An Assembly primer

Guillaume DIDIER
L3 ENS - 2010/2021

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This lecture is fully preemptible
Feel free to interrupt with questions

Assembly / machine code view (ISA)

(user mode)

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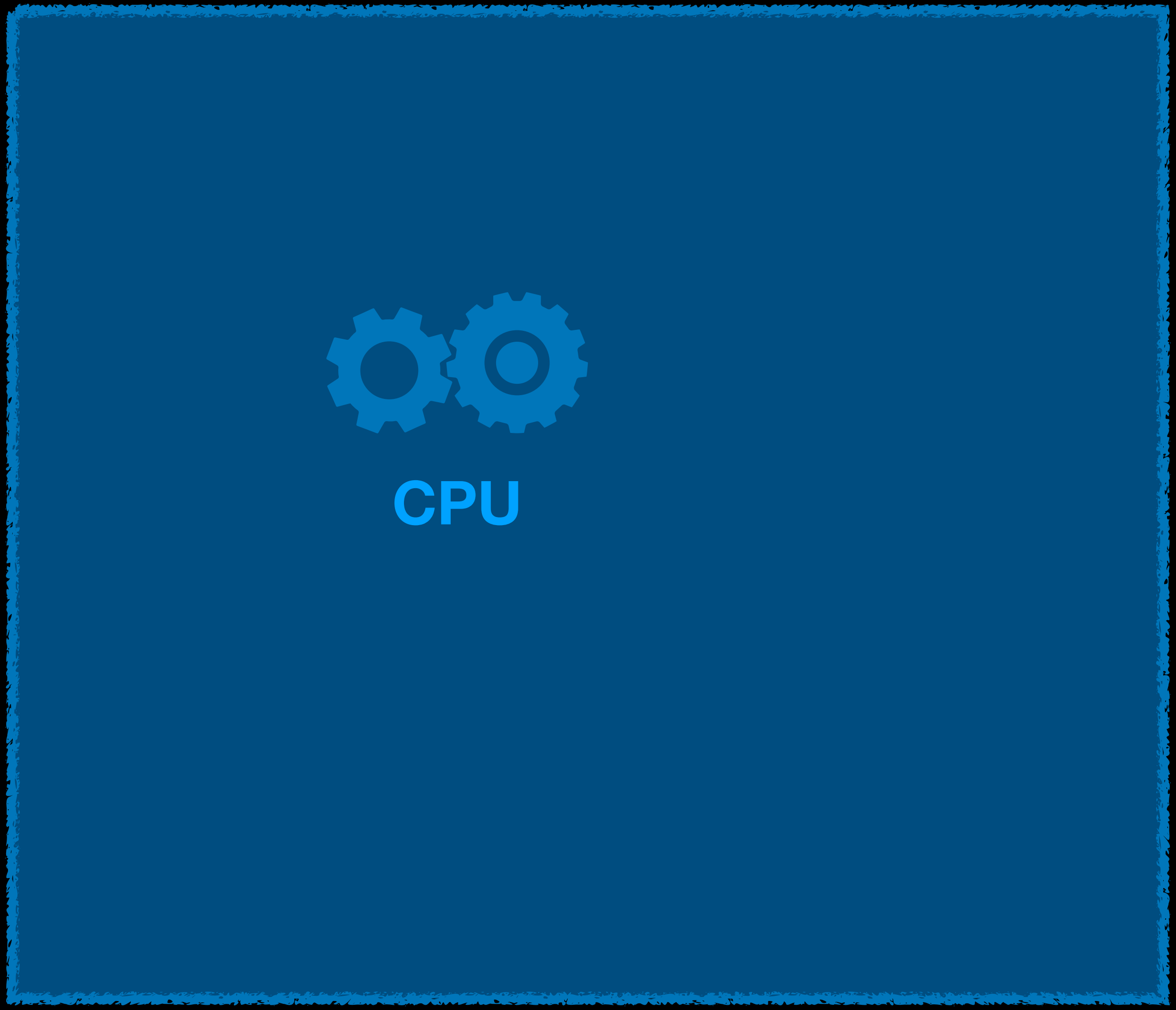

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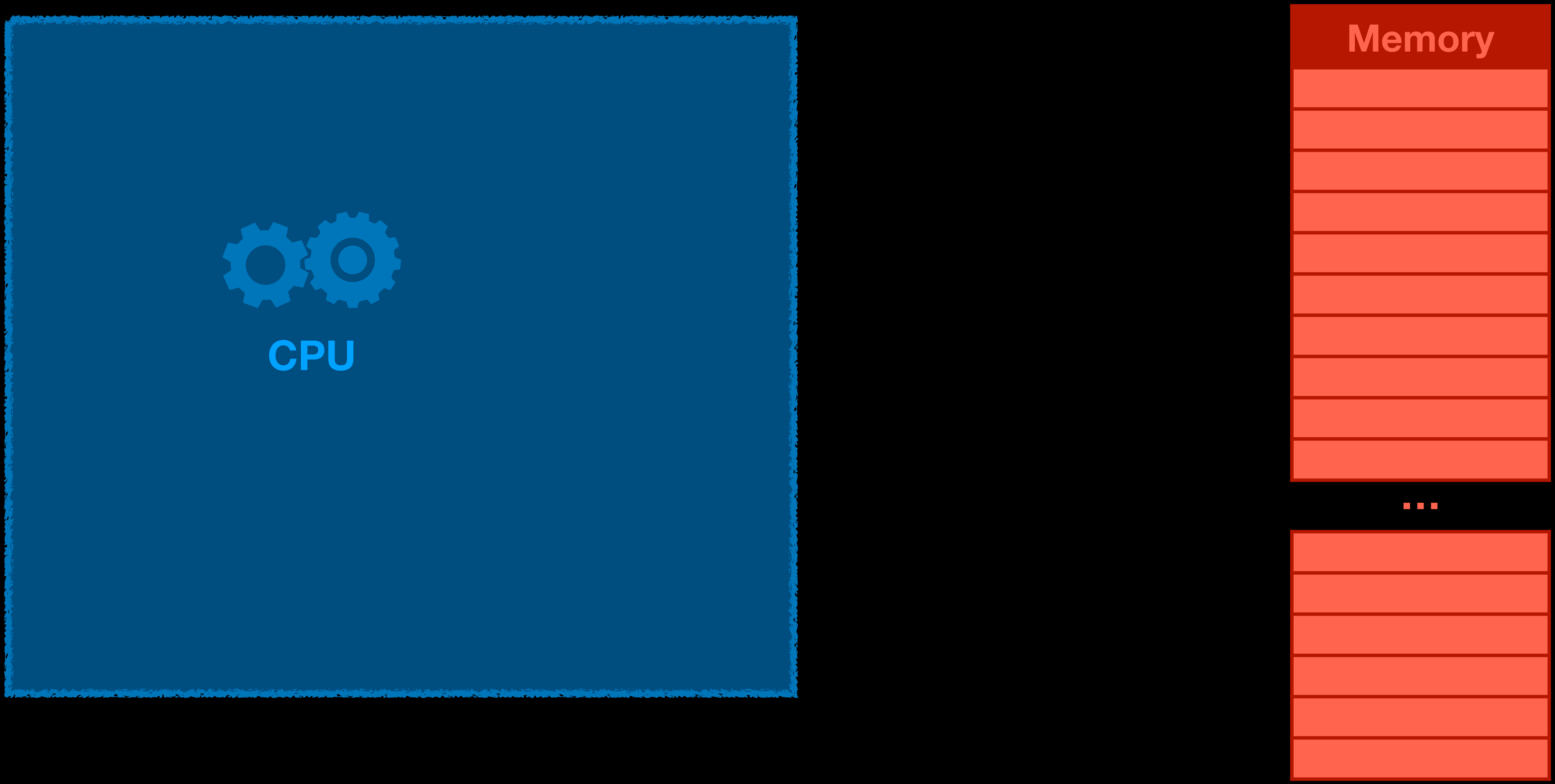

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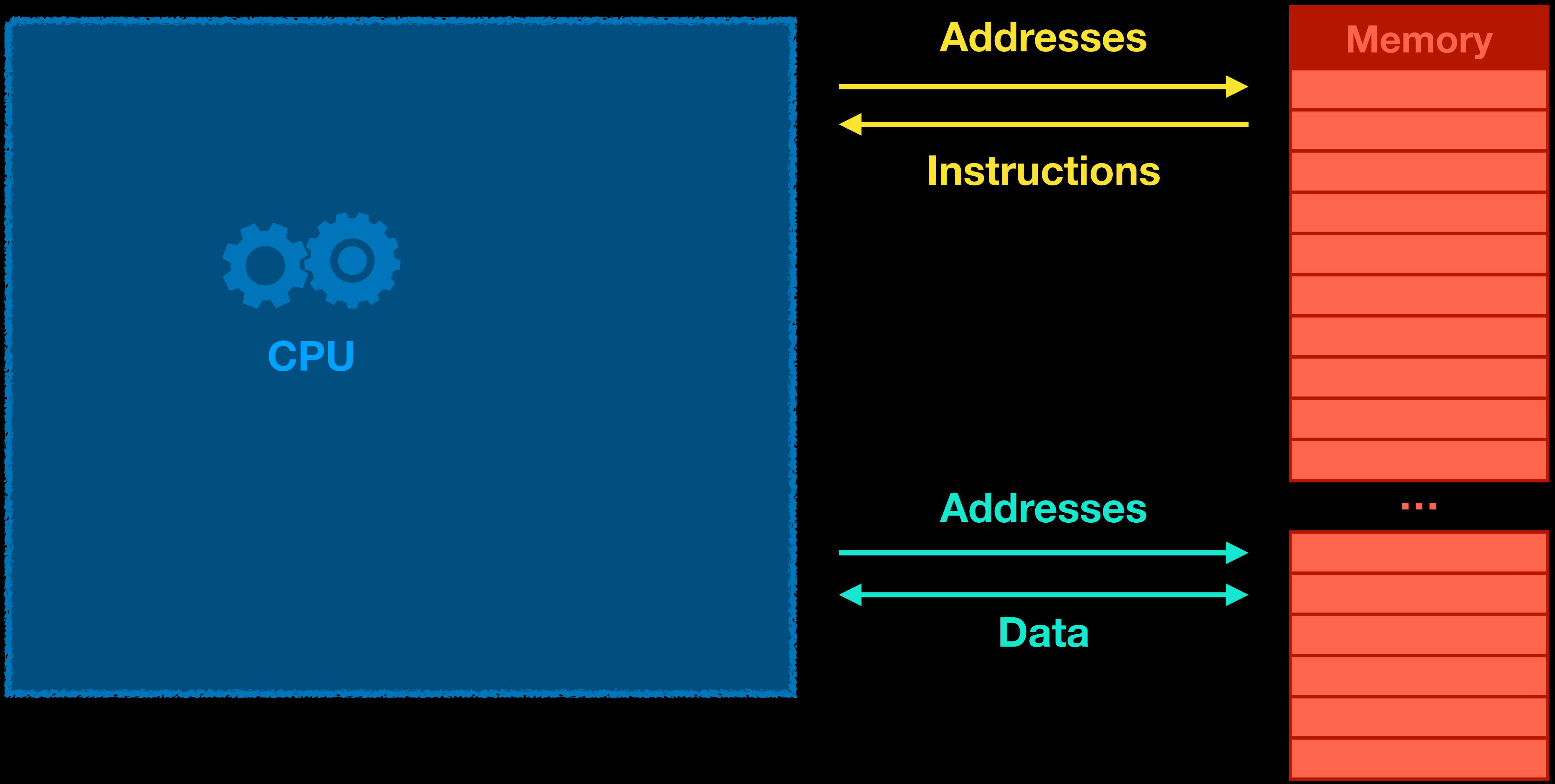

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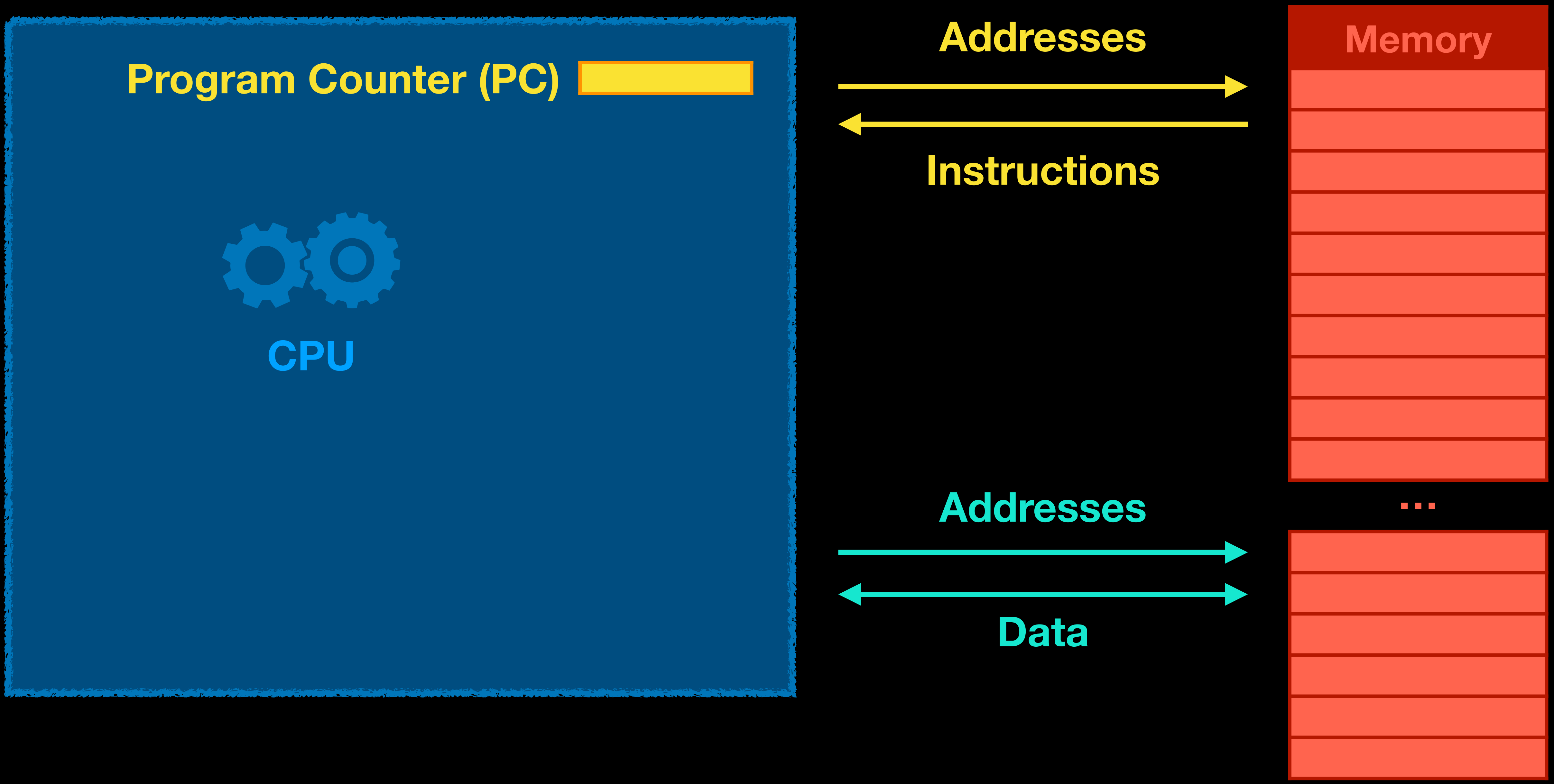

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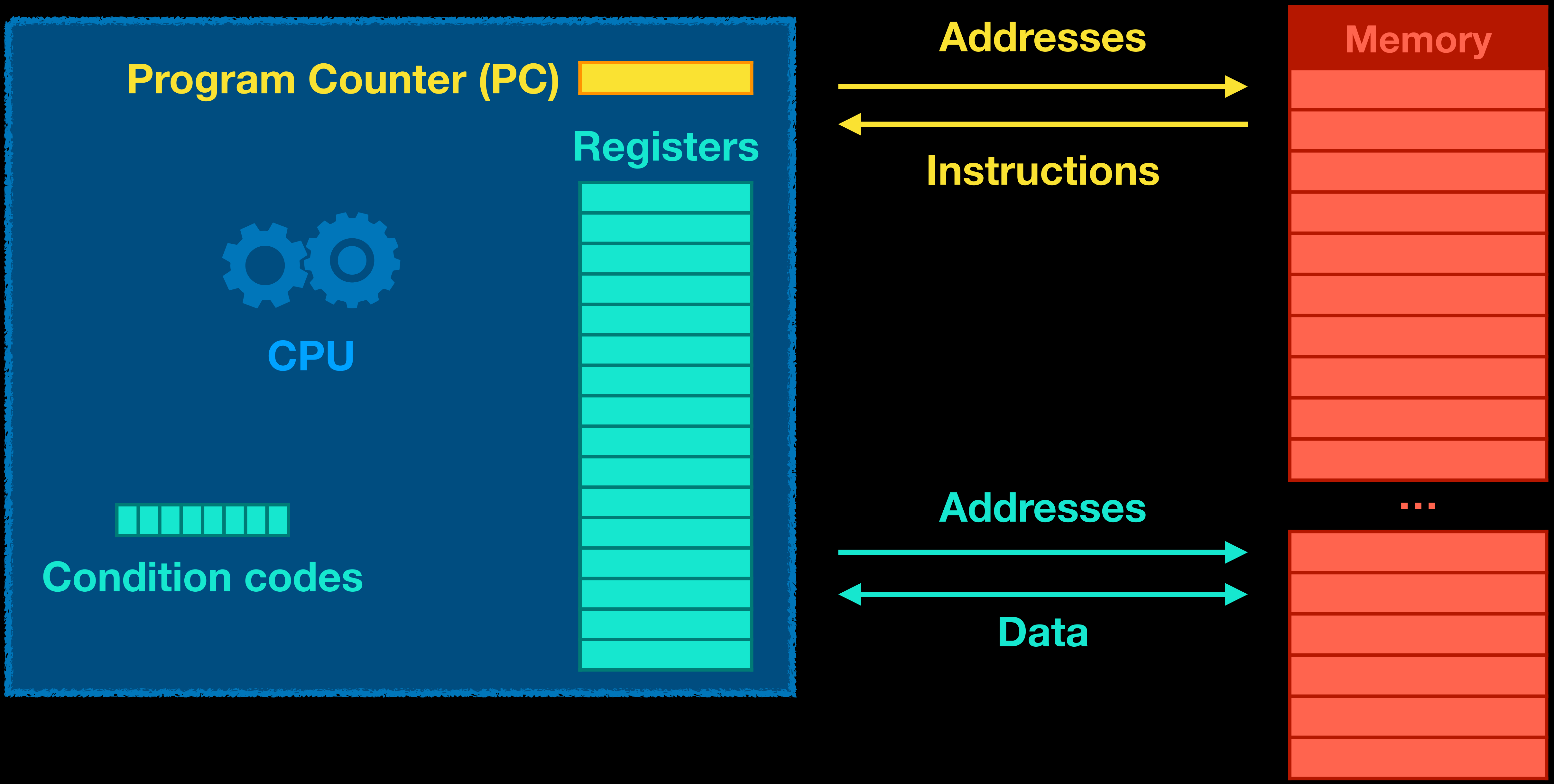

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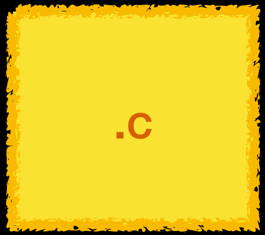

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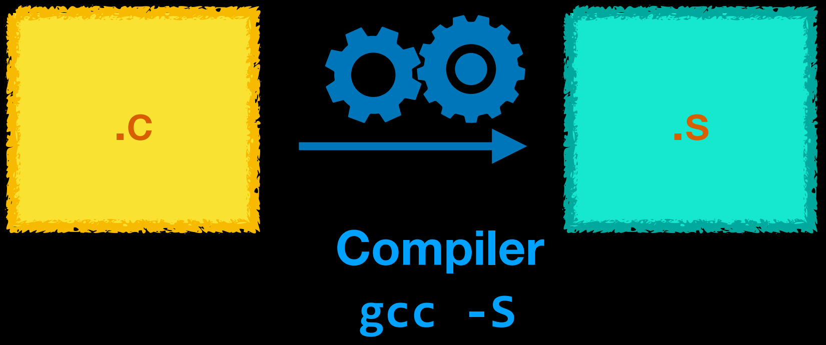

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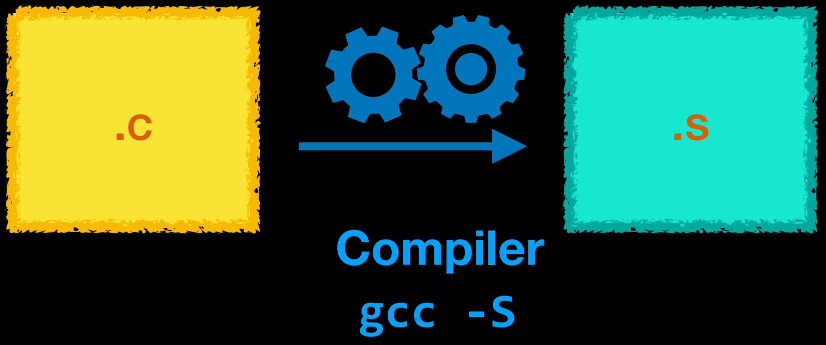

