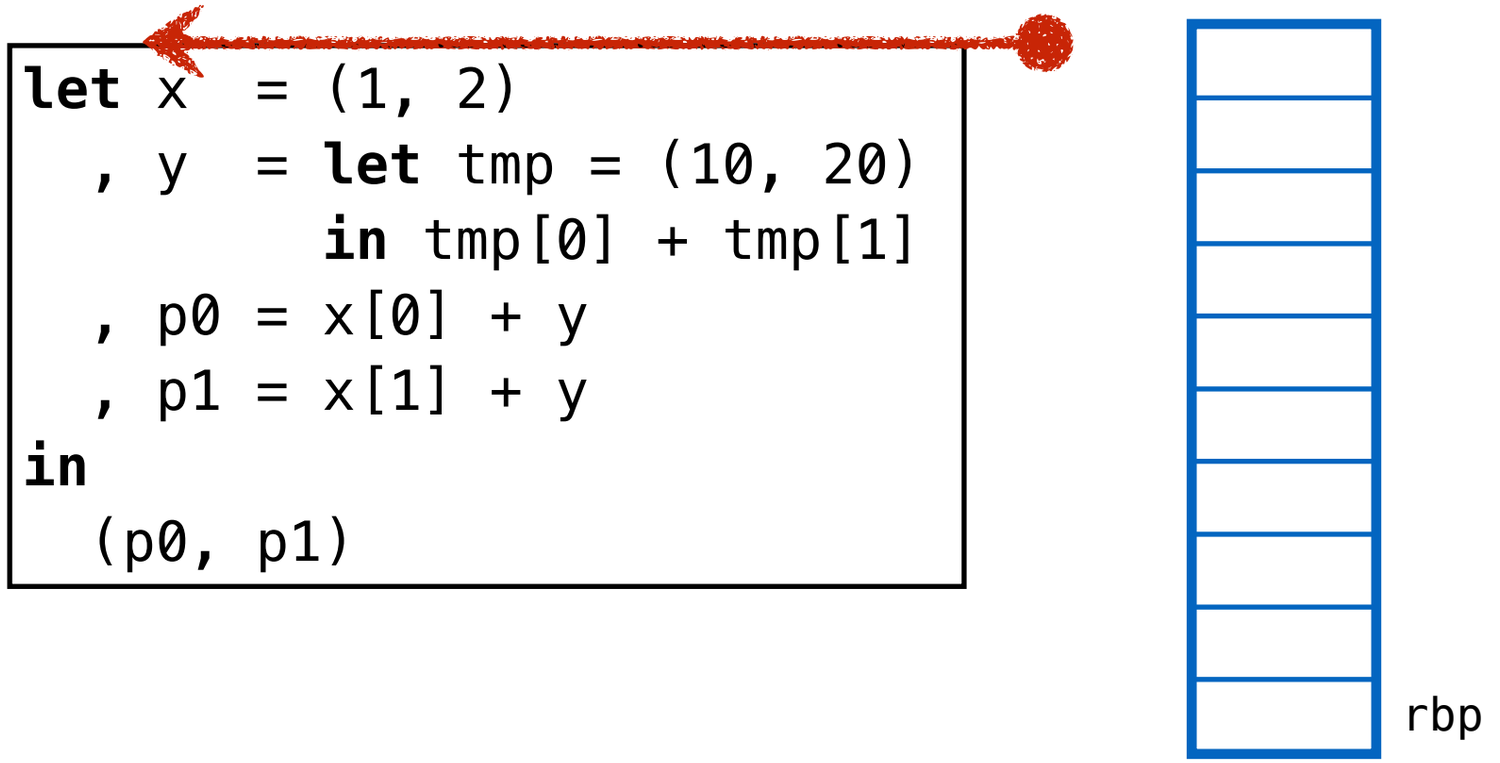
Garter

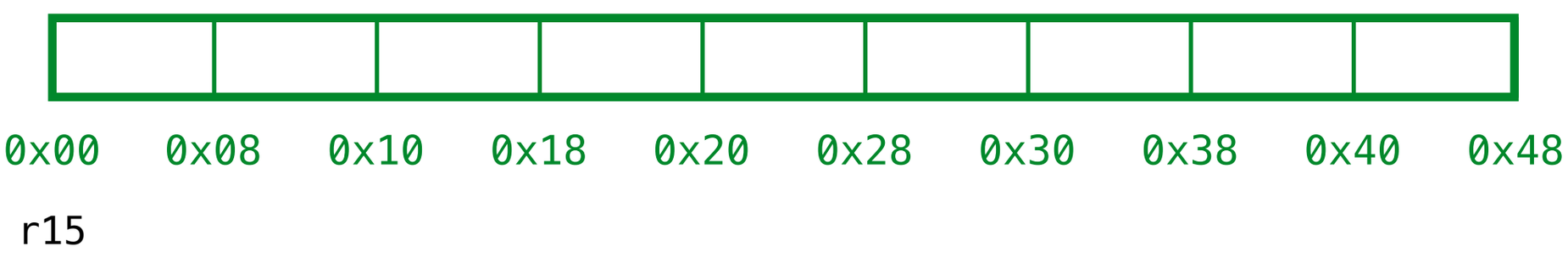
Garbage Collection

Garter / GC

Example 1

ex1: garbage at end





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  , p1 = x[1] + y
in
  (p0, p1)
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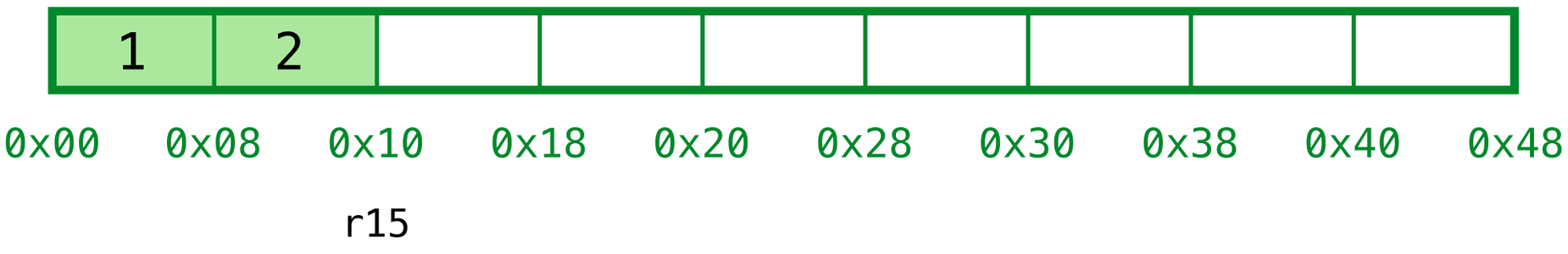

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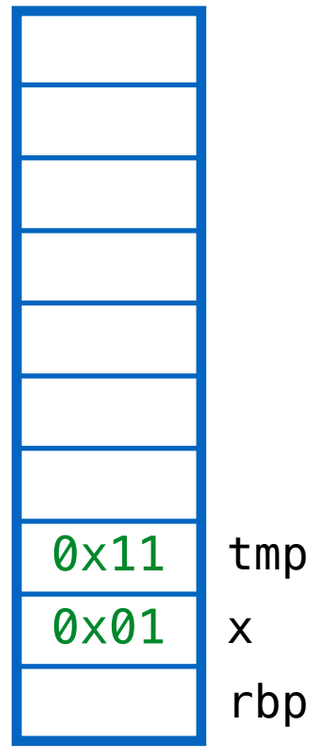

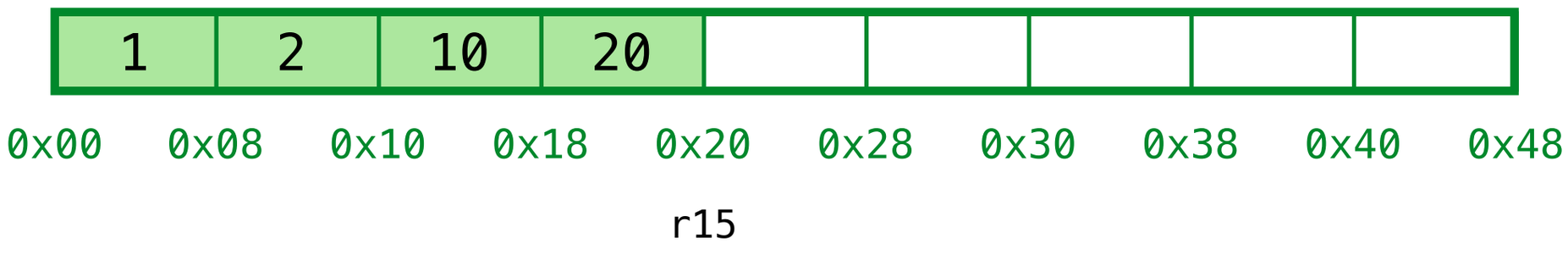

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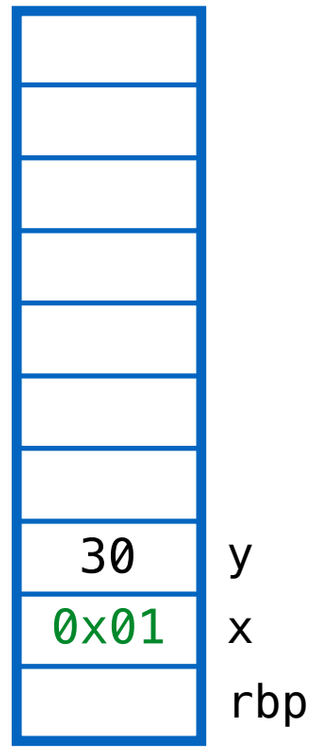

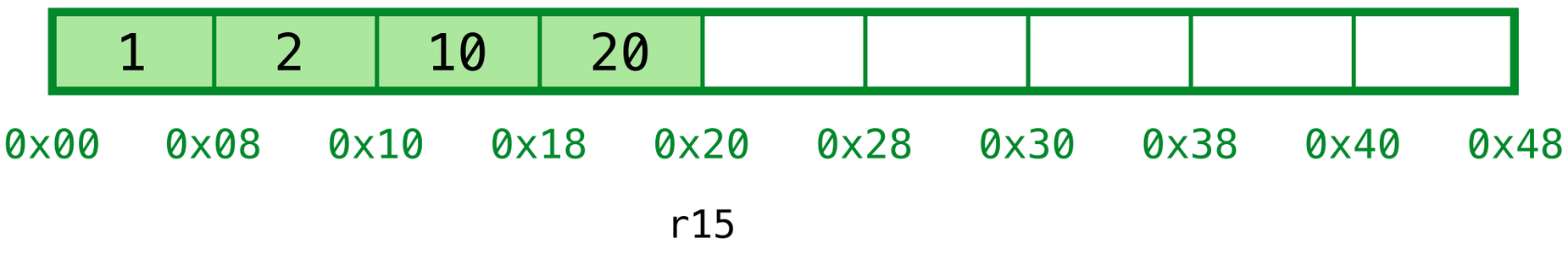

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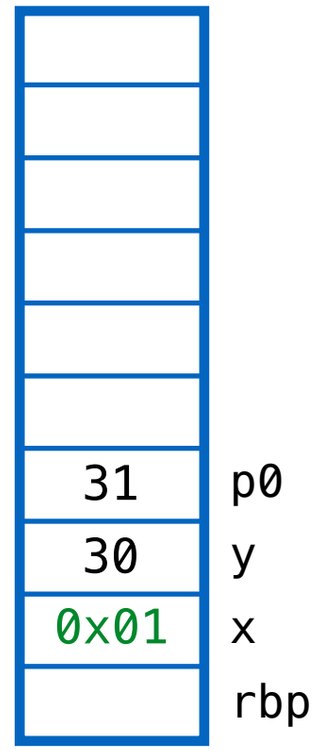

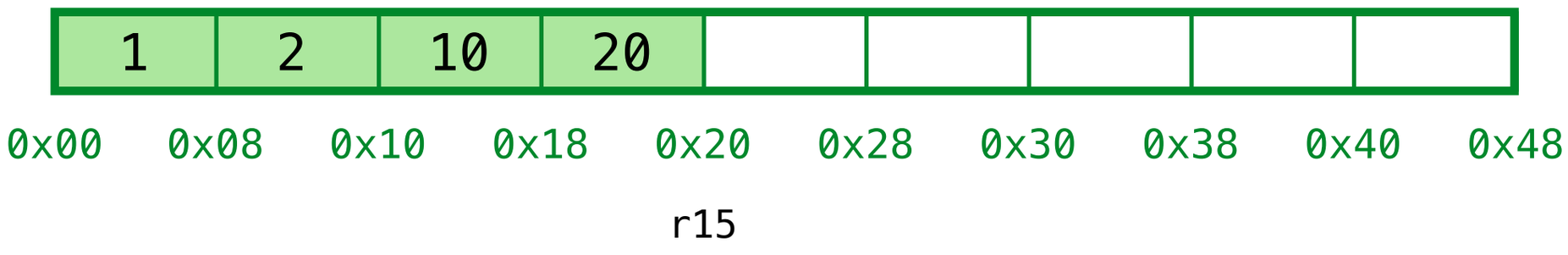

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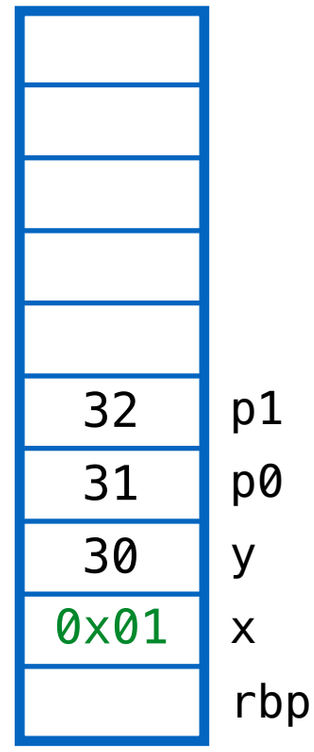

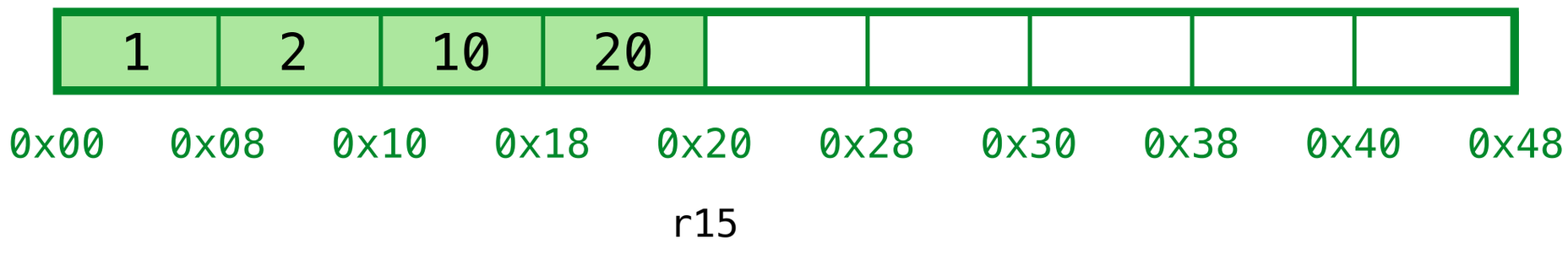

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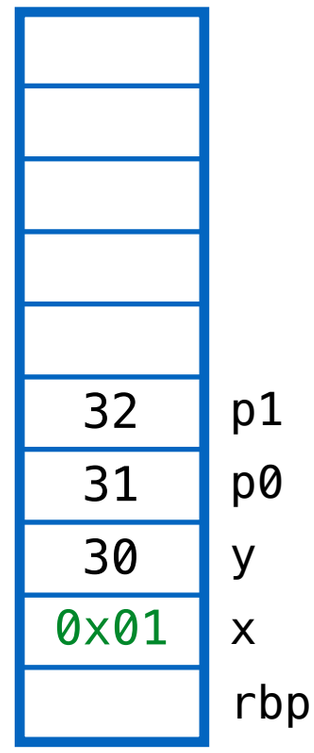
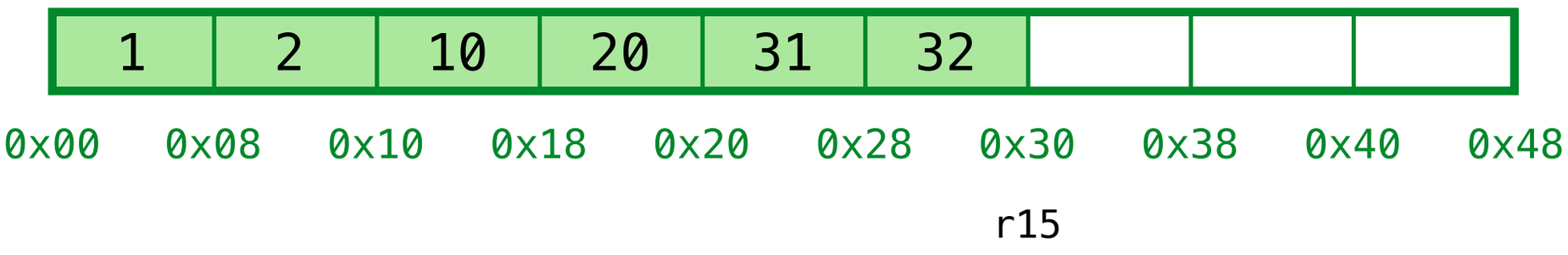


Result (rax) = 0x21



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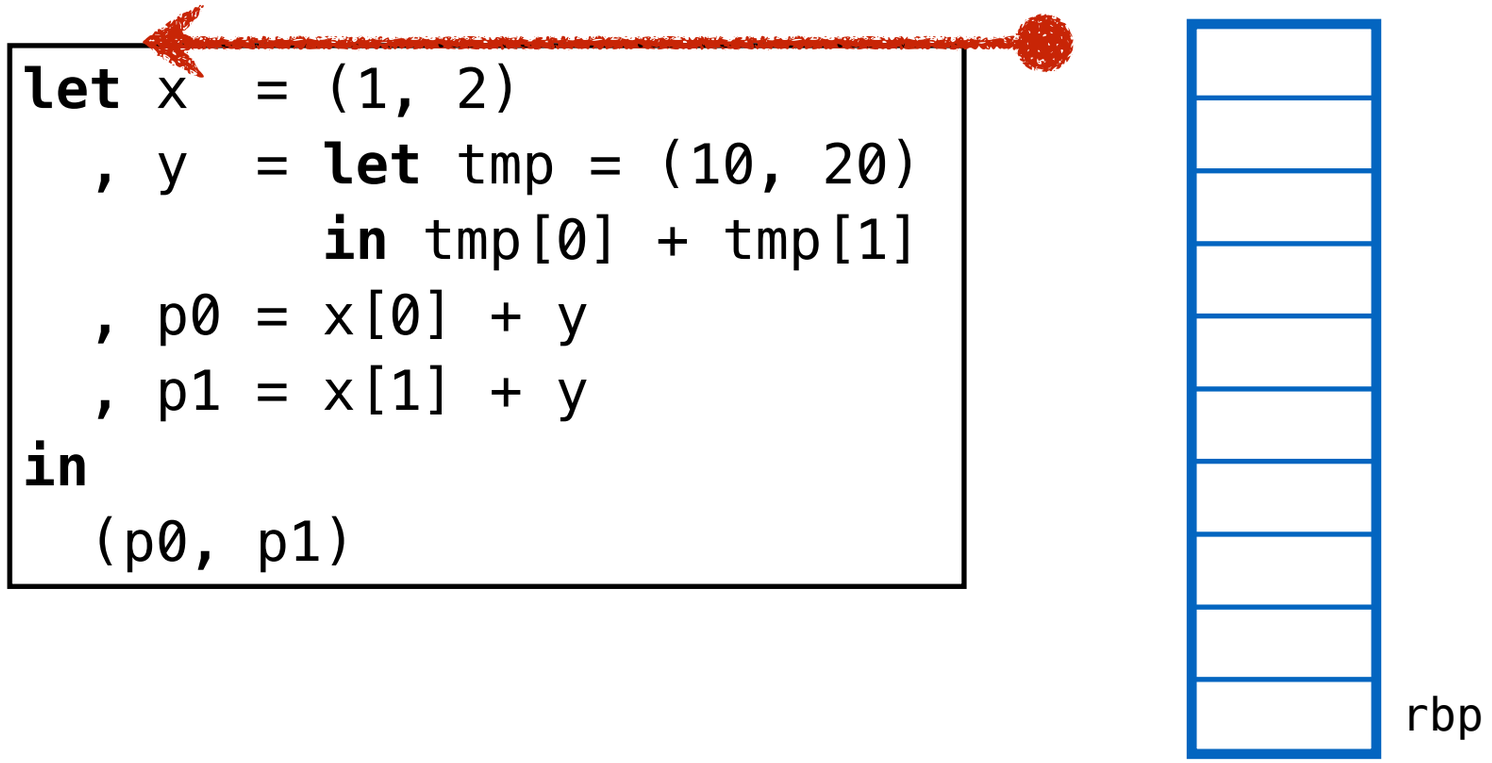

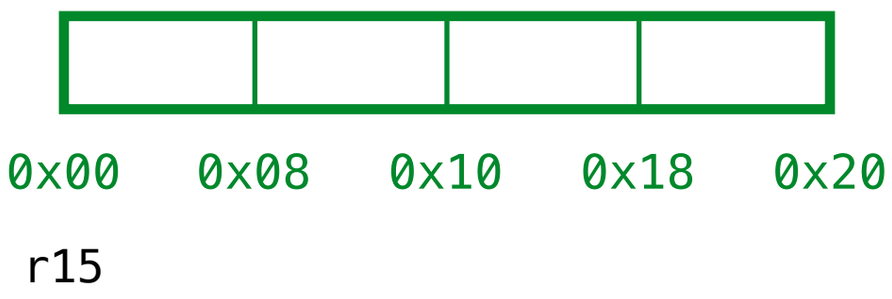

Suppose we had a smaller, 4-word heap

ex1: garbage at end

```
let x  = (1, 2)
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  , p1 = x[1] + y
in
  (p0, p1)
```

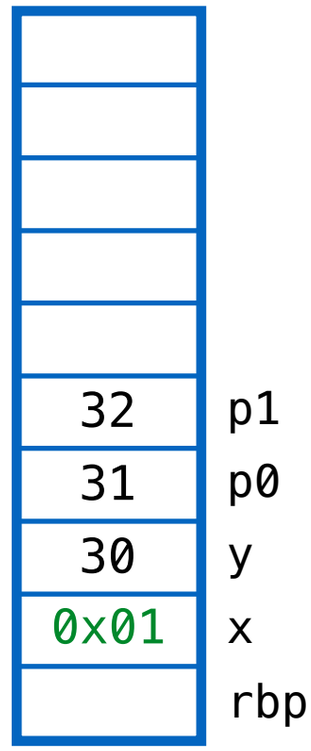

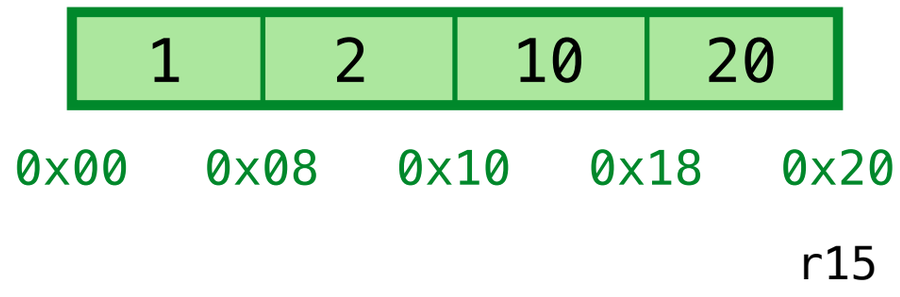

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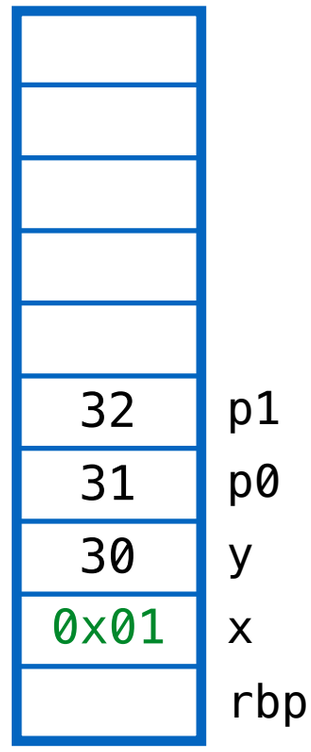
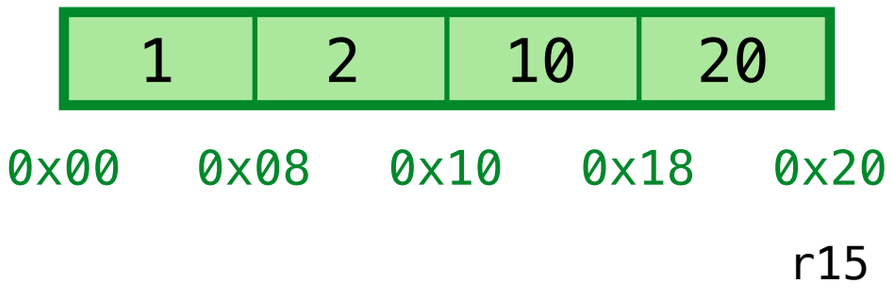
```



Out of memory!

Can't allocate `(p0, p1)`



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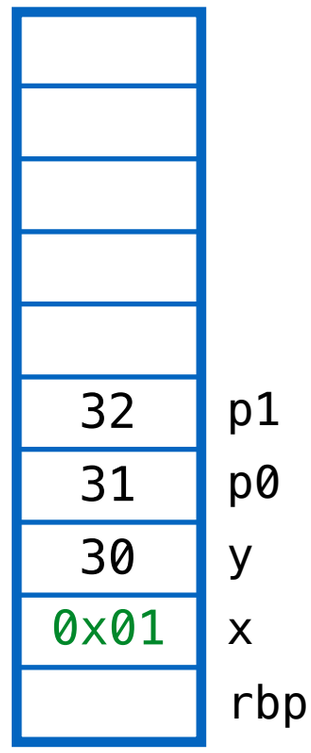
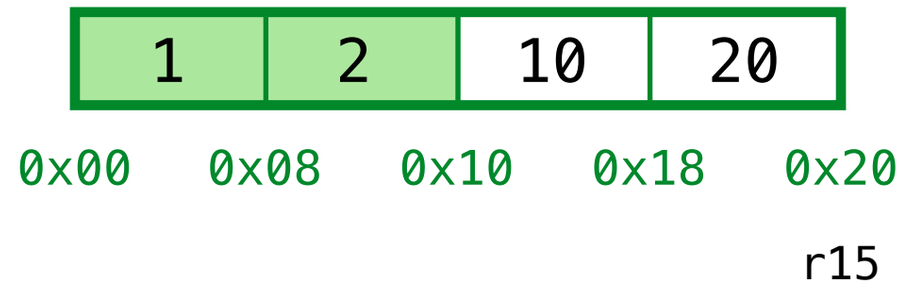


`(10, 20)` is “garbage”



Q: How to determine if cell is garbage?

ex1: garbage at end

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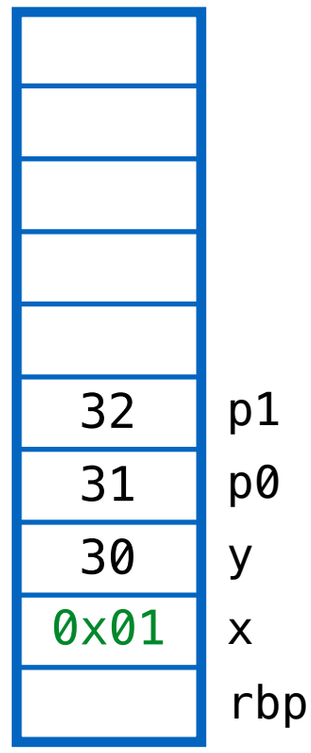

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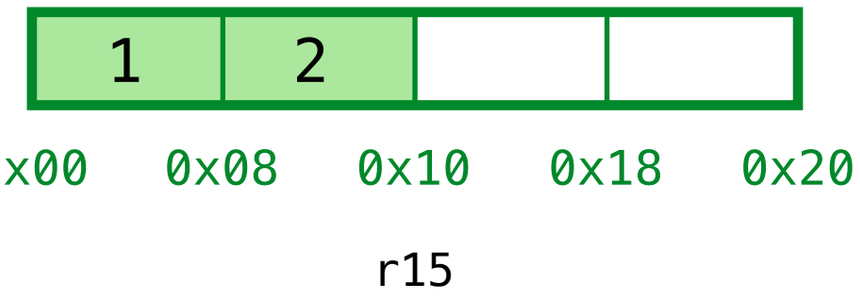

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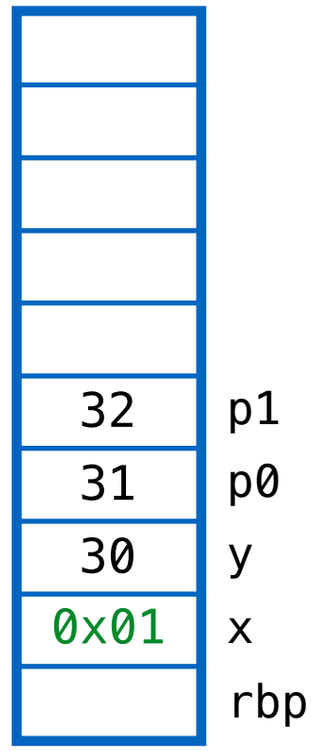

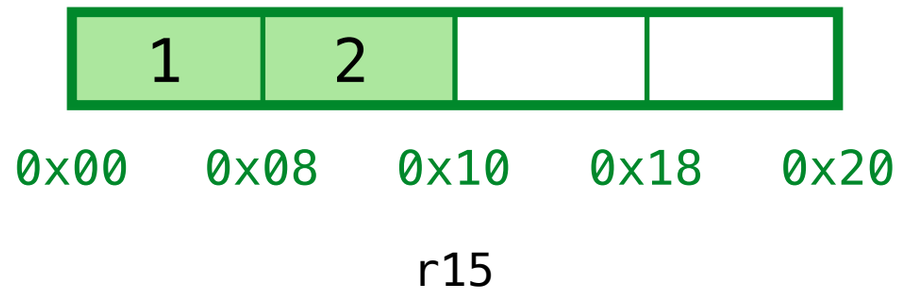

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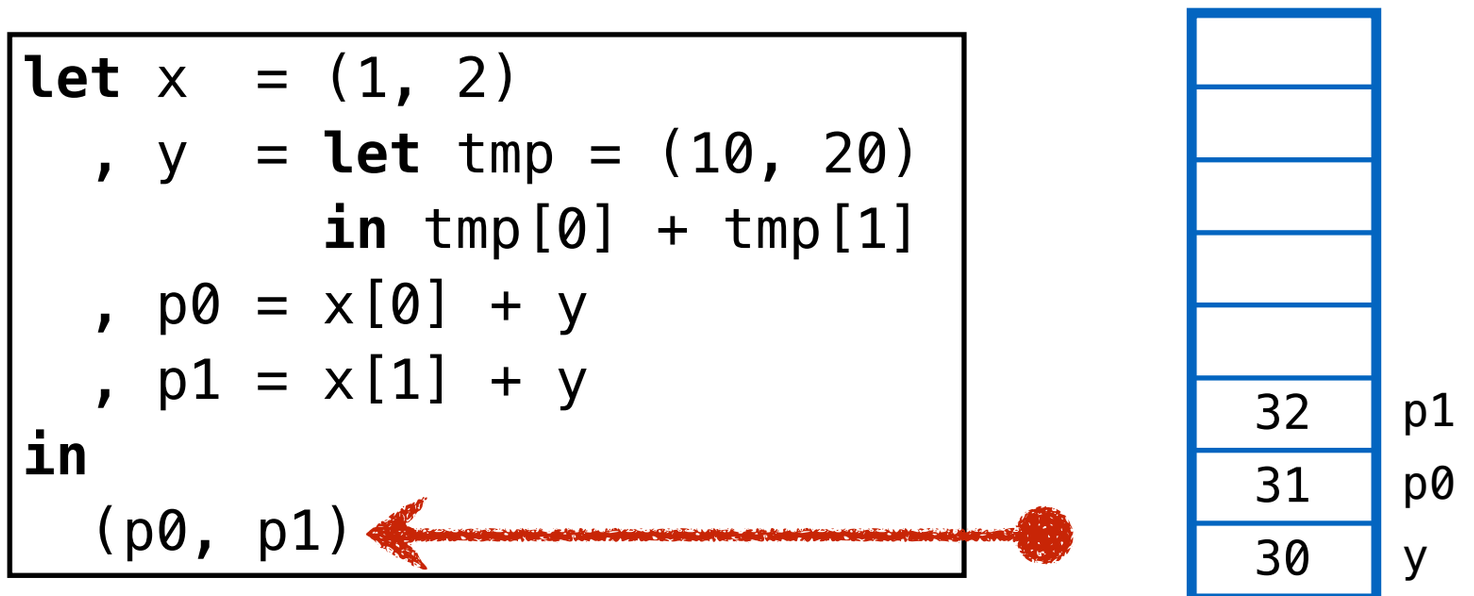
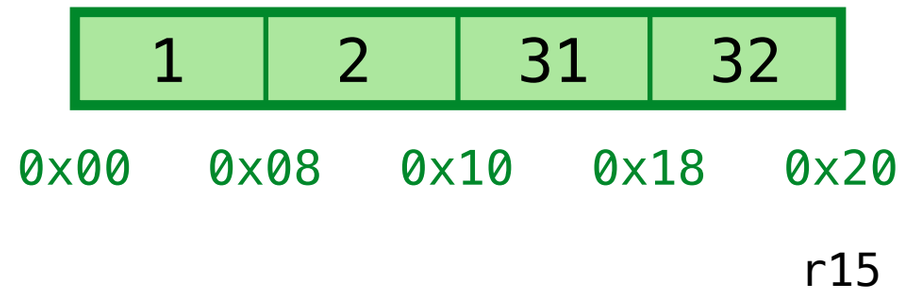


Result (rax) = 0x11



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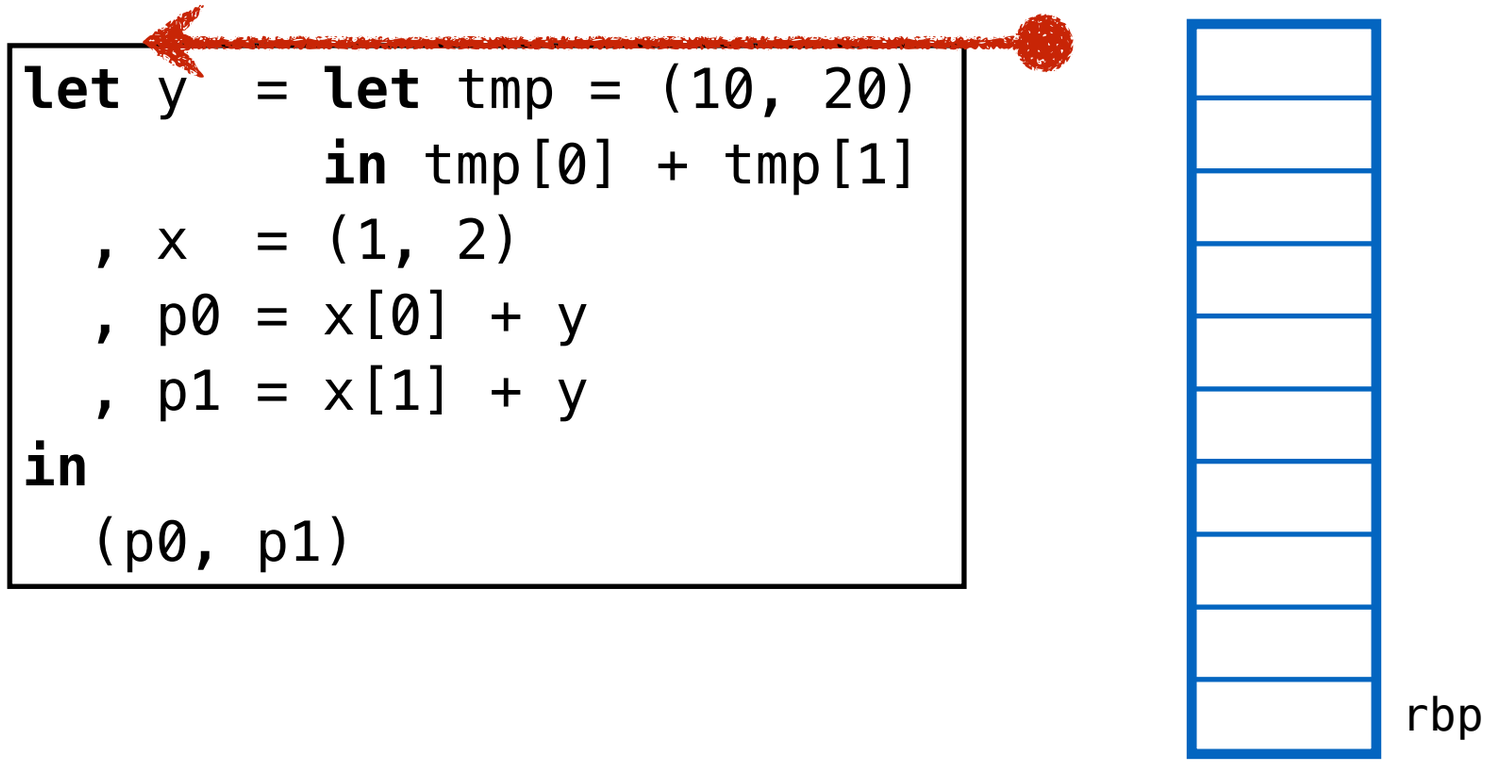
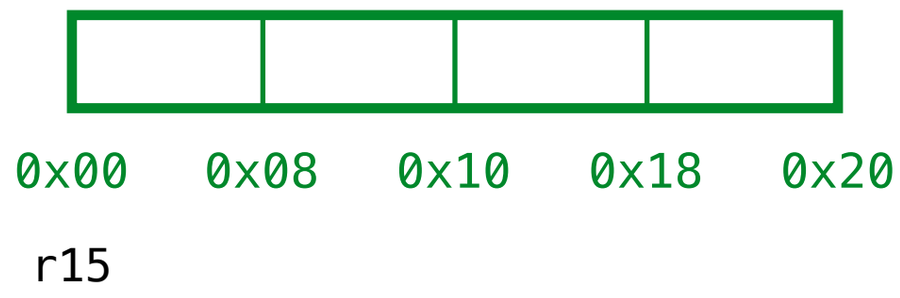
Example 2

ex2: garbage in the middle





Start with a 4-word heap

ex2: garbage in the middle

