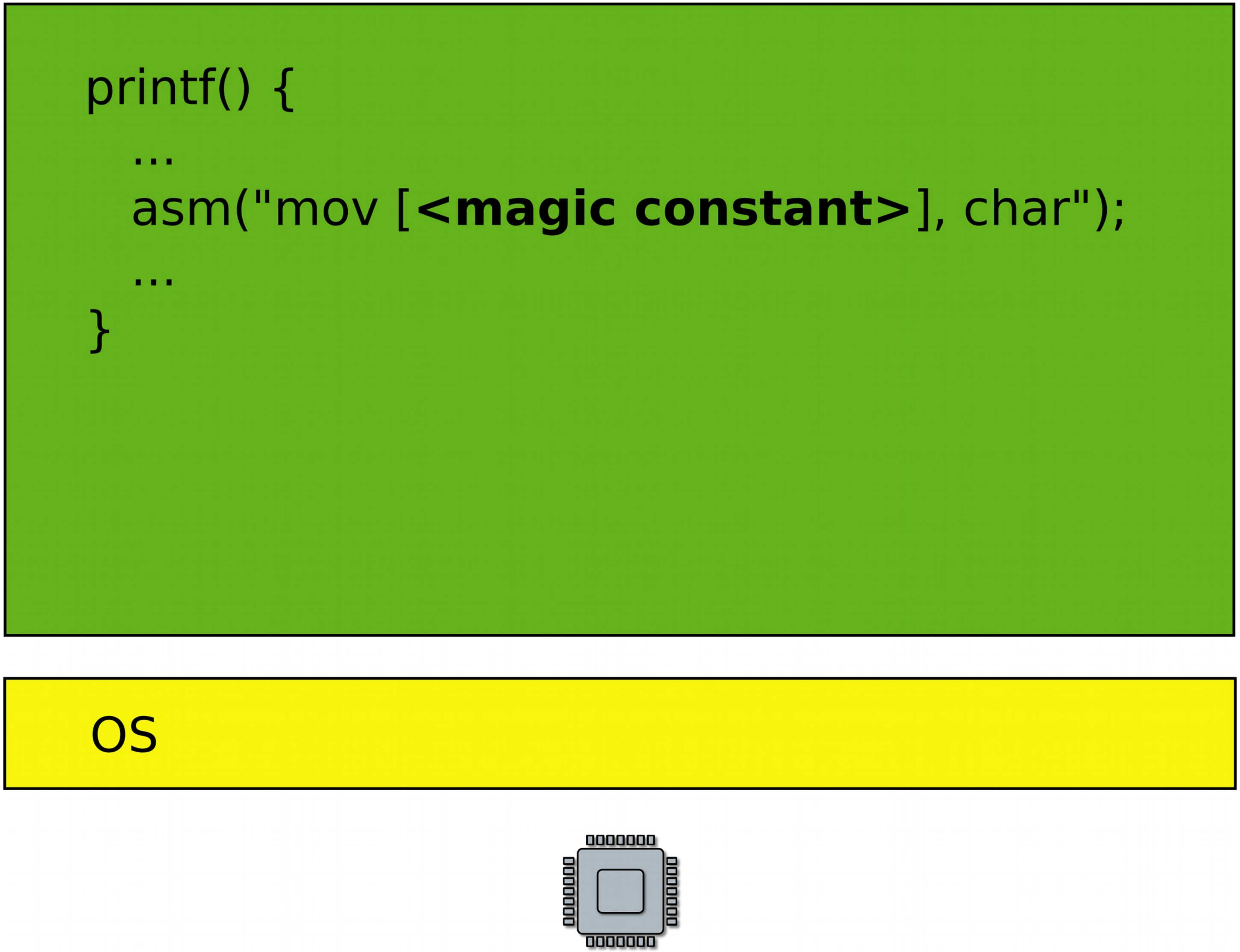
```
main() {
    ...
}
```

Init CPU

- Read CPU manual
- A tiny boot layer
  - Initialize CPU
  - Jump to the entry point of your program
    - main()
  - **This can be the beginning of your OS!**

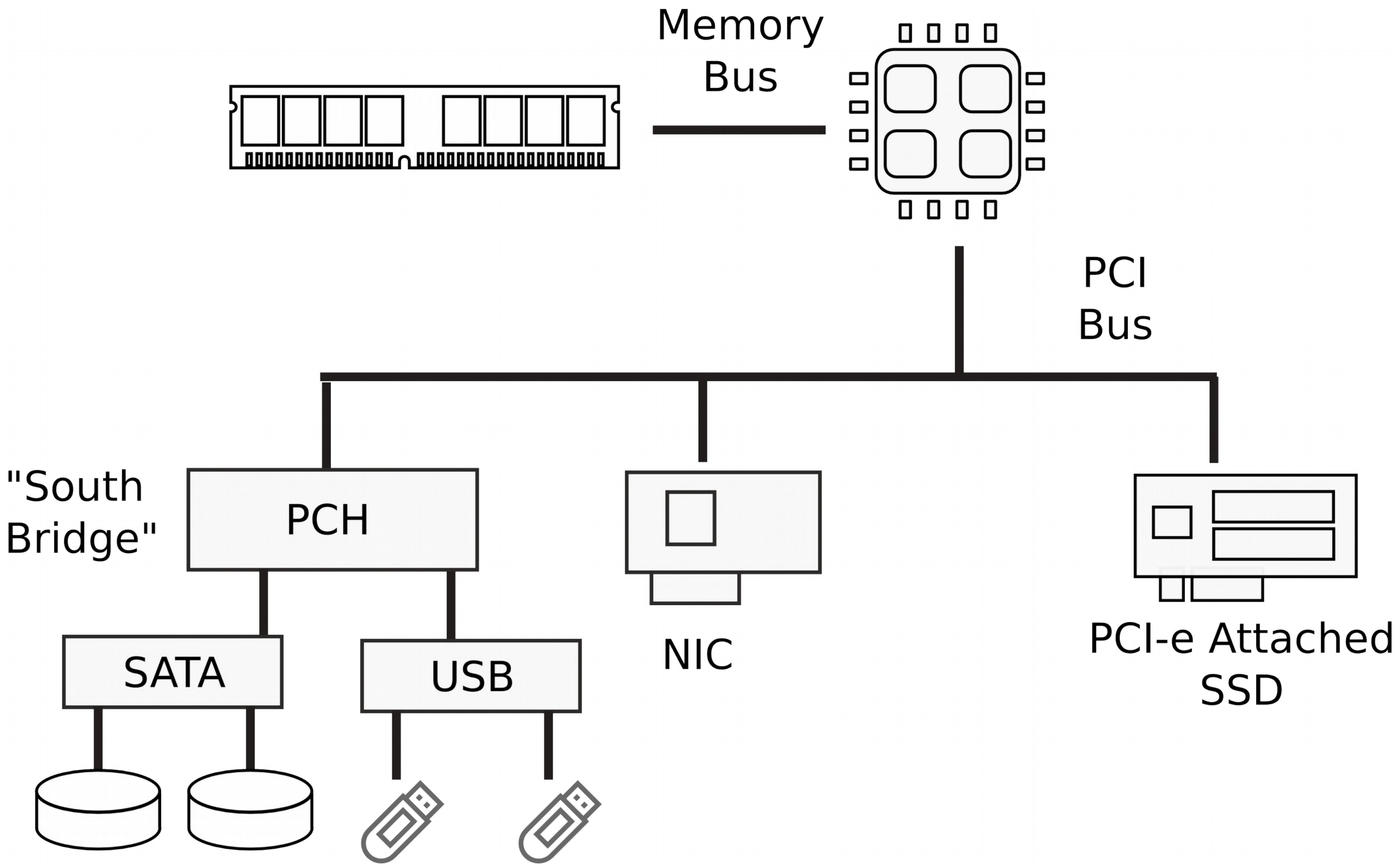
Task #2: Print something on the screen

- On the screen or serial line



```
printf() {
   ...
   asm("mov [<magic constant>], char");
   ...
}
```