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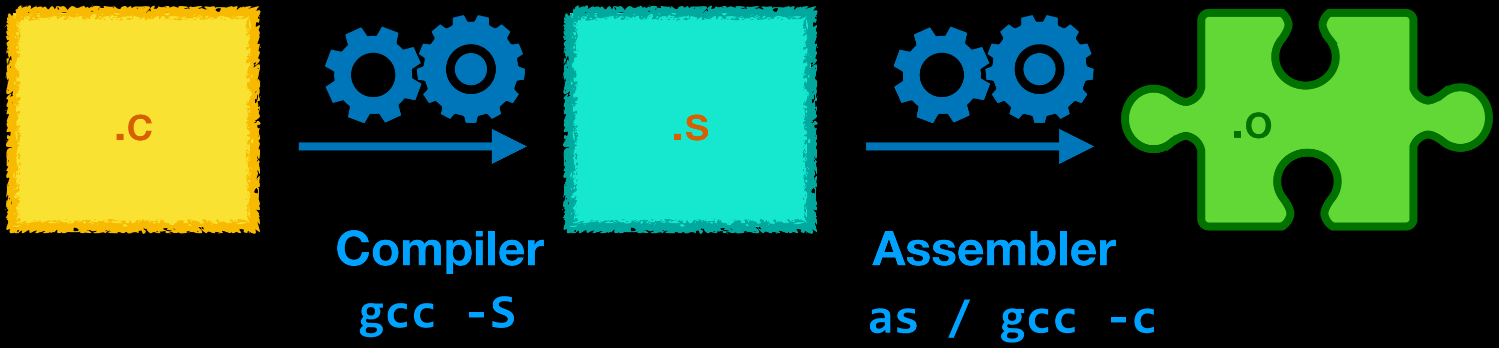

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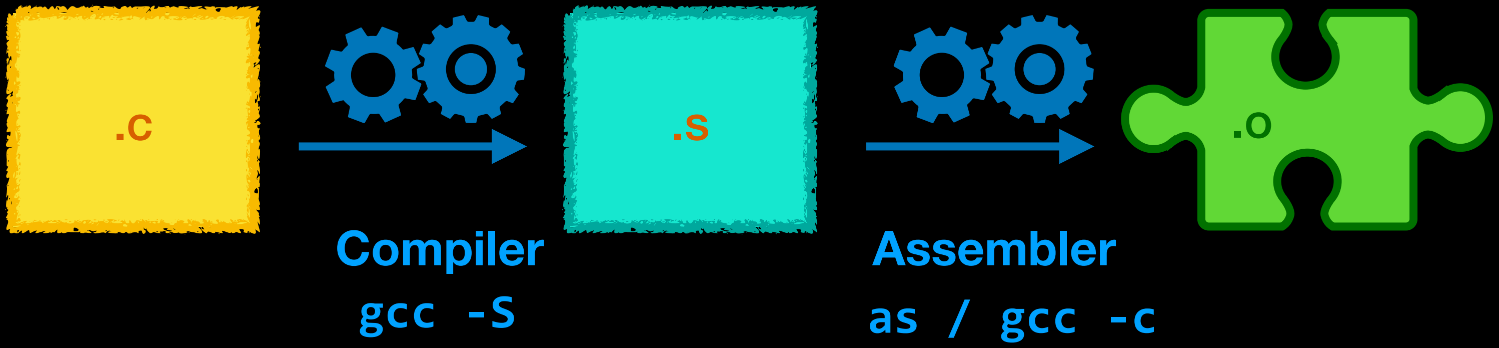

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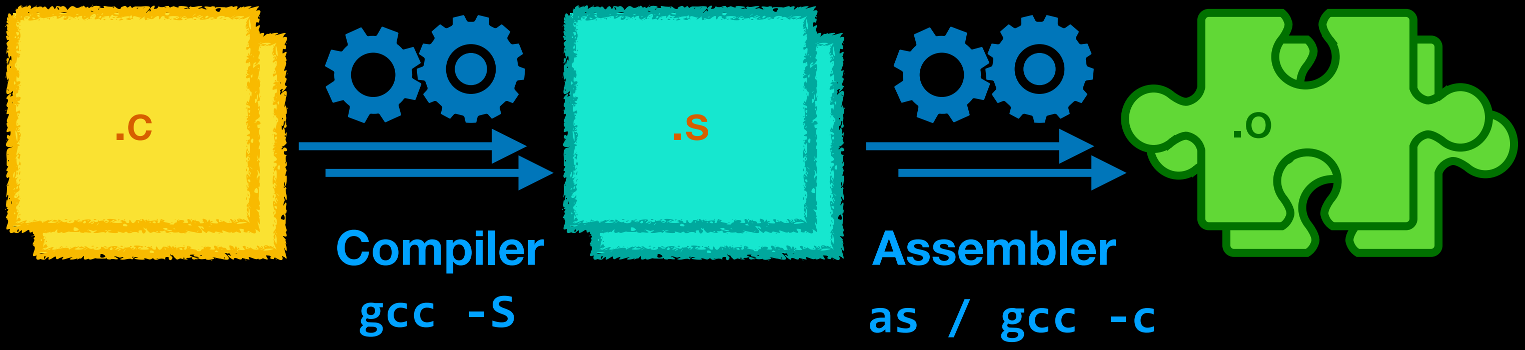

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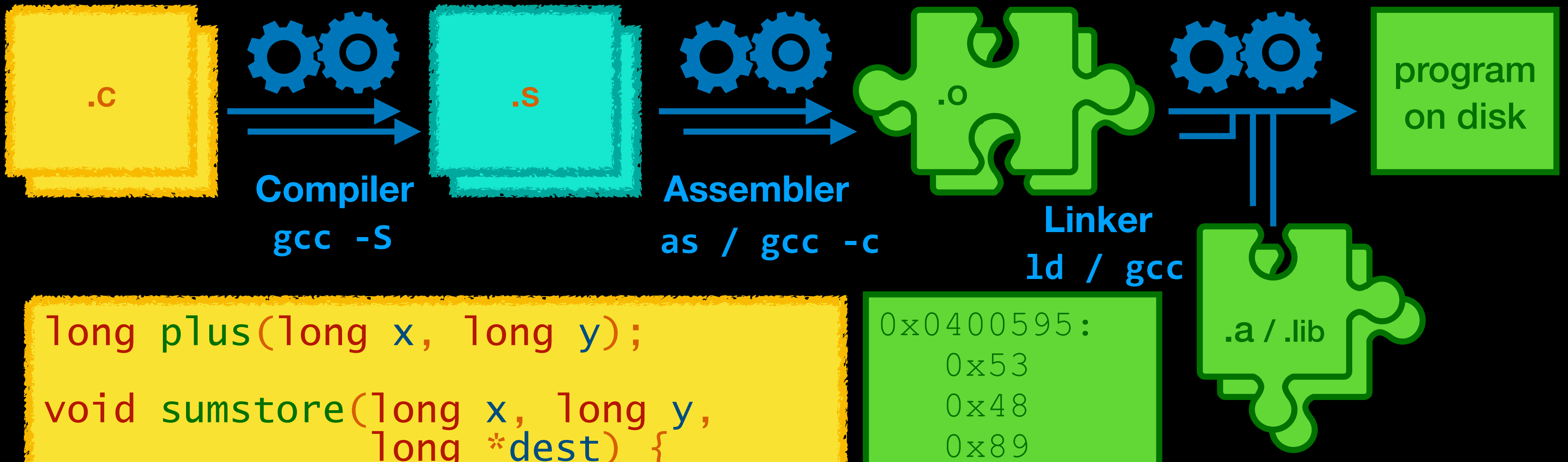

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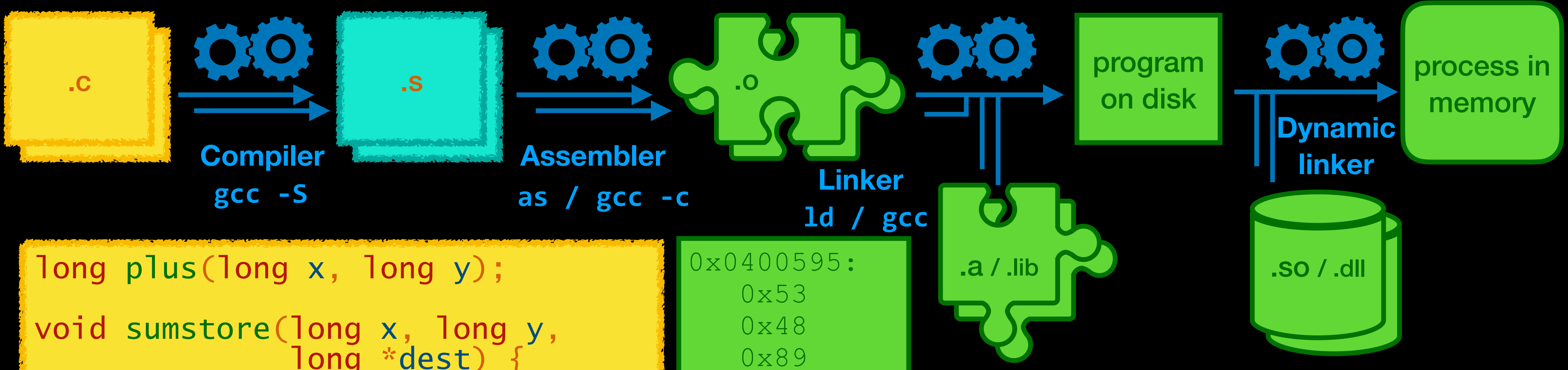

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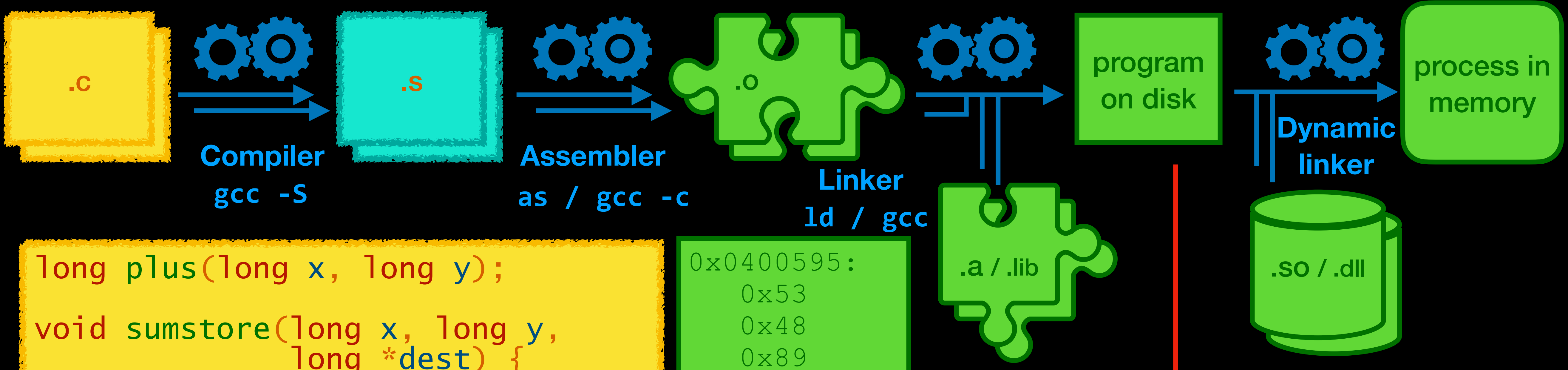

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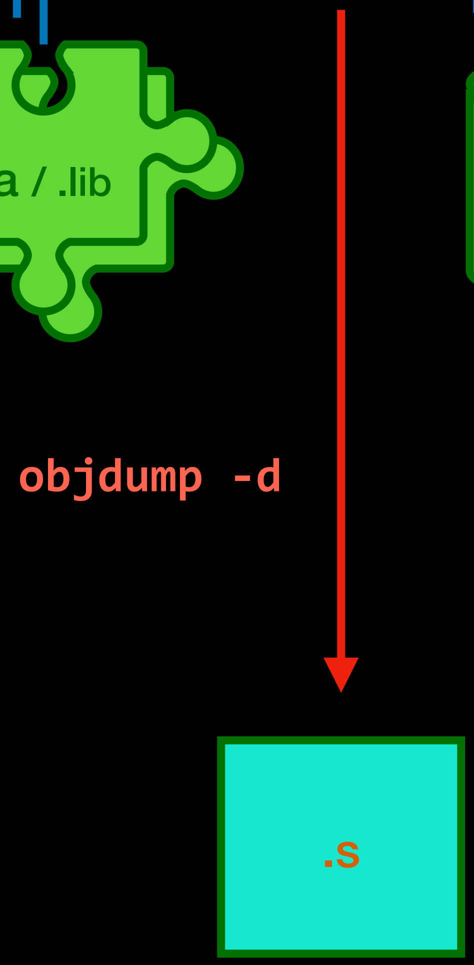

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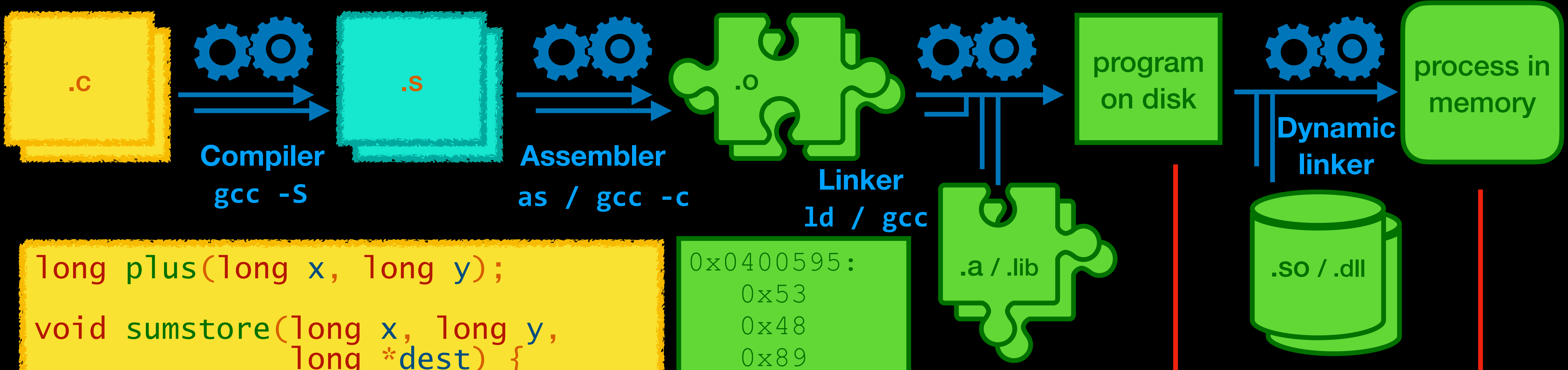

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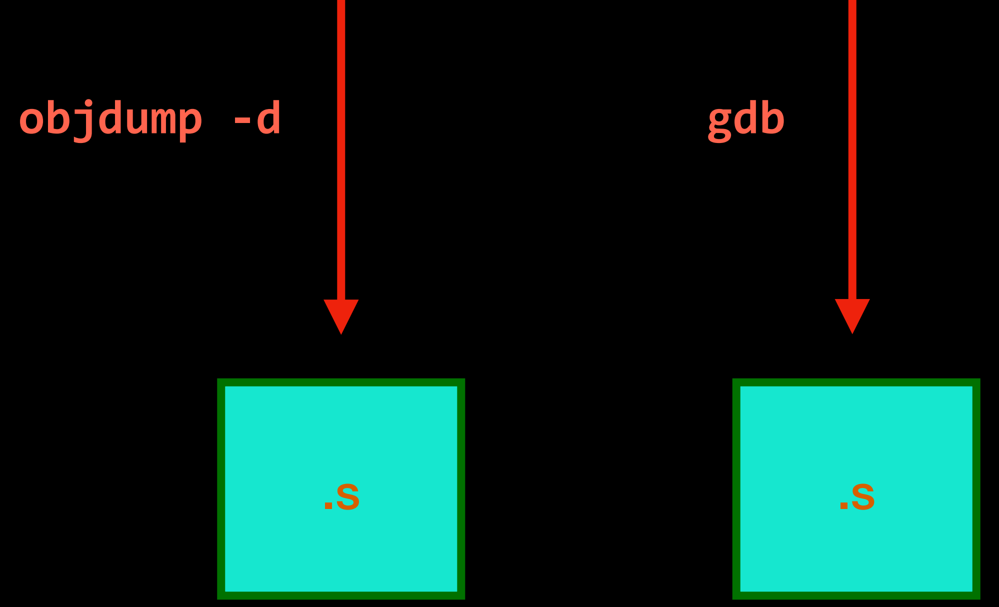

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- You may need it for your work!

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- *A lot of crufts left-over of x86 long and convoluted history.*

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Registers

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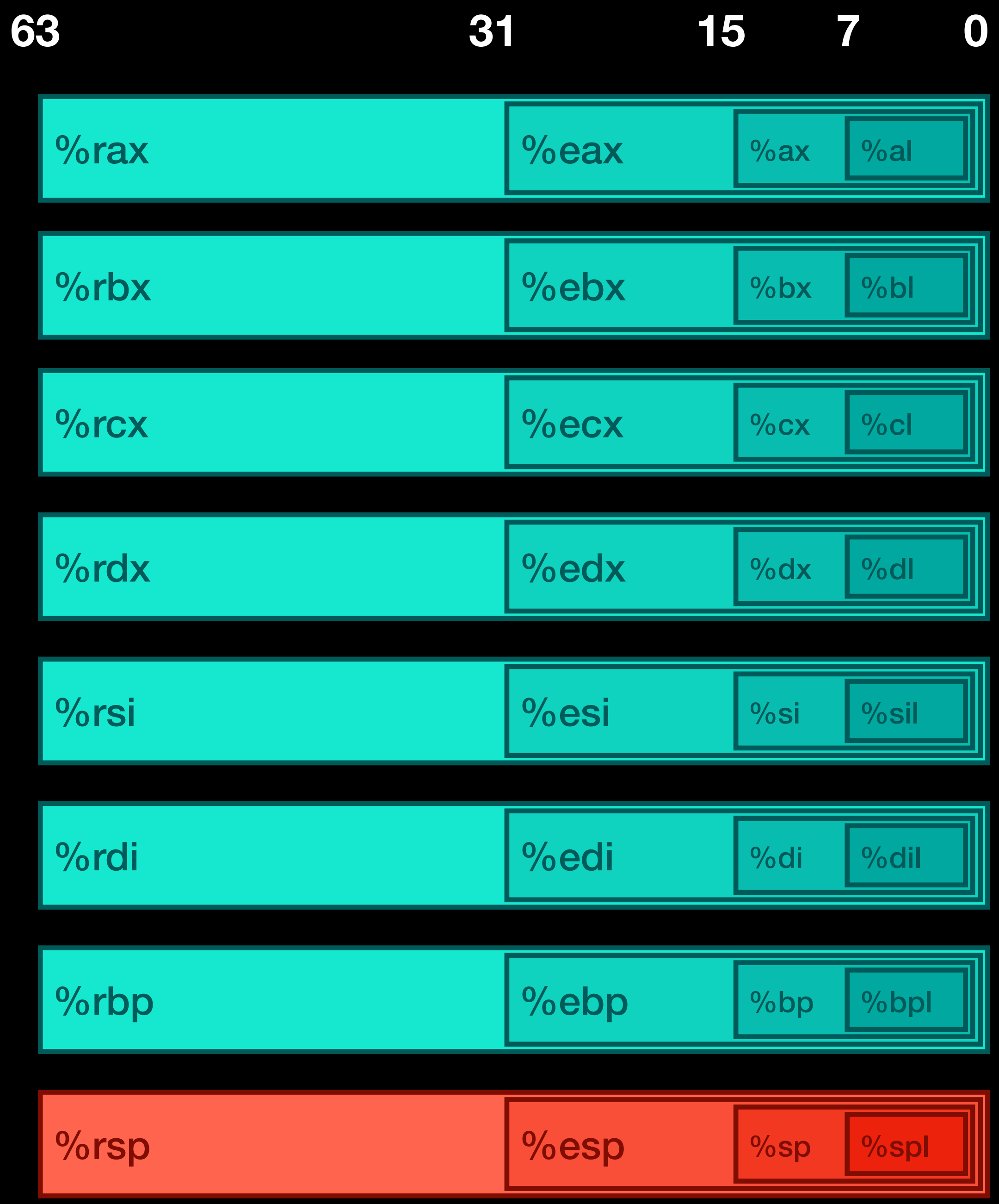
- 16 registers, each 64 bits (8 bytes).