```
let y  = let tmp = (10, 20)
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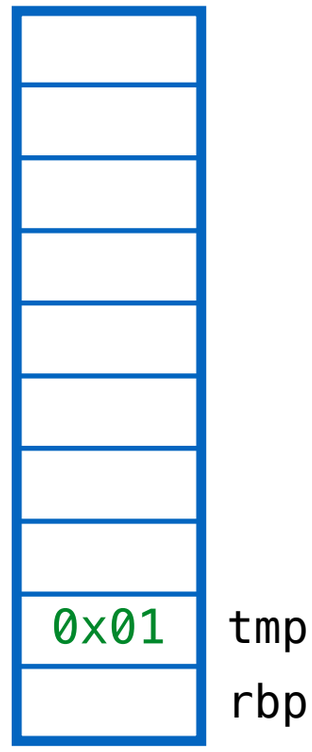
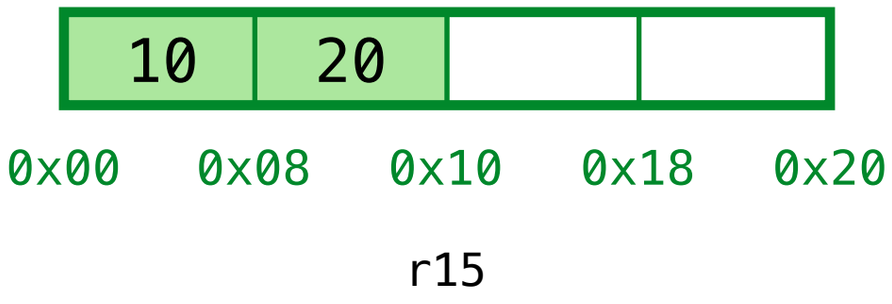
  , p0 = x[0] + y
  , p1 = x[1] + y
in
  (p0, p1)
```





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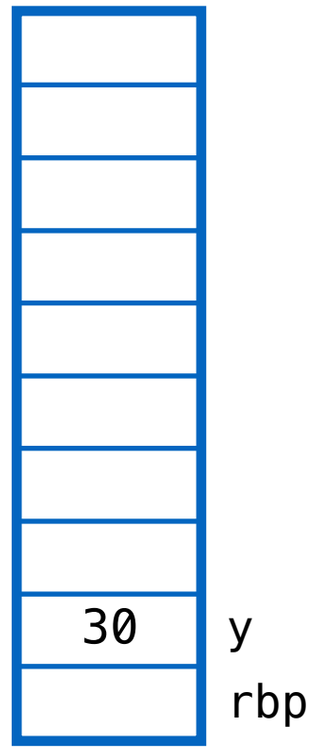

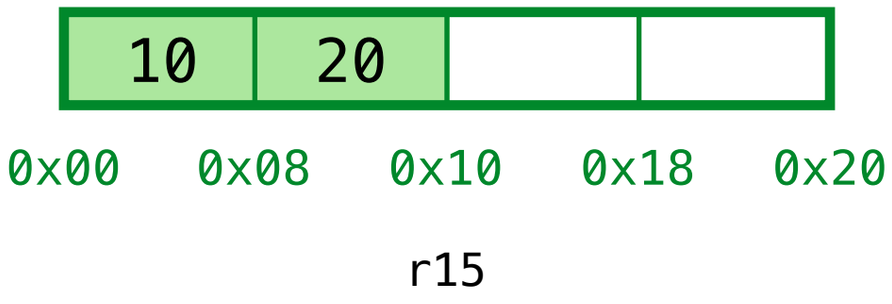

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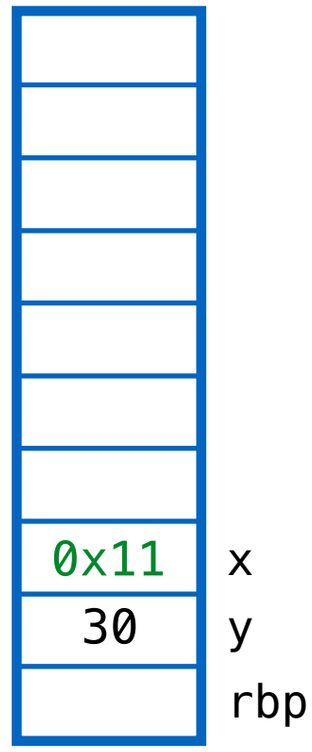

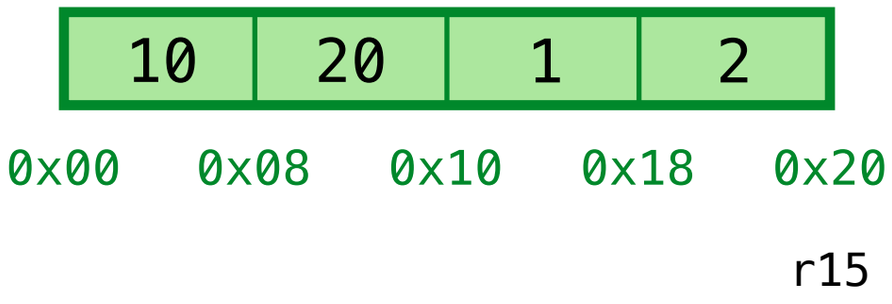

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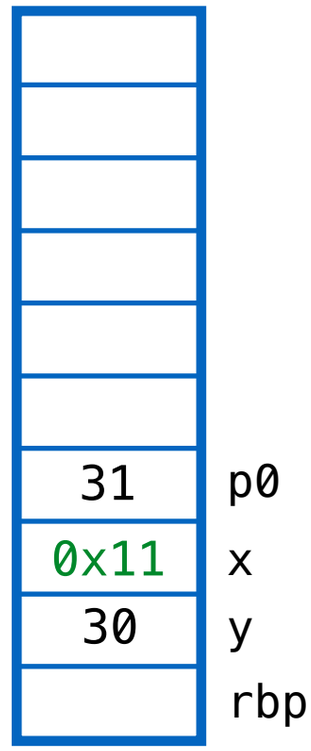

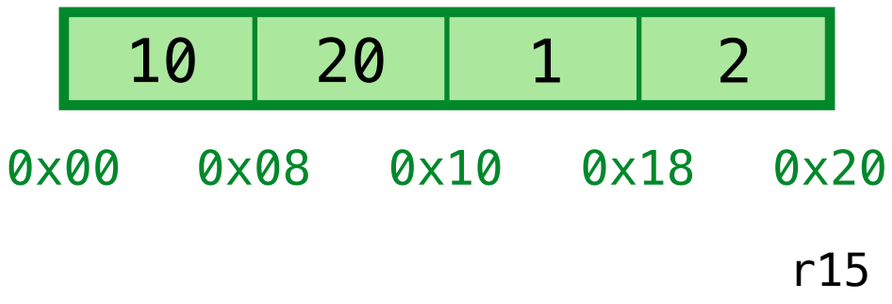

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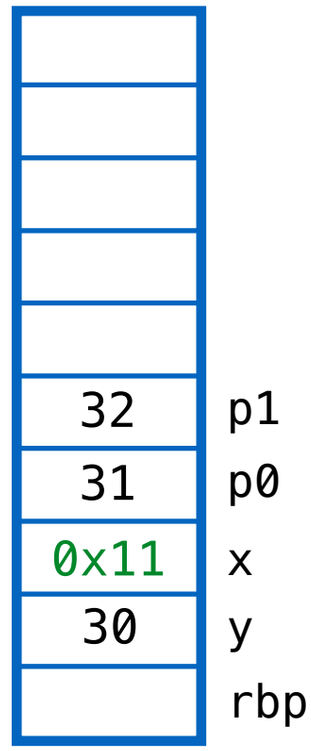

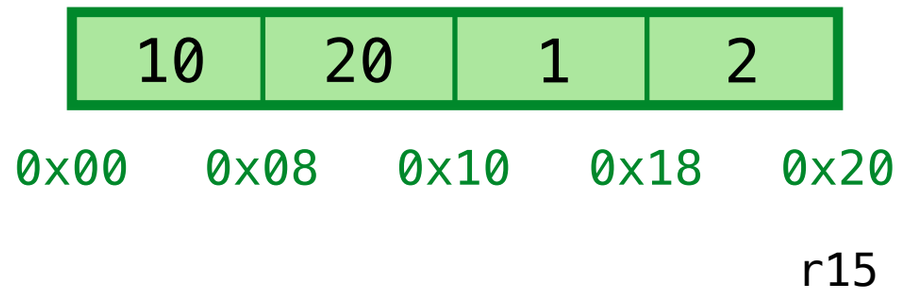

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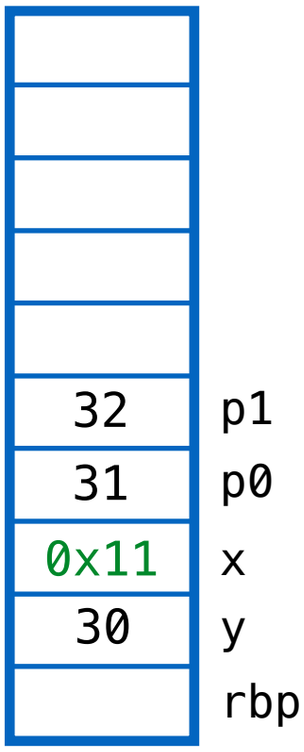
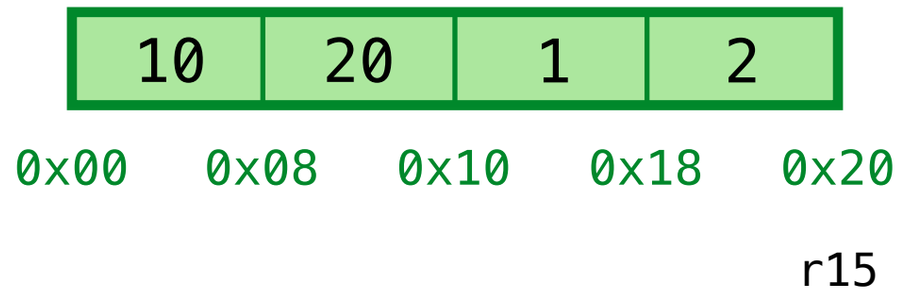


Out of memory!

Can't allocate `(p0, p1)`



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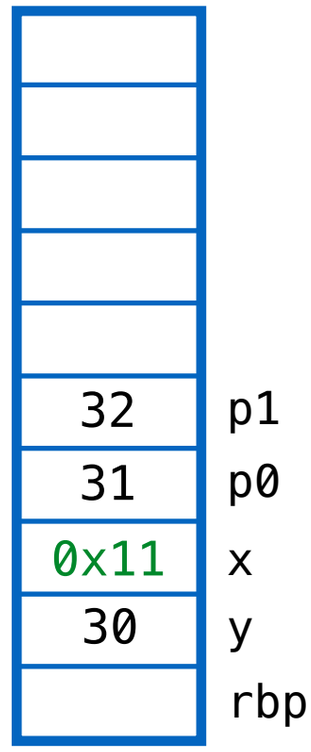
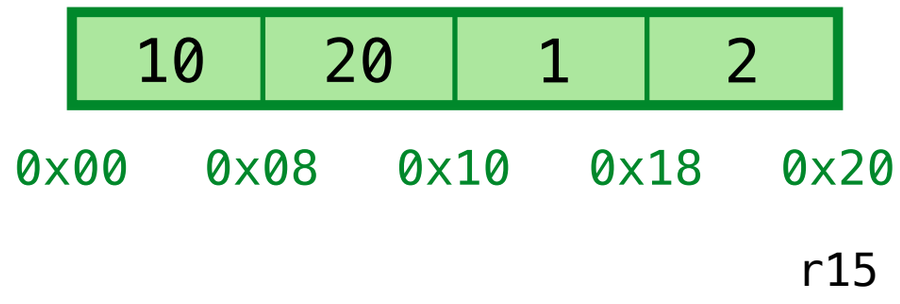


Lets reclaim & recycle garbage!



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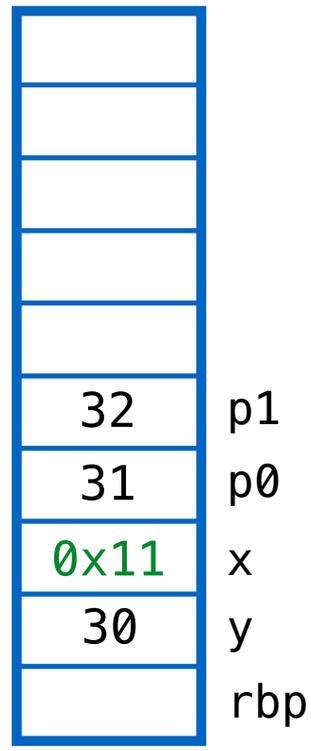

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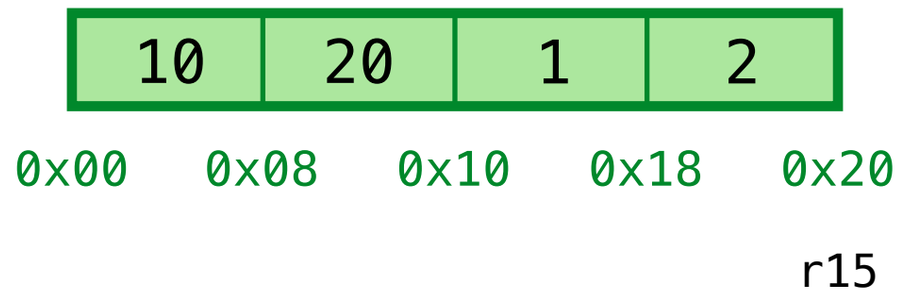

QUIZ: Which cells are garbage?

(A) `0x00, 0x08` (B) `0x08, 0x10` (C) `0x18, 0x20` (D) None (E) All

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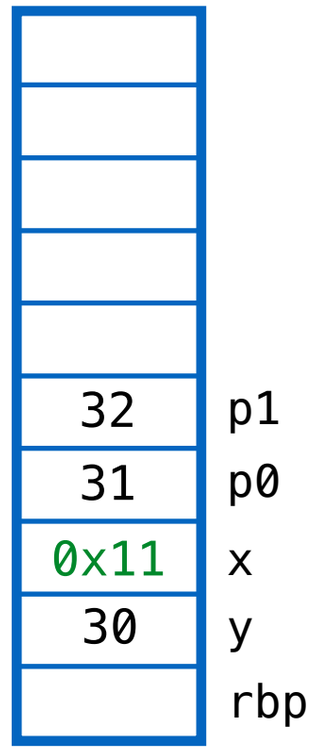
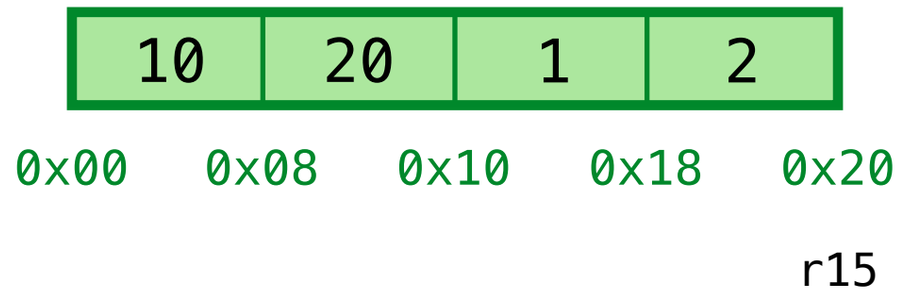


Lets reclaim & recycle garbage!



QUIZ: Which cells are garbage?

Those that are *not reachable from stack*

ex2: garbage in the middle

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  , p0 = x[0] + y
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in
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```

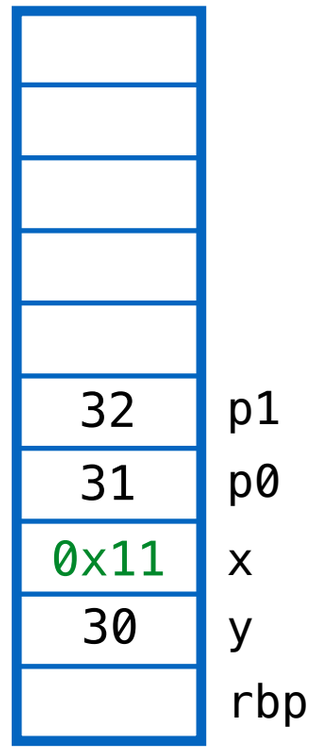

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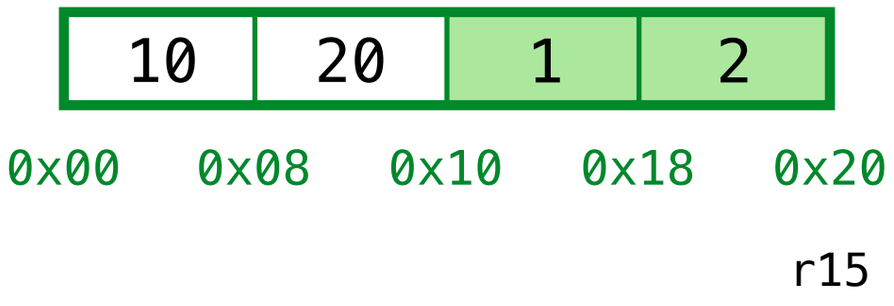

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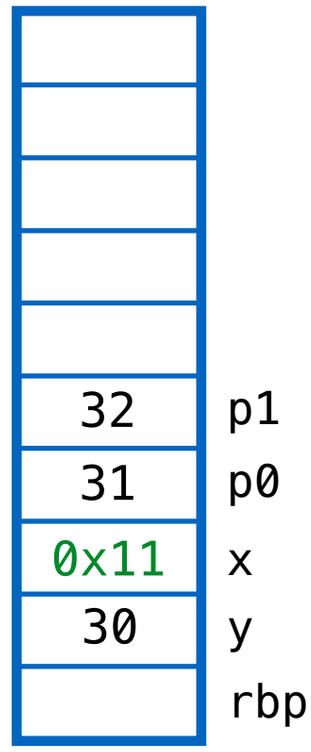

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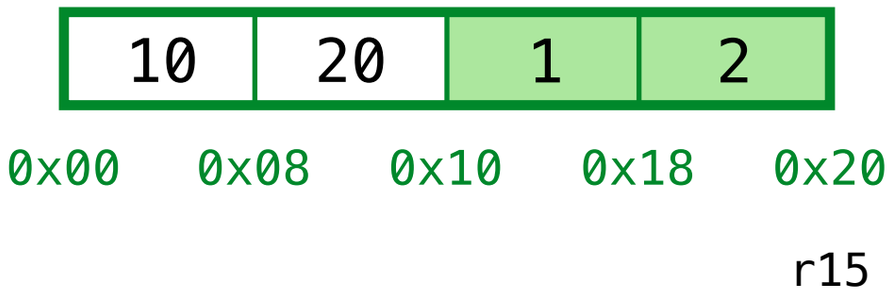
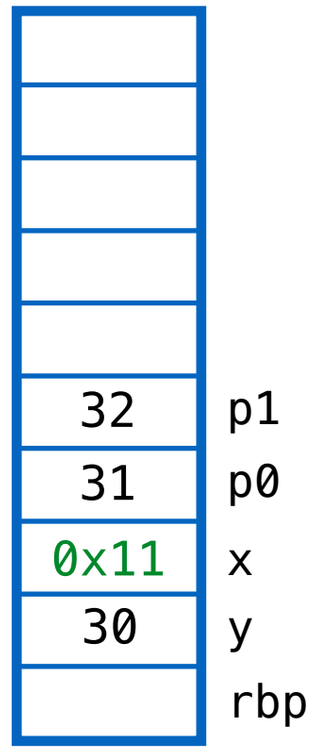


Q: How to reclaim space?

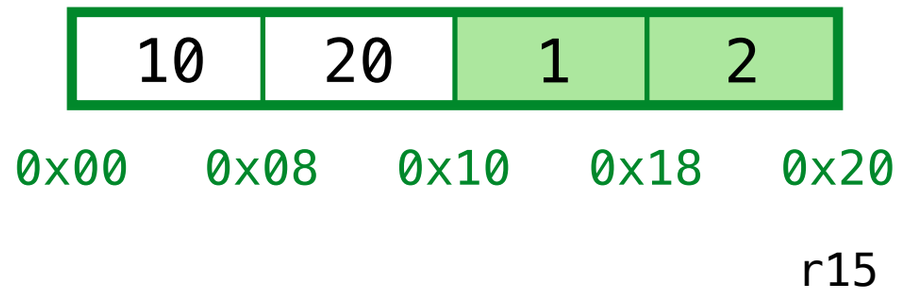
Why is it not enough to rewind `r15`?

ex2: garbage in the middle

```
let y  = let tmp = (10, 20)
         in tmp[0] + tmp[1]
  , x  = (1, 2)
  , p0 = x[0] + y
  , p1 = x[1] + y
in
  (p0, p1)
```



Lets reclaim & recycle garbage!



Why is it not enough to rewind `r15`?

Want free space to be *contiguous* (i.e. go to end of heap)

ex2: garbage in the middle

```
let y  = let tmp = (10, 20)
         in tmp[0] + tmp[1]
  , x  = (1, 2)
  , p0 = x[0] + y
  , p1 = x[1] + y
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```
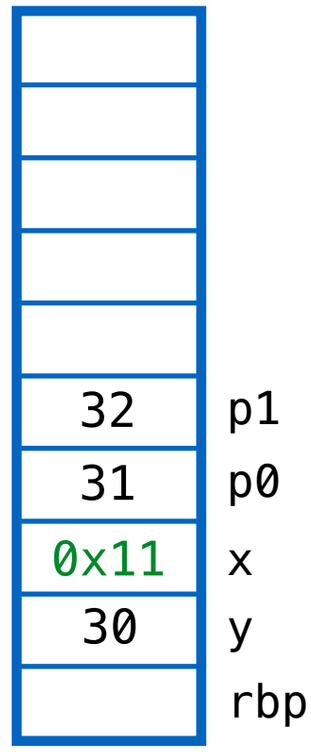
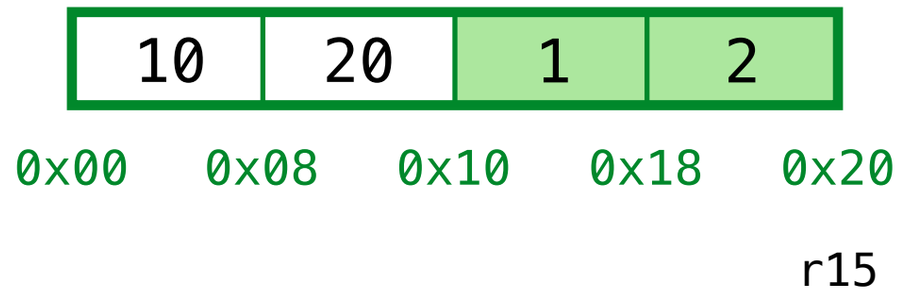



Lets reclaim & recycle garbage!



Solution: Compaction

Copy “live” cells into “garbage” …

ex2: garbage in the middle

```
let y  = let tmp = (10, 20)
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  , p0 = x[0] + y
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in
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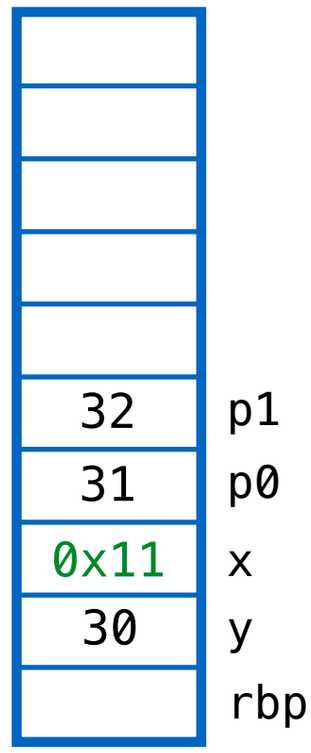

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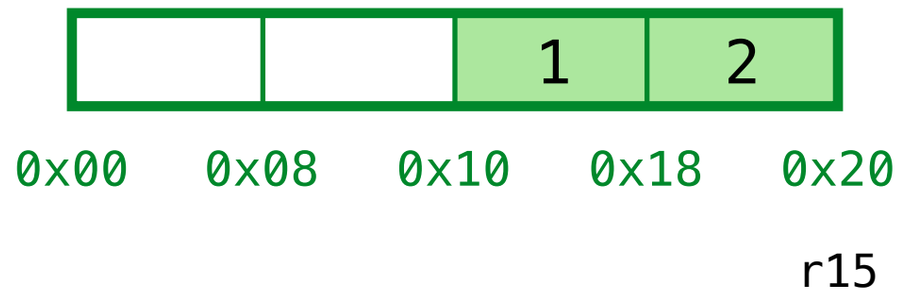

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in
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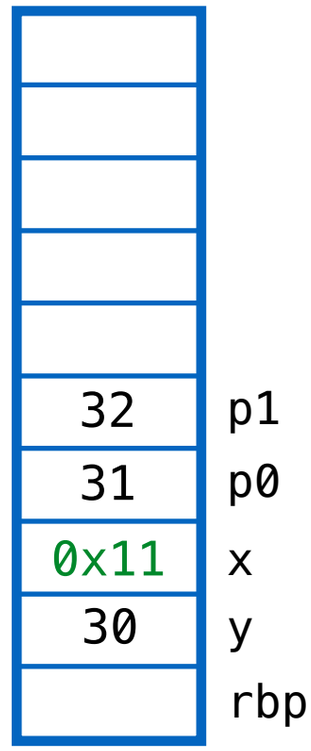
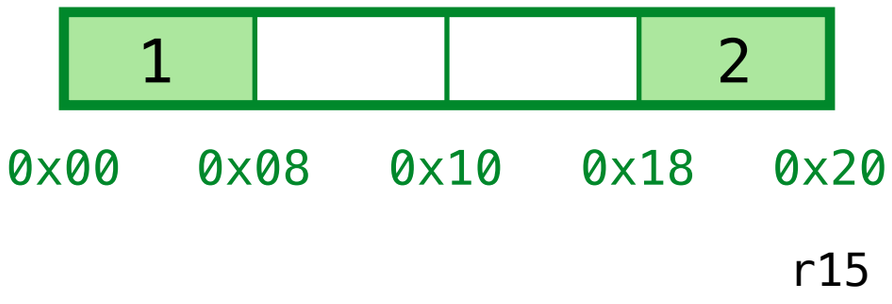


Lets reclaim & recycle garbage!



Solution: Compaction

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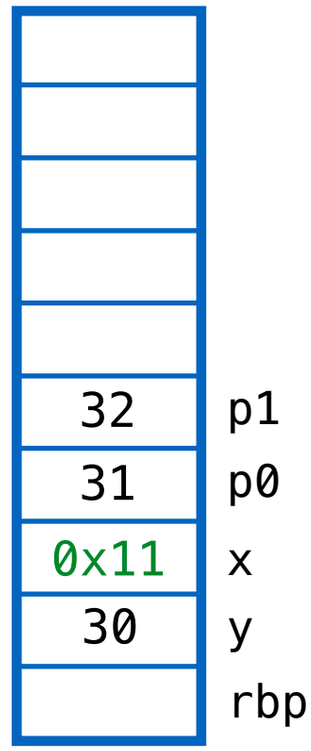
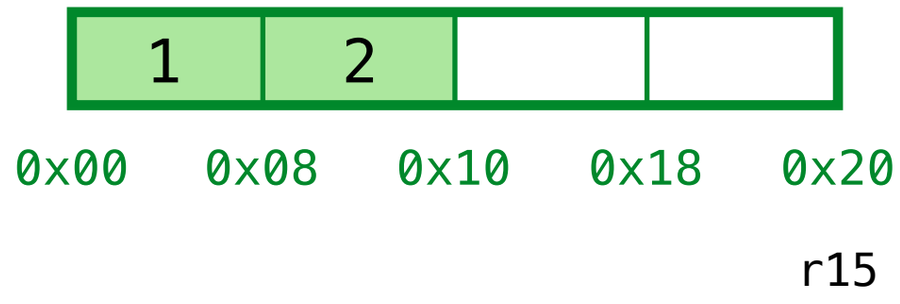


Lets reclaim & recycle garbage!



Solution: Compaction

Copy “live” cells into “garbage” …

ex2: garbage in the middle

```
let y  = let tmp = (10, 20)
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in
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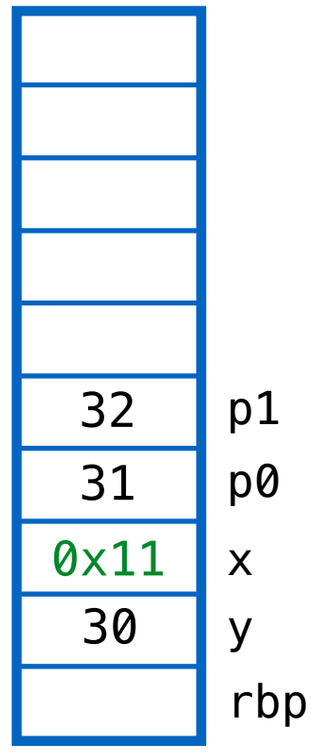

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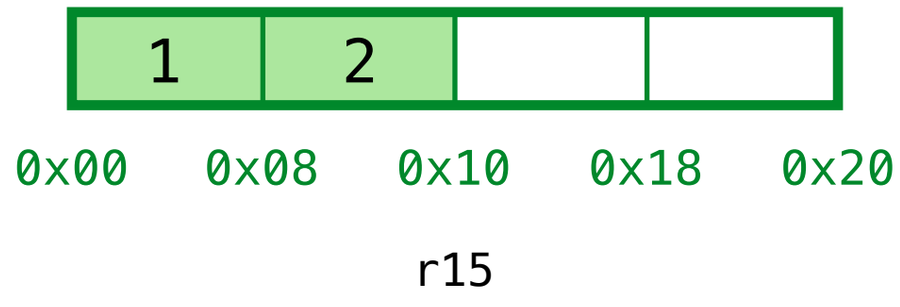

Solution: Compaction

Copy “live” cells into “garbage” … ***and then*** … rewind `r15`!

ex2: garbage in the middle

```
let y  = let tmp = (10, 20)
         in tmp[0] + tmp[1]
  , x  = (1, 2)
  , p0 = x[0] + y
  , p1 = x[1] + y
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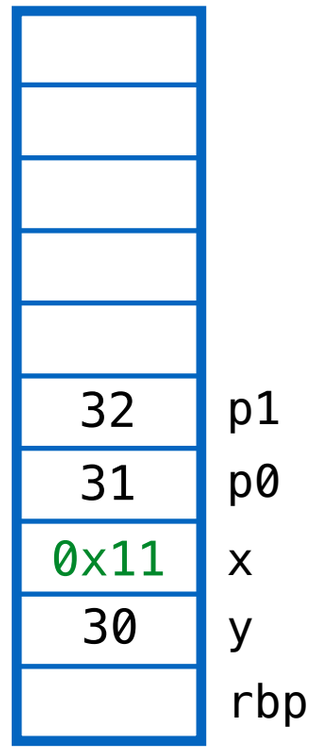
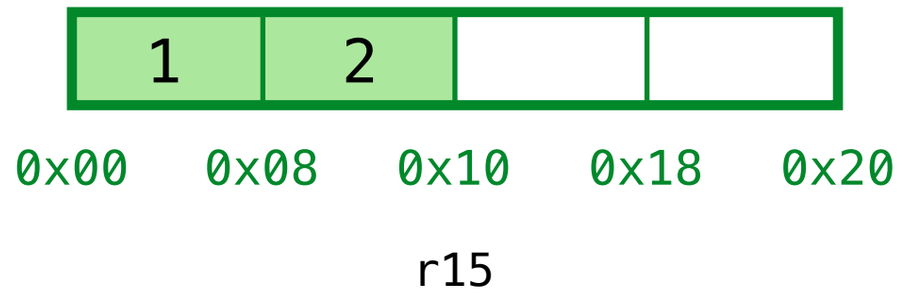


Yay! Have space for `(p0, p1)`



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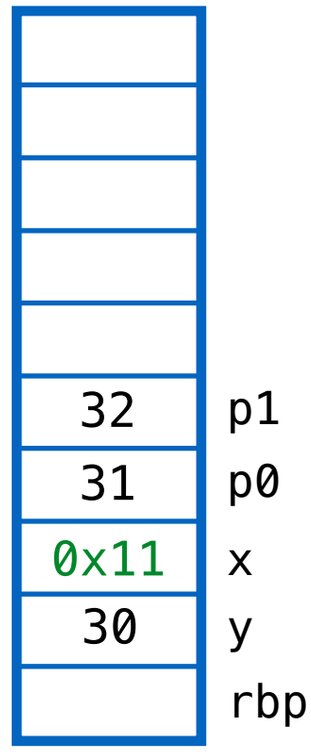

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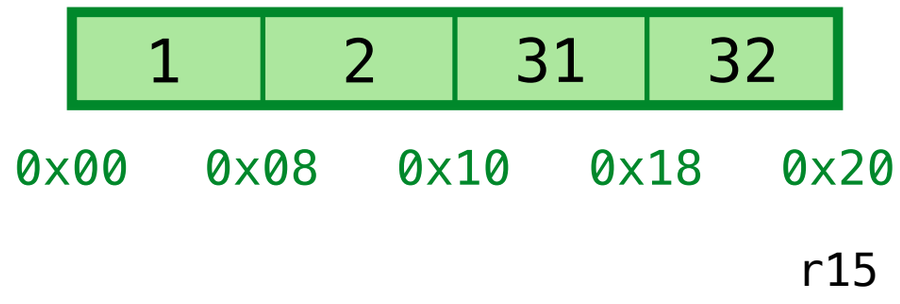

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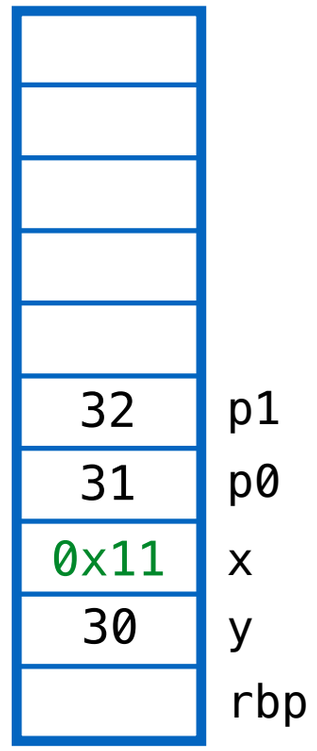
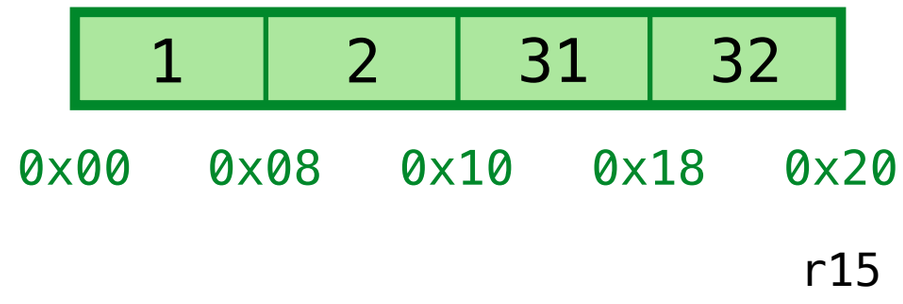


Result (rax) = 0x09



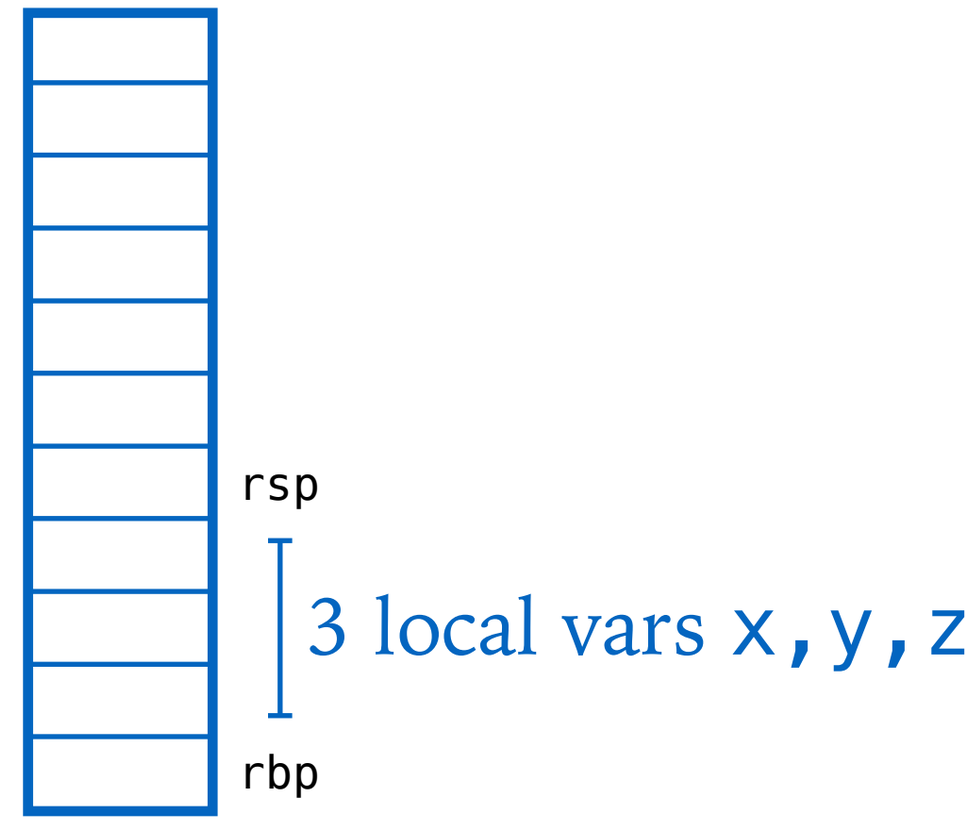
Garter / GC

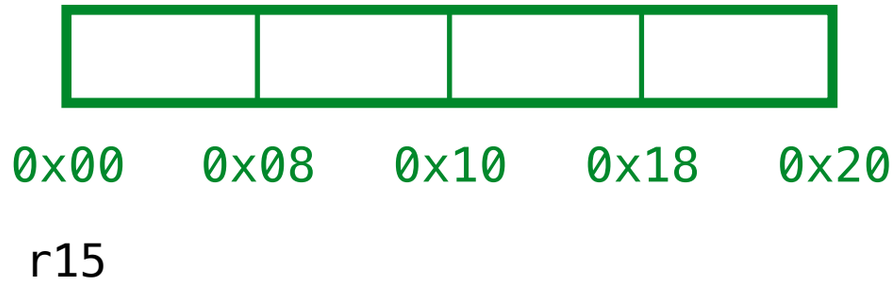
Example 3

ex3: garbage in the middle (with stack)

```
def foo(p, q):
  let tmp = (p, q)
  in tmp[0] + tmp[1]