I/O Devices



Memory
Bus

PCI
Bus

"South
Bridge"

PCH

SATA

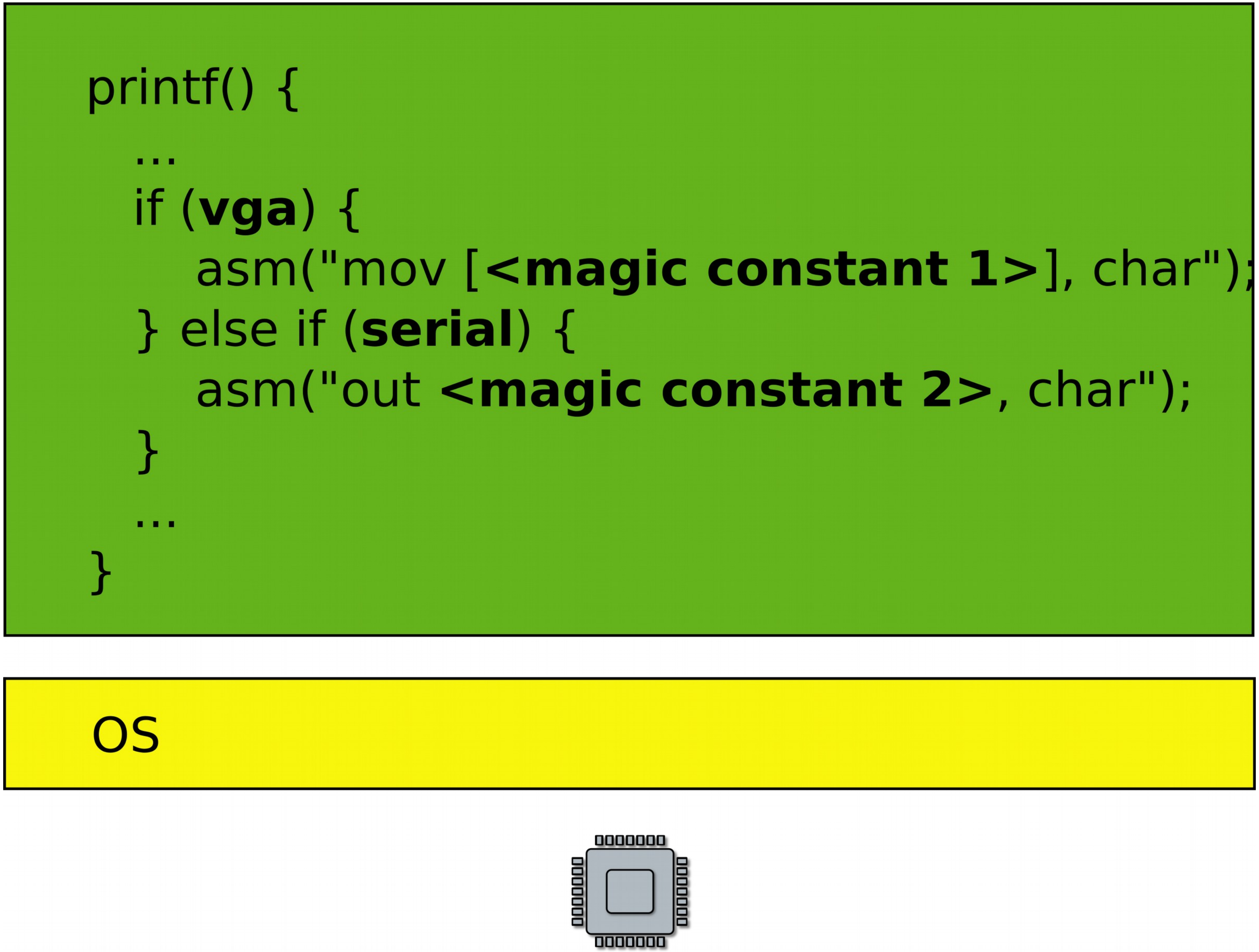
USB

NIC

PCI-e Attached
SSD

Task #2: Print something on the screen

- On the screen or serial line

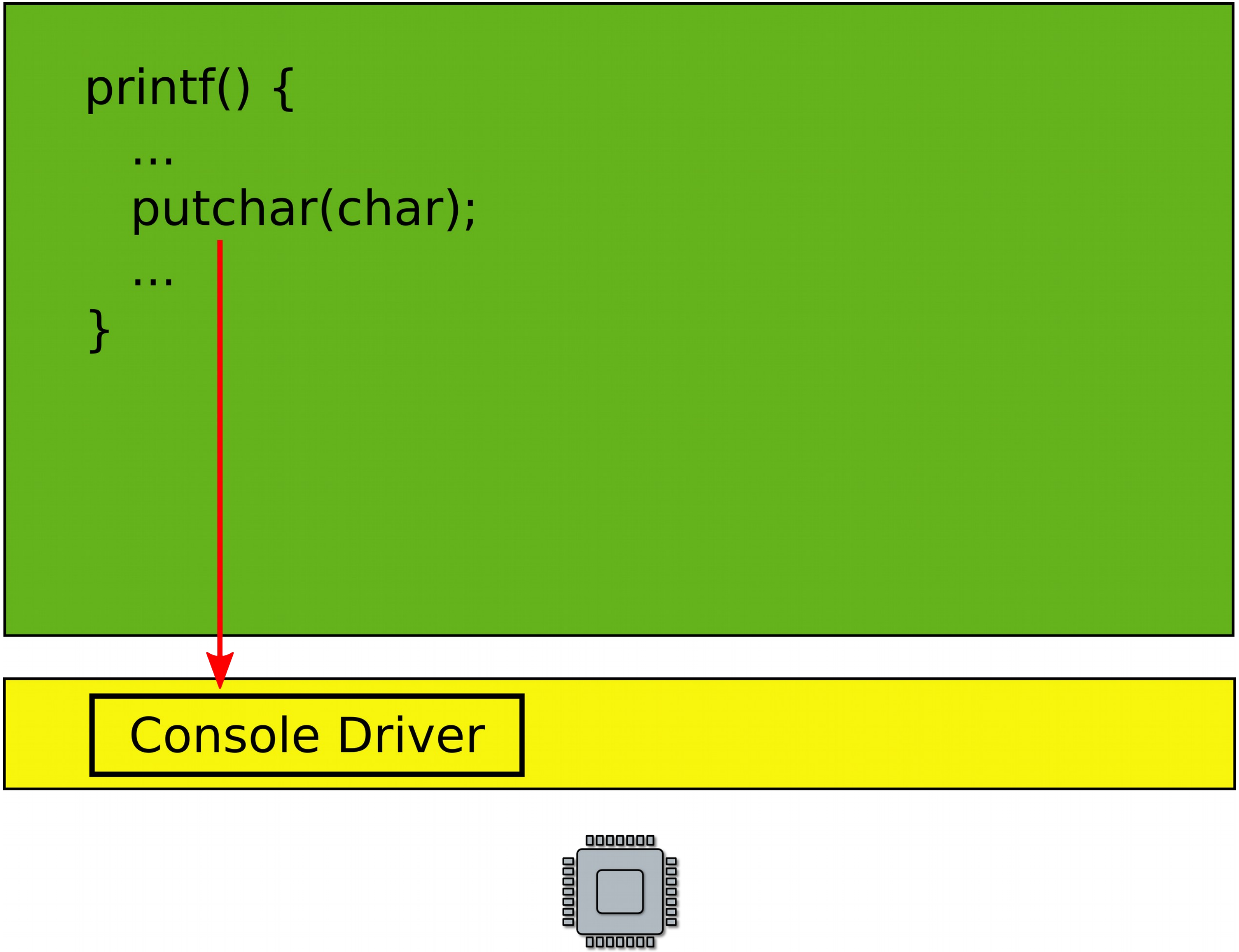


```
printf() {
   ...
   if (vga) {
       asm("mov [<magic constant 1>], char");
   } else if (serial) {
       asm("out <magic constant 2>, char");
   }
   ...
}
```