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%rbx	%ebx	%bx	%bl	
%rcx	%ecx	%cx	%cl	
%rdx	%edx	%dx	%dl	
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%rdi	%edi	%di	%dil	
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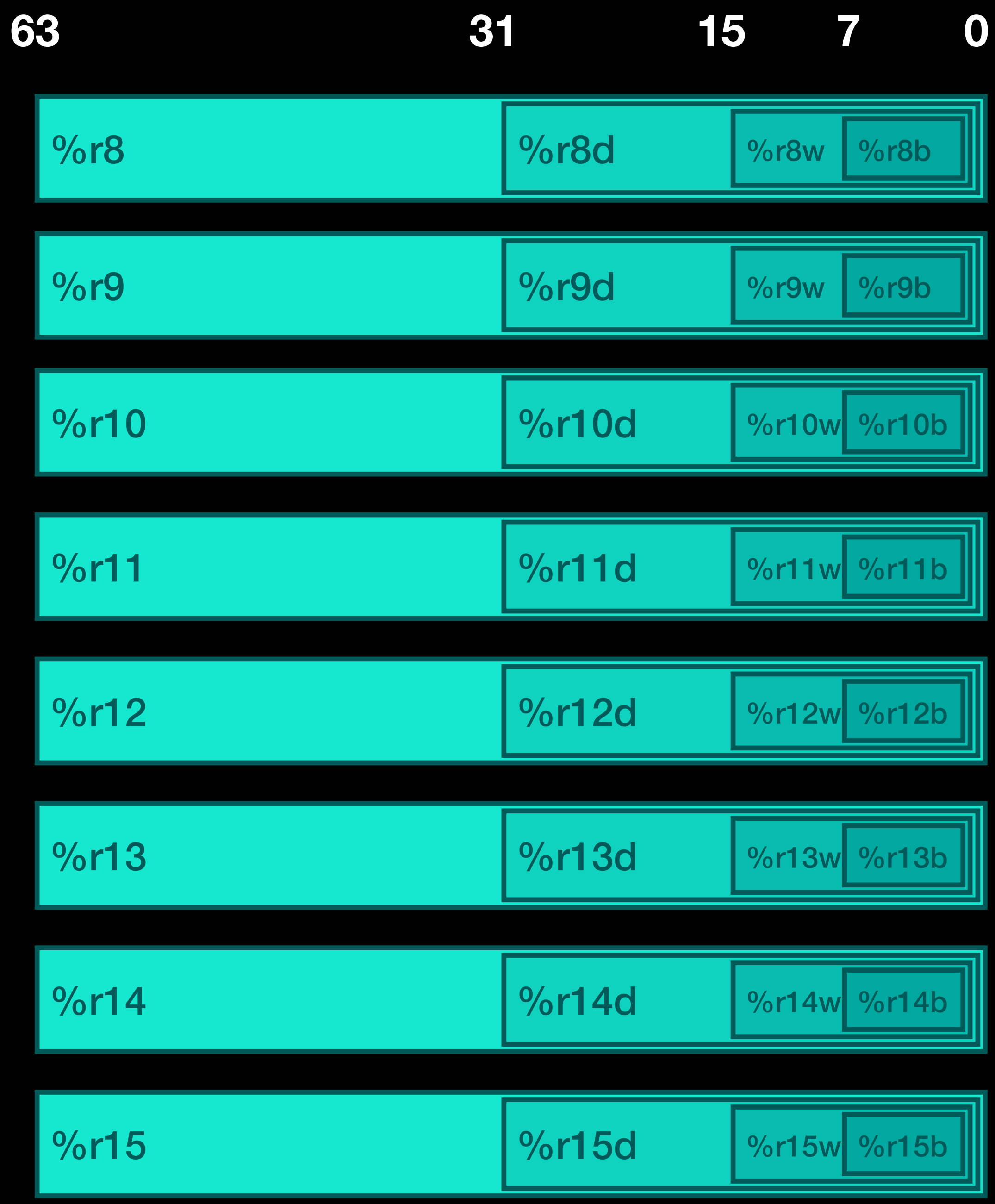

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%r12	%r12d	%r12w	%r12b	
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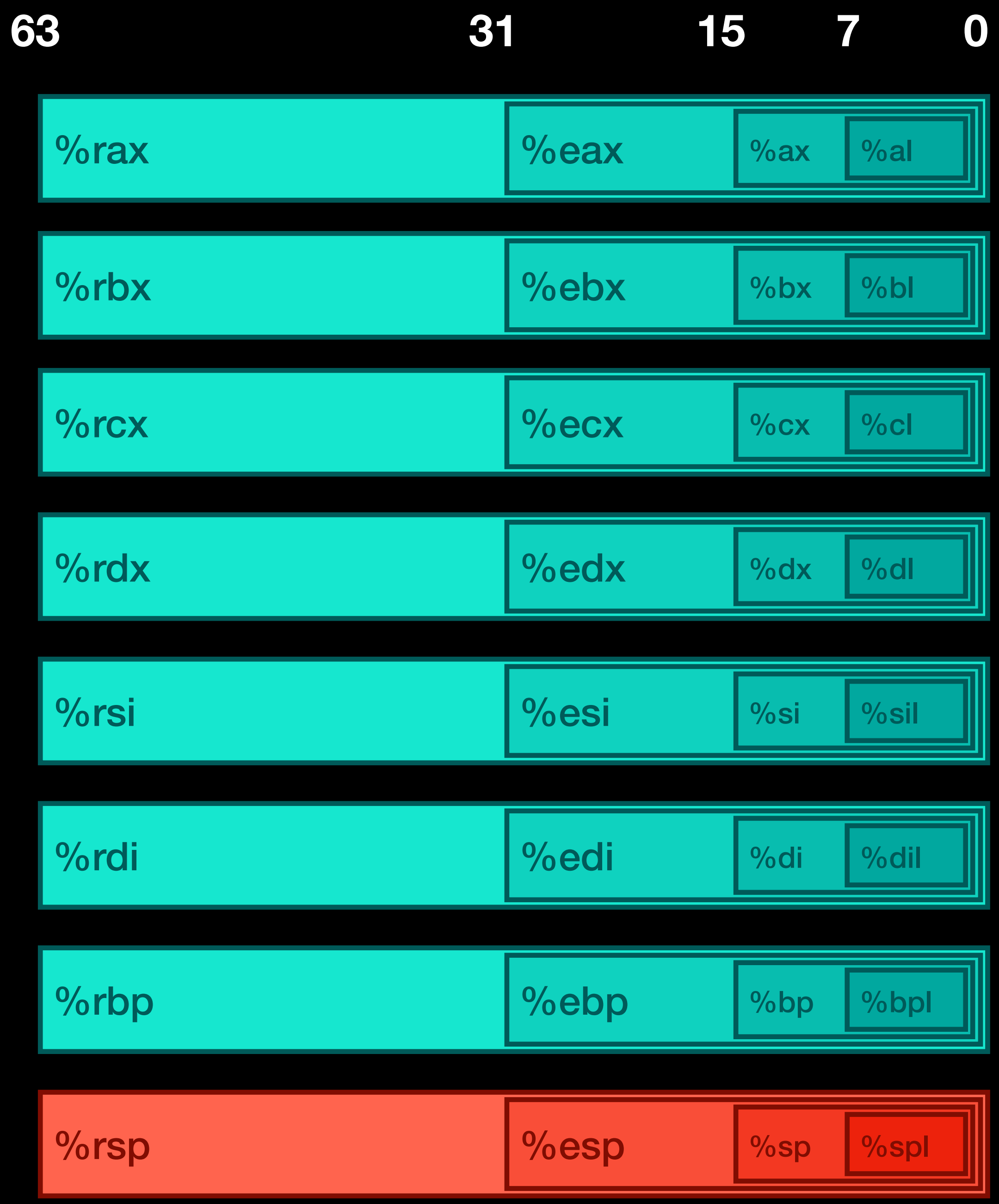

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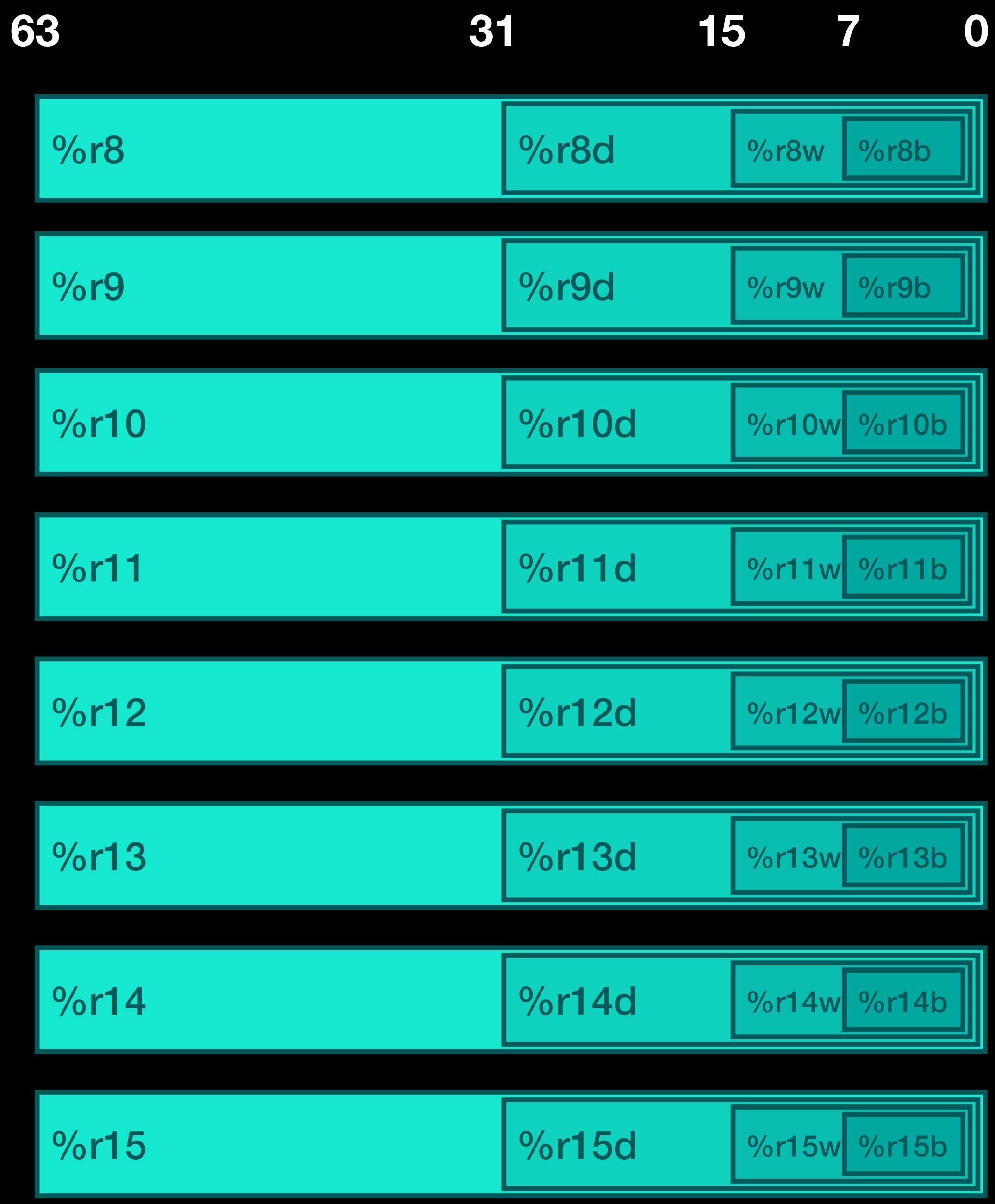

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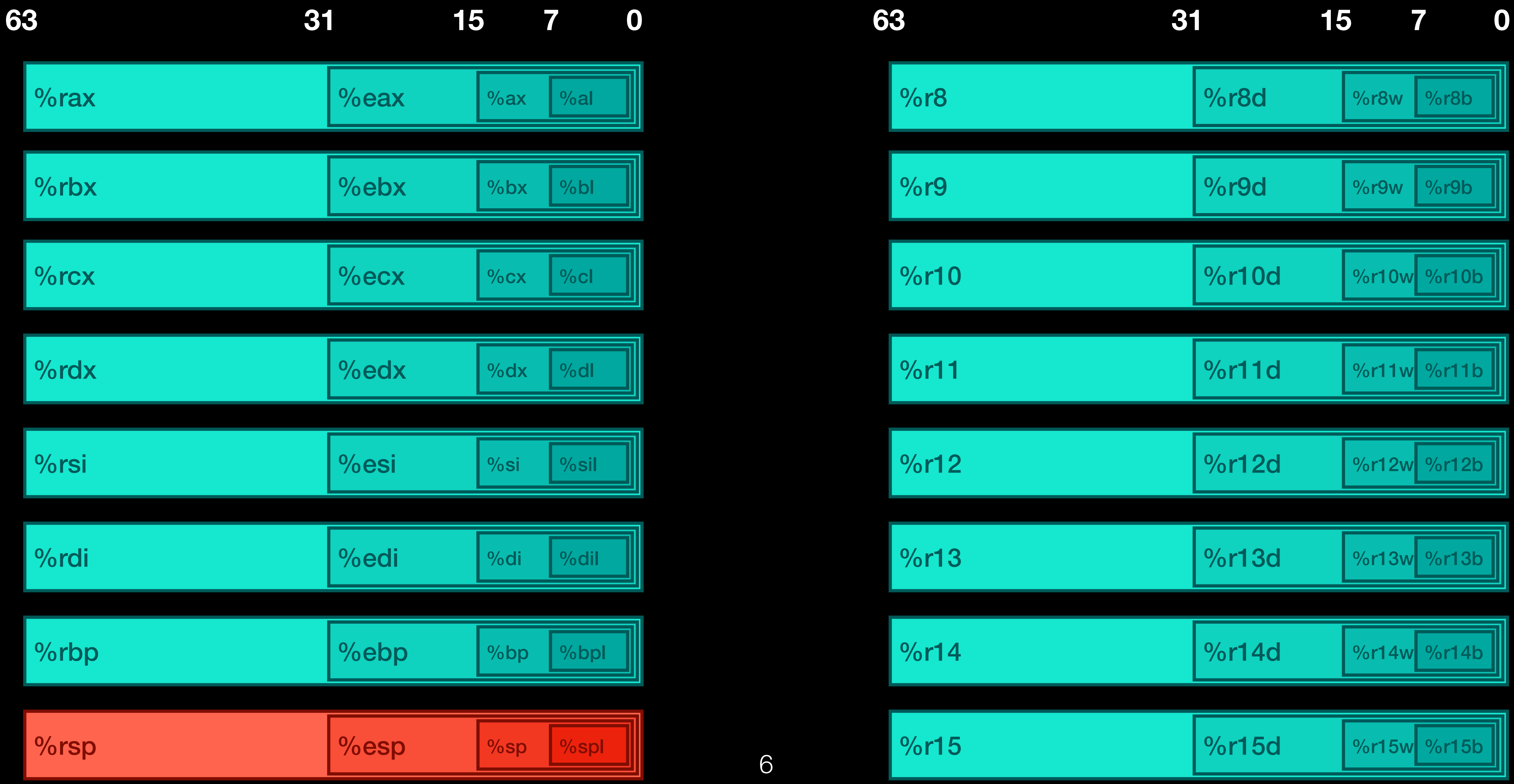
- Suffixes on instructions used to make the size of operands explicit (can be omitted in some cases): q, l, w, b, for resp. 8, 4, 2 and 1 bytes values



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In this presentation we exclusively use AT&T syntax.

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    - Example: `%rax`, `%r13`
    - `%rsp` is special
    - Some instructions have special cases
  - Immediate: an integer constant of 1,2 or 4 bytes
    - `$0x400`, `$42`, `$-1`
    - Same as in C but prefixed with $
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  - Memory (at most one of the two)
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Cannot do memory-memory transfer in a single instruction

Example

Example

```
movq
```

Example

	Source	Dest	Example	C analog
`movq`				

Example

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`movq`	*Imm*	*Reg*	`movq $42, %rax`	`tmp = 42;`

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`movq`	*Imm*	*Reg*	`movq $42, %rax`	`tmp = 42;`
		Mem	`movq $2020, (%rsp)`	`*year = 2020;`

Example

	Source	Dest	Example	C analog
movq	*Imm*	*Reg*	`movq $42, %rax`	`tmp = 42;`
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	Reg	*Reg*	`movq %rdi, %rax`	`tmp2 = tmp1;`

Example

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`movq`	*Imm*	*Reg*	`movq $42, %rax`	`tmp = 42;`
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	Reg	*Reg*	`movq %rdi, %rax`	`tmp2 = tmp1;`
		Mem	`movq %rax, (%rsi)`	`*p = tmp;`

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`movq`	*Imm*	*Reg*	`movq $42, %rax`	`tmp = 42;`
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	Reg	*Reg*	`movq %rdi, %rax`	`tmp2 = tmp1;`
		Mem	`movq %rax, (%rsi)`	`*p = tmp;`
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```
void swap(long *xp, long *yp) {
    long t0 = *xp;
    long t1 = *yp;
    *xp = t1;
    *yp = t0;
}
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Example

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movq	*Imm*	*Reg*	`movq $42, %rax`	`tmp = 42;`
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		Mem	`movq %rax, (%rsi)`	`*p = tmp;`
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void swap(long *xp, long *yp) {
    long t0 = *xp;
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    *xp = t1;
    *yp = t0;
}
```

```
swap:
   movq     (%rdi), %rax
   movq     (%rsi), %rdx
   movq     %rdx, (%rdi)
   movq     %rax, (%rsi)
   ret
```

Addressing modes

Addressing modes

- Most general form :
  `D(Rb,Ri,S)` : Refers to addr = Reg[Rb] + Reg[Ri] * S + D
  - `D:` Constant displacement encoded on 1,2 or 4 bytes
  - `Rb:` Base register: Any of the 16 integer registers
  - `Ri:` Index register: Any except %rsp
  - `S:` scale: One of 1,2,4 or 8 (1 by default if omitted)

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  - `Ri:` Index register: Any except %rsp
  - `S:` scale: One of 1,2,4 or 8 (1 by default if omitted)
- Any element can be omitted.
  - `0x48000` - only D
  - `0x42(,%rsi,2)` - Ri, S and D
  - `(%rdi, %rsi)` - Rb and Ri (S = 1)

Arithmetic operations

Arithmetic operations

Instruction		Computation	
`addq`	*Src, Dest*	Dest = Dest + Src	
`subq`	*Src, Dest*	Dest = Dest - Src	
`imul`	*Src, Dest*	Dest = Dest * Src	
`salq`	*Src, Dest*	Dest = Dest << Src	*Also known as* `shlq`
`sarq`	*Src, Dest*	Dest = Dest >> Src	*Arithmetic right shift*
`shrq`	*Src, Dest*	Dest = Dest >> Src	*Logical right shift*
`xorq`	*Src, Dest*	Dest = Dest ^ Src	
`andq`	*Src, Dest*	Dest = Dest & Src	
`orq`	*Src, Dest*	Dest = Dest | Src	
`incq`	*Dest*	Dest = Dest + 1	
`decq`	*Dest*	Dest = Dest - 1	
`negq`	*Dest*	Dest = – Dest	*Two complement*
`notq`	*Dest*	Dest = ~Dest	*Bitwise negation*

…

This is not an exhaustive list.

Jumping

Jumping

- Redirect the control flow elsewhere than the next instruction:
  - Define a *label* to jump to (`label:` before an instruction),
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```
void loop(long a) {
    a = a + a;
    while(1) {
        a++;
    }
}
```

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```
void loop(long a) {
    a = a + a;
    while(1) {
        a++;
    }
}
```

```
loop:
    addq     %rdi, %rdi
while:
    addq     $1, %rdi
    jmpq     while
```

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Flag	**Name**	**When is it set**
CF	Carry flag	Arithmetic operation generates a carry or a borrow out of the MS bit
PF	Parity flag	LS byte of the result contains an even number of 1 bits

OF	Overflow flag	two's-complement overflow
		`(a > 0 && b > 0 && t < 0) ‖`
		`(a < 0 && b < 0 && t >= 0)`

SF	Sign flag	`t < 0` (as two complement signed)
ZF	Zero flag	`t == 0`

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```
example:
    movq    $42, %rax
    movq    $12, %rdx
    cmpq    %rdx,%rax
    setge   %al
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# al is 1 as 42 >= 12
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`jnb / jae`	not below / above or equal	CF = 0
`je / jz`	equal / zero	ZF =1
`jne / jnz`	not equal / zero	ZF = 0
`jbe / jna`	below or equal / not above	(CF OR ZF) = 1
`jnbe / ja`	neither below nor equal / above	(CF OR ZF)= 0
`js`	sign	SF = 1
`jns`	no sign	SF = 0
`jp / jpe`	parity even	PF = 1
`jnp / jpo`	parity odd	PF = 0
`jl / jnge`	less / not greater or equal	(SF XOR CF) = 1
`jnl / jge`	not less / greater or equal	(SF XOR CF) = 0
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Below / Above refers to unsigned
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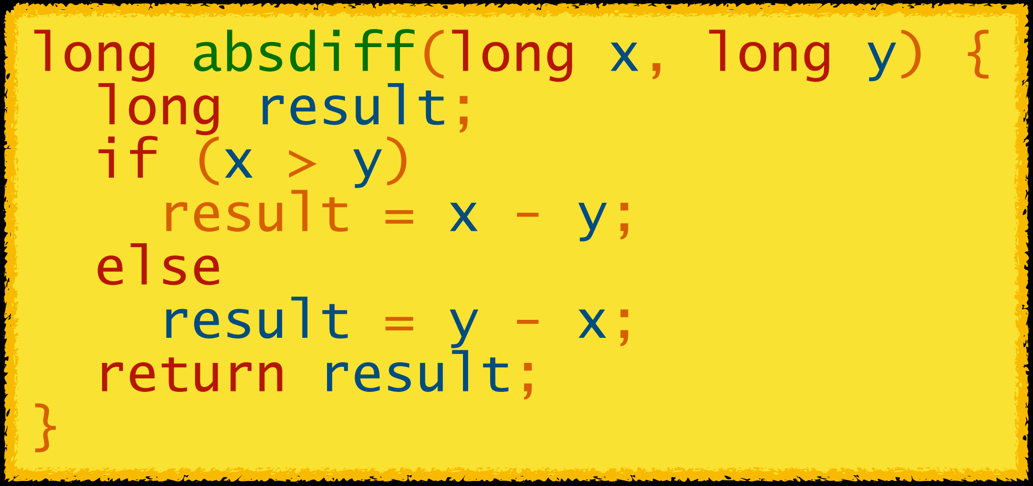
```
example:
   movq  $0,   %rax
   testq %rdi, %rdi
   jz end
   movq  $42,  %rax
end:
# what will %rax contain ?
```

if else, switch case

if else, switch case



```
long absdiff(long x, long y) {
  long result;
  if (x > y)
    result = x - y;
  else
    result = y - x;
  return result;
}
```

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```
absdiff:
   cmpq %rsi, %rdi
   # set flags for x-y
   jle .L4
   movq %rdi, %rax
   subq %rsi, %rax
   ret
.L4: # x <= y
   movq %rsi, %rax
   subq %rdi, %rax
   ret
```

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```
long switch_eg(long x, long y, long z) {
  long w = 1;
  switch(x) {
  case 1:
    w = y * z;
    break;
  case 2:
    w = y / z; /* Fall Through */
  case 3:
    w += z;
    break;
  case 5:
  case 6:
    w -= z;
    break;
  default:
    w = 2;
  }
  return w;
}
```

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y in %rsi,
z in %rdx,
result in %rax

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x in %rdi,
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result in %rax

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   movq %rsi, %rax
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  case 6:
    w -= z;
    break;
  default:
    w = 2;
  }
  return w;
}
```