let y  = foo(10, 20)
  , x  = (y, y + 1)
  , z  = foo(100, 200)
in
  x[0] + y + z
```





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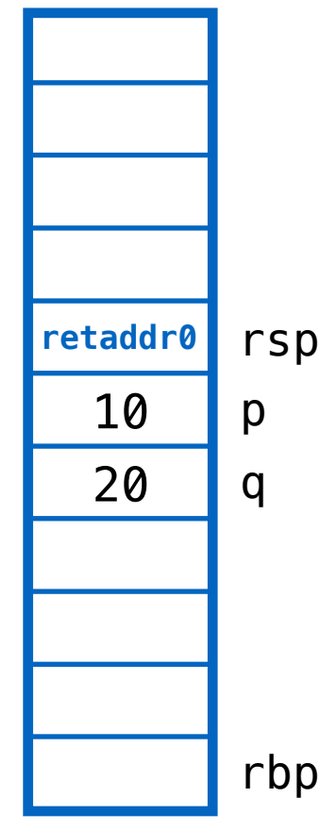

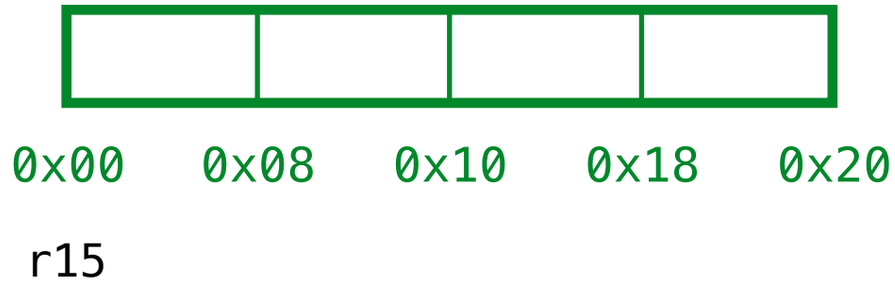

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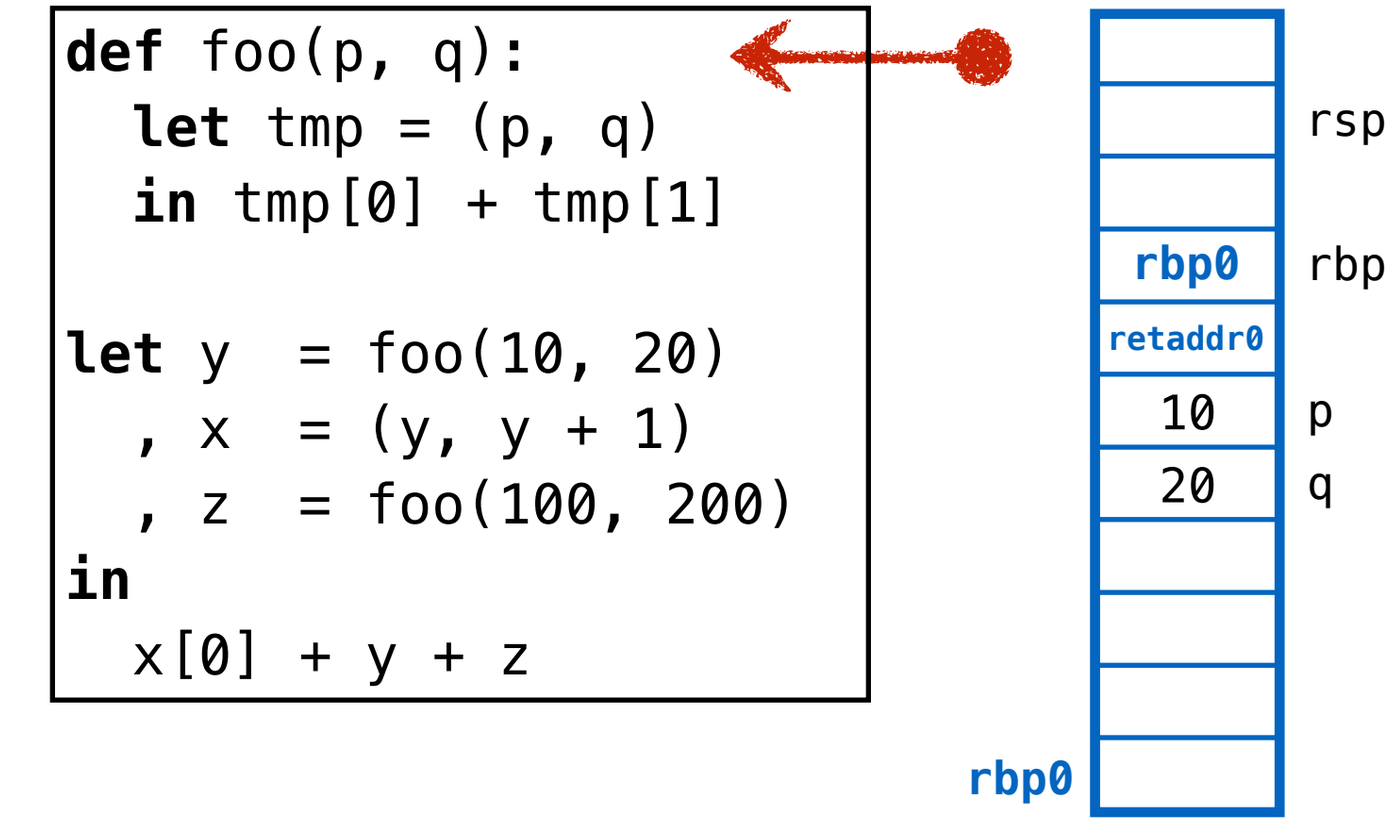

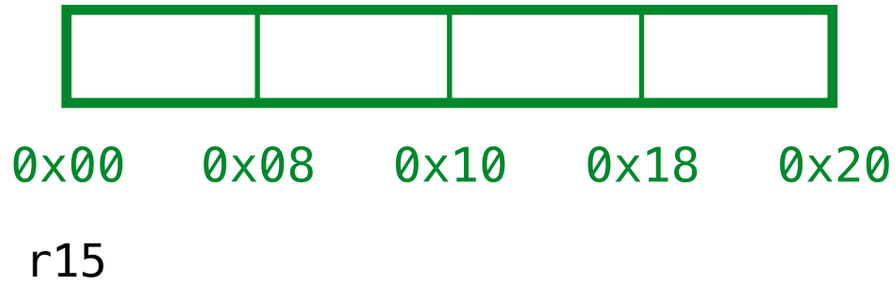

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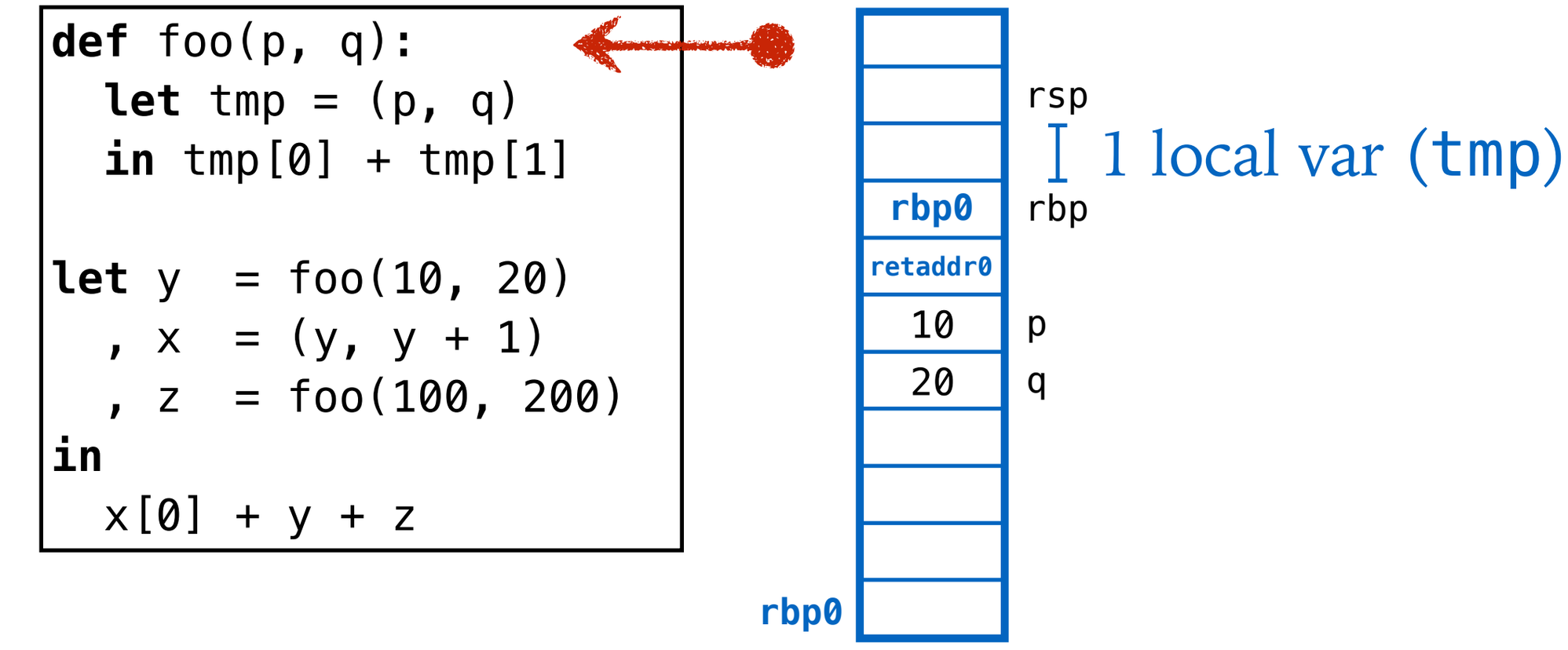

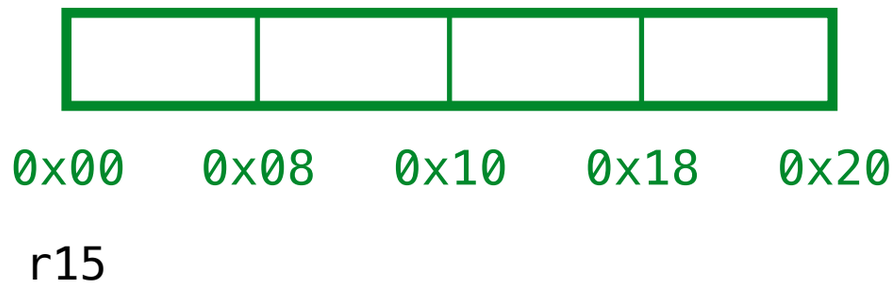

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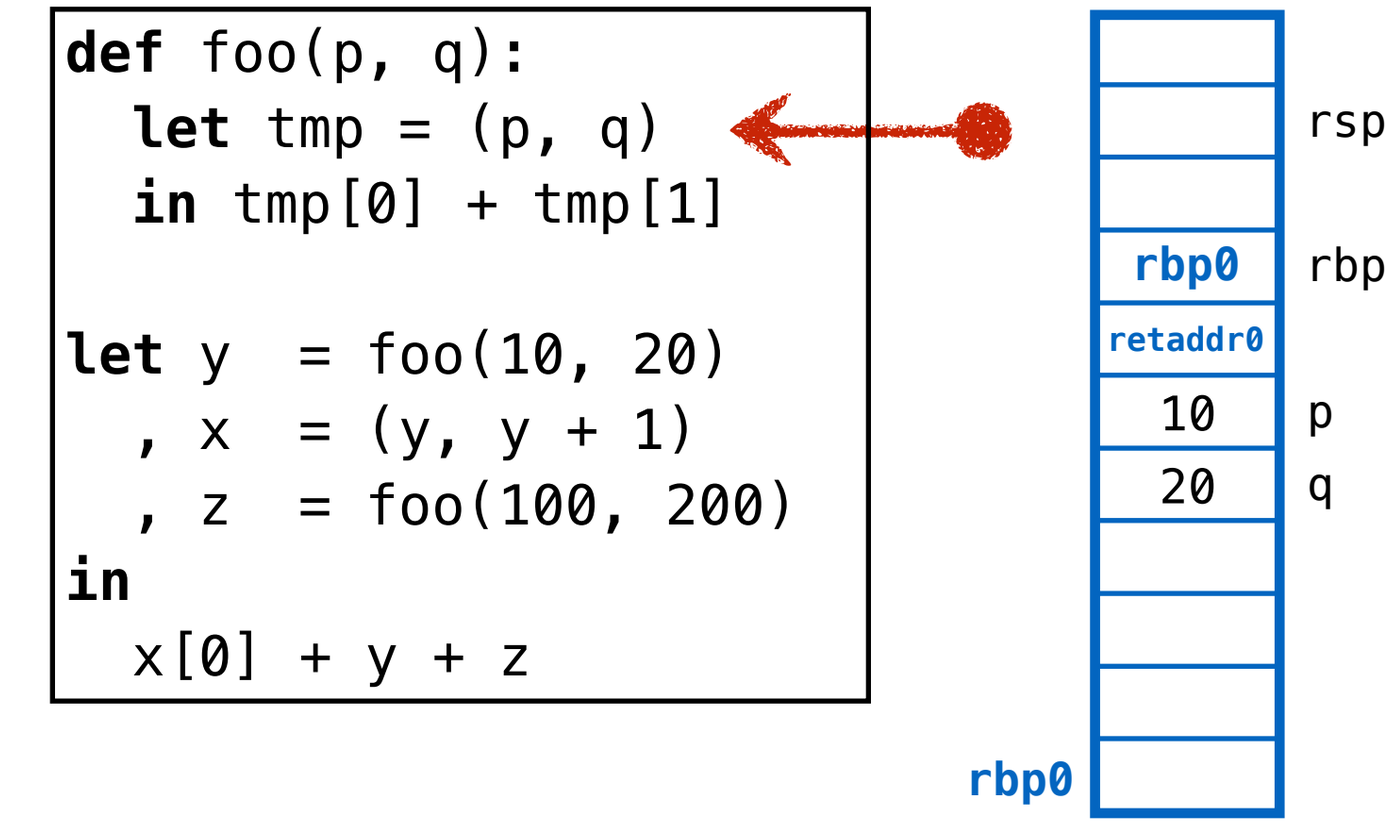

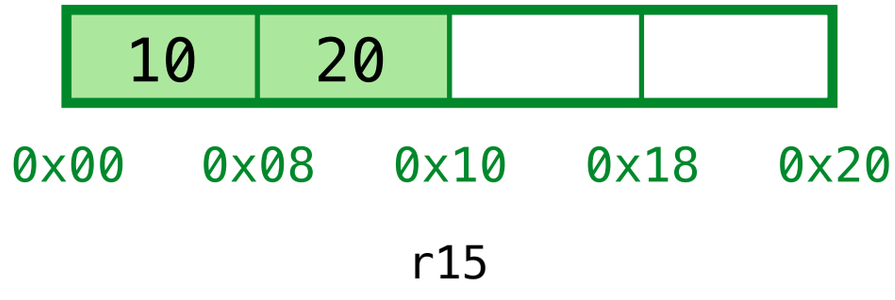

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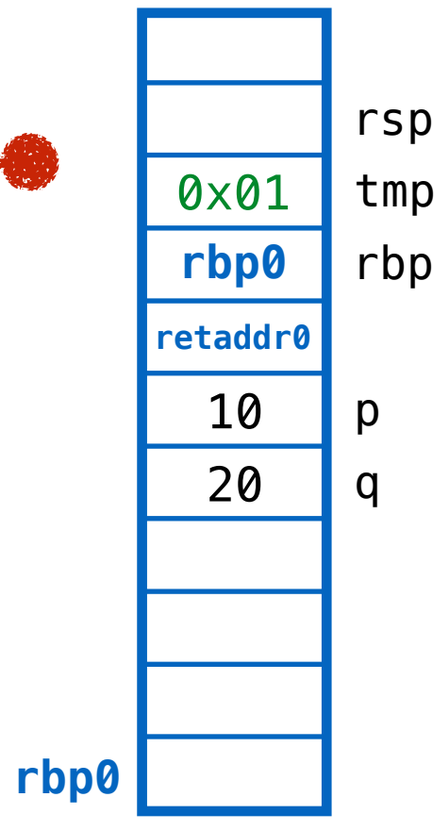

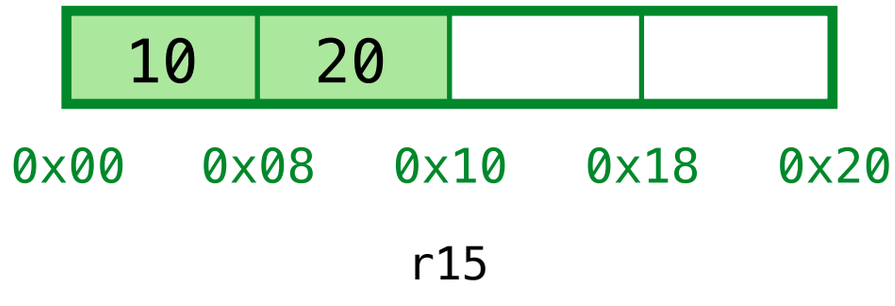

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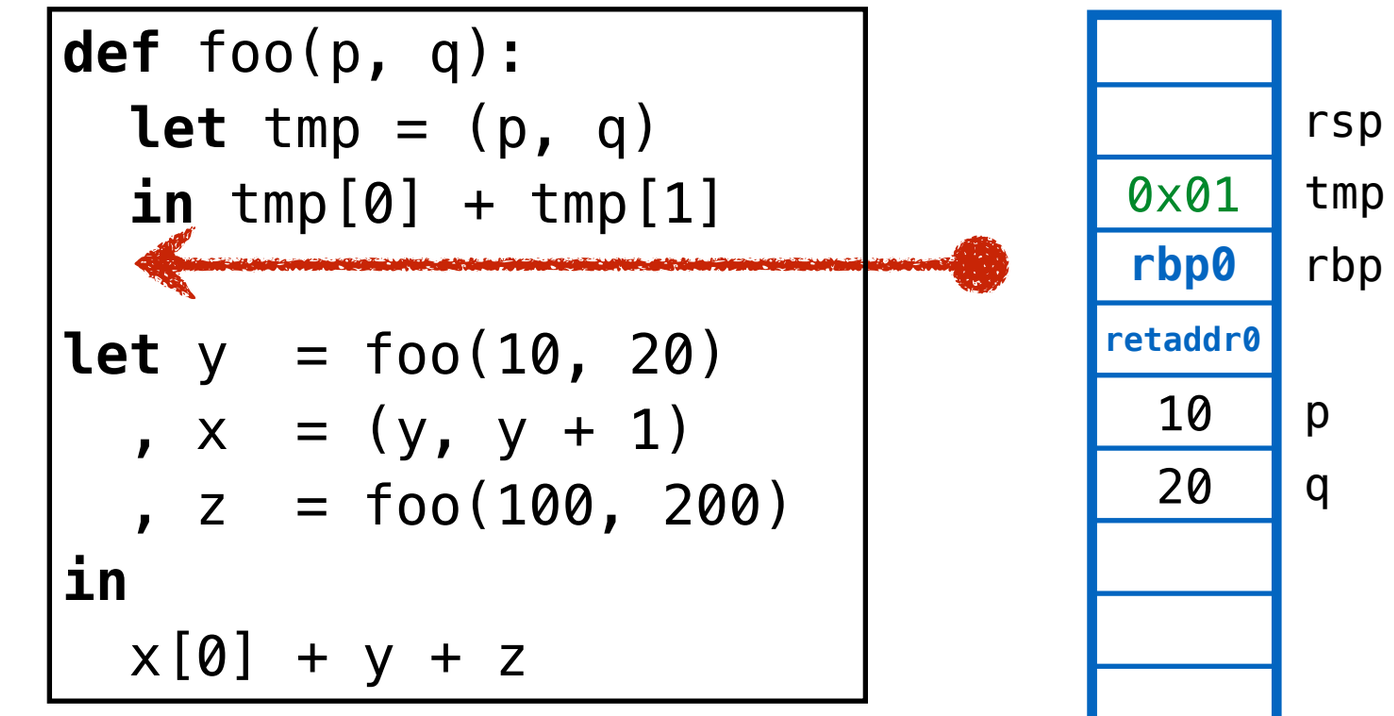
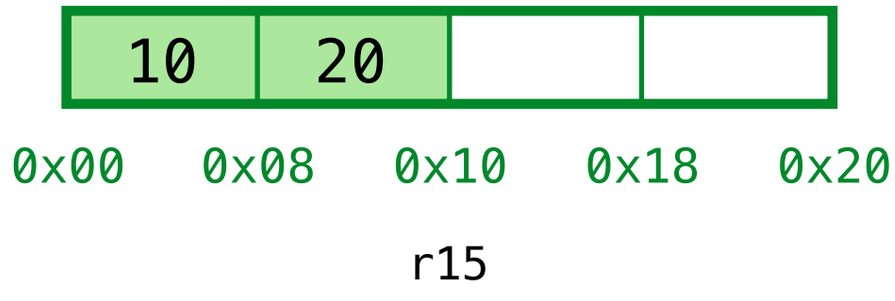


Return (rax) = 30



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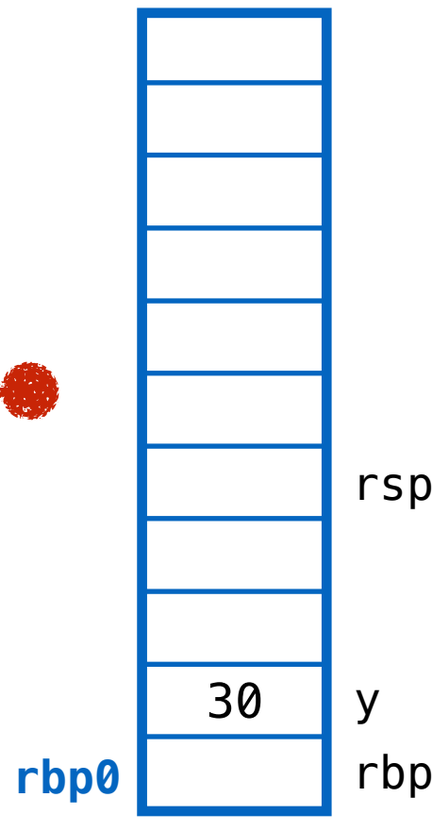

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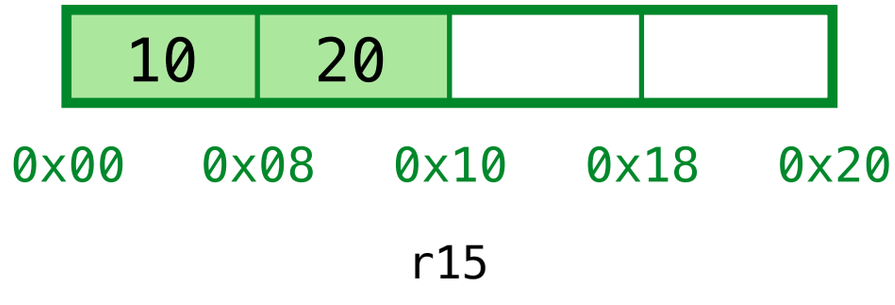

ex3: garbage in the middle (with stack)

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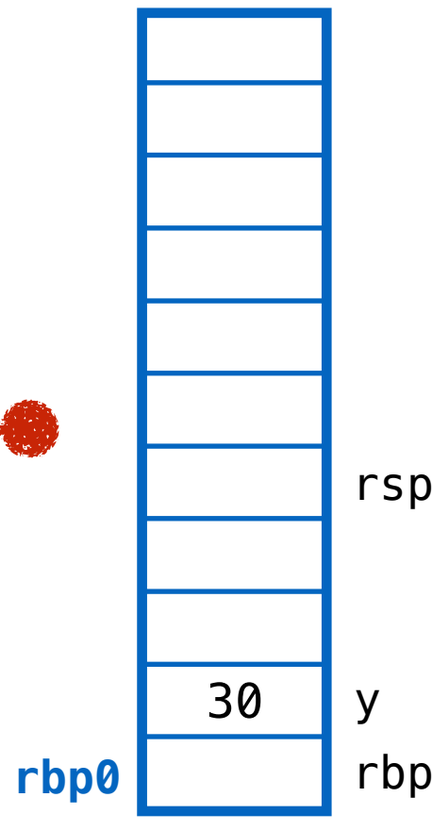

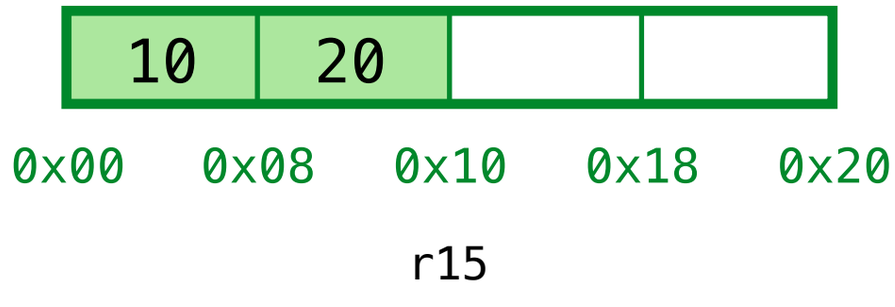

ex3: garbage in the middle (with stack)

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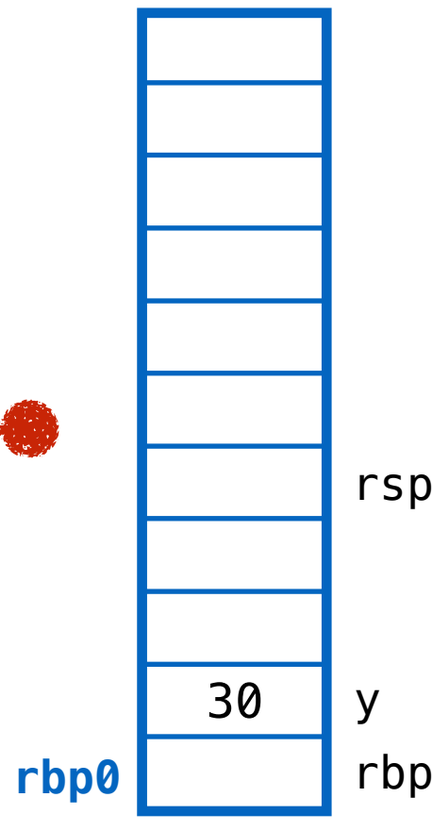

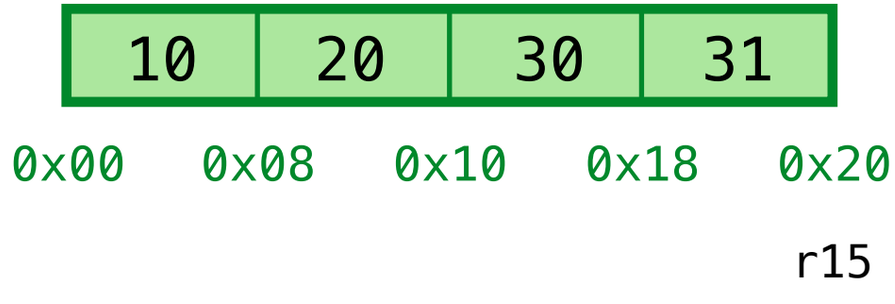

ex3: garbage in the middle (with stack)

```
def foo(p, q):
  let tmp = (p, q)
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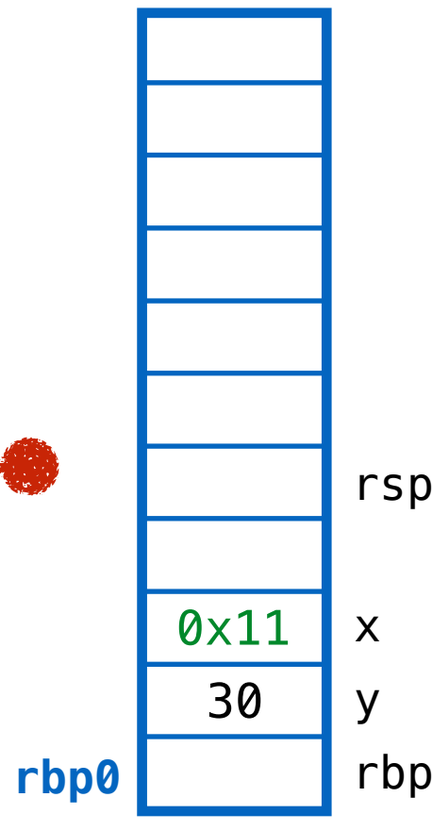

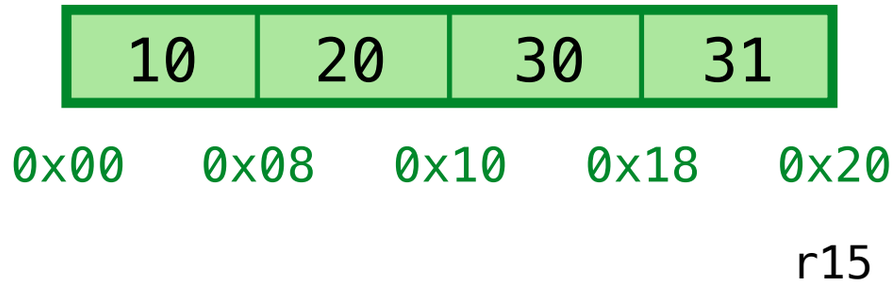

ex3: garbage in the middle (with stack)

```
def foo(p, q):
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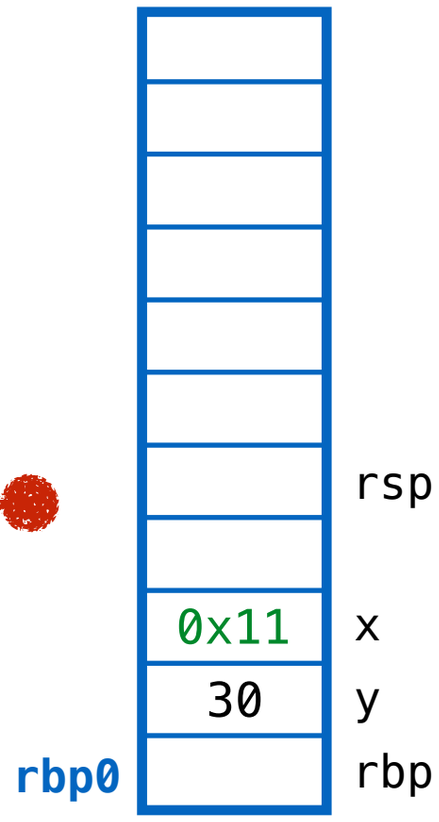

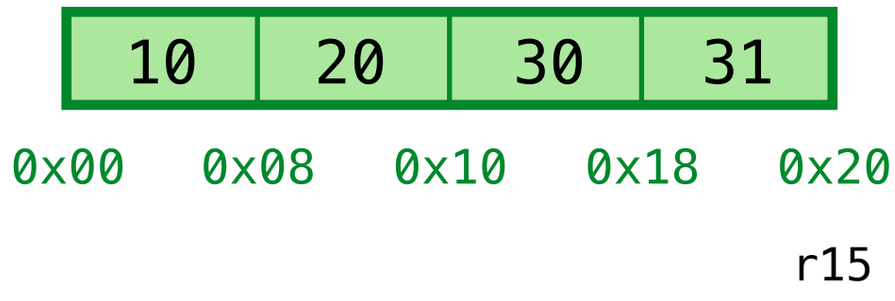

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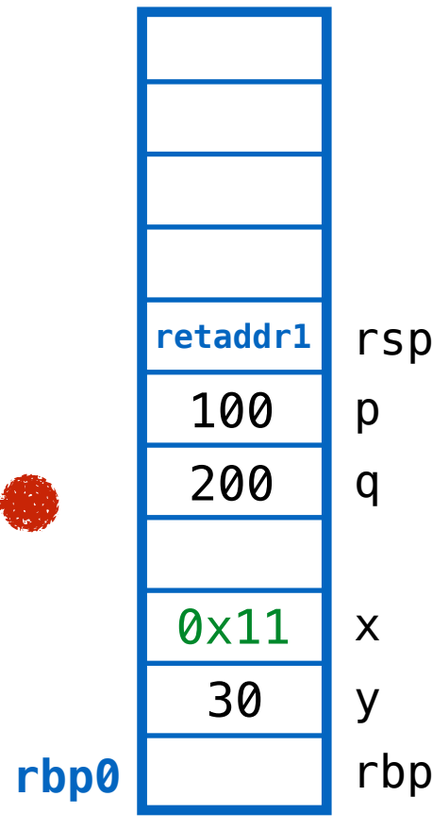

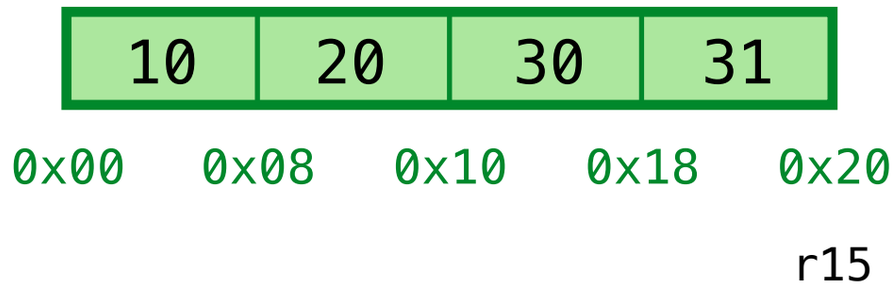

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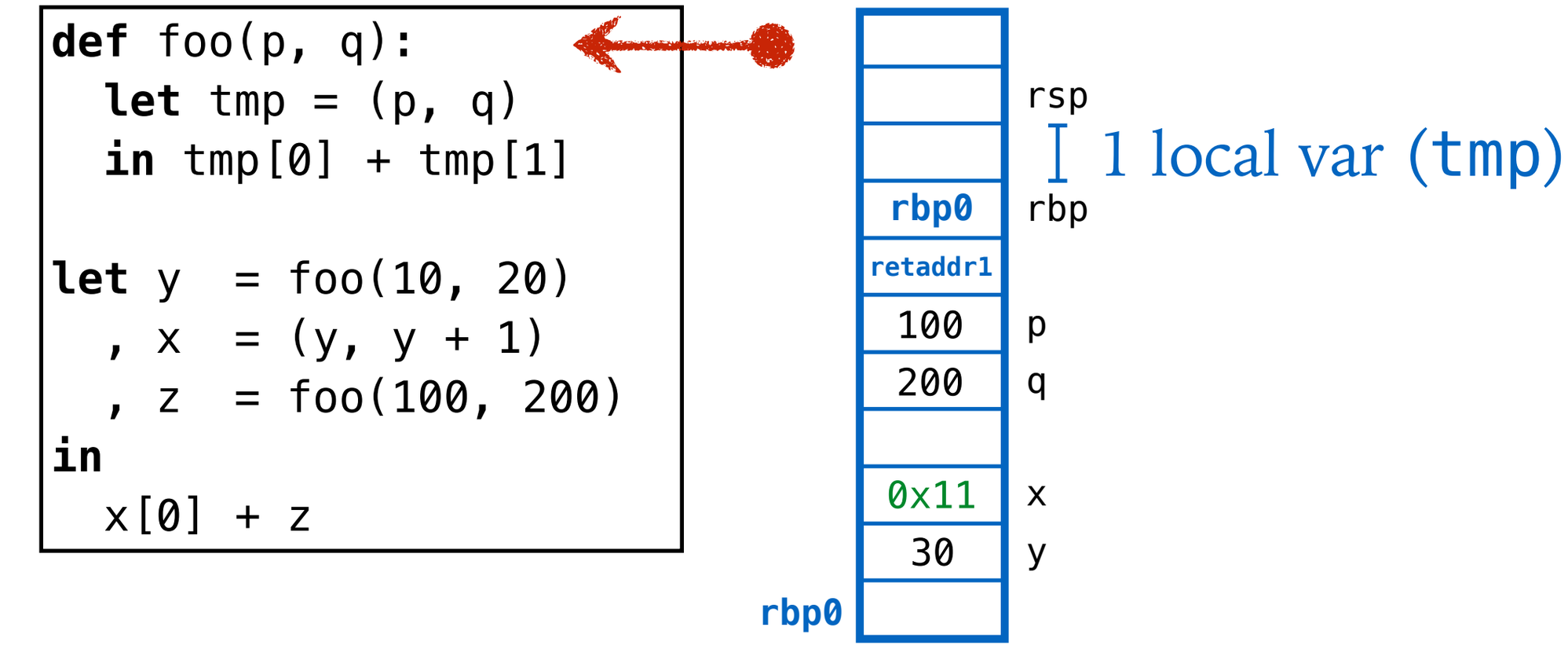

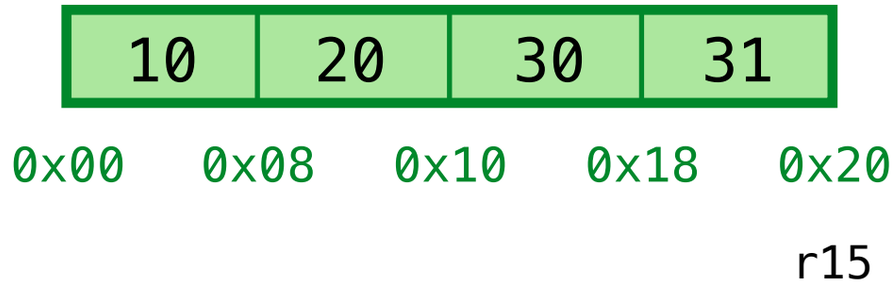

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```
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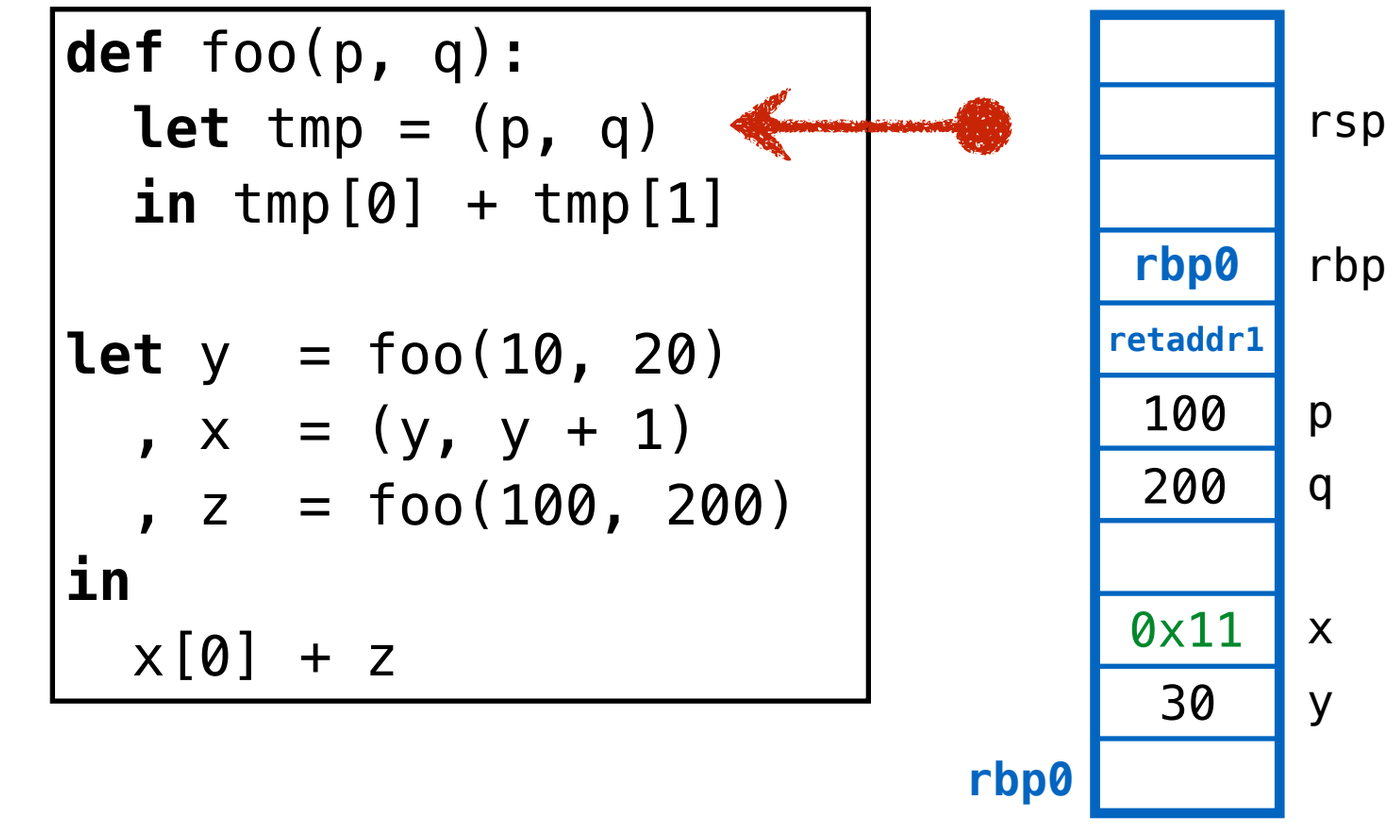

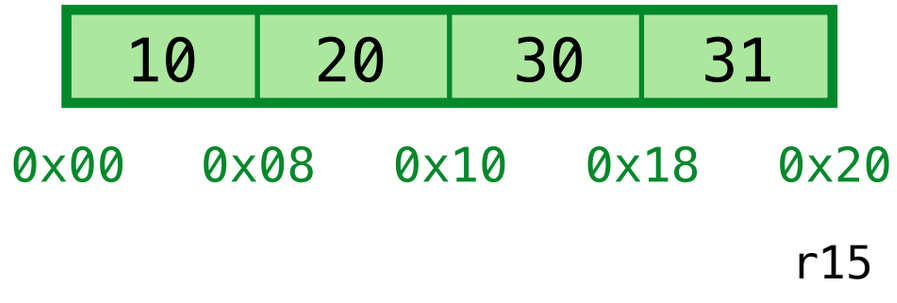

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```
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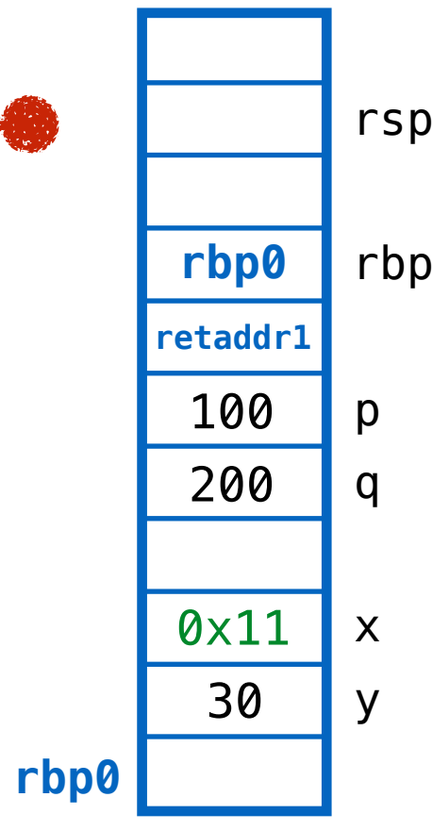
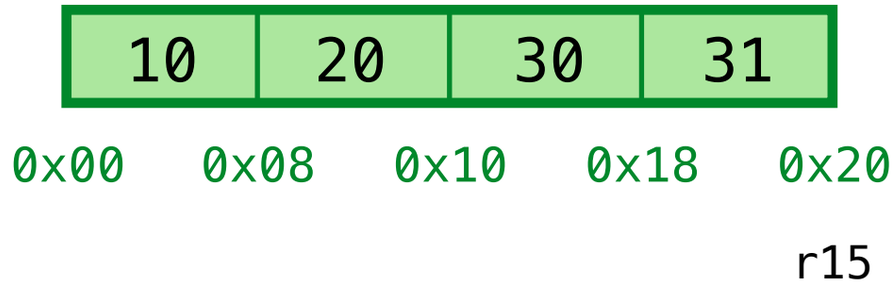


Lets reclaim & recycle garbage!



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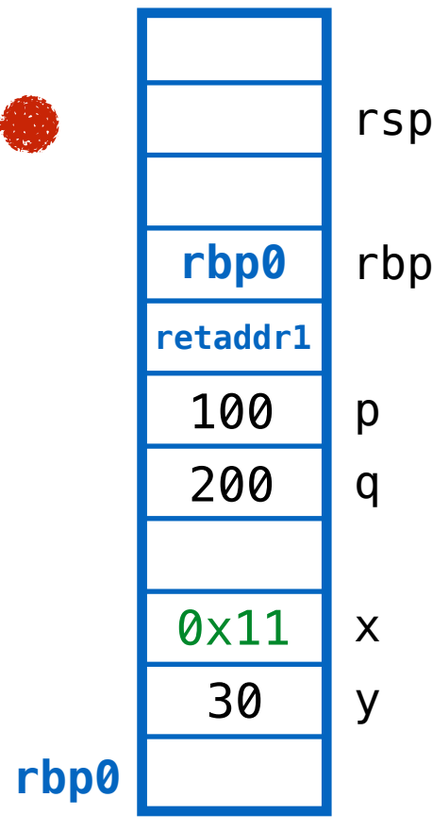

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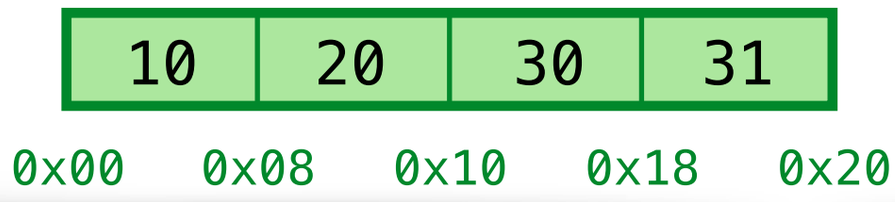

QUIZ: Which cells are garbage?

(A) `0x00, 0x08` (B) `0x08, 0x10` (C) `0x10, 0x18` (D) None (E) All

ex3: garbage in the middle (with stack)

```
def foo(p, q):
  let tmp = (p, q)
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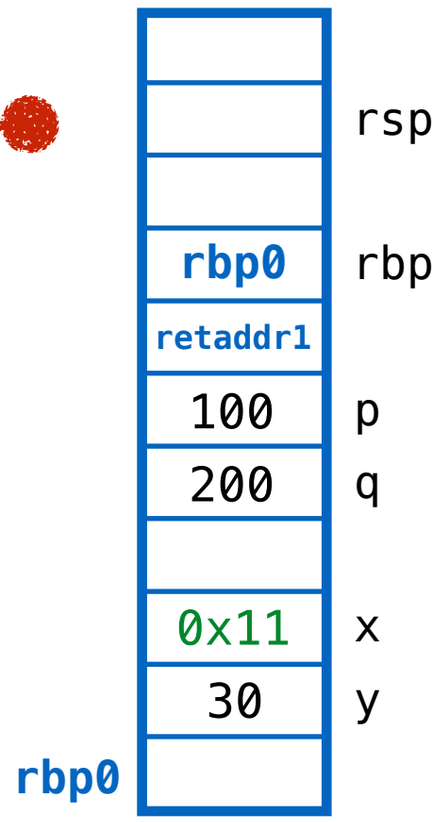

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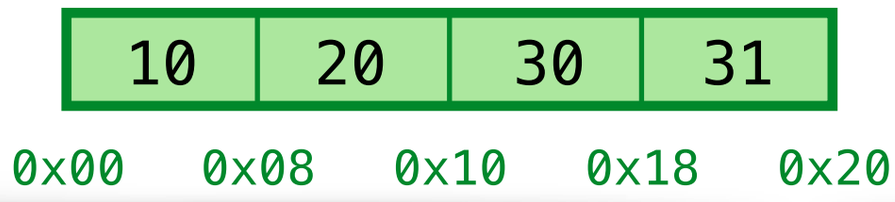

QUIZ: Which cells are garbage?

Those that are *not reachable from any stack frame*

ex3: garbage in the middle (with stack)

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def foo(p, q):
  let tmp = (p, q)
  in tmp[0] + tmp[1]

let y  = foo(10, 20)
  , x  = (y, y + 1)
  , z  = foo(100, 200)
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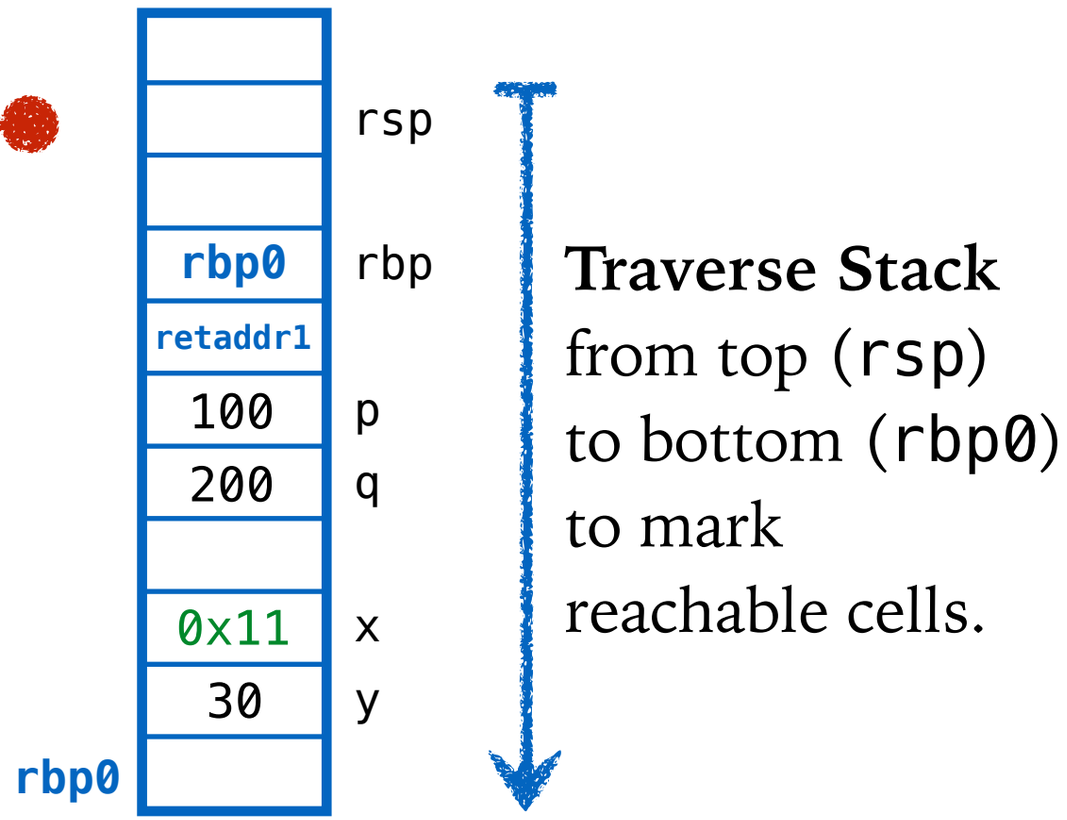
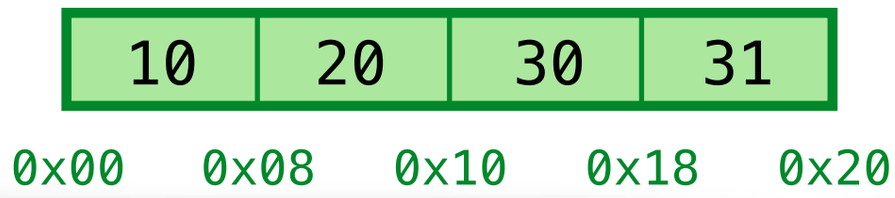


Lets reclaim & recycle garbage!



