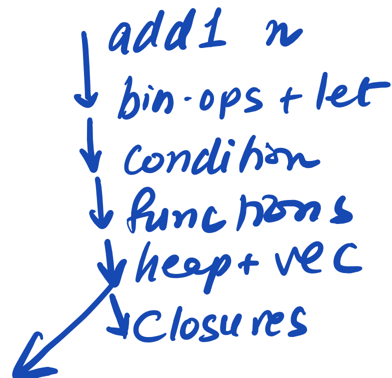
Garter



Garbage Collection

Ranjit Jhala | UCSD

GARTER GC 5/22 DUE → Jun 1 MON

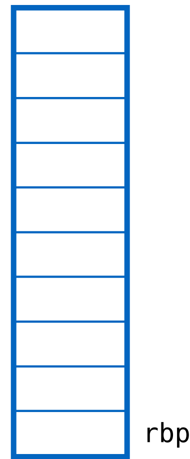
REG-ALLOC DUE → Jun 10 WED

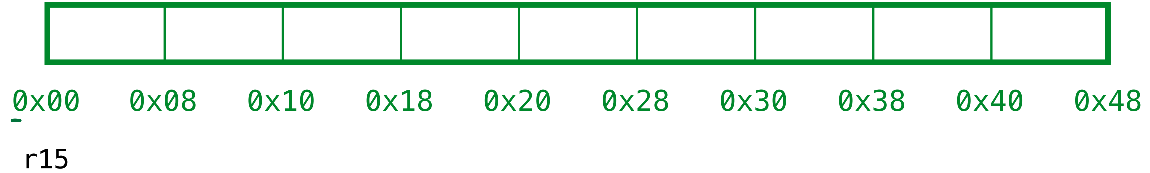
Garter / GC

Example 1

ex1: garbage at end

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





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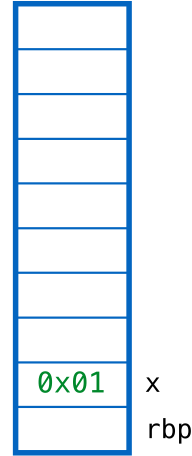

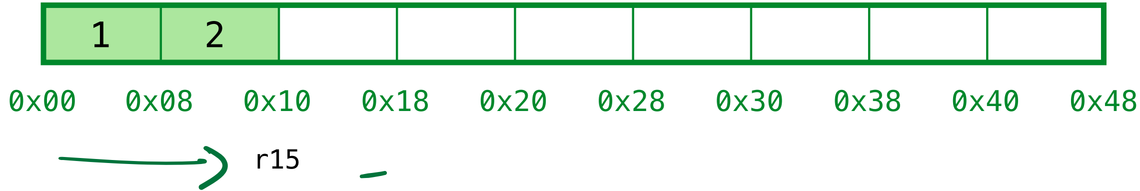

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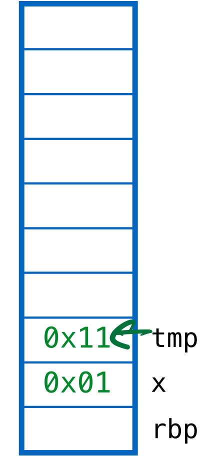

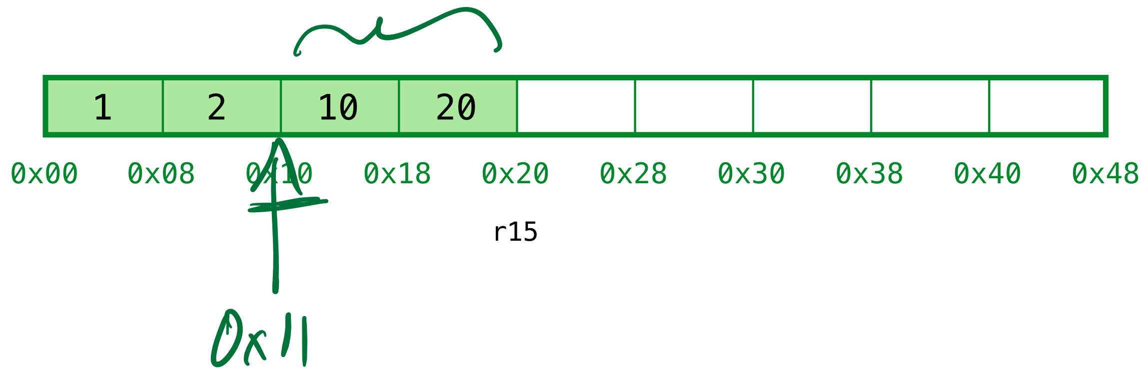

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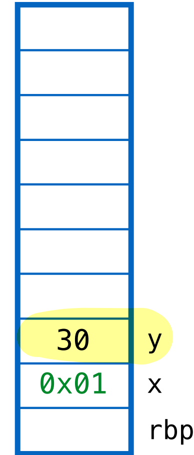

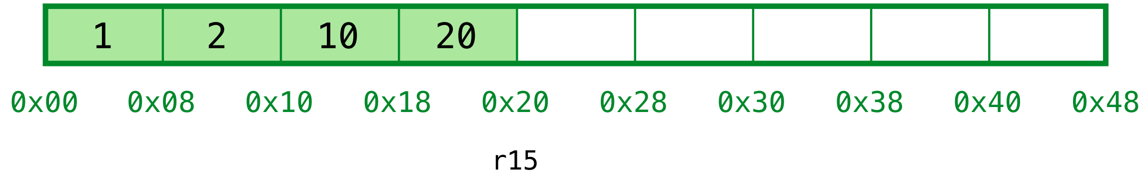

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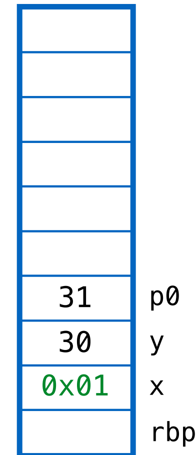

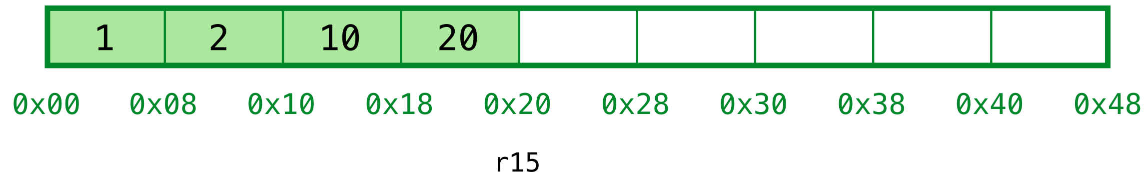

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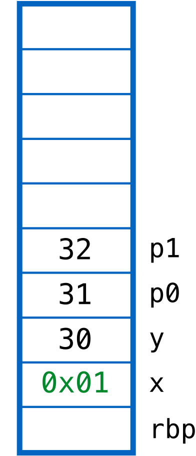
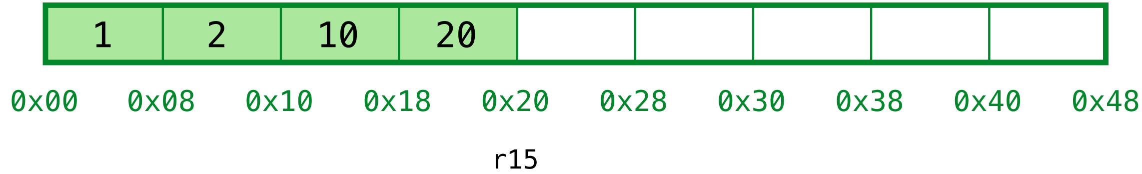
  , p1 = x[1] + y
in
  (p0, p1)
```





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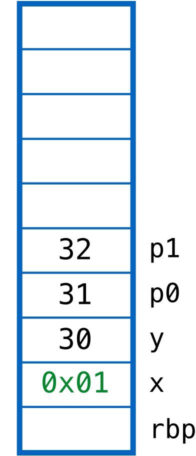
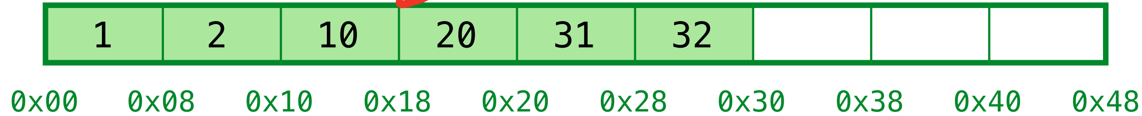
         in tmp[0] + tmp[1]
  , p0 = x[0] + y
  , p1 = x[1] + y
in
  (p0, p1)
```



Result (rax) = 0x21

with tag set!



ex1: garbage at end

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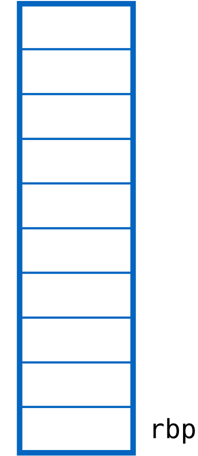
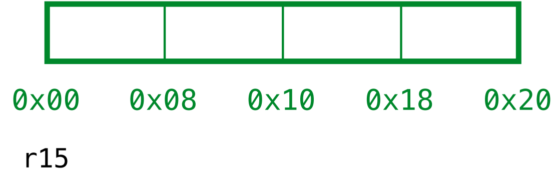
  , p1 = x[1] + y
in
  (p0, p1)
```





Suppose we had a smaller, 4-word heap

ex1: garbage at end

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

32	p1
31	p0
30	y
0x01	x
	rbp

"out of scope"

1	2	10	20

0x00 0x08 0x10 0x18 0x20

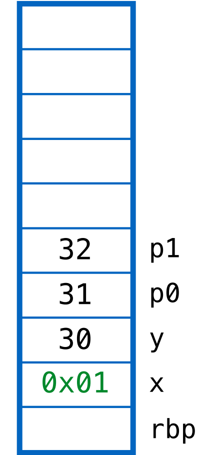
r15

"garbage"

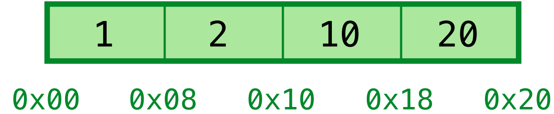
NOT REACH FROM STACK

ex1: garbage at end

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



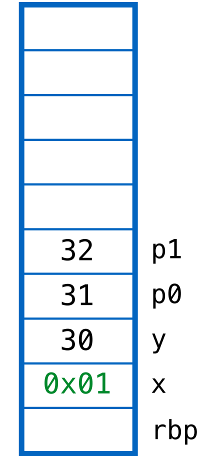
Out of memory!
Can't allocate `(p0, p1)`



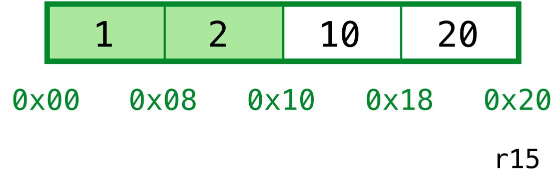
r15

ex1: garbage at end

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



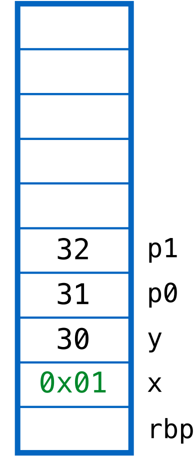
`(10, 20)` is "garbage"



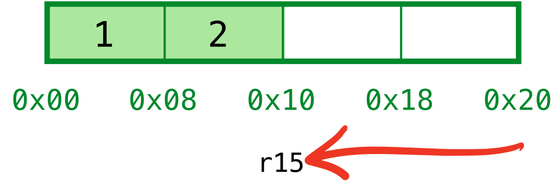
Q: How to determine if cell is garbage?

ex1: garbage at end

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



(10, 20) is “garbage”



ex1: garbage at end

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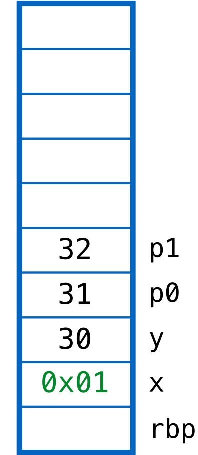
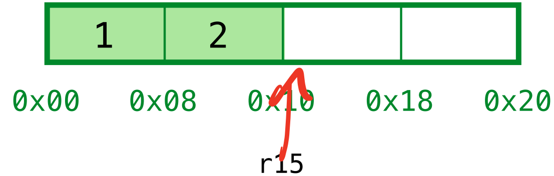
  , p1 = x[1] + y
in
  (p0, p1)
```





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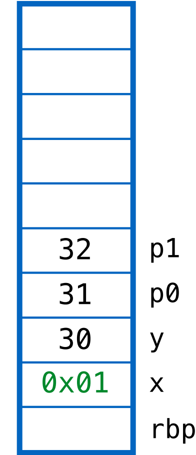
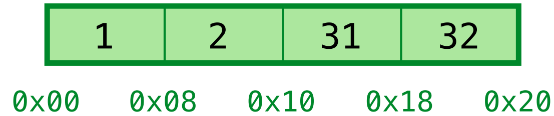
         in tmp[0] + tmp[1]
  , p0 = x[0] + y
  , p1 = x[1] + y
in
  (p0, p1)
```



Result (rax) = 0x11



0x00 0x08 0x10 0x18 0x20

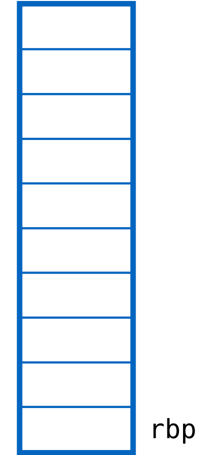
r15

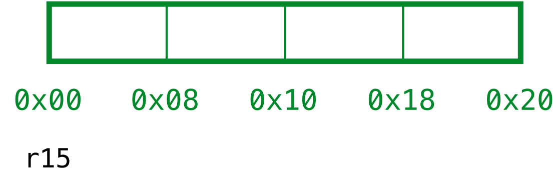
Garter / GC

Example 2

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)
```

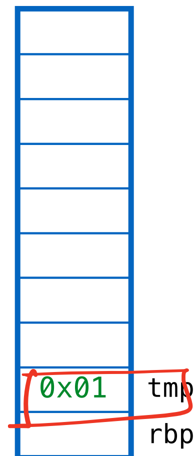


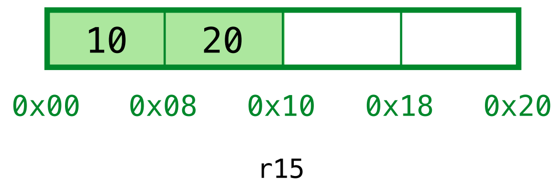


Start with a 4-word heap

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
in
  (p0, p1)
```

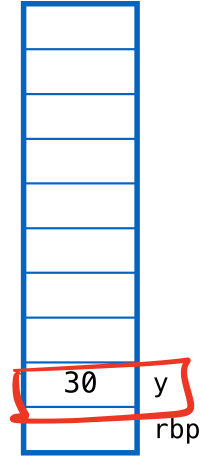


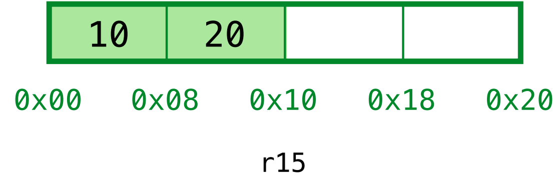


r15

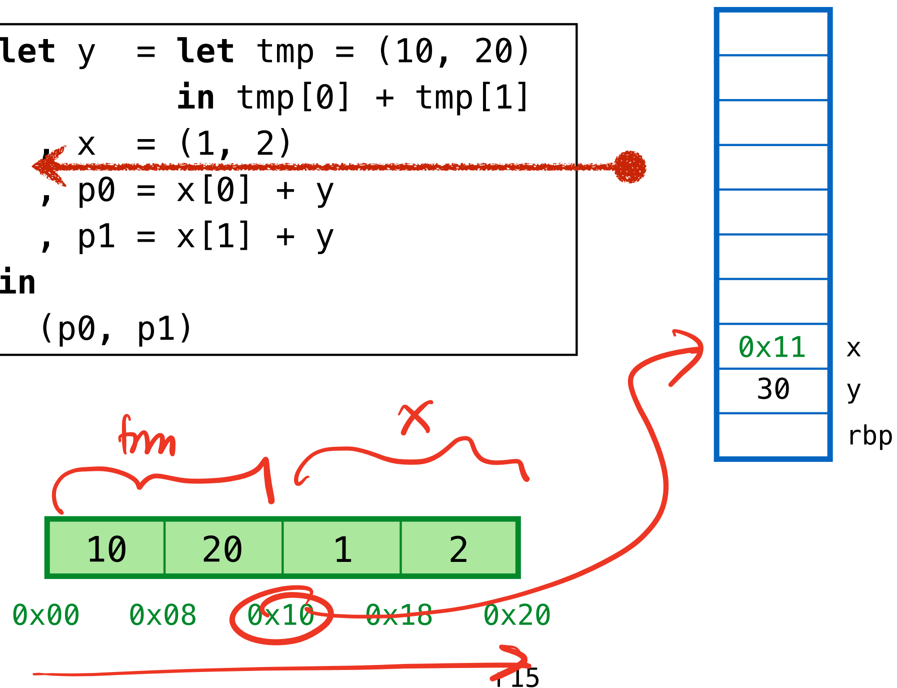
ex2: garbage in the middle