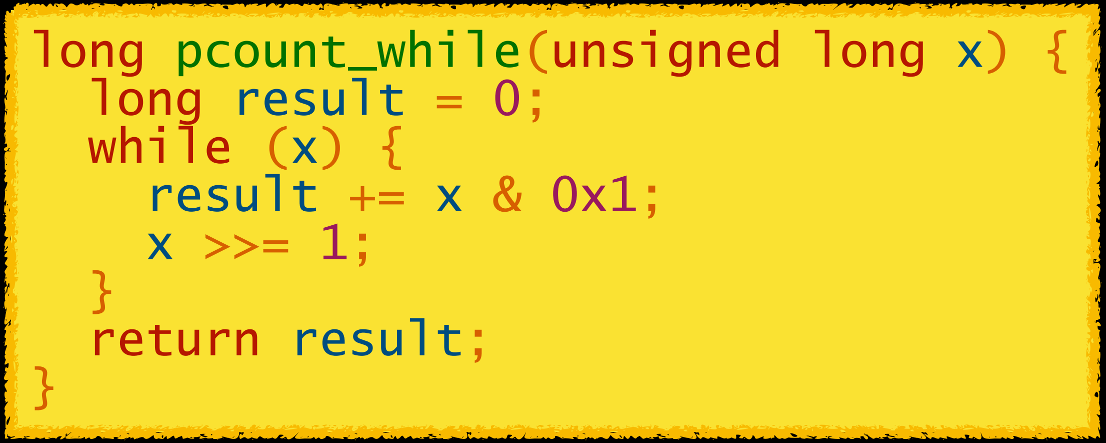
x in %rdi,
y in %rsi,
z in %rdx,
result in %rax

```
switch_eg:
  movq %rdx, %rcx
  cmpq $6, %rdi # x:6
  ja .L8 # Use default
  jmp *.L4(,%rdi,8)
# … code for each case.
.Li: # in in 3,5,7,8,9
  …
```

```
.section .rodata .align 8
.L4:
  .quad .L8 #x == 0
  .quad .L3 #x == 1
  .quad .L5 #x == 2
  .quad .L9 #x == 3
  .quad .L8 #x == 4
  .quad .L7 #x == 5
  .quad .L7 #x == 6
```

Loops

Loops



```
long pcount_while(unsigned long x) {
  long result = 0;
  while (x) {
    result += x & 0x1;
    x >>= 1;
  }
  return result;
}
```

Loops

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```

```
long pcount_goto_jtm(unsigned long x) {
  long result = 0;
  goto test;
loop:
  result += x & 0x1;
  x >>= 1;
test:
  if (x)
    goto loop;
  return result;
}
```

Loops

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loop:
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  x >>= 1;
test:
  if (x)
    goto loop;
  return result;
}
```

```
long pcount_goto_dw(unsigned long x) {
  long result = 0;
  if (!x)
    goto done;
loop:
  result += x & 0x1;
  x >>= 1;
  if (x)
    goto loop;
done:
  return result;
}
```

Loops

```c
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  while (x) {
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    x >>= 1;
  }
  return result;
}
```

```c
long pcount_goto_jtm(unsigned long x) {
  long result = 0;
  goto test;
loop:
  result += x & 0x1;
  x >>= 1;
test:
  if (x)
    goto loop;
  return result;
}
```

```
pcount_goto_jtm:
  movl  $0,   %eax
  jmp   .L2
.L3:
  movq  %rdi, %rdx
  andl  $1,   %edx
  addq  %rdx, %rax
  shrq  %rdi
.L2:
  testq %rdi, %rdi
  jne   .L3
  rep ret
```

```c
long pcount_goto_dw(unsigned long x) {
  long result = 0;
  if (!x)
    goto done;
loop:
  result += x & 0x1;
  x >>= 1;
  if (x)
    goto loop;
done:
  return result;
}
```

Loops

```
long pcount_while(unsigned long x) {
  long result = 0;
  while (x) {
    result += x & 0x1;
    x >>= 1;
  }
  return result;
}
```

```
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  return result;
}
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```
pcount_goto_dw:
  testq %rdi, %rdi
  je    .L4
  movl  $0,   %eax
.L3:
  movq  %rdi, %rdx
  andl  $1,   %edx
  addq  %rdx, %rax
  shrq  %rdi
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```
long m12(long x)
{
  return x*12;
}
```

