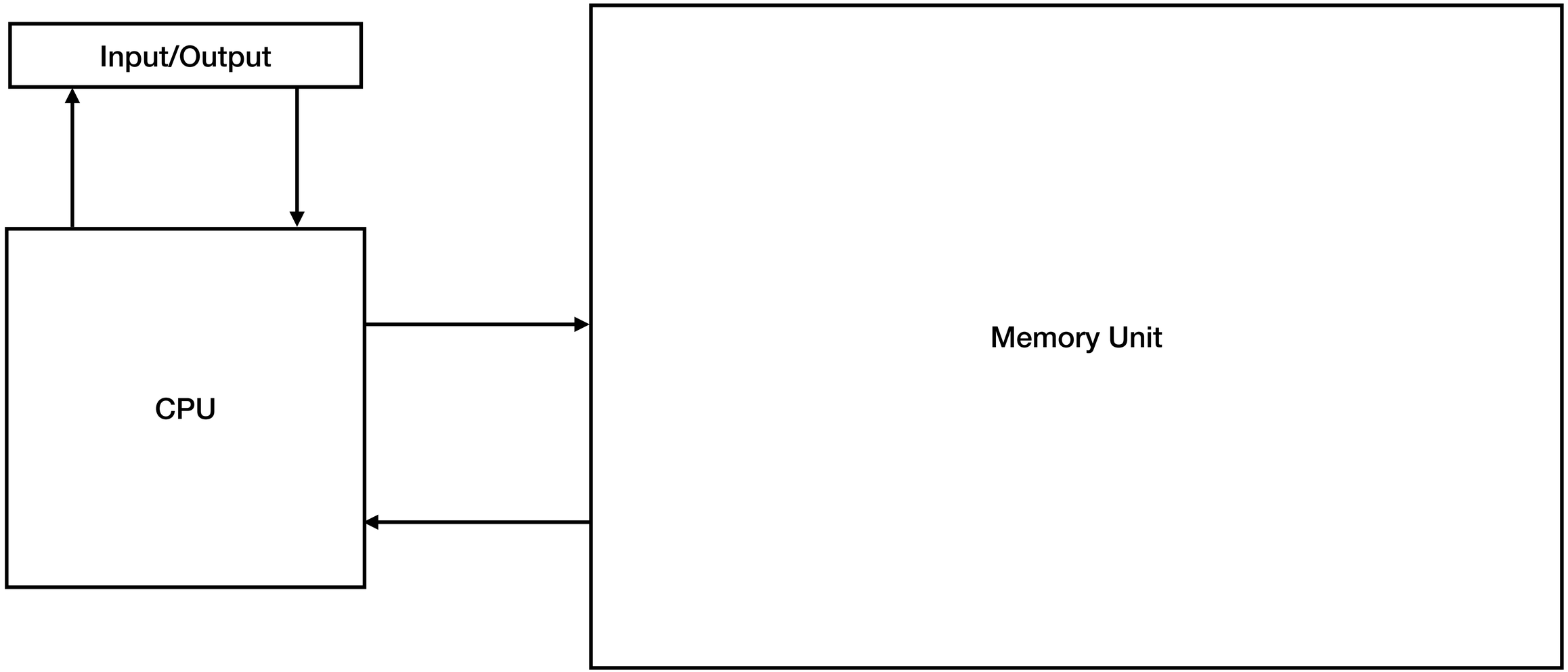
Machine Structure

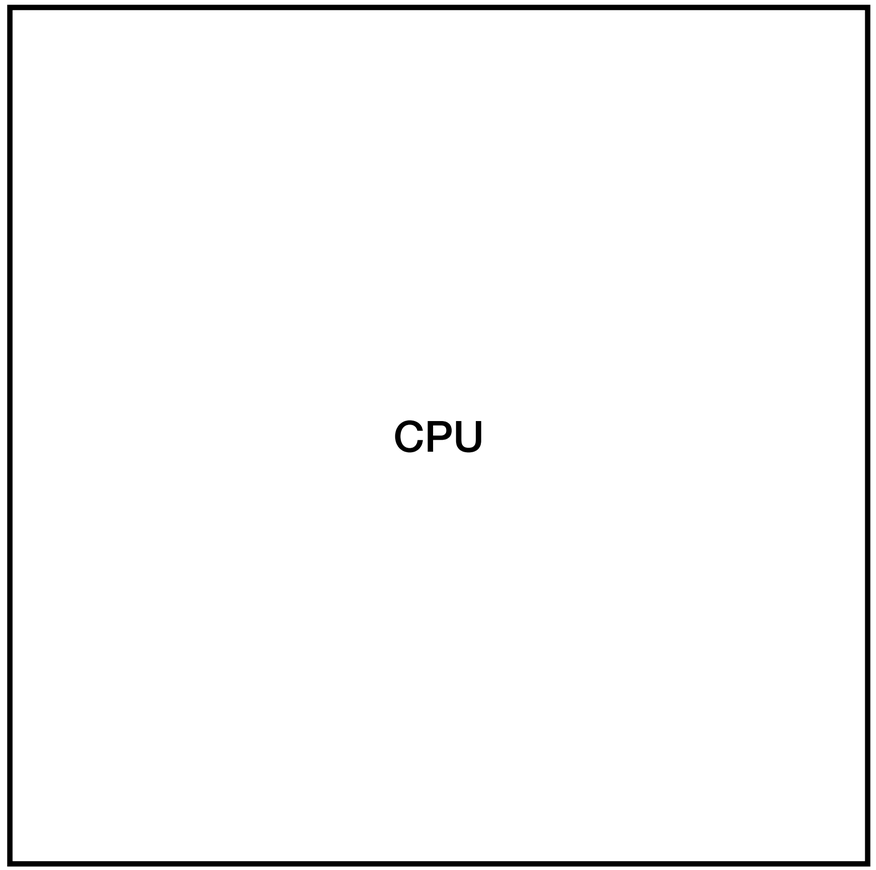
CS143: lecture 19

Byron Zhong, July 25

A Von Neumann Machine

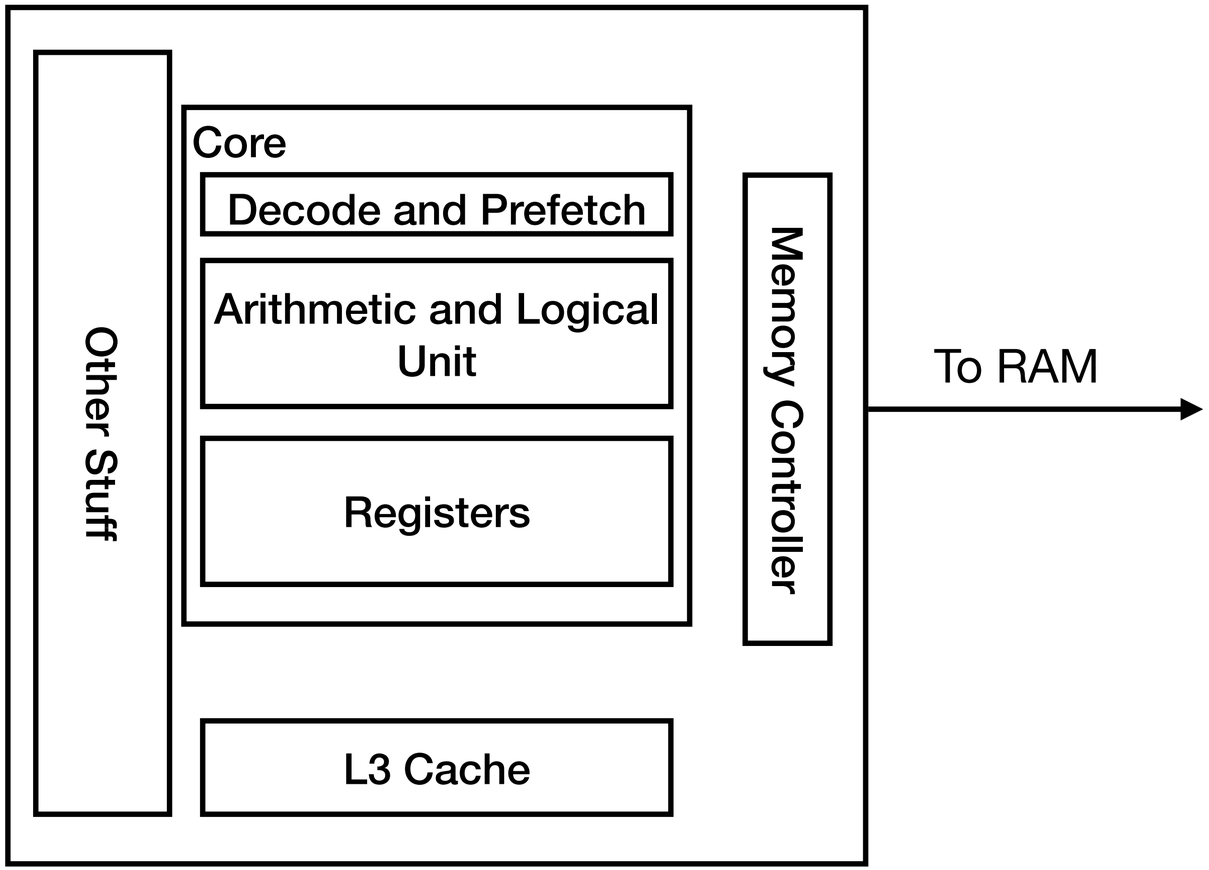


A Von Neumann Machine



CPU

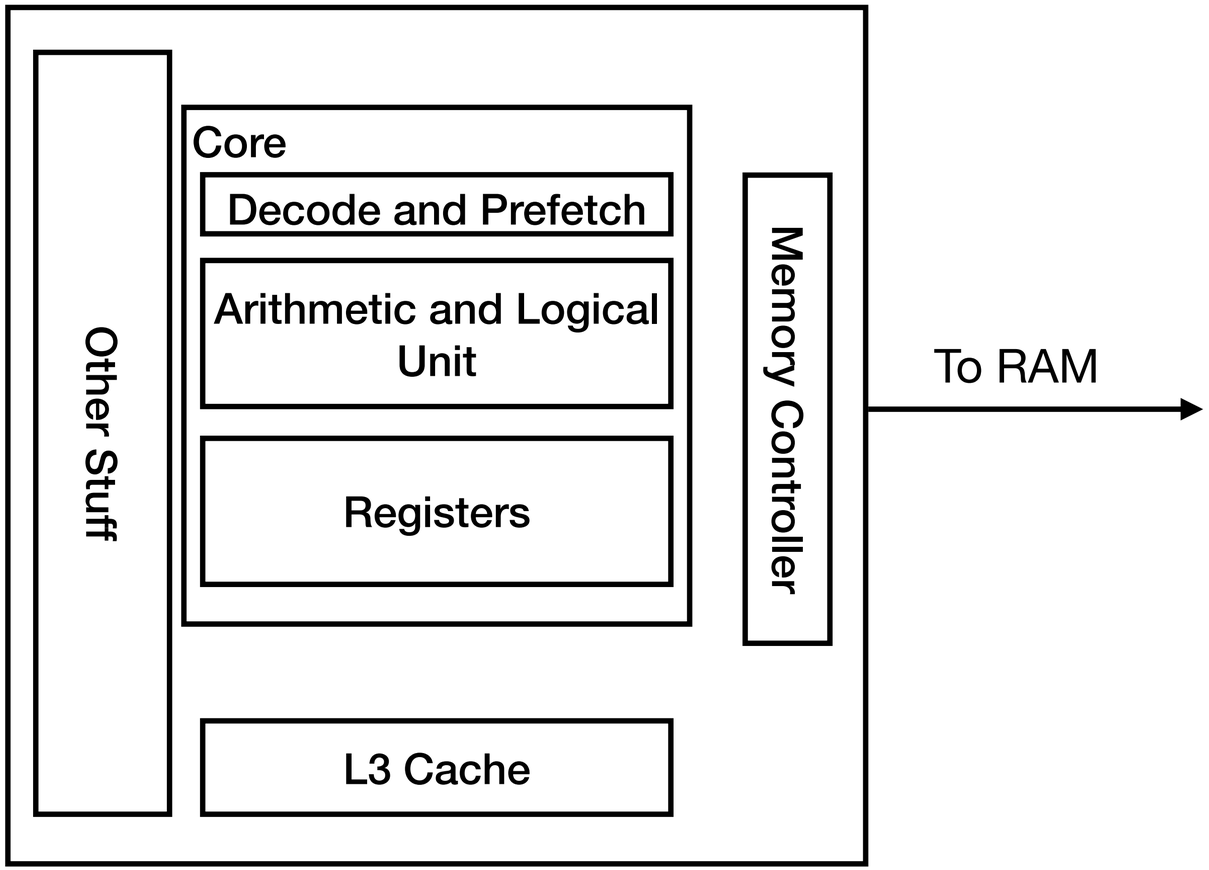
Review



- *Registers*: named locations storing 64-bit values. These registers can hold integers or addresses (pointers).
  - Some registers keep track of program states; others hold temporary data, such as local variables
- *ALU*: reads from registers and perform calculations.

CPU

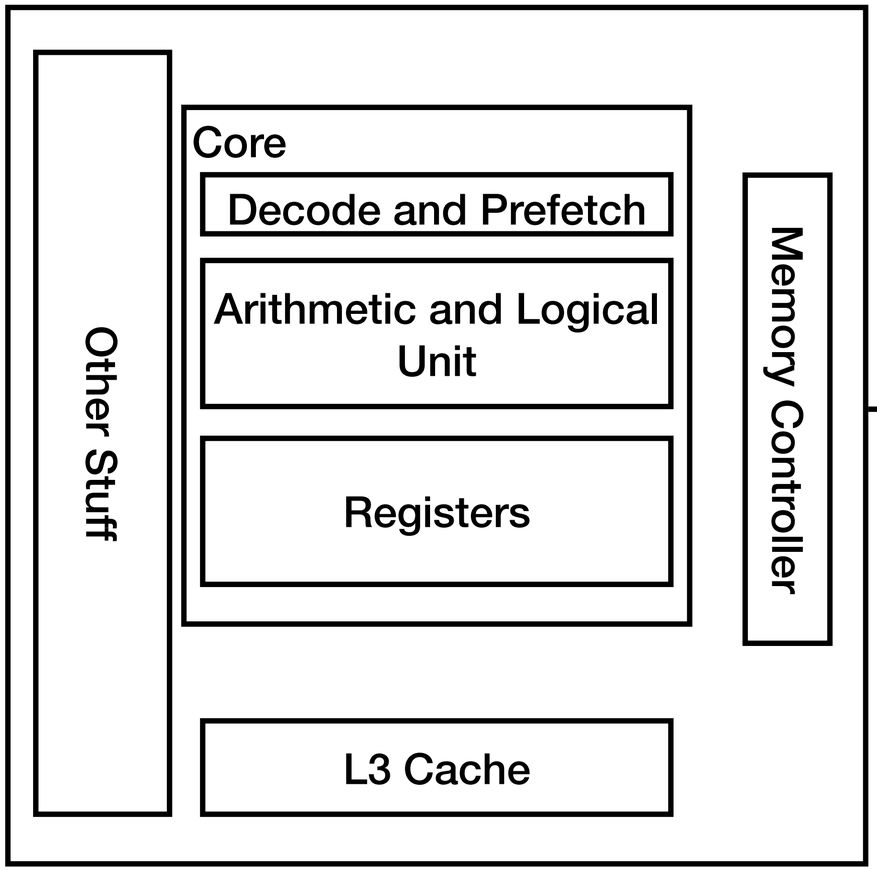
Review



- *Cache*: stores recently read memory to improve performance.
  - 144!
- *Program counter* (pc), or *instruction pointer* (ip), points at some instruction in memory.