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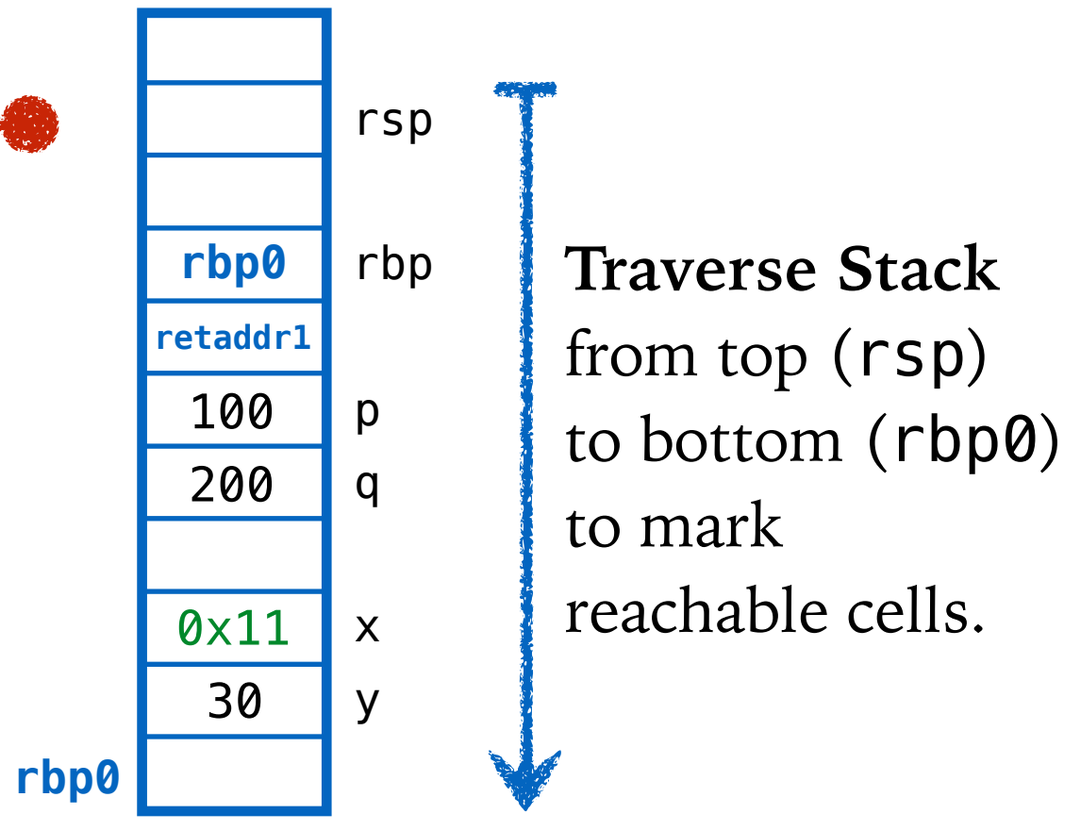

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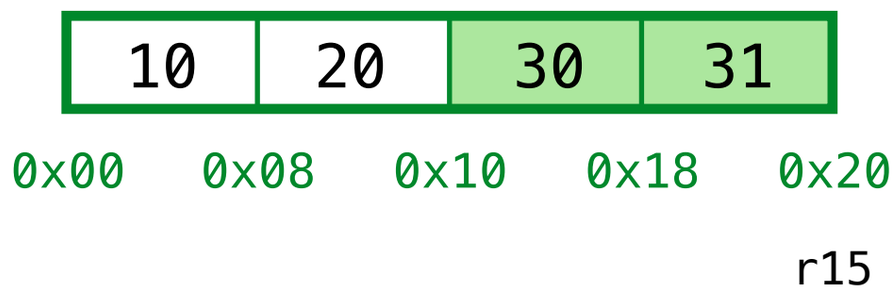

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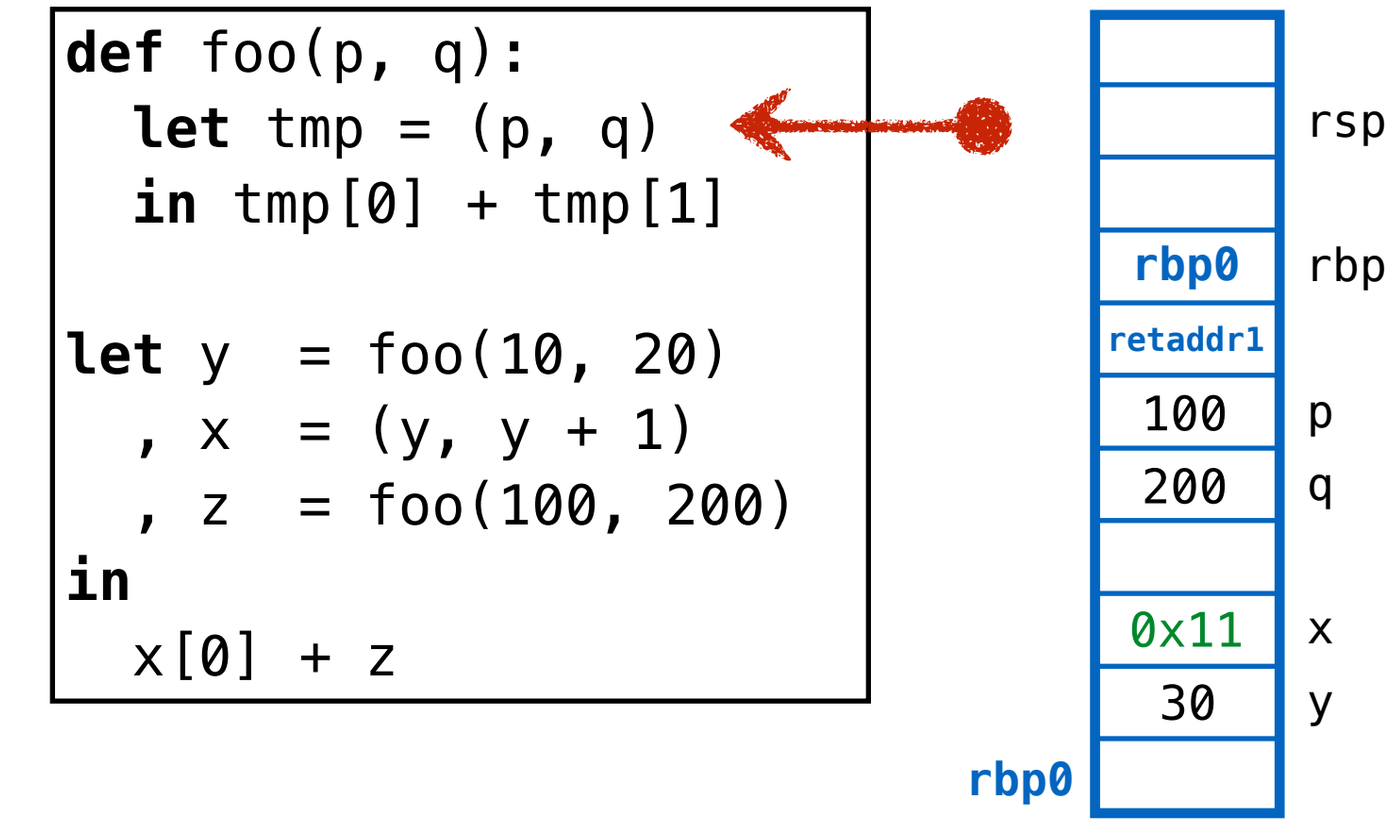

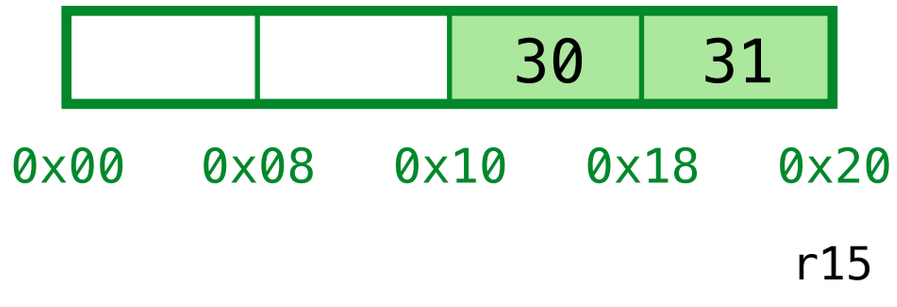

Compact the live cells

ex3: garbage in the middle (with stack)

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def foo(p, q):
  let tmp = (p, q)
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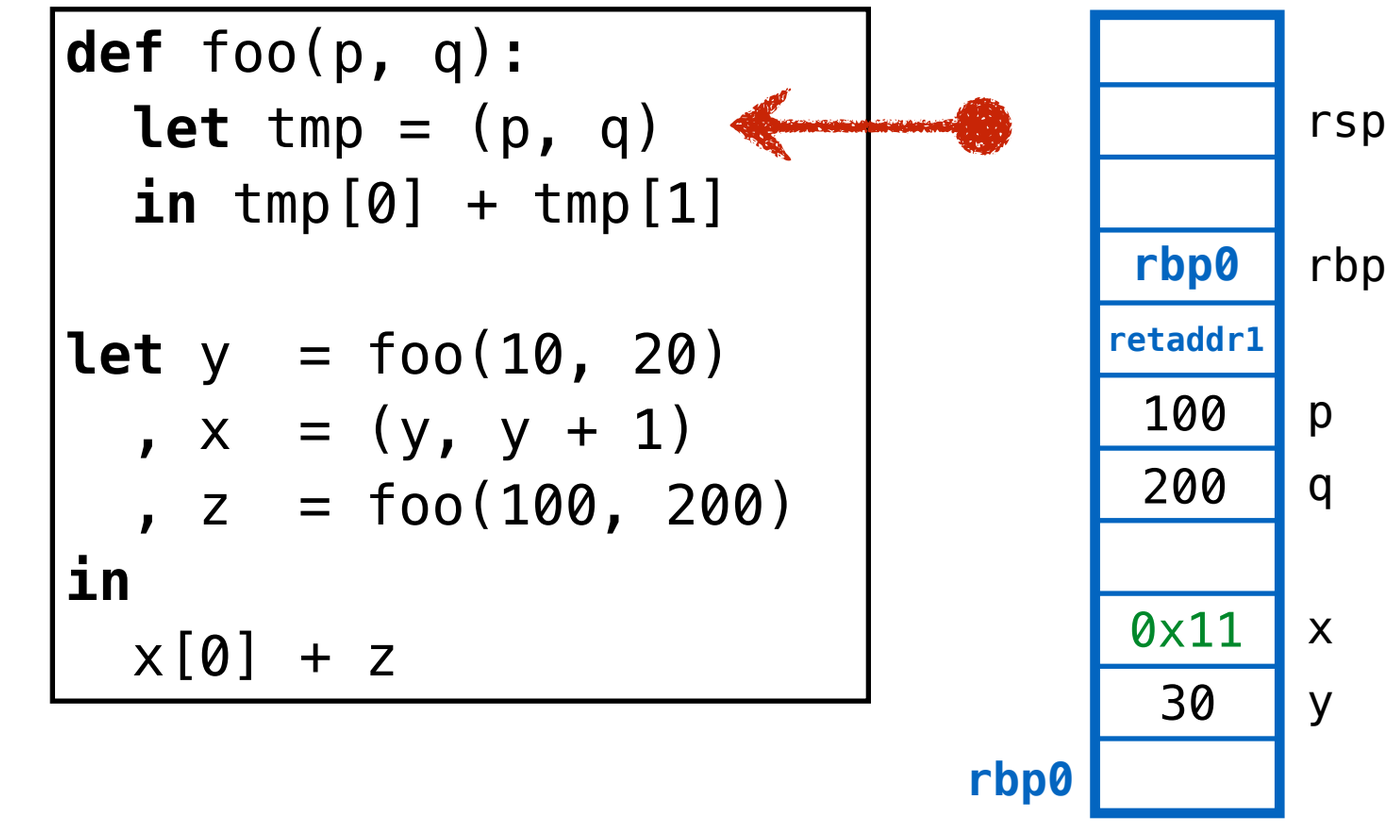

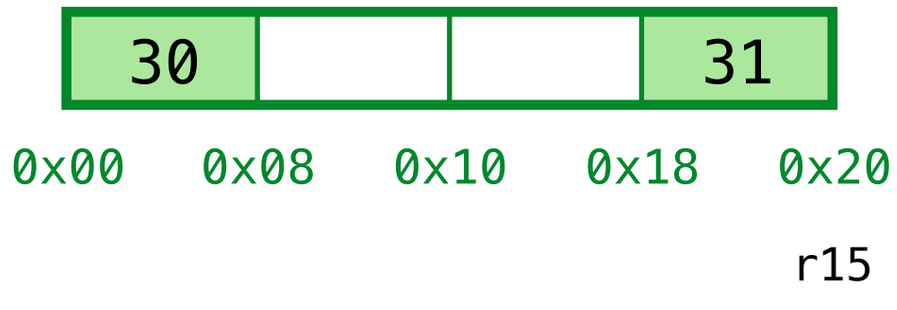

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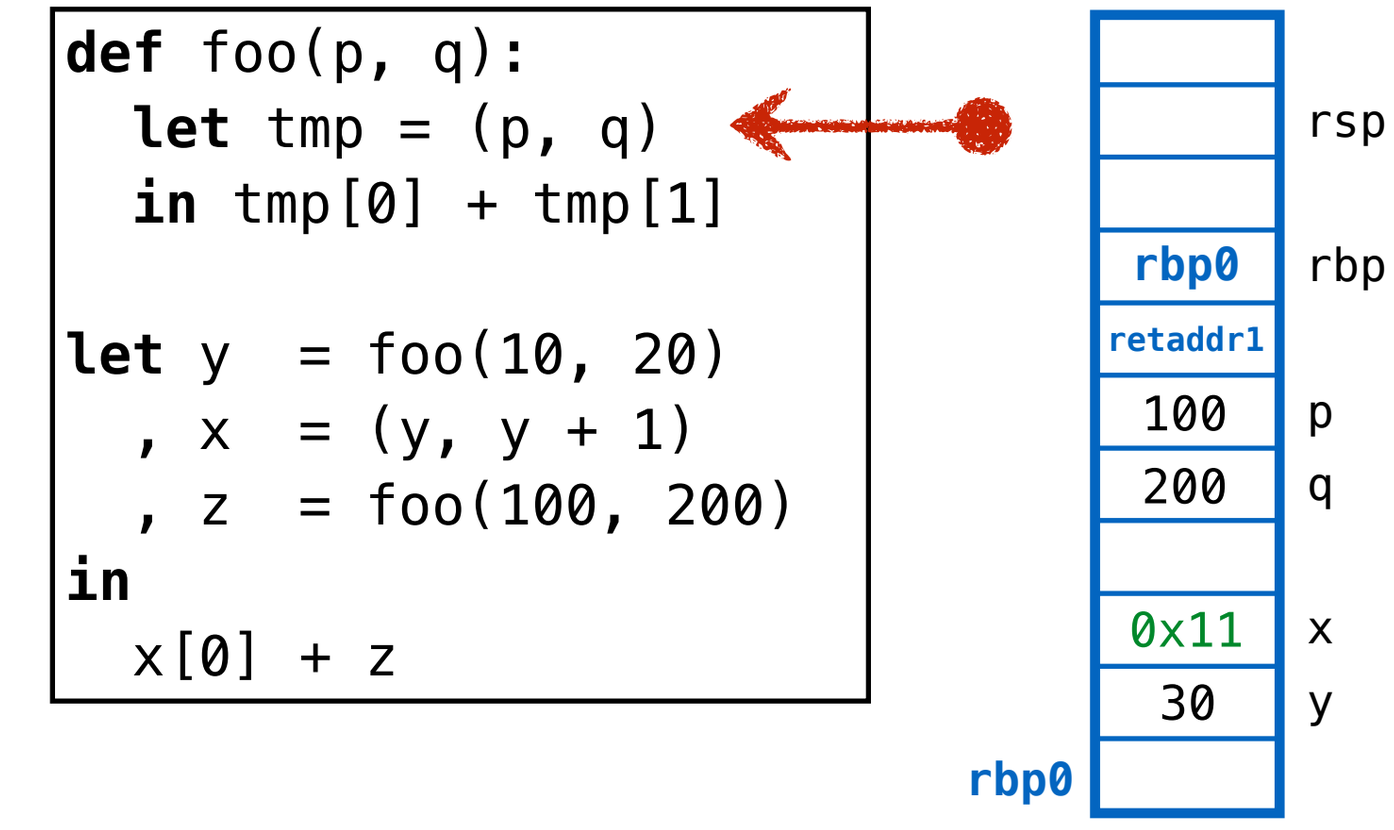
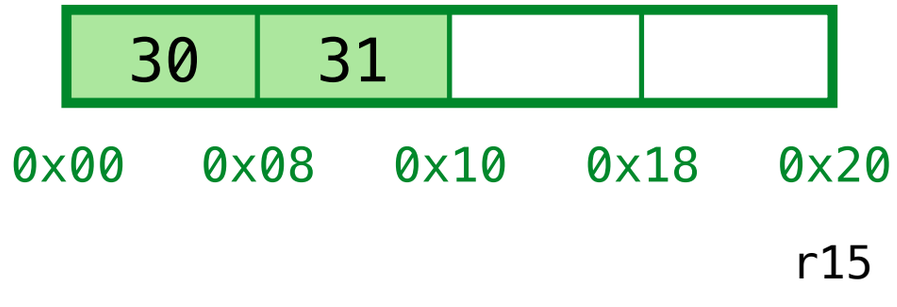
```





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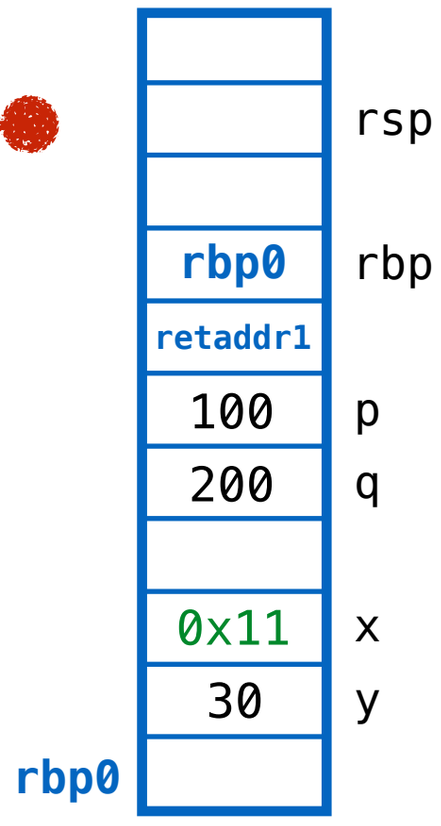

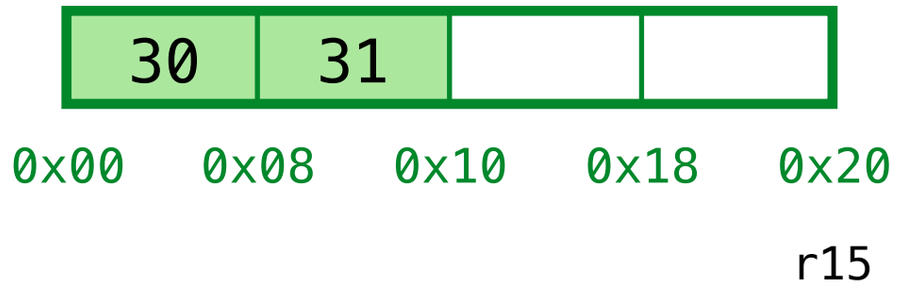

Compact the live cells ... then rewind `r15`

ex3: garbage in the middle (with stack)

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def foo(p, q):
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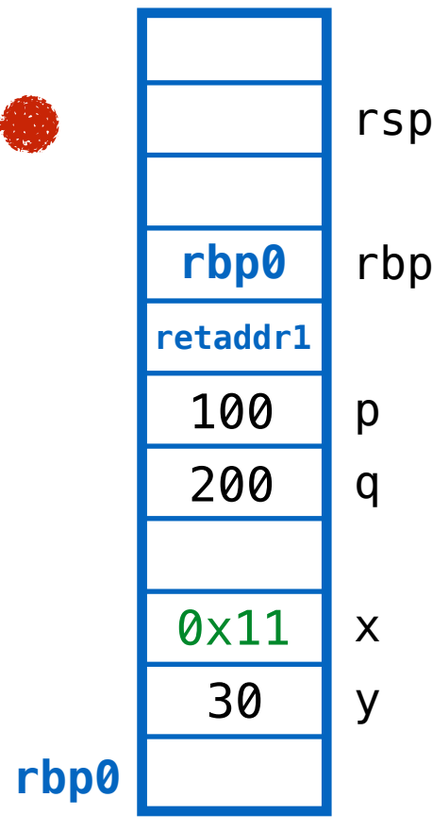

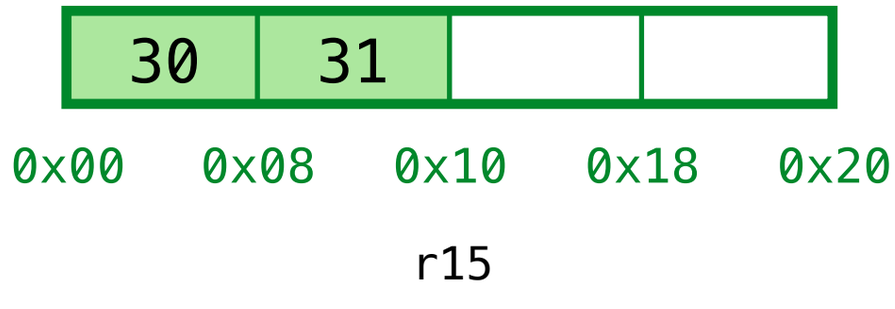

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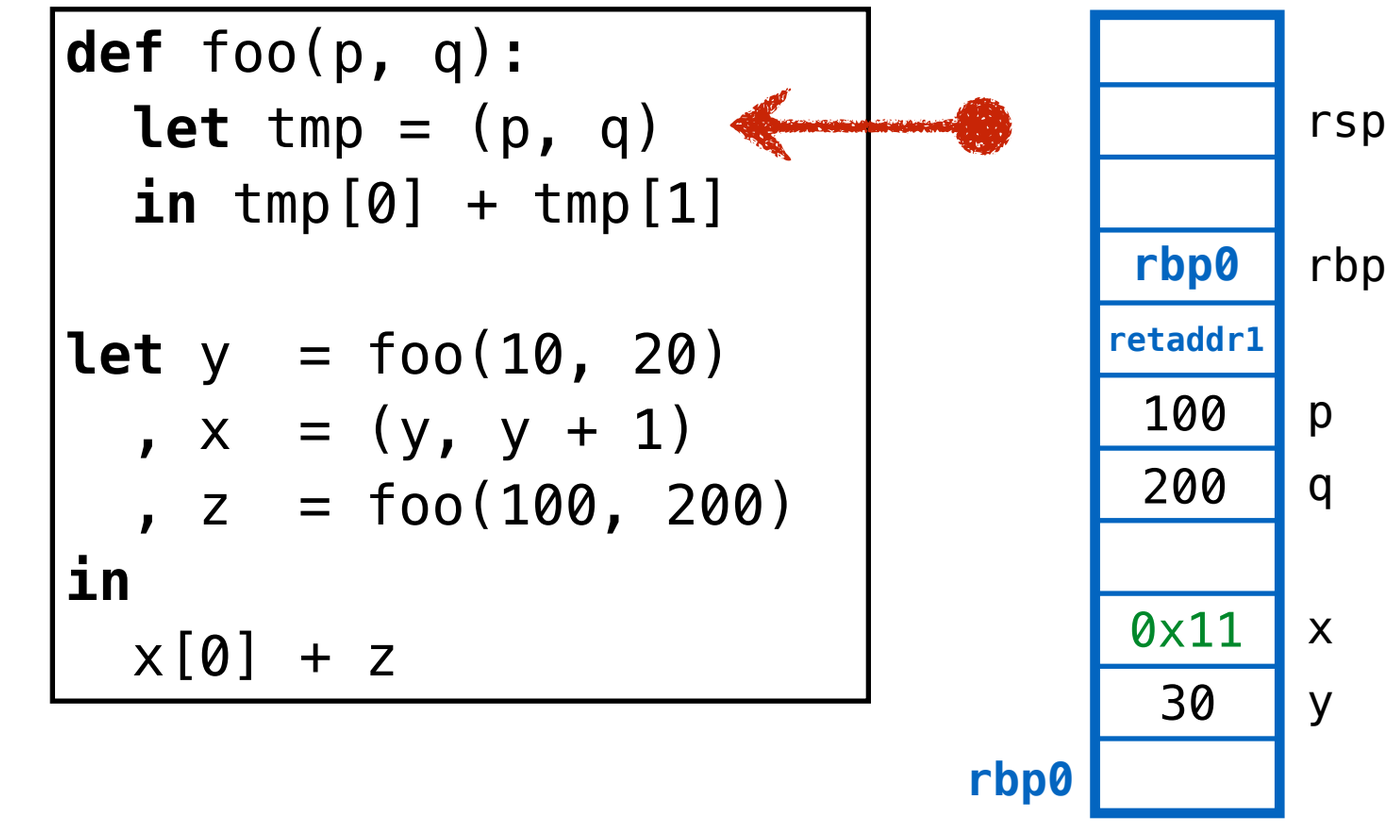

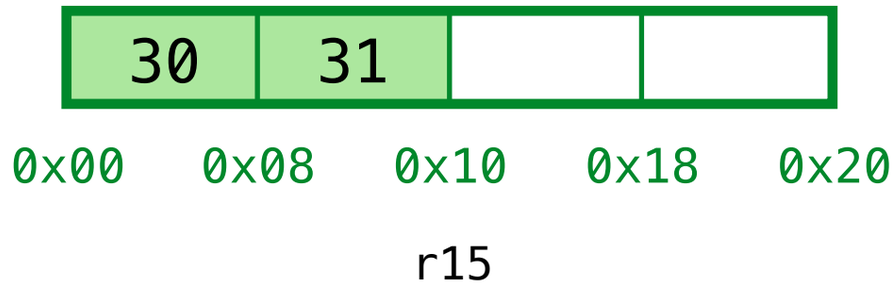

Problem???

ex3: garbage in the middle (with stack)

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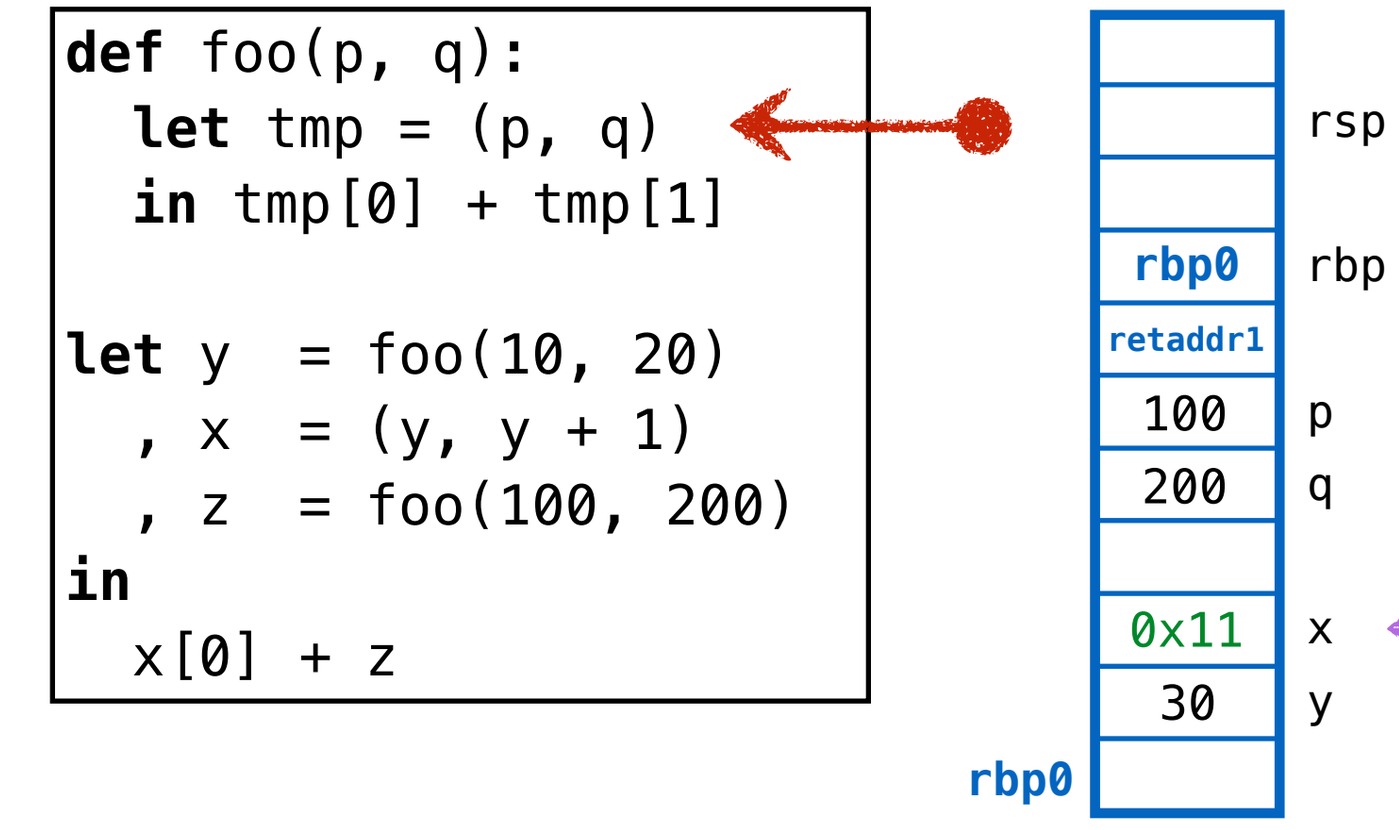

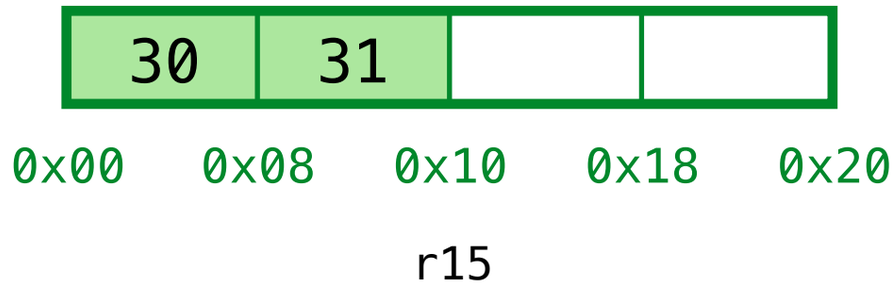

Problem! Have to REDIRECT existing pointers

ex3: garbage in the middle (with stack)

```
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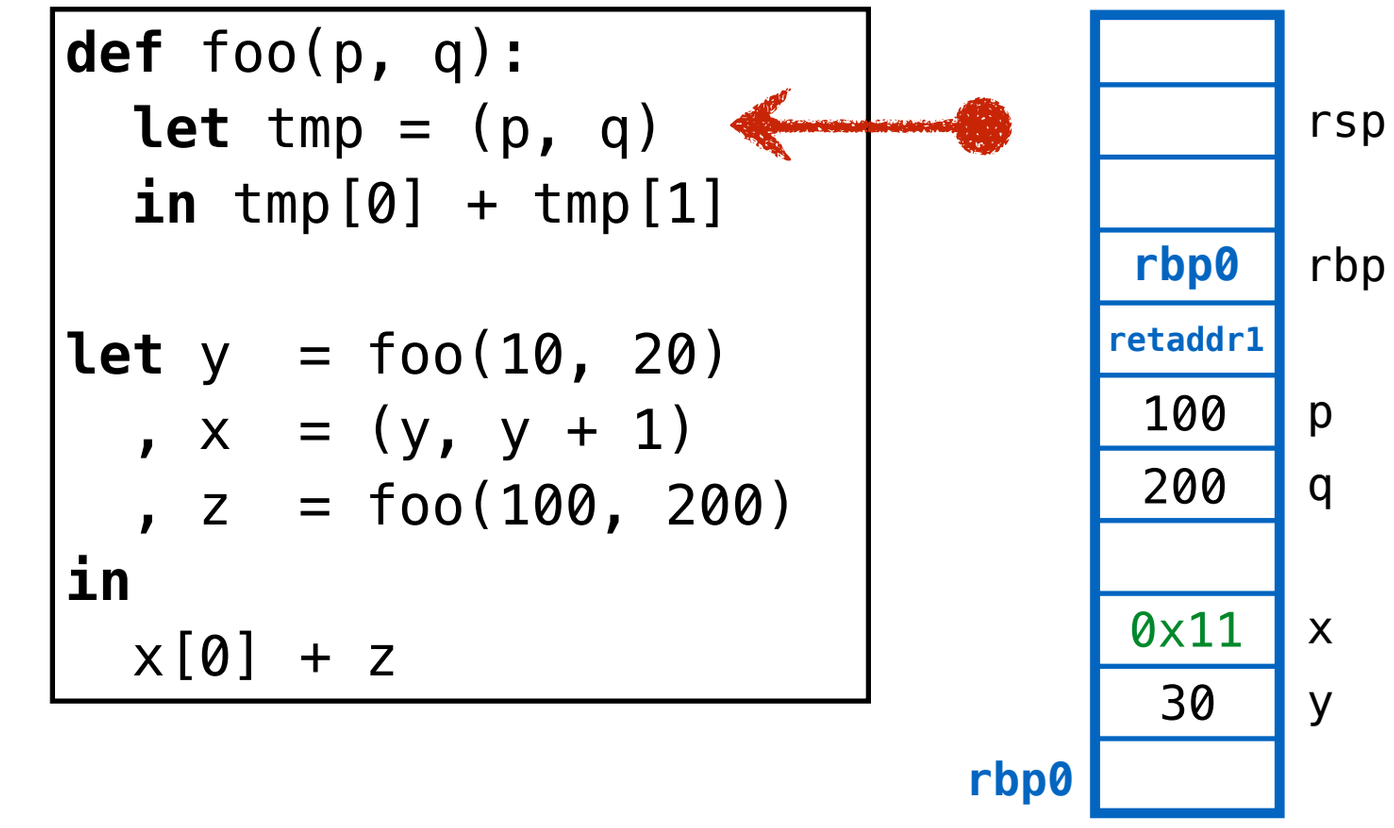

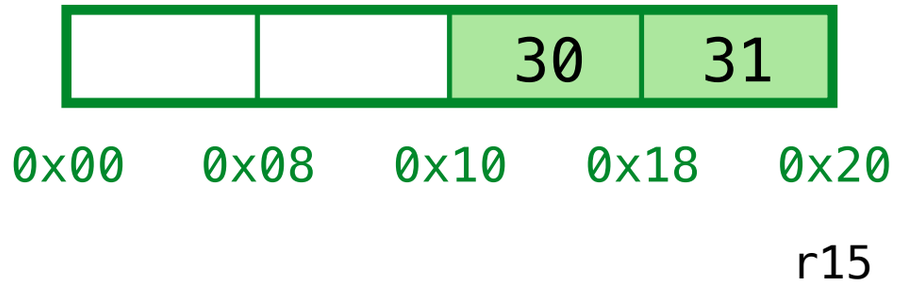

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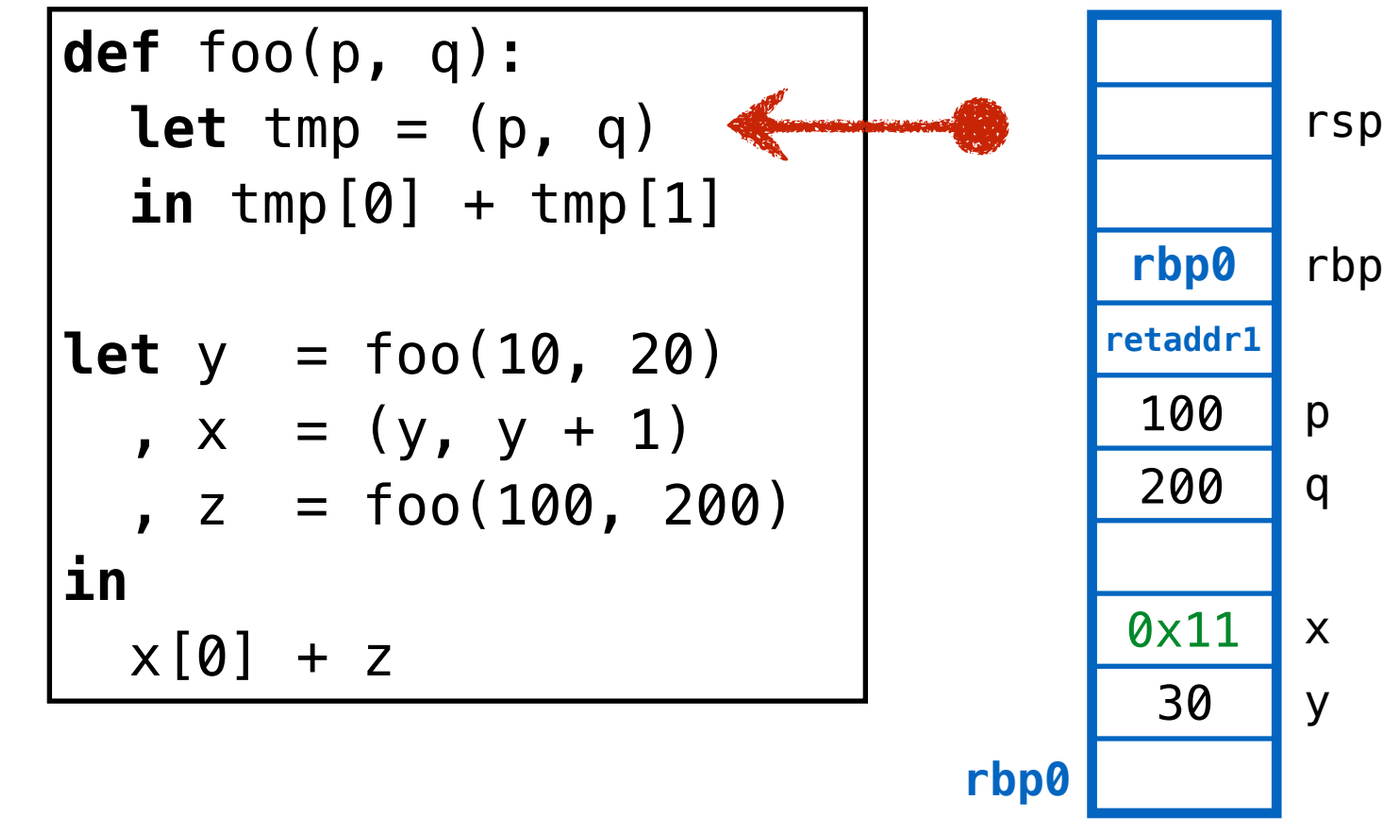
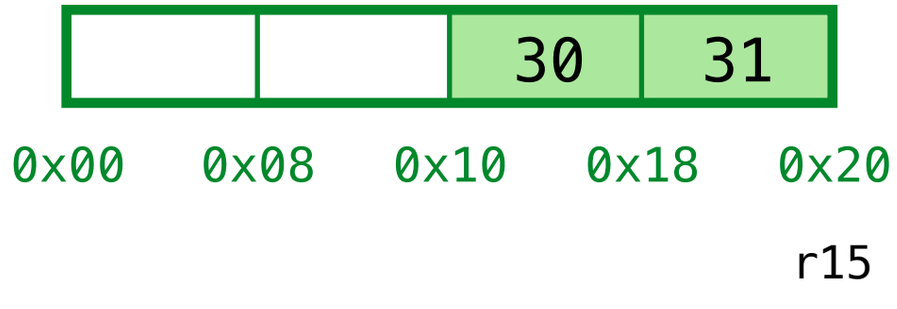
```





1. Compute FORWARD addrs (i.e. new compacted addrs)

ex3: garbage in the middle (with stack)