OS

A more general interface

- First device driver



```
printf() {
   ...
   putchar(char);
   ...
}
```

Console Driver

Device drivers

- Abstract hardware
  - Provide high-level interface
  - Hide minor differences
  - Implement some optimizations
    - Batch requests
- Examples
  - Console, disk, network interface
  - ...virtually any piece of hardware you know

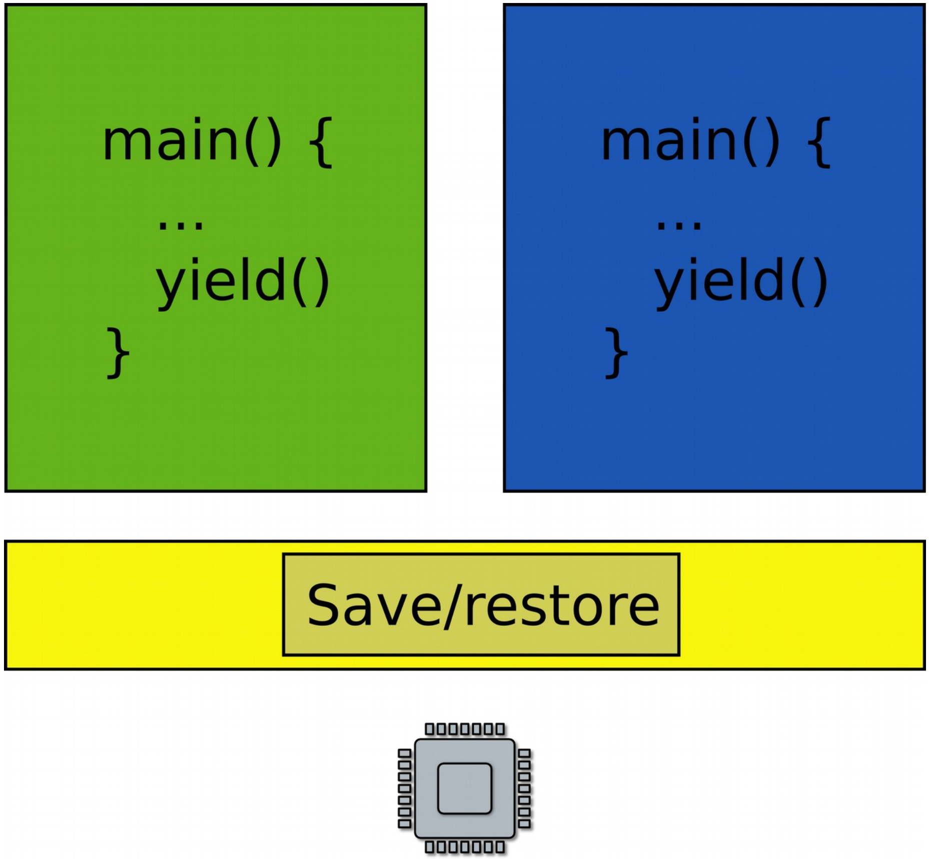
OS is like a library that provides a collection of useful functions

How hard it is to boot into main and print something on the screen?

- If you want to run this demo
  https://github.com/mars-research/hello-os.git

```
printf("Hello world\n");
```

Task #3: Want to run two programs



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

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

Save/restore

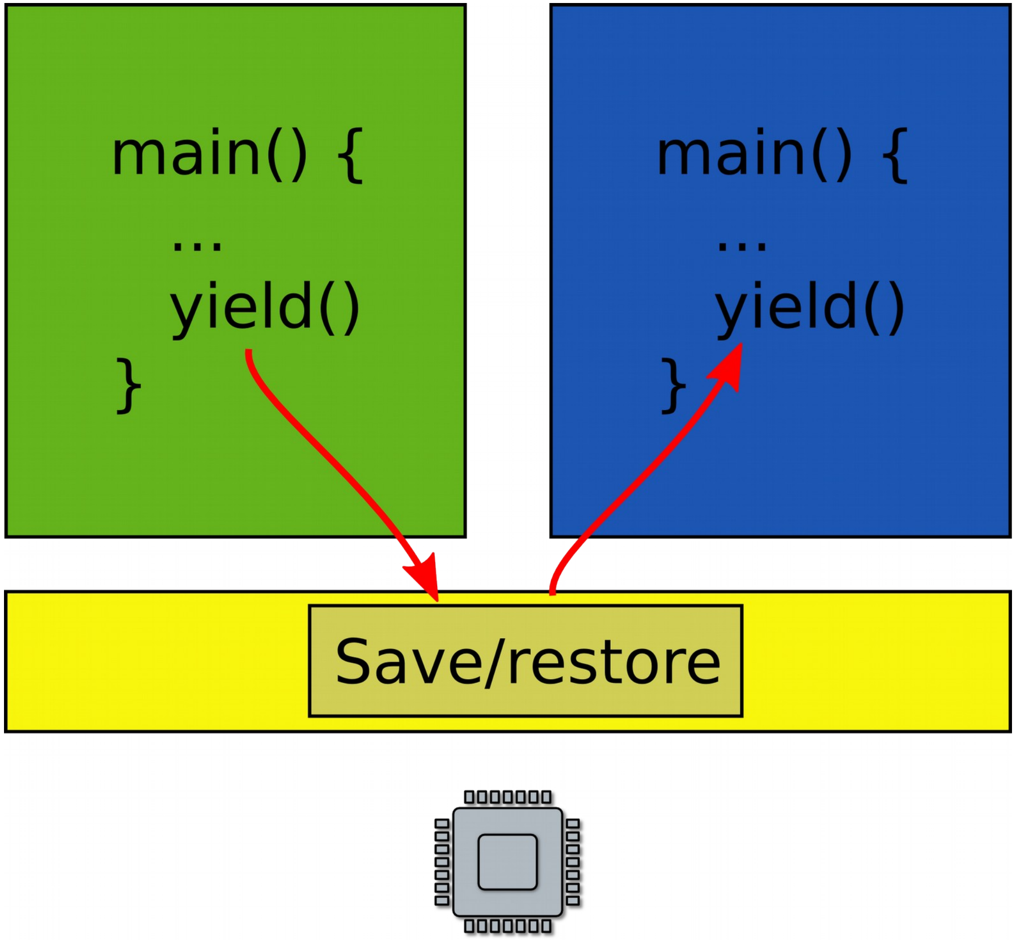
- What does it meaning?
  - Only one CPU
- Run one, then run another one

Very much like car sharing

Time sharing

- Programs use CPU in turns
    - One program runs
    - Then OS takes control
    - Launches another program
    - Then another program runs
    - OS takes control again
    - ...

Task #3: Want to run two programs



- Exit into the kernel periodically
- Context switch
  - Save state of one program
  - Restore state of another program

What is this state?