CPU

Review



- From the time power is applied to the system, until the power is shut off, CPU performs the same basic tasks repeatedly:
- Reads the instruction pointed by *pc*
- Interprets the bits in the instruction
- Performs some operations as instructed
- Updates the *pc* to point to the *next* instruction

Instructions

Review

```
int accum = 0;

int sum(int x, int y)
{
        int t = x + y;
        accum += t;
        return t;
}
```

code.c

```
clang -O2 -c code.c

89 f3 01 f0 01 05 00 00 00 00 c3
```

- This function is compiled to 11 bytes of instructions

Instructions

Review

```c
int accum = 0;

int sum(int x, int y)
{
        int t = x + y;
        accum += t;
        return t;
}
```

code.c

```
$ objdump -d code.o

code.o:     file format elf64-x86-64


Disassembly of section .text:

0000000000000000 <sum>:
   0:   89 f8                   mov    %edi,%eax
   2:   01 f0                   add    %esi,%eax
   4:   01 05 00 00 00 00       add    %eax,0x0(%rip)
   a:   c3                      retq
```

`Objdump` displays info about object files. `-d` "disassembles" machine code.

Instructions

Review

```c
int accum = 0;

int sum(int x, int y)
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   a:   c3                      retq
```

%xxx are register names

Instructions

Review

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        return t;
}
```

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   a:   c3                      retq
```

By convention, %edi stores the first arg, %esi stores the second.

Instructions

Review

```c
int accum = 0;

int sum(int x, int y)
{
        int t = x + y;
        accum += t;
        return t;
}
```

code.c

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$ objdump -d code.o

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   4:   01 05 00 00 00 00       add    %eax,0x0(%rip)
   a:   c3                      retq
```

%eax stores the return value.

Instructions

Review

```c
int accum = 0;

int sum(int x, int y)
{
        int t = x + y;
        accum += t;
        return t;
}
```

code.c

```
$ objdump -d code.o

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```

move the first argument (edi) to the return value (eax)

Instructions

Review

```
int accum = 0;

int sum(int x, int y)
{
        int t = x + y;
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        return t;
}
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code.c

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$ objdump -d code.o

code.o:     file format elf64-x86-64


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```

add the second argument (esi) to the return value (eax)

Instructions

Review

```
int accum = 0;

int sum(int x, int y)
{
        int t = x + y;
        accum += t;
        return t;
}
```

code.c

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$ objdump -d code.o

code.o:     file format elf64-x86-64


Disassembly of section .text:

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   0:                                    mov    %edi,%eax
   2:                                    add    %esi,%eax
   4:                                    add    %eax,0x0(%rip)
   a:    c3                              retq
```

add eax to a location.

Instructions

Review

```
int accum = 0;

int sum(int x, int y)
{
        int t = x + y;
        accum += t;
        return t;
}
```

code.c

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$ objdump -d code.o

code.o:     file format elf64-x86-64


Disassembly of section .text:

0000000000000000 <sum>:
   0:                                    mov    %edi,%eax
   2:    return                          add    %esi,%eax
   4:                                    add    %eax,0x0(%rip)
   a:    c3                              retq
```

Instructions

Review

```
int accum = 0;

int sum(int x, int y)
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        int t = x + y;
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        return t;
}
```

code.c

- Load: copy some bytes from memory to a register
- Store: copy some bytes from a register to memory
- Update: copy the contents of two registers to the ALU, which does some calculation and stores the result in a register
- I/O operations: read/write from an I/O device into a register
- Jump: Set the *pc* to be some arbitrary value

Instructions

Review

```c
int accum = 0;

int sum(int x, int y)
{
        int t = x + y;
        accum += t;
        return t;
}
```

code.c

```c
int sum(int x, int y);

int main(void)
{
        return sum(1, 3);
}
```

main.c

clang -O2 -o prog code.o main.c

Instructions

Review

```
0000000000401110 <sum>:
  401110:89 f8                    mov    %edi,%eax
  401112:01 f0                    add    %esi,%eax
  401114:01 05 12 2f 00 00        add    %eax,0x2f12(%rip)        # 40402c <accum>
  40111a:c3                       retq
  40111b:0f 1f 44 00 00           nopl   0x0(%rax,%rax,1)

0000000000401120 <main>:
  401120:bf 01 00 00 00           mov    $0x1,%edi
  401125:be 03 00 00 00           mov    $0x3,%esi
  40112a:e9 e1 ff ff ff           jmpq   401110 <sum>
  40112f:90                       nop
```

Instructions

Review

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Instructions

Review

```
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  40112a:e9 e1 ff ff ff           jmpq   401110 <sum>
  40112f:90                       nop
```

jump to location 401110

Instructions

Review