```
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  let tmp = (p, q)
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let y  = foo(10, 20)
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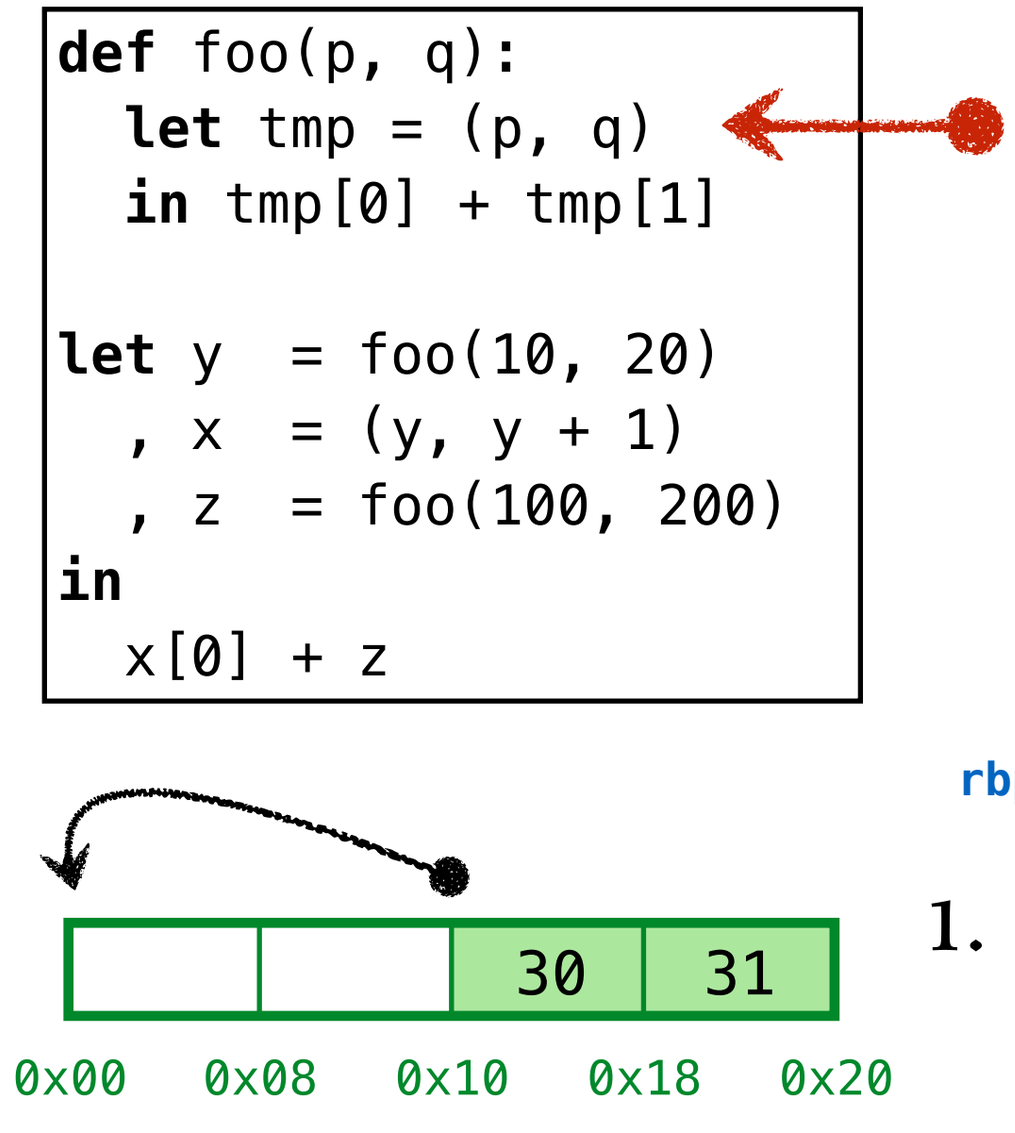
```



1. Compute FORWARD addrs
   e.g. `0x11` —> `0x01`

ex3: garbage in the middle (with stack)

```
def foo(p, q):
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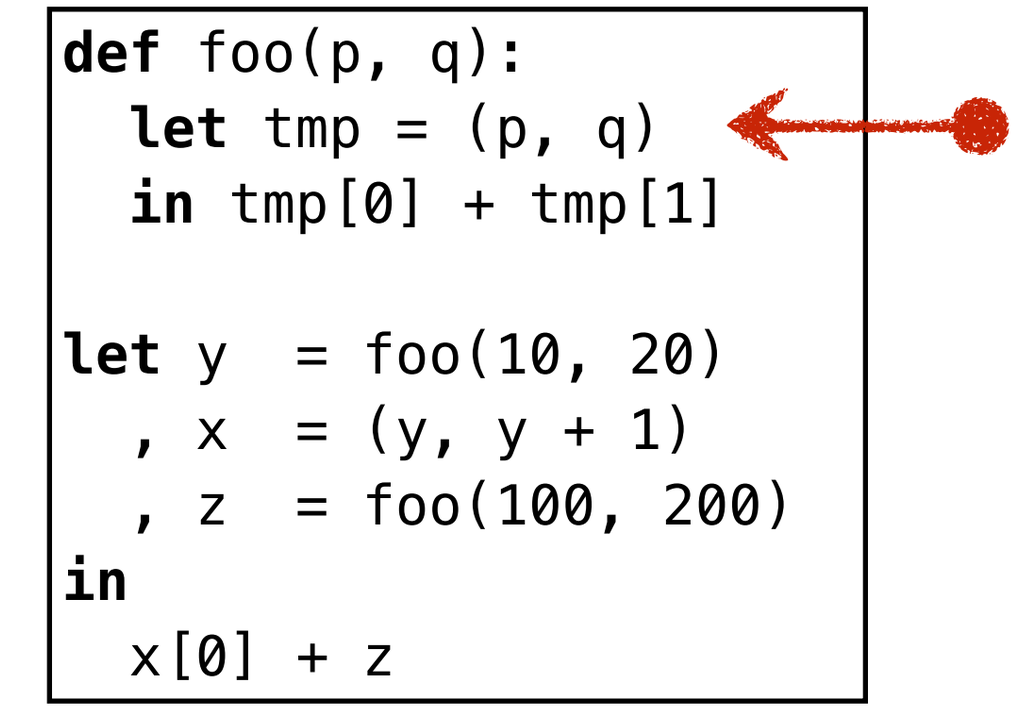

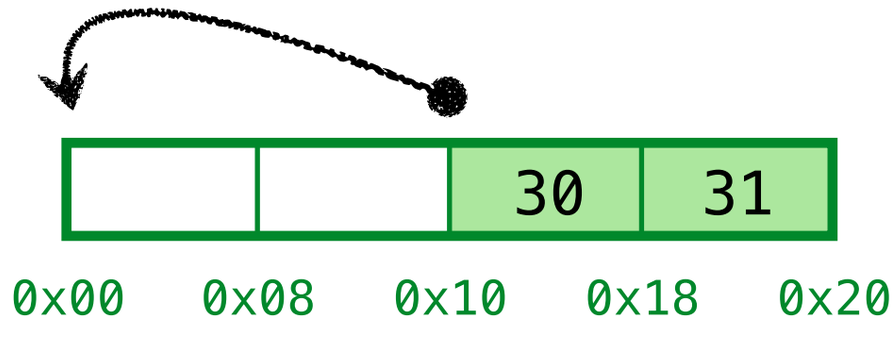

1. Compute FORWARD addrs
   e.g. `0x11` —> `0x01`
2. REDIRECT addrs on stack

ex3: garbage in the middle (with stack)

```
def foo(p, q):
  let tmp = (p, q)
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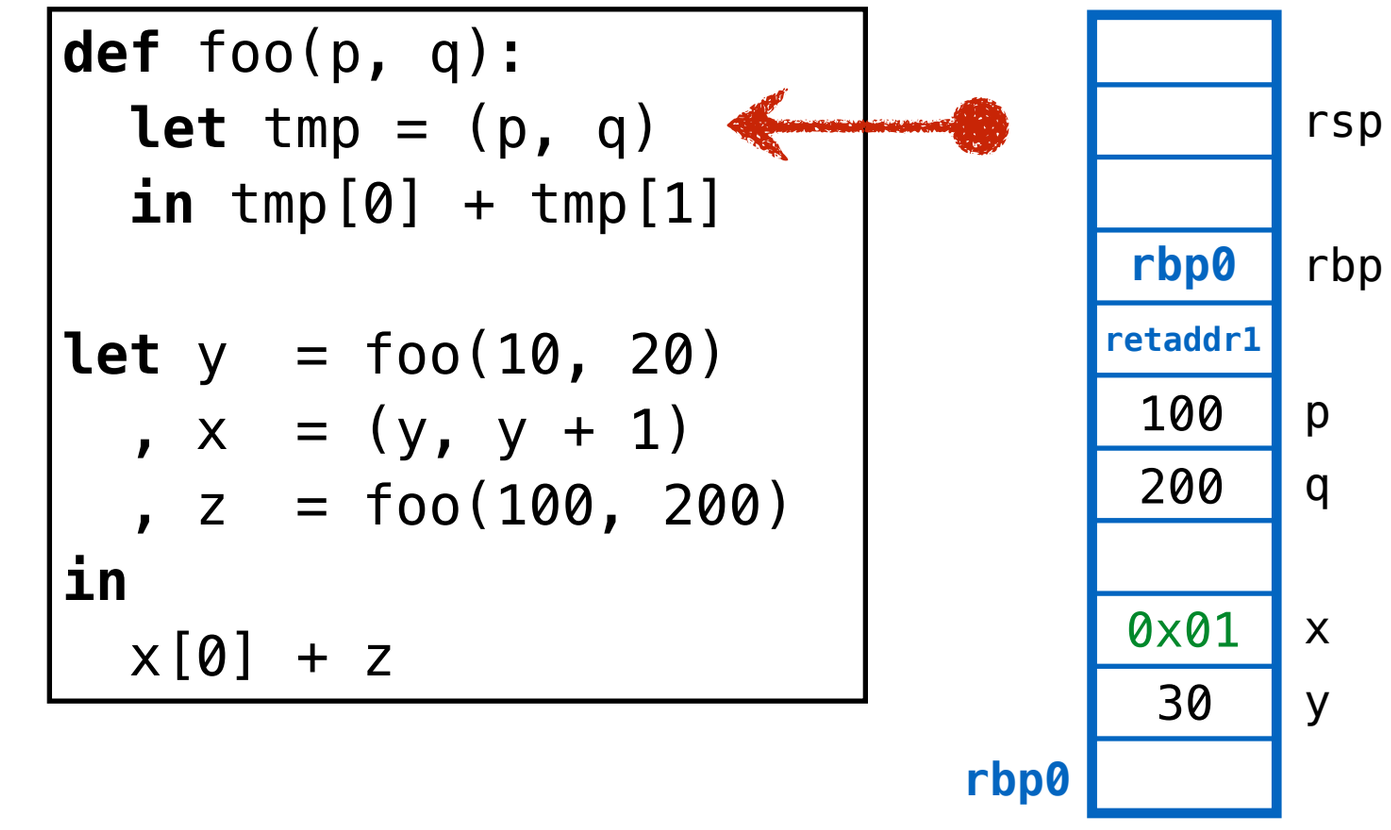

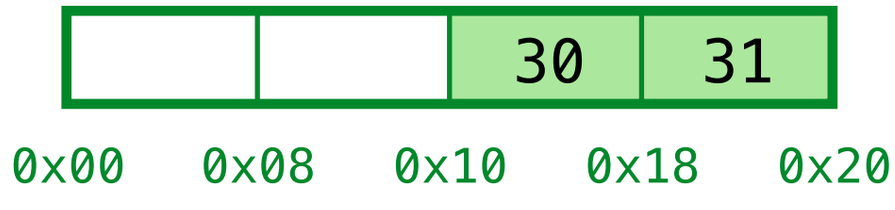

1. Compute FORWARD addrs
   e.g. `0x11` —> `0x01`
2. REDIRECT addrs on stack
3. COMPACT cells on heap

ex3: garbage in the middle (with stack)

```
def foo(p, q):
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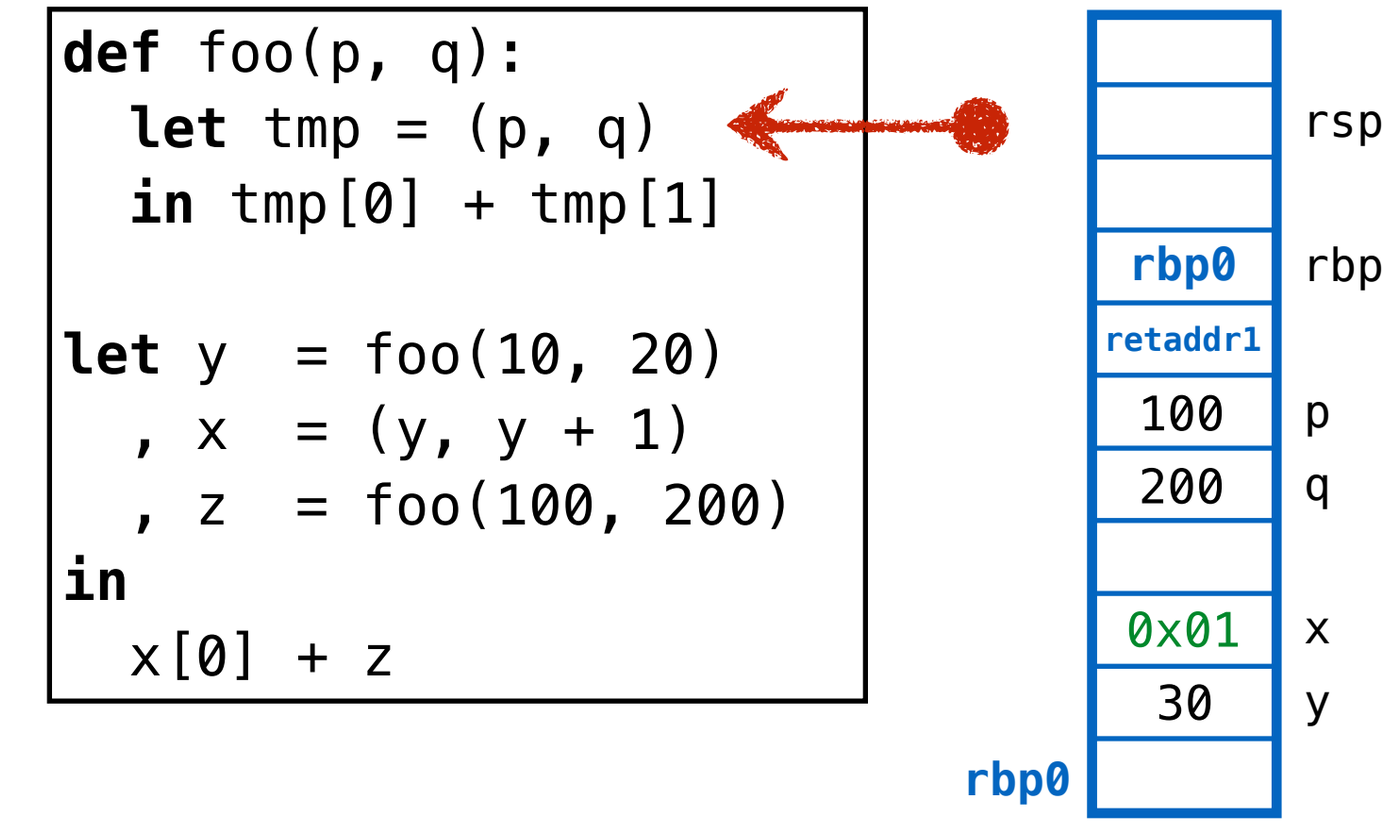
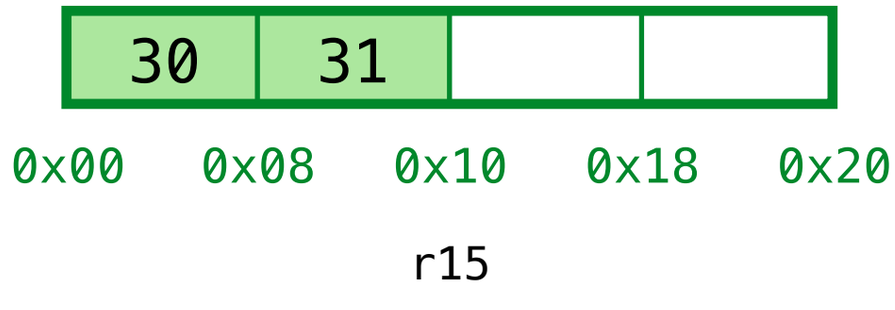
  in tmp[0] + tmp[1]

let y  = foo(10, 20)
  , x  = (y, y + 1)
  , z  = foo(100, 200)
in
  x[0] + z
```



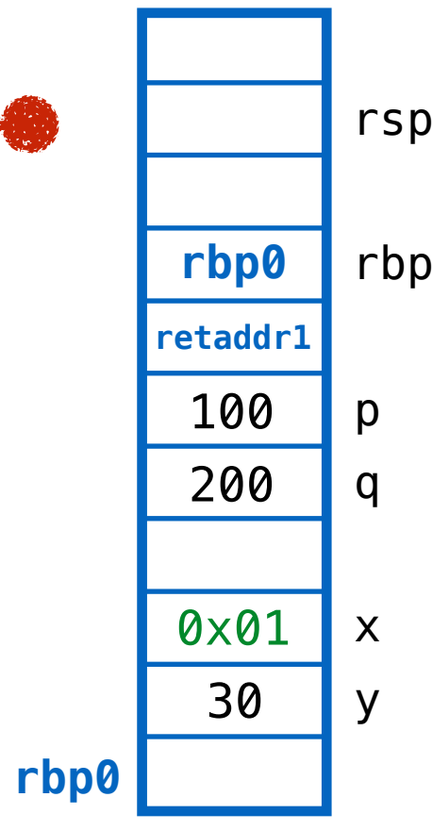


1. Compute FORWARD addrs
   e.g. `0x11` —> `0x01`
2. REDIRECT addrs on stack
3. COMPACT cells on heap

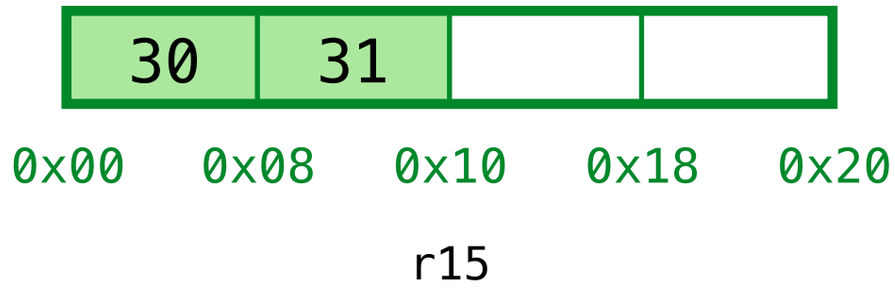
ex3: garbage in the middle (with stack)

```
def foo(p, q):
  let tmp = (p, q)
  in tmp[0] + tmp[1]

let y  = foo(10, 20)
  , x  = (y, y + 1)
  , z  = foo(100, 200)
in
  x[0] + z
```



Yay! Have space for `(p, q)`



ex3: garbage in the middle (with stack)

```
def foo(p, q):
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  , x  = (y, y + 1)
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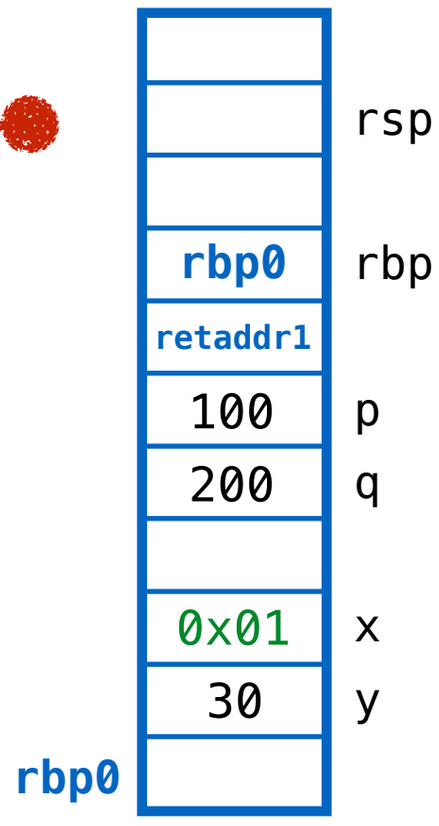
  x[0] + z
```



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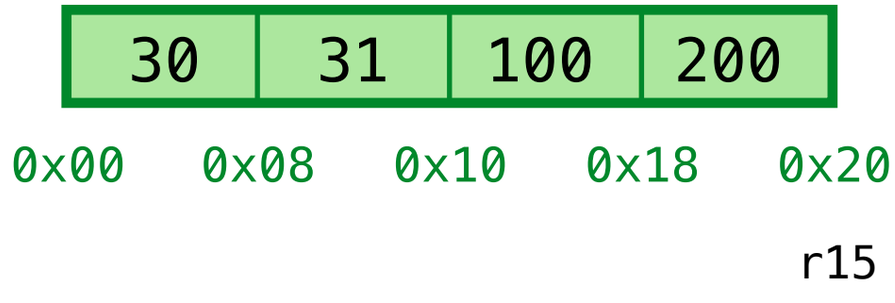

ex3: garbage in the middle (with stack)

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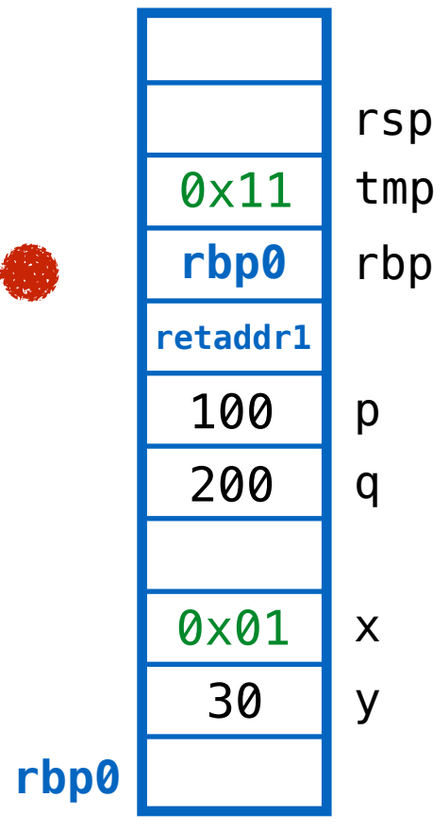
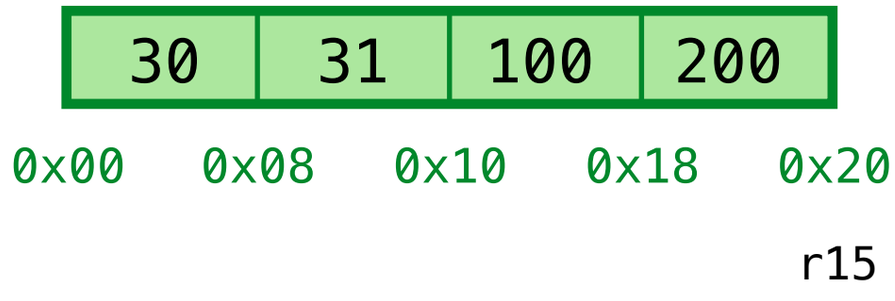


Return (rax) = 300



ex3: garbage in the middle (with stack)

```
def foo(p, q):
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  in tmp[0] + tmp[1]

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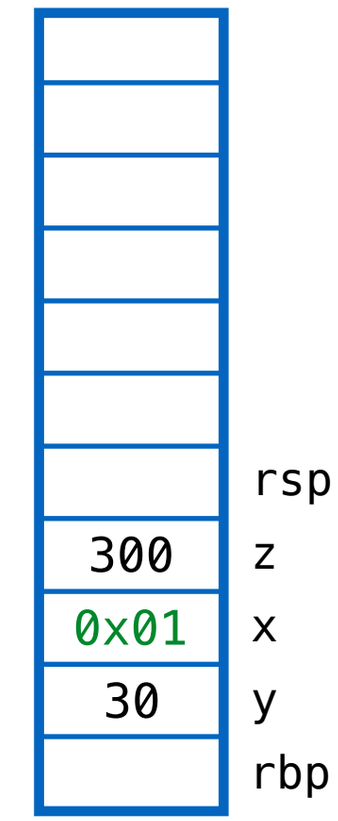
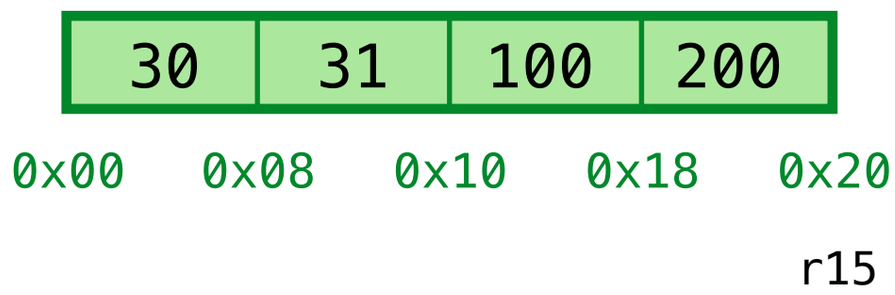
in
  x[0] + z
```



Return (rax) = 300



ex3: garbage in the middle (with stack)

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  , x  = (y, y + 1)
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  x[0] + z
```

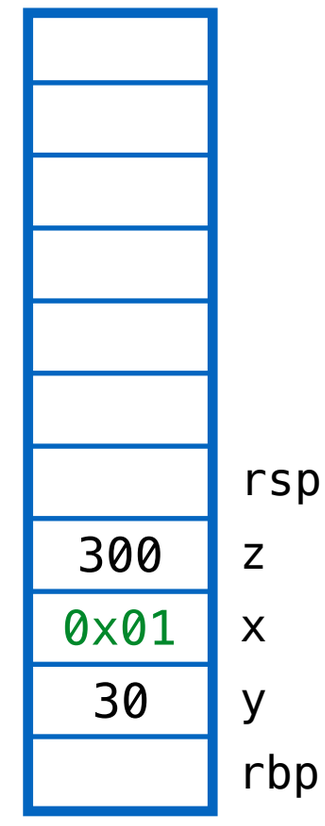

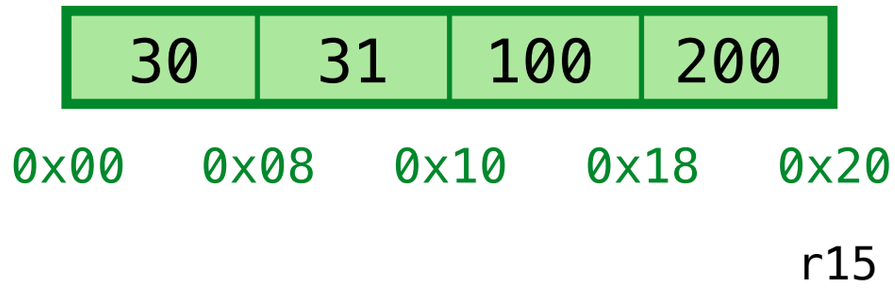

ex3: garbage in the middle (with stack)

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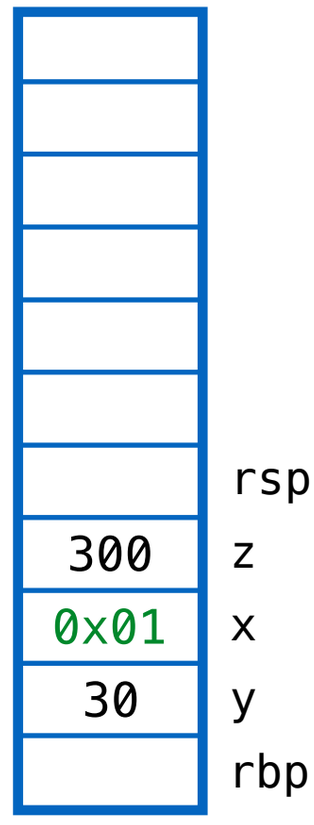
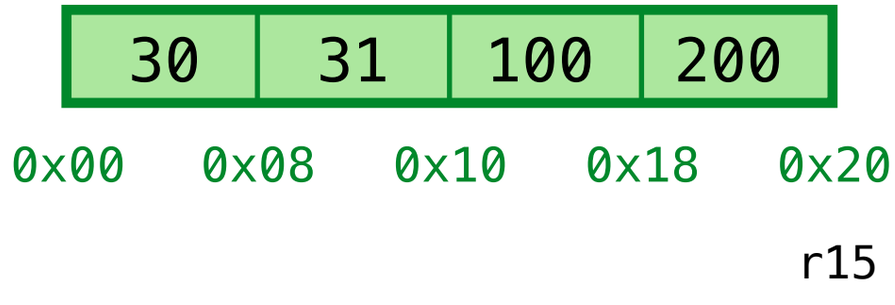
```



Return (rax) = 30+300 = 330



Garter / GC

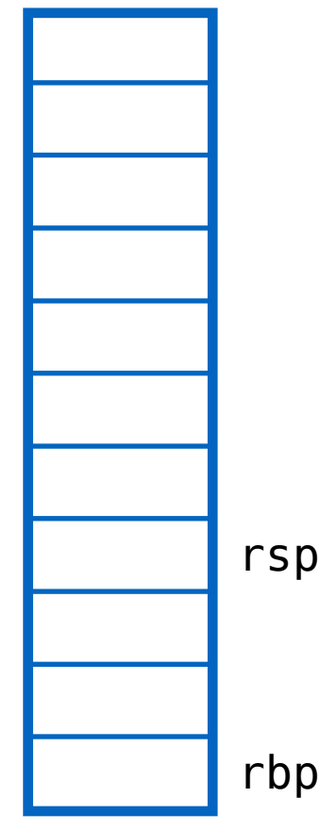
Example 4

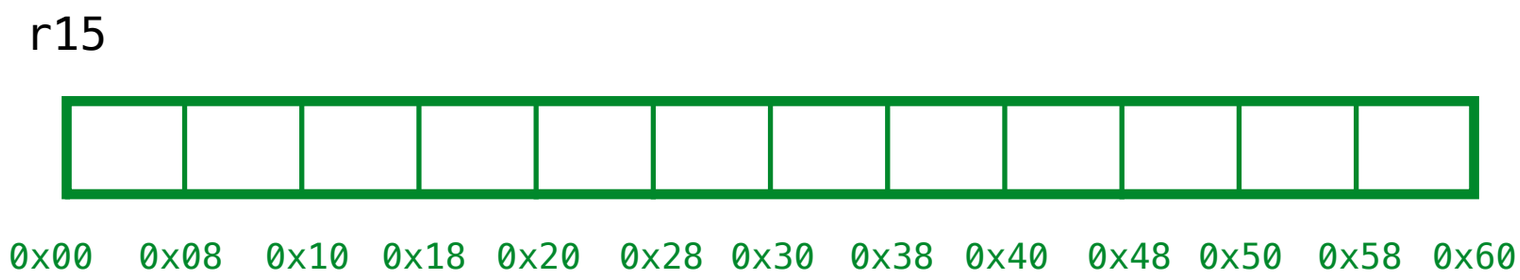
ex4: recursive data

```
def range(i, j):
  if (j <= i): false else: (i,range(i+1, j))

def sum(l):
  if l == false: 0 else: l[0] + sum(l[1])

let t1 = let l1 = range(0, 3)
         in sum(l1)
  , l  = range(t1, t1 + 3)
in
  (1000, l)
```





ex4: recursive data

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  , l  = range(t1, t1 + 3)
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```
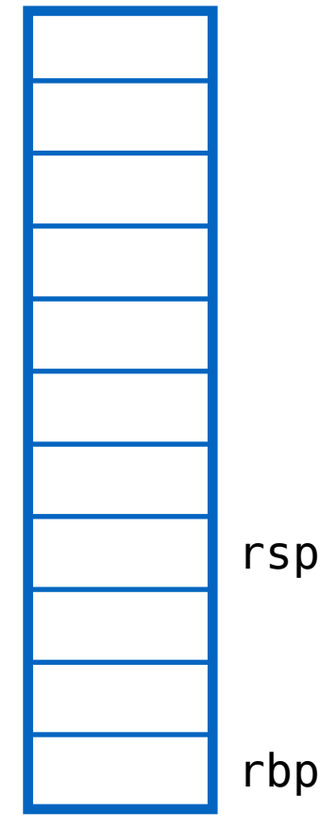
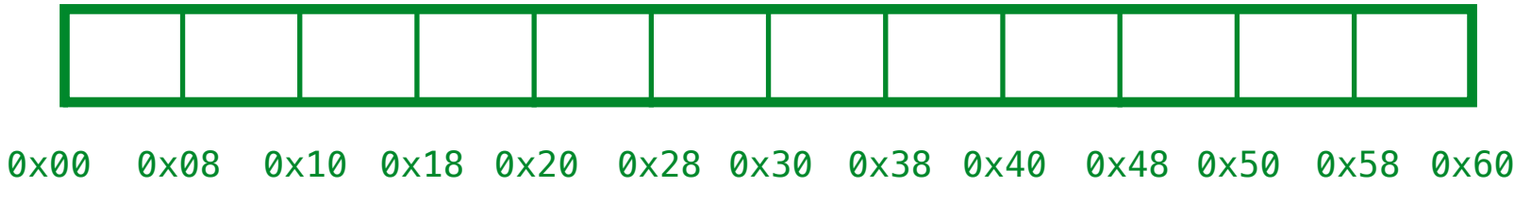



call range(0, 3)

r15



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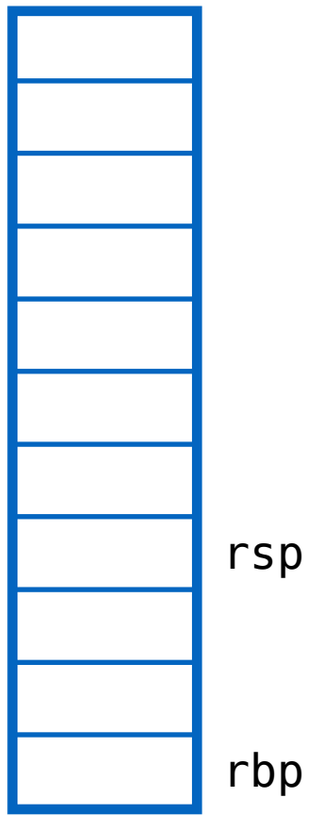
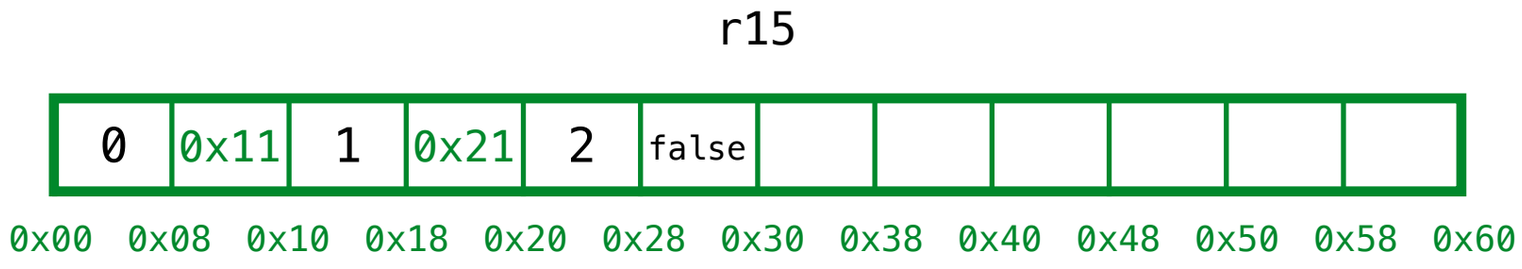
```

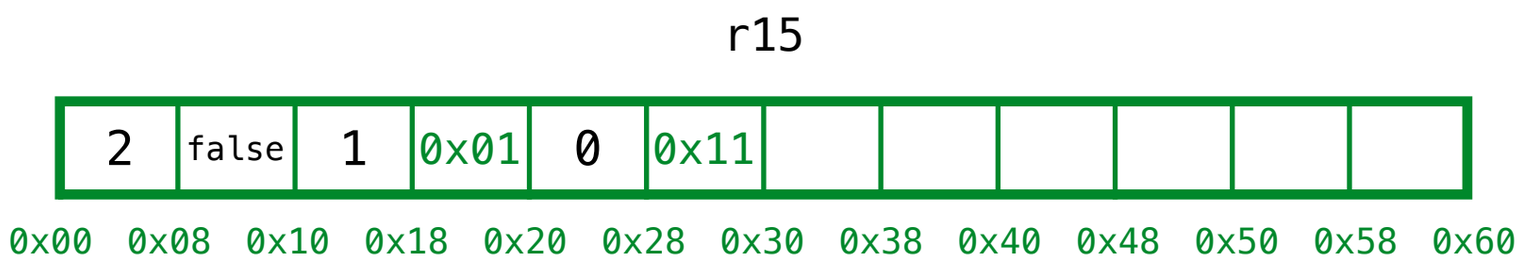


QUIZ: What is heap when `range(0,3)` returns?

(A)



(B)



ex4: recursive data

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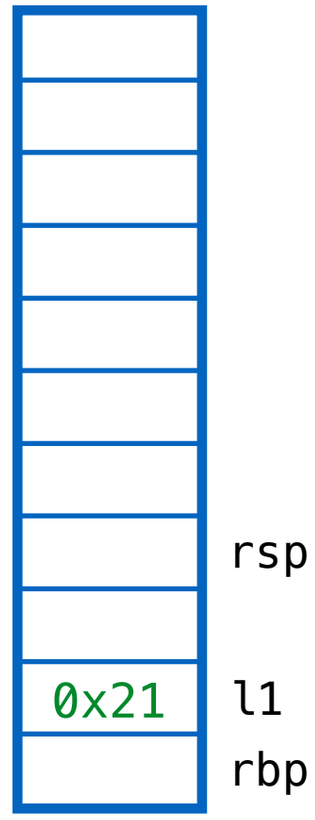

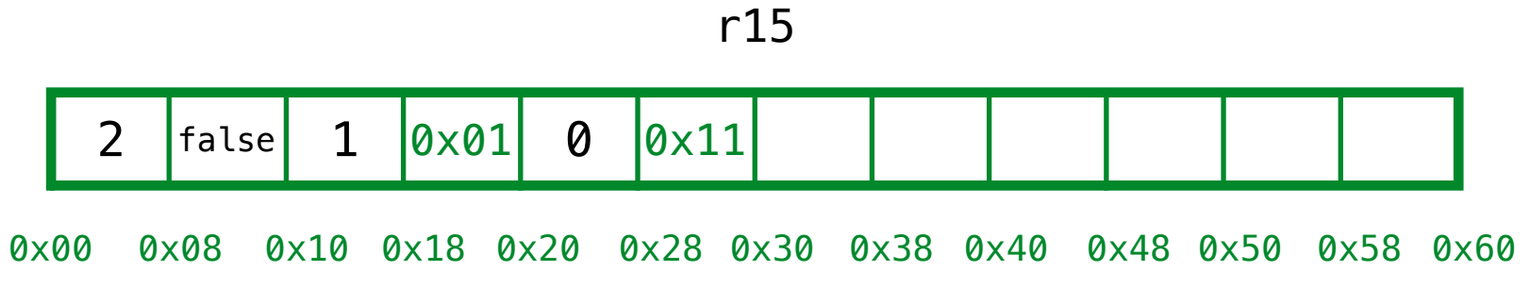

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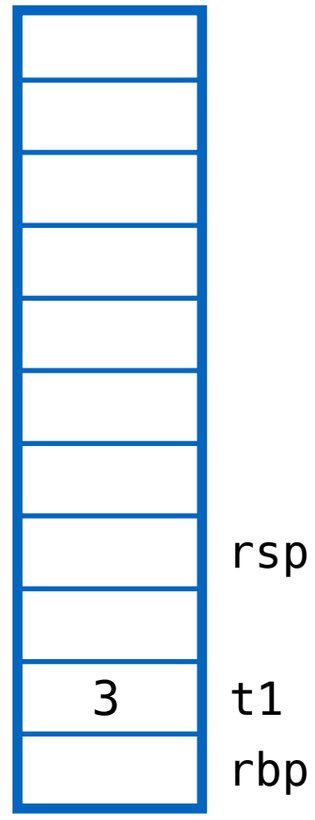
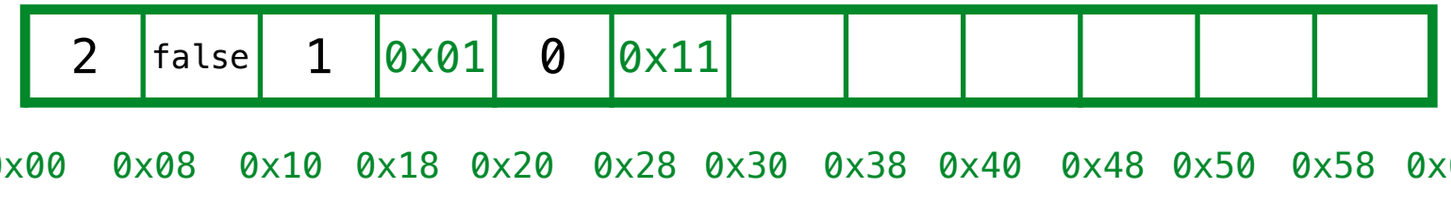


Result sum(0x11) = 3

r15



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```

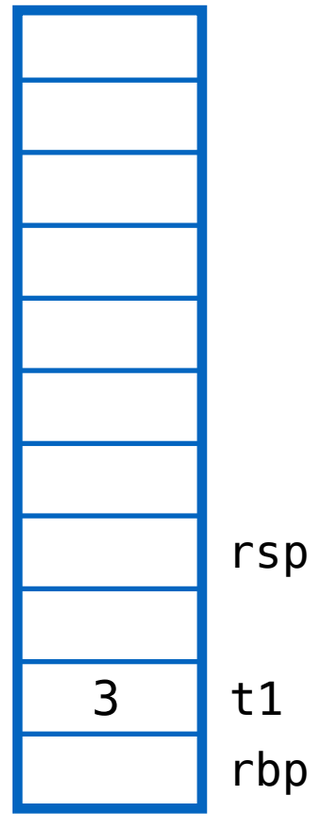

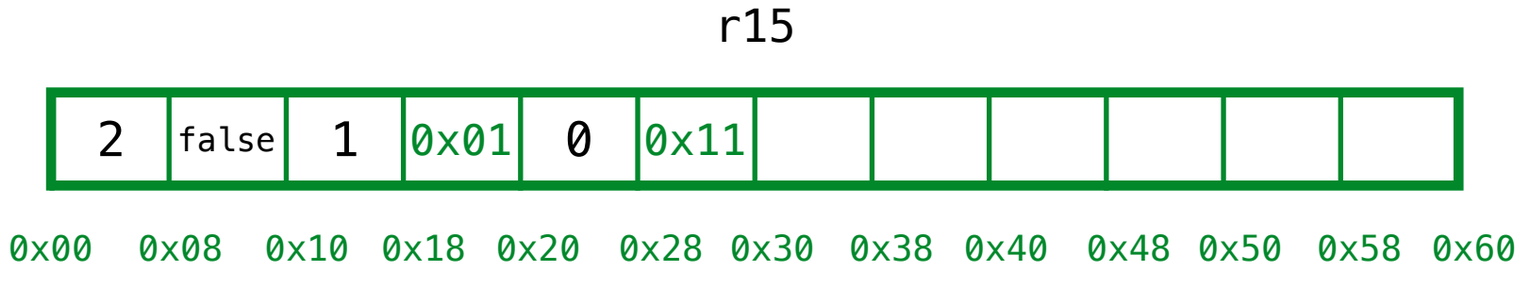

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  , l  = range(t1, t1 + 3)
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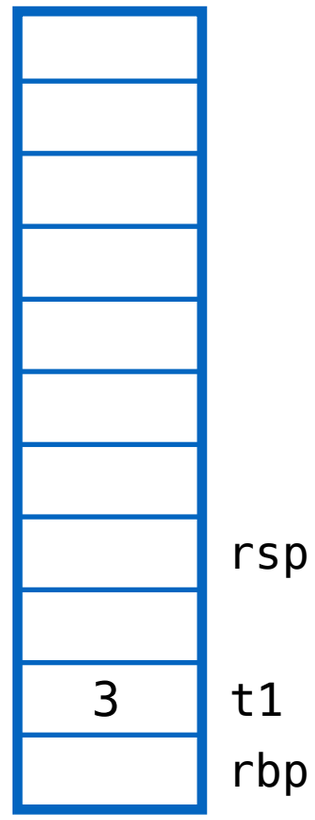
  (1000, l)
```



call range(3,6)

r15

0x00 0x08 0x10 0x18 0x20 0x28 0x30 0x38 0x40 0x48 0x50 0x58 0x60

ex4: recursive data