State of the program

- Roughly it’s
  - Registers
  - Memory

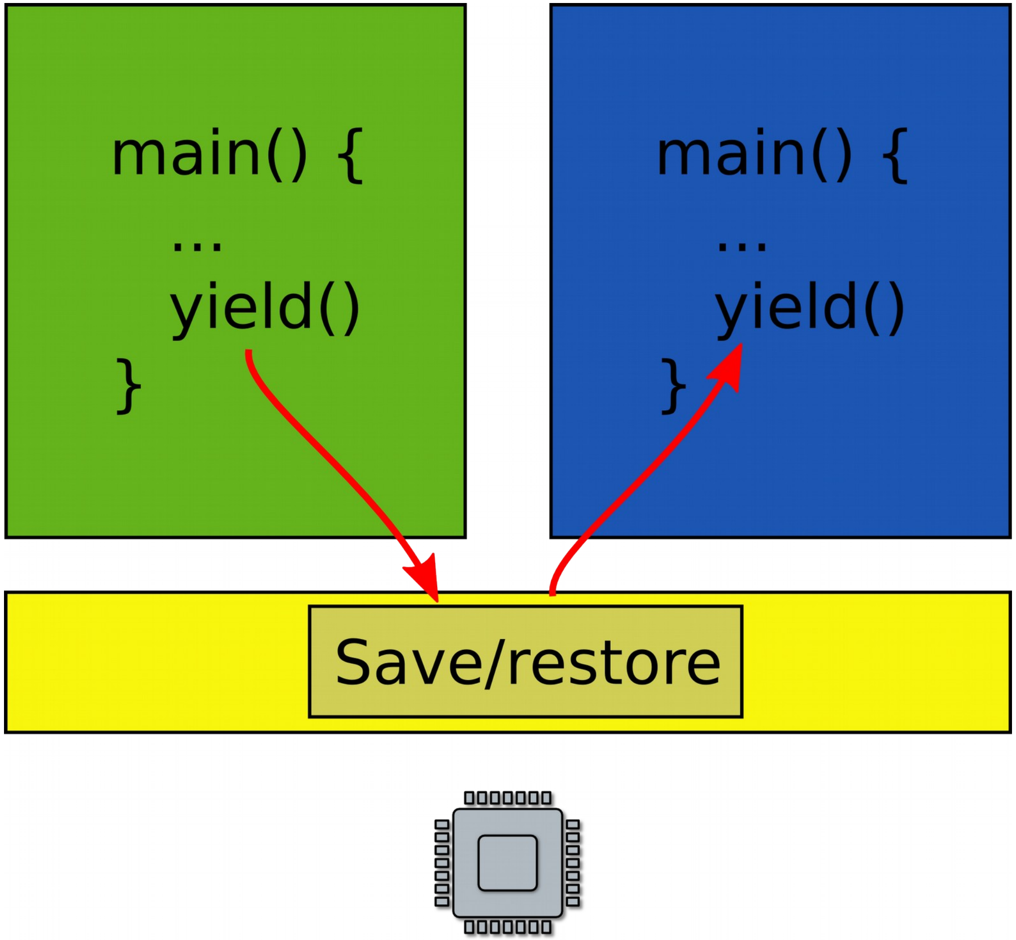
  - Plus some state (data structures) in the kernel associated with the program
    - Information about files opened by the program, i.e. file descriptors
    - Information about network flows
    - Information about address space, loaded libraries, communication channels to other programs, etc.

Saving and restoring state

- Note that you do not really have to save/restore in-kernel state on the context switch
    - It’s in the kernel already, i.e., in some part of the memory where kernel keeps its data structures
    - You only have to switch from using one to using another
        - i.e., instead of using the file descriptor table (can be as simple as array) for program X start using at file descriptor table for program Y

What about memory?

- Two programs, one memory?