```
0000000000401110 <sum>:
  401110:89 f8                    mov    %edi,%eax
  401112:01 f0                    add    %esi,%eax
  401114:01 05 12 2f 00 00        add    %eax,0x2f12(%rip)        # 40402c <accum>
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  40112f:90                       nop
```
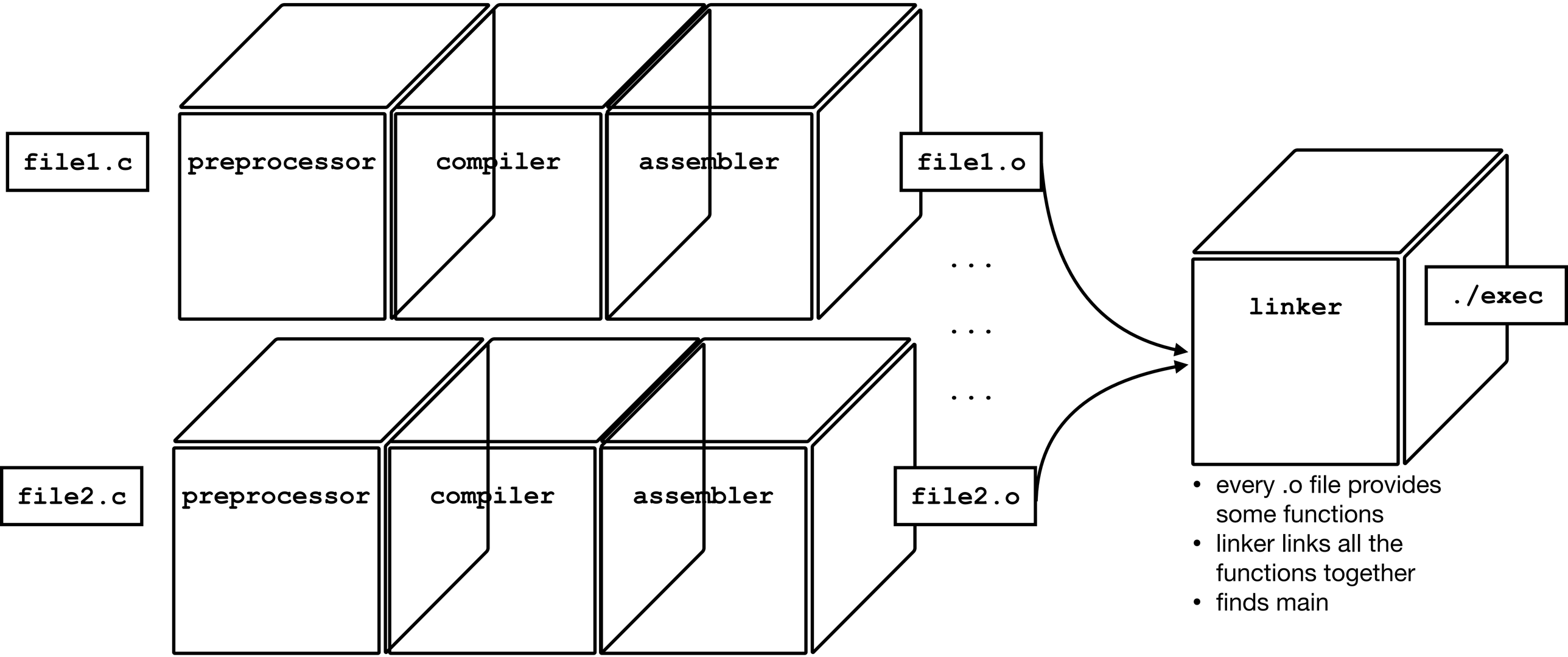

The global variable has been assigned a location 40402c

Separate Compilation

Review



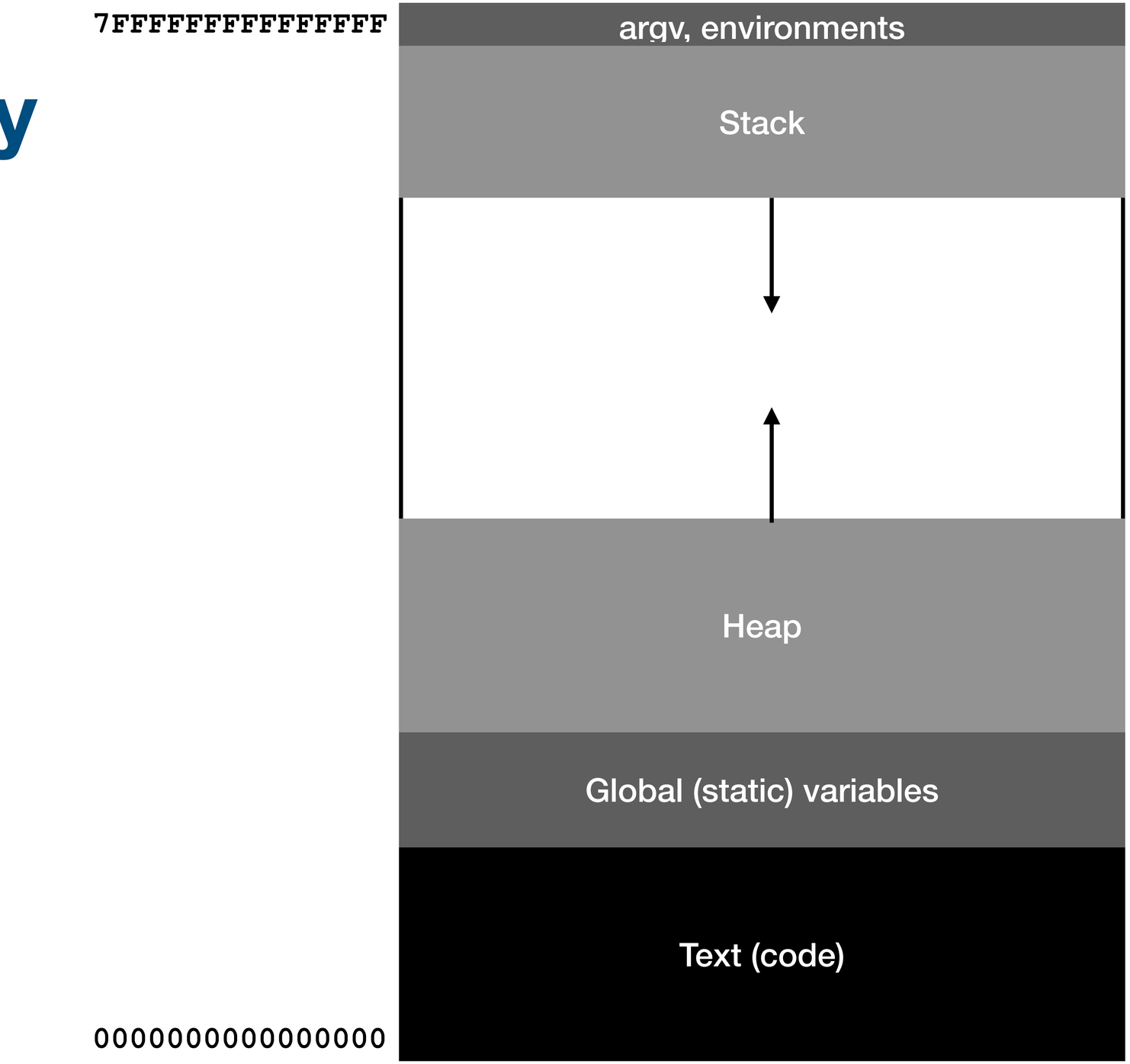
- every .o file provides some functions
- linker links all the functions together
- finds main

Instructions

Review

- C is compiled to a low-level language called *assembly* language.
  - Assembly language expresses a sequence of CPU *instructions*.
- The *assembly* language is *assembled* by an *assembler* to machine code (byte sequences).
- *Disassembler* does the opposite.
- CPU executes instructions in a loop from power-on to power-off
- A CPU core contains an ALU and a number of registers (and other stuff).

Process Memory



Instructions

- When you run **`./prog arg1 arg2 arg3`**, a *loader* puts the content of **`prog`** into memory, and:
  - Moves the *pc* to the first instruction in **`prog`**
  - Initializes the stack
  - Copies the command-line arguments into memory
  - ...

Machine