```
m12:
    leaq (%rdi,%rdi,2), %rax # t <- x+x*2
    salq $2, %rax # return t<<2
    ret
```

The stack

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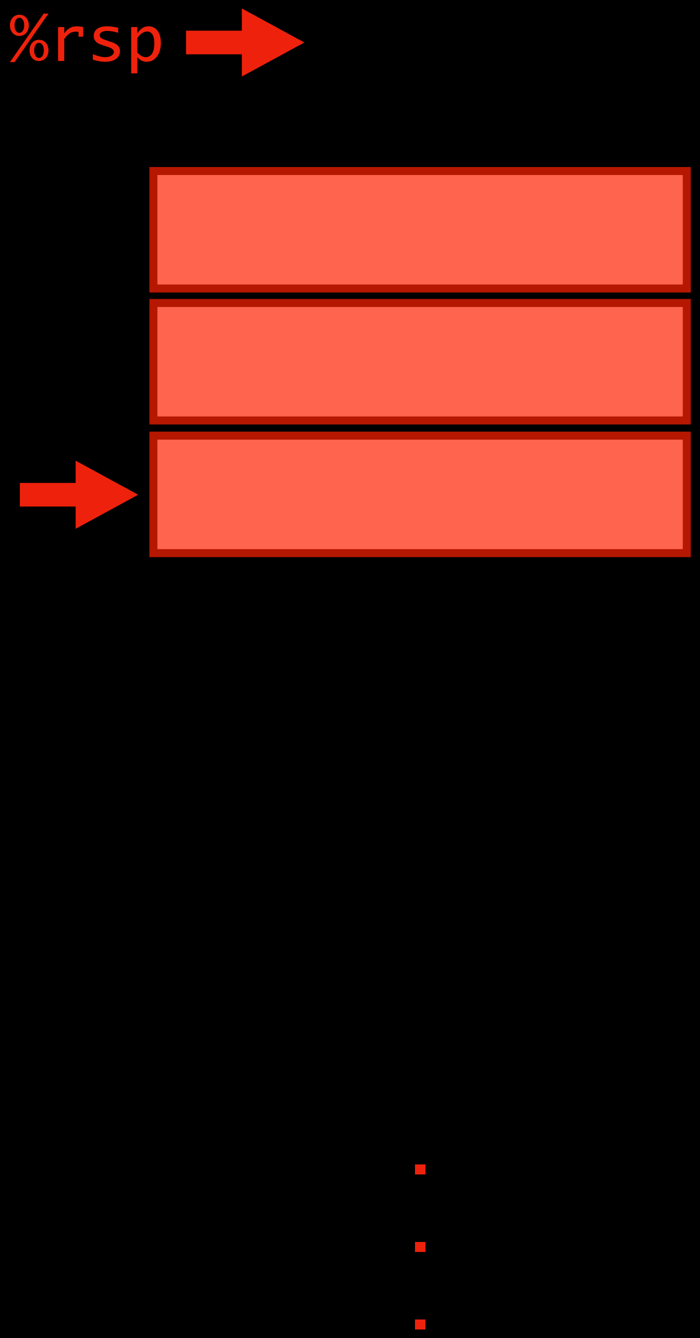

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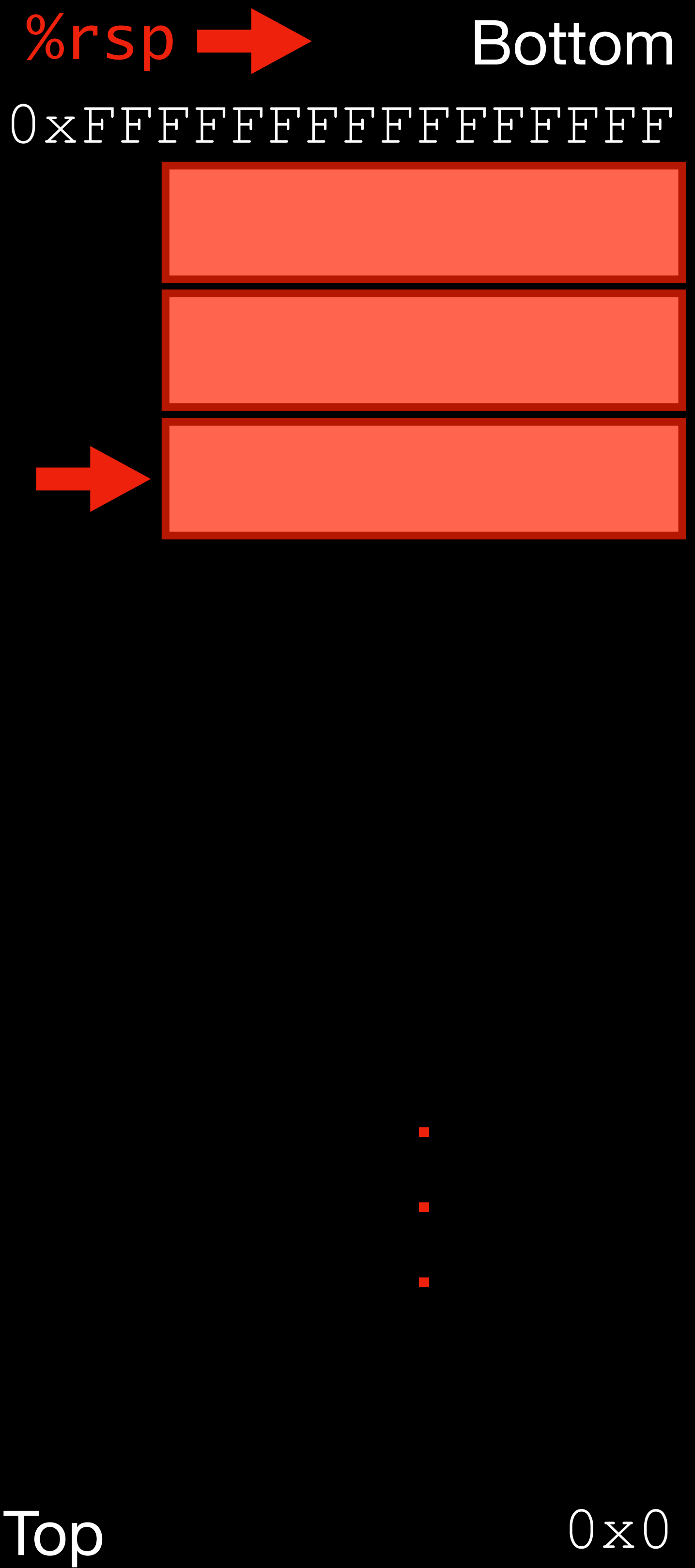

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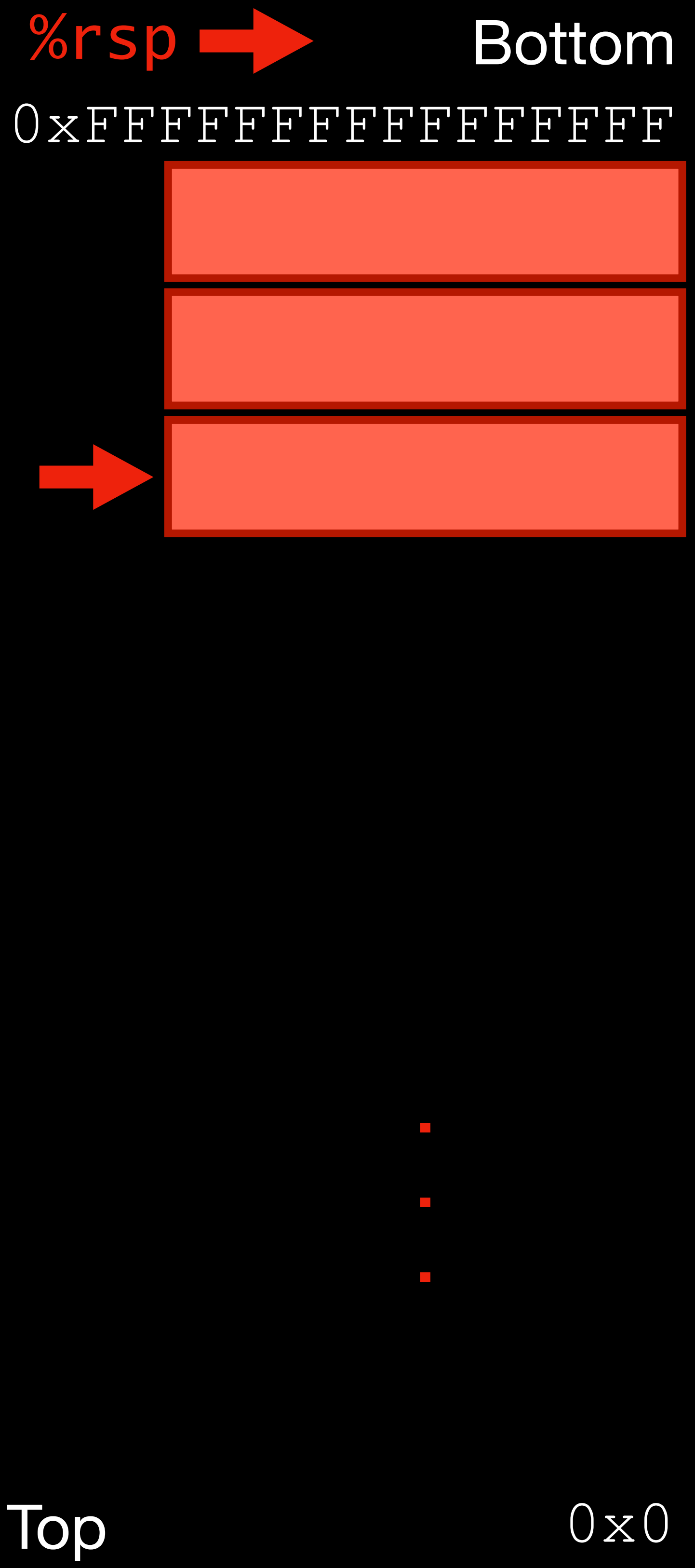

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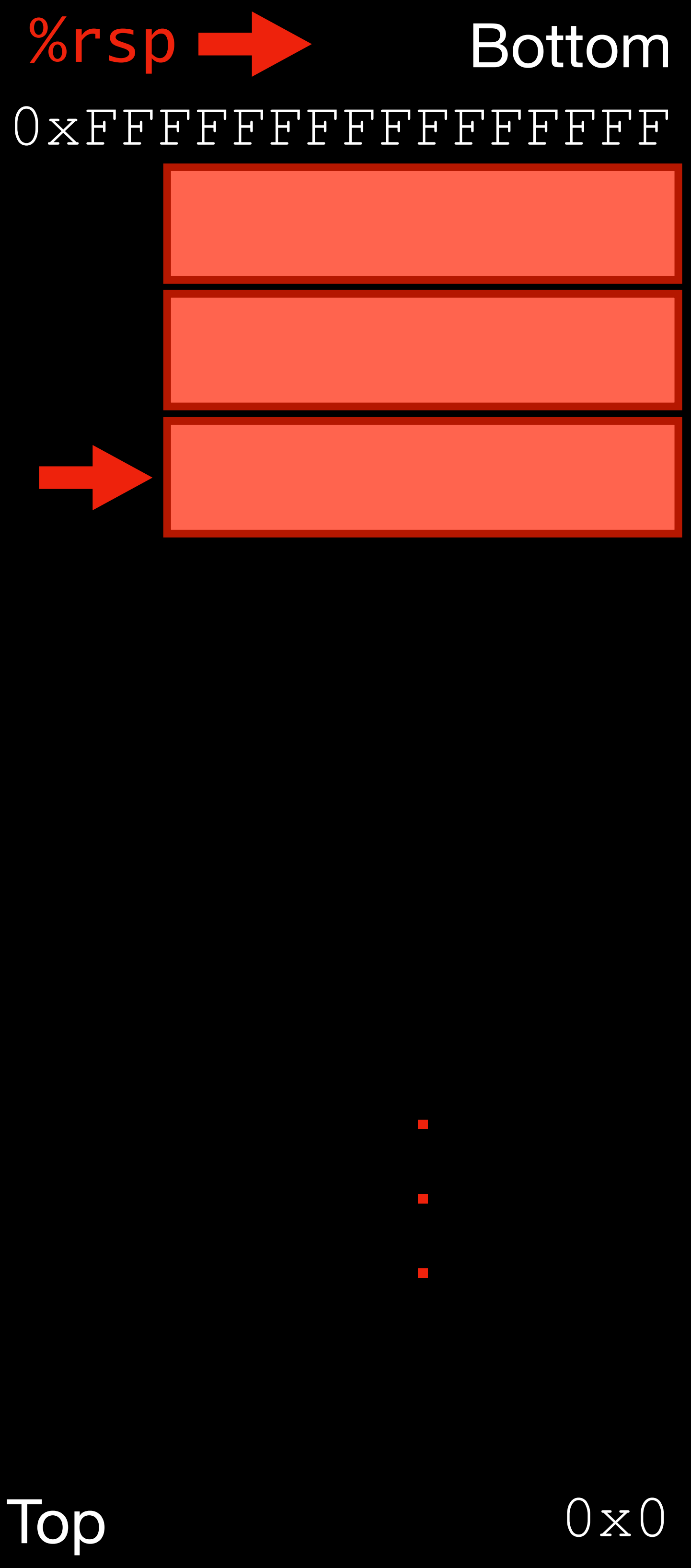

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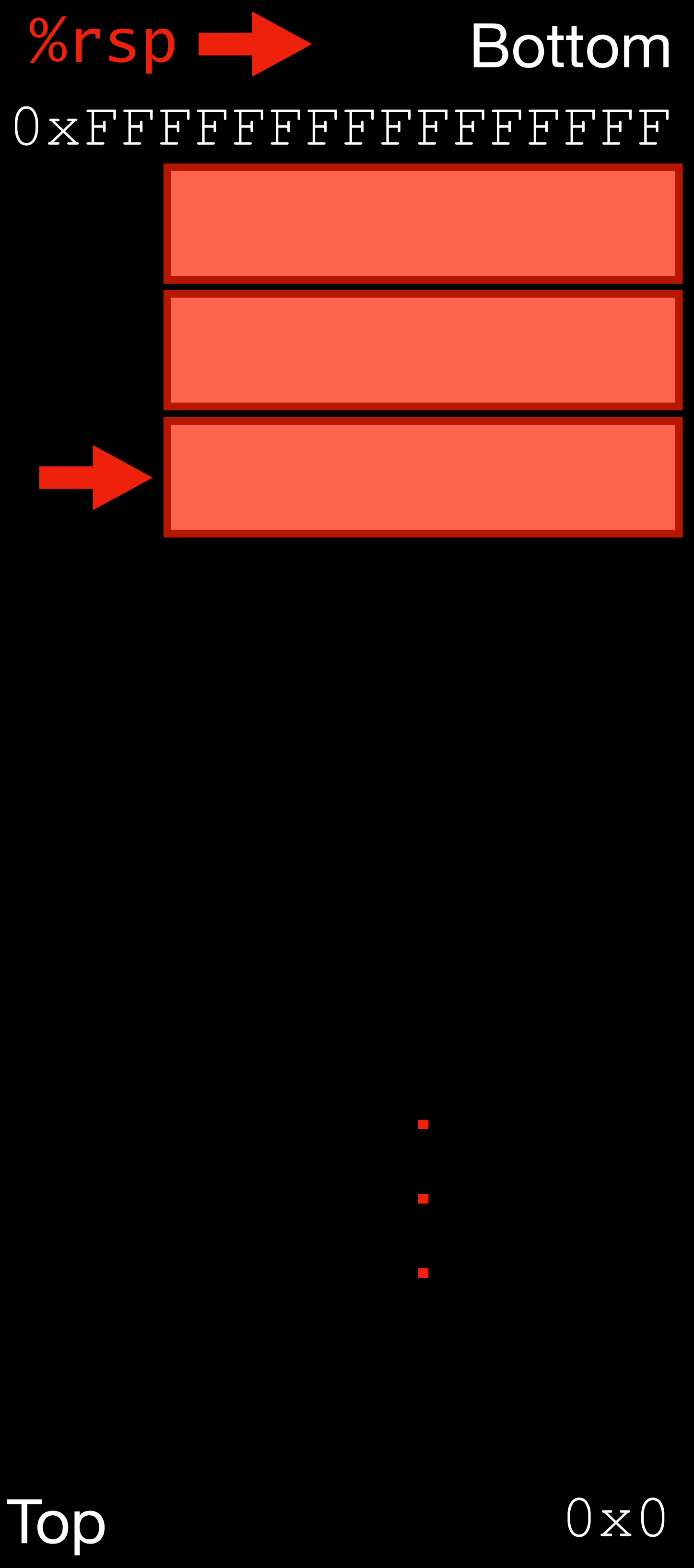

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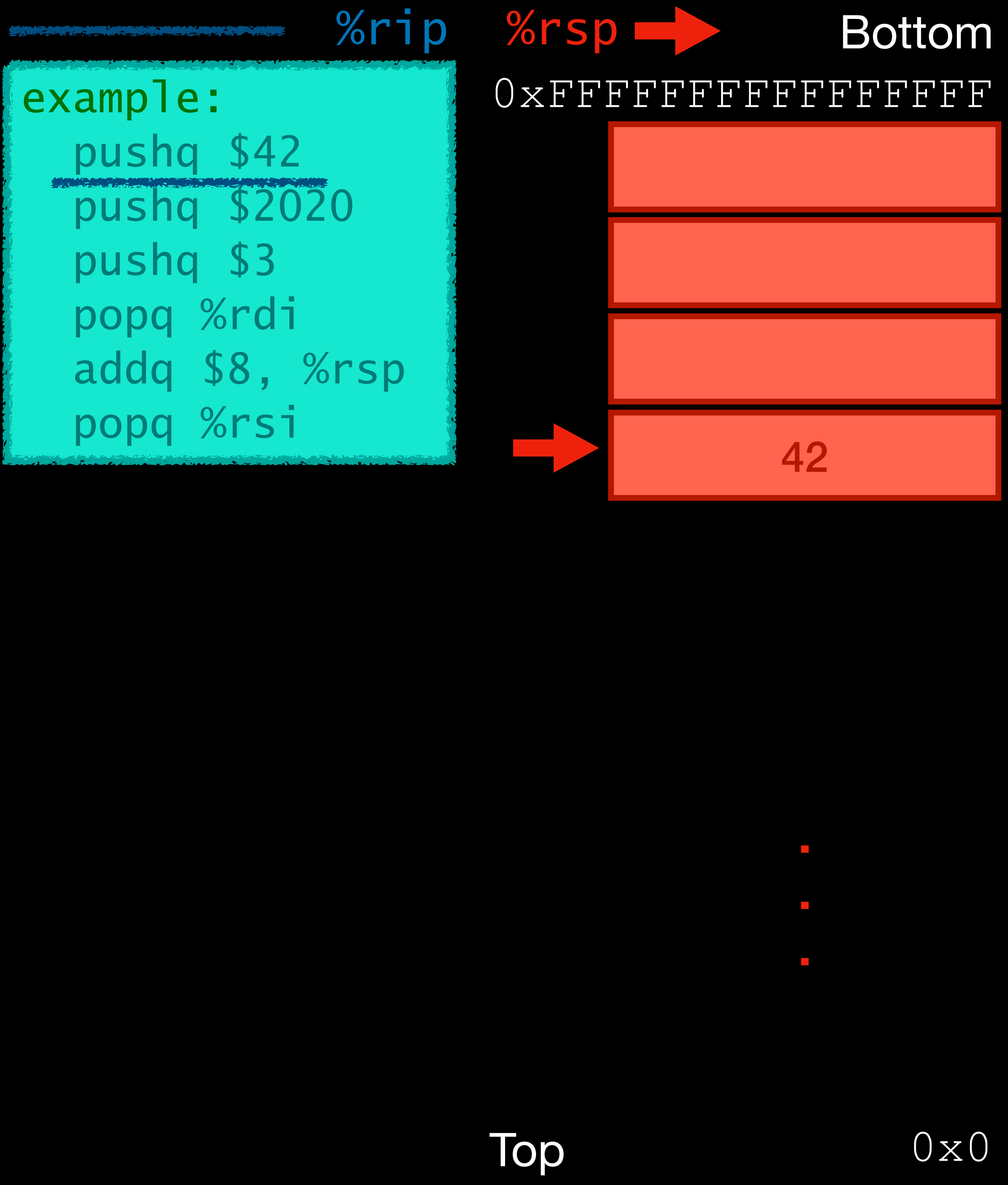

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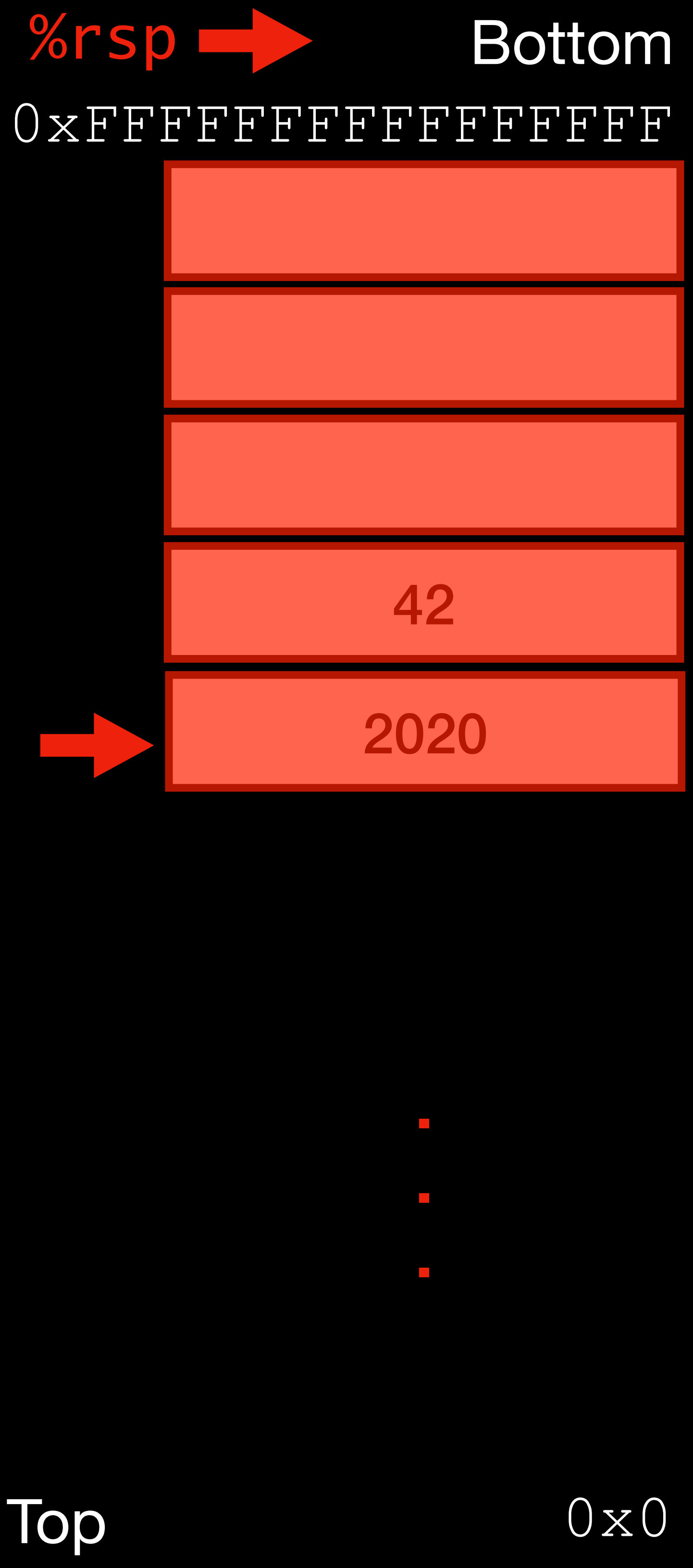

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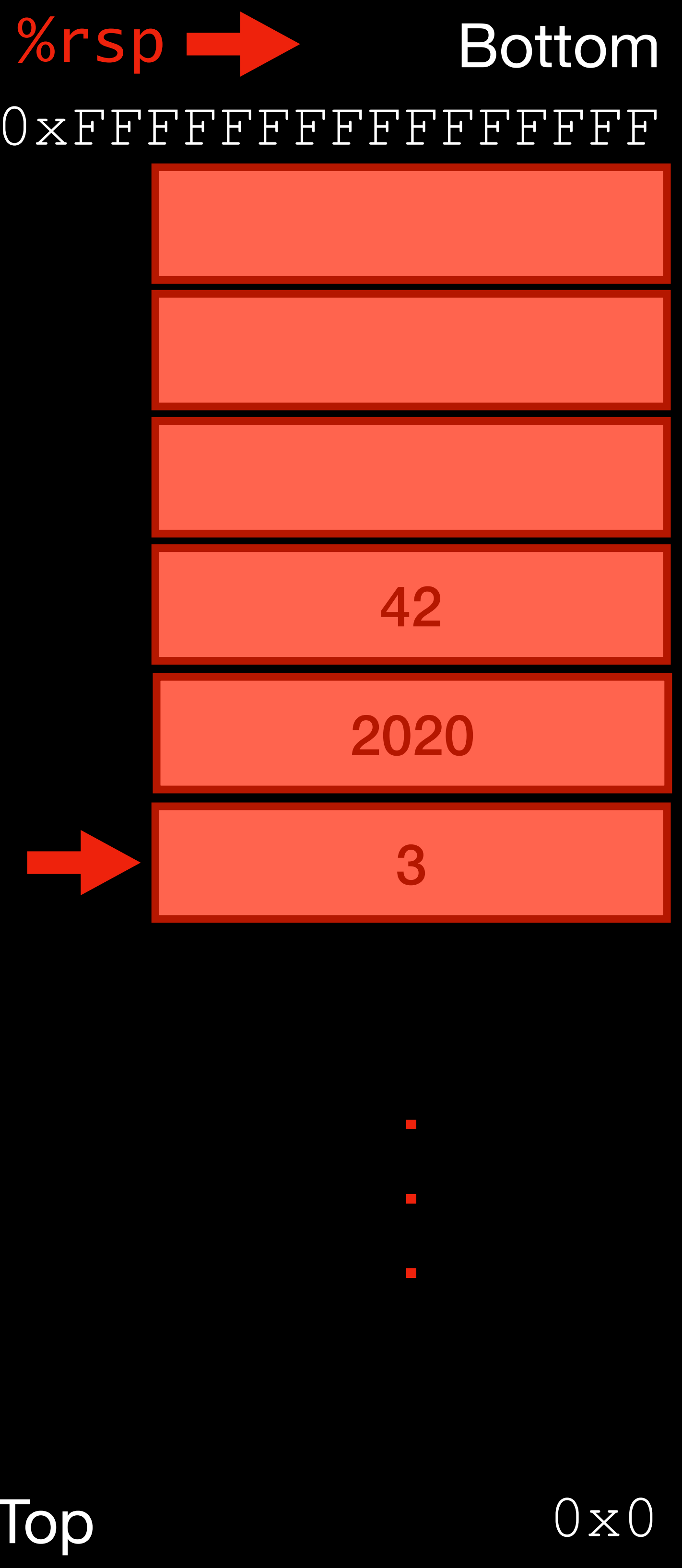

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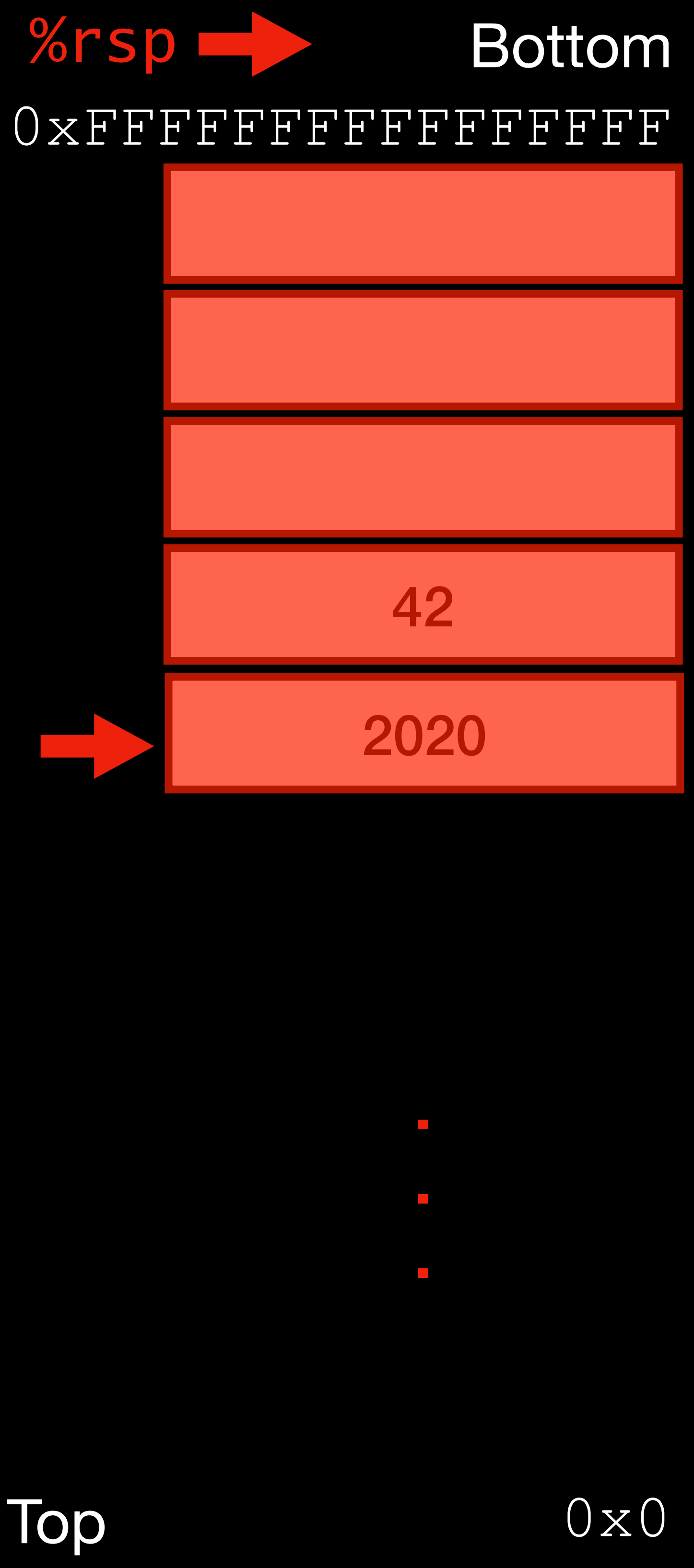

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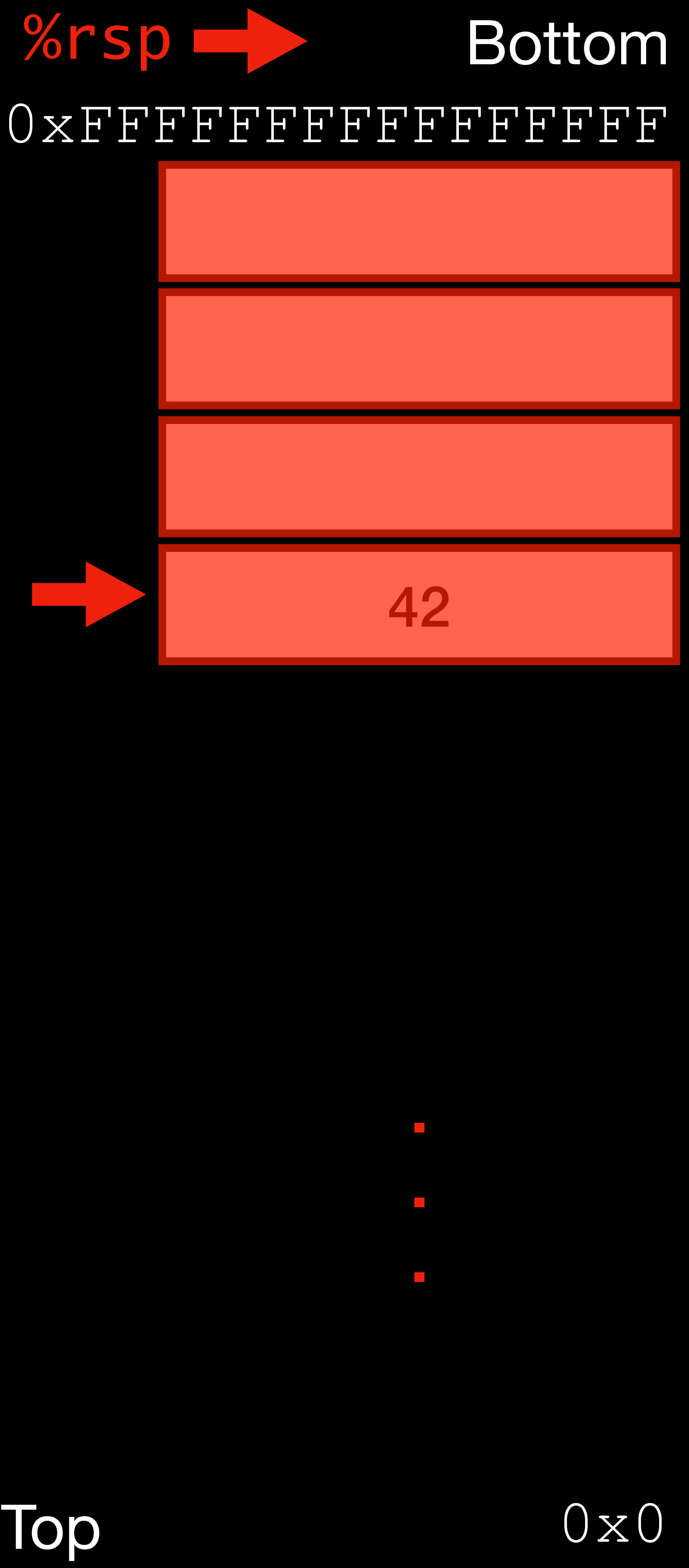

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`%rsi = 42`

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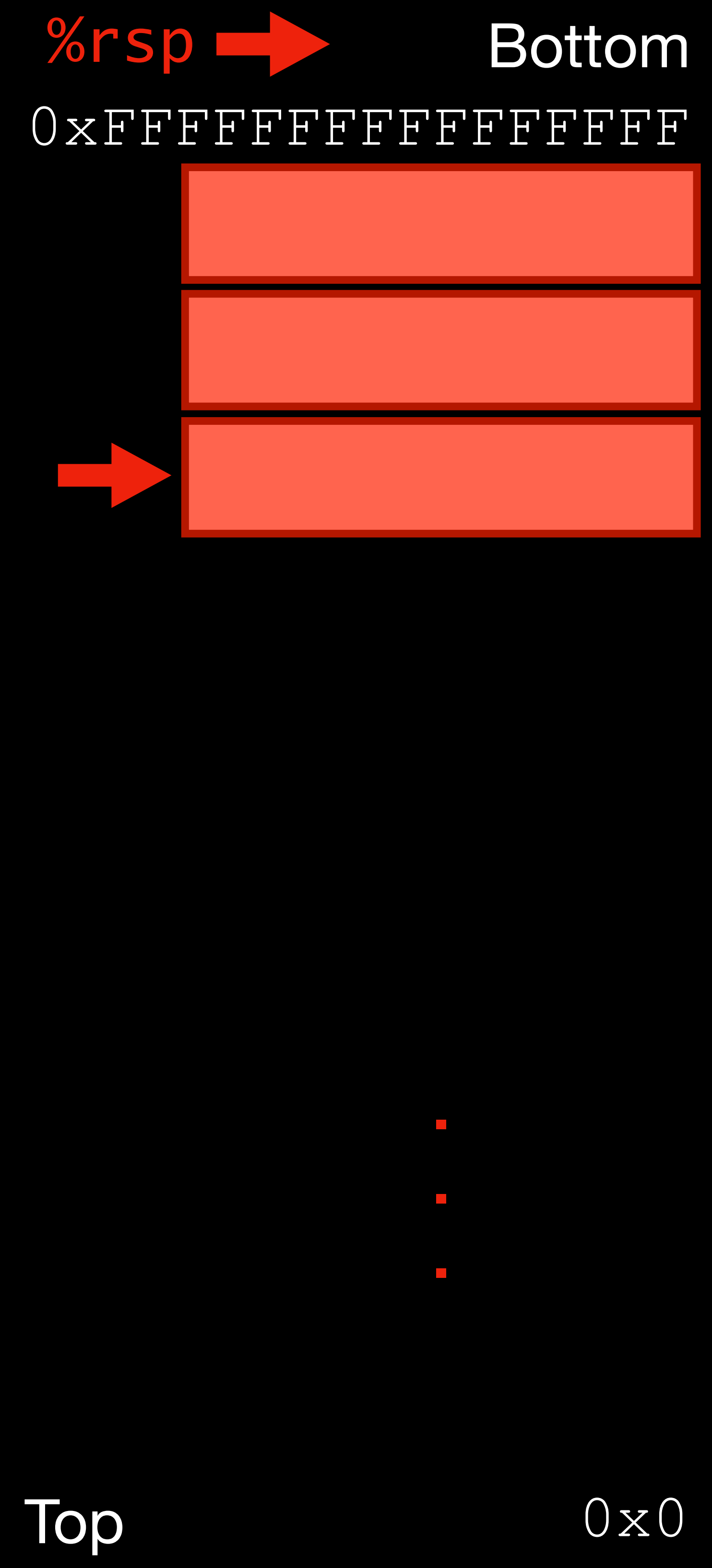