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

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main() {
   ...
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}
```

Save/restore

Time-share memory

- Well you can copy in and out the state of the program into a region of memory where it can run
    - Similar to time-sharing the CPU

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- What do you think is wrong with this approach?

Time-share memory

- Well you can copy in and out the state of the program into a region of memory where it can run
  - Similar to time-sharing the CPU

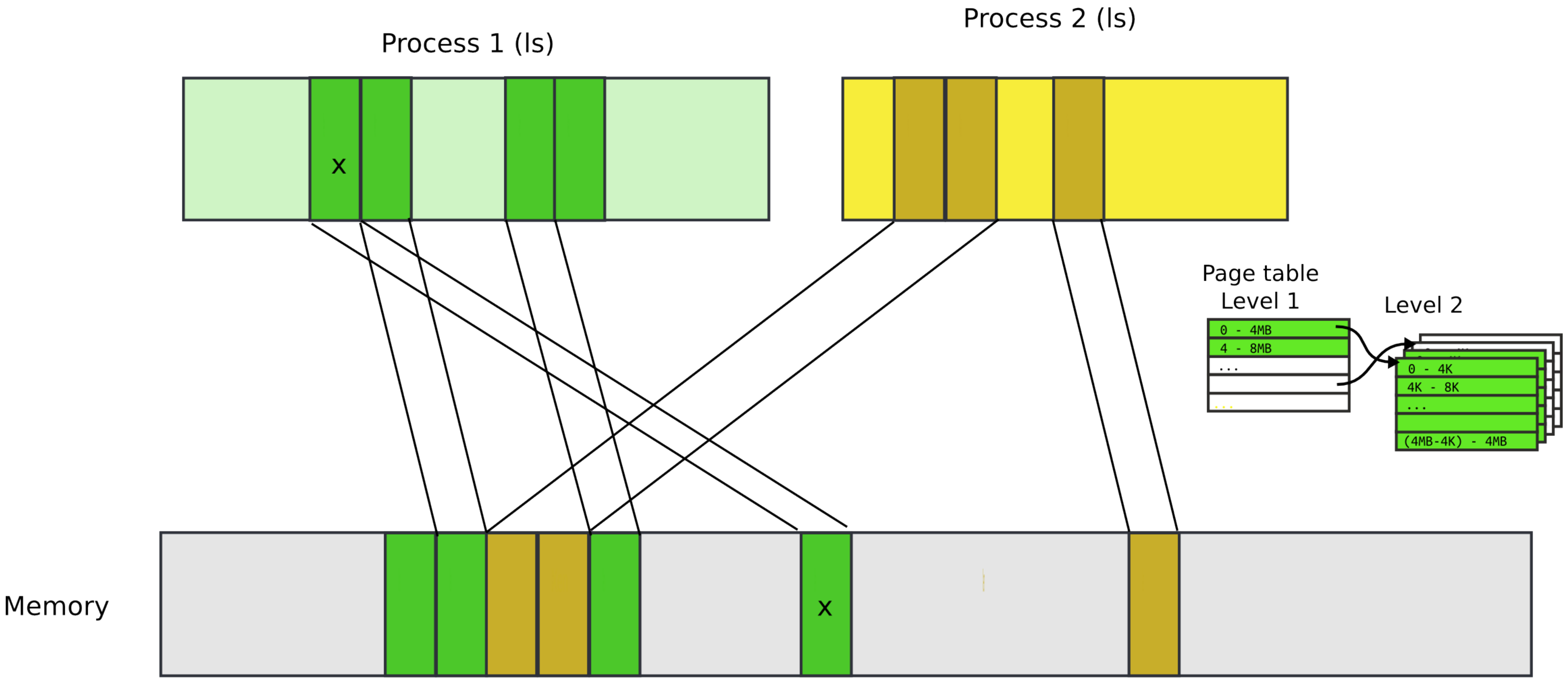
- What do you think is wrong with this approach?
  - Unlike registers the state of the program in memory can be large
  - Takes time to copy it in and out

Virtual address spaces

- Illusion of a private memory for each application
  - Keep a description of an address space
  - In one of the registers

- OS maintains description of address spaces
  - Switches between them

Address spaces with page tables