Your computer can do many things at the same time...






Machine

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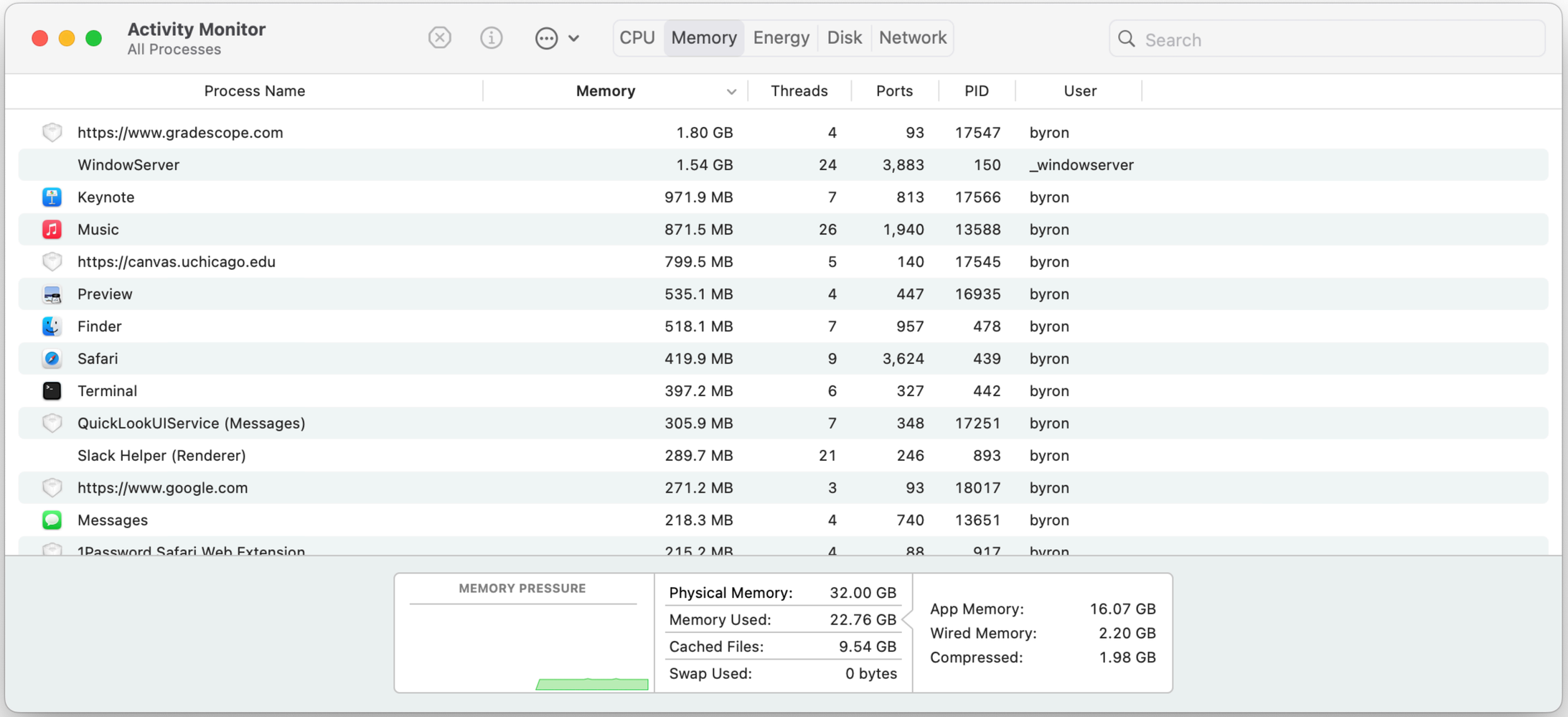

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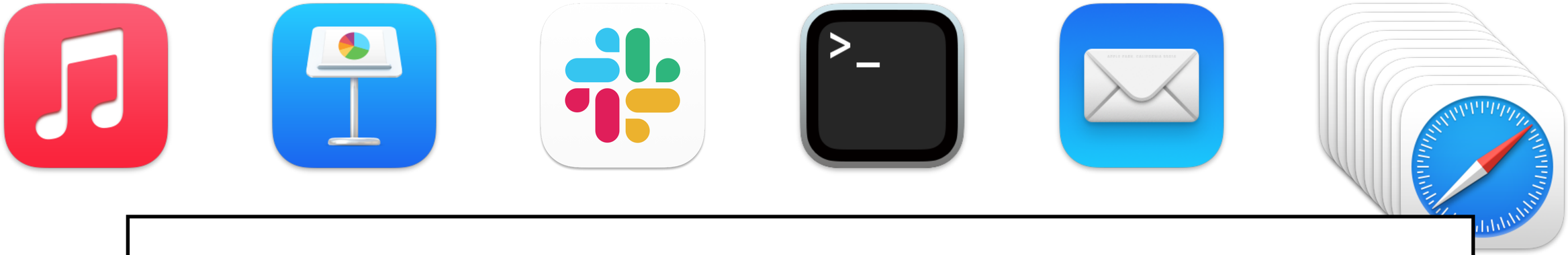
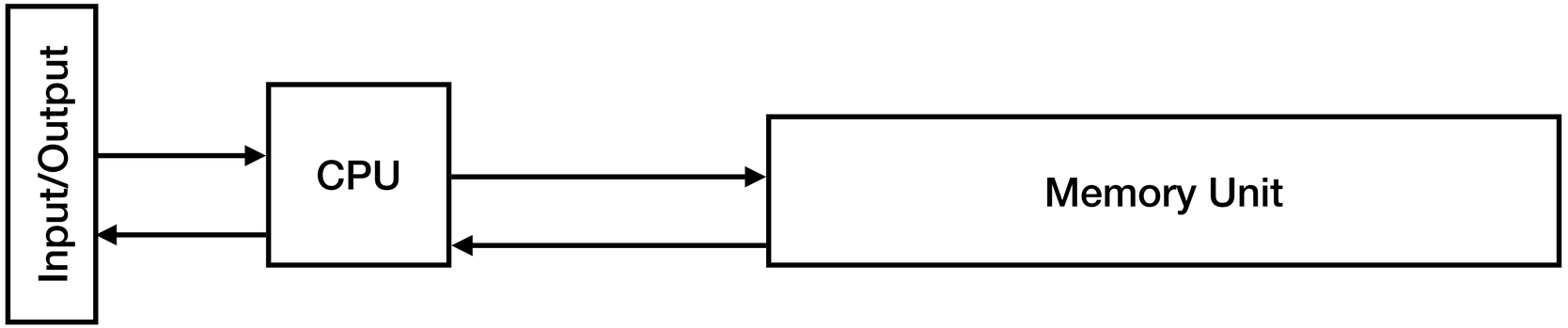
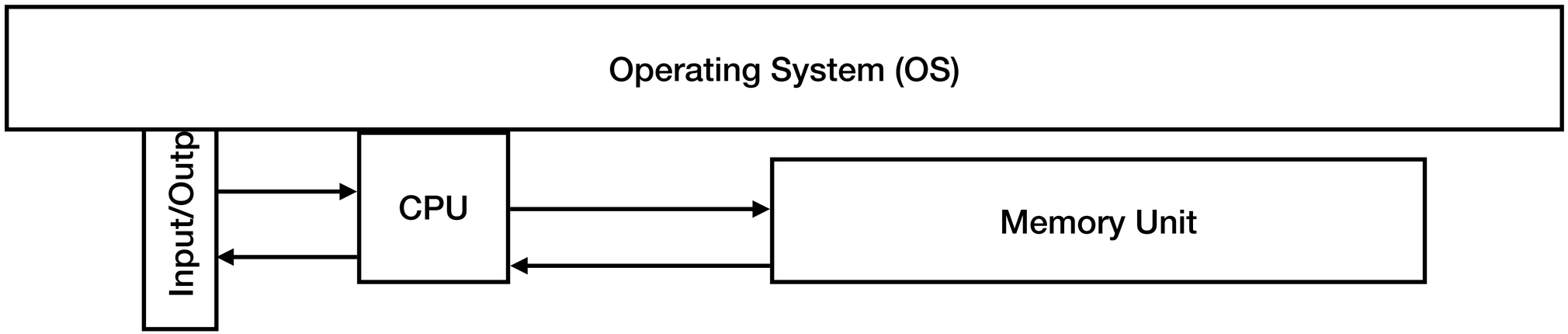




Machine

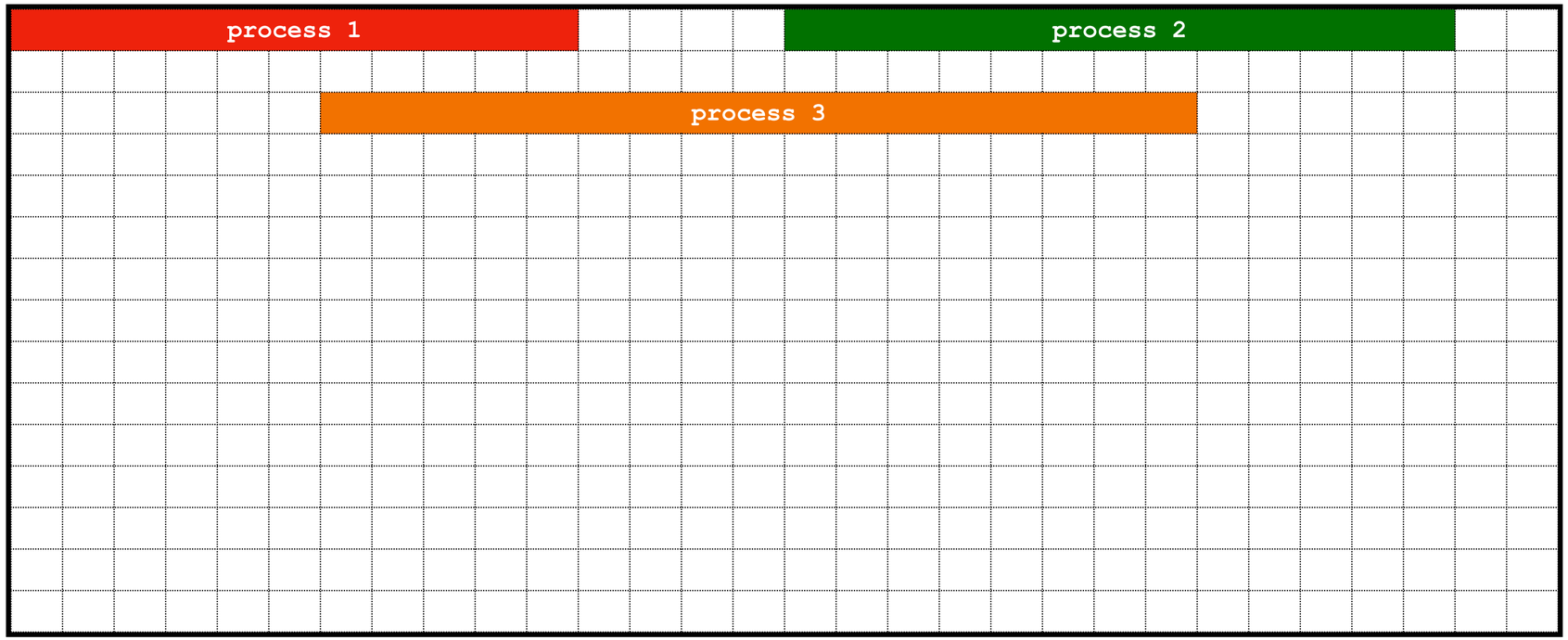
Your computer can do many things at the same time...

- The operating system creates an illusion that each process is running by itself by:
  - *Context switching* -- rapidly switching which process has control over the CPU
  - *Virtual memory* -- providing each process with its own address space



Virtual Memory

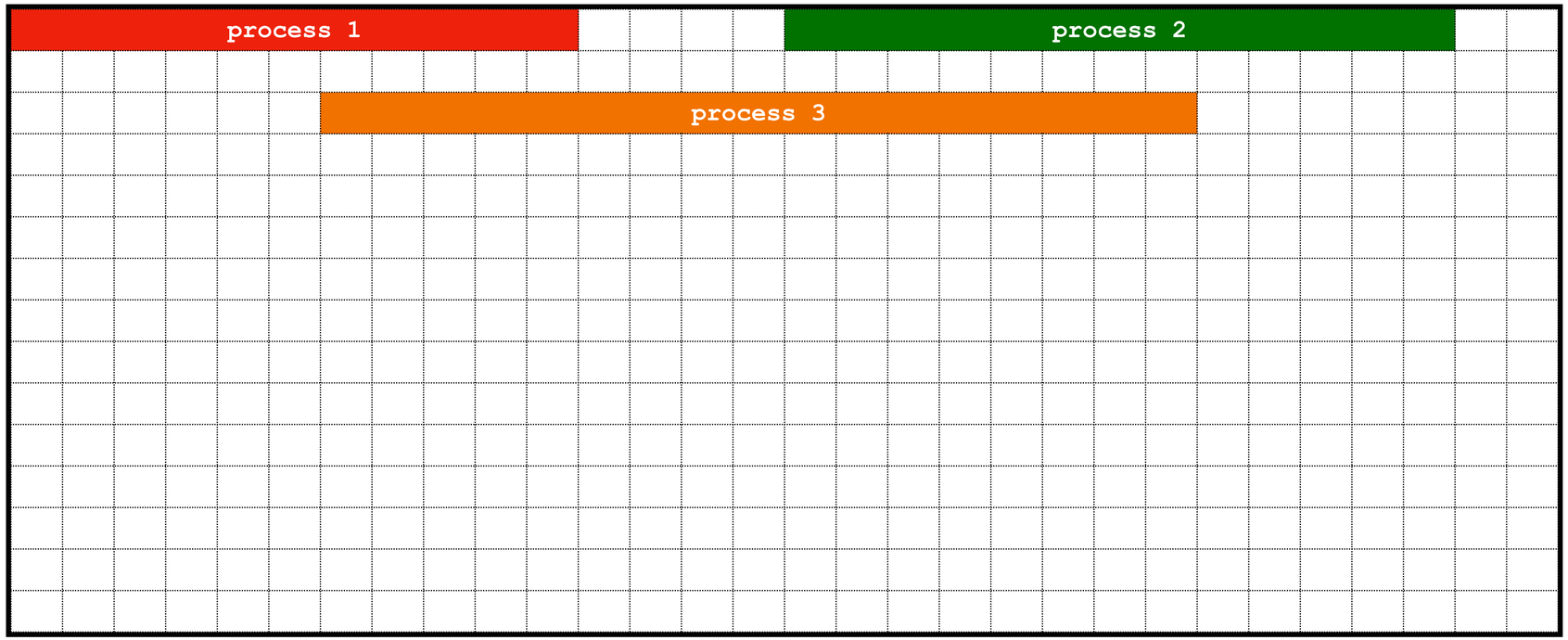
Physical memory



Virtual Memory

What if process 1 needs more memory?

Physical memory



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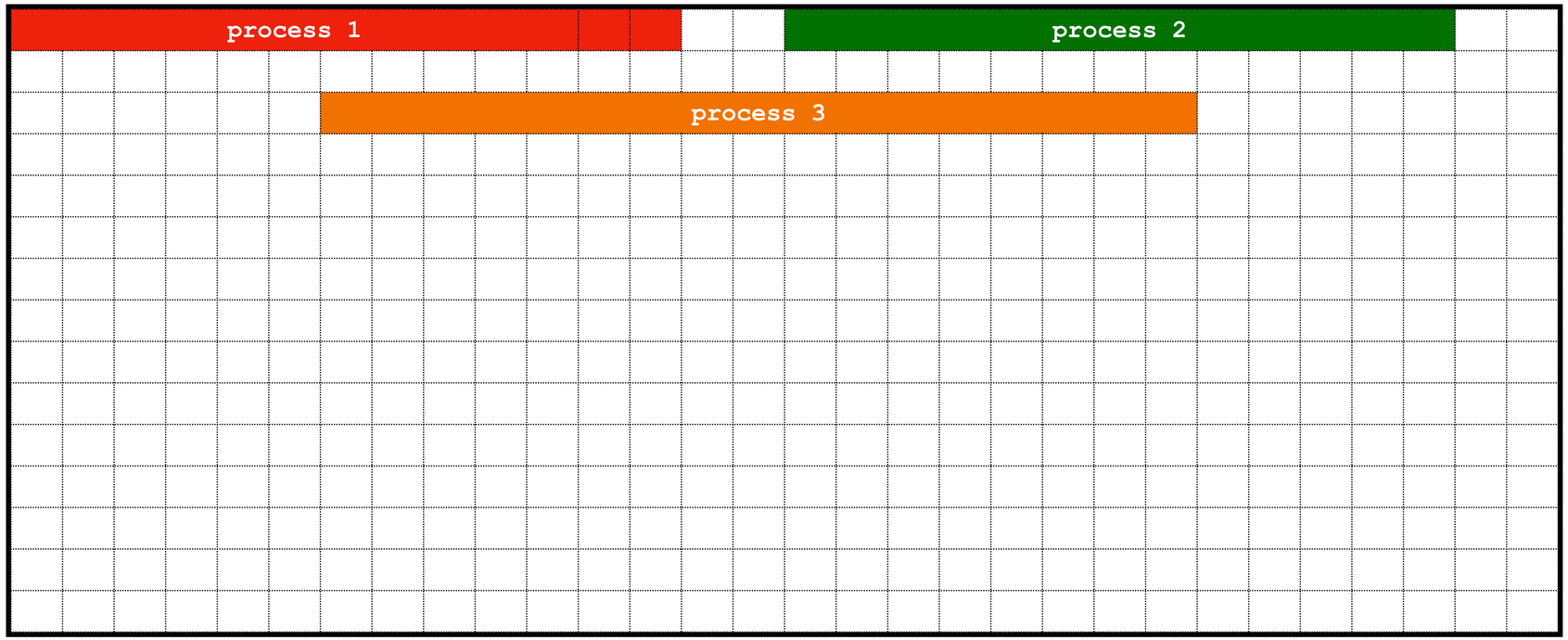

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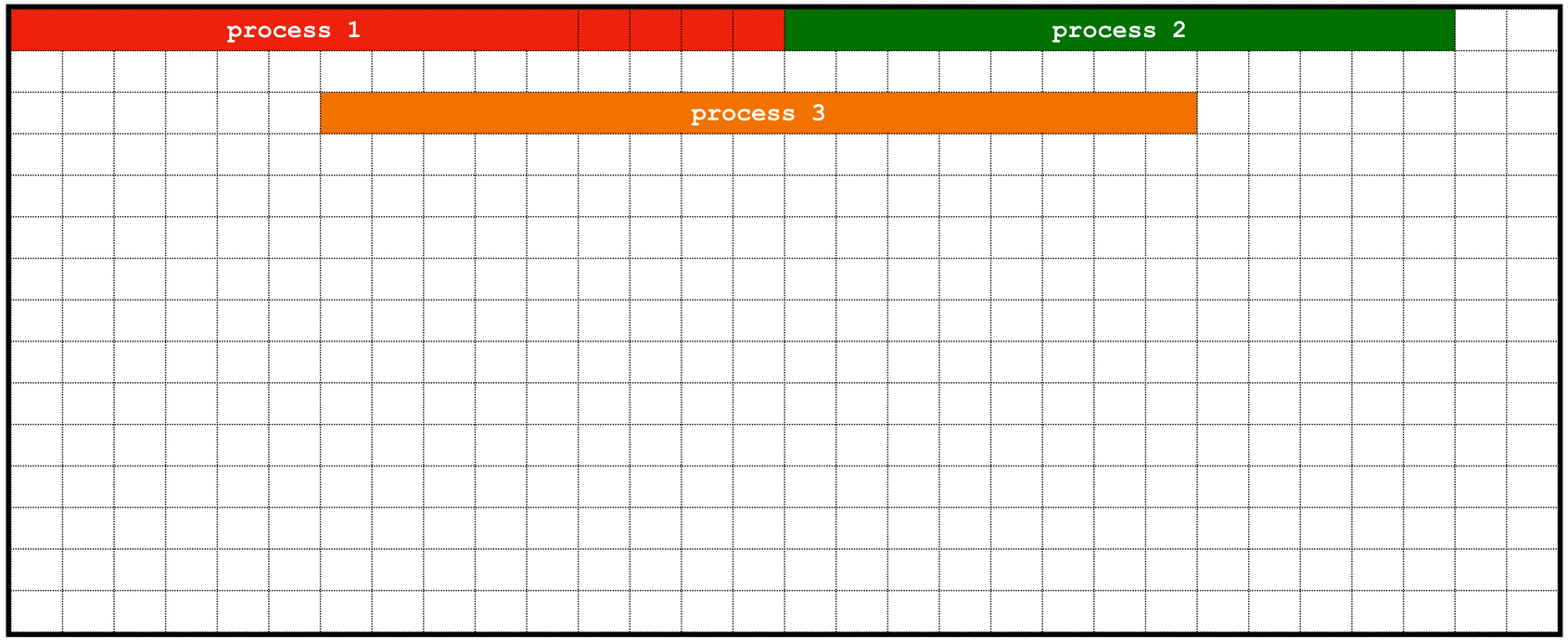

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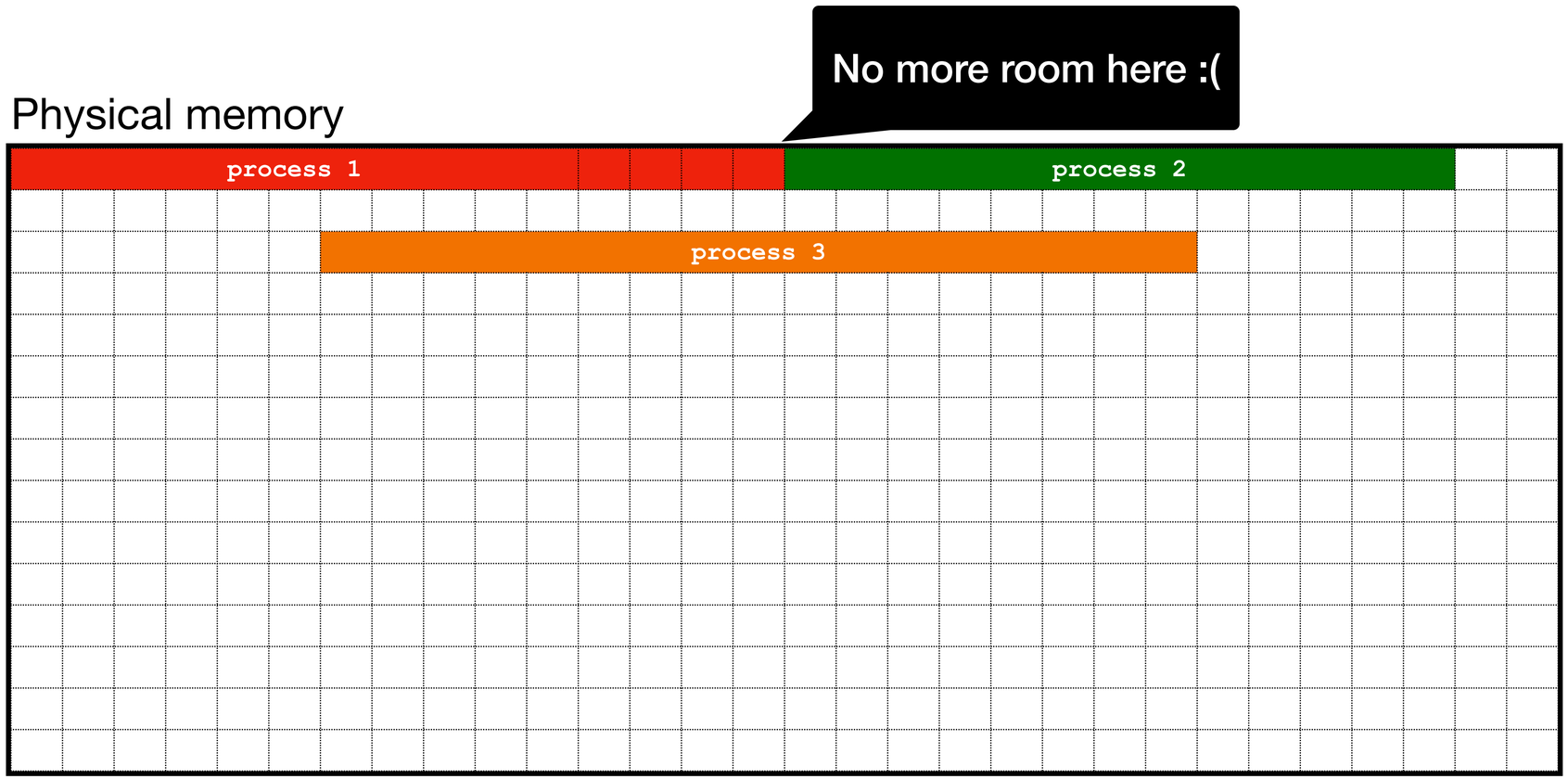
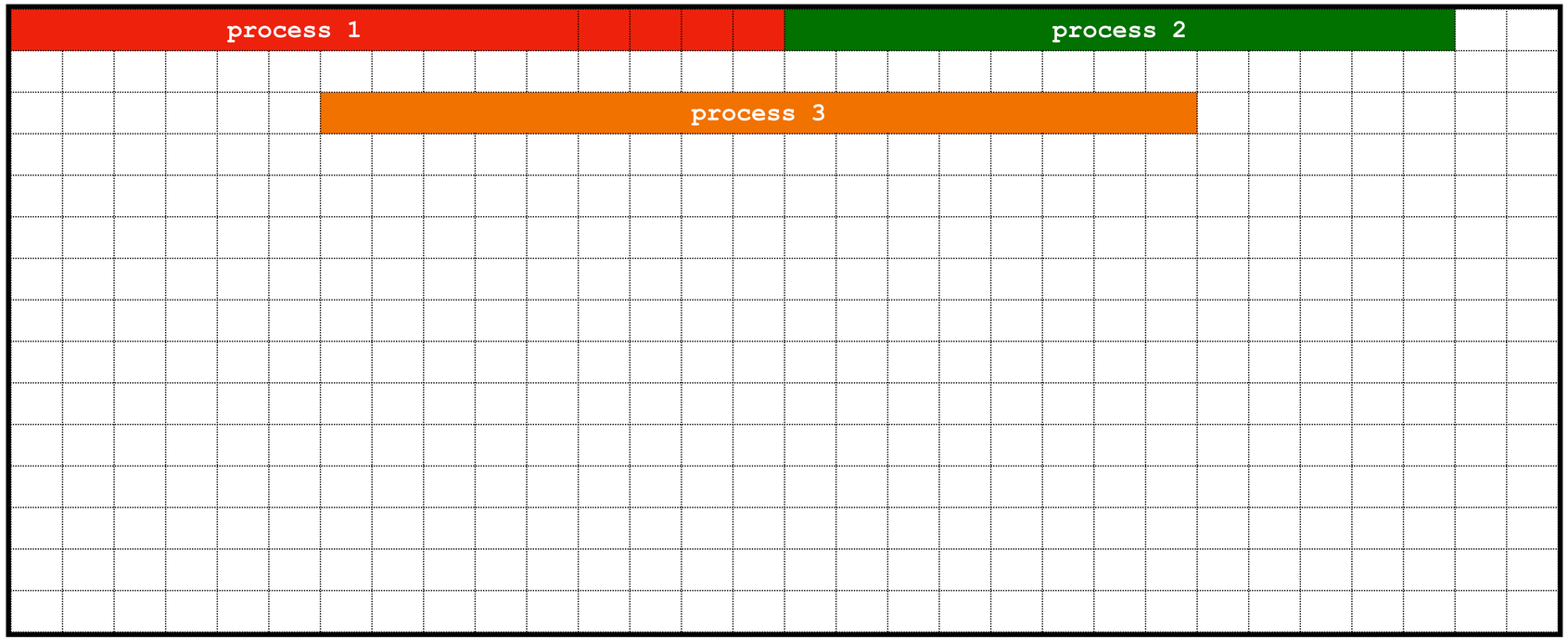


Virtual Memory

What if process 1 is buggy or malicious?

Physical memory