```
def range(i, j):
  if (j <= i): false else: (i,range(i+1, j))

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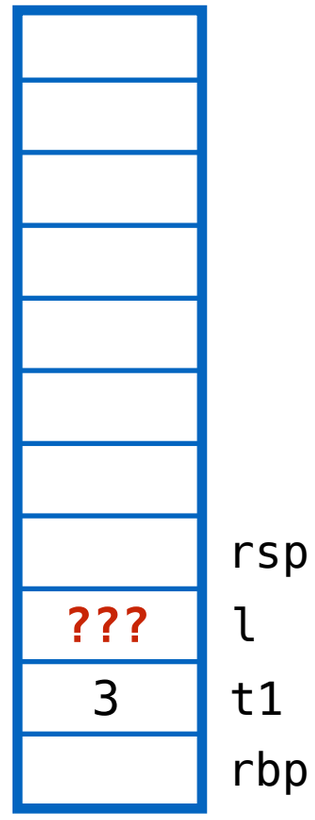
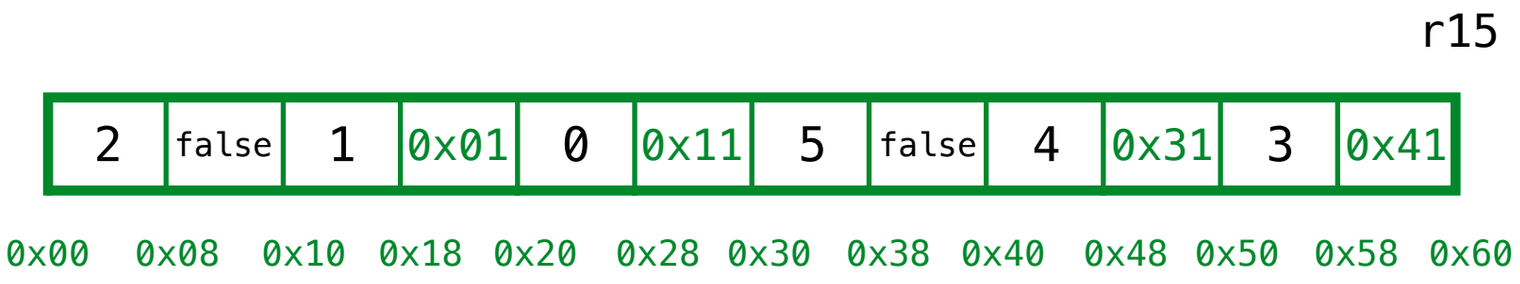
          let l1 = range(0, 3)
          in sum(l1)
  , l  = range(t1, t1 + 3)
in
  (1000, l)
```



call range(3,6)



QUIZ: What is the value of **l**?

(A) 0x30 (B) 0x31 (C) 0x50 (D) 0x51 (E) 0x60

ex4: recursive data

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def range(i, j):
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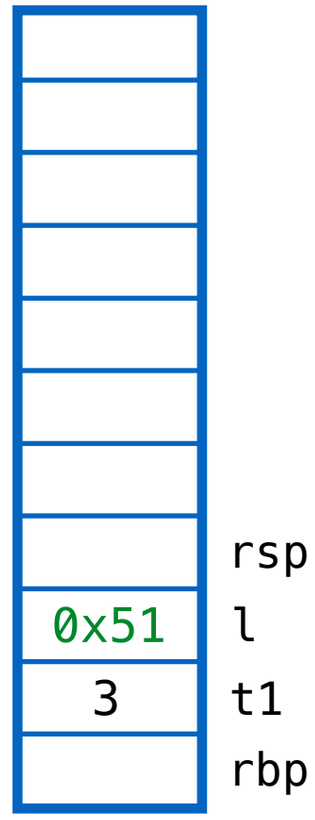
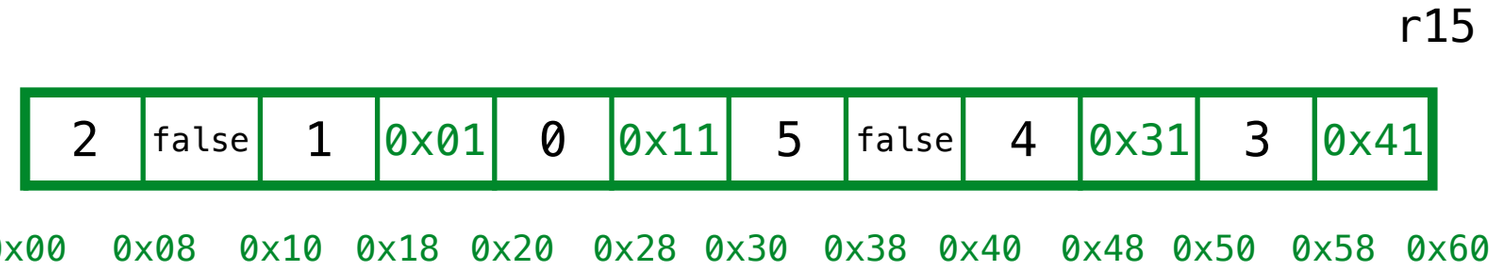


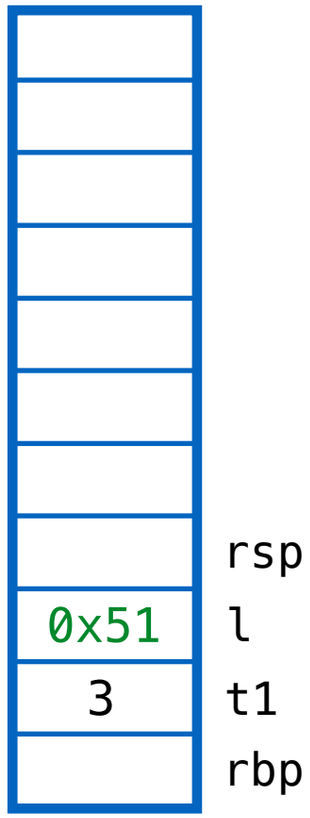
Yikes! Out of Memory!

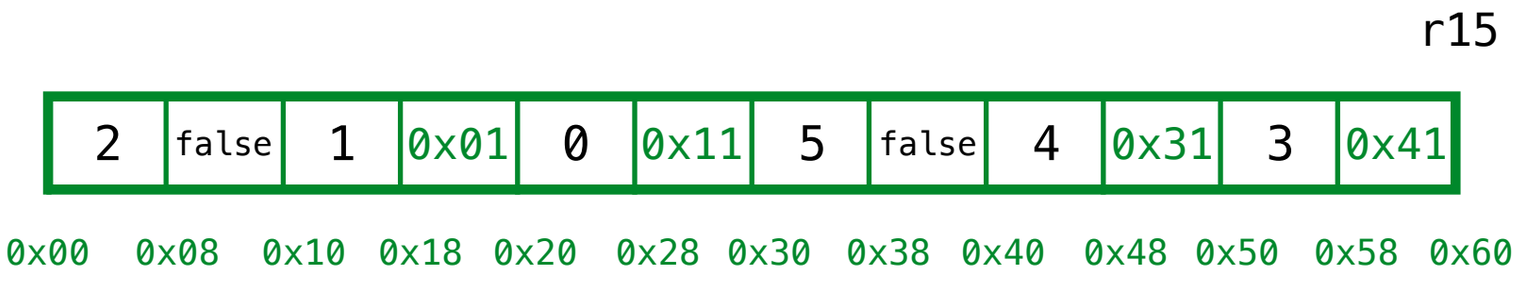


ex4: recursive data

QUIZ: Which cells are "live" on the heap?

(A) 0x00
(B) 0x10
(C) 0x20
(D) 0x30
(E) 0x40
(F) 0x50





ex4: recursive data