```
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)
```





ex2: garbage in the middle



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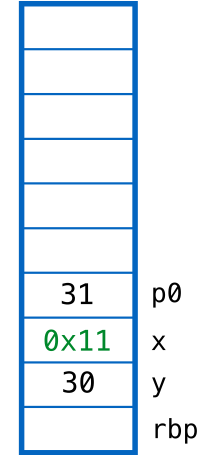
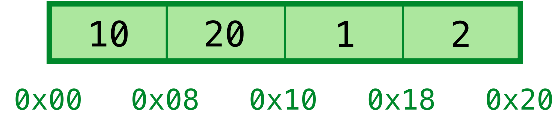
  , p1 = x[1] + y
in
  (p0, p1)
```





ex2: garbage in the middle

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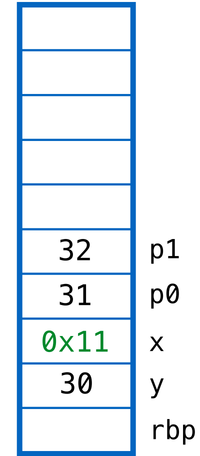

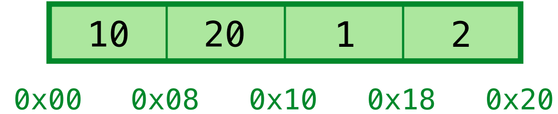

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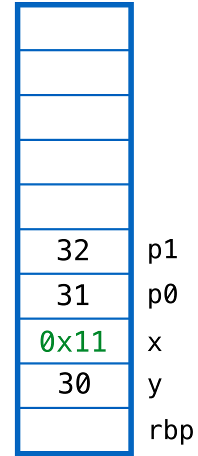
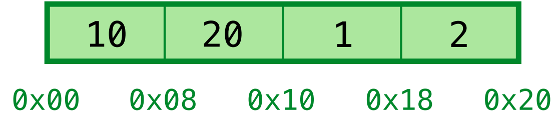


Out of memory!
Can't allocate **`(p0, p1)`**



0x00 0x08 0x10 0x18 0x20

r15

ex2: garbage in the middle

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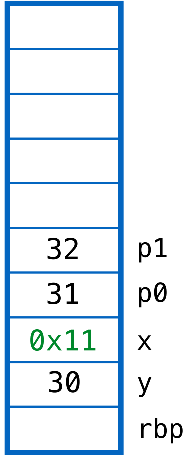
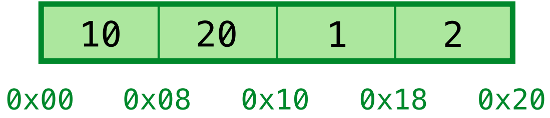


Lets reclaim & recycle garbage!



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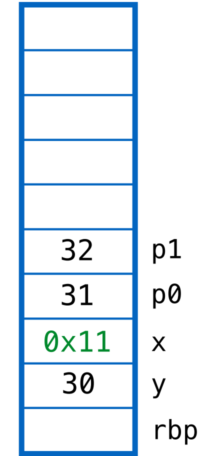
  (p0, p1)
```



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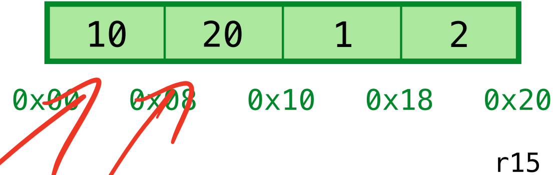
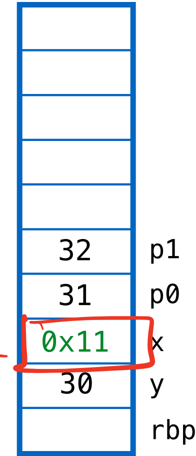


QUIZ: Which cells are garbage?

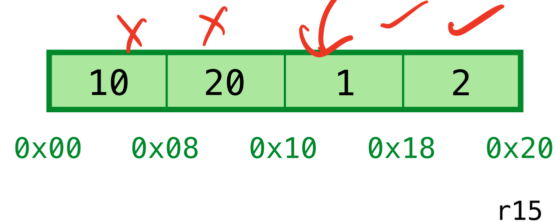
(A) `0x00, 0x08` (B) `0x08, 0x10` (C) `0x18, 0x20` (D) None (E) All

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!

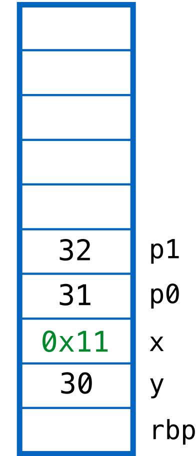


QUIZ: Which cells are garbage?

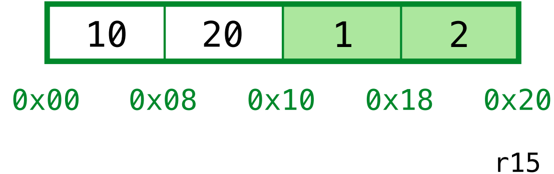
Those that are *not reachable from stack*

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!



QUIZ: Which cells are garbage?

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ex2: garbage in the middle

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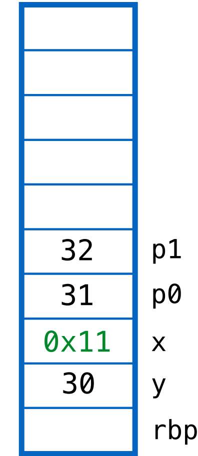
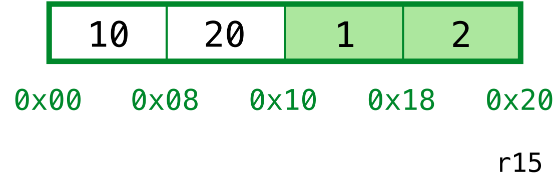
  (p0, p1)
```



Lets reclaim & recycle garbage!

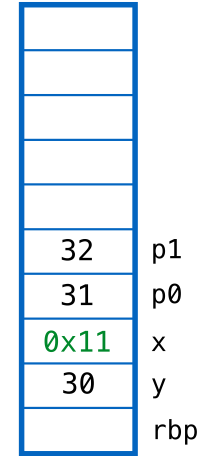


Q: How to reclaim space?

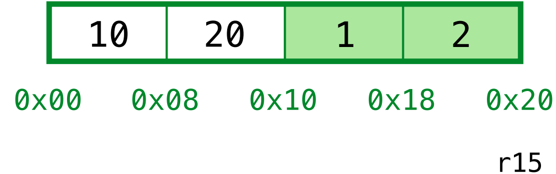
Why is it not enough to rewind `r15`?

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!

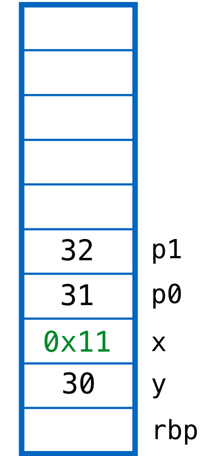


Why is it not enough to rewind `r15`?

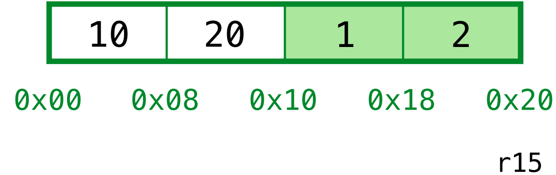
Want free space to be *contiguous* (i.e. go to end of heap)

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
in
  (p0, p1)
```



Lets reclaim & recycle garbage!

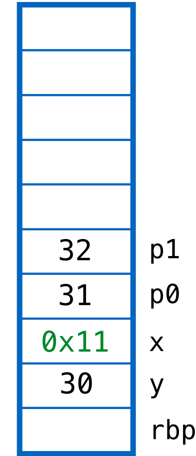


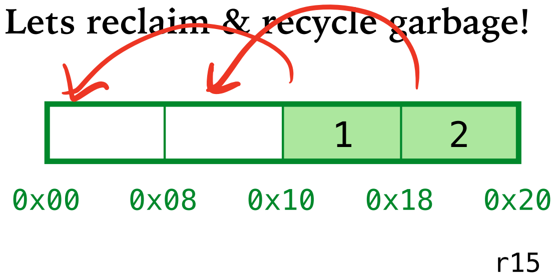
Solution: Compaction

Copy "live" cells into "garbage" ...

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)
```



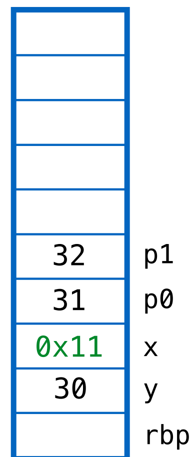


Solution: Compaction

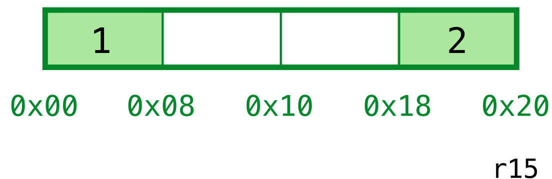
Copy “live” cells into “garbage” …

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!

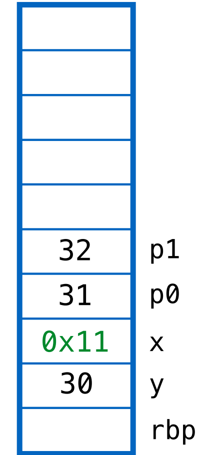


Solution: Compaction

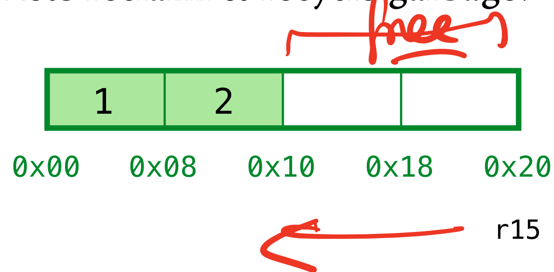
Copy "live" cells into "garbage" ...

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!

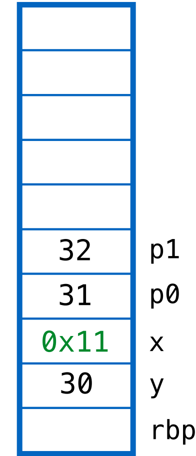


Solution: Compaction

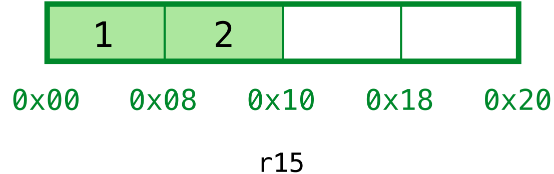
Copy "live" cells into "garbage" ...

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!

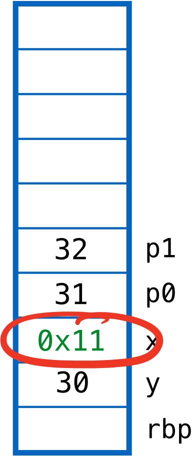


Solution: Compaction

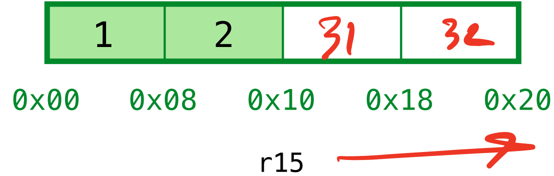
Copy "live" cells into "garbage" ... ***and then*** ... rewind `r15`!

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
in
  (p0, p1)
```

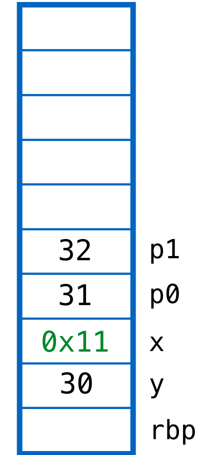


Yay! Have space for `(p0, p1)`

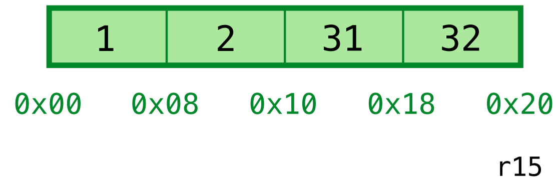


ex2: garbage in the middle

```
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)
```

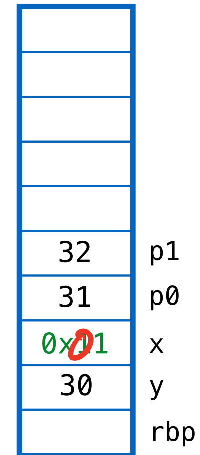


Yay! Have space for `(p0, p1)`



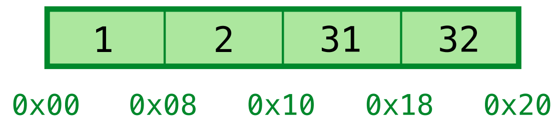
ex2: garbage in the middle

```
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)
```



Boo!

Result (rax) = 0x09

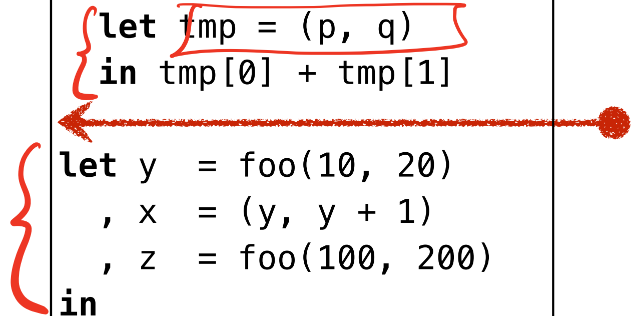


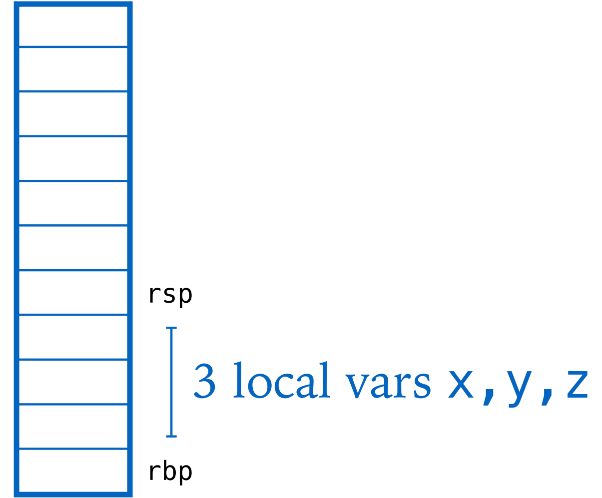
r15

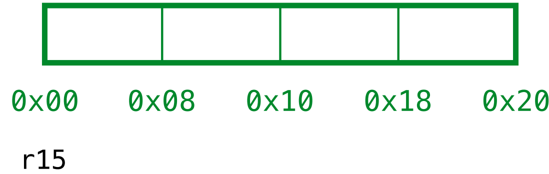
Garter / GC

Example 3

ex3: garbage in the middle (with stack)



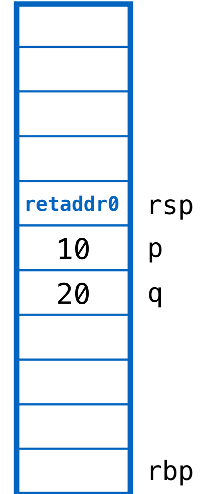


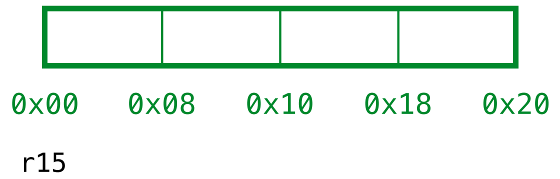


ex3: garbage in the middle (with stack)