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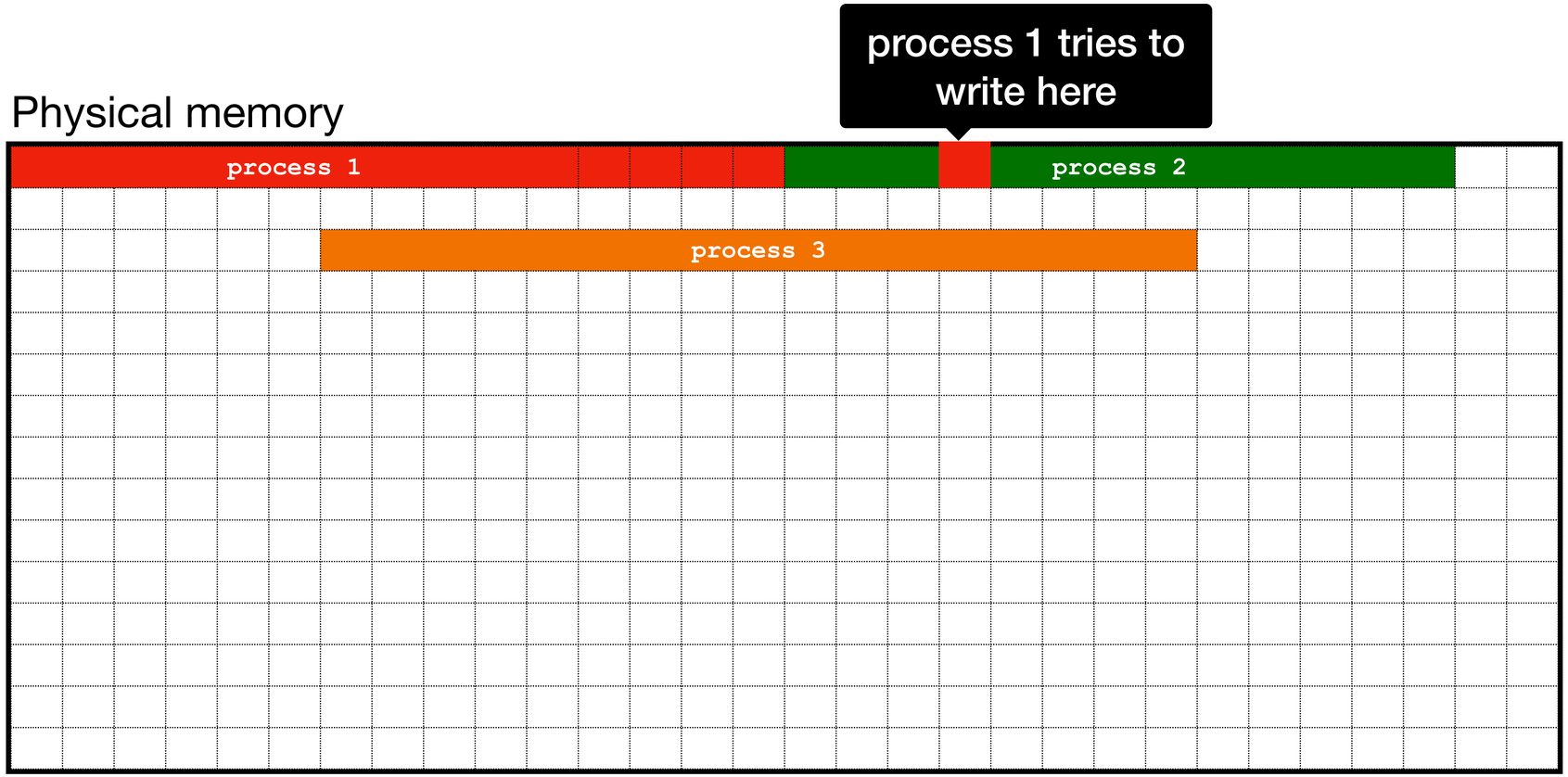
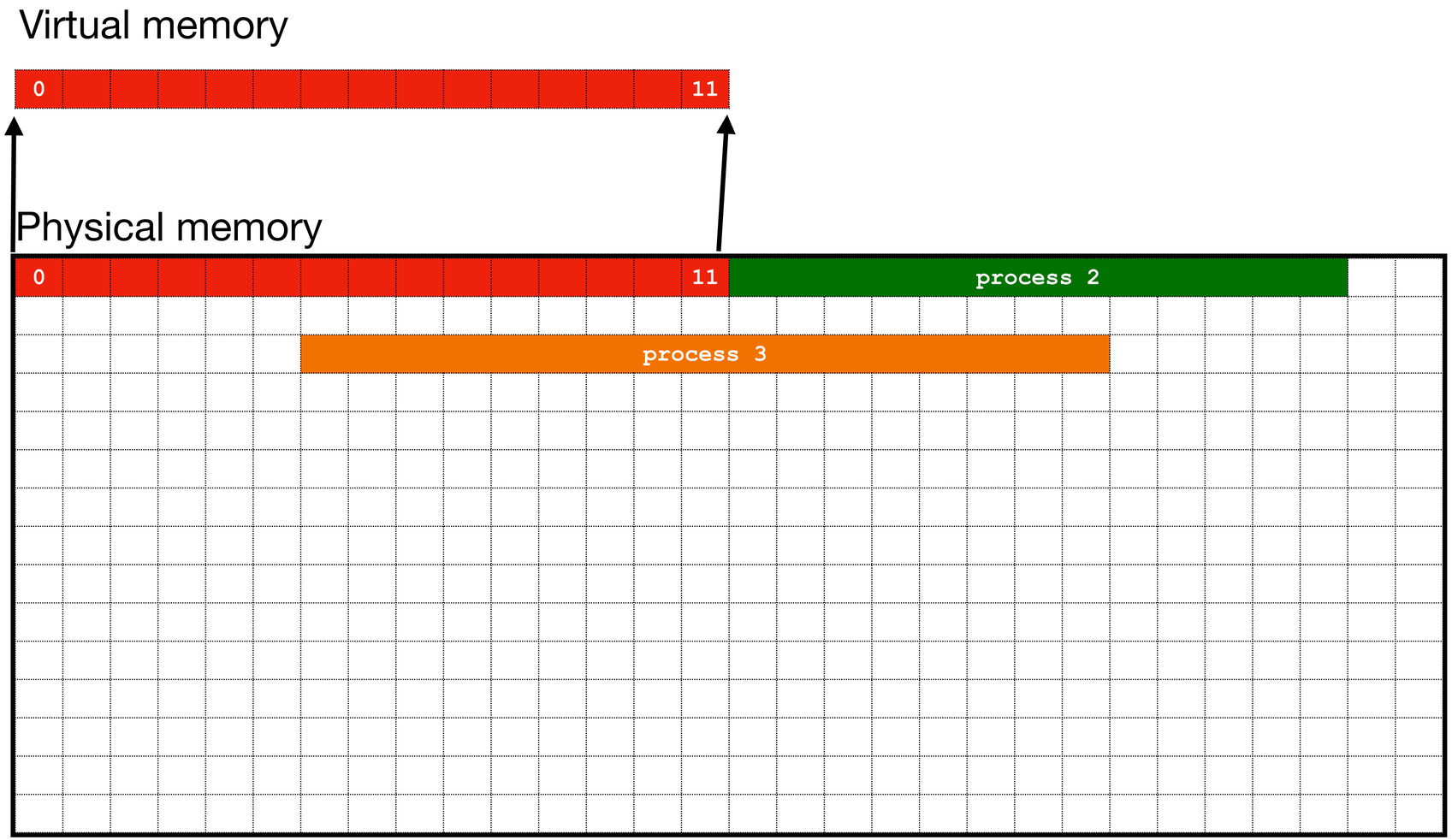


Virtual Memory



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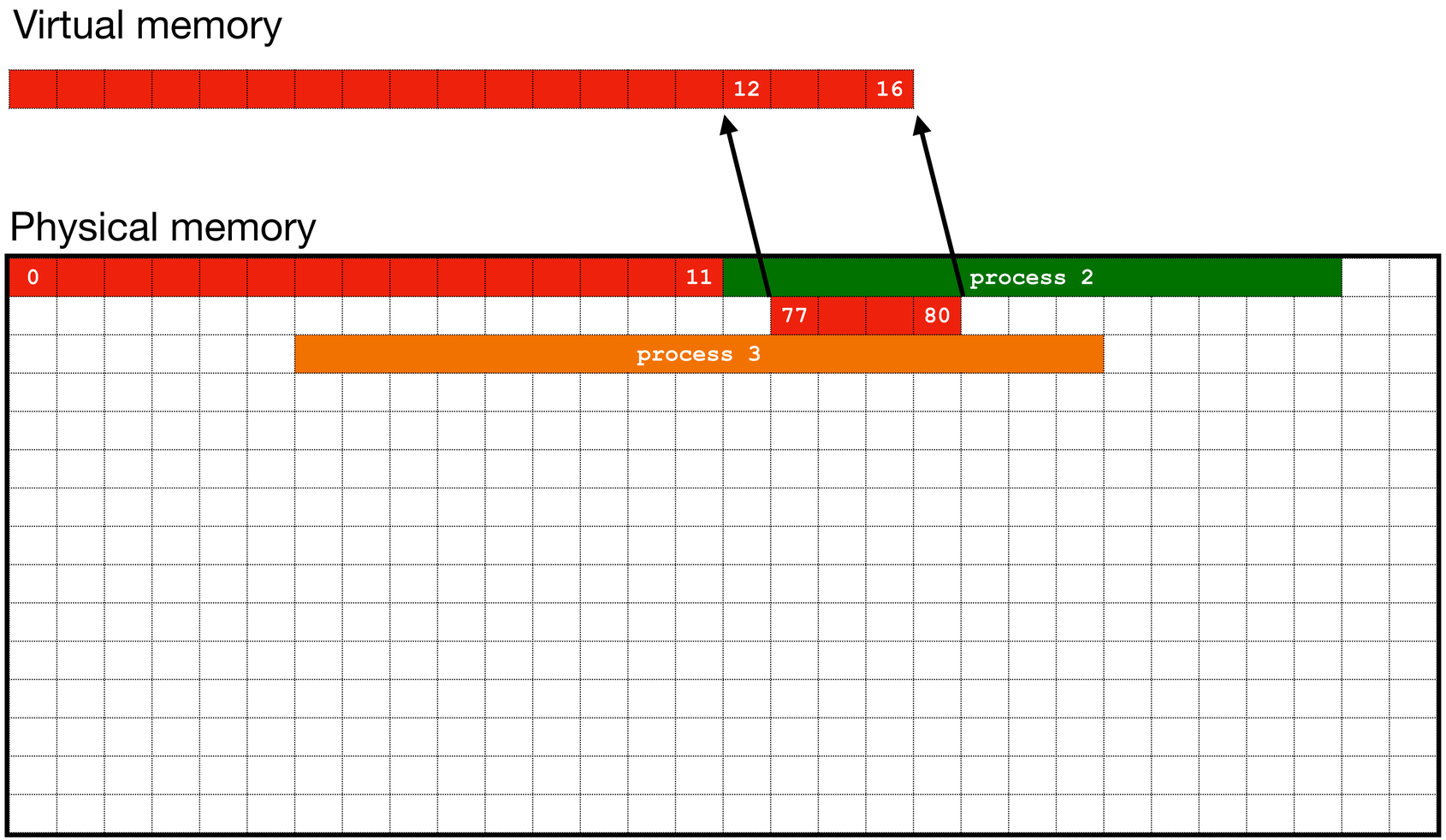

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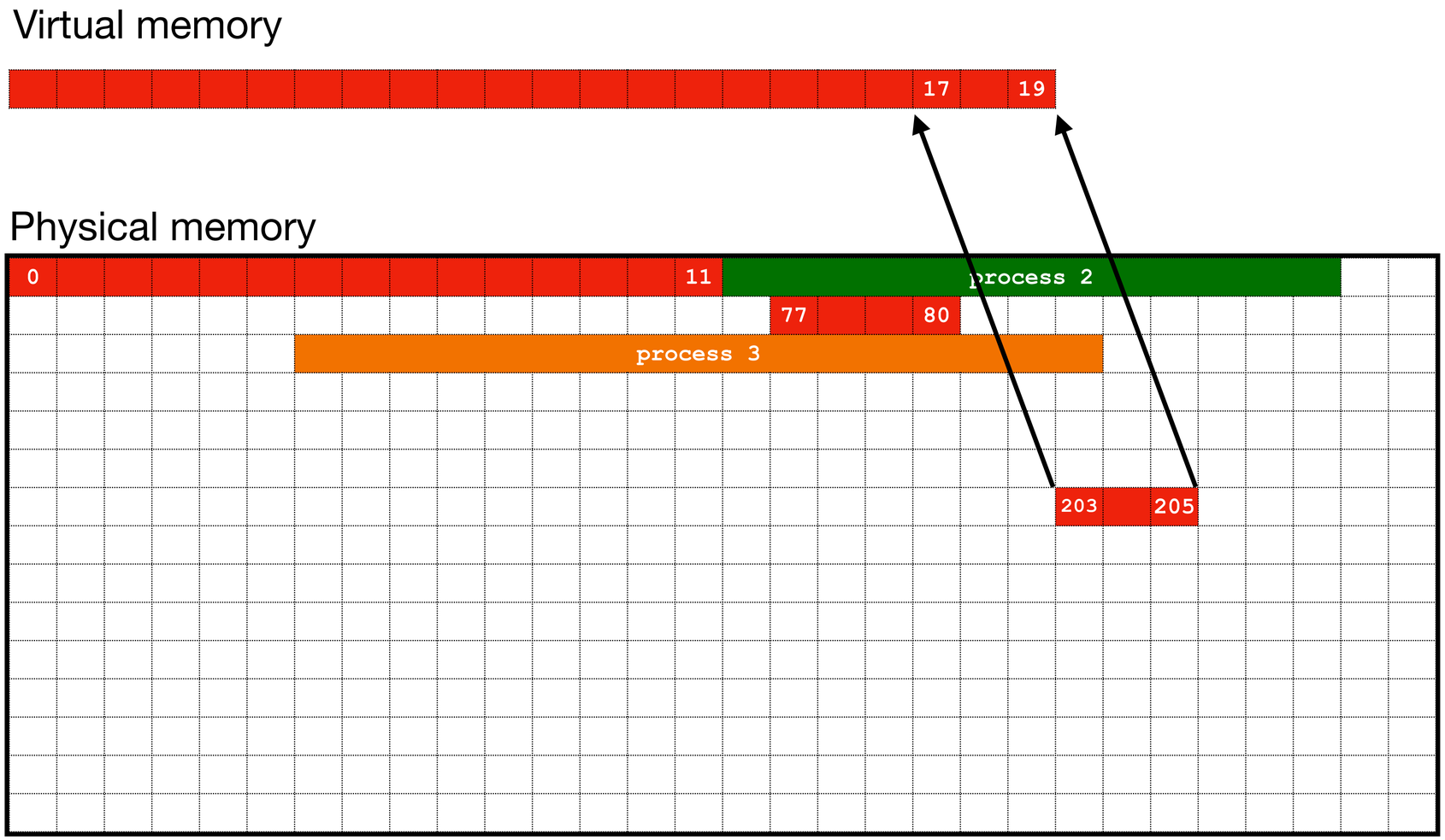
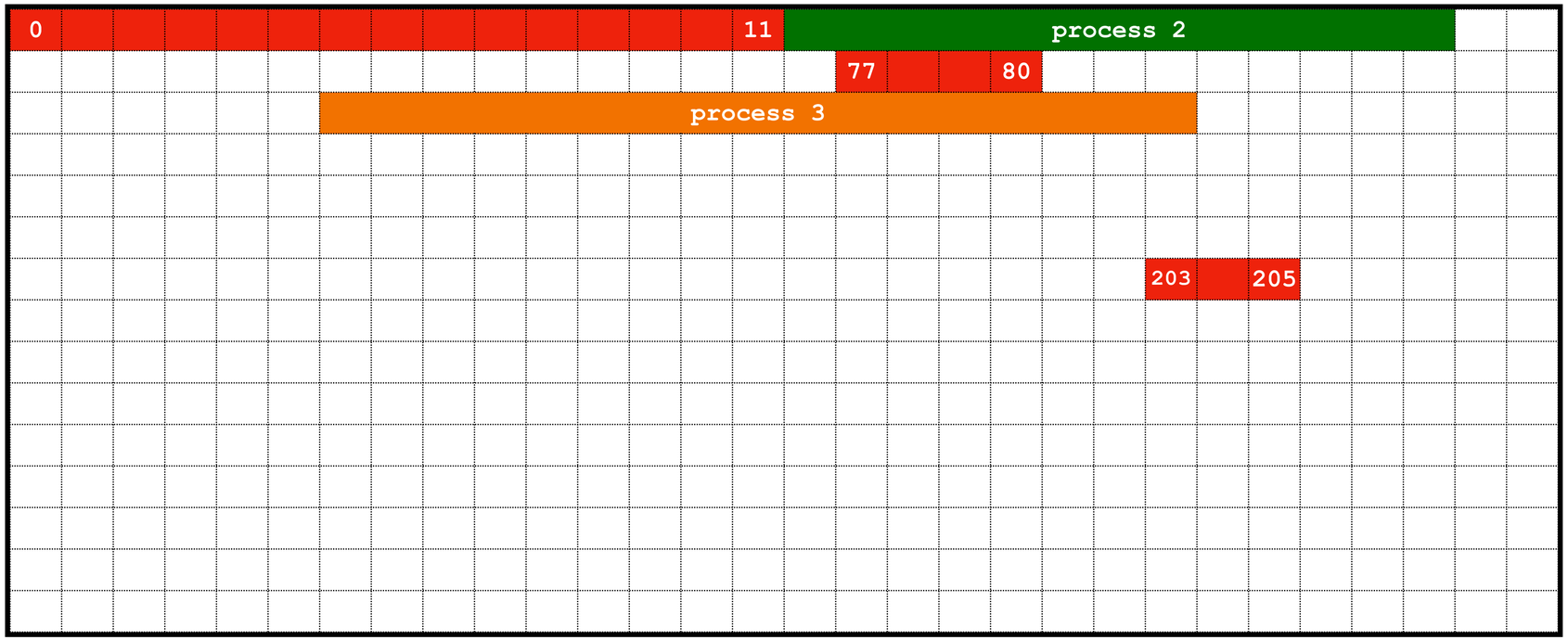


Virtual Memory

Virtual memory

Get address 18

Physical memory



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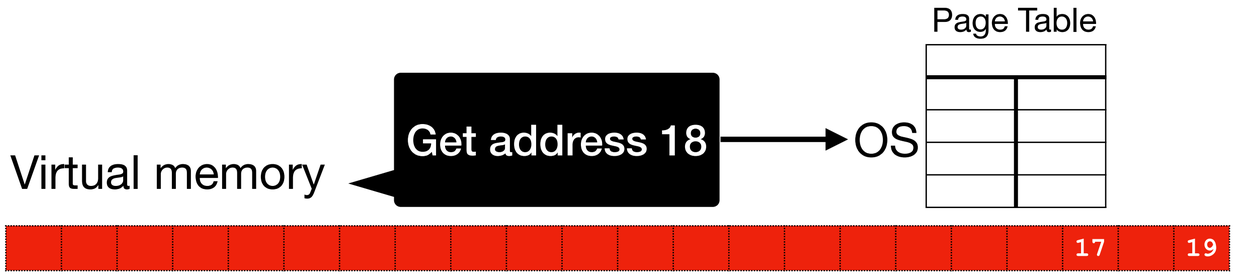
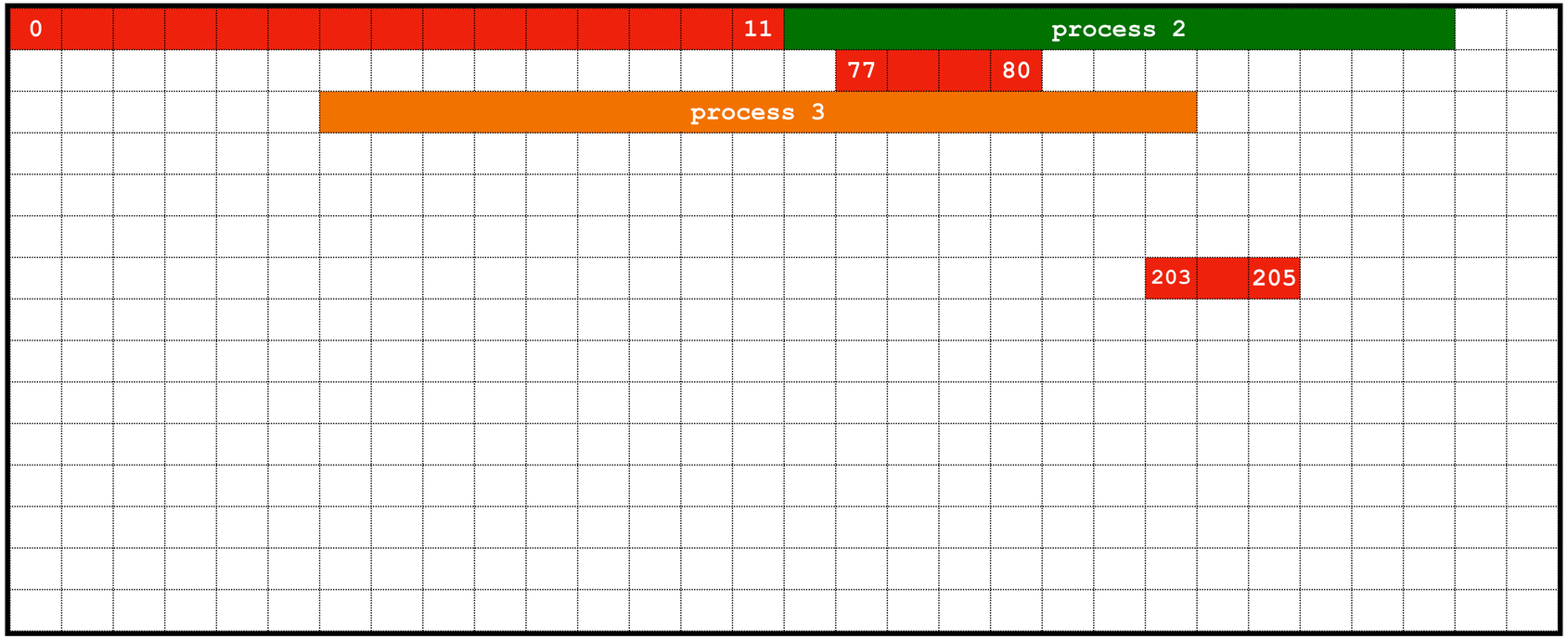
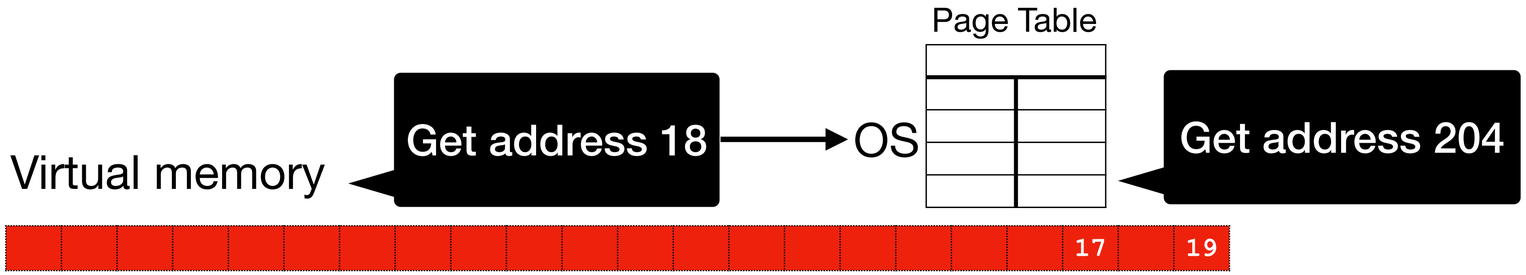


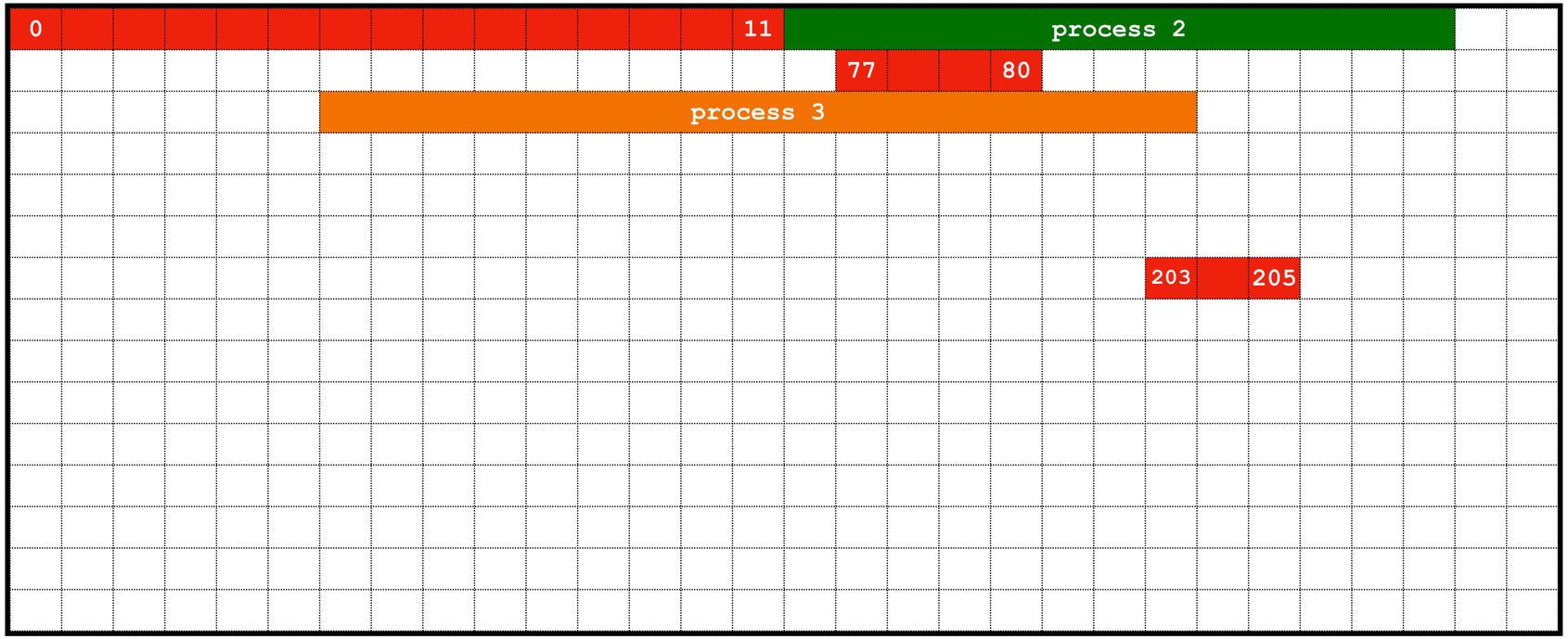
Physical memory



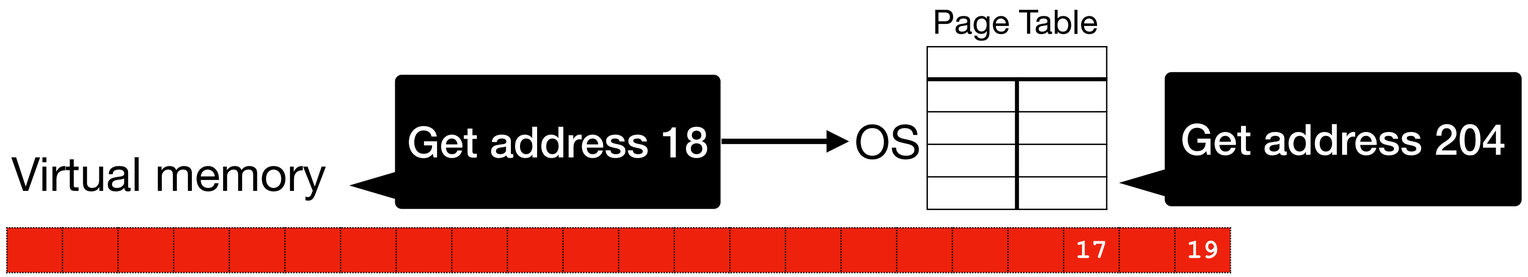
Virtual Memory

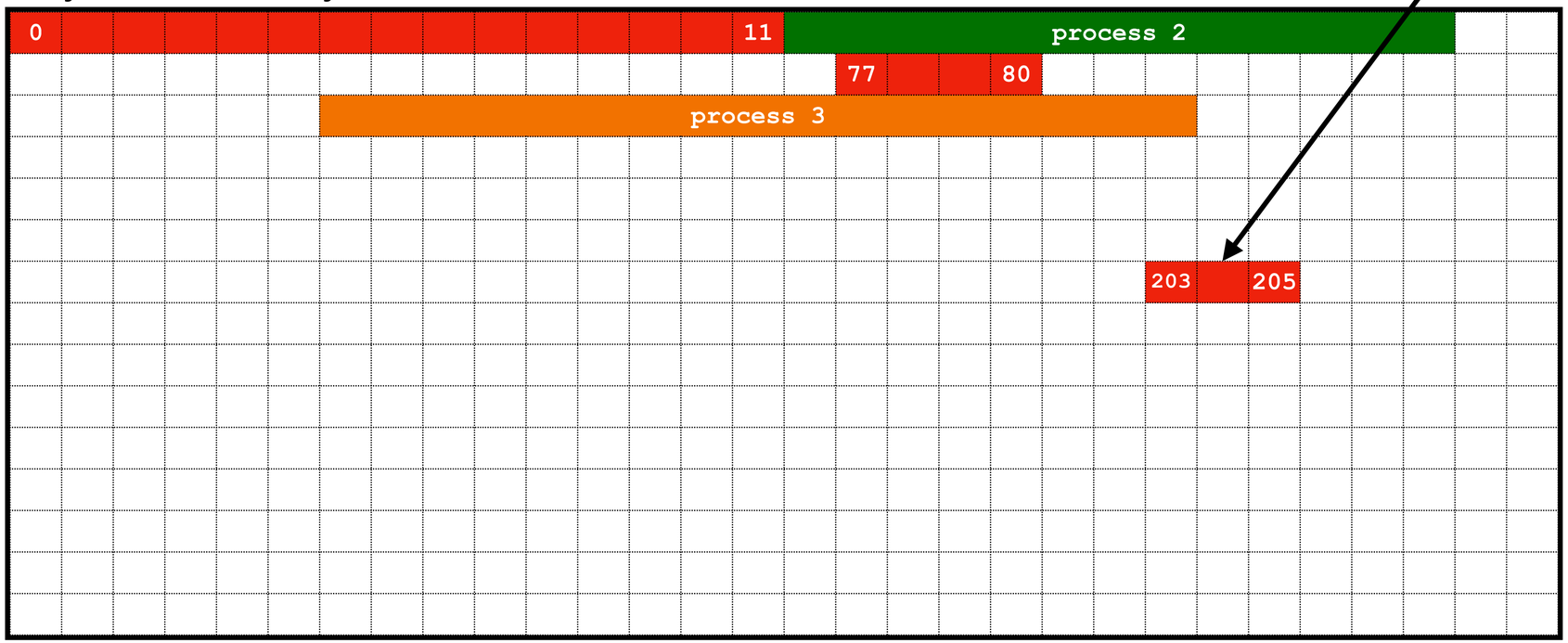


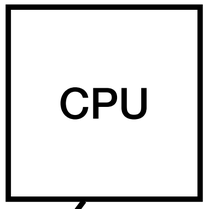
Physical memory



Virtual Memory





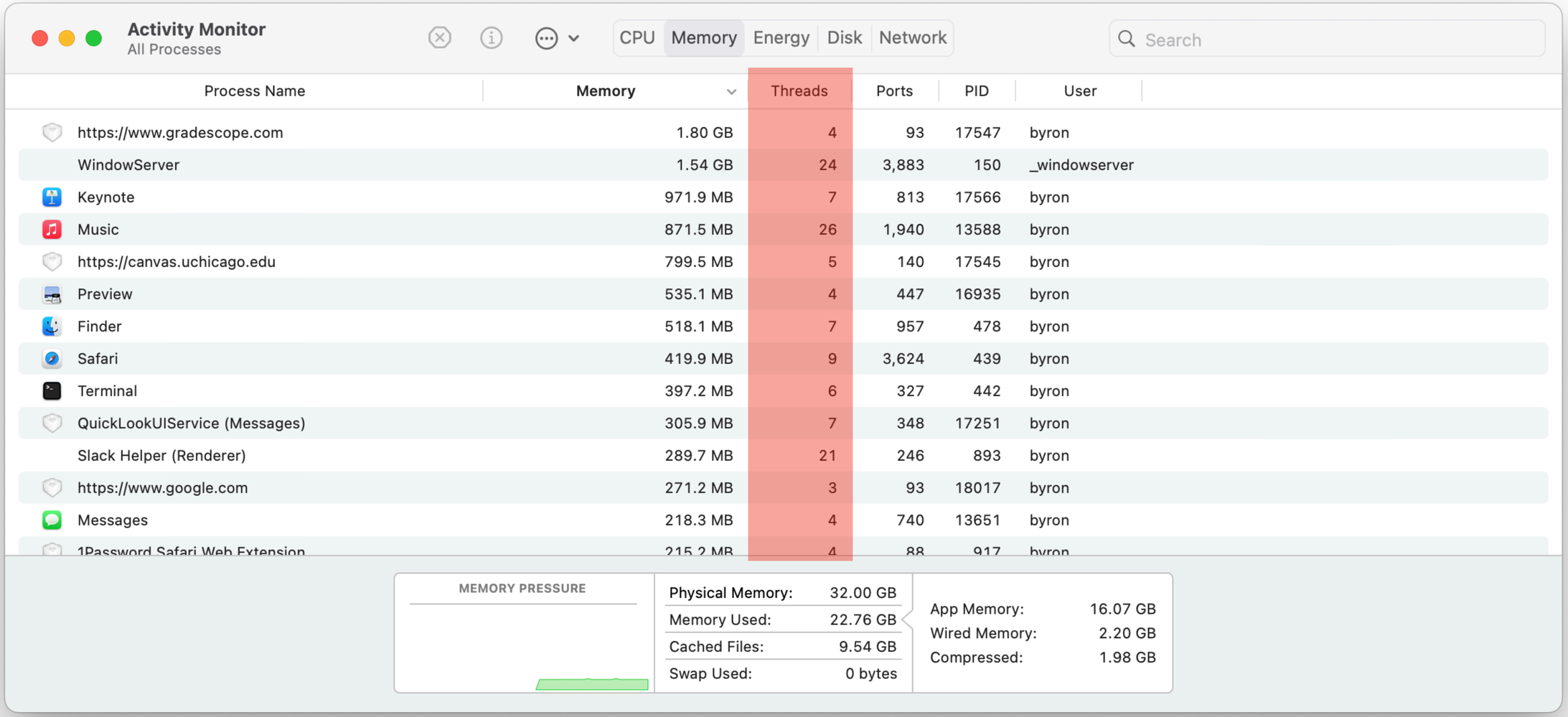


- CPU can do this translation very efficiently
- The chunks of memory used to be called *segments*.
- segmentation fault!

Context Switching

- Each process has its own
  - Virtual memory
  - Registers
  - Program counter
  - ...
- OS keeps track of these data in its internal data structure.

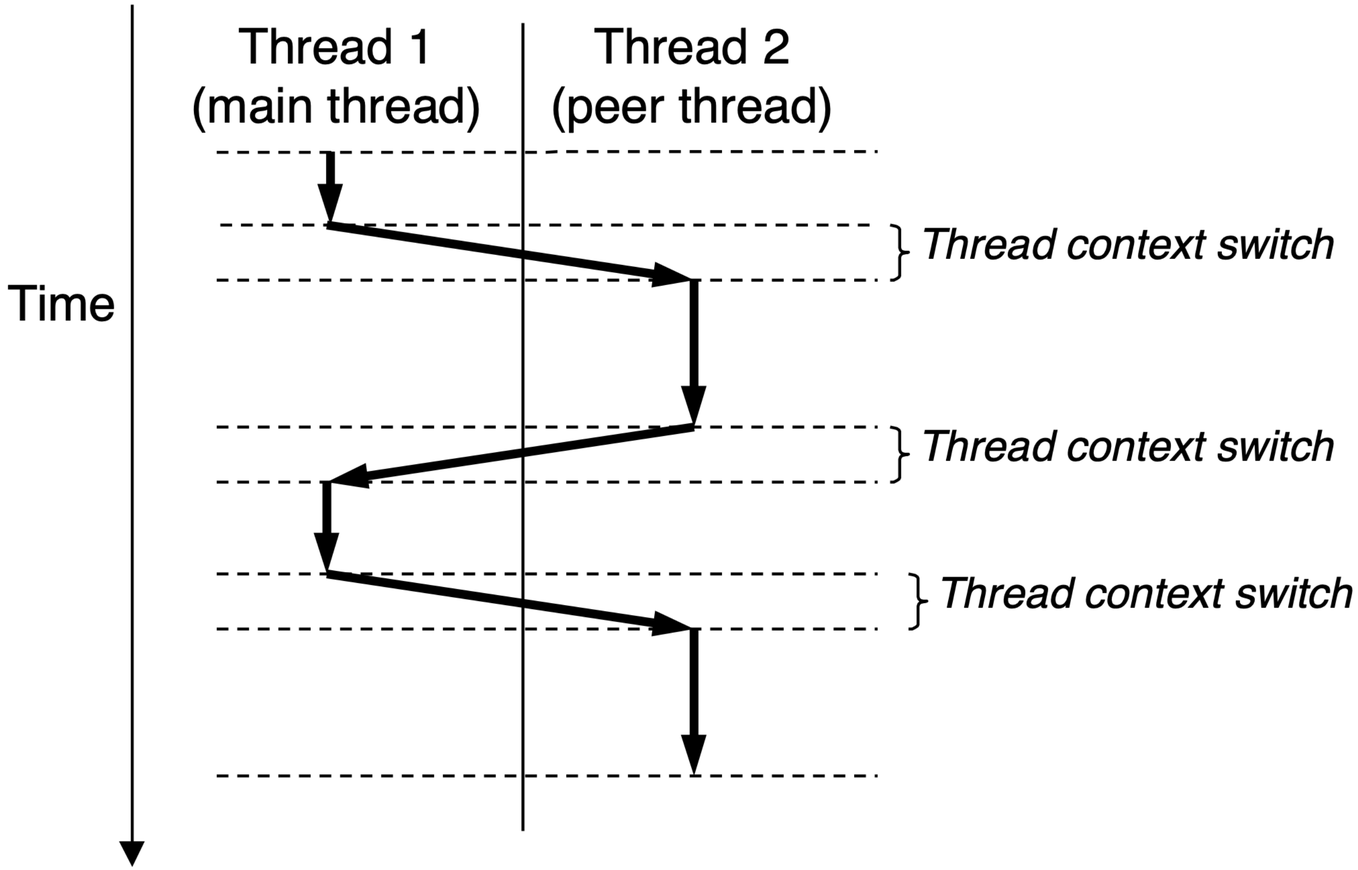
Threads


Activity Monitor
All Processes
CPU
Memory
Energy
Disk
Network
Search
Process Name