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- You can also
  - drop a value with addq $8, %rsp,
  - make room for values using subq, and access them with D(%rsp).

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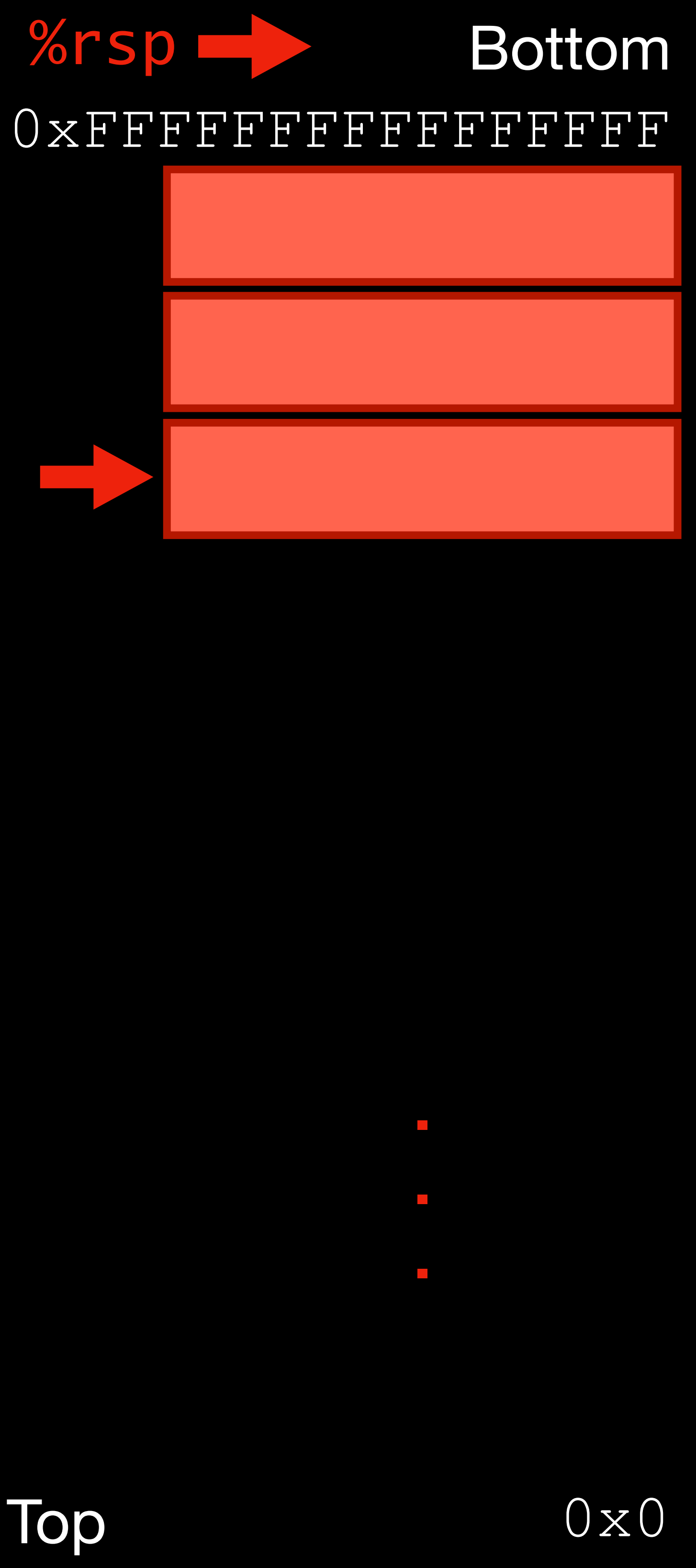

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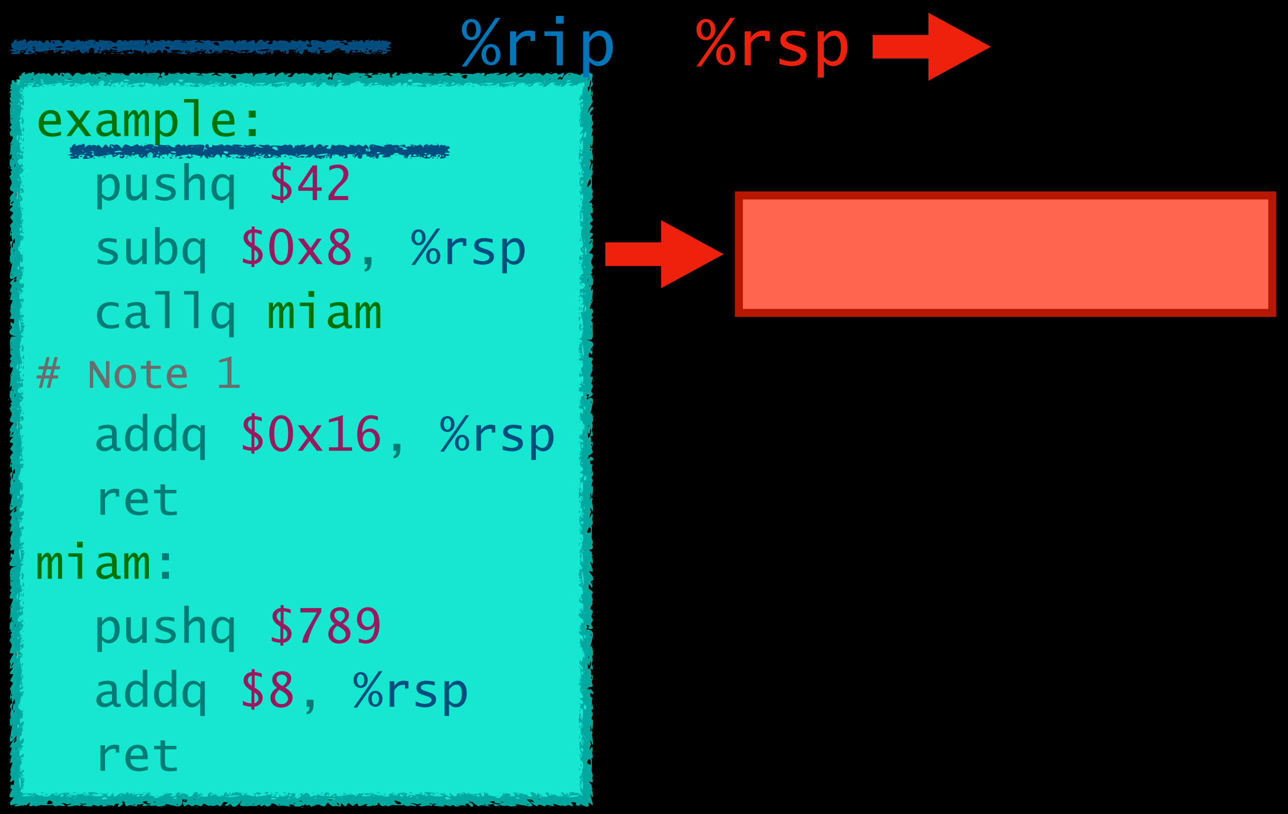

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example:
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# Note 1
  addq $0x16, %rsp
  ret
miam:
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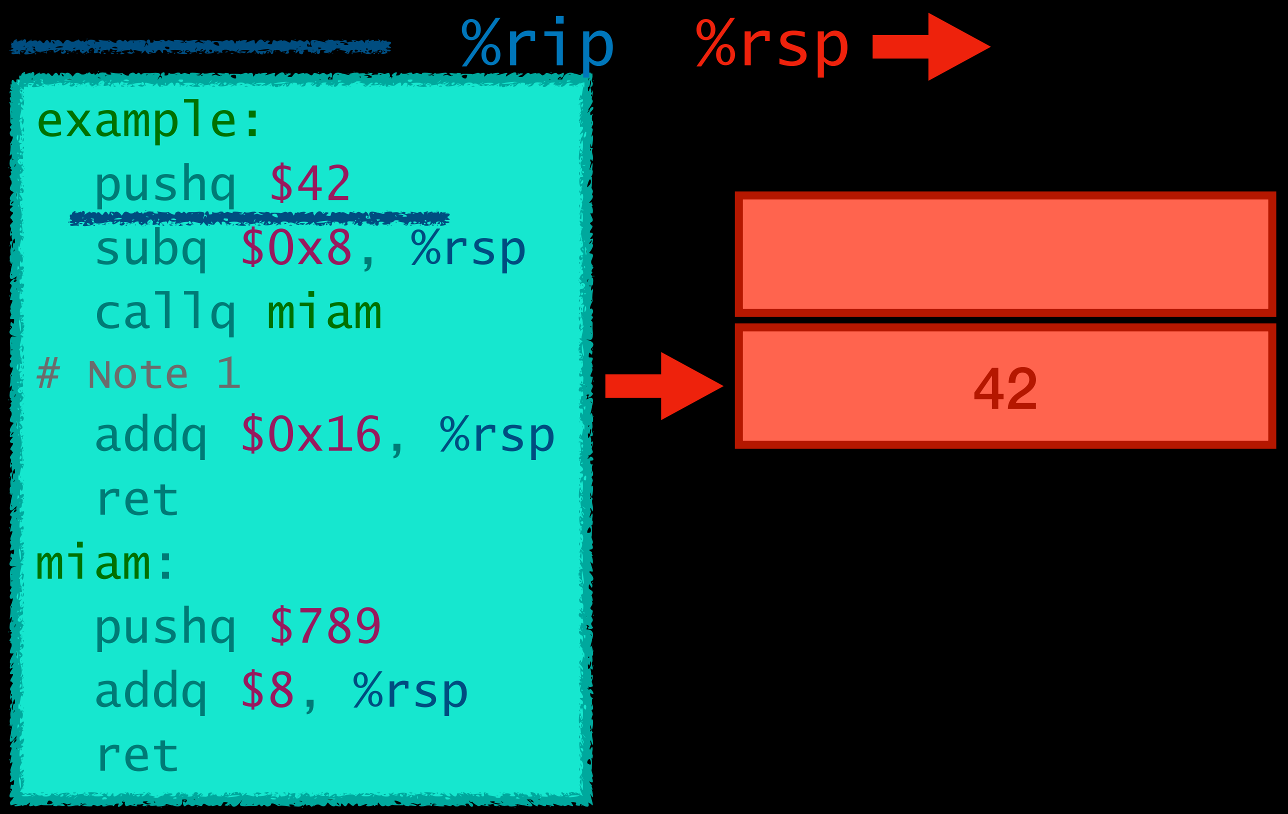

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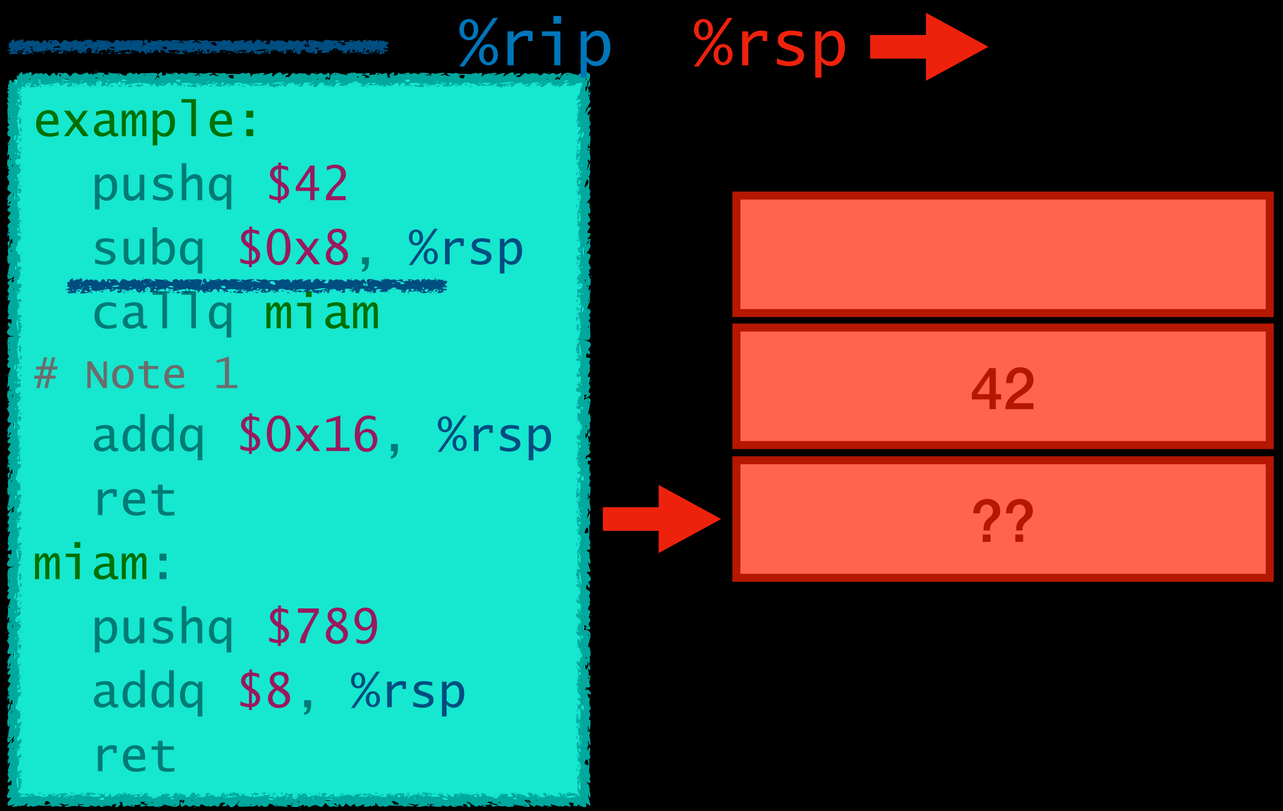

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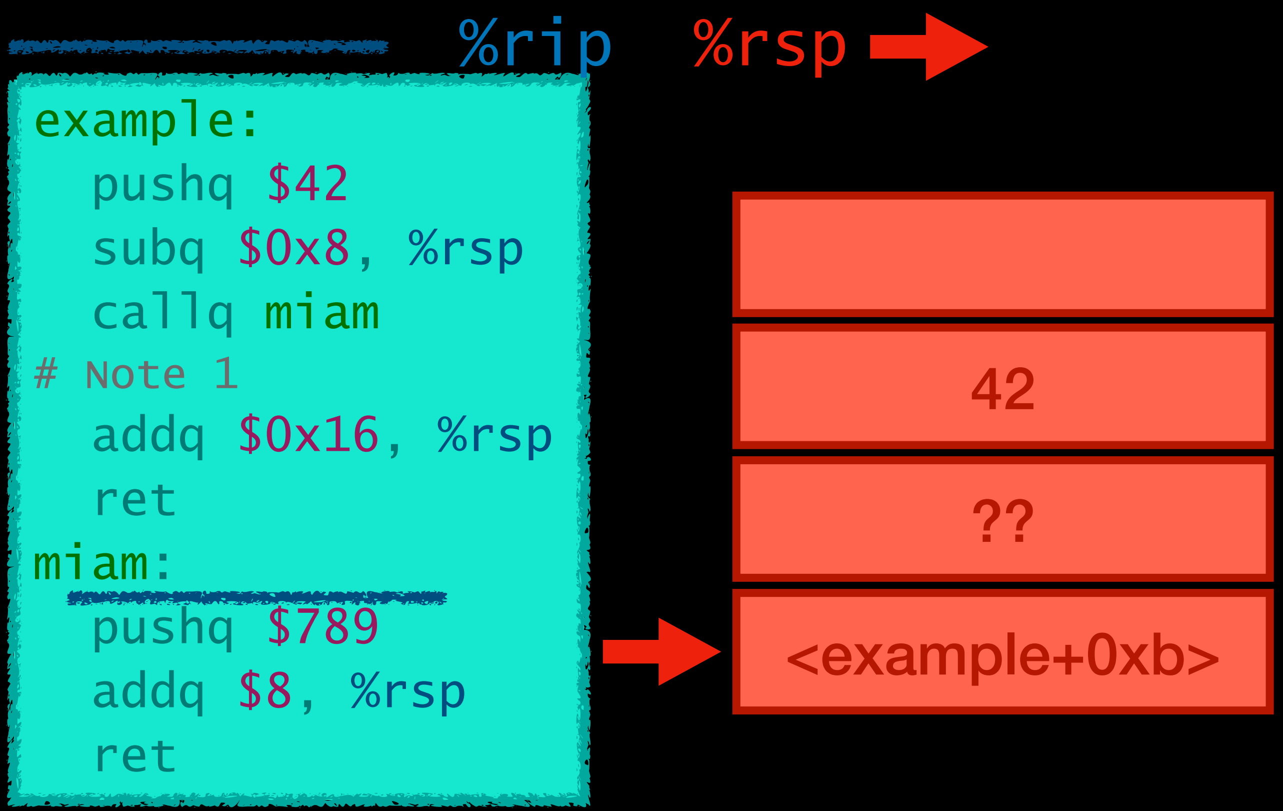

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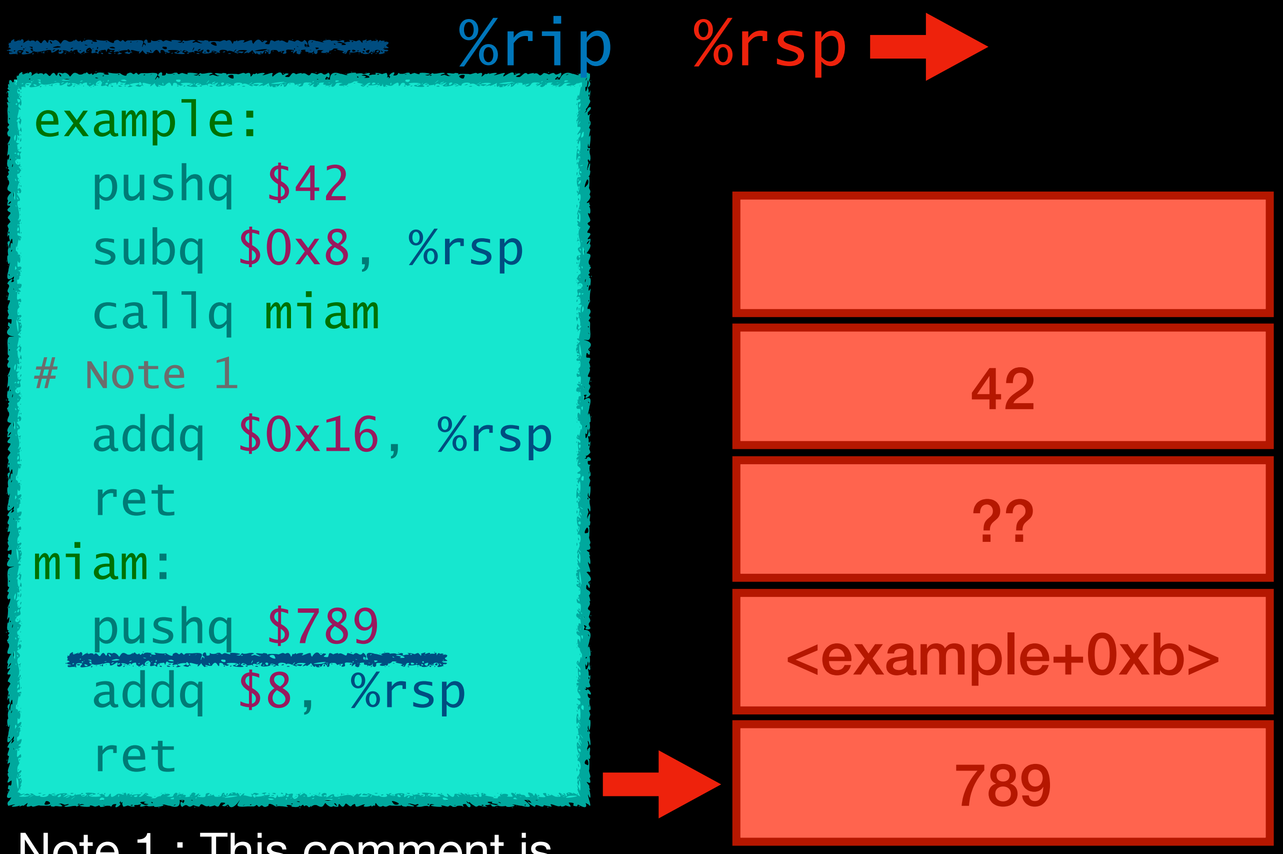

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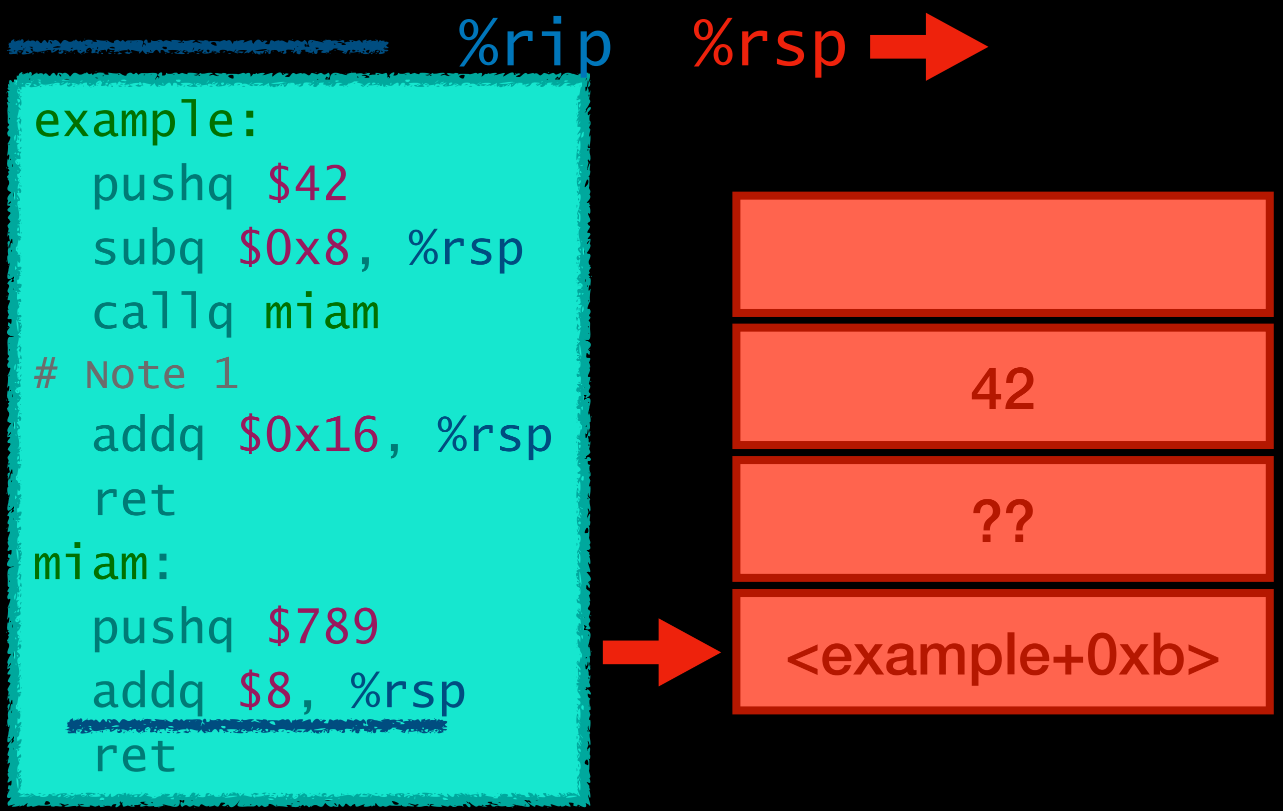

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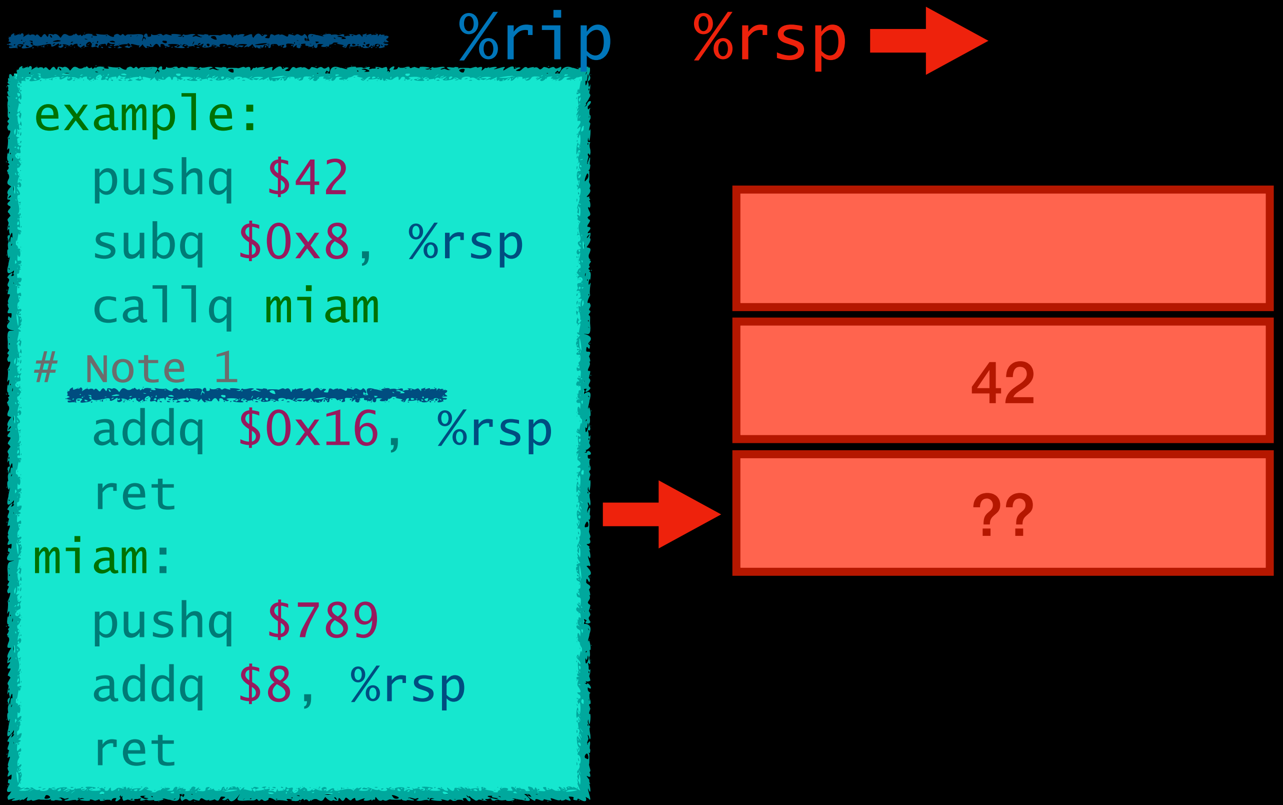

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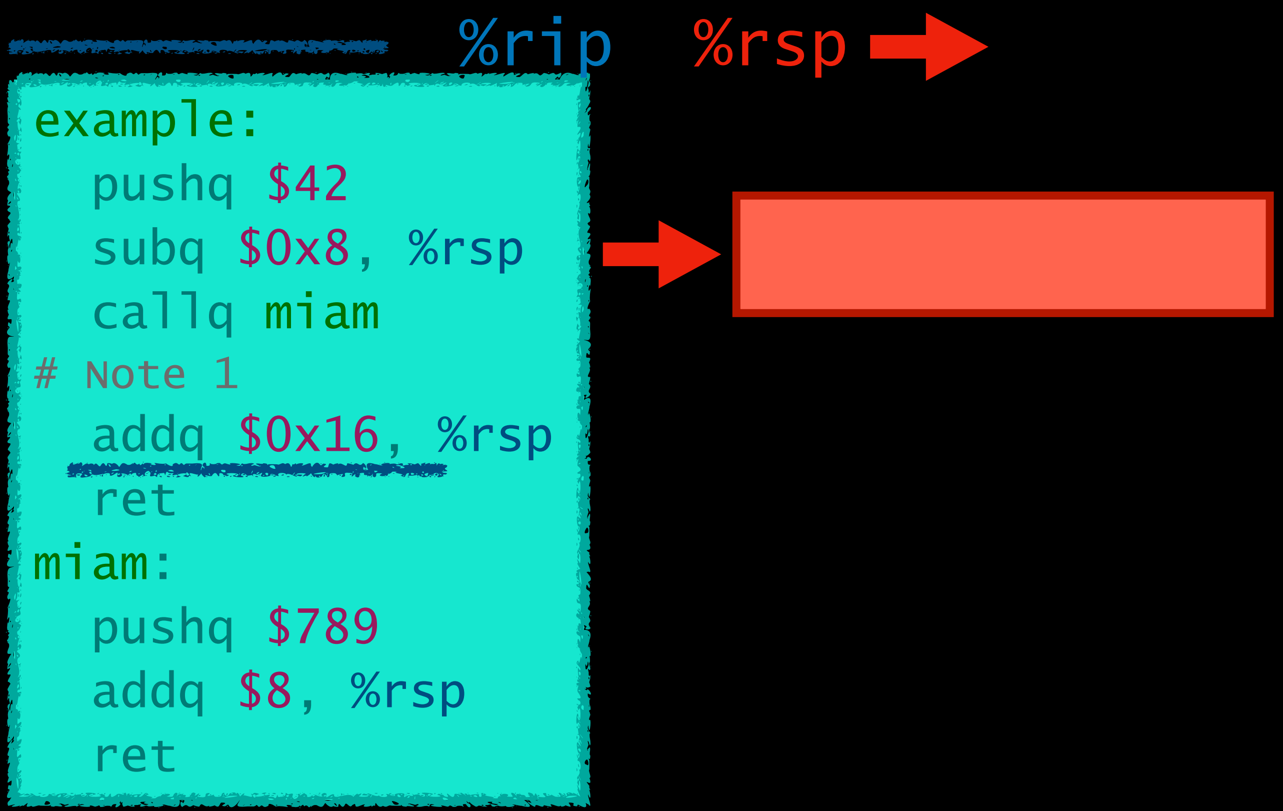
  addq $8, %rsp
  ret
```