```
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
```

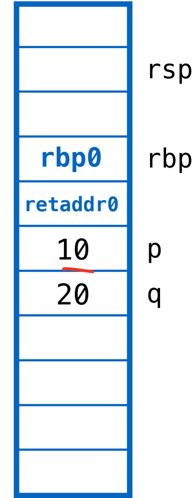




ex3: garbage in the middle (with stack)

```
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
```



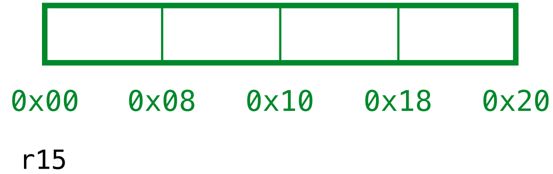
rsp

rbp

p

q

rbp0

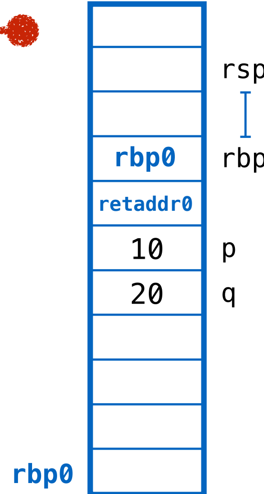


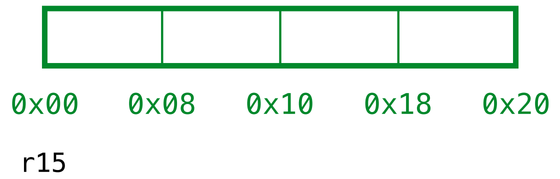
r15

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
```

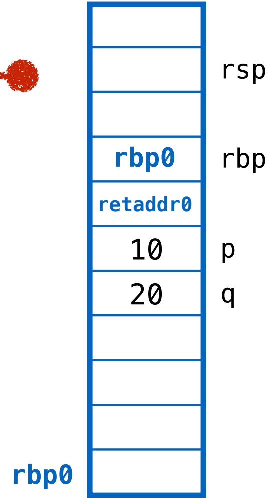


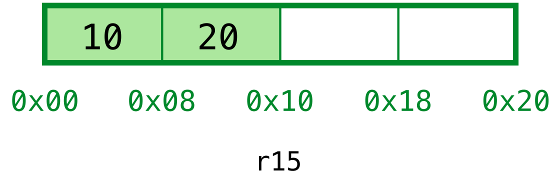


ex3: garbage in the middle (with stack)

```
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
```

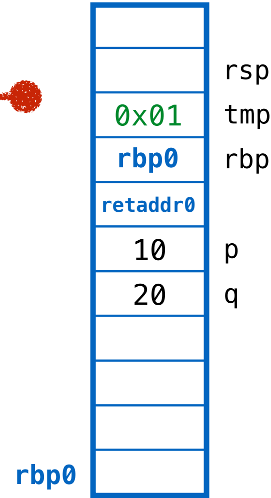


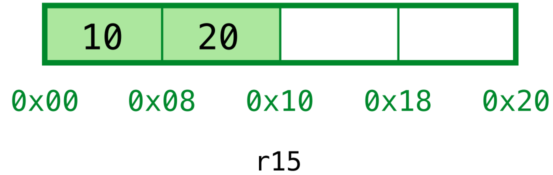


ex3: garbage in the middle (with stack)

```
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
```





ex3: garbage in the middle (with stack)

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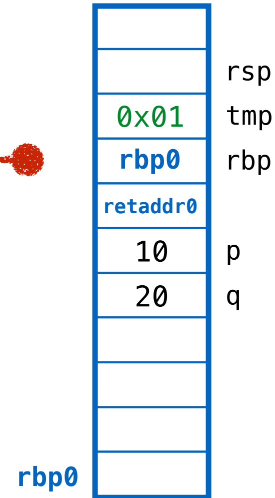
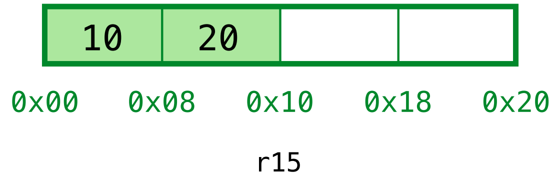
let y  = foo(10, 20)
  , x  = (y, y + 1)
  , z  = foo(100, 200)
in
  x[0] + y + z
```



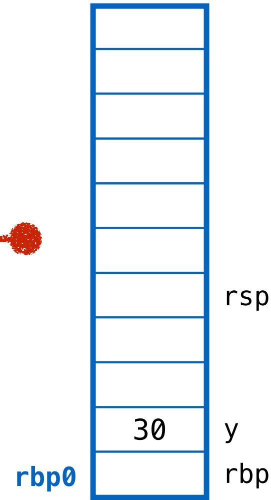
Return (rax) = 30



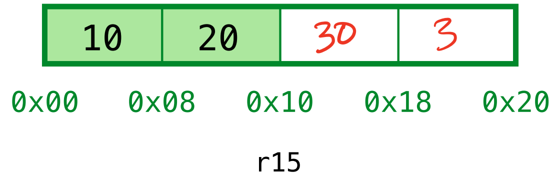
ex3: garbage in the middle (with stack)

```
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
```



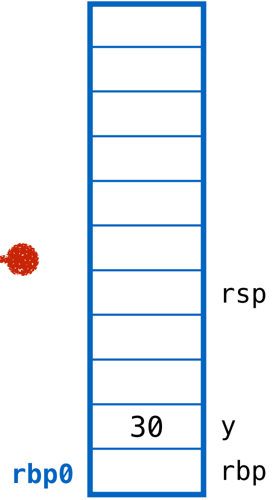
Return (rax) = 30

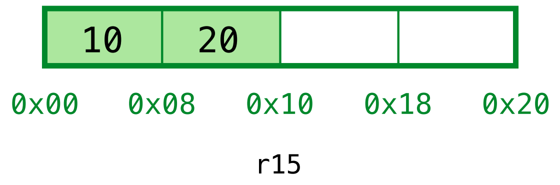


ex3: garbage in the middle (with stack)

```
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
```





ex3: garbage in the middle (with stack)

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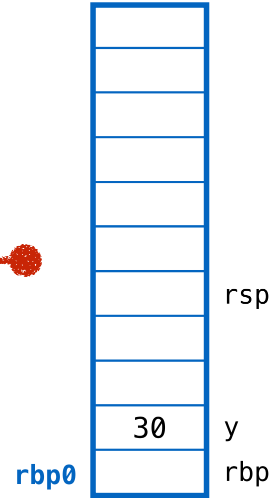
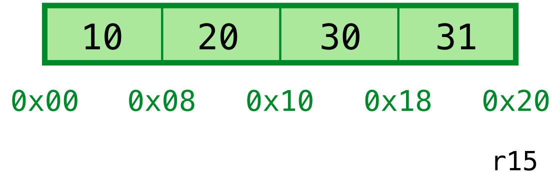
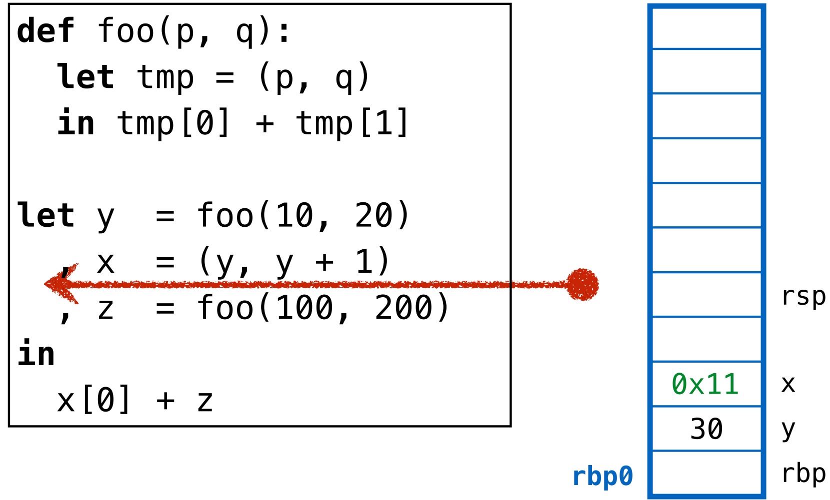
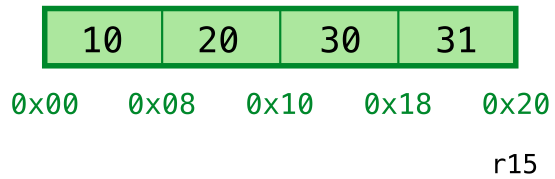
let y  = foo(10, 20)
  , x  = (y, y + 1)
  , z  = foo(100, 200)
in
  x[0] + z
```





ex3: garbage in the middle (with stack)





ex3: garbage in the middle (with stack)

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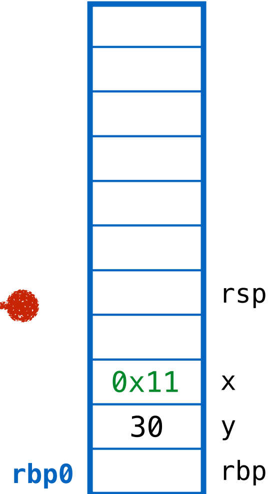
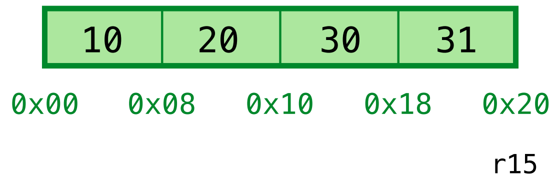
  let tmp = (p, q)
  in tmp[0] + tmp[1]

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

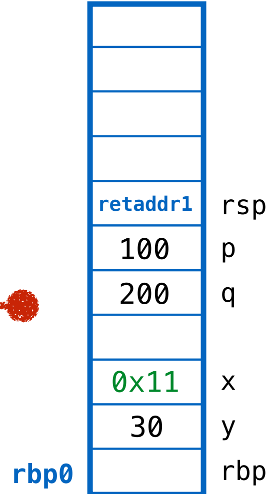


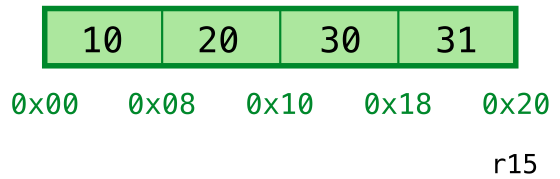


ex3: garbage in the middle (with stack)

```
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
```





ex3: garbage in the middle (with stack)

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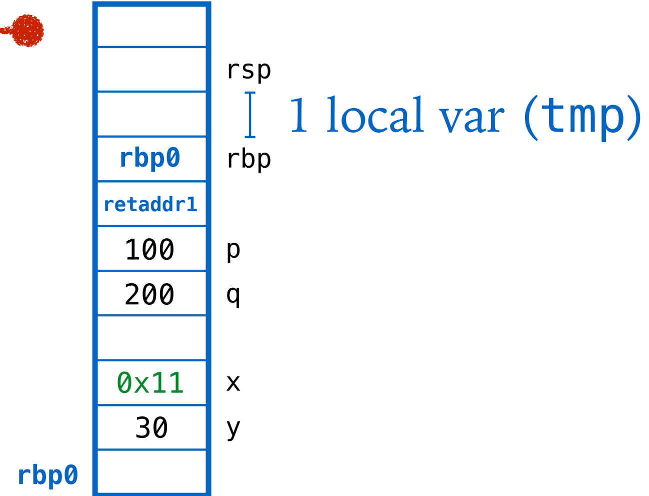
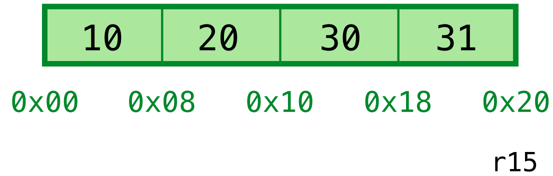
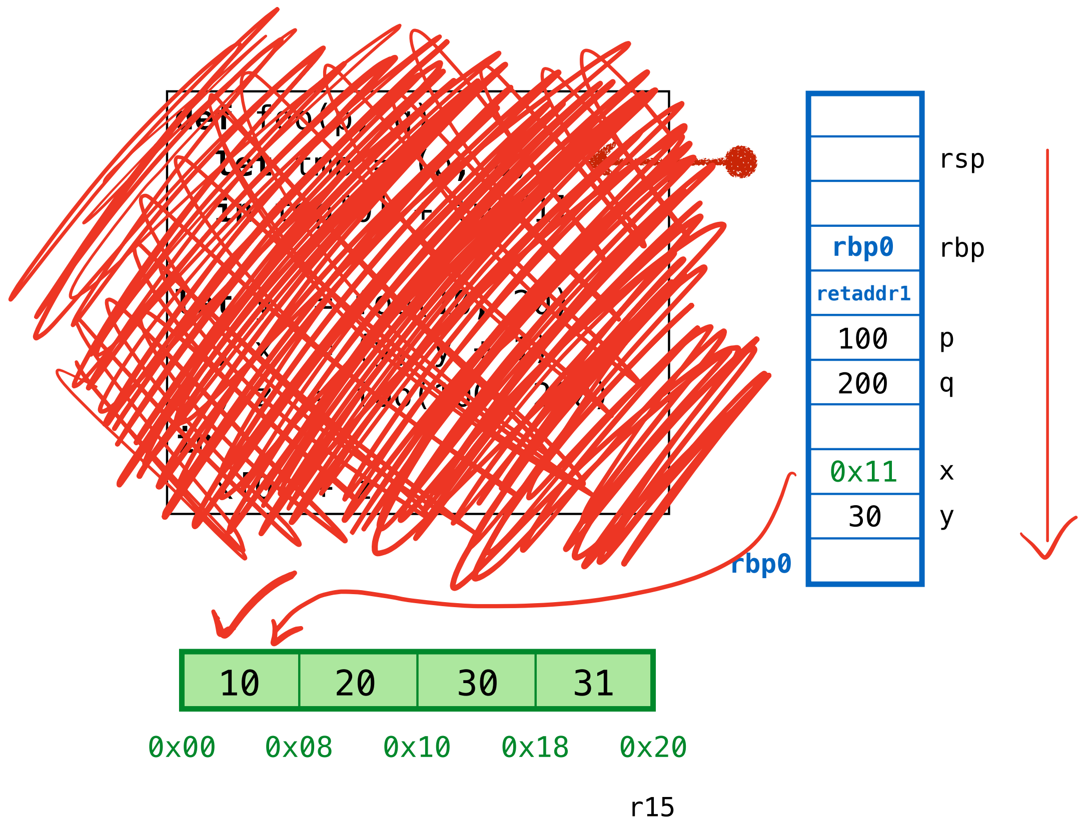
let y  = foo(10, 20)
  , x  = (y, y + 1)
  , z  = foo(100, 200)
in
  x[0] + z
```





ex3: garbage in the middle (with stack)



ex3: garbage in the middle (with stack)

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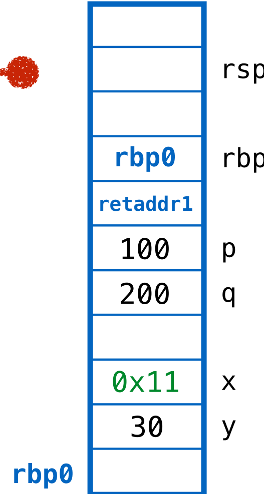
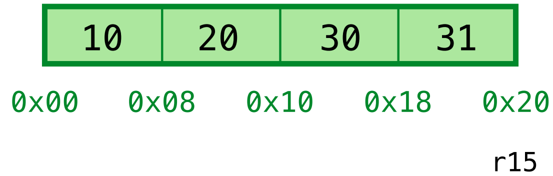
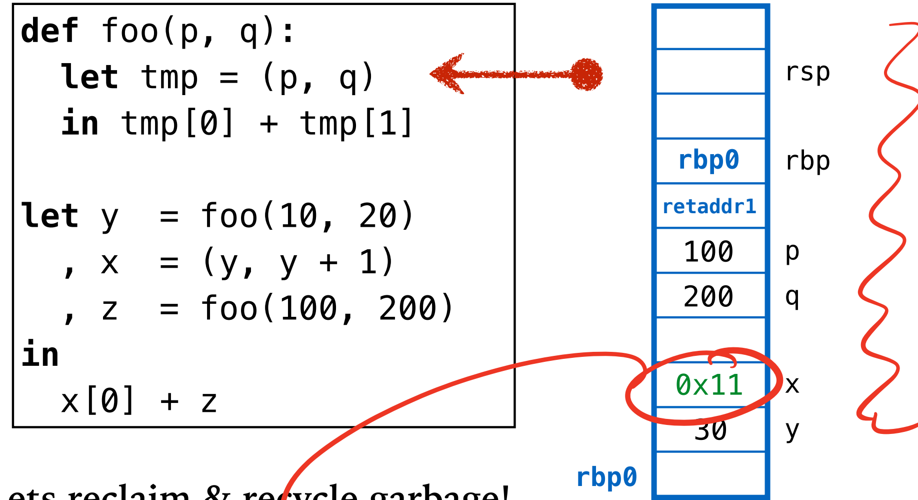
  x[0] + z
```