Memory
Threads
Ports
PID
User
https://www.gradescope.com 1.80 GB 4 93 17547 byron
WindowServer 1.54 GB 24 3,883 150 _windowserver
Keynote 971.9 MB 7 813 17566 byron
Music 871.5 MB 26 1,940 13588 byron
https://canvas.uchicago.edu 799.5 MB 5 140 17545 byron
Preview 535.1 MB 4 447 16935 byron
Finder 518.1 MB 7 957 478 byron
Safari 419.9 MB 9 3,624 439 byron
Terminal 397.2 MB 6 327 442 byron
QuickLookUIService (Messages) 305.9 MB 7 348 17251 byron
Slack Helper (Renderer) 289.7 MB 21 246 893 byron
https://www.google.com 271.2 MB 3 93 18017 byron
Messages 218.3 MB 4 740 13651 byron
1Password Safari Web Extension 215.2 MB 4 88 917 byron
MEMORY PRESSURE
Physical Memory: 32.00 GB
Memory Used: 22.76 GB
Cached Files: 9.54 GB
Swap Used: 0 bytes
App Memory: 16.07 GB
Wired Memory: 2.20 GB
Compressed: 1.98 GB

Threads

- A thread is a unit of execution. Each thread has its own:
  - Thread ID
  - Stack
  - Program counter (pc)
  - Registers
- A process contains a number of threads. Threads within a process share:
  - Code, data
- Threads are executed *concurrently*.

Threads


Thread 1
(main thread)
Thread 2
(peer thread)
Time
Thread context switch
Thread context switch
Thread context switch

Threads

- In C, threads are managed by a library called **`pthread`**

Threads

Creation