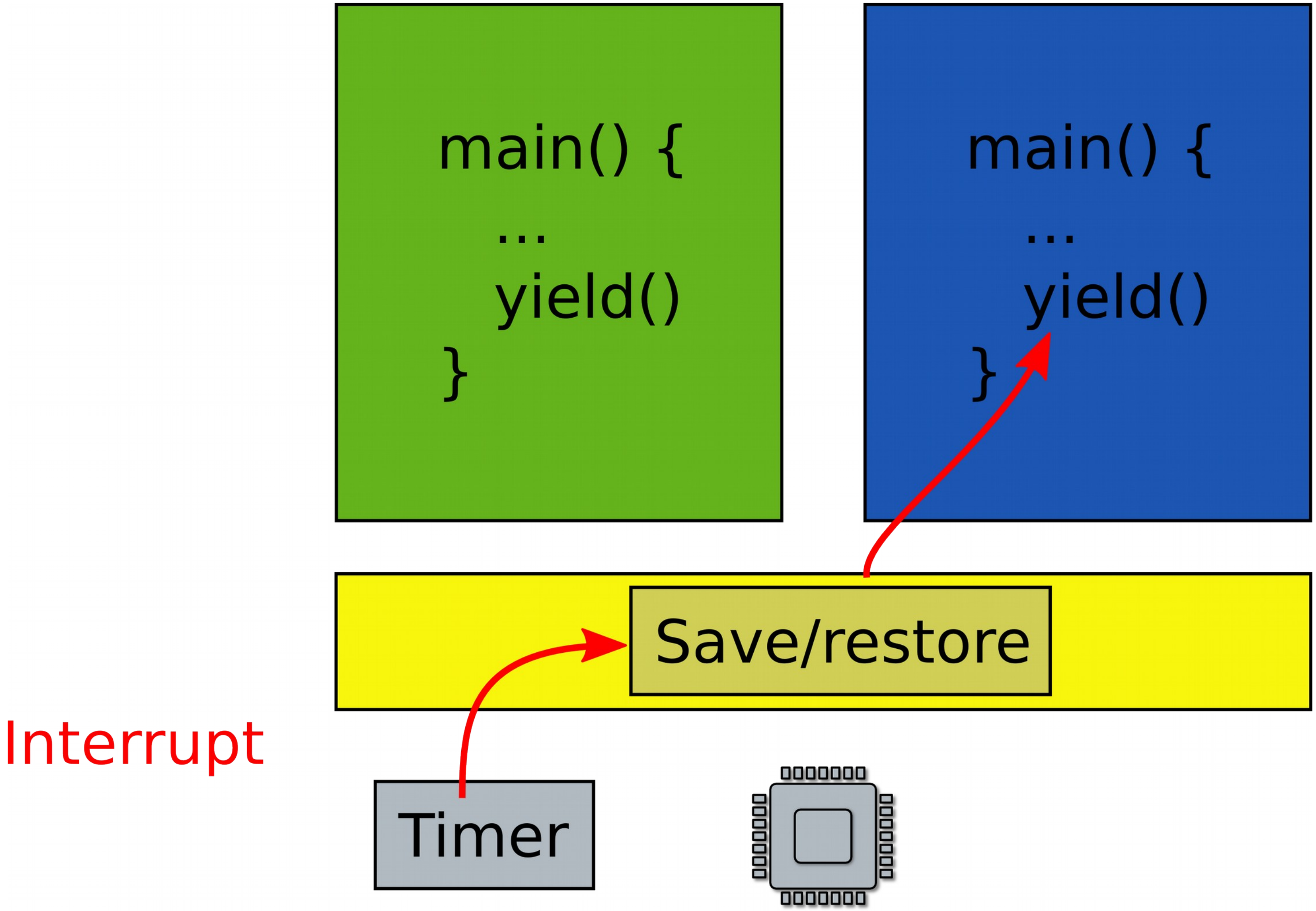


Page tables high-level idea

- Break up memory into 4096-byte chunks called pages
    - Modern hardware supports 2MB, 4MB, and 1GB pages
- Independently control mapping for each page of linear address space

Staying in control

- What if one program fails to release the CPU?
- It will run forever. Need a way to preempt it. How?

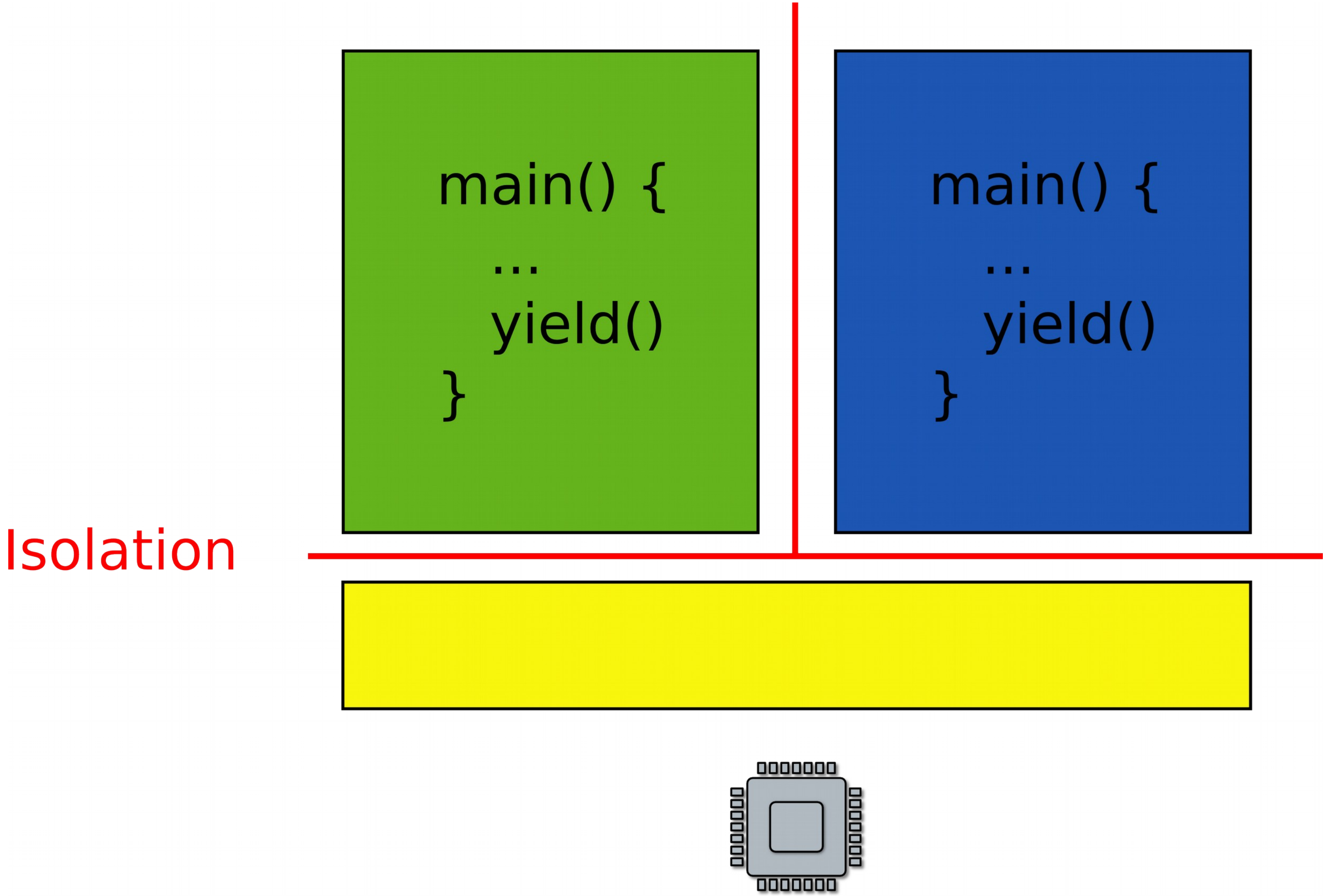


Scheduling

- Pick which application to run next
  - And for how long
- Illusion of a private CPU for each task
  - Frequent context switching

Isolation

- What if one faulty program corrupts the kernel?
- Or other programs?



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

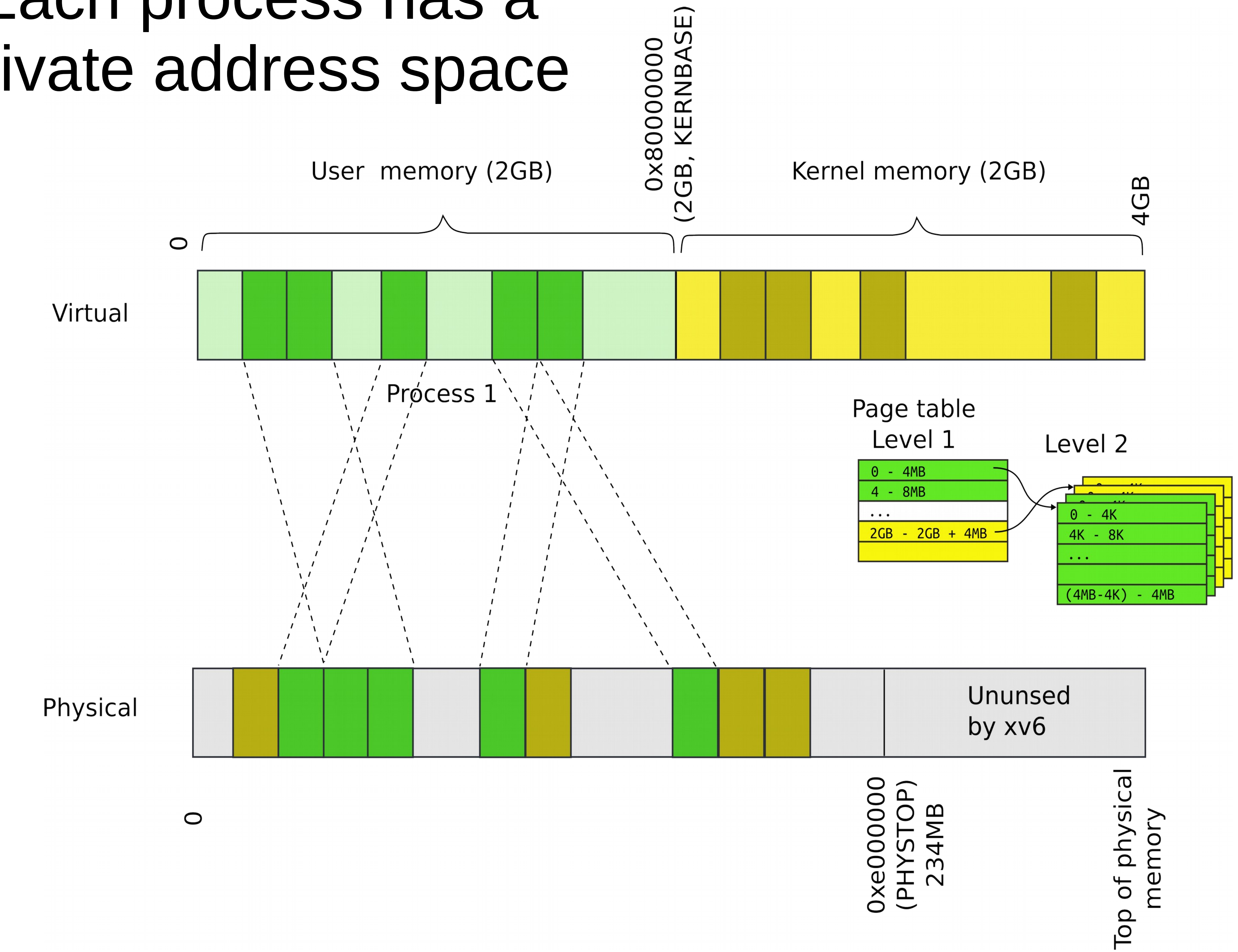
```
main() {
   ...
   yield()
}
```

Isolation

No isolation: open space office

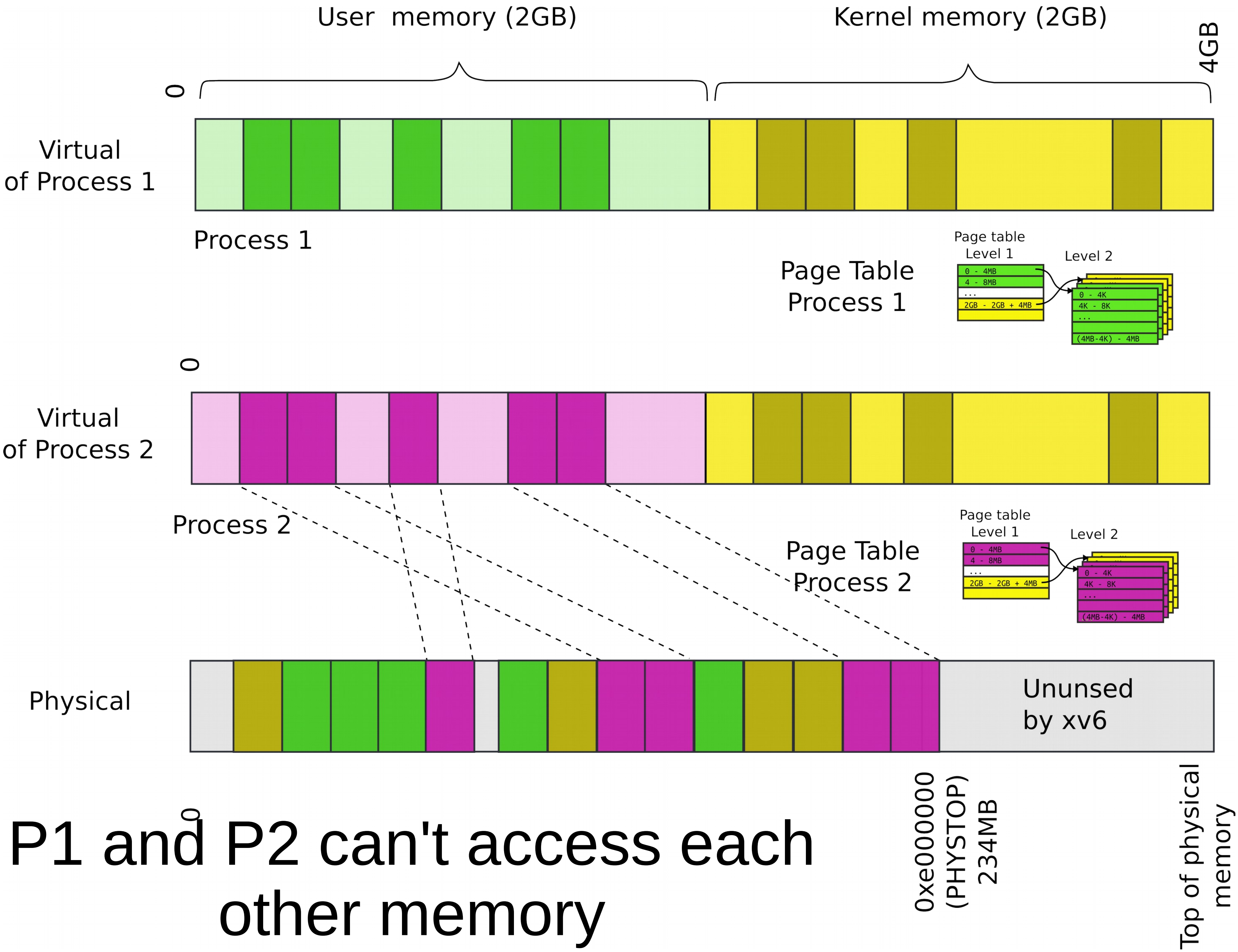
Isolated rooms

Each process has a private address space



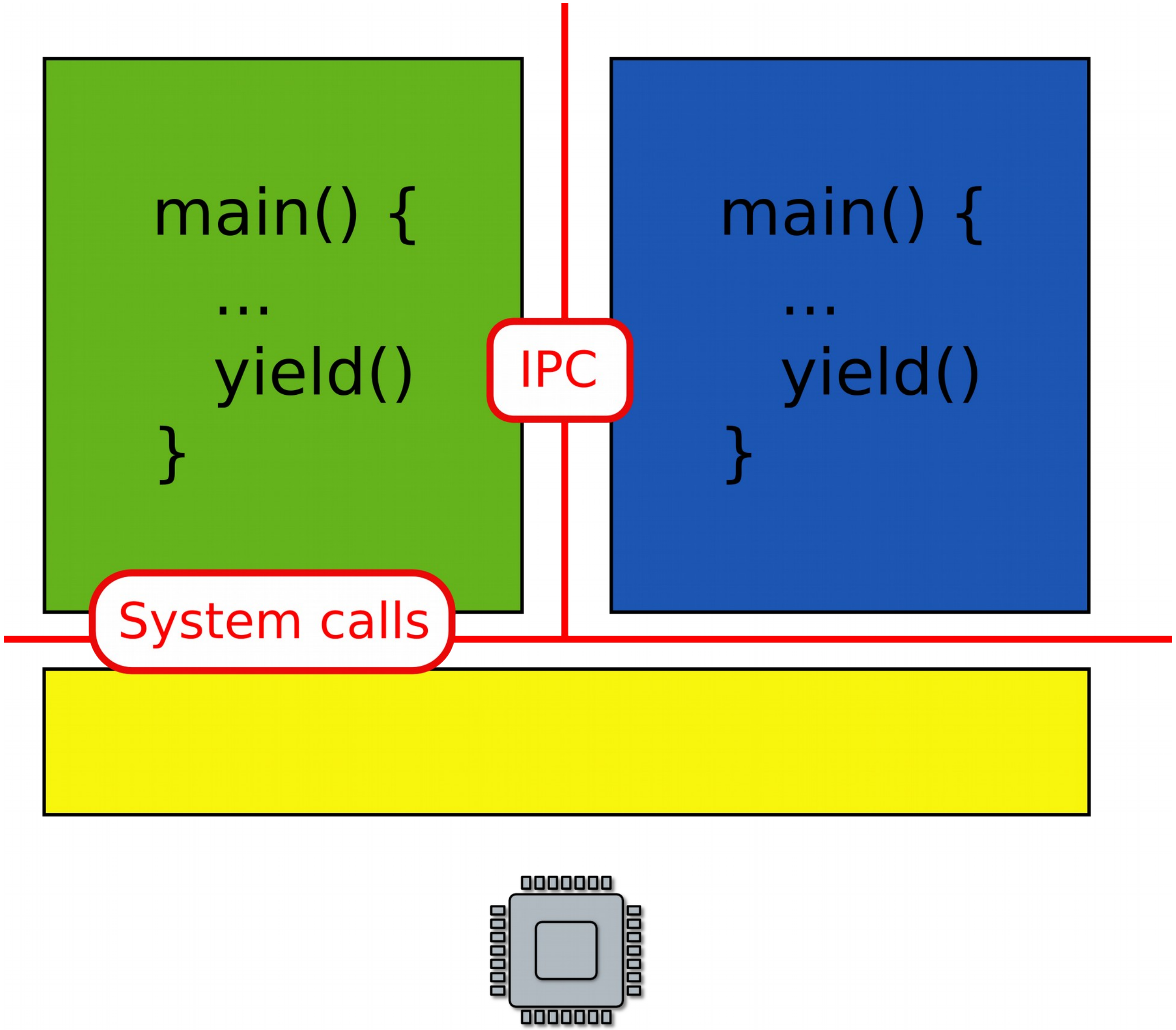
Each process maps the kernel

- It's not strictly required