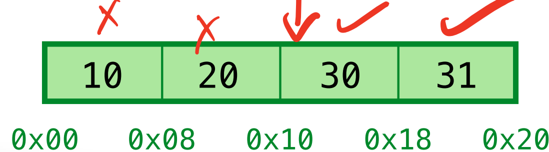


Lets reclaim & recycle garbage!



ex3: garbage in the middle (with stack)





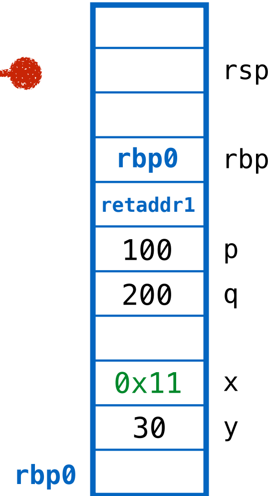
QUIZ: Which cells are garbage?

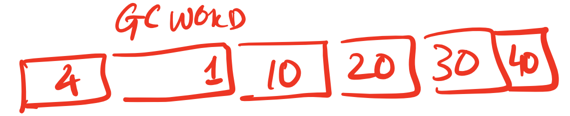
(A) `0x00, 0x08` (B) `0x08, 0x10` (C) `0x10, 0x18` (D) None (E) All

ex3: garbage in the middle (with stack)

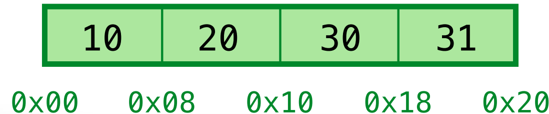
```
def foo(p, q):
  let tmp = (p, q)
  in tmp[0] + tmp[1]

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





Lets reclaim & recycle garbage!



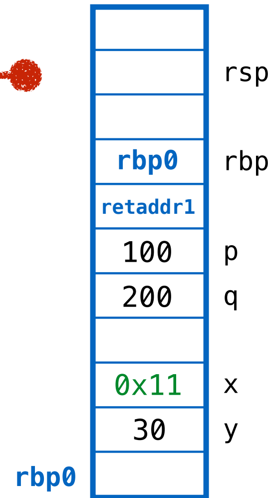
QUIZ: Which cells are garbage?

Those that are *not reachable from any stack frame*

ex3: garbage in the middle (with stack)

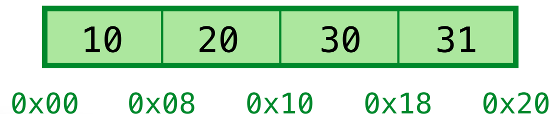
```
def foo(p, q):
  let tmp = (p, q)
  in tmp[0] + tmp[1]

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



Traverse Stack
from top (`rsp`)
to bottom (`rbp0`)
to mark
reachable cells.

Lets reclaim & recycle garbage!



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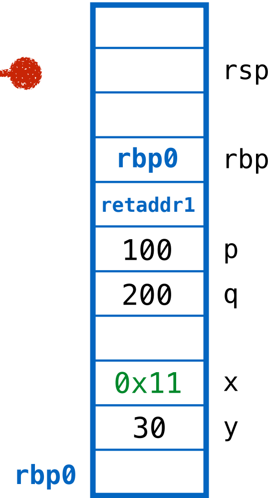
ex3: garbage in the middle (with stack)

```
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
```



Traverse Stack
from top (`rsp`)
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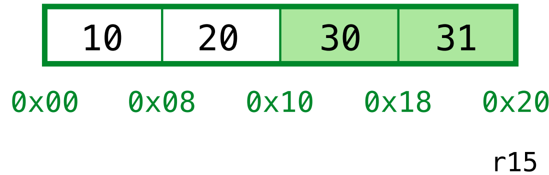
Lets reclaim & recycle garbage!



Which cells are garbage?

ex3: garbage in the middle (with stack)

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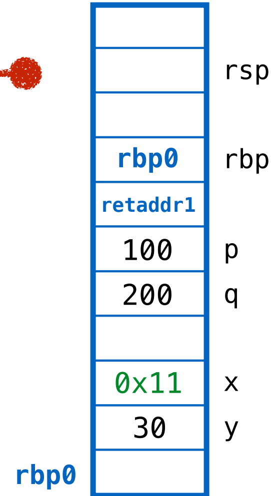
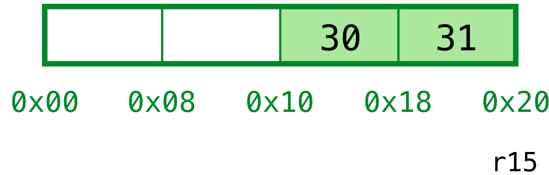
  x[0] + z
```

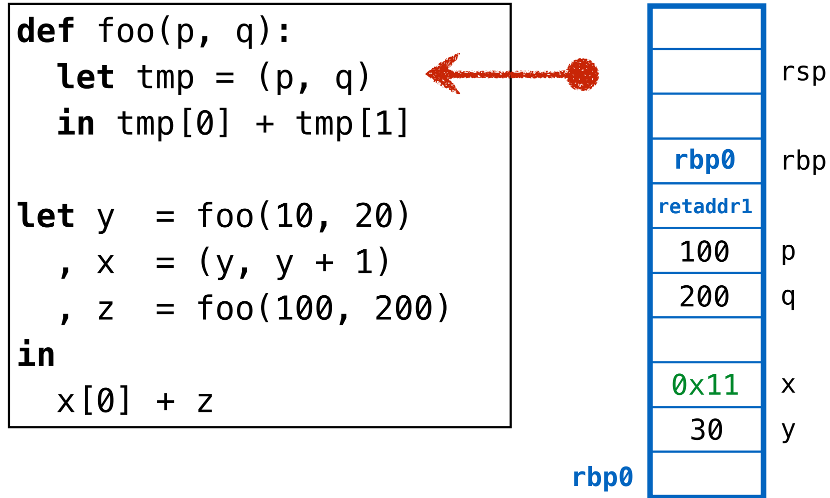


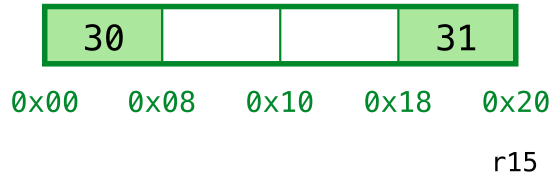


r15

Compact the live cells

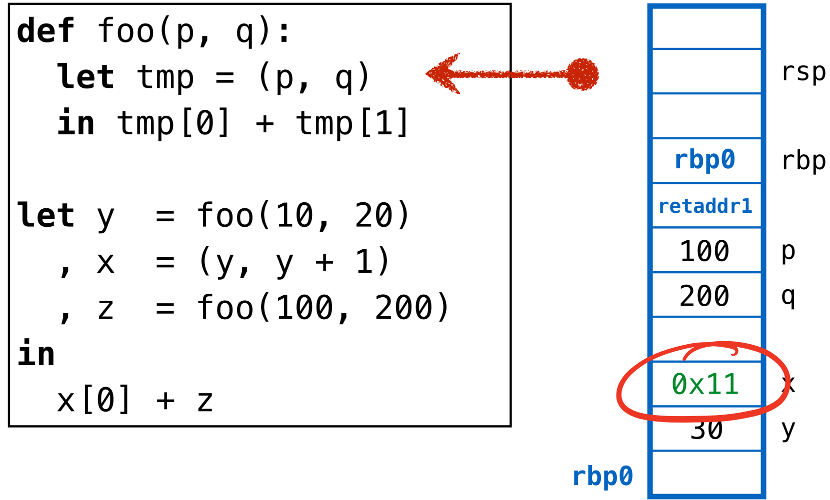
ex3: garbage in the middle (with stack)

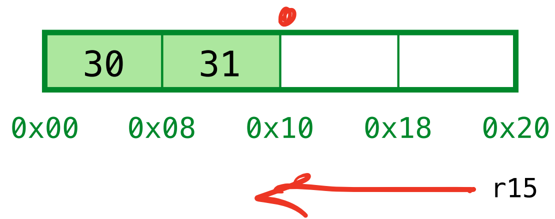




Compact the live cells

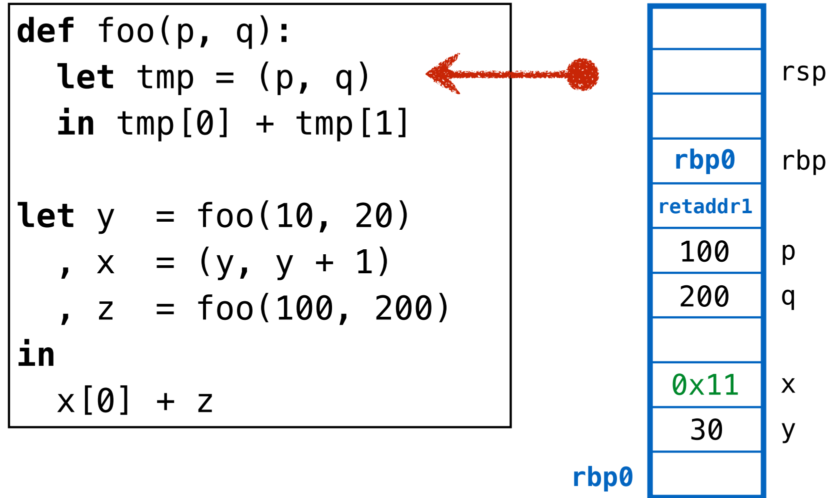
ex3: garbage in the middle (with stack)

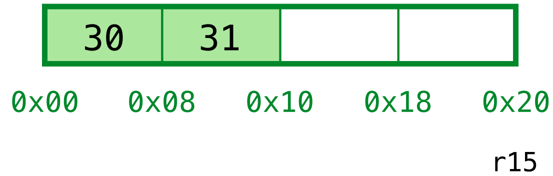




Compact the live cells

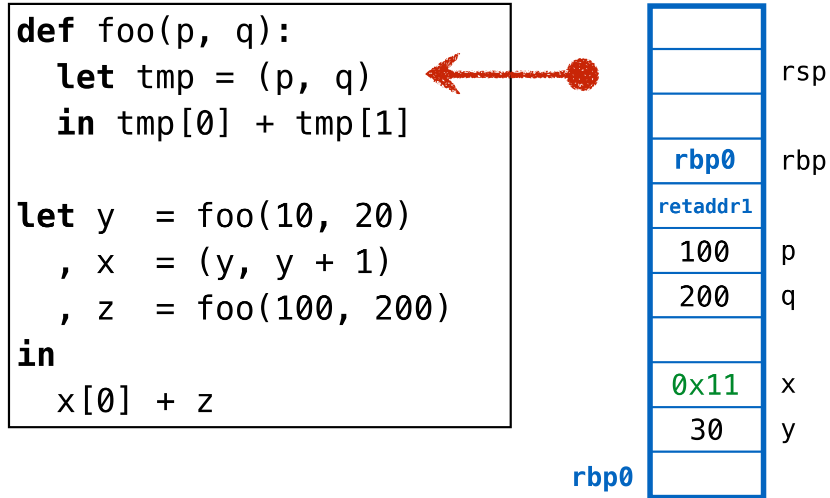
ex3: garbage in the middle (with stack)

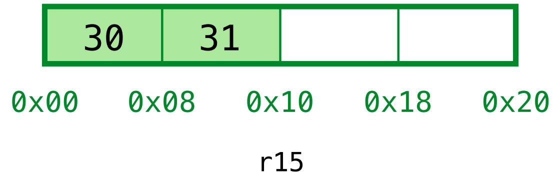




Compact the live cells … then rewind `r15`

ex3: garbage in the middle (with stack)



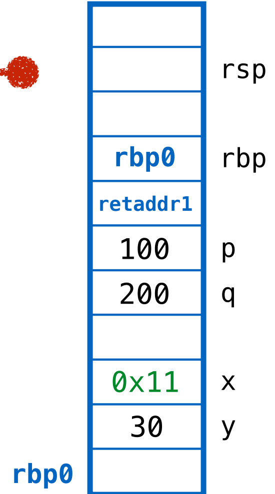


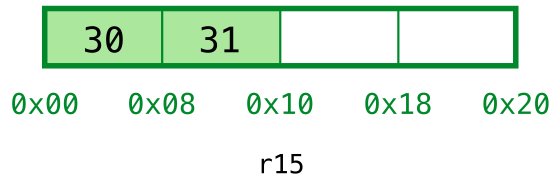
Compact the live cells … then rewind `r15`

ex3: garbage in the middle (with stack)

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

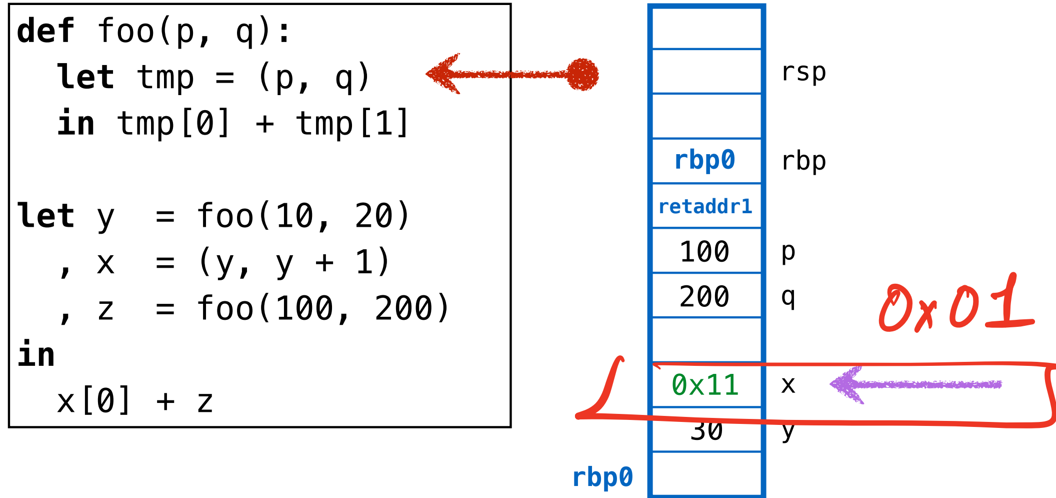
let y  = foo(10, 20)
  , x  = (y, y + 1)
  , z  = foo(100, 200)
in
  x[0] + z
```