```
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          let l1 = range(0, 3)
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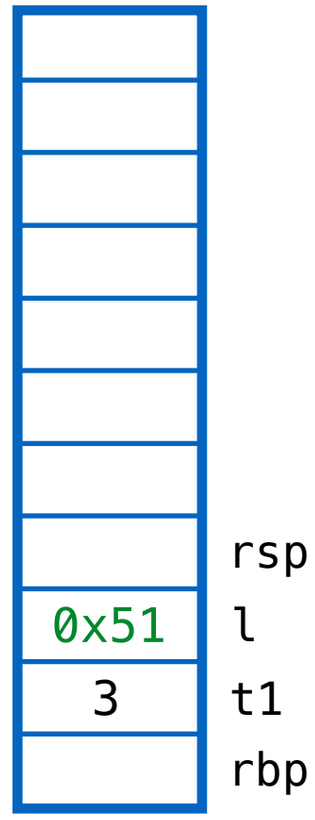
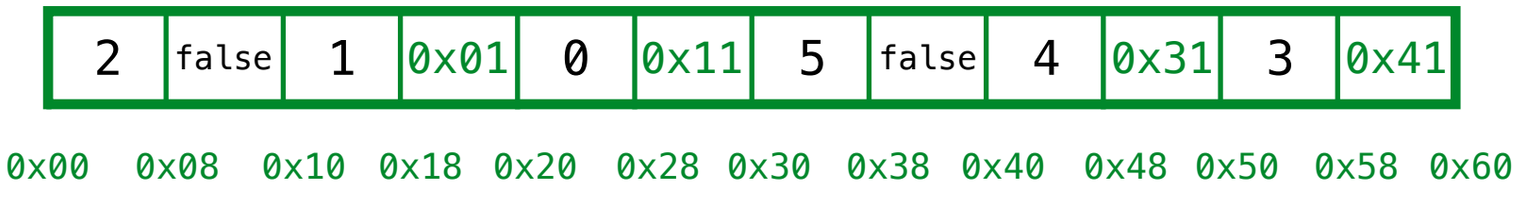
in
  (1000, l)
```



r15



1. MARK live addrs
2. Compute FORWARD addrs
3. REDIRECT addrs on stack
4. COMPACT cells on heap

ex4: recursive data

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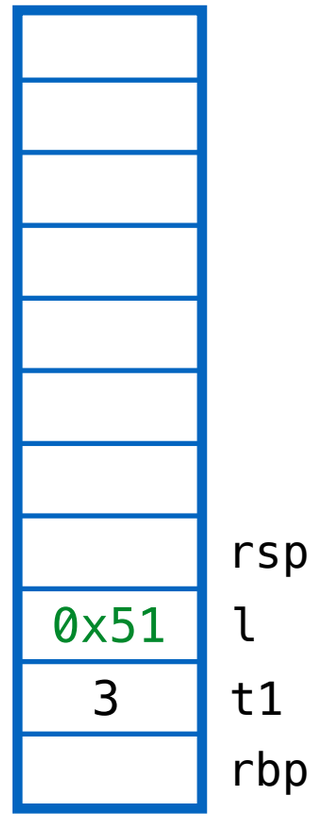
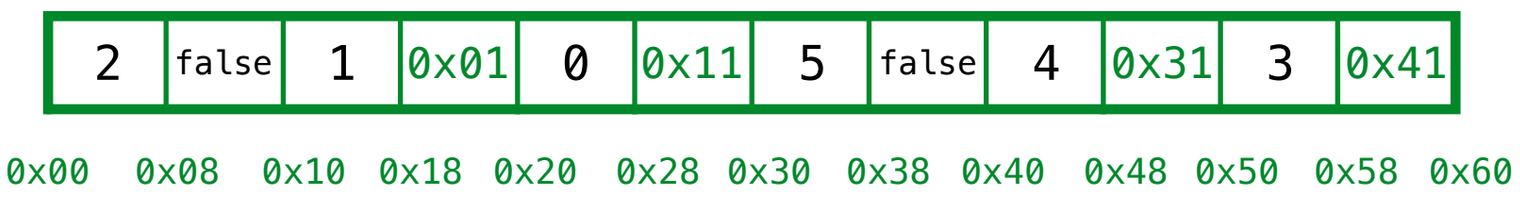


r15



1. MARK live addrs

reachable from stack

ex4: recursive data

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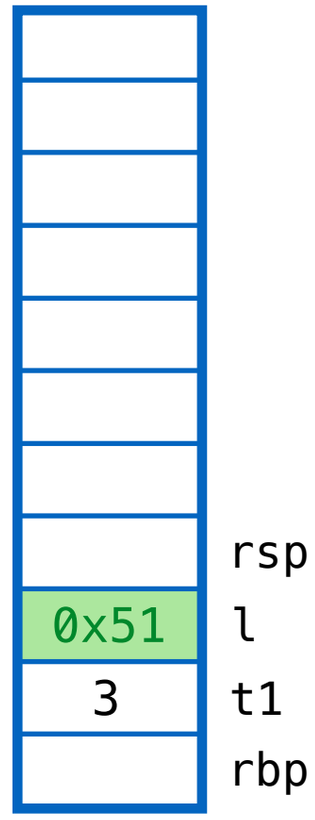
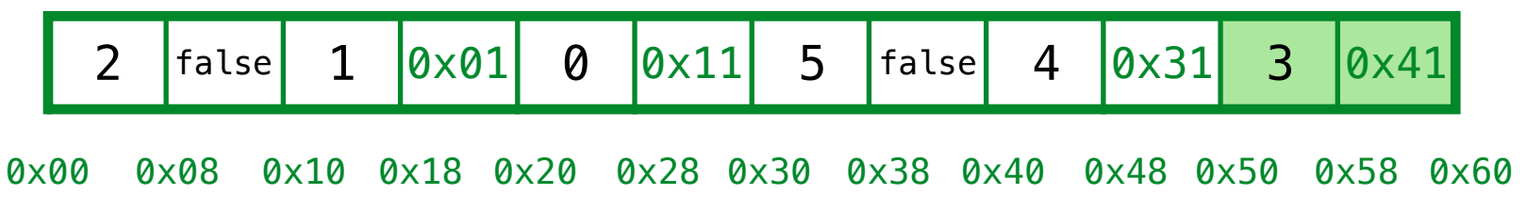


r15



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```

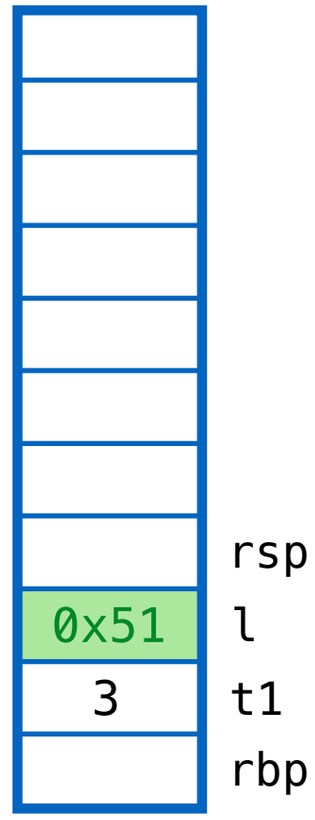

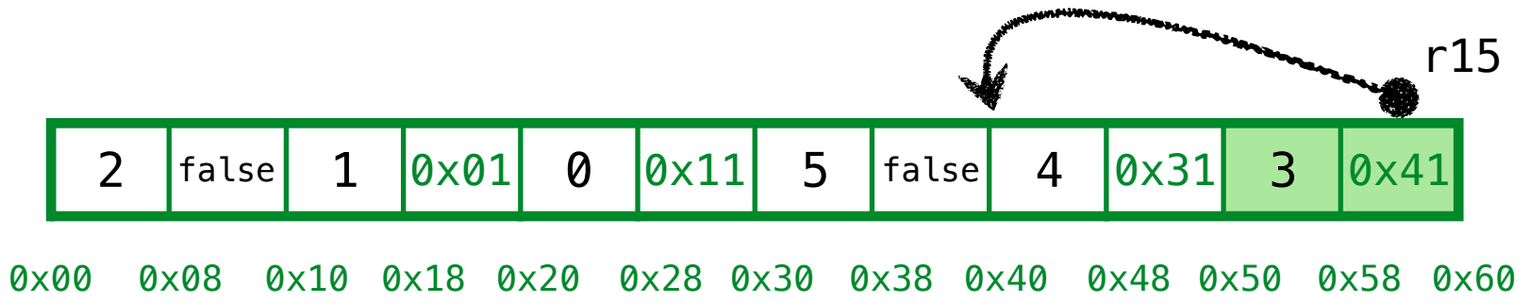

1. MARK live addrs

reachable from stack

ex4: recursive data

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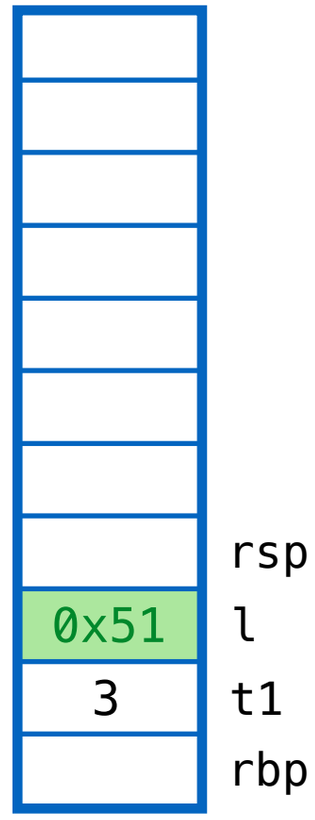

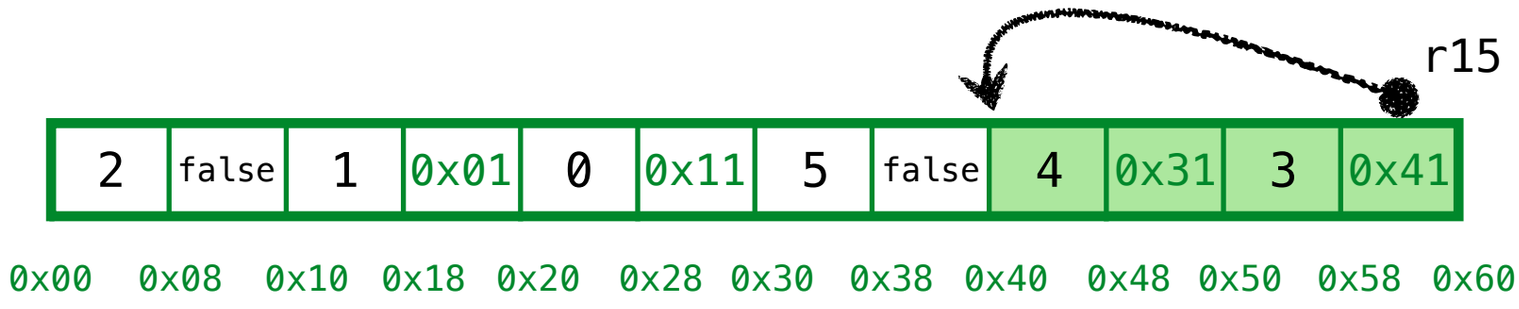

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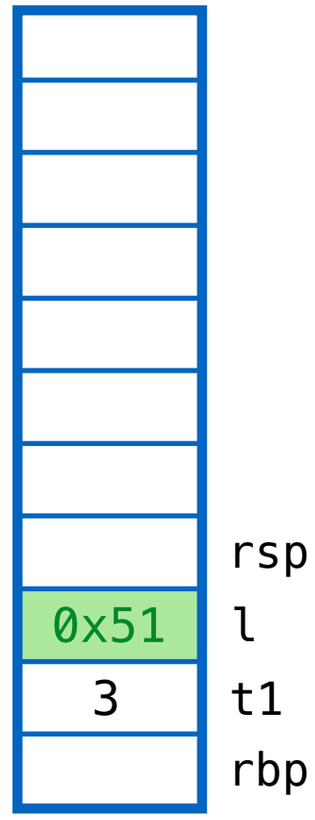

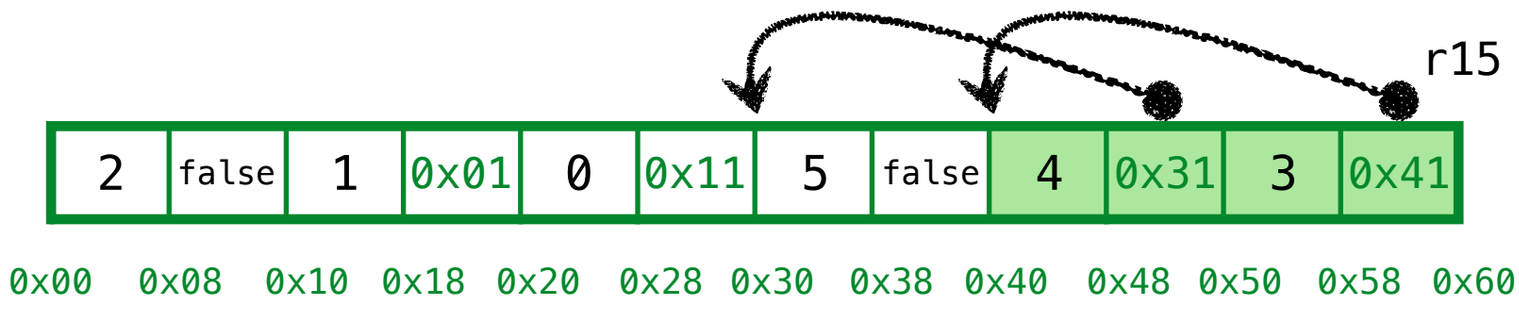

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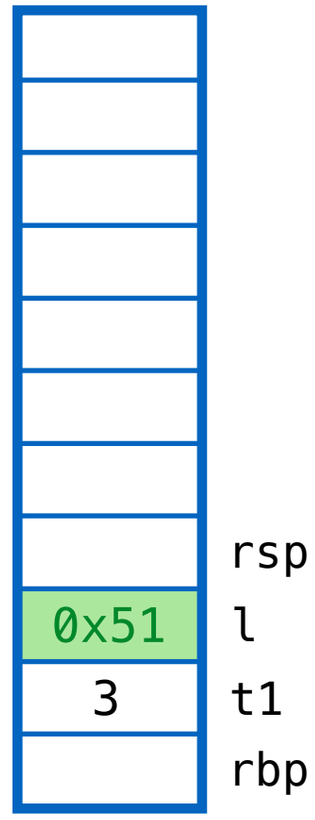

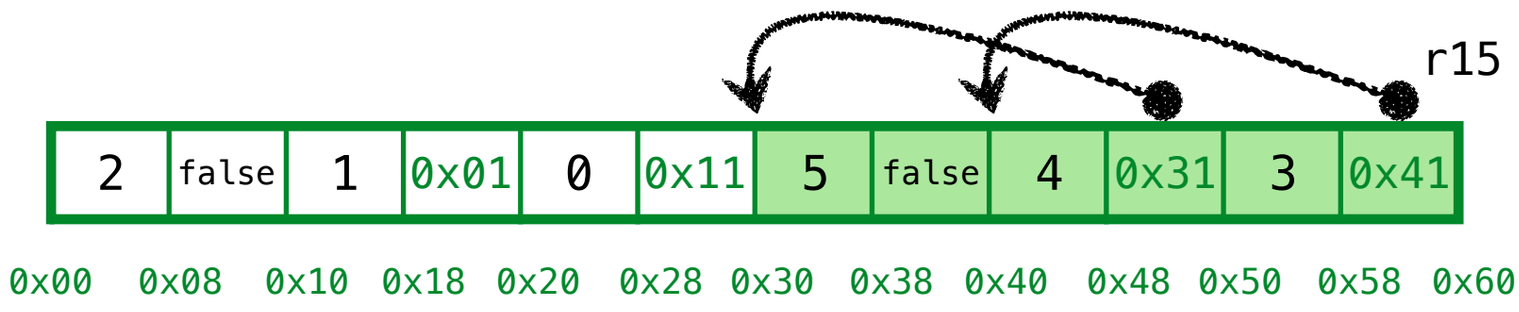

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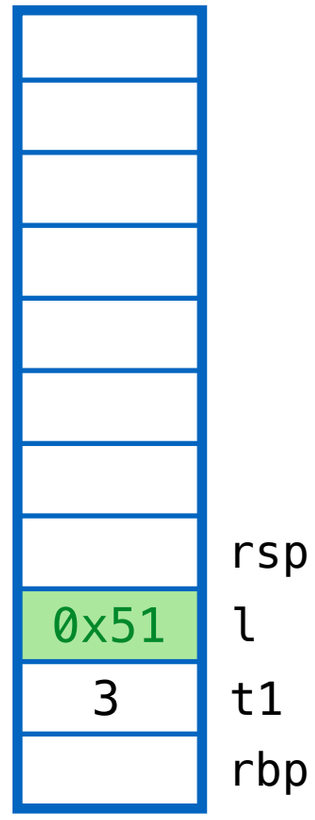

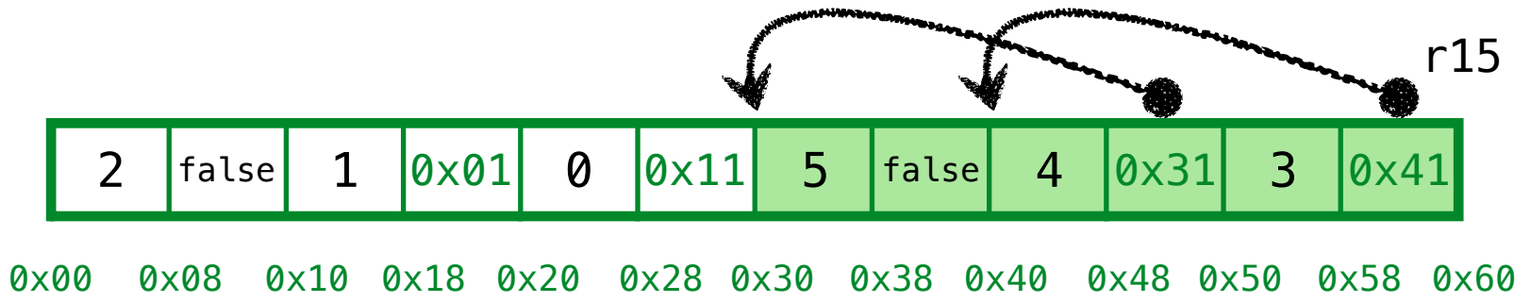

Done!

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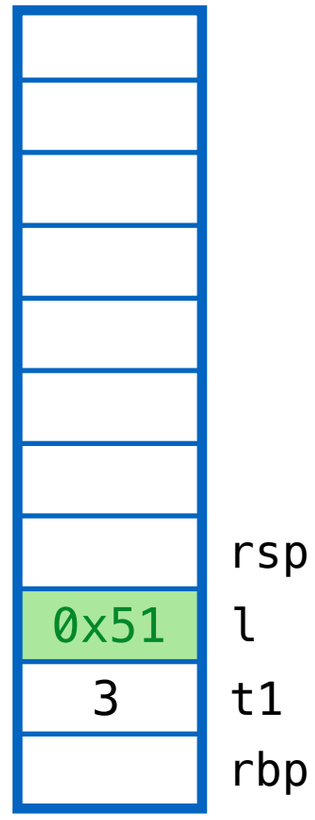

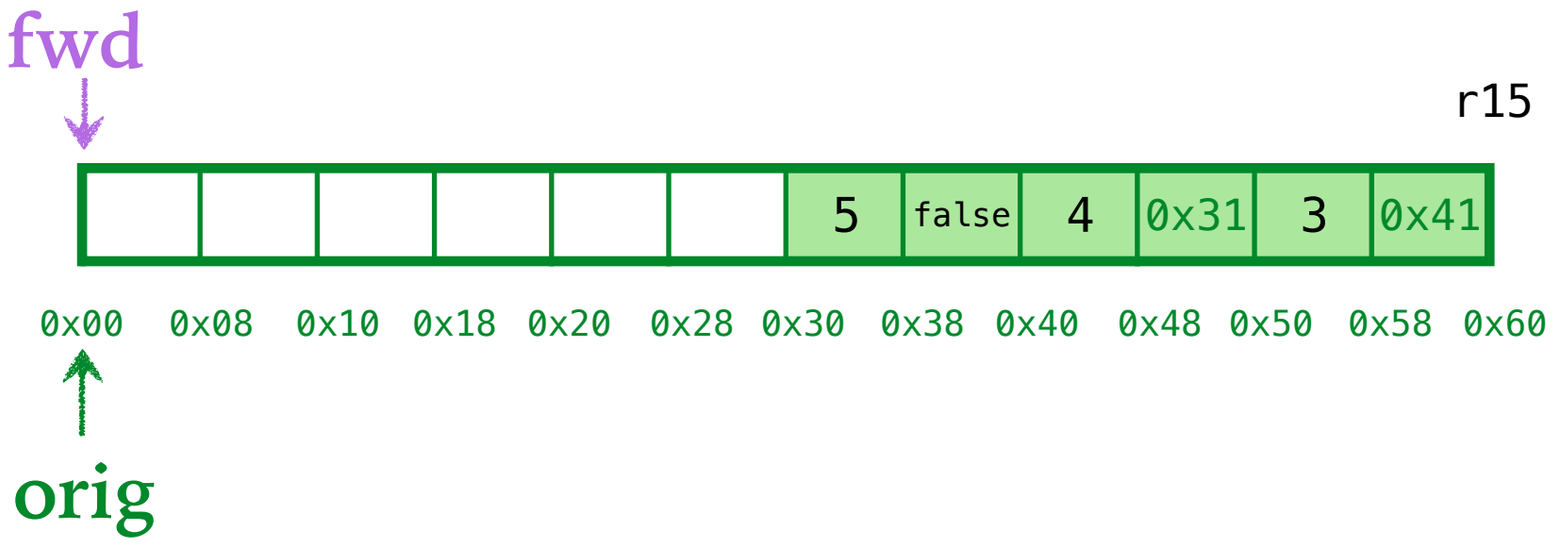

2. Compute FORWARD addrs

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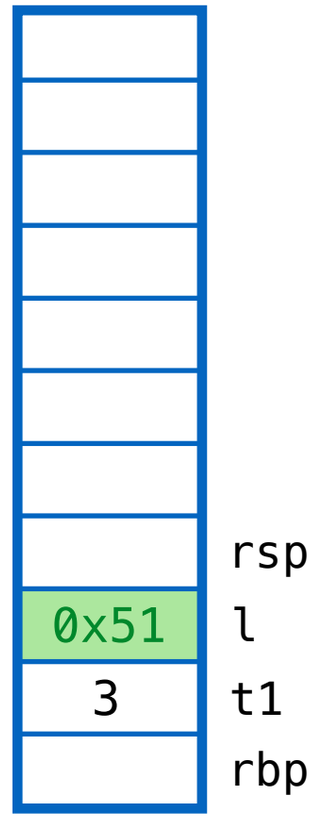

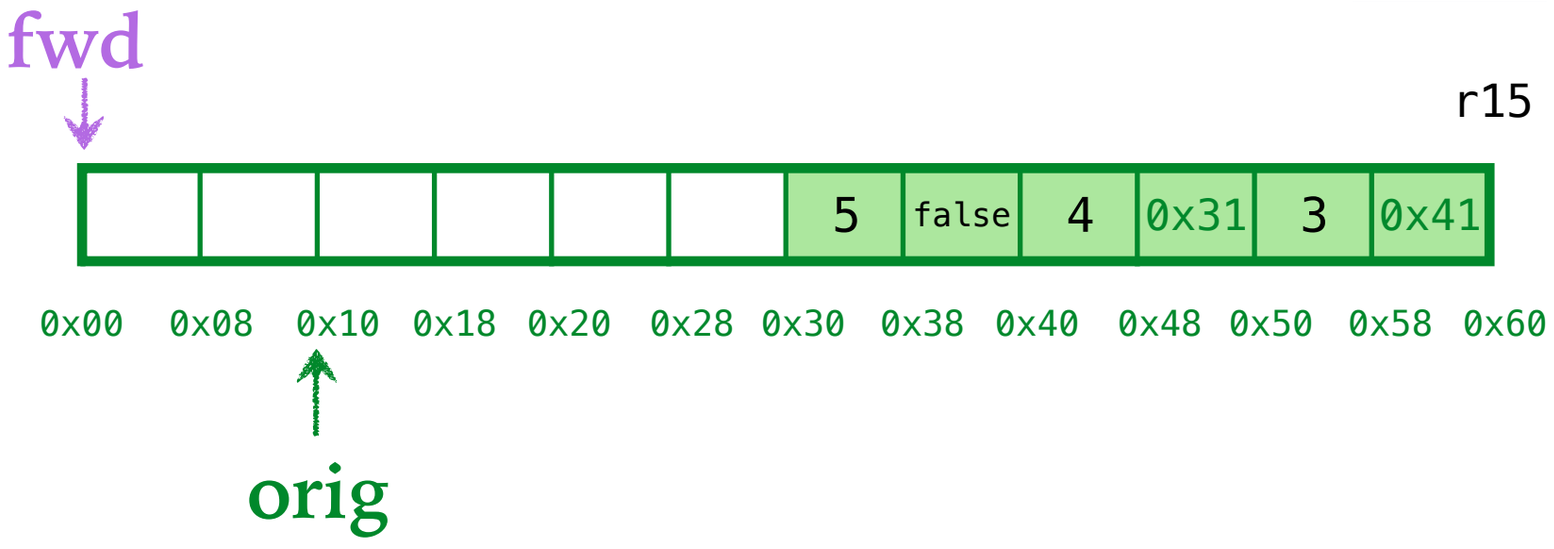

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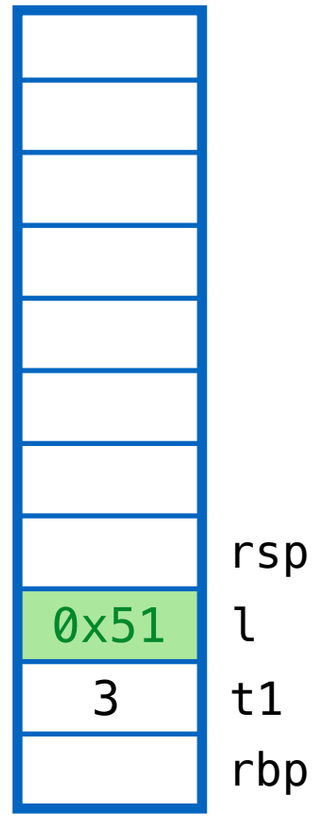

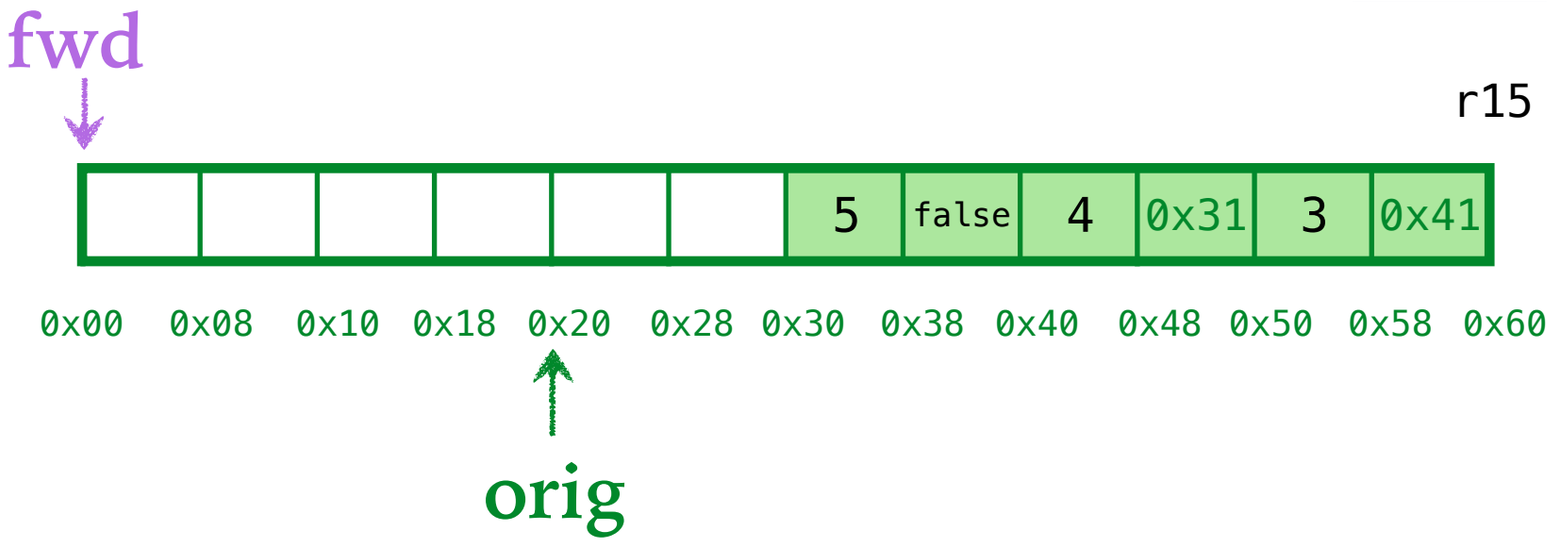

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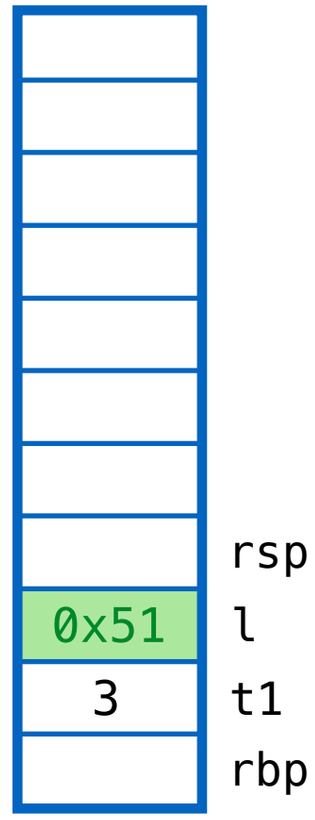

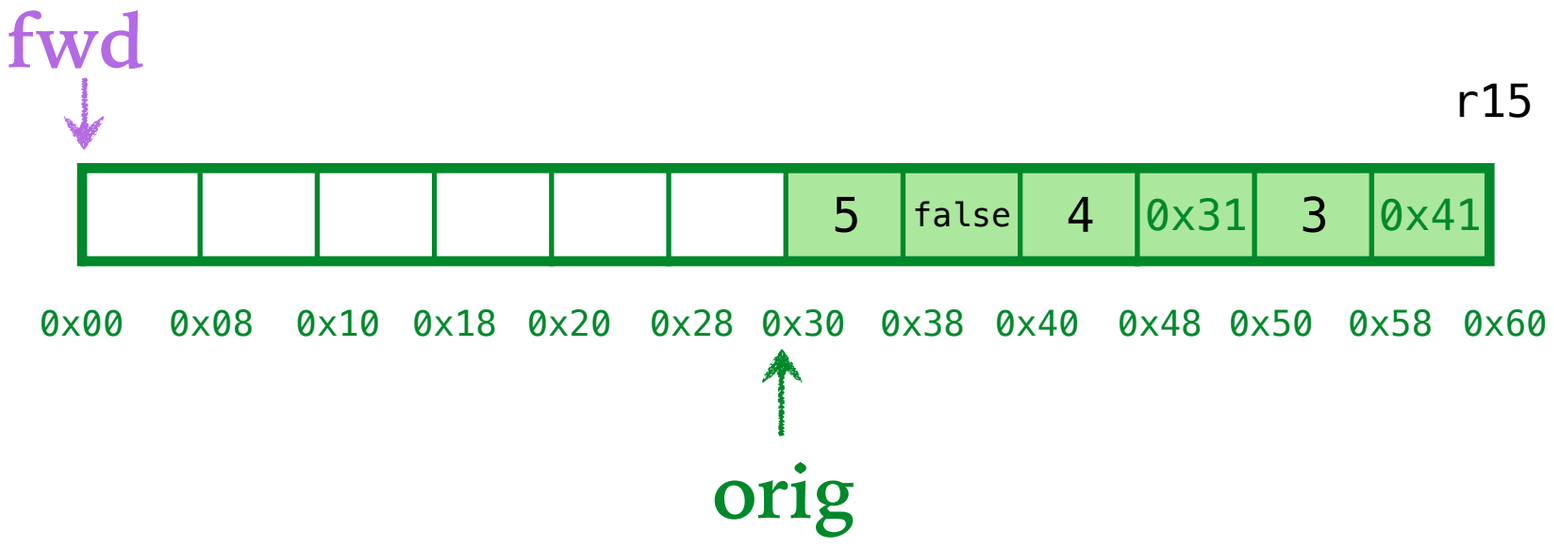

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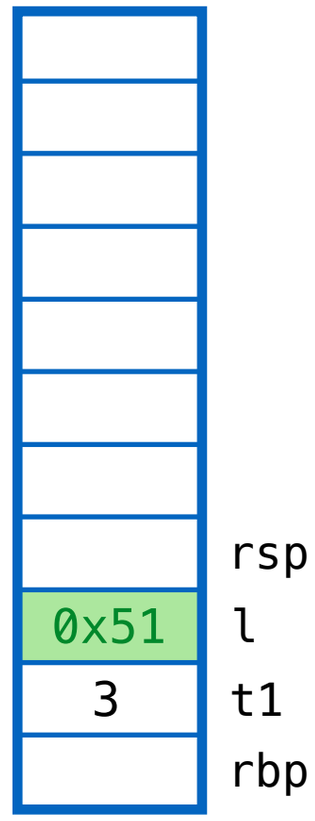

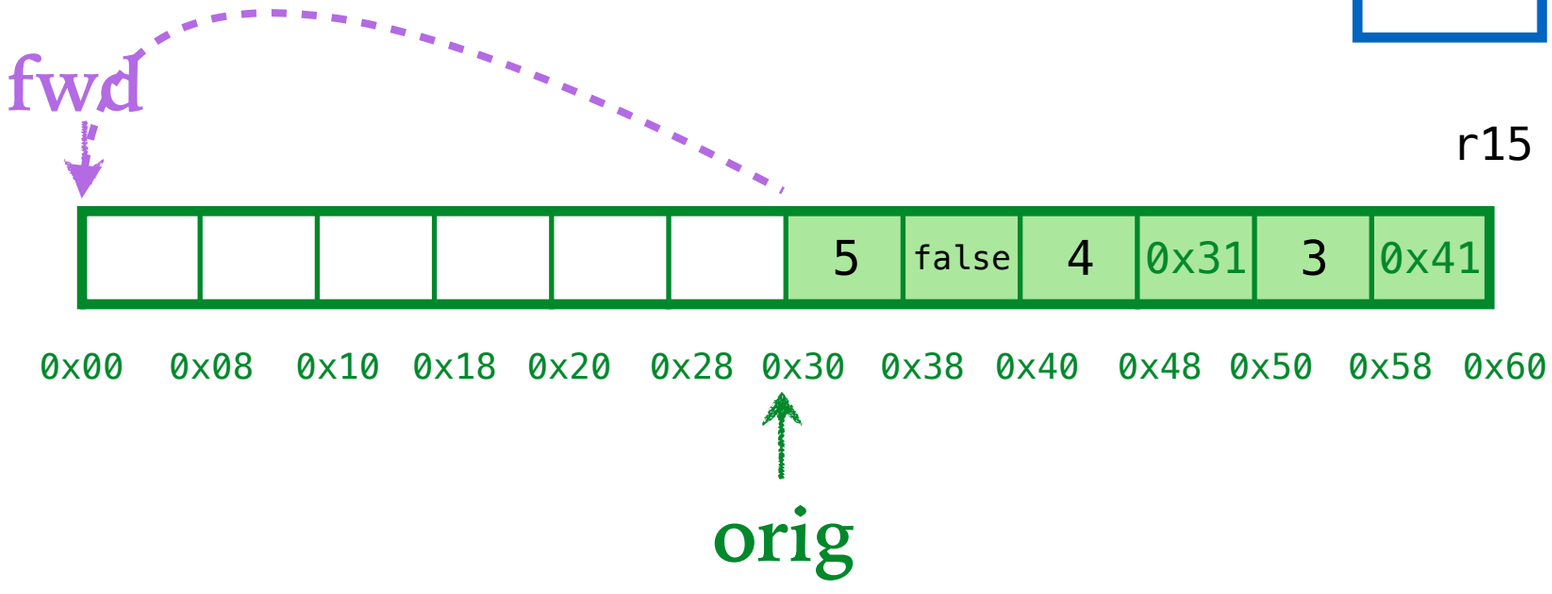

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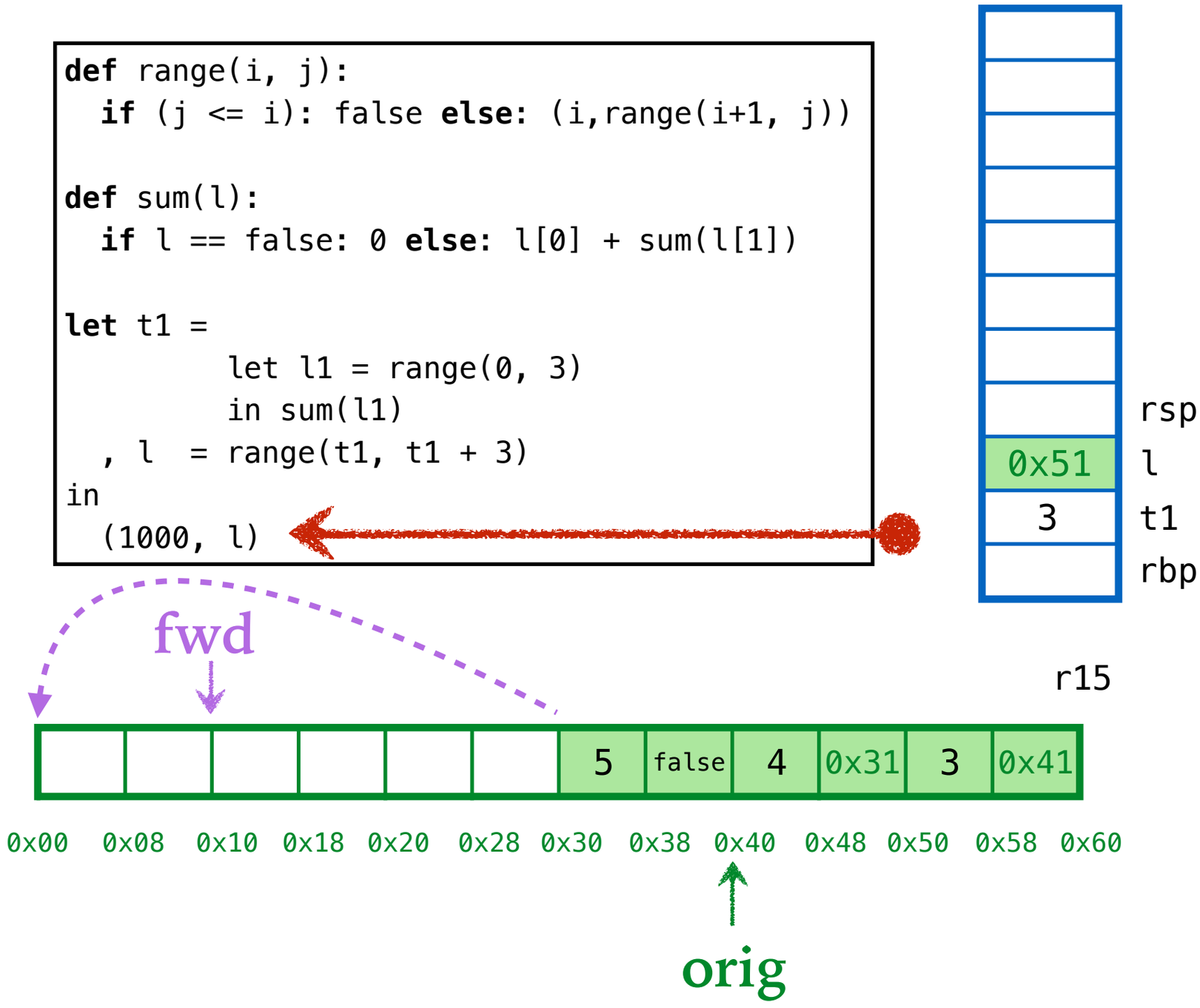

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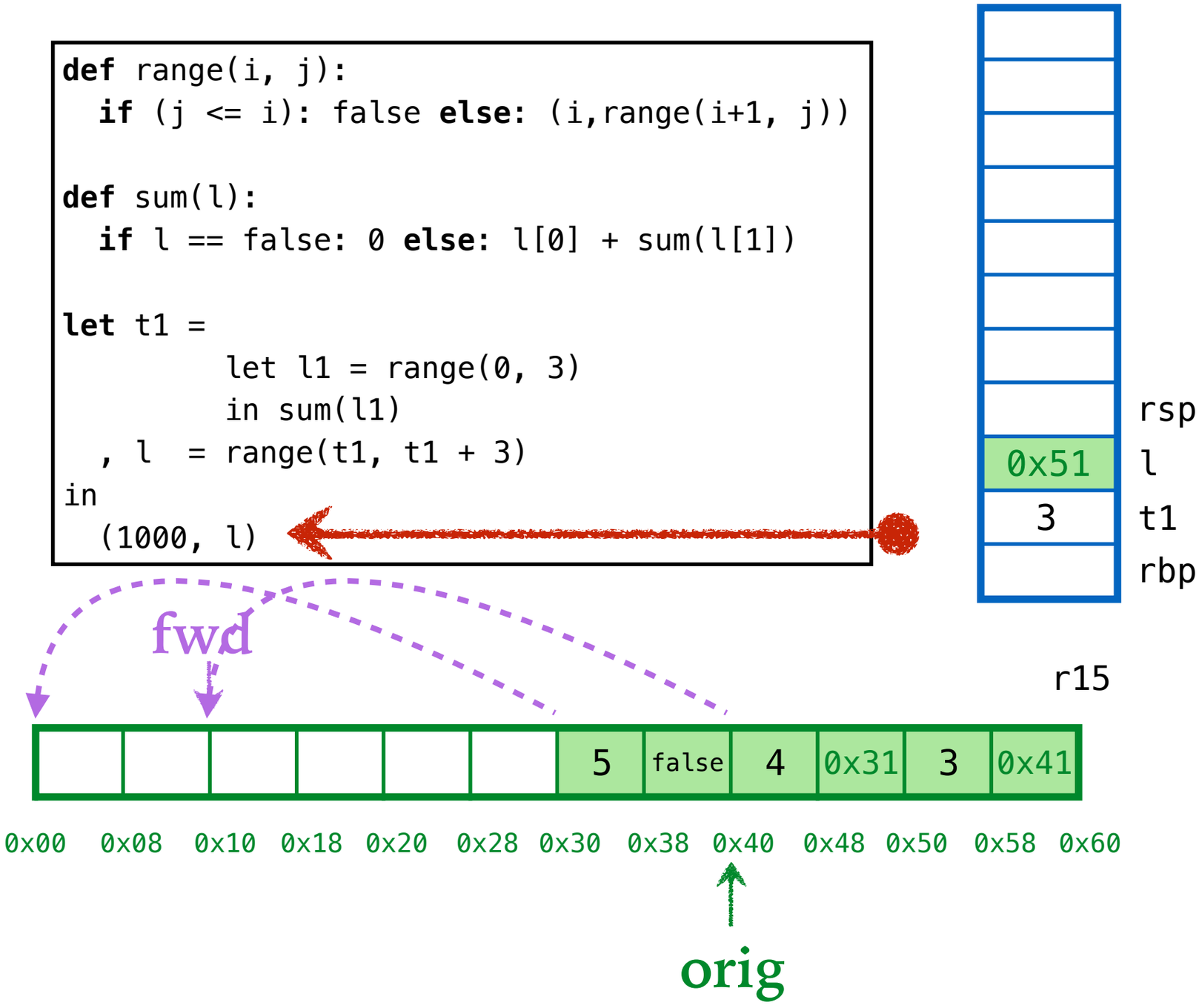

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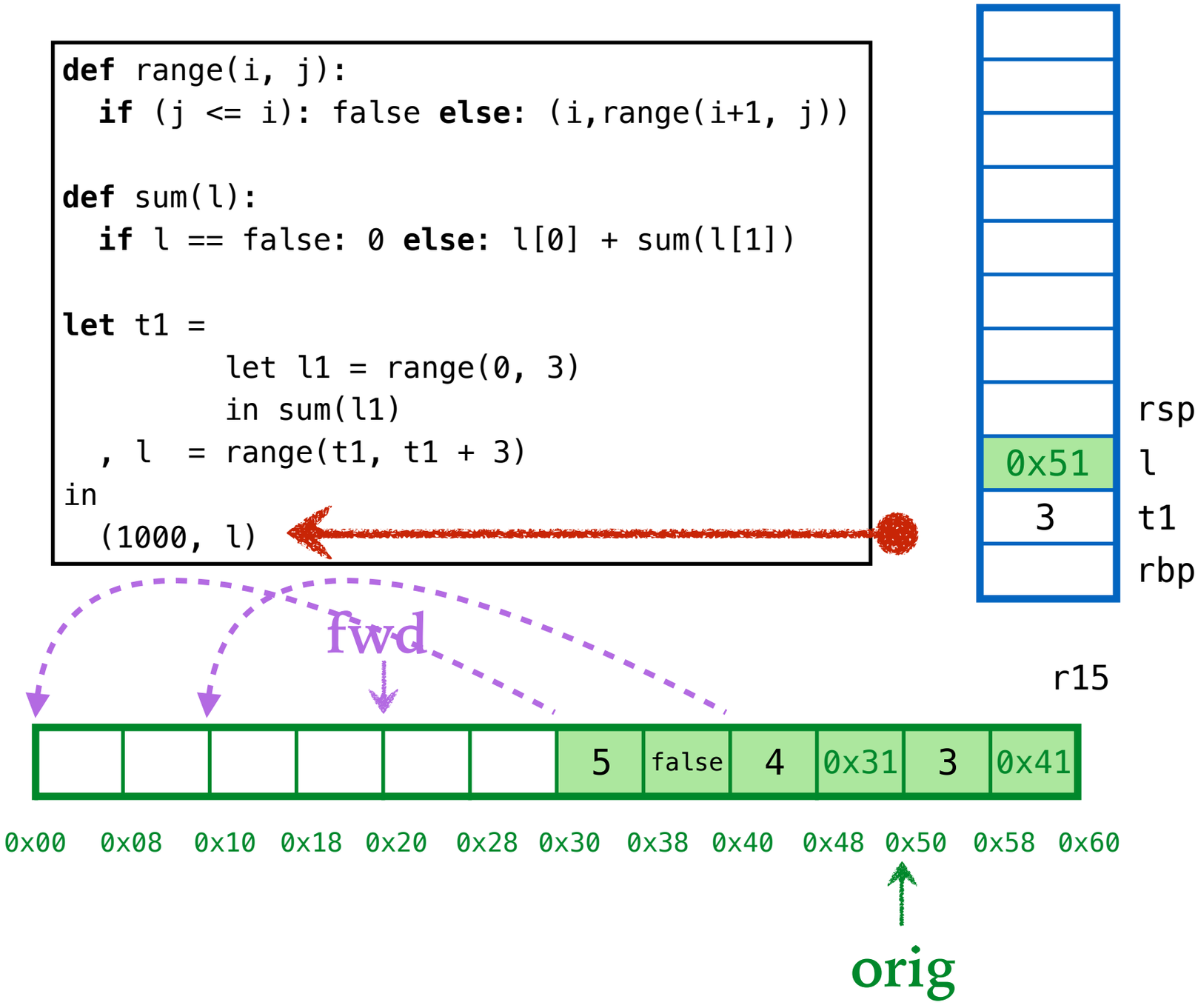