```c
#include <pthread.h>
#include <stdio.h>

void *thread(void *data);

int main()
{
        pthread_t tid;

        pthread_create(&tid, NULL, thread, "hello, world!");
        pthread_join(tid, NULL);

        return 0;
}

void *thread(void *data)
{
        char *str = data;
        printf("%s\n", str);

        return NULL;
}
```

Threads

Creation

```c
#include <pthread.h>
#include <stdio.h>

void *thread(void *data);

int main()
{
        pthread_t tid;

        pthread_create(&tid, NULL, thread, "hello, world!");
        pthread_join(tid, NULL);

        return 0;
}

void *thread(void *data)
{
        char *str = data;
        printf("%s\n", str);

        return NULL;
}
```

launches a new thread

Threads

Creation

```c
#include <pthread.h>
#include <stdio.h>

void *thread(void *data);

int main()
{
        pthread_t tid;

        pthread_create(&tid, NULL, thread, "hello, world!");
        pthread_join(tid, NULL);

        return 0;
}

void *thread(void *data)
{
        char *str = data;
        printf("%s\n", str);

        return NULL;
}
```

waits for the thread to terminate

Threads

Creation

```c
#include <pthread.h>
#include <stdio.h>

void *thread(void *data);

int main()
{
        pthread_t tid;

        pthread_create(&tid, NULL, thread, "hello, world!");
        pthread_join(tid, NULL);

        return 0;
}
```

```c
void *thread(void *data)
{
        char *str = data;
        printf("%s\n", str);

        return NULL;
}
```

function to run

Threads

Creation

```
int
pthread_create(pthread_t *thread, const pthread_attr_t *attr,
               void *(*start_routine)(void *),
               void *arg);
```

Threads

Creation

`pthread_create` creates a new thread and immediately starts running the thread.

```
int
pthread_create(pthread_t *thread, const pthread_attr_t *attr,
               void *(*start_routine)(void *),
               void *arg);
```

Threads

Creation

Once created, each thread is assigned a thread ID by the OS.

```
int
pthread_create(pthread_t *thread, const pthread_attr_t *attr,
               void *(*start_routine)(void *),
               void *arg);
```

Threads

Creation

```
int
pthread_create(pthread_t *thread, const pthread_attr_t *attr,
               void *(*start_routine)(void *),
               void *arg);
```

Thread attribute.
Almost always just
`NULL`

Threads

Creation

```
int
pthread_create(pthread_t *thread, const pthread_attr_t *attr,
               void *(*start_routine)(void *),
               void *arg);
```

The function to run in the thread. Arg: void *, Return: void *

Threads

Creation

```
int
pthread_create(pthread_t *thread, const pthread_attr_t *attr,
               void *(*start_routine)(void *),
               void *arg);
```

The argument to the function. Similar to the data pointer in `*_walk`

Threads

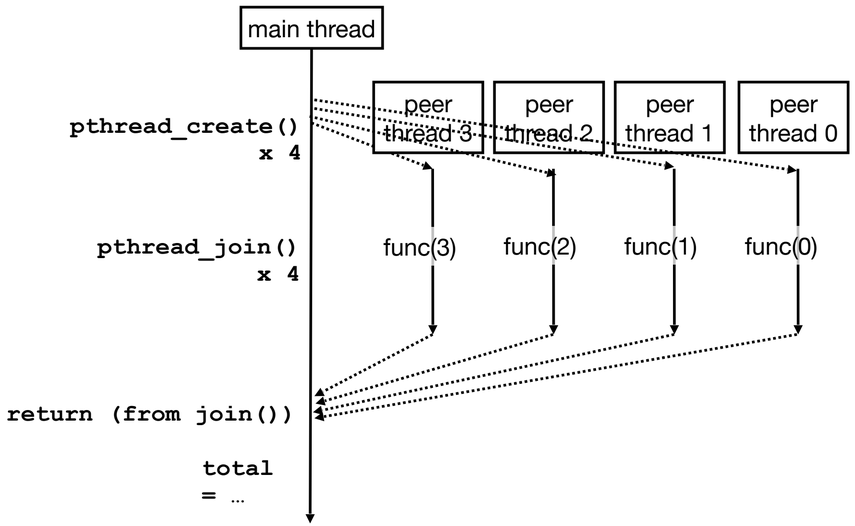
Creation

```
int
pthread_join(pthread_t thread, void **value_ptr);
```

- Demo

Moral: `slowprimes.c`

- C is so much better than Python at number crunching
- If a problem can be broken down into disjoint subproblems, parallelism shortens the running time by a lot



Moral: `primes.c`

- The best kind of performance improvement is algorithmic improvement -- the one that improves the asymptotic running time.
- Thread creation has its own cost. This cost needs to be factored in when one decides whether to use concurrency.
- Multithreading loses some benefit when the problem cannot be cleanly sliced into subproblems
- Multithreading code is usually a lot more complicated than single-threaded code.

Moral: `badcnt.c`

- Concurrency bug can happen when threads share resources.
- Threads do not have its own virtual memory space like processes do
  - Memory access is not atomic -- x += 1 is three separate steps
    - Read x to a register (load)
    - Increment the register (update)
    - Write the register to memory (store)
  - Memory updates need to be synchronized

Moral: `goodcnt.c`

- Synchronization can be done via `semaphores` (e.g. locks)
  - `pthread_mutex_lock` waits the value to be positive
  - `pthread_mutex_unlock` increments the value
- Synchronized code is not parallel :(

Moral: `bomb.c`

- Asynchronous I/O
- Semaphores can be used to indicate the readiness of a value

When should I use threads?

- Spot parallelizable code
  - Code that doesn't depend on other's result
  - E.g. loop where each iteration is independent
- Beware of concurrency bugs
  - Read-write conflict
  - Write-write conflict
  - Semaphore

Thread (cont.)

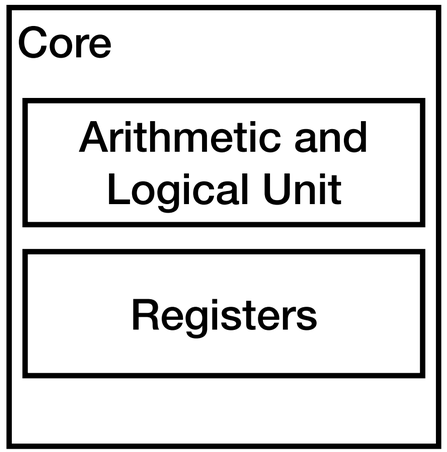
badcnt.c

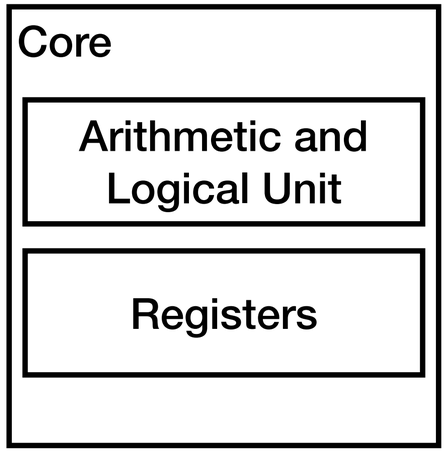
```c
/* shared variable */
unsigned int cnt = 0;
void *count(void *);

int main(void)
{
        pthread_t tid1, tid2;

        pthread_create(&tid1, NULL, count, NULL);
        pthread_create(&tid2, NULL, count, NULL);

        pthread_join(tid1, NULL);
        pthread_join(tid2, NULL);

        if (cnt == N * 2) {
                printf("OK cnt=%u\n", cnt);
        } else {
                printf("BOOM cnt=%u\n", cnt);
        }

        return 0;
}
```

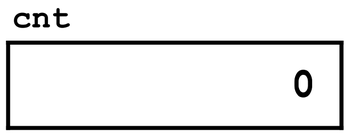
```c
void *count(void *arg)
{
        (void) arg;

        for (unsigned int i = 0; i < N; i++) {
                cnt++;
        }

        return NULL;
}
```

Thread (cont.)

badcnt.c



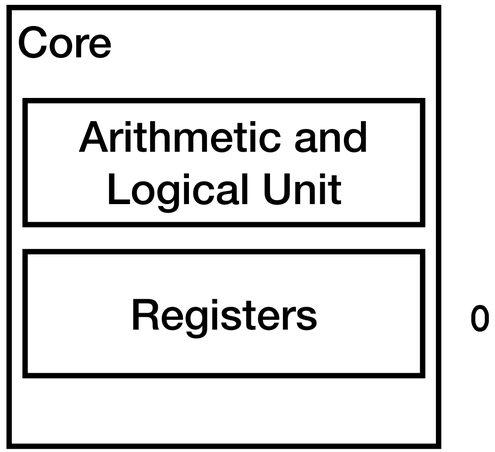





```c
void *count(void *arg)
{
        (void) arg;

        for (unsigned int i = 0; i < N; i++) {
                cnt++;
        }

        return NULL;
}
```

Thread (cont.)

badcnt.c



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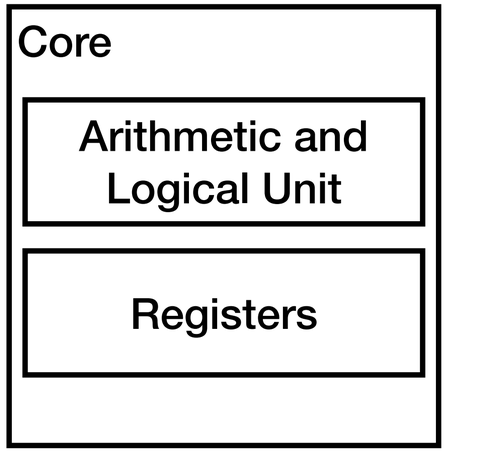
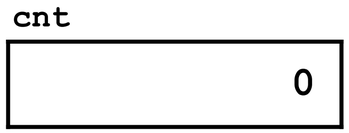
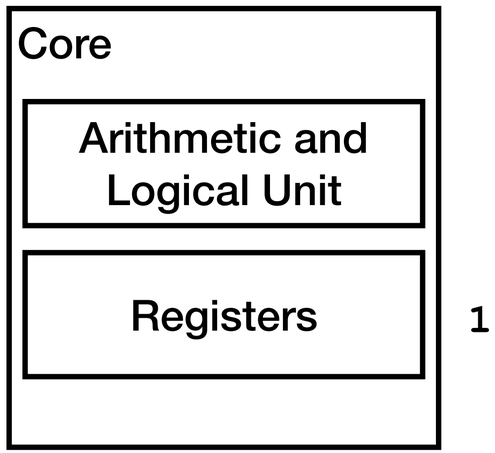




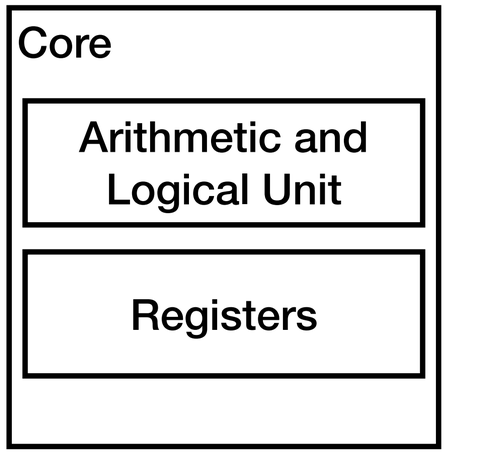

```c
void *count(void *arg)
{
        (void) arg;

        for (unsigned int i = 0; i < N; i++) {
                cnt++;
        }

        return NULL;
}
```

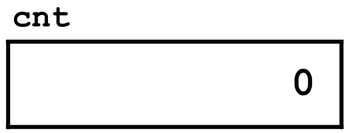
Thread (cont.)

badcnt.c



1

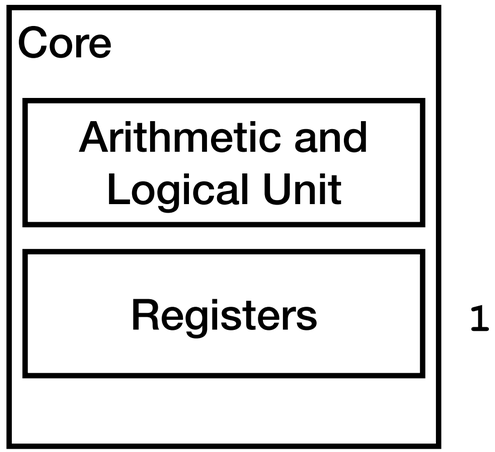




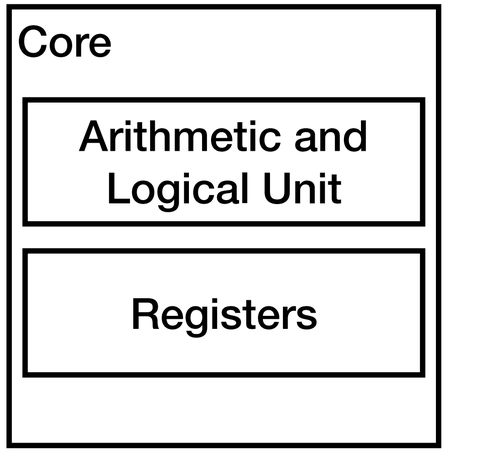