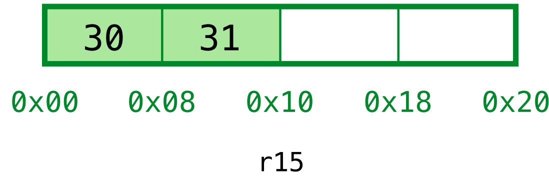




Problem???

ex3: garbage in the middle (with stack)



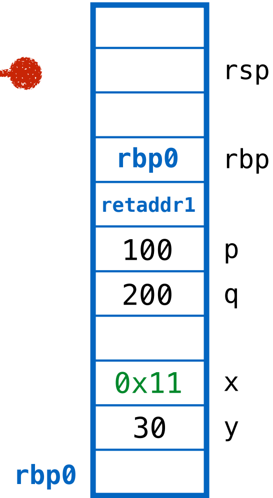


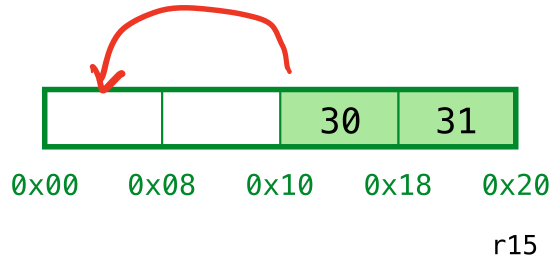
Problem! Have to REDIRECT existing pointers

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
```

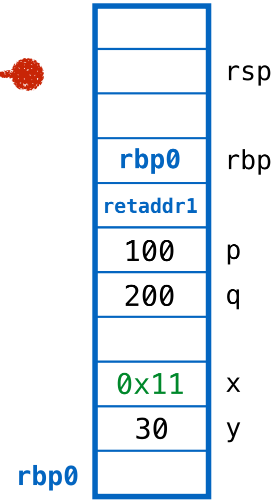


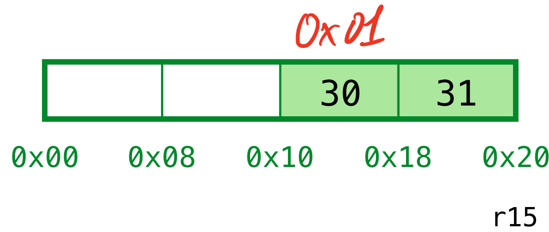


ex3: garbage in the middle (with stack)

```
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
```



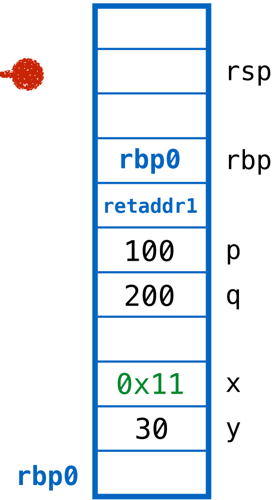


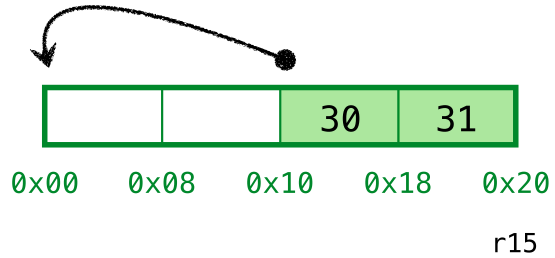
1. Compute FORWARD addrs (i.e. new compacted addrs)

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
```



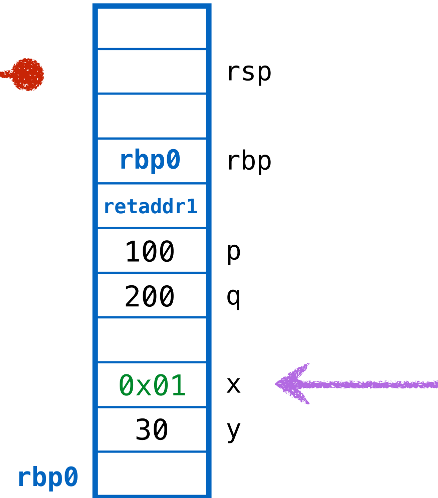


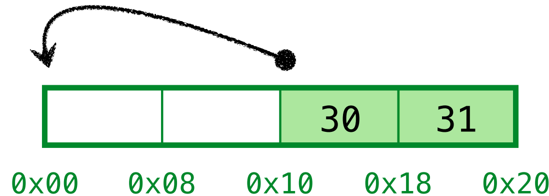
1. Compute FORWARD addrs
   e.g. 0x11 —> 0x01

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
```





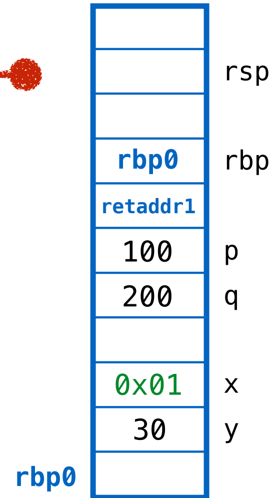
r15

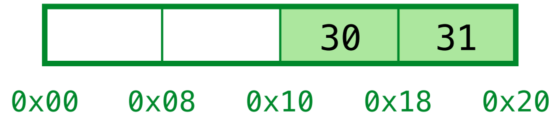
1. Compute FORWARD addrs
   e.g. 0x11 —> 0x01
2. REDIRECT addrs on stack

ex3: garbage in the middle (with stack)

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

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



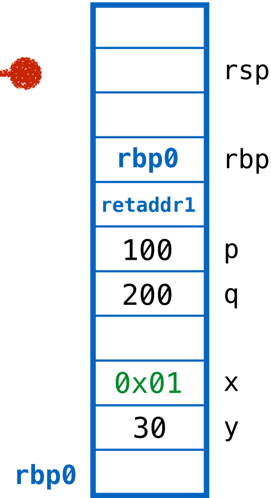


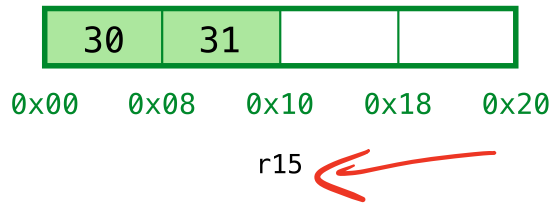
1. Compute FORWARD addrs
   e.g. 0x11 —> 0x01
2. REDIRECT addrs on stack
3. COMPACT cells on heap

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
```





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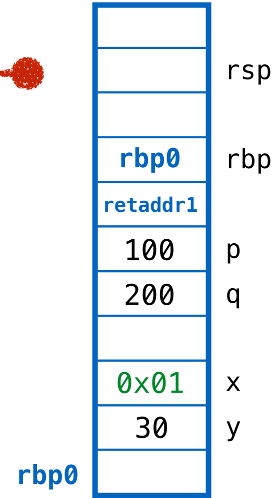
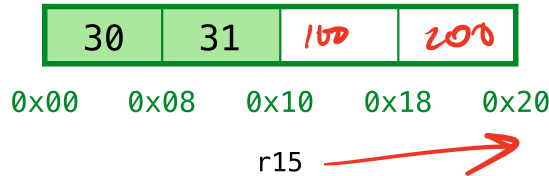
let y  = foo(10, 20)
  , x  = (y, y + 1)
  , z  = foo(100, 200)
in
  x[0] + z
```



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

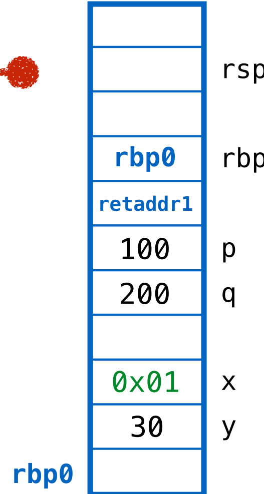


ex3: garbage in the middle (with stack)

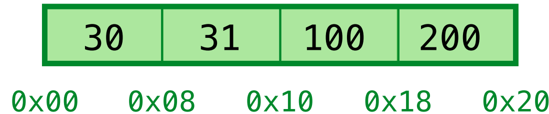
```
def foo(p, q):
  let tmp = (p, q)
  in tmp[0] + tmp[1]

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

300



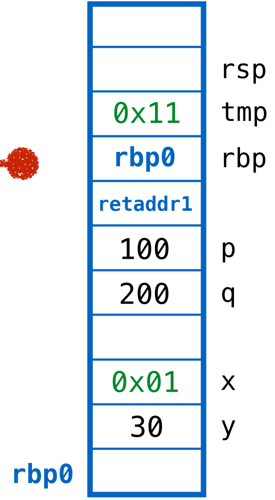
Yay! Have space for `(p, q)`



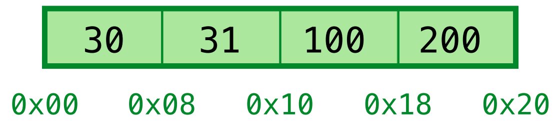
ex3: garbage in the middle (with stack)

```
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
```



Return (rax) = 300



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
```

330

Return (rax) = 300

30	31	100	200

0x00 0x08 0x10 0x18 0x20

	rsp
300	z
0x01	x
30	y
	rbp

r15

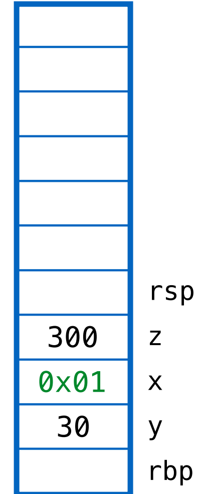
2

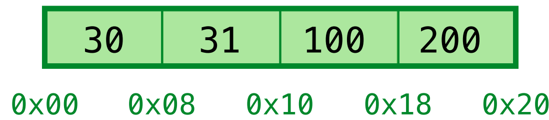
4

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
```



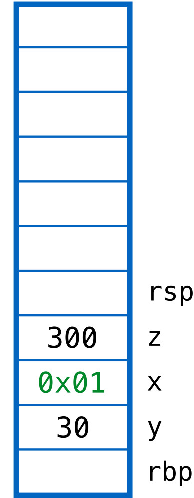


r15

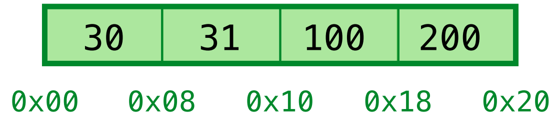
ex3: garbage in the middle (with stack)

```
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
```



Return (rax) = 30+300 = 330



Garter / GC

Example 4

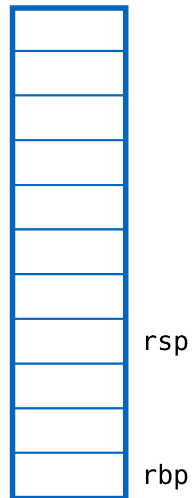
ex4: recursive data

range(0,3) ⇝ (0, (1, (2, false))) 3

```
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)
```



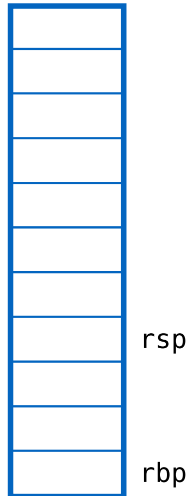
r15

ex4: recursive data

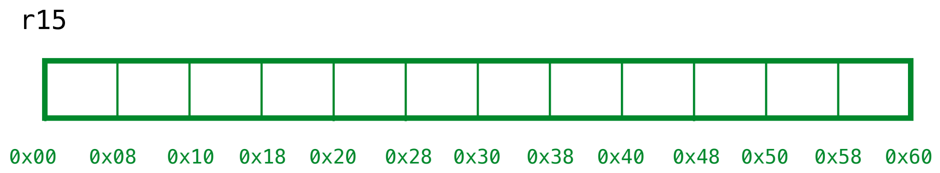
```
def range(i, j):
  if (j <= i): false else: (i,range(i+1, j))

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)
```



call range(0, 3)



(vec e_1 e_2)

- bob ← r11; r11 += 16

<< e_1 >>

mov tmp_1, rax

<< e_2 >>

mov tmp_2, rax

[bob] ← tmp_1
[bob+8] ← tmp_2

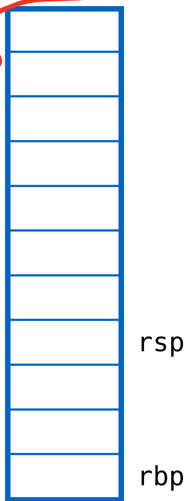
ex4: recursive data

```
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])

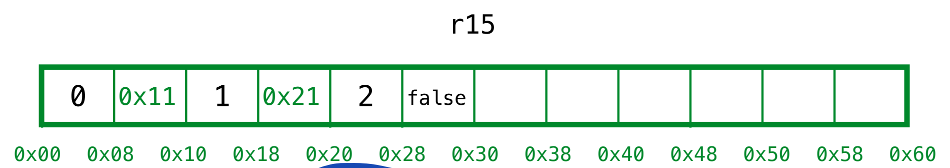
let t1 =
          let l1 = range(0, 3)
          in sum(l1)
  , l  = range(t1, t1 + 3)
in
  (1000, l)
```

let tail = range (i+1, j)
in (i, tail)

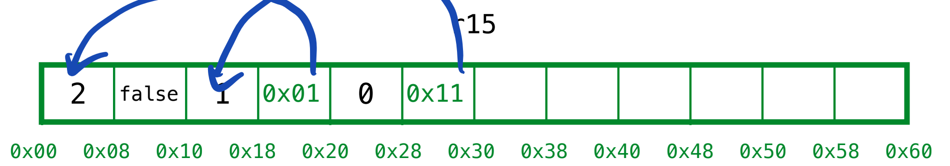


QUIZ: What is heap when `range(0,3)` returns?

(A)



(B)



ex4: recursive data

① Midterm
3p Fri 5/29

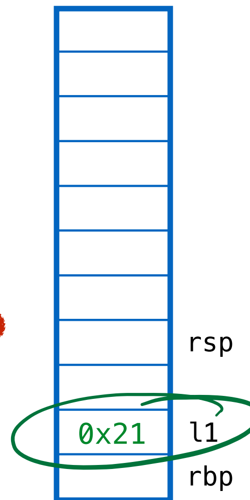
② Assignments are all on homepage

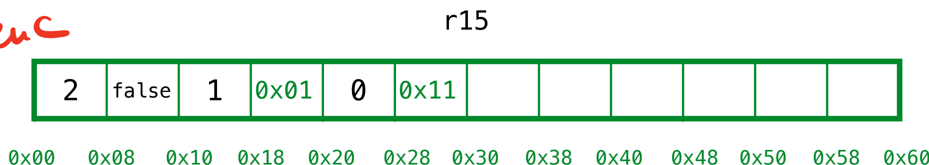
③ - GC
Register Alloc
Type Inference

```
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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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)
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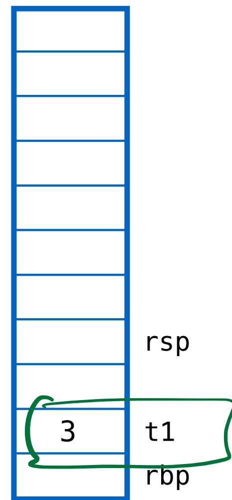
  (1000, l)
```



Result sum(0x11) = 3

r15

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

ex4: recursive data

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  (1000, l)
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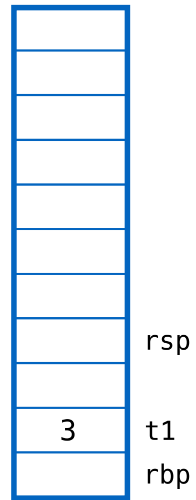
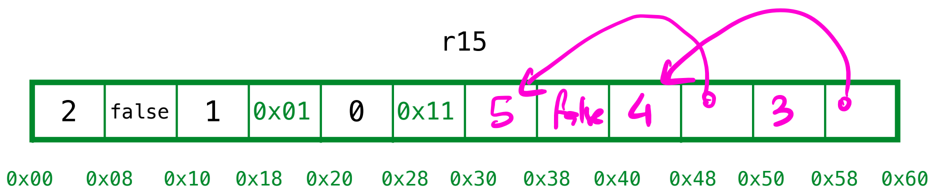
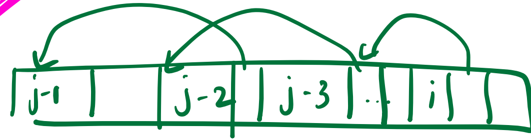




ex4: recursive data

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  (1000, l)
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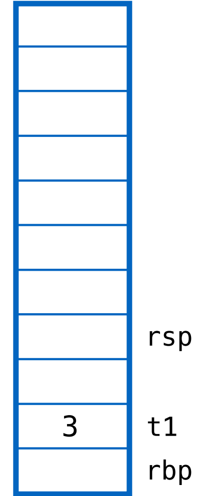
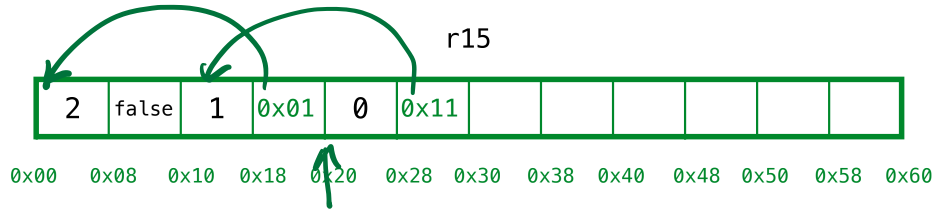


call range(3,6)



ex4: recursive data

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

	rsp
???	l
3	t1
	rbp

call range(3,6)

r15

2	false	1	0x01	0	0x11	5	false	4	0x31	3	0x41

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

QUIZ: What is the value of l?