Note 1 : This comment is 11 (0xb) machine code bytes in `example`

Building functions

- Problem:
  - Jump to function code
  - Go back where you came from ?
- Solution: Use the stack !
- A `callq` instruction
  1. push the return address
  2. jump to the function code
- The `retq` instruction is used at the end of the function
  1. pop the return address
  2. jump back to it.
  3. (That can be though of as `popq %rip`)
- Functions can modify `%rsp` to use the stack but have to restore it to the correct value before `ret`
- Make sure you balance the `pushq` and `subq $8` with the `popq` and `addq $8` to `%rsp`



```
example:
  pushq $42
  subq $0x8, %rsp
  callq miam
# Note 1
  addq $0x16, %rsp
  ret
miam:
  pushq $789
  addq $8, %rsp
  ret
```

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Calling functions

Calling functions

- How do we make sure we can keep our register values when we call functions ?
  How can we pass a function parameters and get a return value ?

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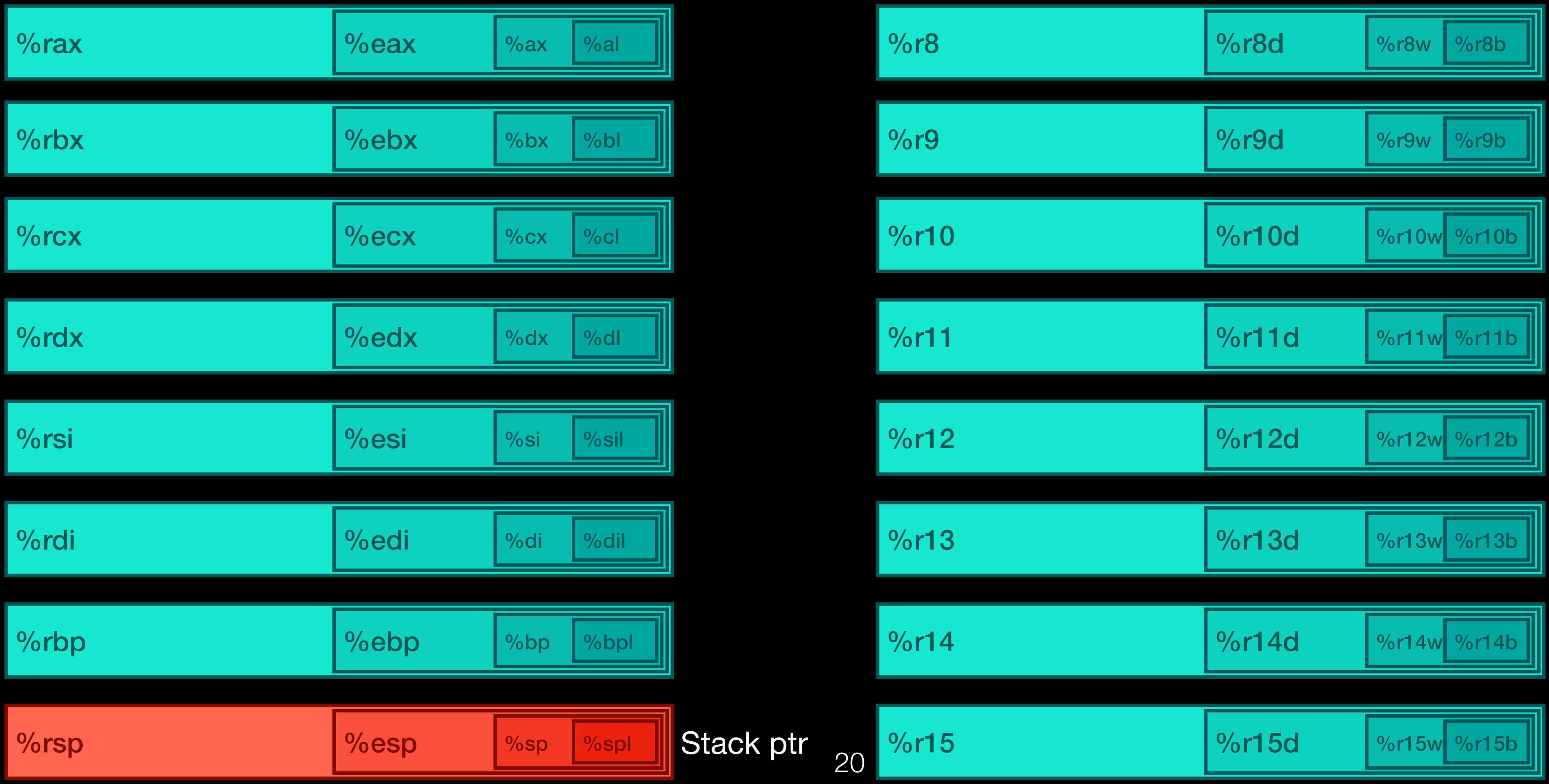

%rax	%eax	%ax	%al		%r8	%r8d	%r8w	%r8b
%rbx	%ebx	%bx	%bl		%r9	%r9d	%r9w	%r9b
%rcx	%ecx	%cx	%cl		%r10	%r10d	%r10w	%r10b
%rdx	%edx	%dx	%dl		%r11	%r11d	%r11w	%r11b
%rsi	%esi	%si	%sil		%r12	%r12d	%r12w	%r12b
%rdi	%edi	%di	%dil		%r13	%r13d	%r13w	%r13b
%rbp	%ebp	%bp	%bpl		%r14	%r14d	%r14w	%r14b
%rsp	%esp	%sp	%spl	Stack ptr	%r15	%r15d	%r15w	%r15b

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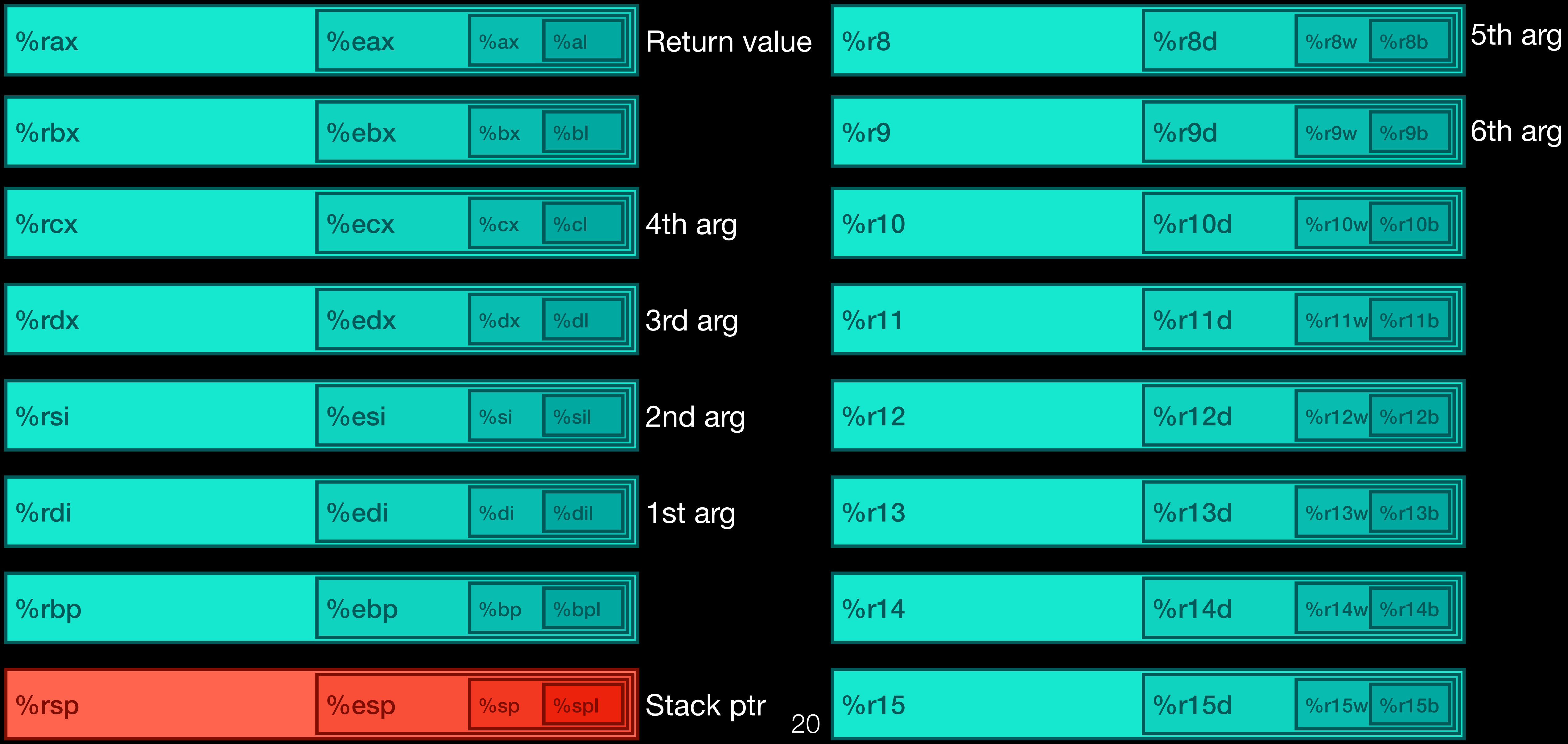
- How do we make sure we can keep our register values when we call functions ?
  How can we pass a function parameters and get a return value ?
- We use a convention (ABI) that defines how to use registers. (We present the linux x86_64 one)



%rax	%eax	%ax	%al	Return value
%rbx	%ebx	%bx	%bl	
%rcx	%ecx	%cx	%cl	4th arg
%rdx	%edx	%dx	%dl	3rd arg
%rsi	%esi	%si	%sil	2nd arg
%rdi	%edi	%di	%dil	1st arg
%rbp	%ebp	%bp	%bpl	
%rsp	%esp	%sp	%spl	Stack ptr

%r8	%r8d	%r8w	%r8b	5th arg
%r9	%r9d	%r9w	%r9b	6th arg
%r10	%r10d	%r10w	%r10b	
%r11	%r11d	%r11w	%r11b	
%r12	%r12d	%r12w	%r12b	
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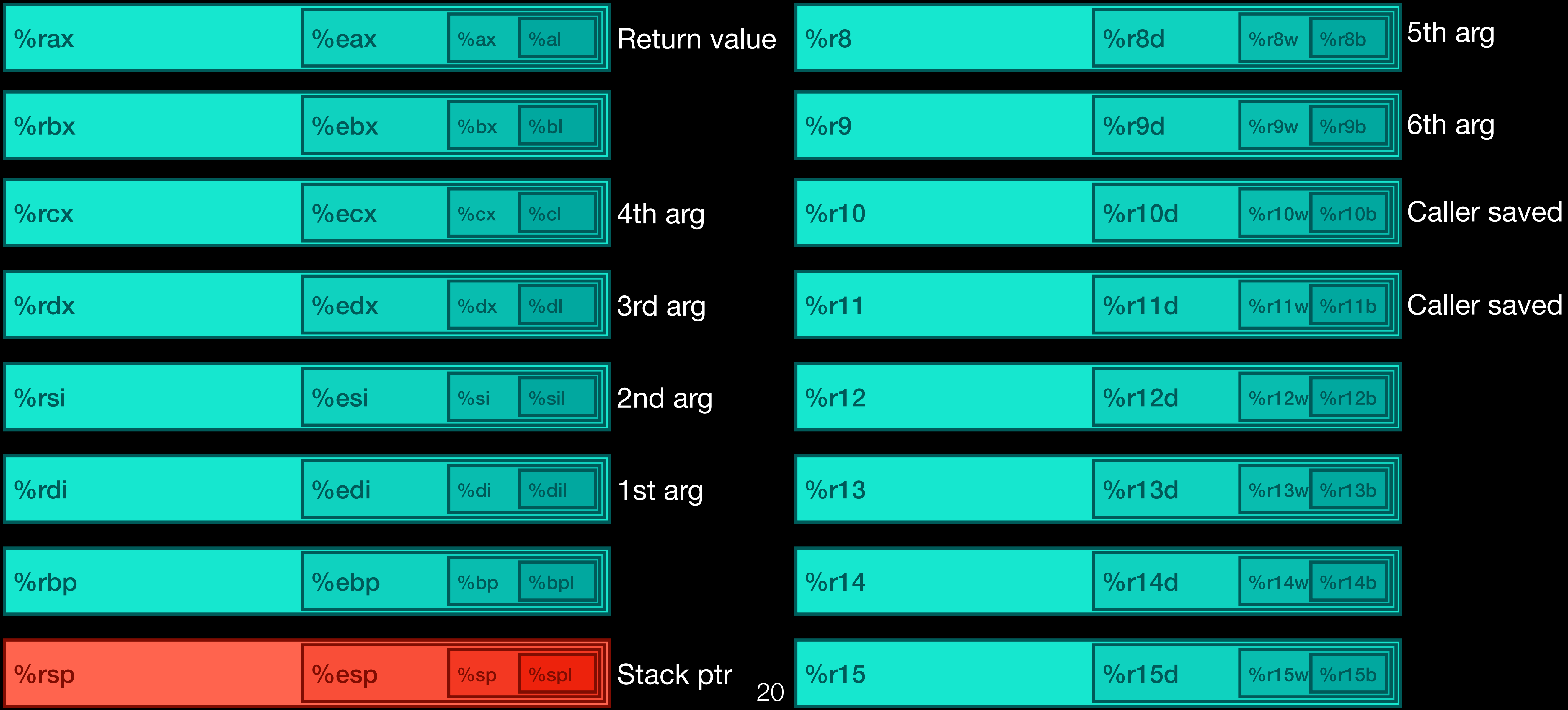

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%r10	%r10d	%r10w	%r10b	Caller saved
%r11	%r11d	%r11w	%r11b	Caller saved
%r12	%r12d	%r12w	%r12b	
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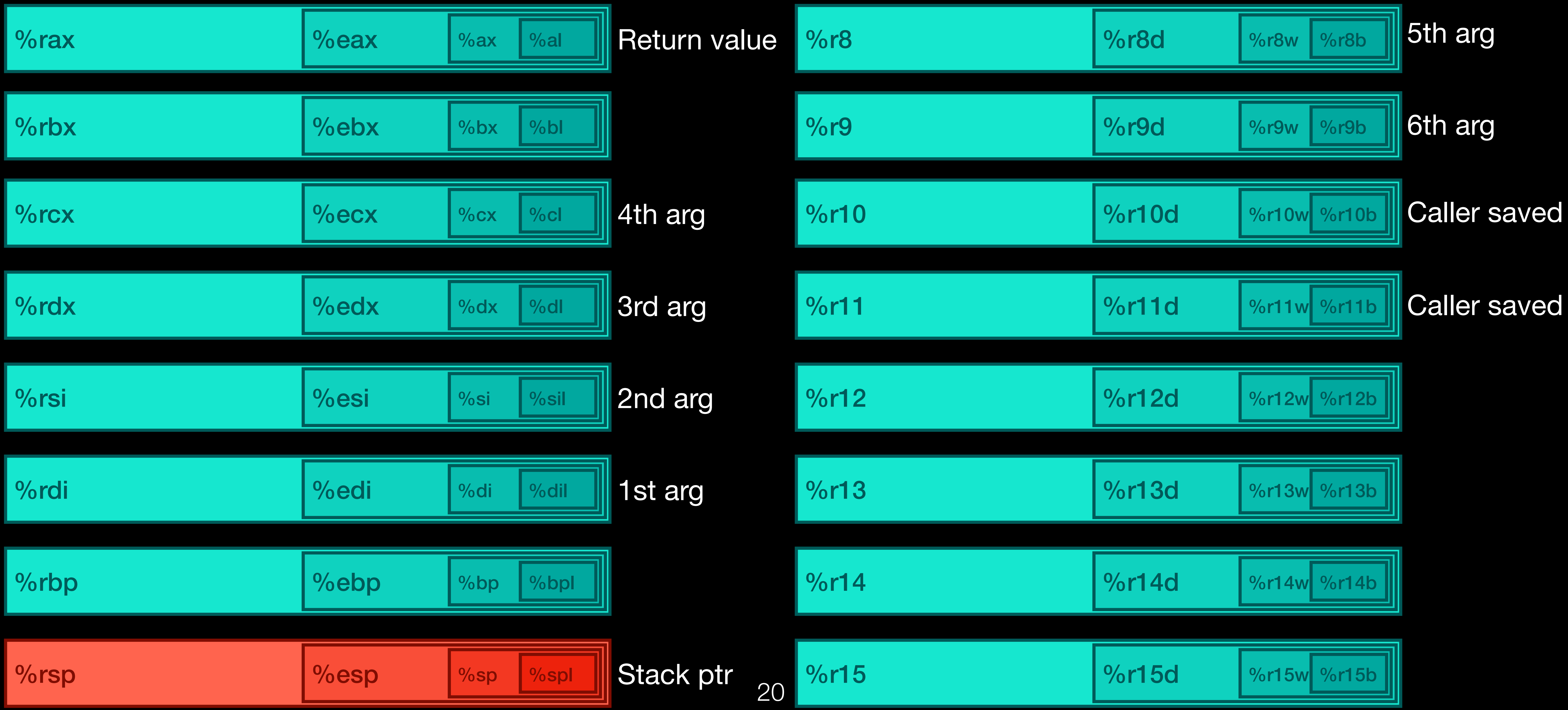

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- *Caller* saved register must be saved on the stack before calling functions if needed.
- *Callee* saved must be saved by the function that wants to use it.
- Too many arguments ? Use the stack !