  - But convenient for system calls
  - No need to change the page table when process enters the kernel with a system call
  - **Things are much faster!**



P1 and P2 can't access each other memory

- What about communication?
- Can we invoke a function in a kernel?



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

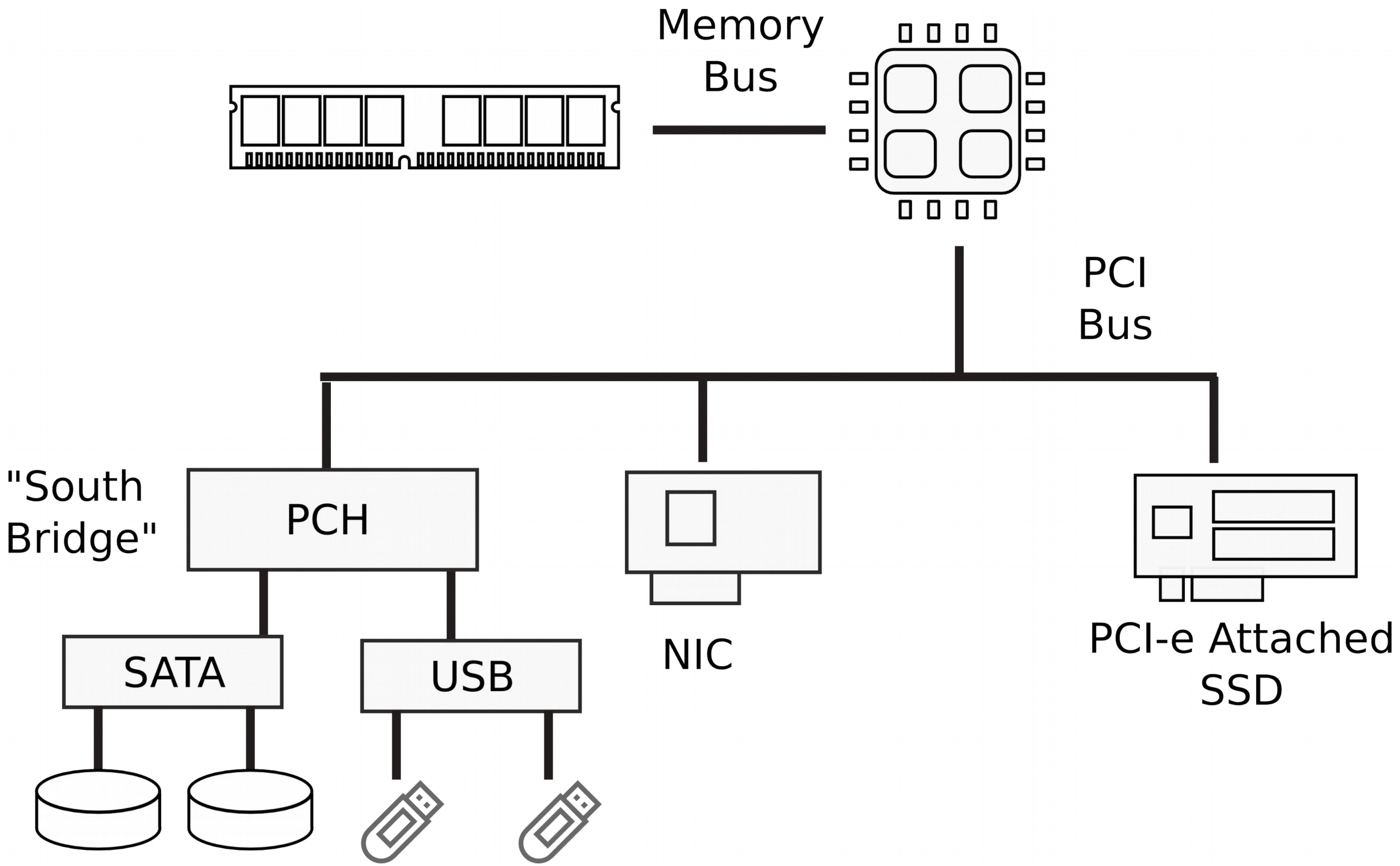
```
main() {
  ...
  yield()
}
```

Files and network

- What if you want to save some data to a file?

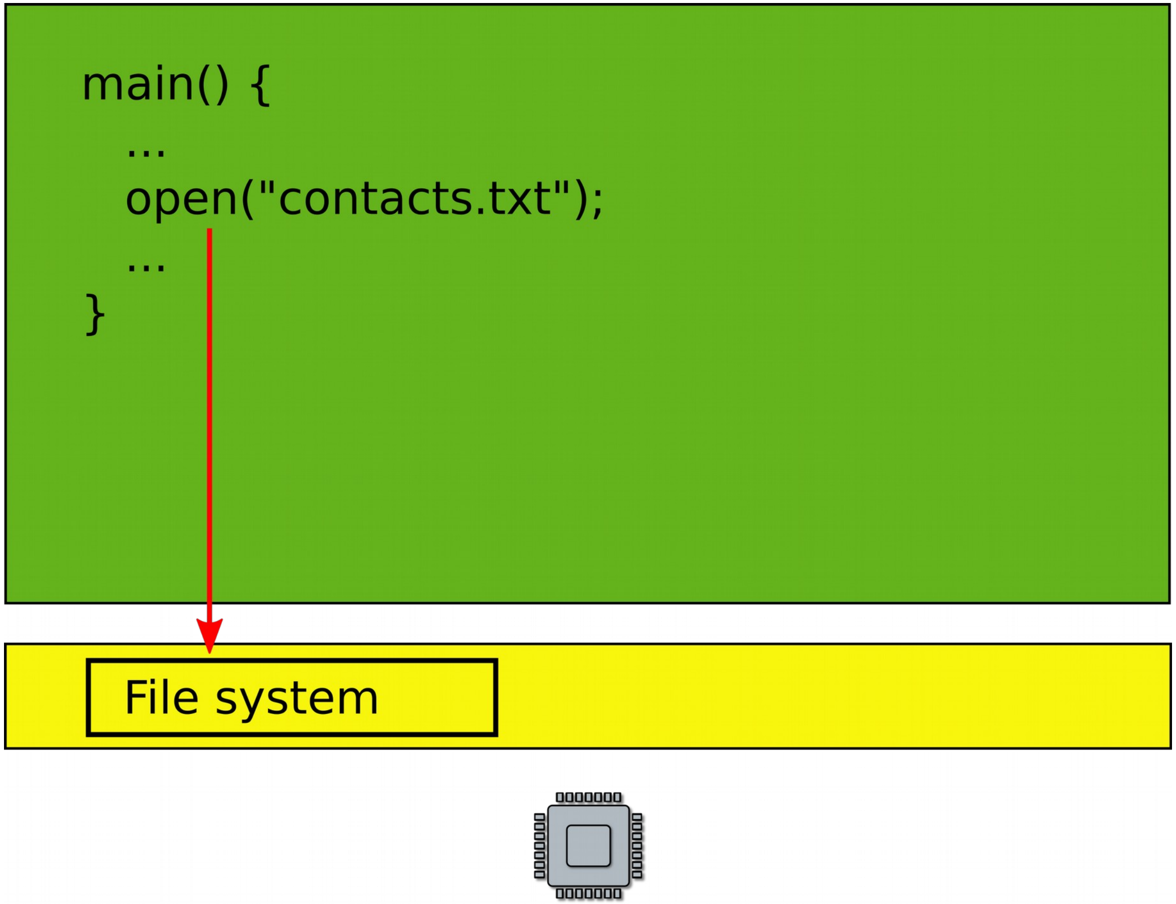
- What if you want to save some data to a file?
- Permanent storage
  - E.g., disks
- Disks are just arrays of blocks
  - write(block_number, block_data)

I/O Devices


Memory
Bus
PCI
Bus
"South
Bridge"
PCH
SATA
USB
NIC
PCI-e Attached
SSD

- File system and block device provide similar abstractions
- Permanent storage
  - E.g., disks
- Disks are just arrays of blocks
  - write(block_number, block_data)
- Files
  - High level abstraction for saving data
  - fd = open(“contacts.txt”);
  - fpritnf(fd, “Name:%s\n”, name);

File system