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

ex4: recursive data

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

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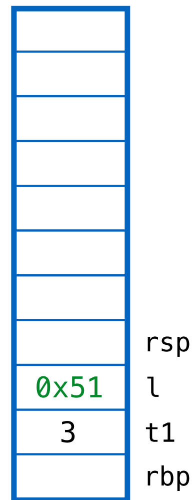
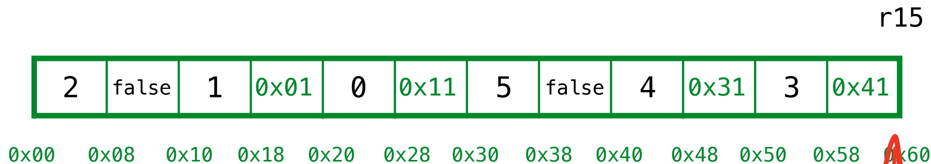


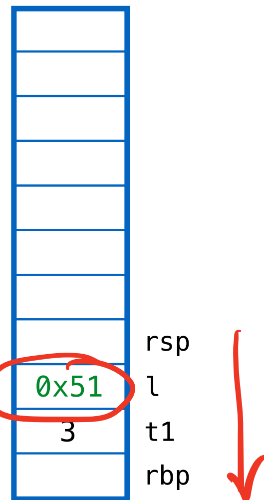
Yikes! Out of Memory!

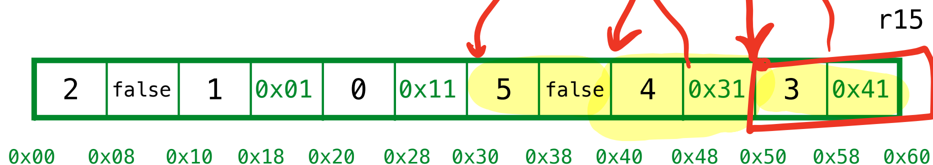


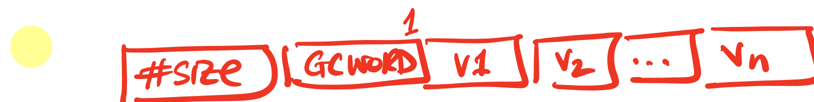
ex4: recursive data

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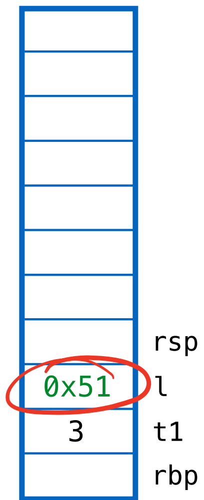

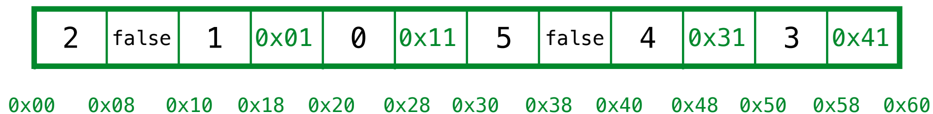

1. MARK live addrs
2. Compute FORWARD addrs
3. REDIRECT addrs on stack &heap
4. COMPACT cells on heap

ex4: recursive data

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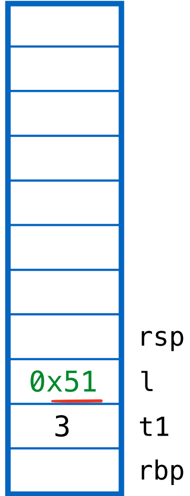
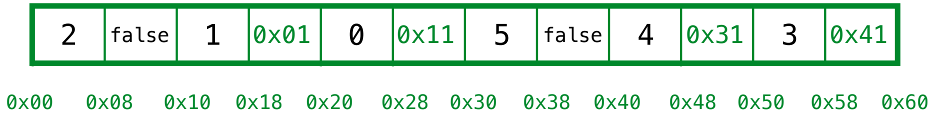


r15



1. MARK live addrs

reachable from stack

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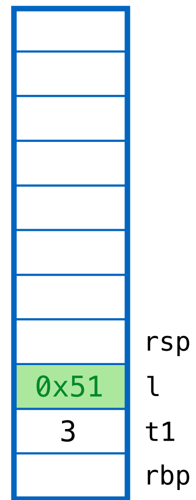
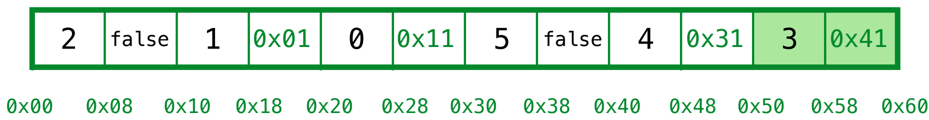


r15



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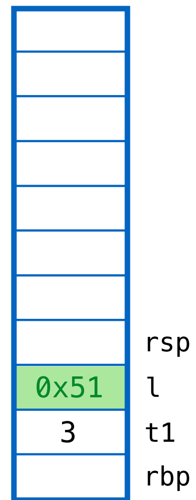

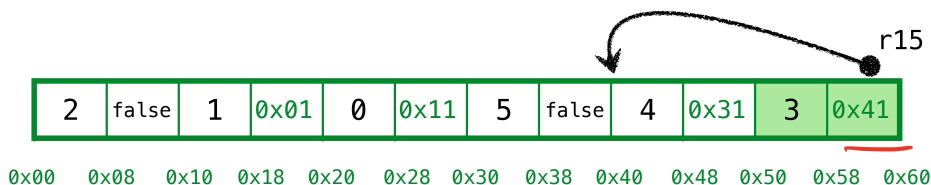

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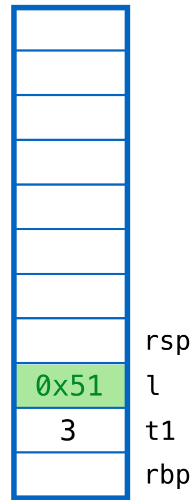

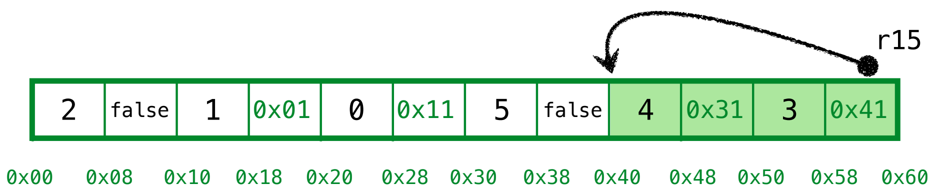

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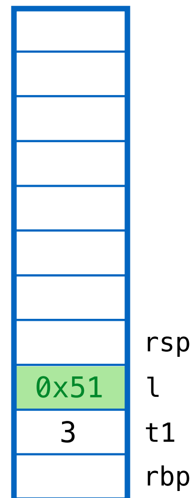

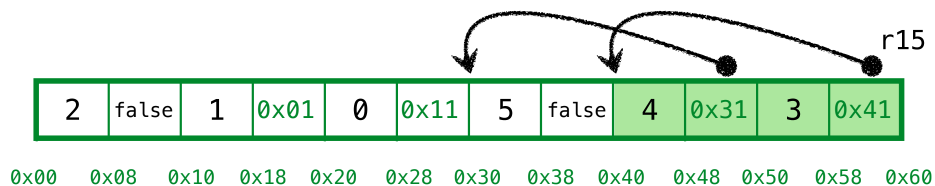

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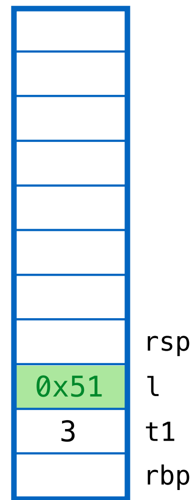

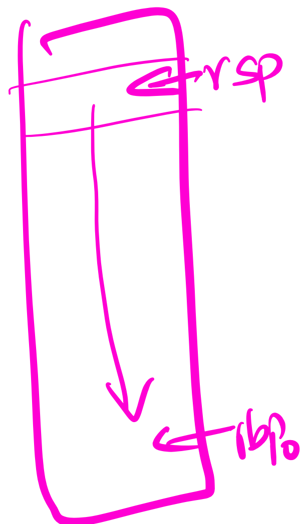

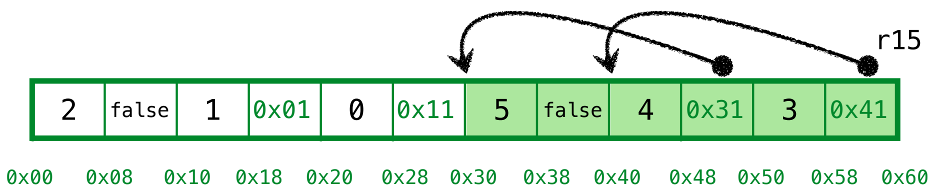

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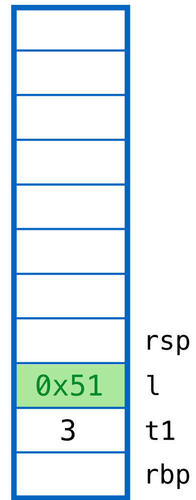

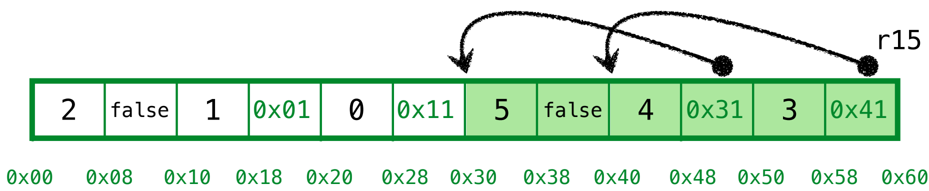

Done!

ex4: recursive data

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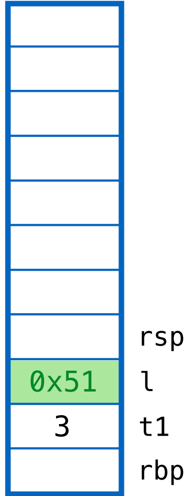

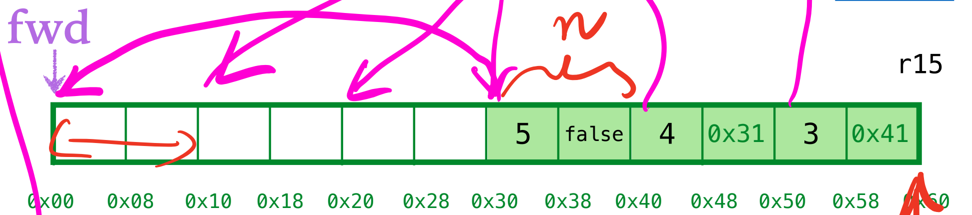

2. Compute FORWARD addrs

ex4: recursive data

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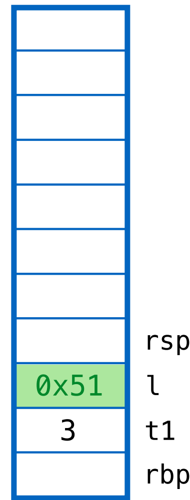

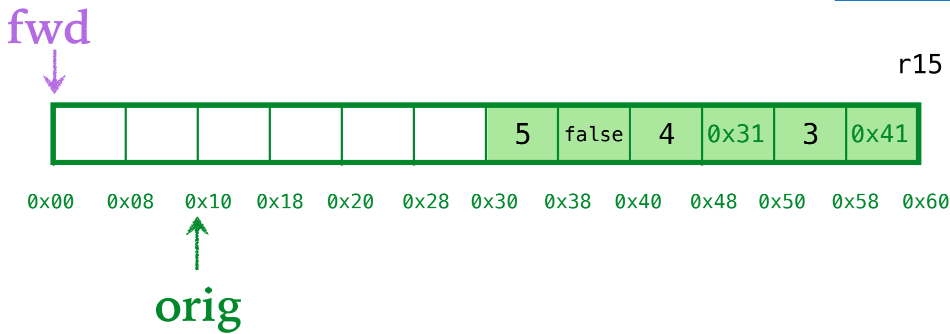

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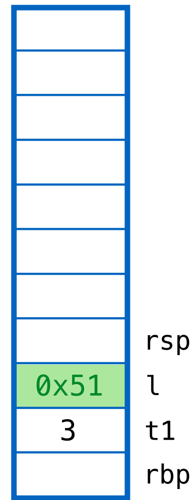

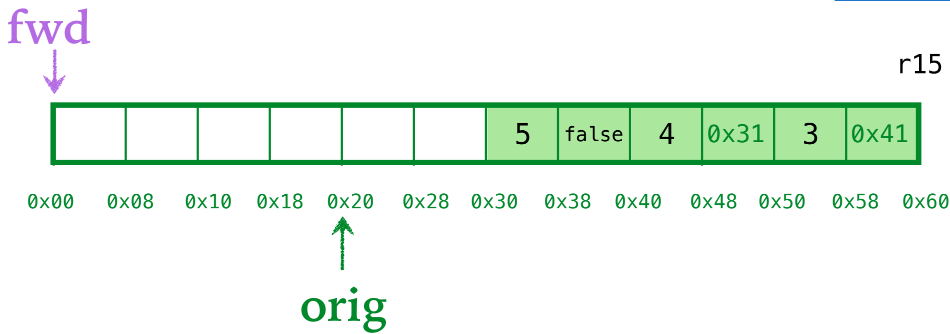

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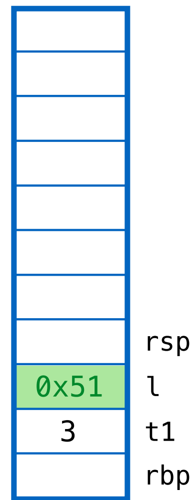

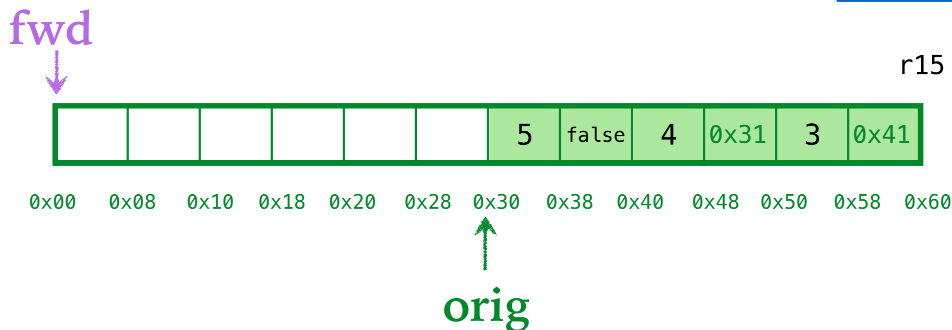

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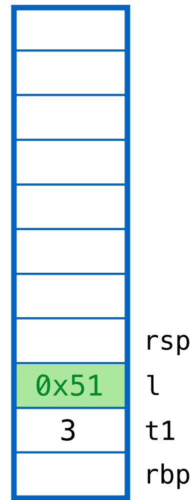