```c
void *count(void *arg)
{
        (void) arg;

        for (unsigned int i = 0; i < N; i++) {
                cnt++;
        }

        return NULL;
}
```

Thread (cont.)

badcnt.c



1



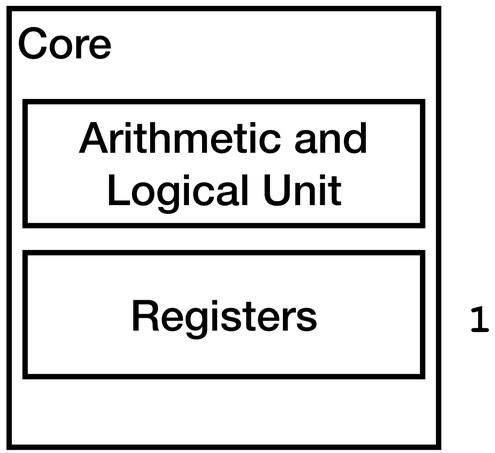
cnt

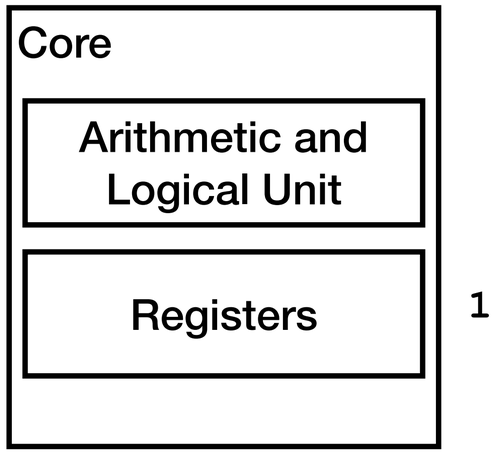
1

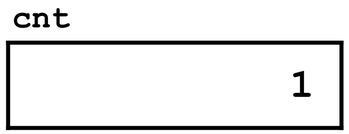
```c
void *count(void *arg)
{
        (void) arg;

        for (unsigned int i = 0; i < N; i++) {
                cnt++;
        }

        return NULL;
}
```

Thread (cont.)

badcnt.c



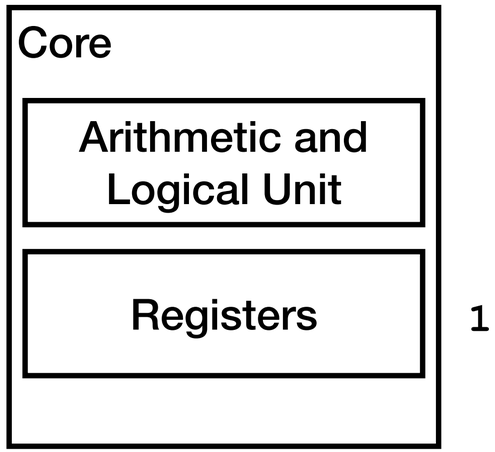


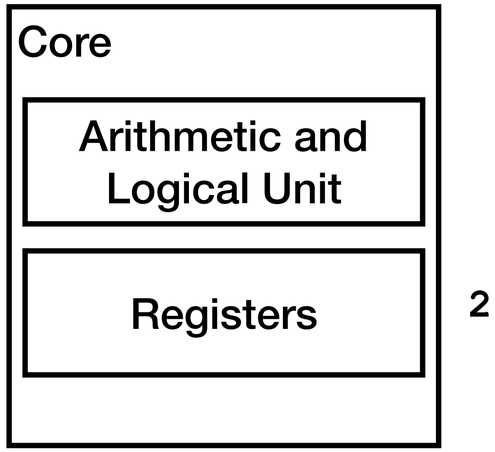


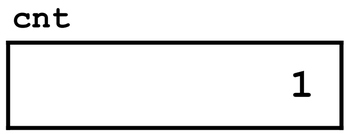

```c
void *count(void *arg)
{
        (void) arg;

        for (unsigned int i = 0; i < N; i++) {
                cnt++;
        }

        return NULL;
}
```

Thread (cont.)

badcnt.c








```c
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{
        (void) arg;

        for (unsigned int i = 0; i < N; i++) {
                cnt++;
        }

        return NULL;
}
```
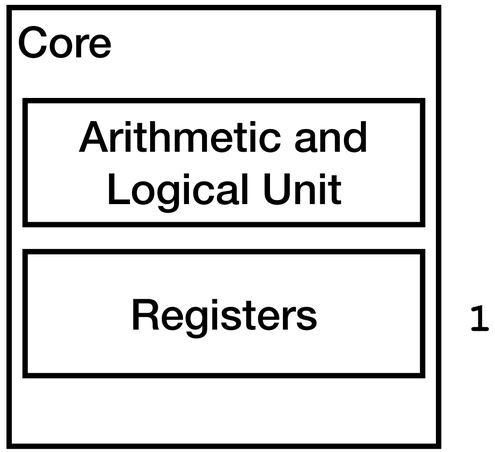
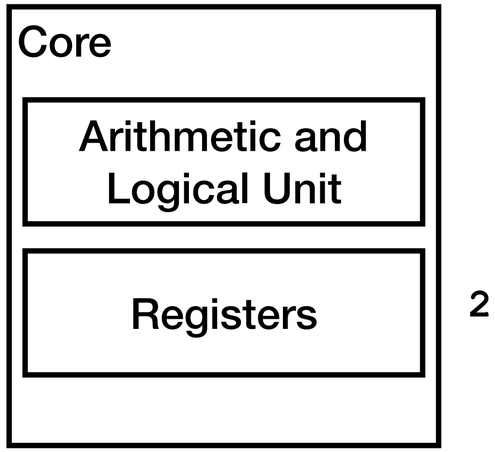
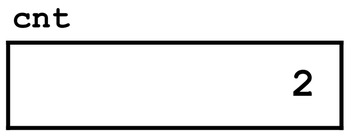

Thread (cont.)

badcnt.c



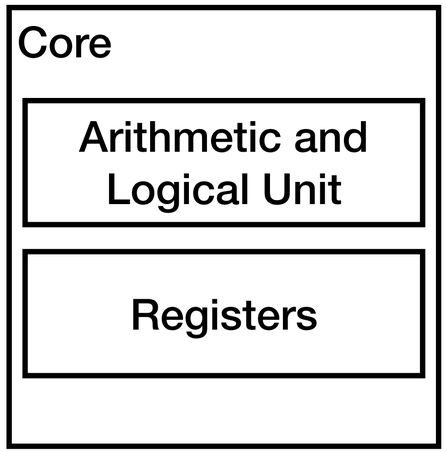


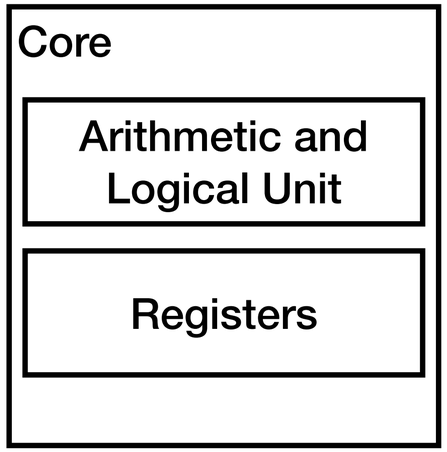


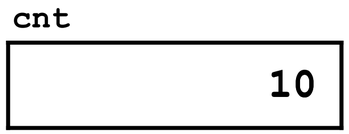

```c
void *count(void *arg)
{
        (void) arg;

        for (unsigned int i = 0; i < N; i++) {
                cnt++;
        }

        return NULL;
}
```

Thread (cont.)

badcnt.c



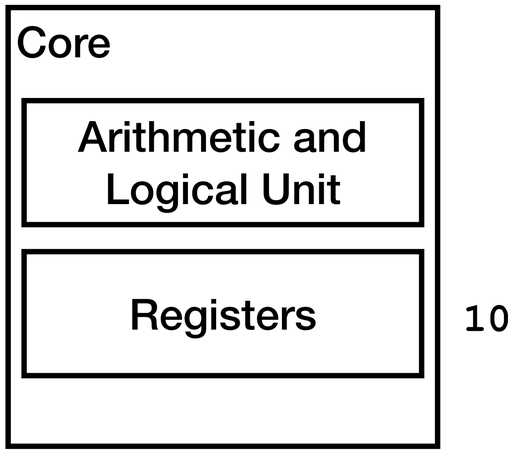


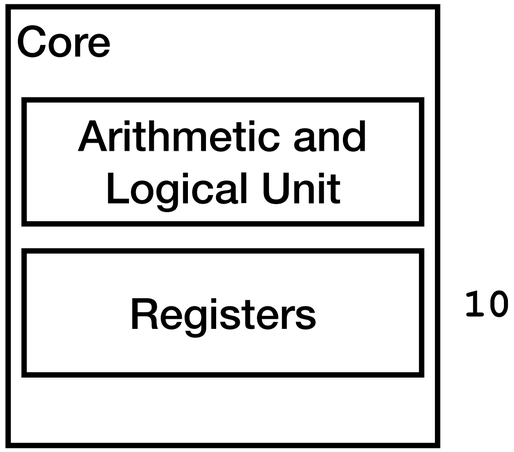


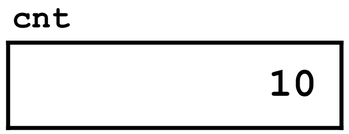

```c
void *count(void *arg)
{
        (void) arg;

        for (unsigned int i = 0; i < N; i++) {
                cnt++;
        }

        return NULL;
}
```

Thread (cont.)

badcnt.c



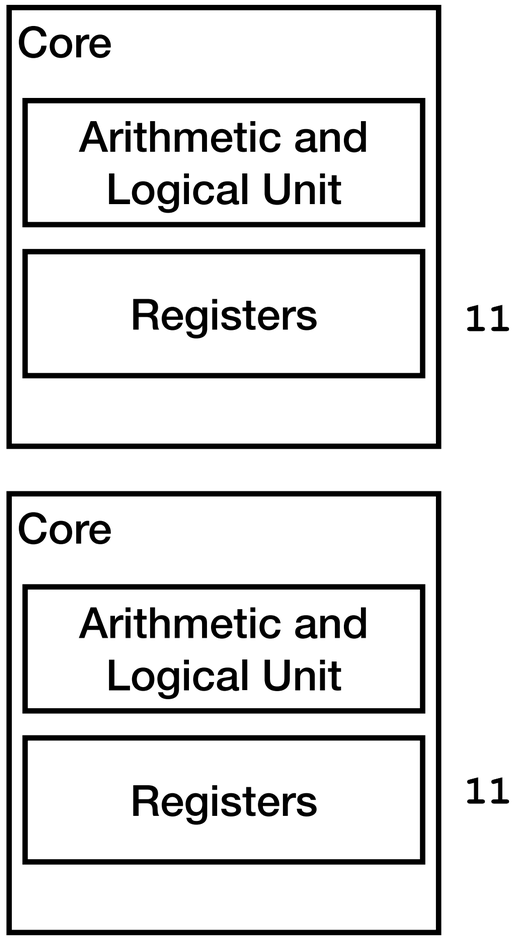


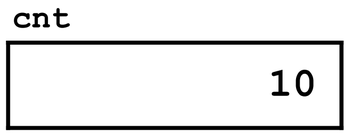



```c
void *count(void *arg)
{
        (void) arg;

        for (unsigned int i = 0; i < N; i++) {
                cnt++;
        }

        return NULL;
}
```

Thread (cont.)

badcnt.c

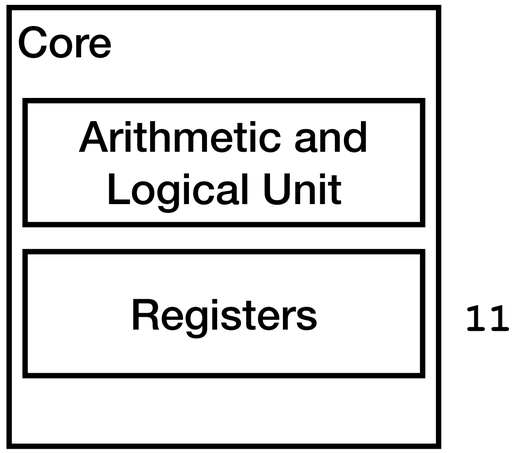


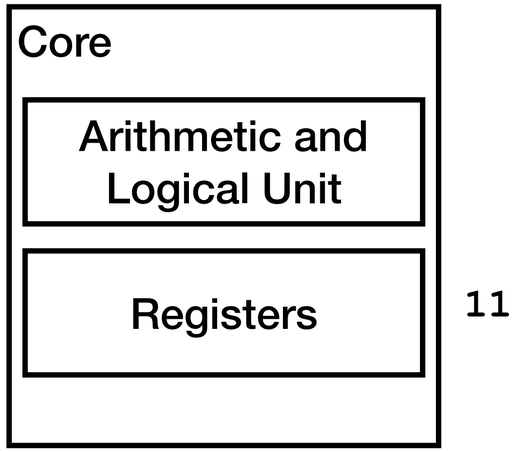


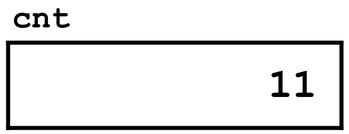

```c
void *count(void *arg)
{
        (void) arg;

        for (unsigned int i = 0; i < N; i++) {
                cnt++;
        }

        return NULL;
}
```

Thread (cont.)

badcnt.c



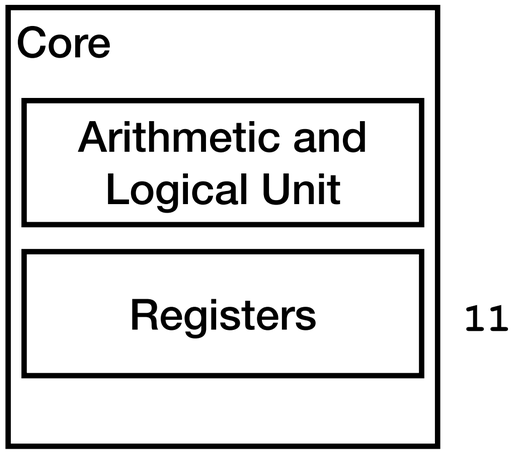


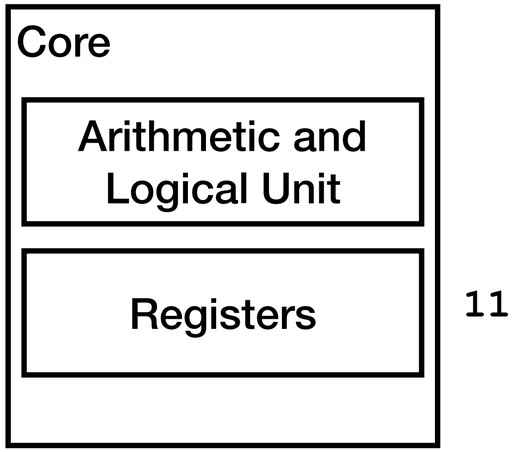


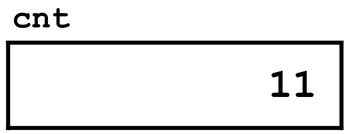

```c
void *count(void *arg)
{
        (void) arg;

        for (unsigned int i = 0; i < N; i++) {
                cnt++;
        }

        return NULL;
}
```

Thread (cont.)

goodcnt.c








```c
void *count(void *arg)
{
        (void) arg;

        for (unsigned int i = 0; i < N; i++) {
                pthread_mutex_lock(&sem);
                cnt++;
                pthread_mutex_unlock(&sem);

        }

        return NULL;
}
```

- `pthread_mutex_lock` "locks" `cnt`, if it is already locked, `pthread_mutex_lock` will wait
- `pthread_mutex_unlock` "unlocks" `cnt`
- Each loop now becomes
  - lock
  - read cnt
  - incr
  - write to cnt
  - unlock
- No other thread will touch the number between reading and writing