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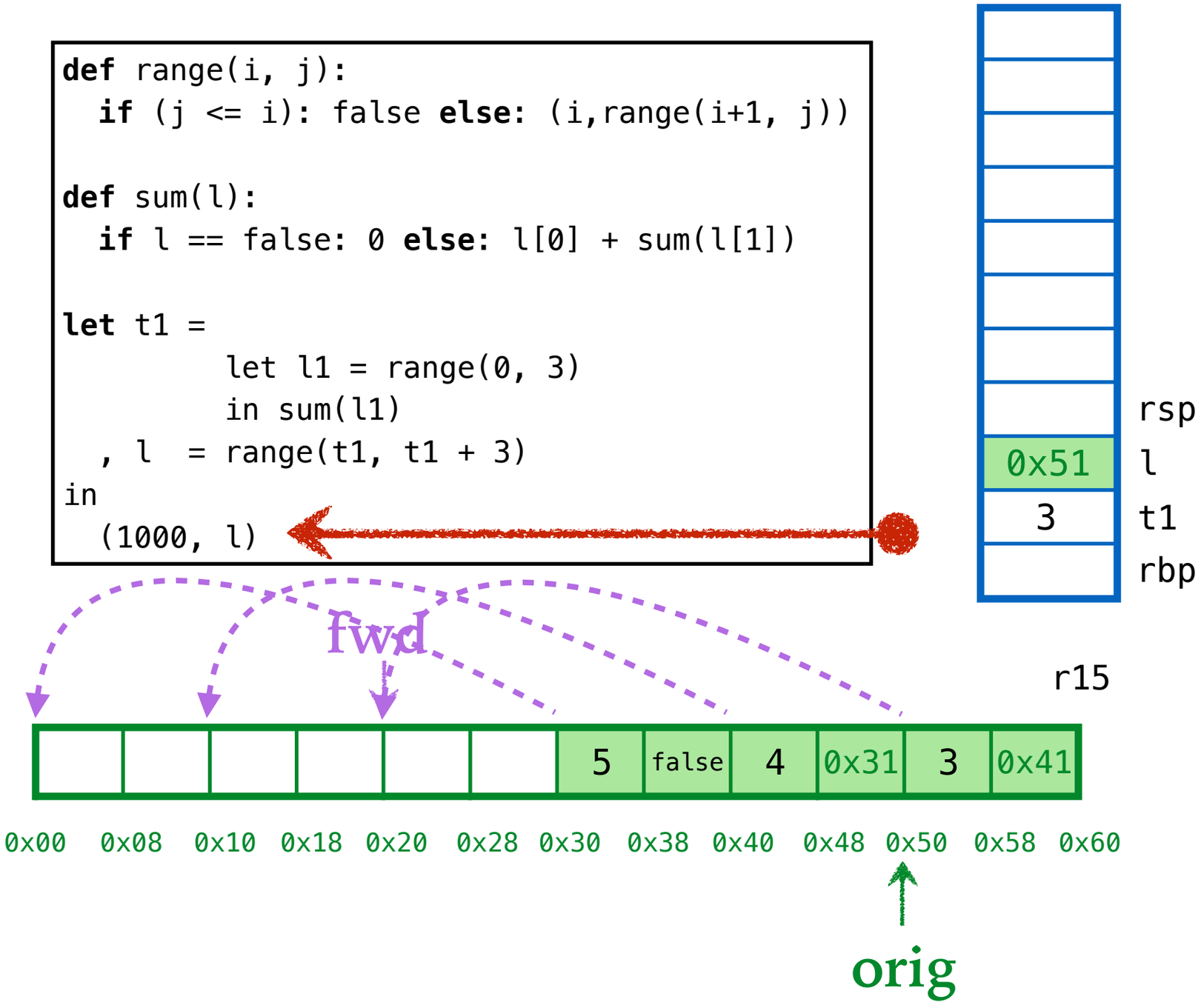

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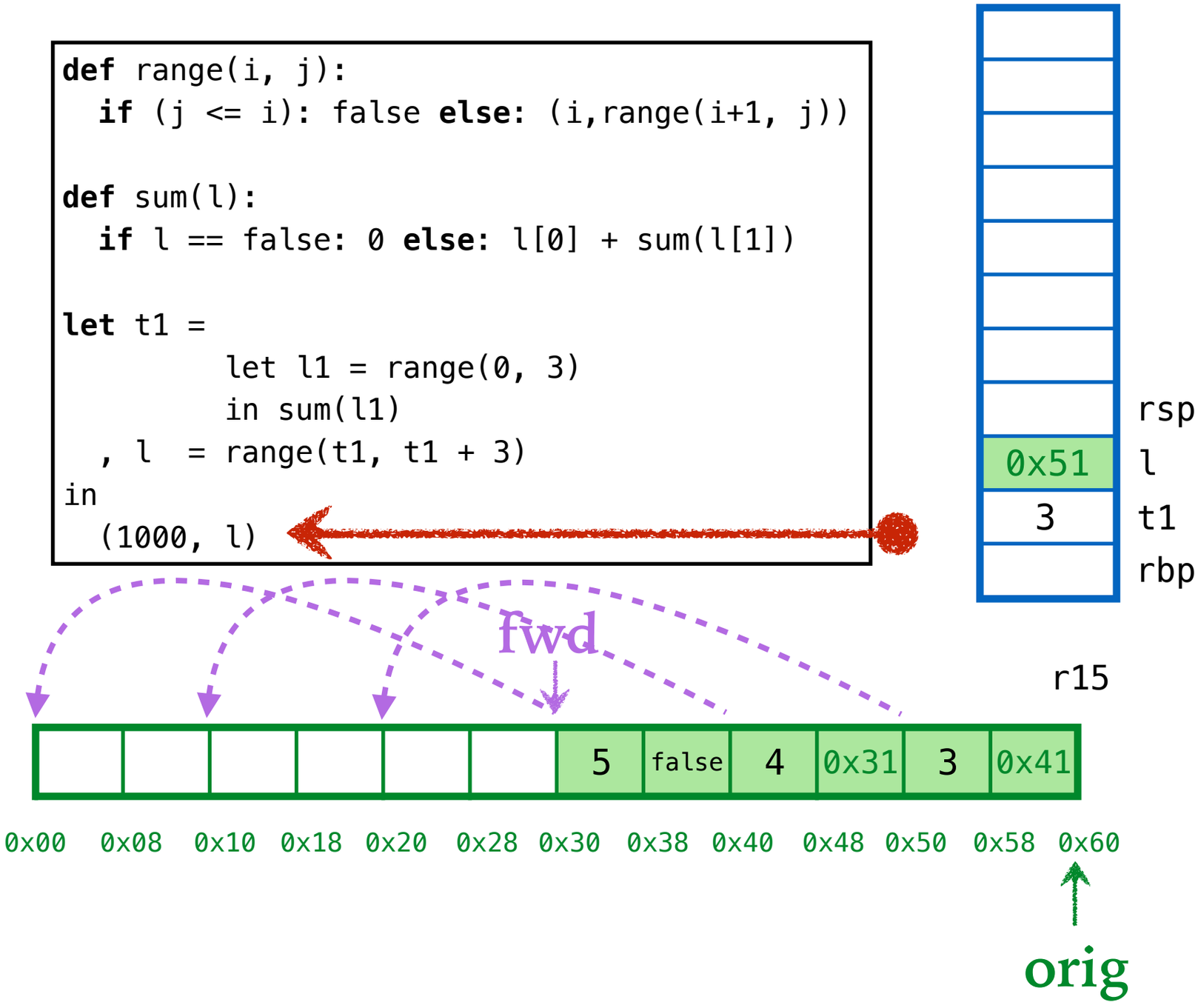

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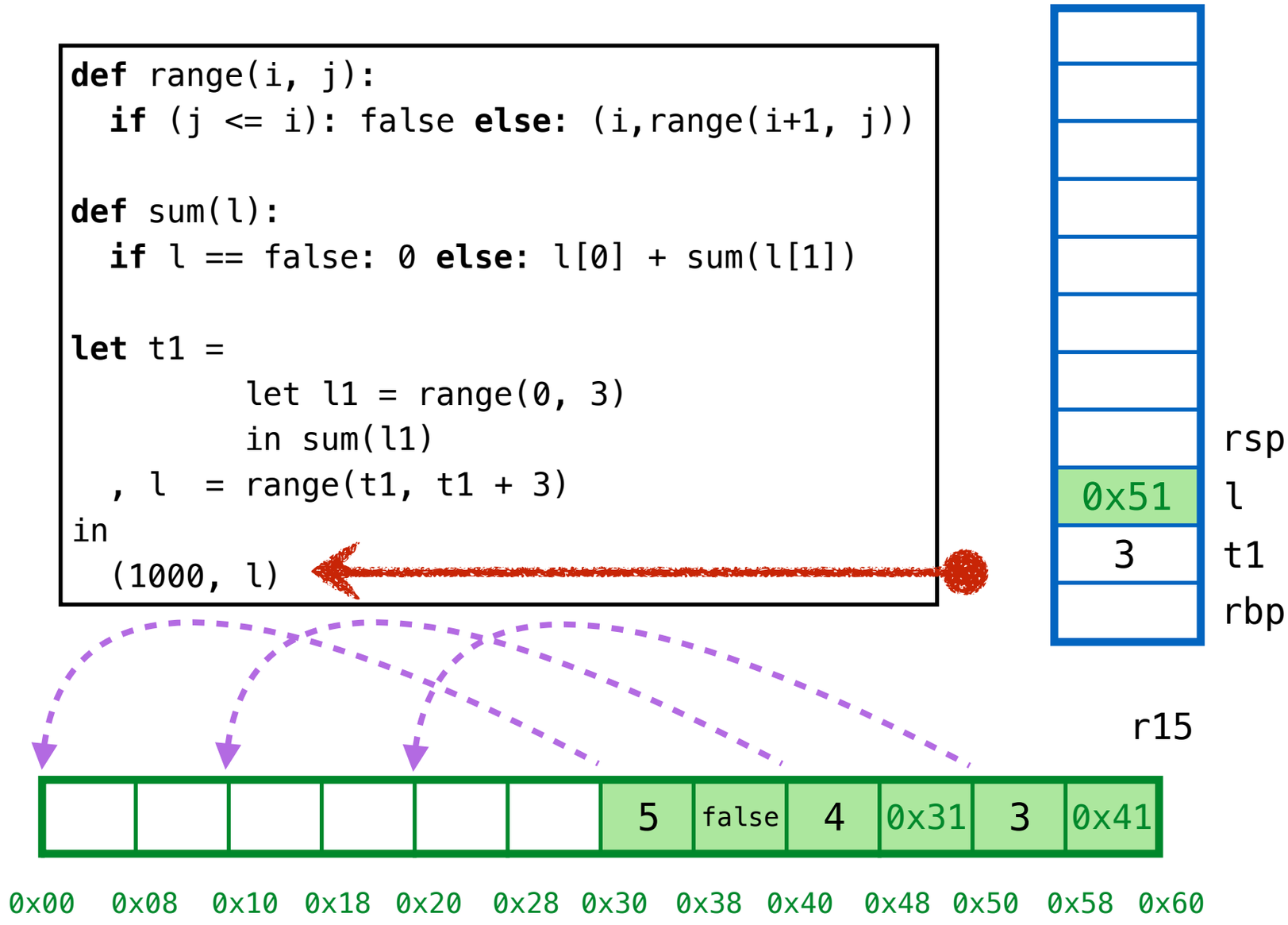

2. Compute FORWARD addrs

Where should we store the forward addrs?

ex4: recursive data

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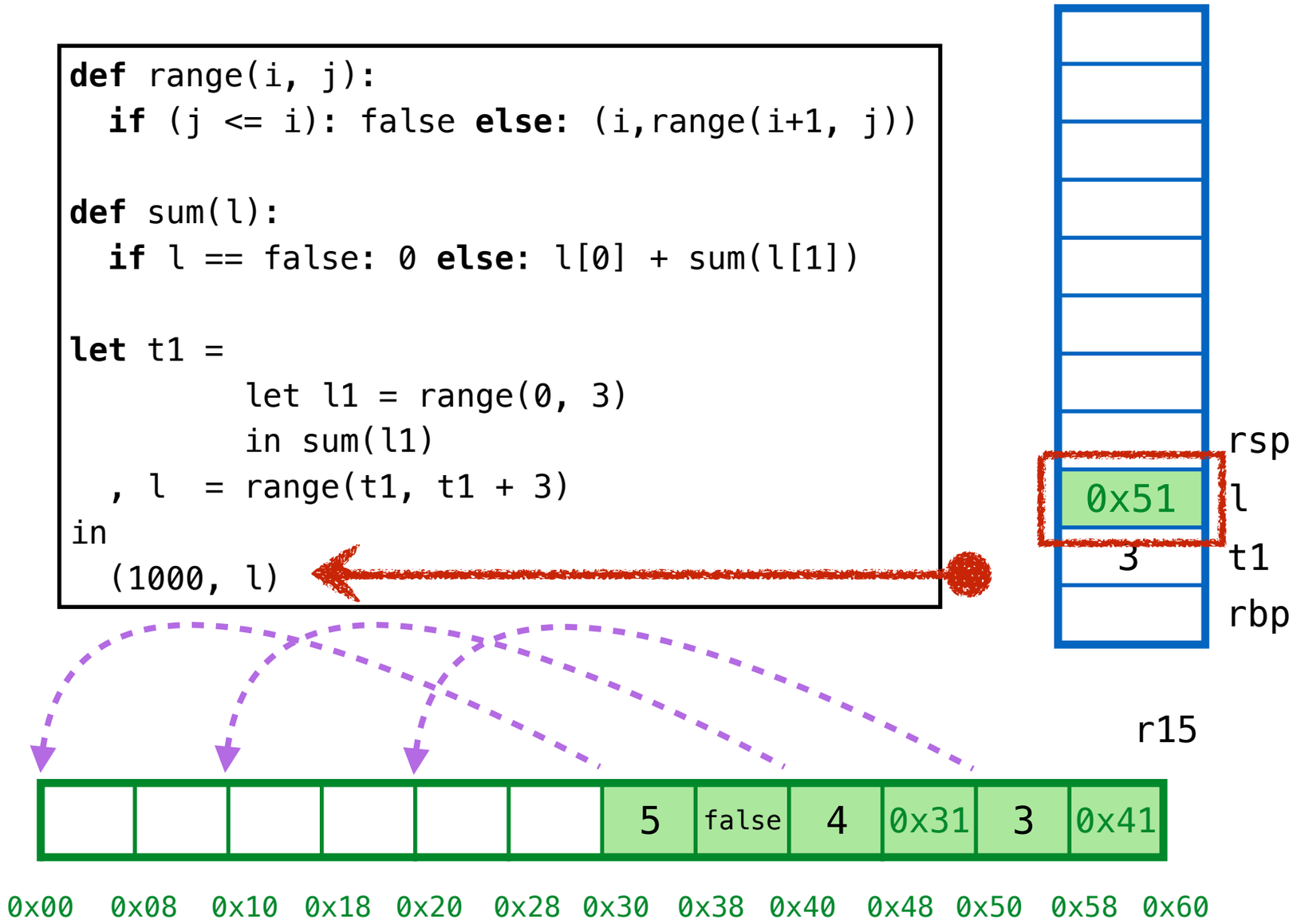

3. REDIRECT addrs on stack

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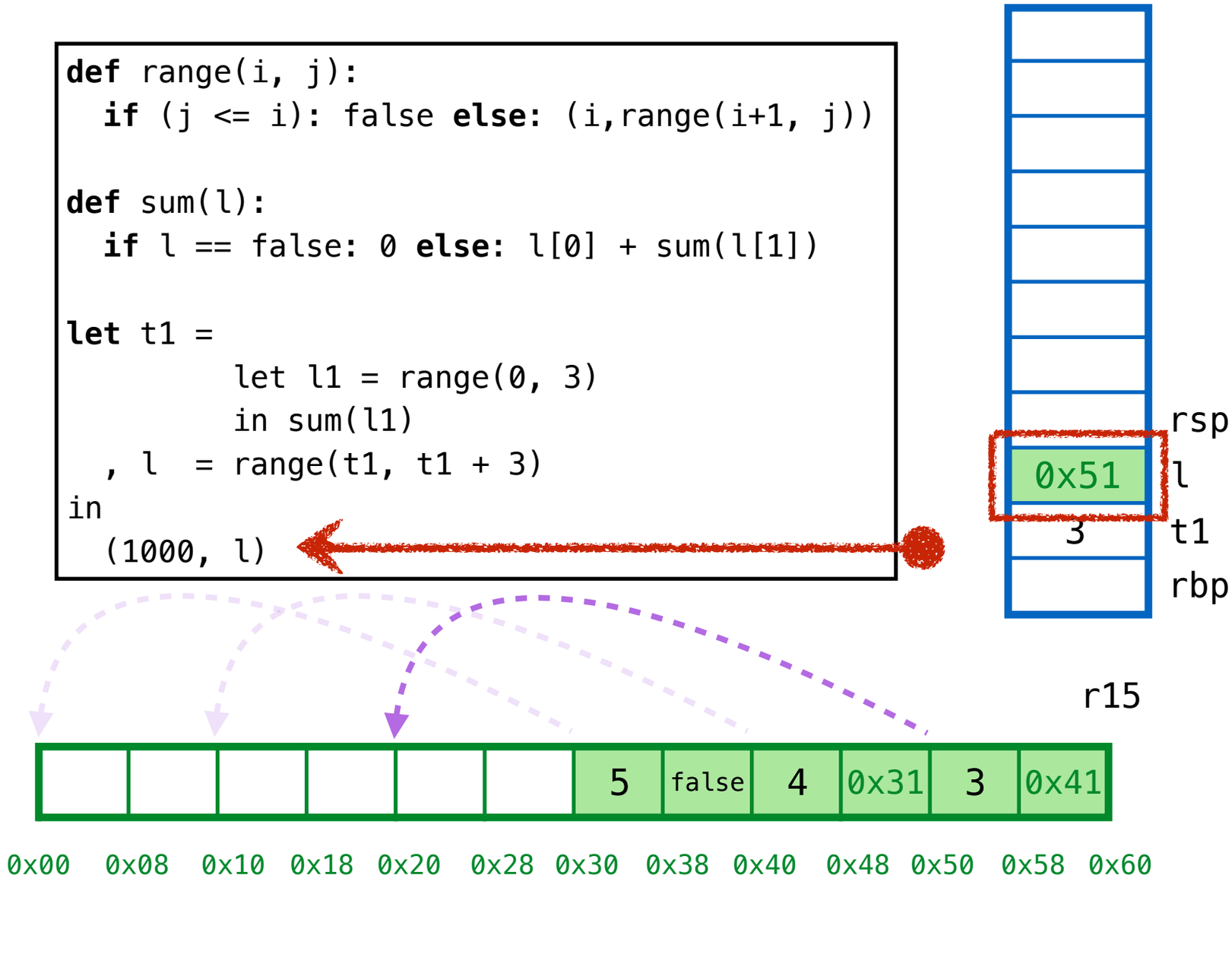

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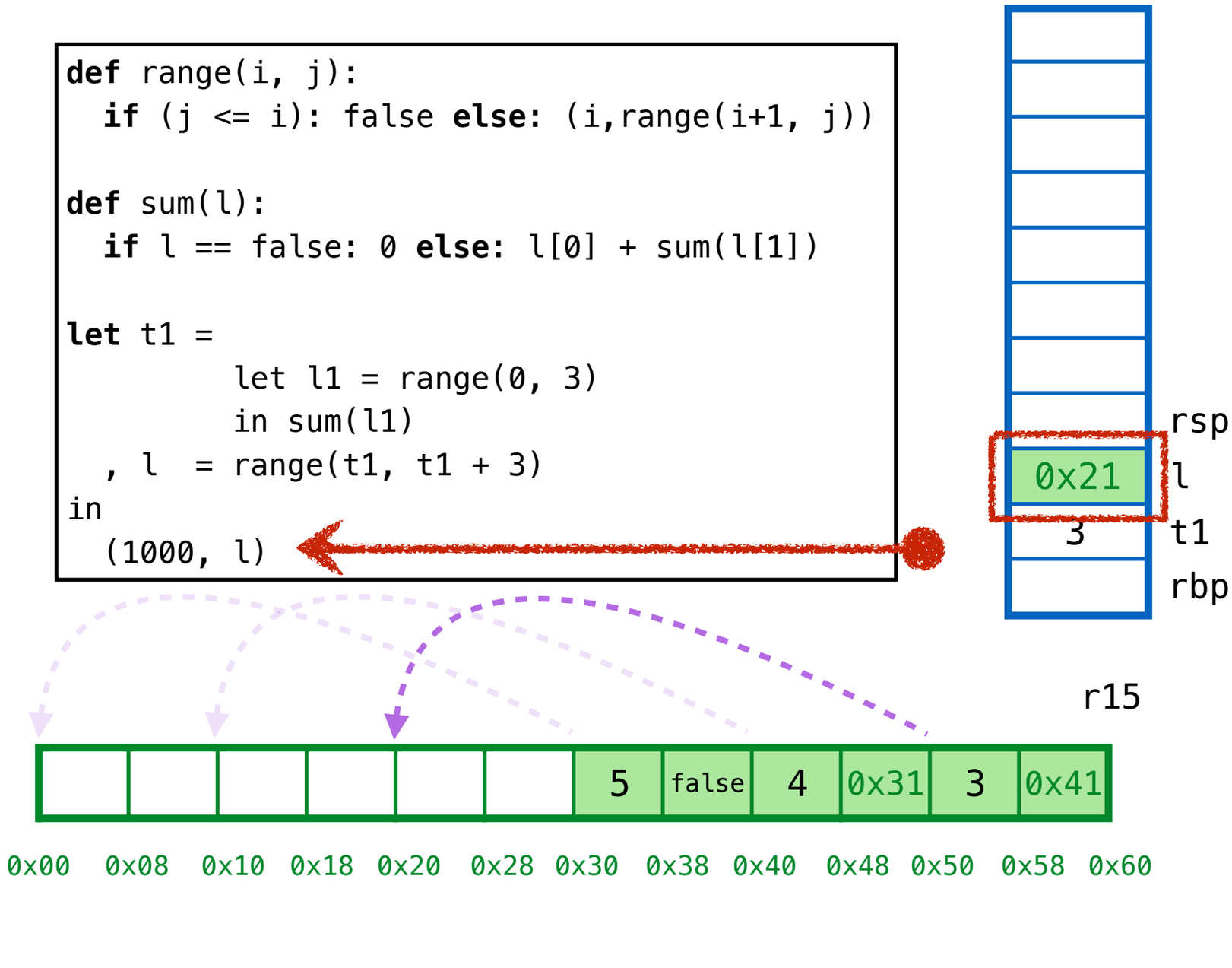

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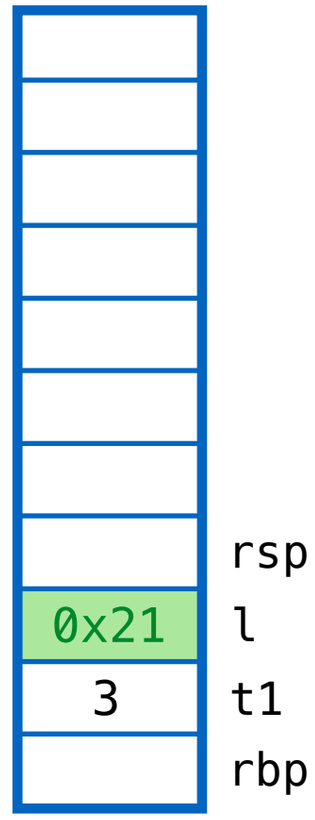

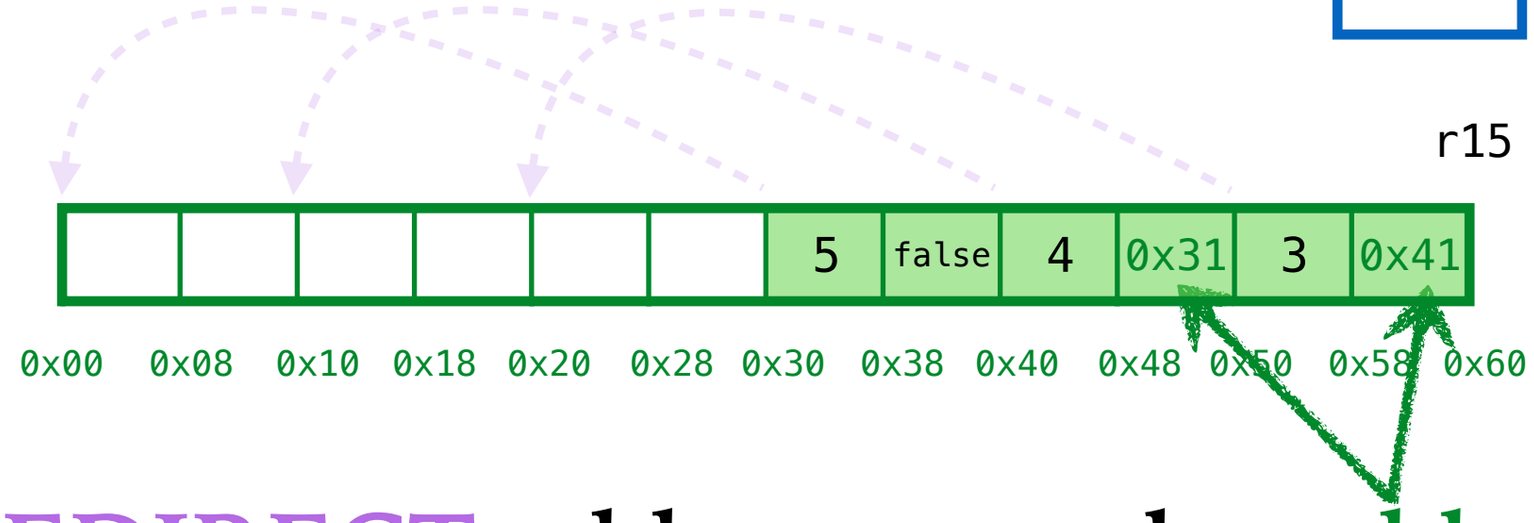

3. REDIRECT addrs on stack and heap!

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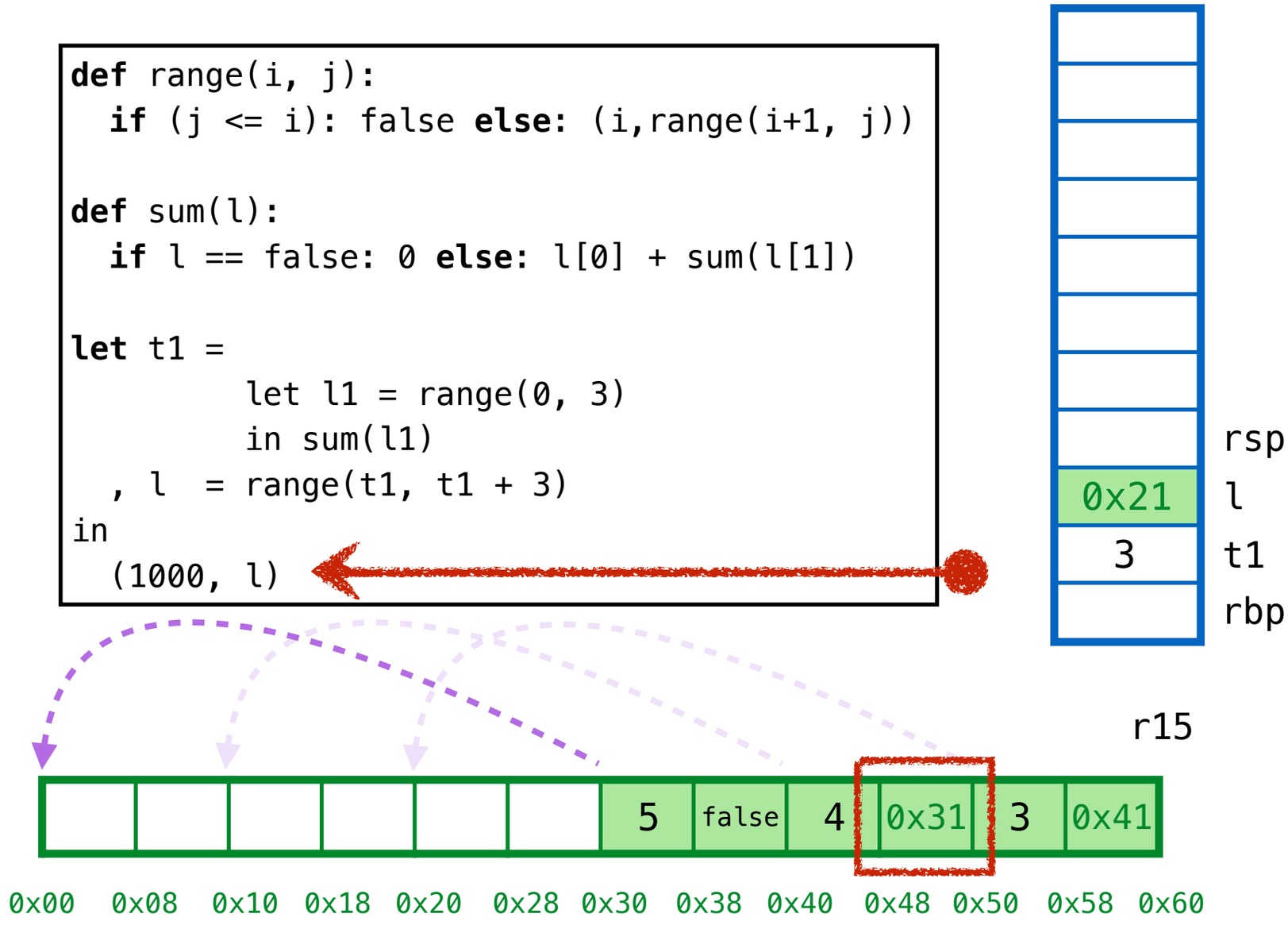

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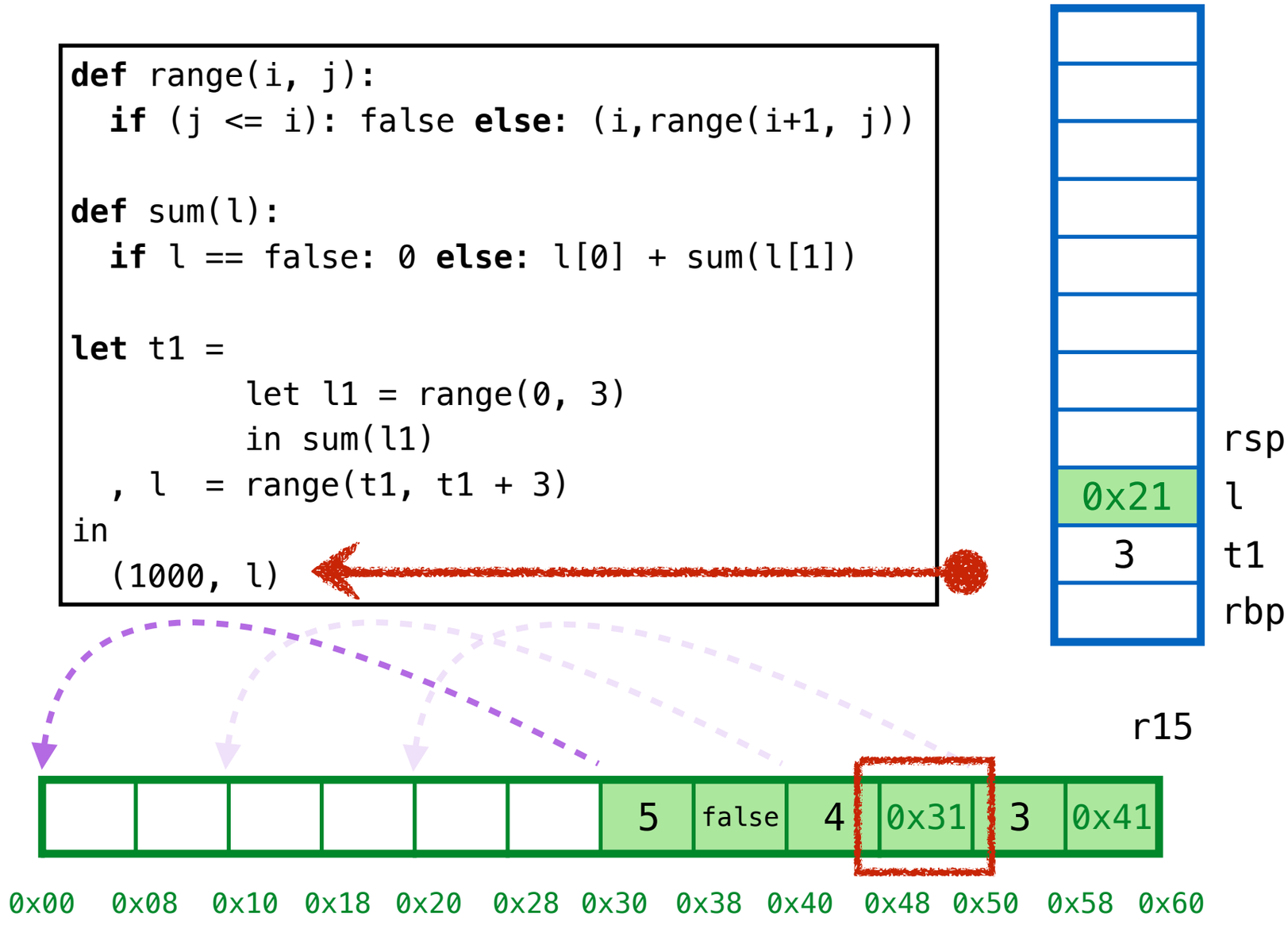

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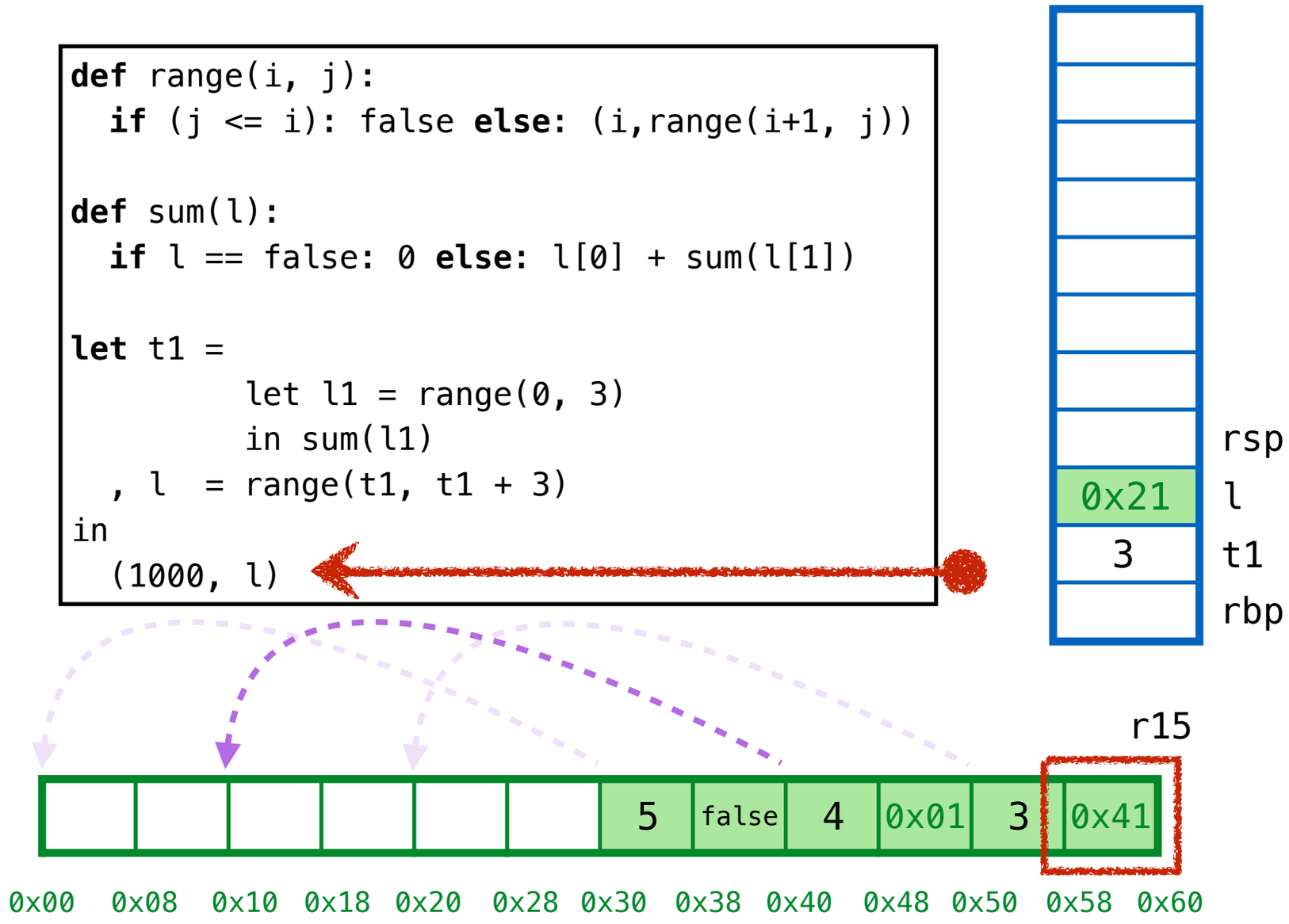

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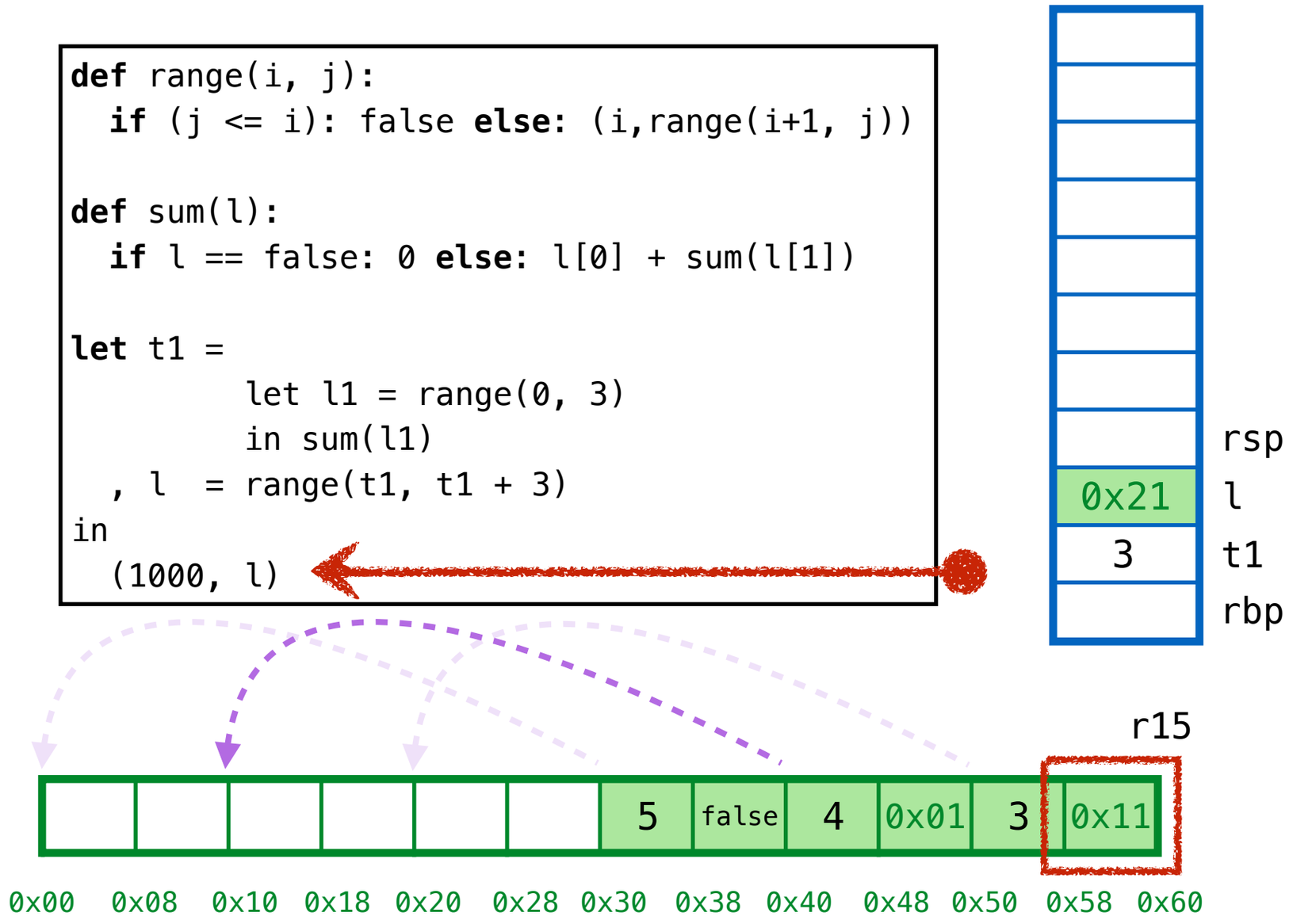

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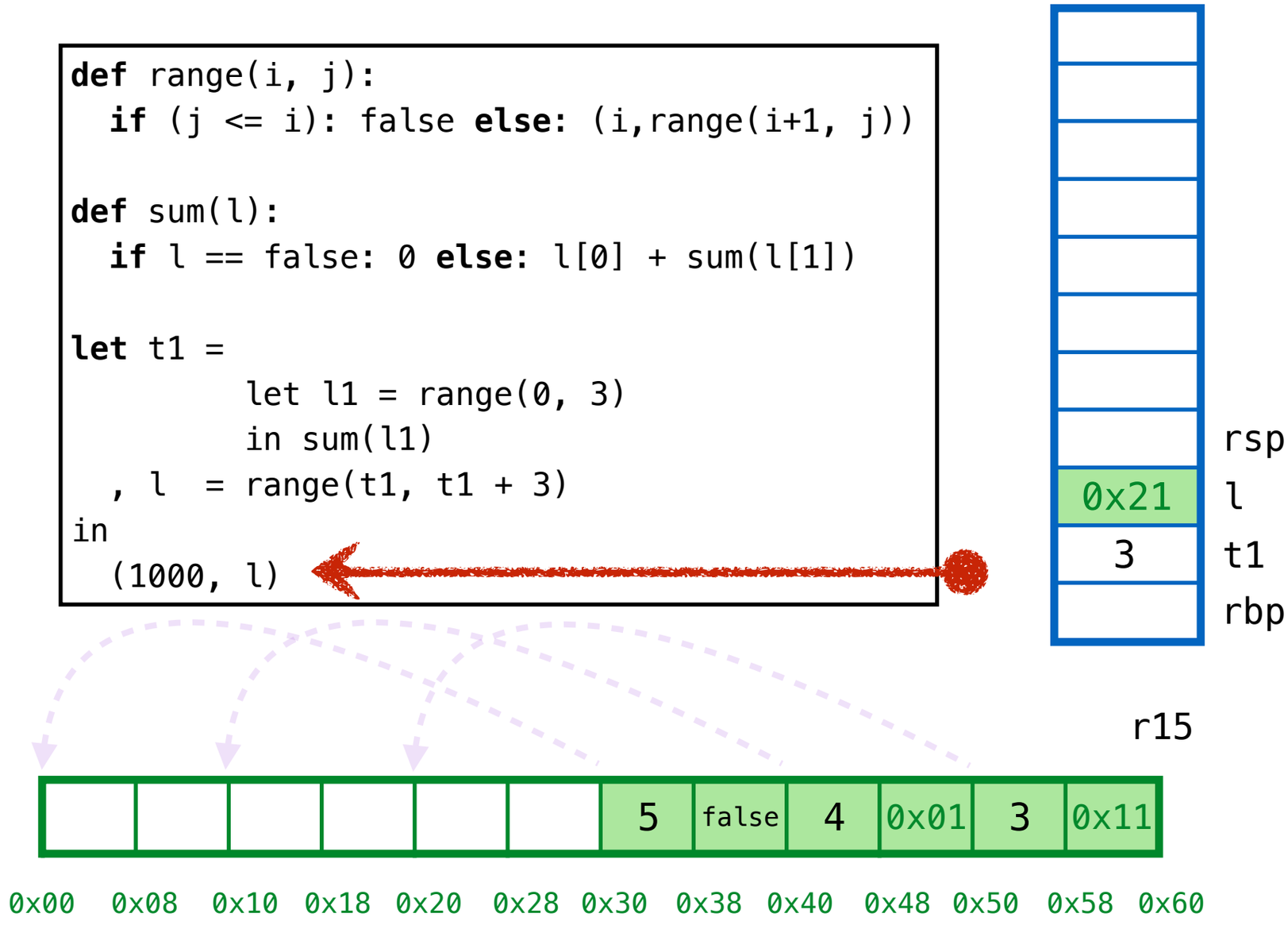

4. COMPACT cells on heap

Copy cell to forward addr!

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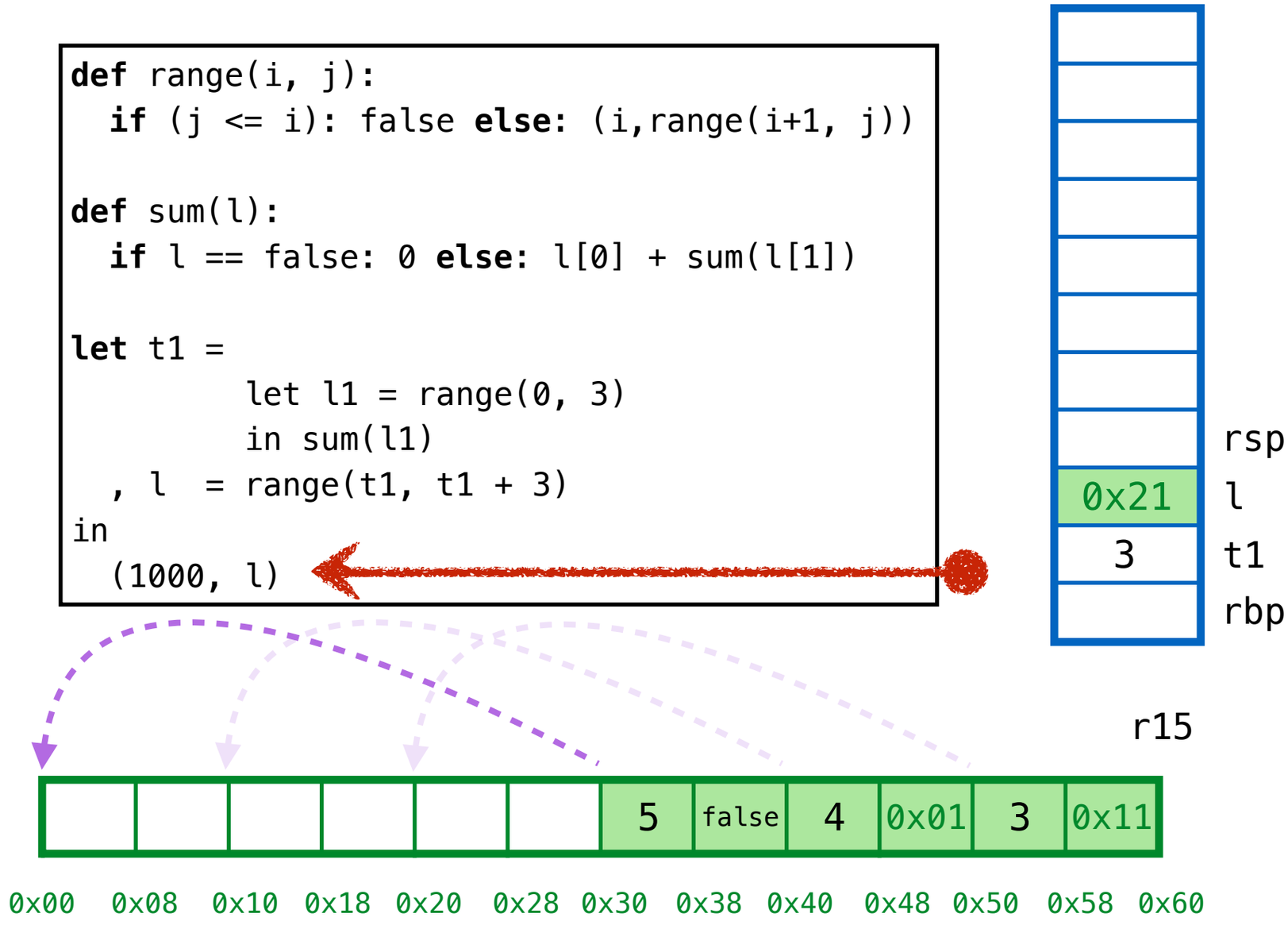

4. COMPACT cells on heap

Copy cell to forward addr!

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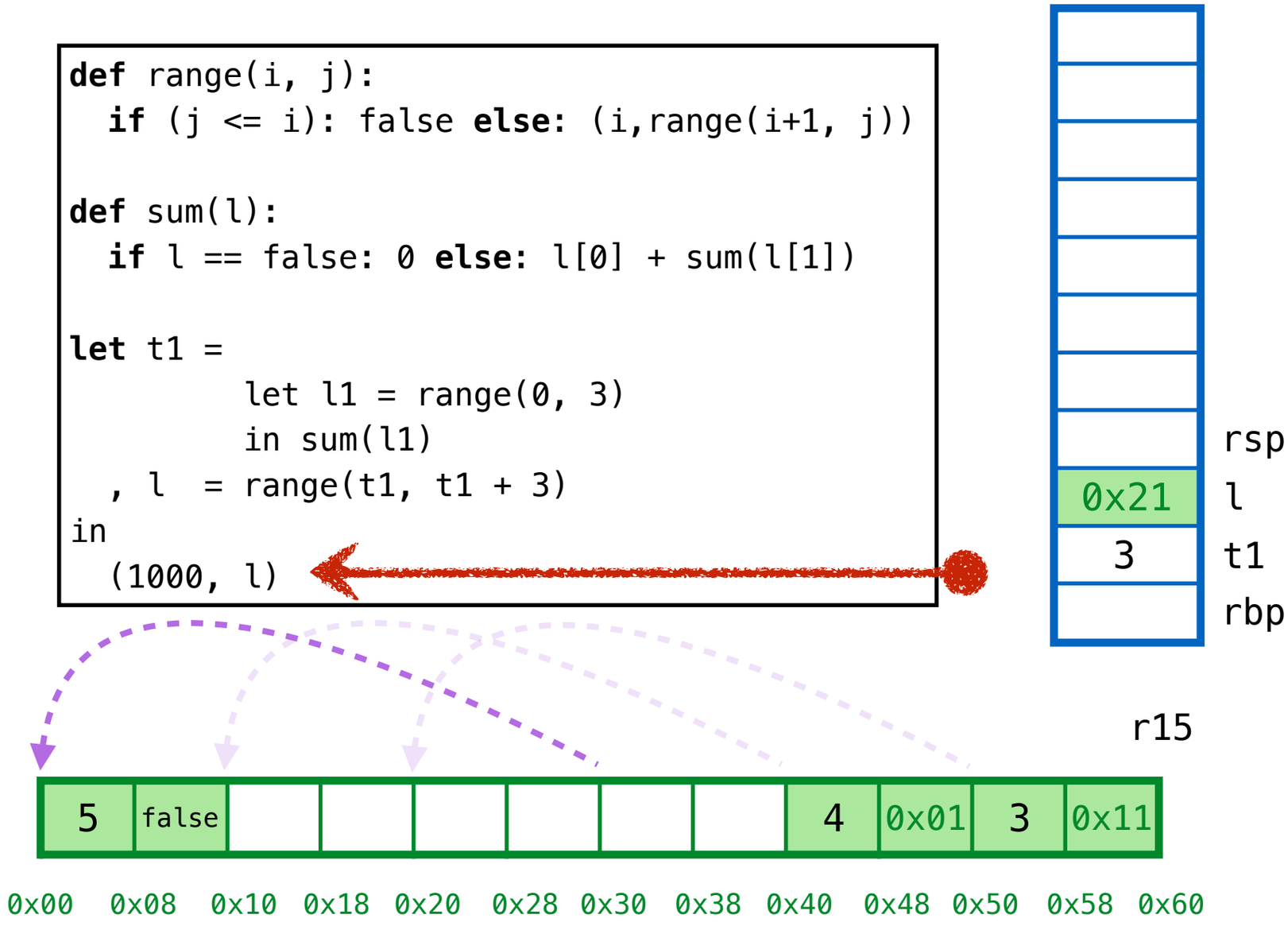

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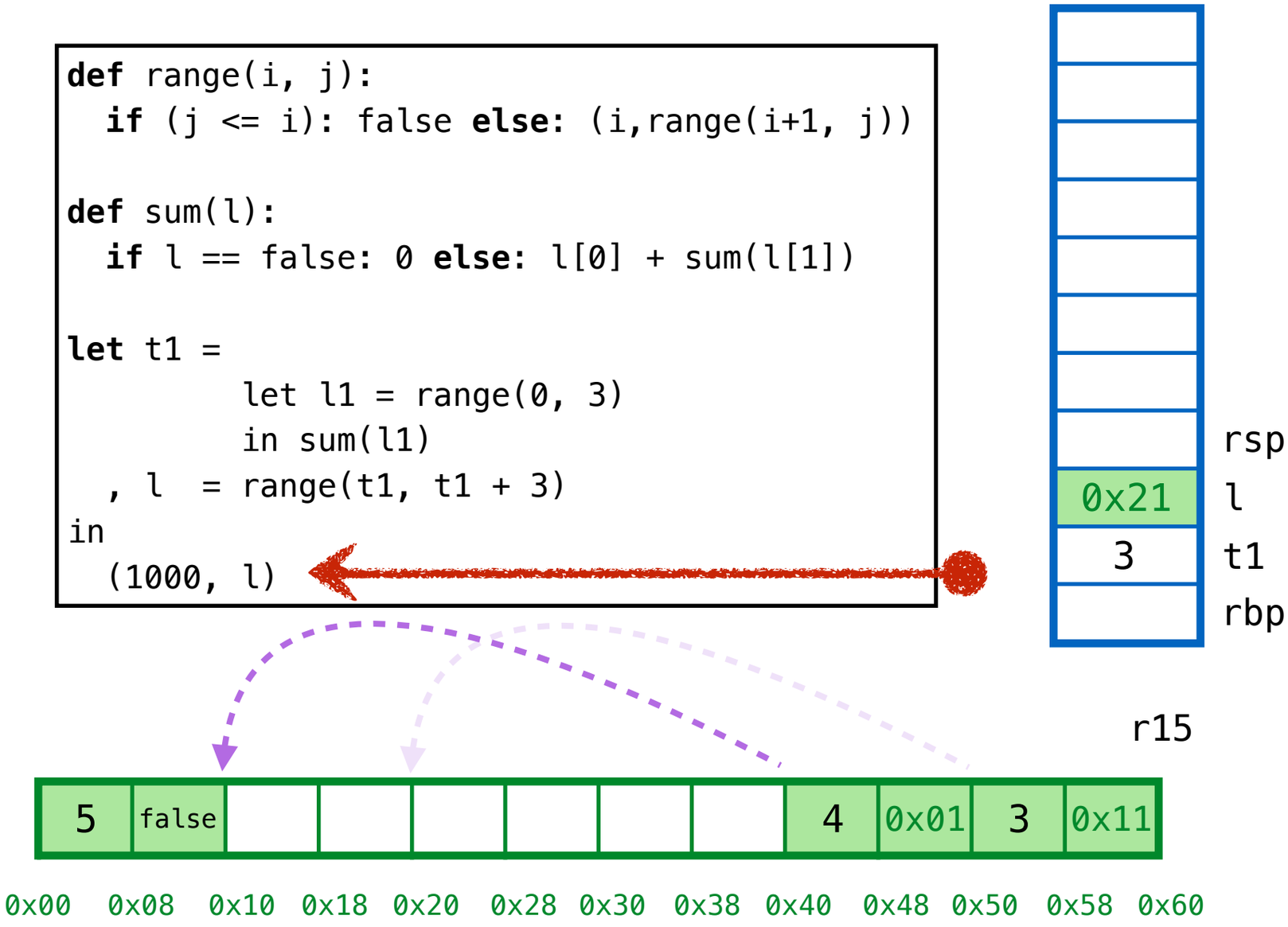

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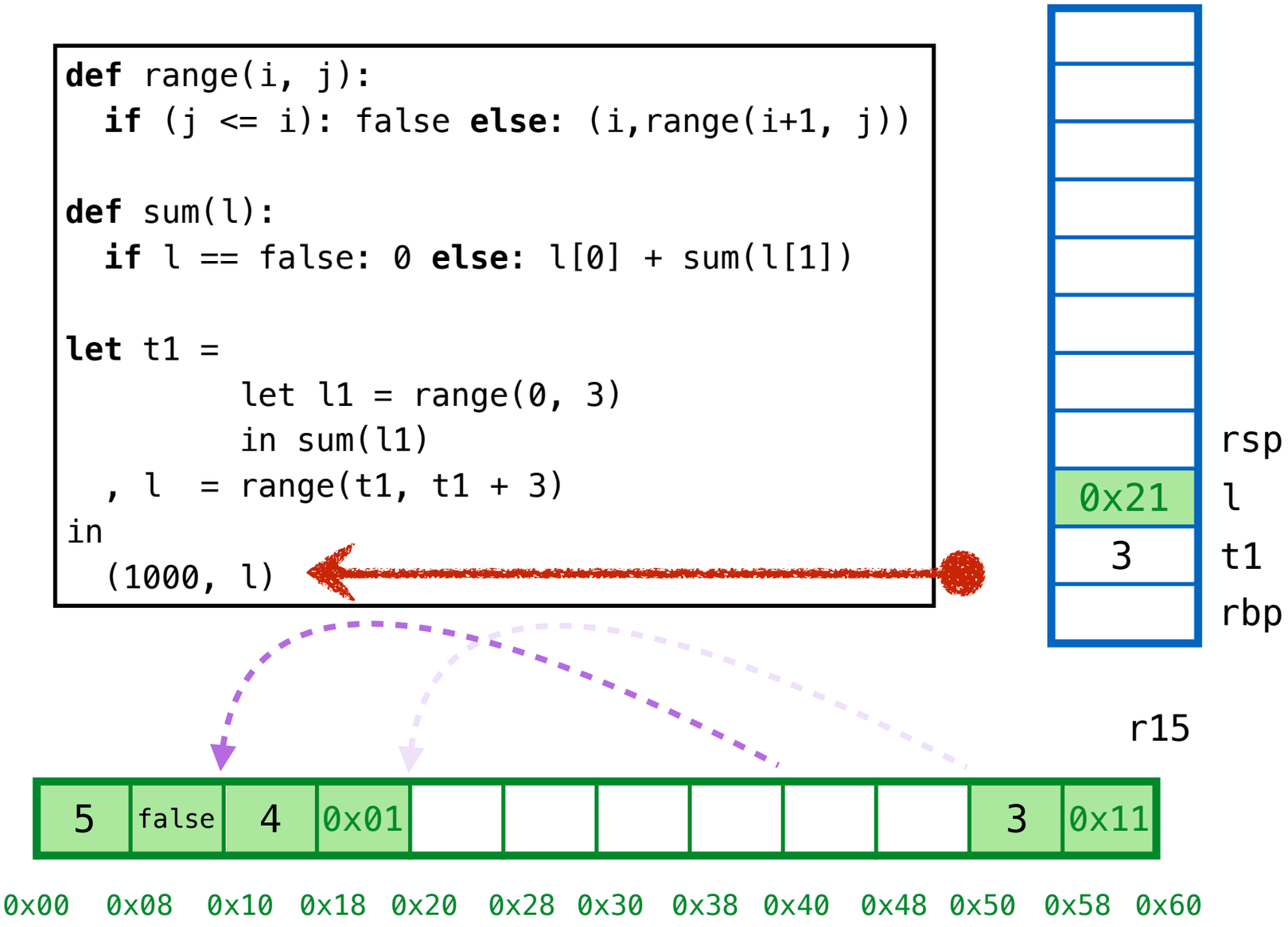

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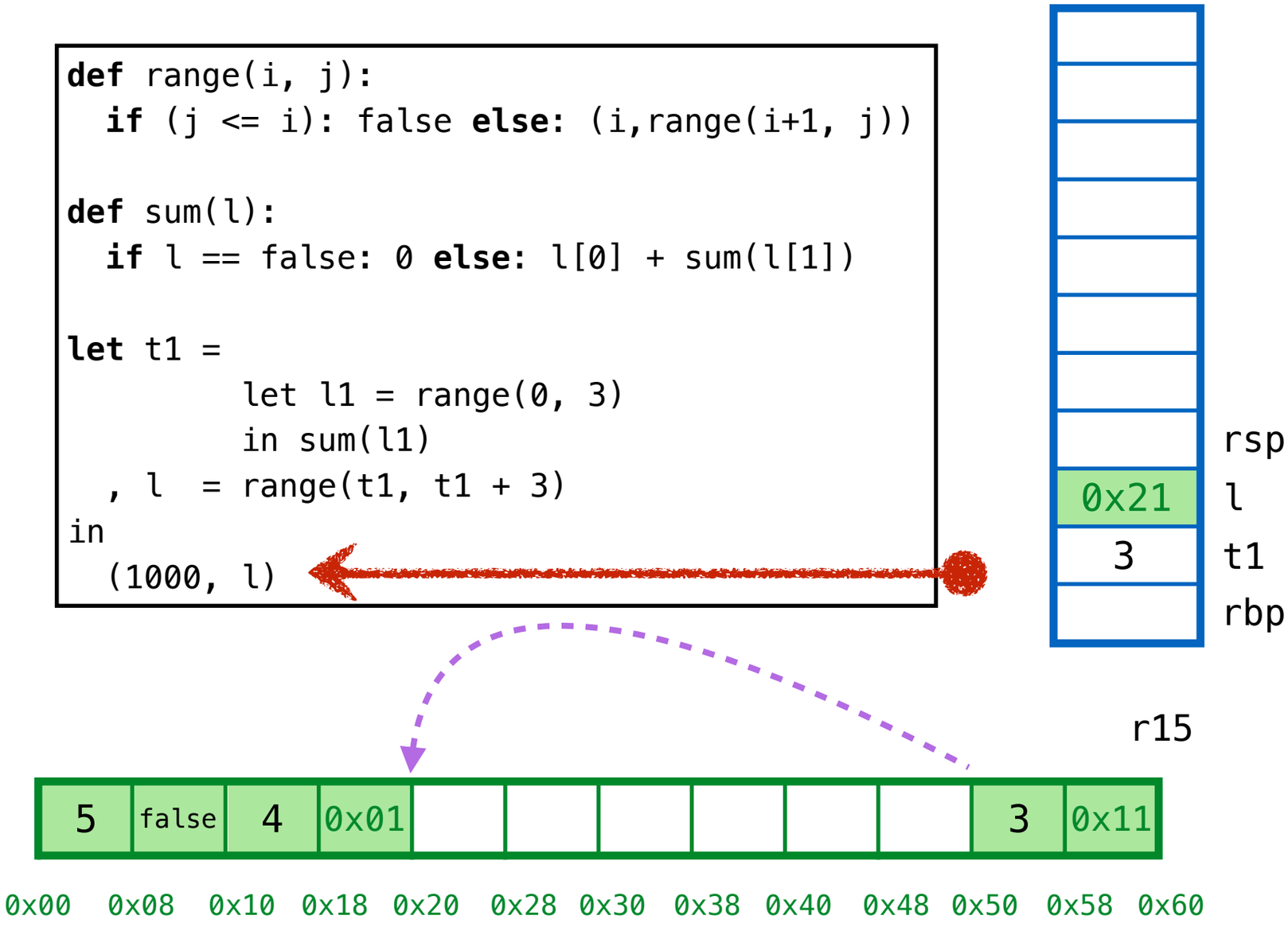

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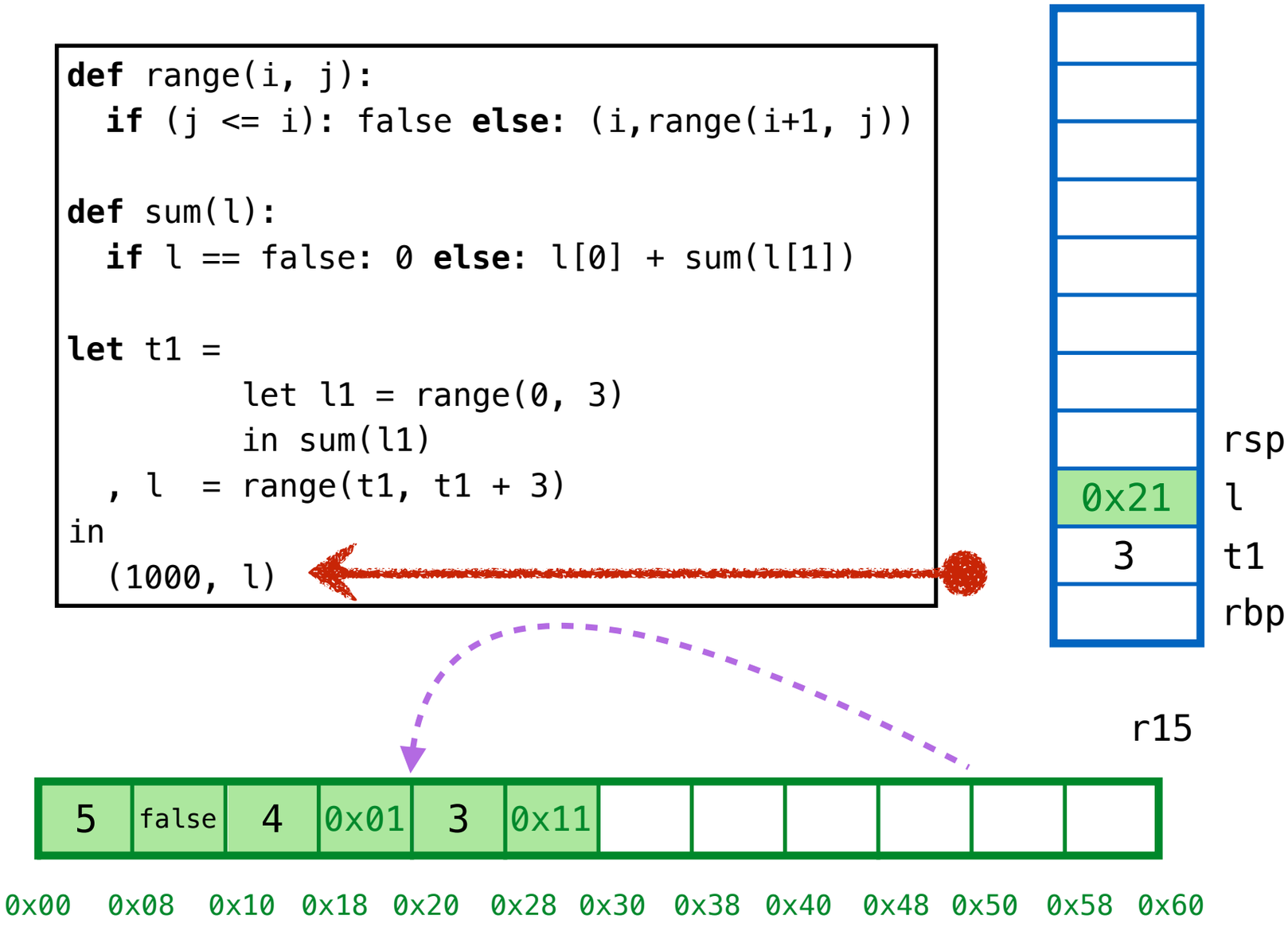

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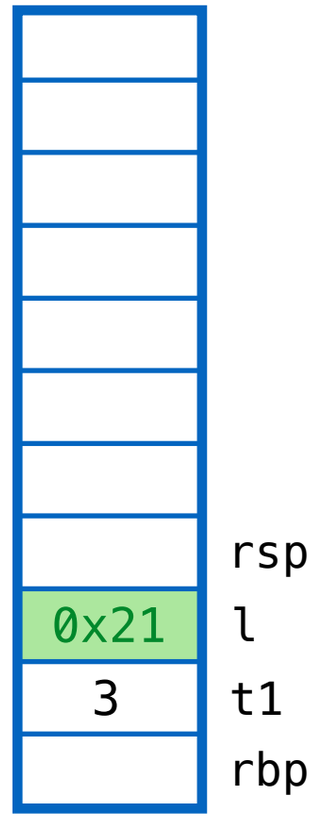

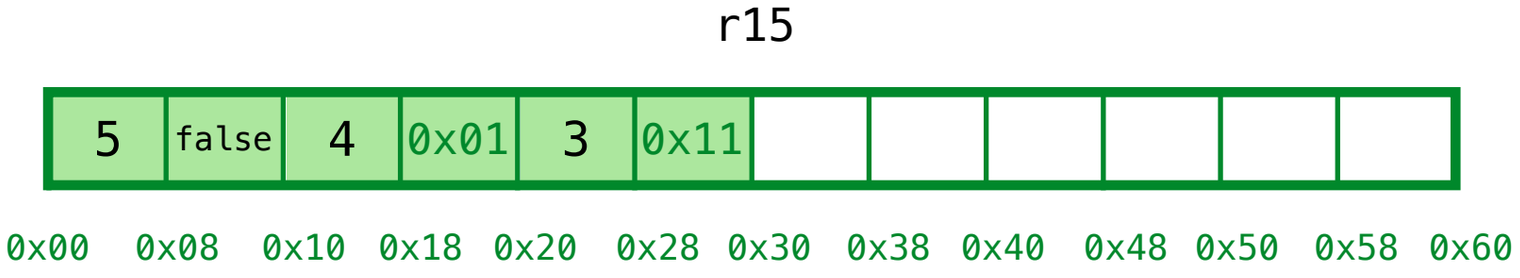

GC Complete!

Have space for `(1000, l)`

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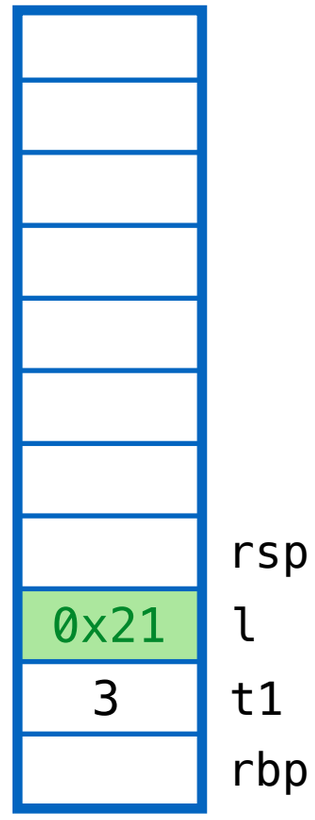

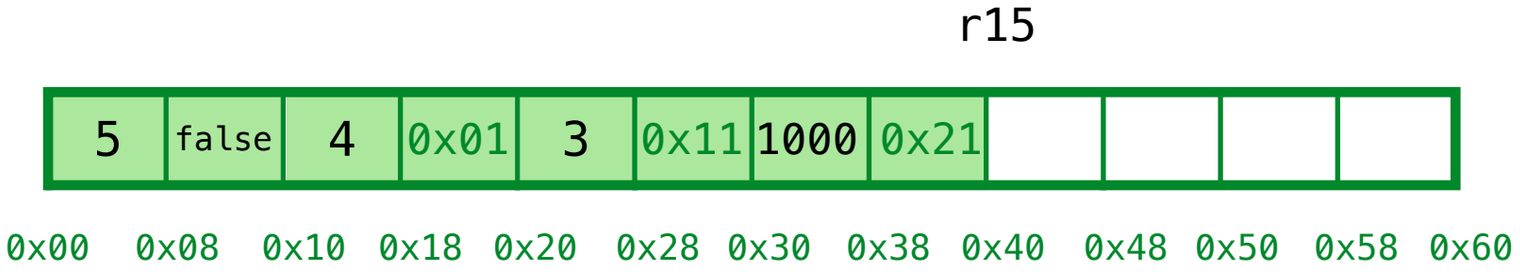

GC Complete!

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