```
main() {
   ...
   open("contacts.txt");
   ...
}
```

File system

File system and block layer

System calls	File descriptors
Pathnames	Recursive lookup
Directories	Directory inodes
Files	Inodes and block allocator
Transactions	Logging
Blocks	Buffer cache

- Reliable storage on top of raw disc blocks
- Disks are just arrays of blocks

```
write(block_number, block_data)
```

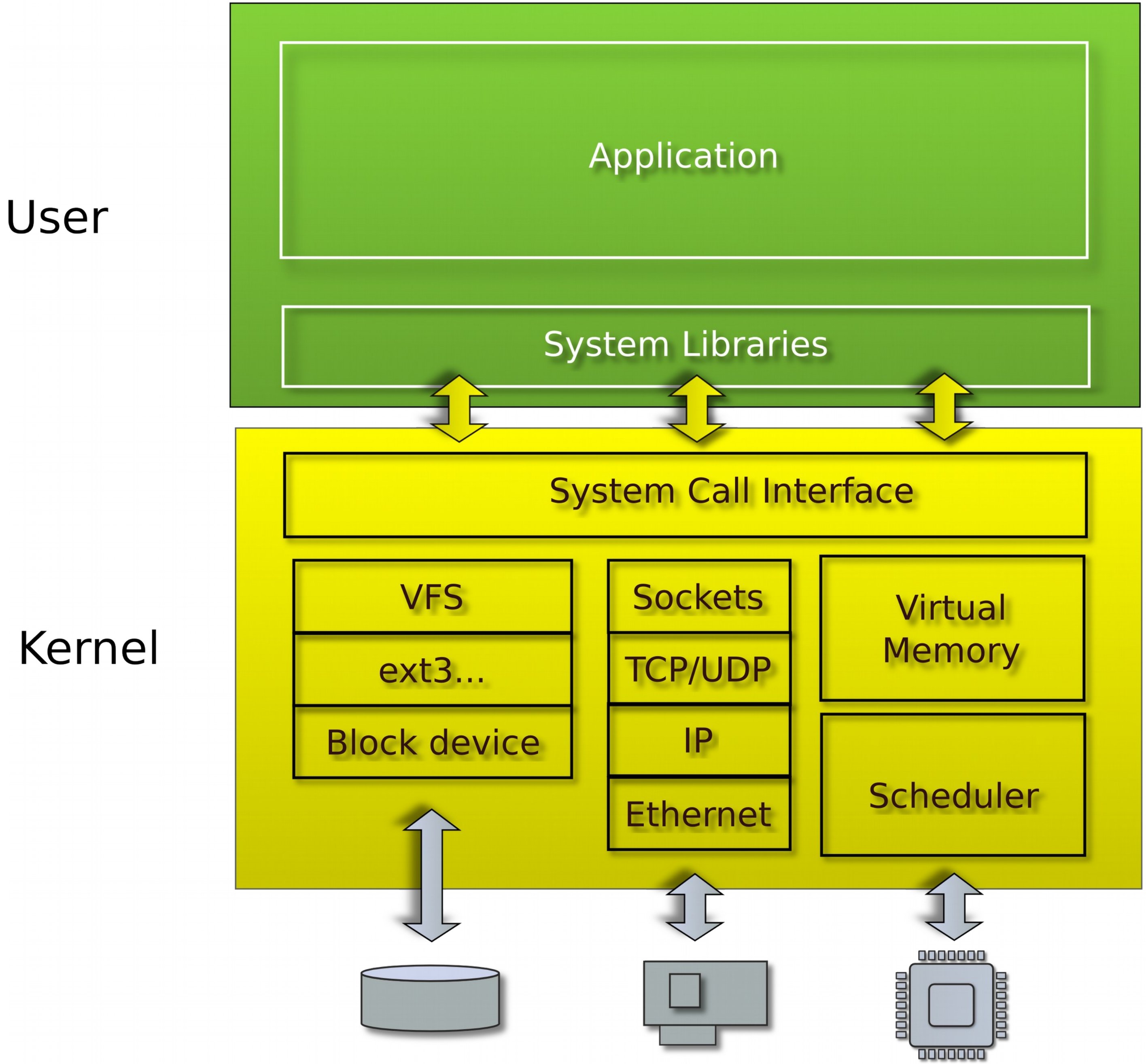
- Human readable names (files)
  - High level abstraction for saving data

```
fd = open("contacts.txt");
fpritnf(fd, "Name:%s\n",
name);
```

What if you want to send data over the network?

- Similar idea
  - Send/receive Ethernet packets (Level 2)
  - Two low level
- Sockets
  - High level abstraction for sending data

- Linux/Windows/Mac



User

Application

System Libraries

Kernel

System Call Interface

VFS

ext3...

Block device

Sockets

TCP/UDP

IP

Ethernet

Virtual Memory

Scheduler

Recap

- Run multiple programs
  - Each has illusion of a private memory and CPU
    - Context switching
    - Isolation and protection
  - Management of resources
    - Scheduling (management of CPU)
    - Memory management (management of physical memory)
- High-level abstractions for I/O
  - File systems
    - Multiple files, concurrent I/O requests
    - Consistency, caching
  - Network protocols
    - Multiple virtual network connections

Questions?