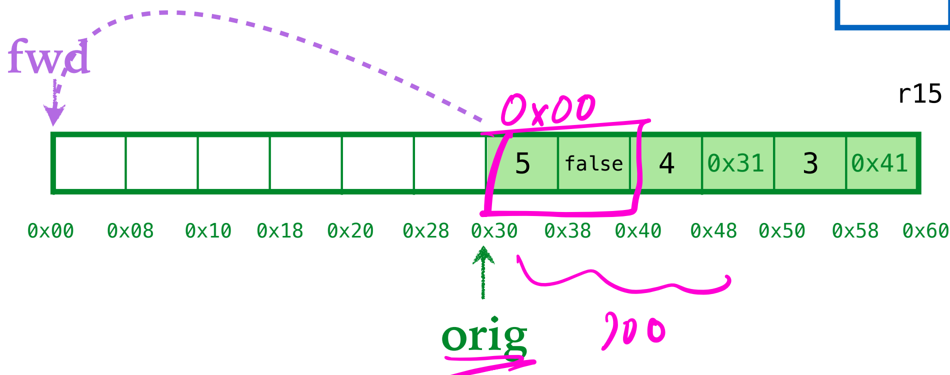

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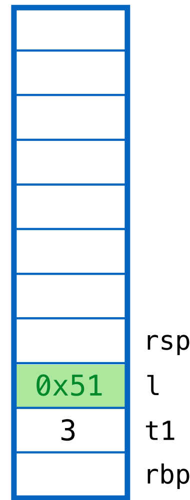

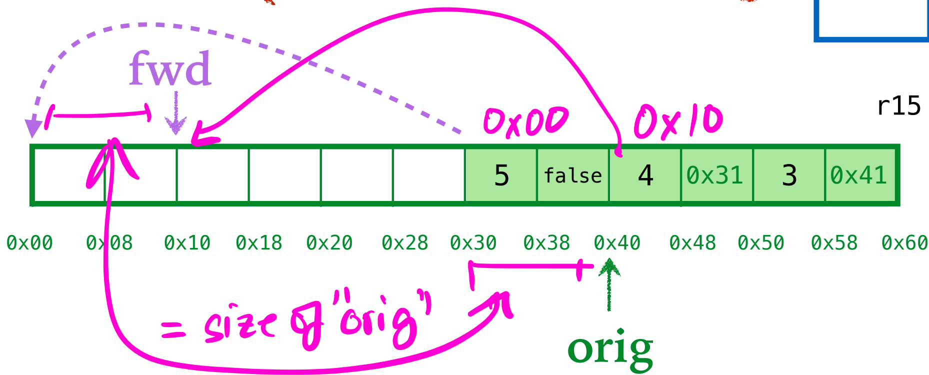

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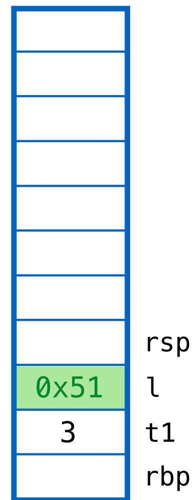

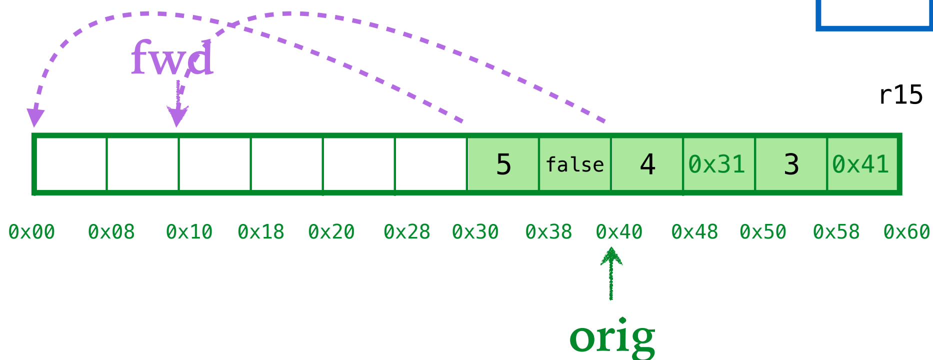

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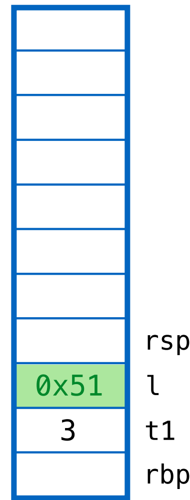
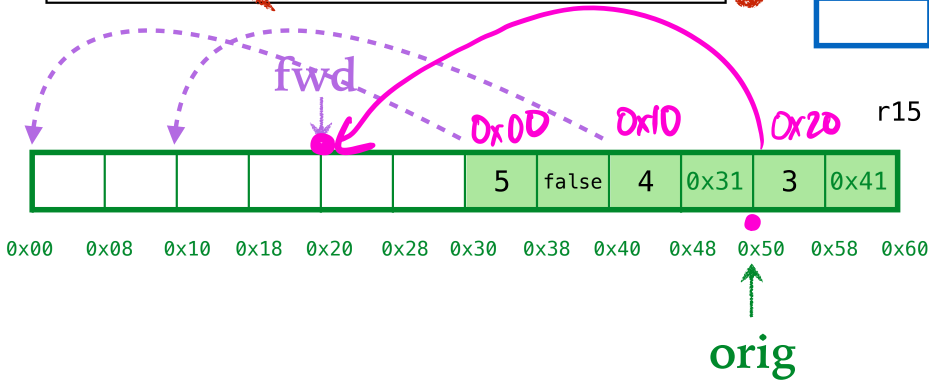
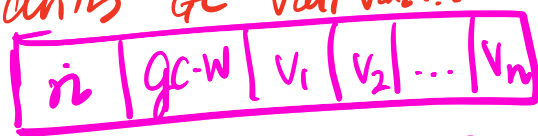




2. Compute FORWARD addrs

ex4: recursive data



gc-word ≡ 0 when normal exec
= 1 if live, o.w. after mark

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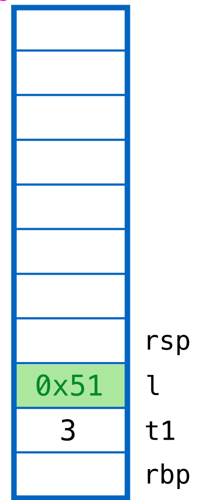
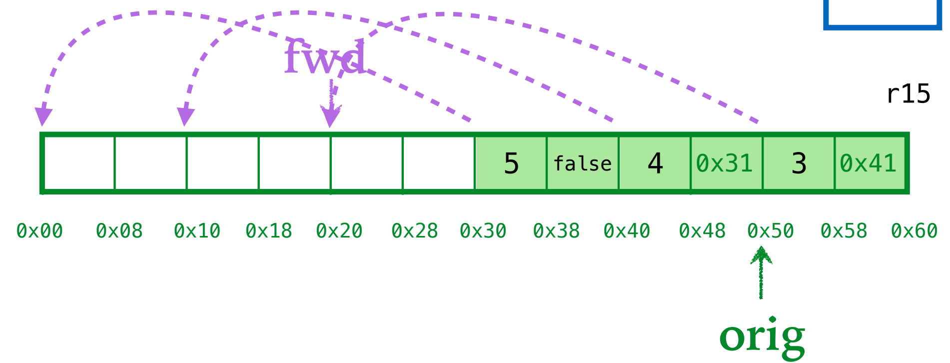
  , l  = range(t1, t1 + 3)
in
  (1000, l)
```





2.Compute FORWARD addrs

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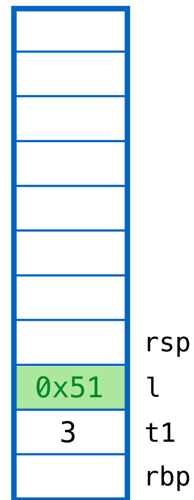

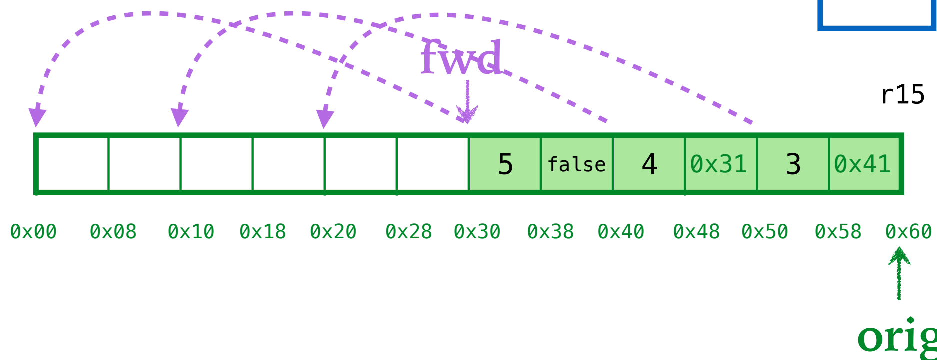

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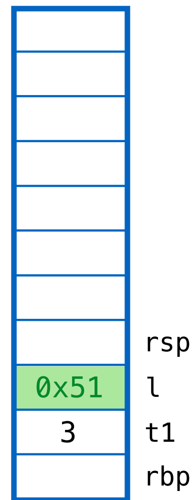

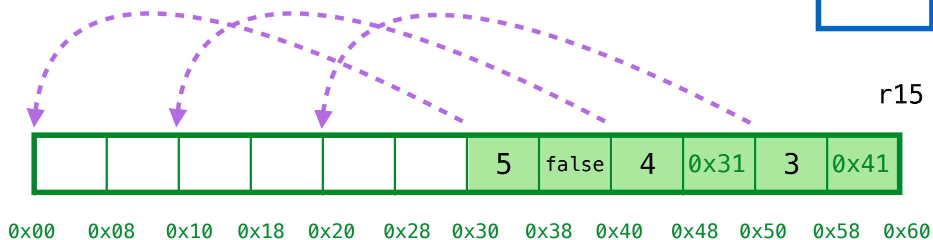

2. Compute FORWARD addrs

Where should we store the forward addrs?

ex4: recursive data

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

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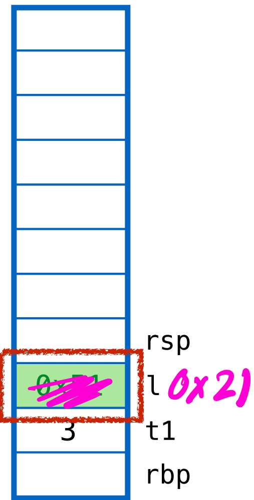
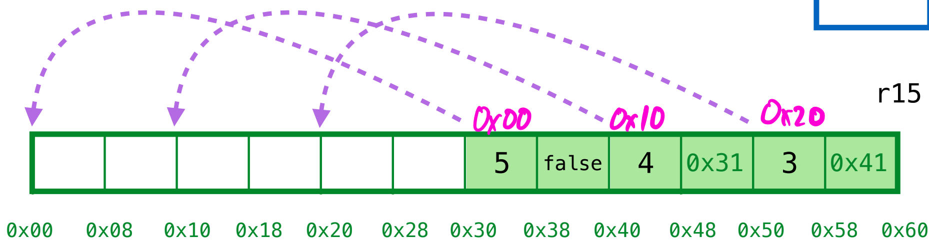
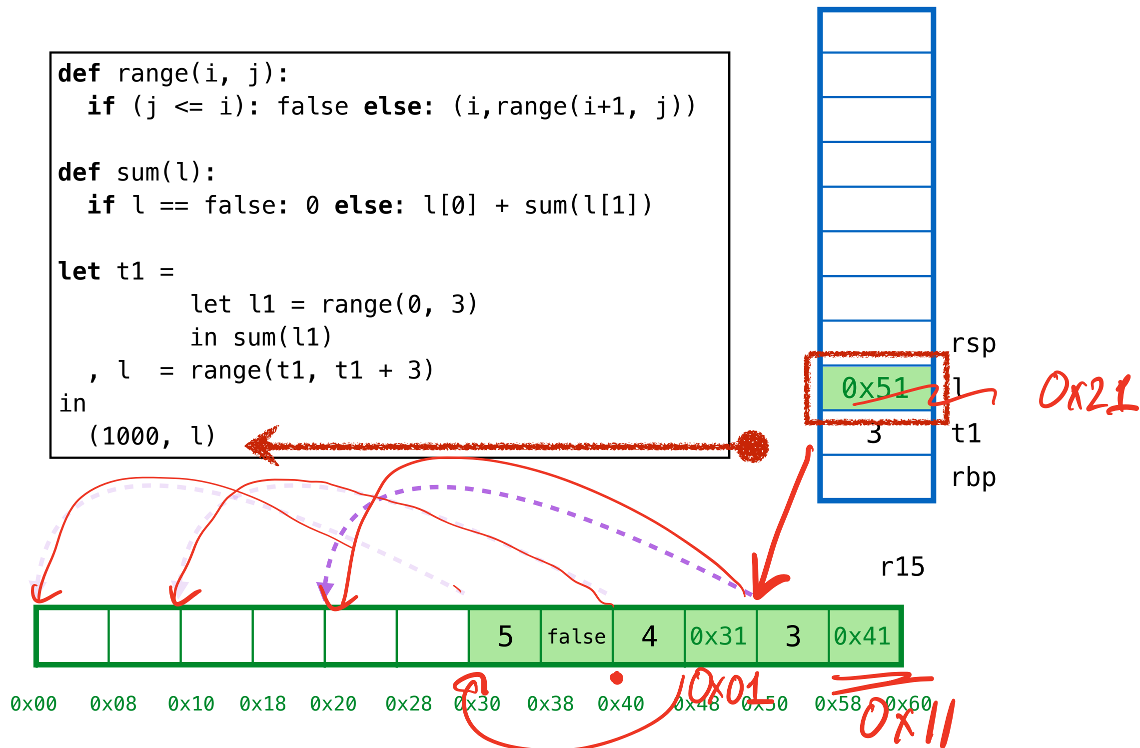
```





3. REDIRECT addrs on stack

ex4: recursive data



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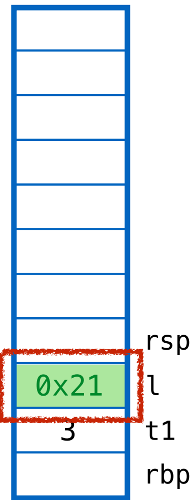
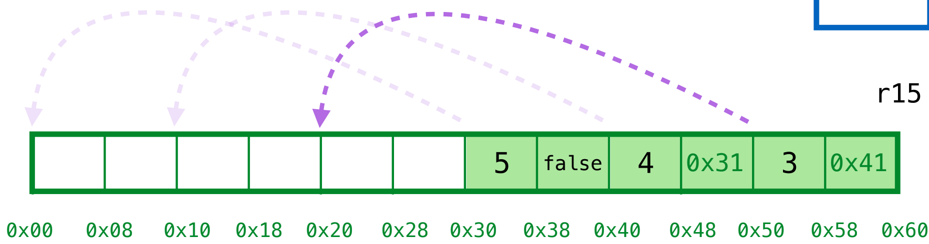
```





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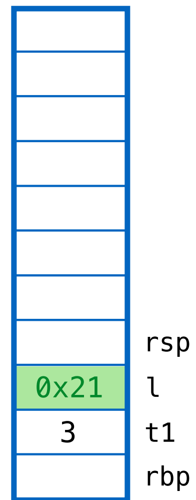
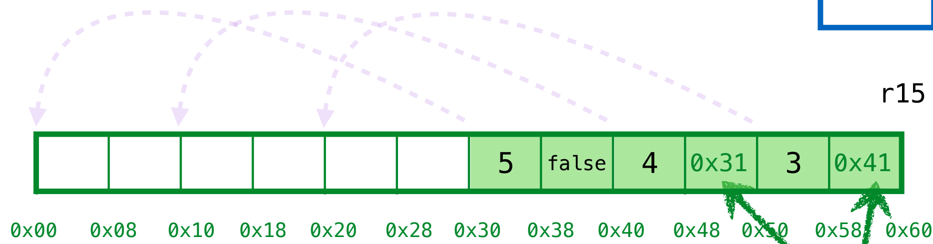
```