%rax	%eax	%ax	%al	Return value	%r8	%r8d	%r8w	%r8b	5th arg
%rbx	%ebx	%bx	%bl	Callee saved	%r9	%r9d	%r9w	%r9b	6th arg
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%rdi	%edi	%di	%dil	1st arg	%r13	%r13d	%r13w	%r13b	Callee saved
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An example

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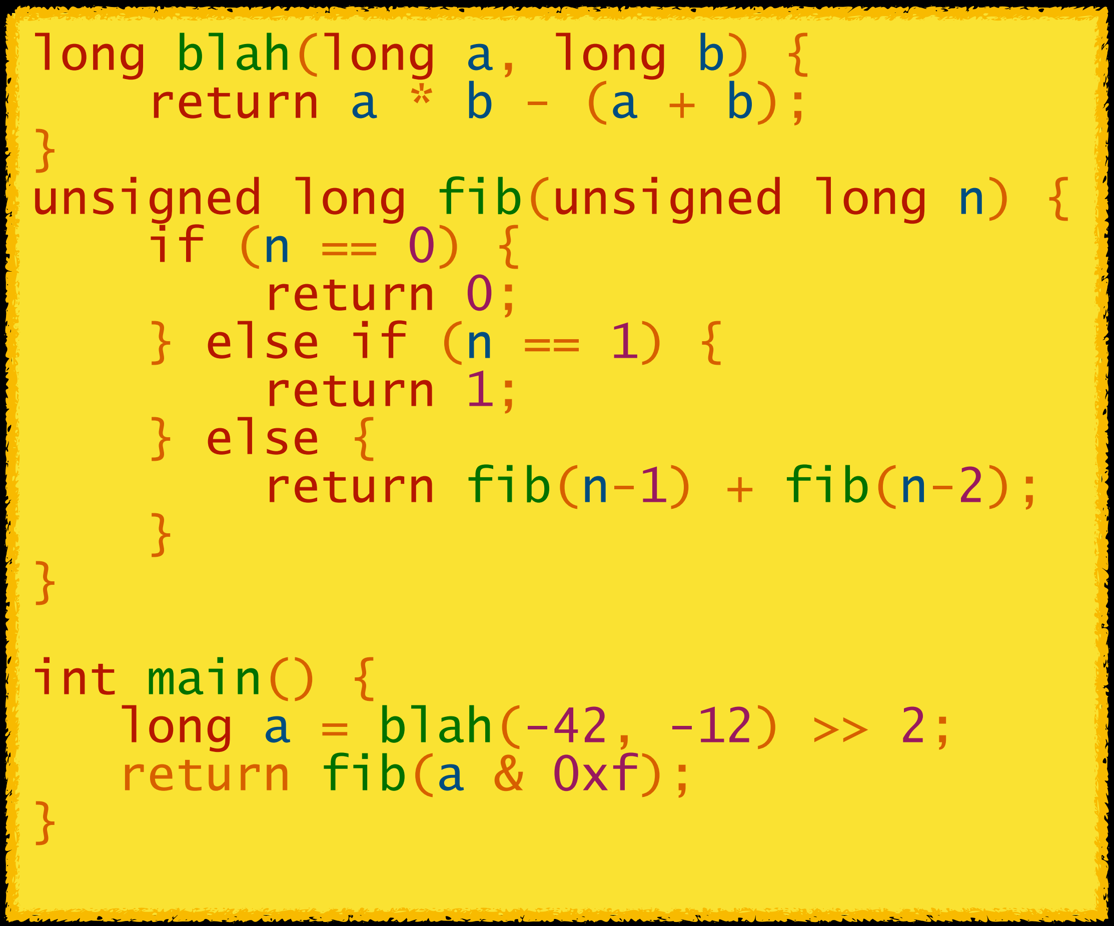
long blah(long a, long b) {
    return a * b - (a + b);
}
unsigned long fib(unsigned long n) {
    if (n == 0) {
        return 0;
    } else if (n == 1) {
        return 1;
    } else {
        return fib(n-1) + fib(n-2);
    }
}

int main() {
   long a = blah(-42, -12) >> 2;
   return fib(a & 0xf);
}
```

An example



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blah:
  movq    %rsi, %rax
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  addq    %rdi, %rsi
  subq    %rsi, %rax
  retq
```

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  retq
```

```
main:
  movq     $-42, %rdi
  movq     $-12, %rsi
  callq    blah
  shrl     $2,   %eax
  andl     $15,  %eax
  movq     %rax, %rdi
  jmp      fib # TAILCALL
```

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  shrl     $2,   %eax
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  movq     %rax, %rdi
  jmp      fib # TAILCALL
```

```
fib:
  pushq    %r14
  pushq    %rbx
  movq     %rdi, %rbx
  testq    %rdi, %rdi
  je       LBB1_3
  cmpq     $1,   %rbx
  jne      LBB1_5
  movl     $1,   %ebx
LBB1_3:
  movq     %rbx, %rax
  jmp      LBB1_4
LBB1_5:
  leaq     -1(%rbx), %rdi
  callq    fib
  movq     %rax, %r14
  addq     $-2,  %rbx
  movq     %rbx, %rdi
  callq    fib
  addq     %r14, %rax
LBB1_4:
  popq     %rbx
  popq     %r14
  retq
```

Stack frame

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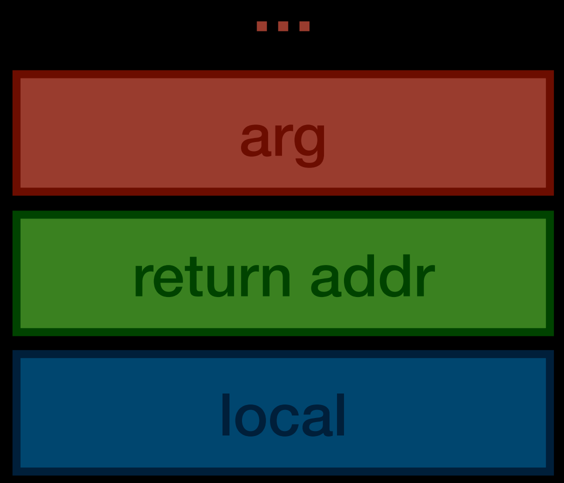


...

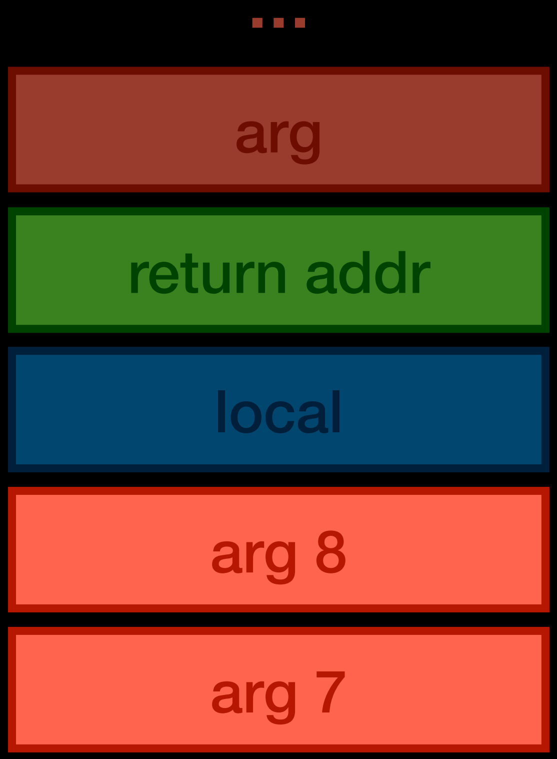
arg

return addr

local

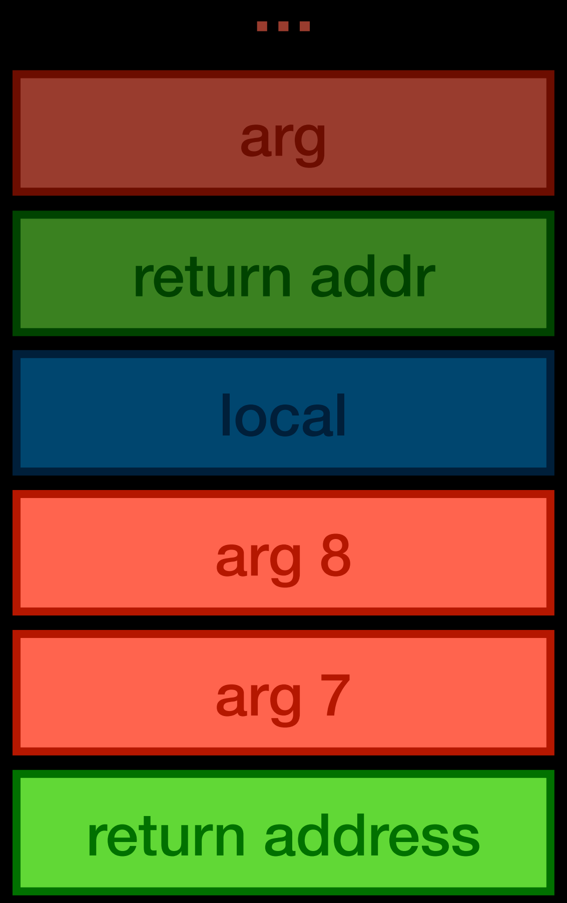
Stack frame

- Each function call takes up space on the stack
  - First any arguments that had to be pushed on the stack



Stack frame

- Each function call takes up space on the stack
  - First any arguments that had to be pushed on the stack
  - Then the return address



...

arg

return addr

local

arg 8

arg 7

return address

Stack frame

- Each function call takes up space on the stack
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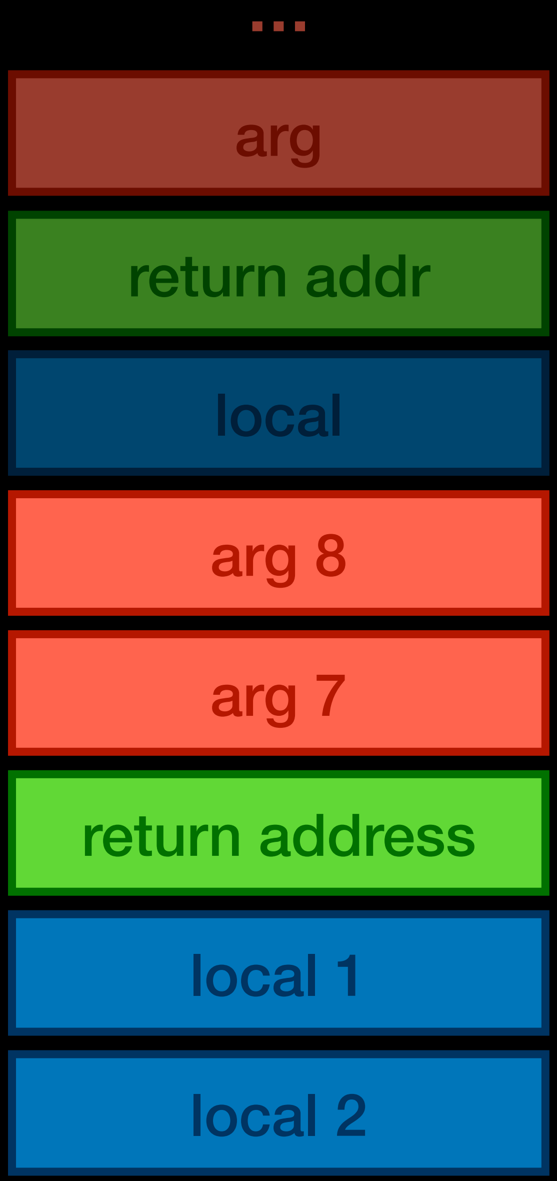

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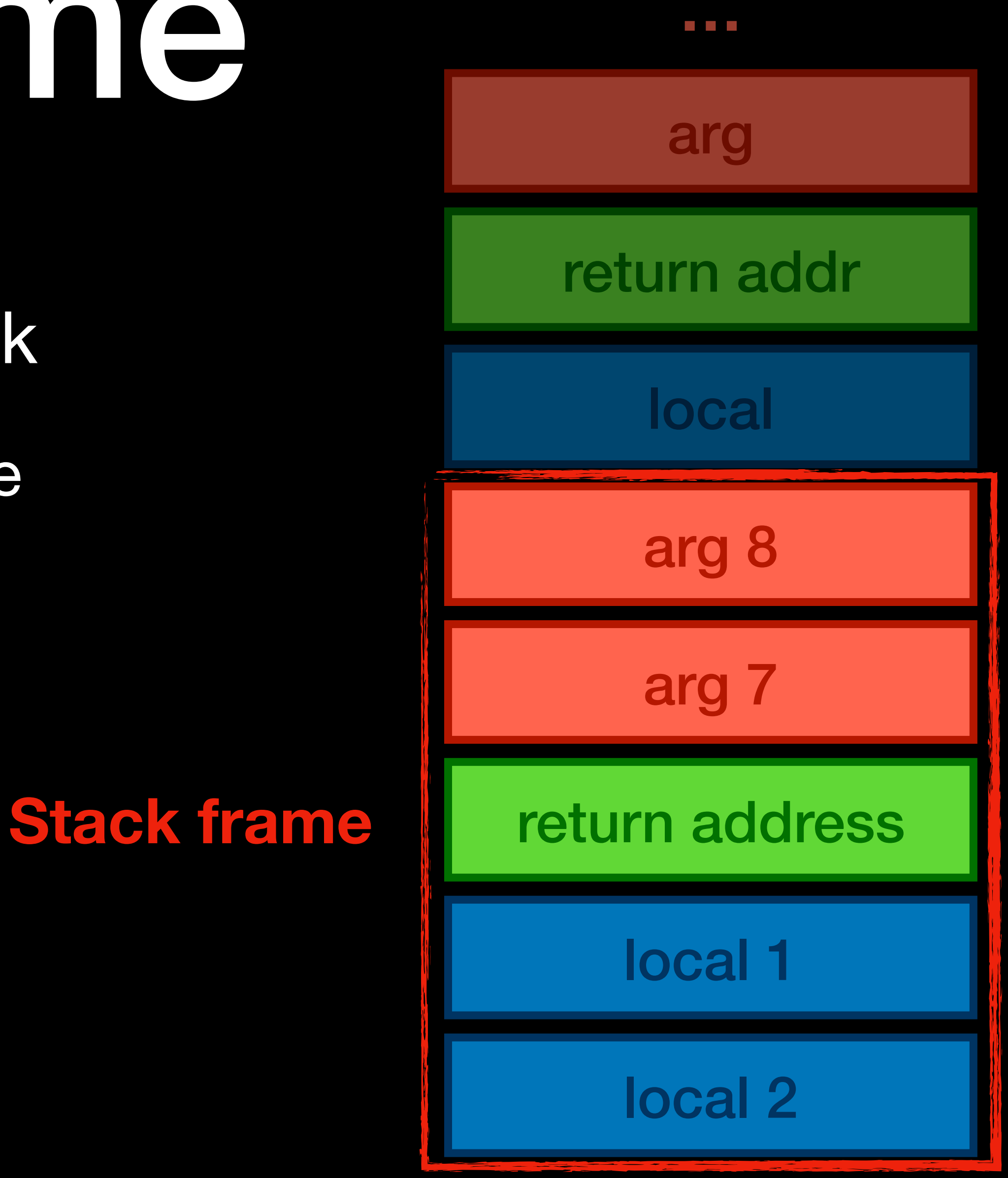

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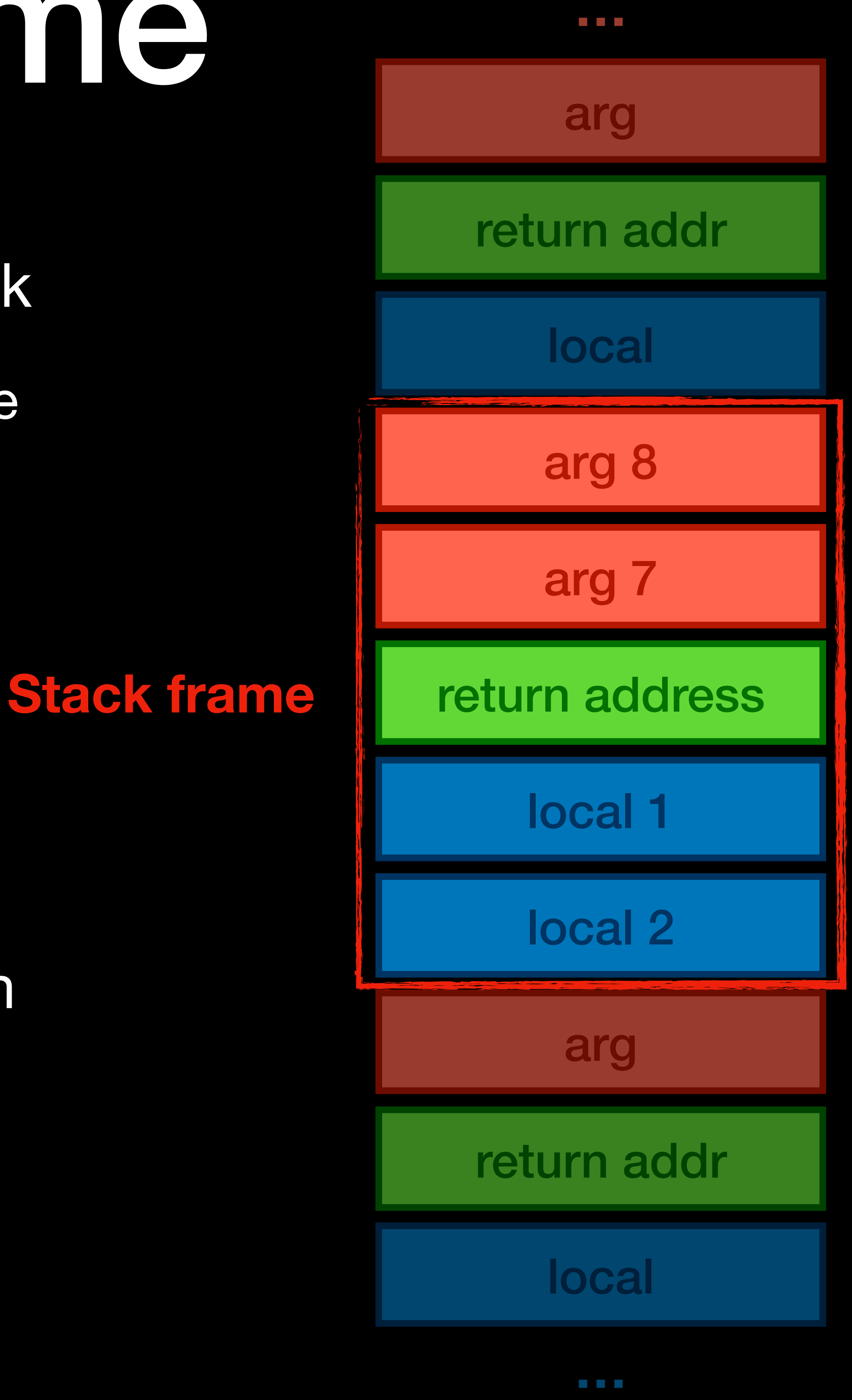

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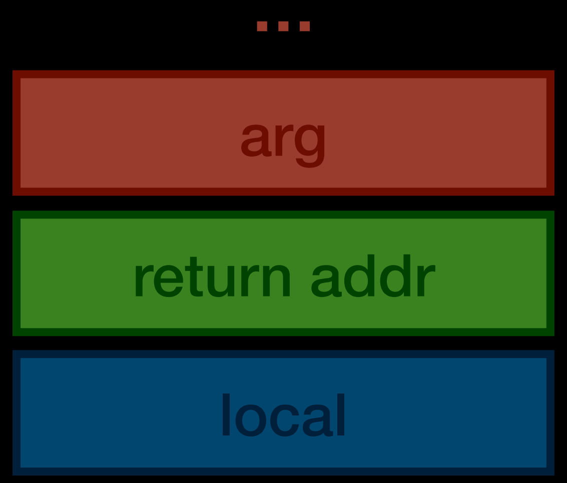

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Questions