3. REDIRECT addrs on stack and heap!

ex4: recursive data

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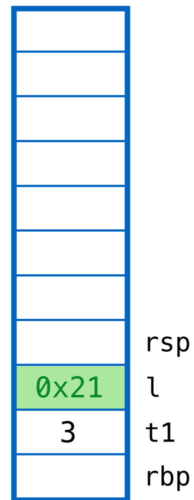
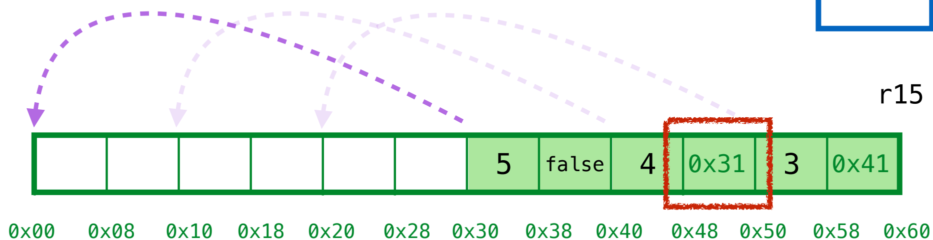
  (1000, l)
```





3. REDIRECT addrs on stack and heap!

ex4: recursive data

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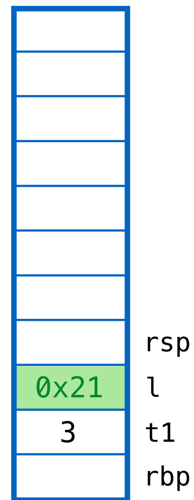
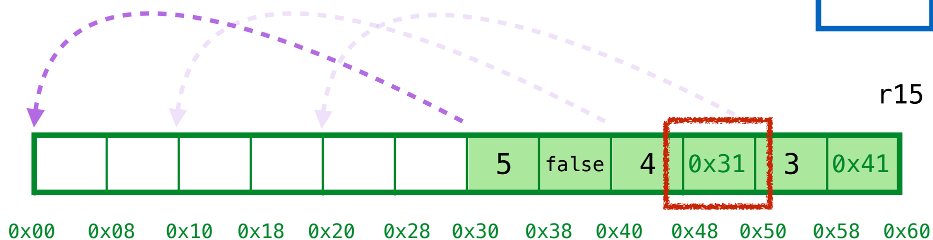
  (1000, l)
```





3. REDIRECT addrs on stack and heap!

ex4: recursive data

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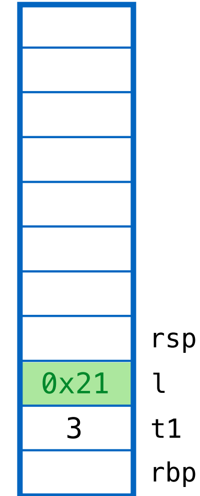
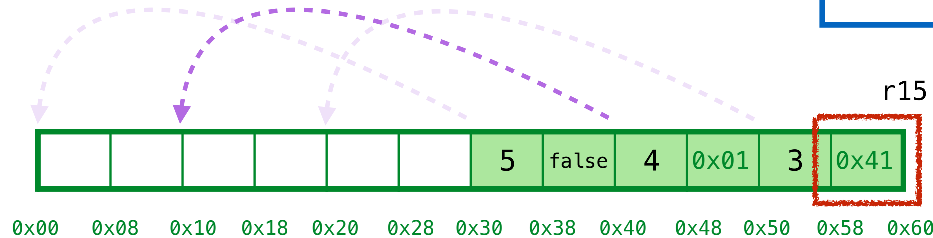
  , l  = range(t1, t1 + 3)
in
  (1000, l)
```

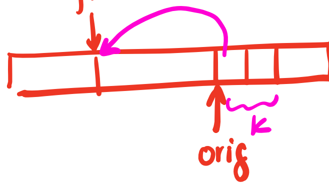




3. REDIRECT addrs on stack and heap!

fwd

ex4: recursive data



orig + k < MAX
fwd < orig
fwd + k < MAX

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

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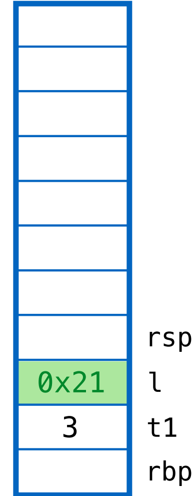

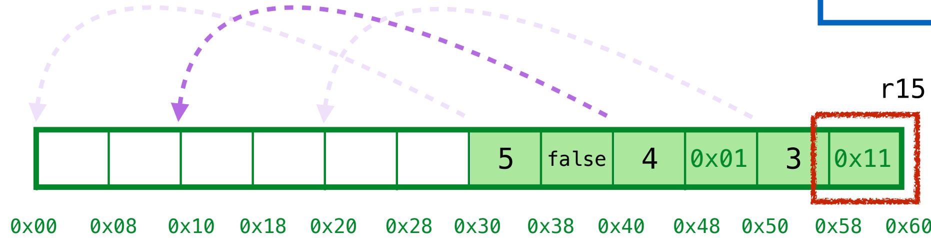

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ex4: recursive data

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  (1000, l)
```

rsp	
l	0x21
t1	3
rbp	

r15

0x00	0x08	0x10	0x18	0x20	0x28	0x30	0x38	0x40	0x48	0x50	0x58
						5	false	4	0x01	3	0x11

0x60

4. COMPACT cells on heap

Copy cell to forward addr!

ex4: recursive data

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  (1000, l)
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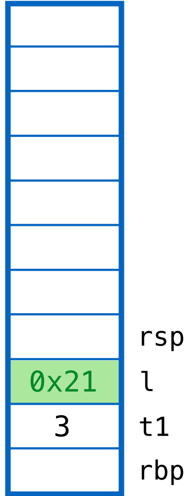

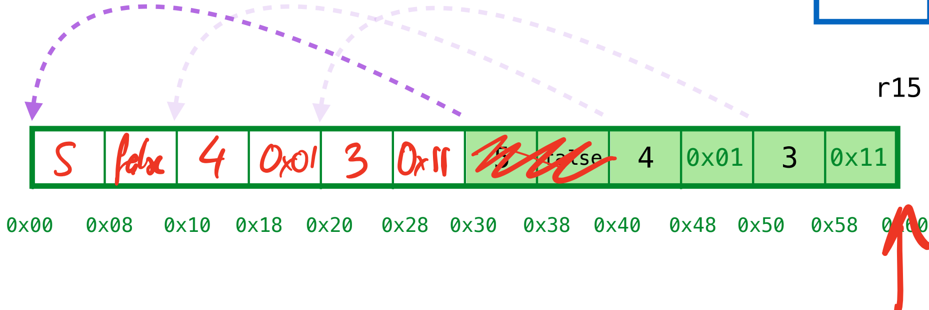

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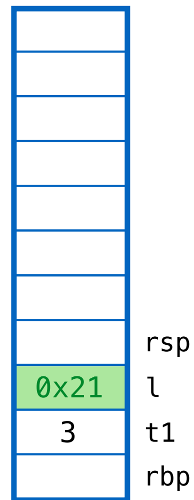

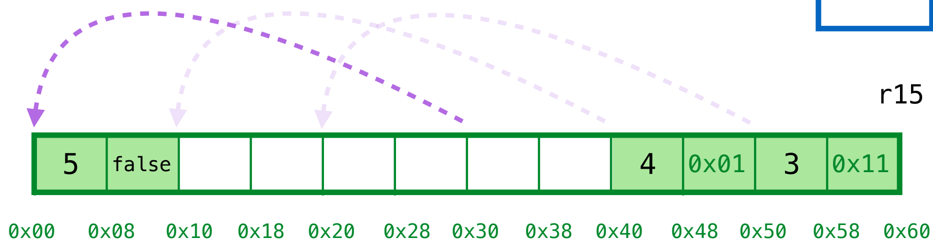

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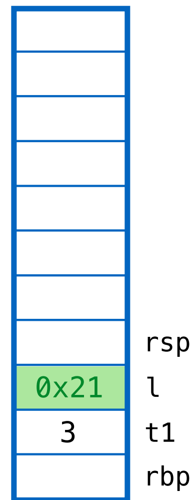

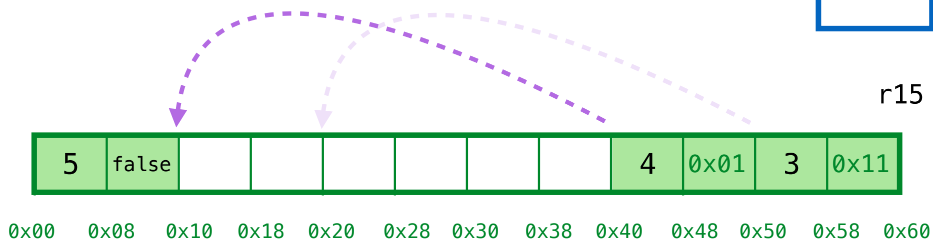

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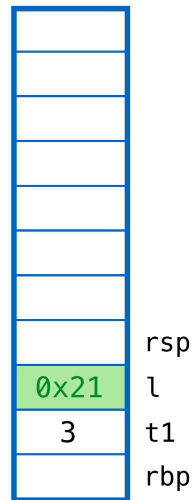

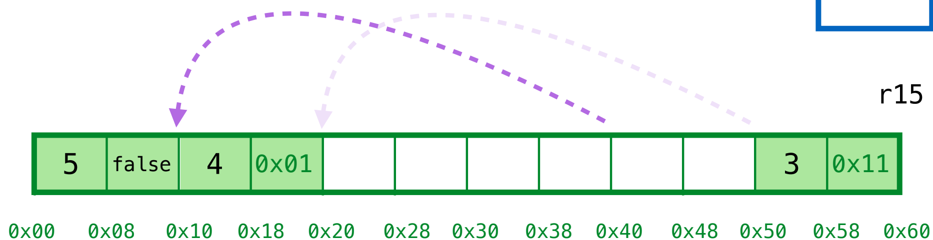

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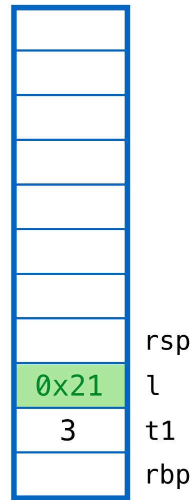

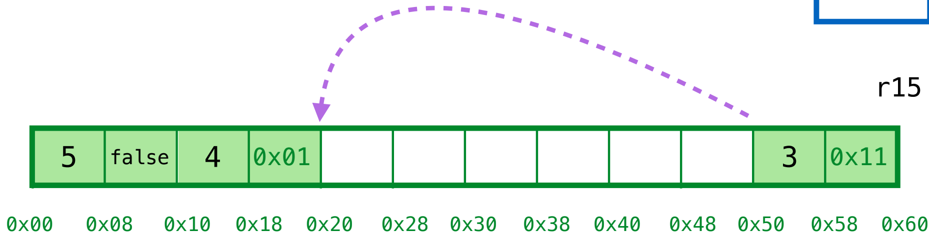

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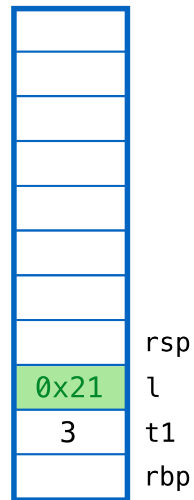

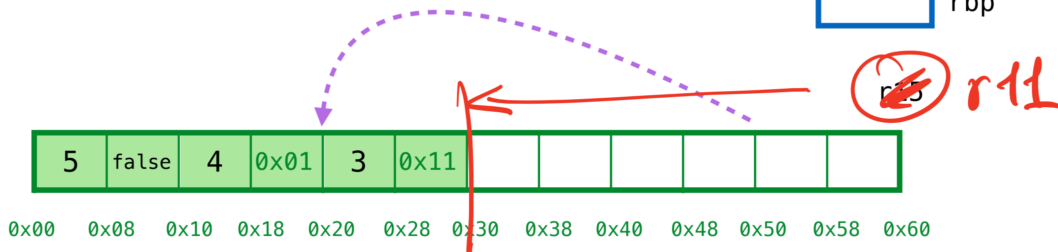

4. COMPACT cells on heap

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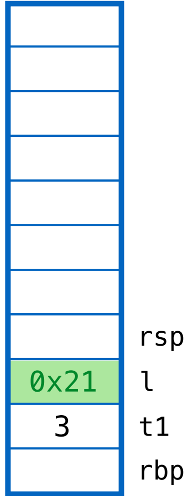

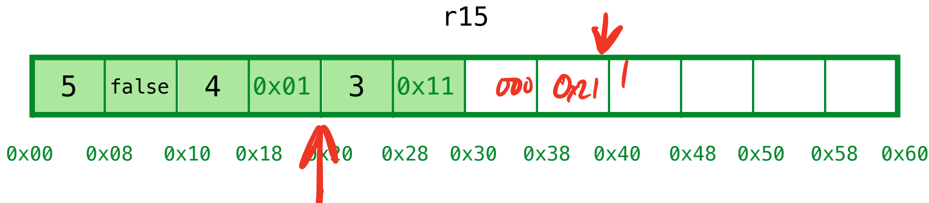

GC Complete!

Have space for `(1000, l)`

ex4: recursive data

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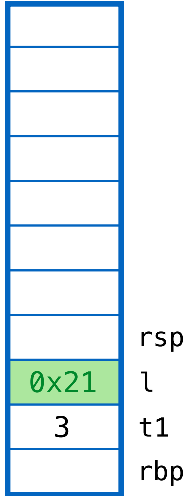
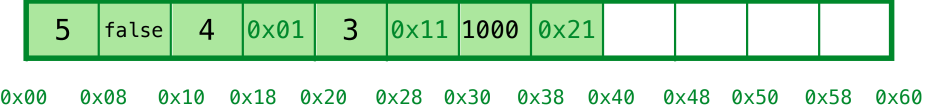


r15



GC Complete!

Have space for `(1000, l)`

ex4: recursive data

QUIZ: What should `print(0x21)` show?

```
(A) (0, (1, (2, false)))
(B) (3, (4, (5, false)))
(C) (0, (1, (2, (3, (4, (5, false))))))
(D) (3, (4, (5, (0, (1, (2, false))))))
(E) (2, (1, (0, (3, (4, (5, false))))))
```

Stack	
	rsp
0x21	l
3	t1
	rbp

r15

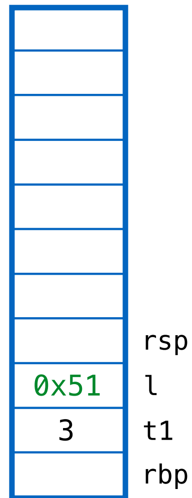
③		②		①		⑥		⑤		④	
2	0x51	1	0x01	0	0x11	5	false	4	0x31	3	0x41
0x00	0x08	0x10	0x18	0x20	0x28	0x30	0x38	0x40	0x48	0x50	0x58

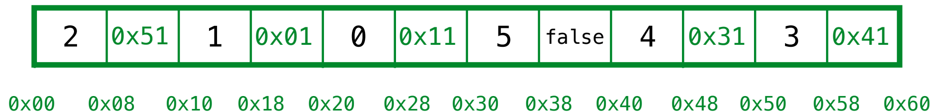
0x60

ex4: recursive data

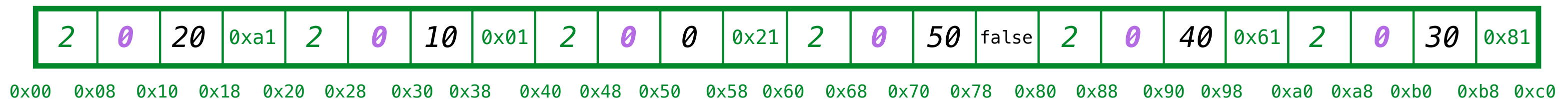
QUIZ: Which cells are “live” on the heap?

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





Heap



Stack