# Part I

# Allocation

Constructor calls are allocation:

```
(define (interp)
  (type-case ExpD expr-reg
    ....
    [(lamD body-expr)
     (begin
       (set! v-reg (closV body-expr env-reg))
       (continue))]
    ....))

(define (continue)
  ....
  [(plusSecondK r env k)
   (begin
     (set! expr-reg r)
     (set! env-reg sc)
     (set! k-reg (doPlusK v-reg k))
     (interp))]
  ....)
```

# Deallocation

Where does **`free`** go?

```
(define (continue)
  ....
  [(doPlusK v1 k)
   (begin
     (set! v-reg (num+ v1 v-reg))
     (free k-reg) ; ???
     (set! k-reg k)
     (continue))]
  ....
  [(doAppK fun-val k)
   (begin
     (set! expr-reg (closV-body fun-val))
     (set! env-reg (cons v-reg
                         (closV-env fun-val)))
     (set! k-reg k)
     (free fun-val) ; ???
     (interp))]
  ....)
```

# Deallocation

```
[(doPlusK v1 k)
 (begin
   (set! v-reg (num+ v1 v-reg))
   (free k-reg) ; ???
   (set! k-reg k)
   (continue))]
```

- Without **`let/cc`**, this free is fine, because the continuation can't be referenced anywhere else
- A continuation object is always freed as **`(free k-reg)`**, which is why many language implementations use a stack

# Deallocation

```
[(doAppK fun-val k)
 (begin
   (set! expr-reg (closV-body fun-val))
   (set! env-reg (cons v-reg
                       (closV-env fun-val)))
   (set! k-reg k)
   (free fun-val) ; ???
   (interp))]
```

- This free is *not* ok, because the closure might be kept in a environment somewhere
- Need to free only if no one else is using it...

# Code and Data

An ***object*** is any record allocated during `interp` and `continue`

Assume that expressions are allocated “statically”

- `compile` uses `code-malloc1`, etc.
- Only try to free objects allocated during `interp` and `continue`

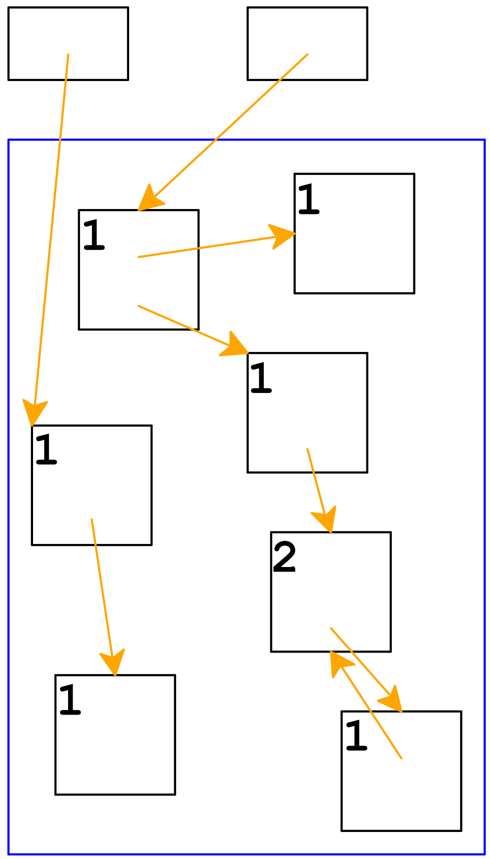
# Part 2

# Reference Counting

***Reference counting:*** a way to know whether an object has other users

- Attatch a count to every object, starting at 0
- When installing a pointer to an object (into a register or another object), increment its count
- When replacing a pointer to an object, decrement its count
- When a count is decremented to 0, decrement counts for other objects referenced by the object, then free

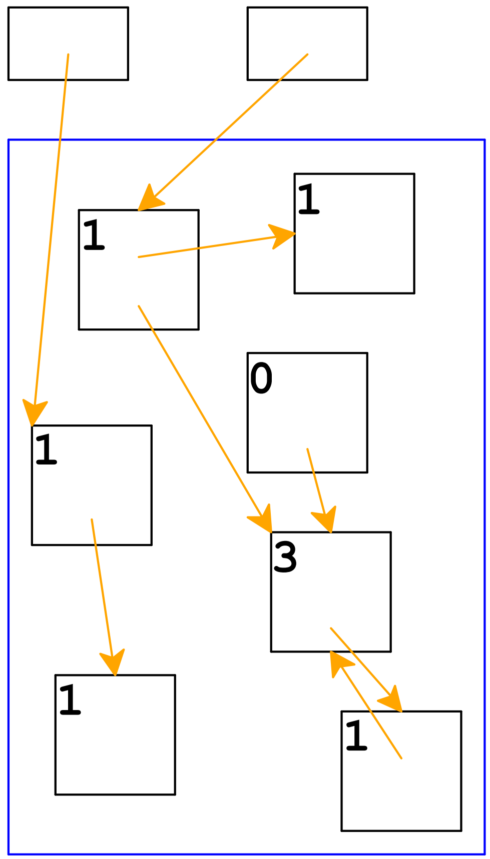
# Reference Counting




Top boxes are the registers **`k-reg`**, **`v-reg`**, etc.

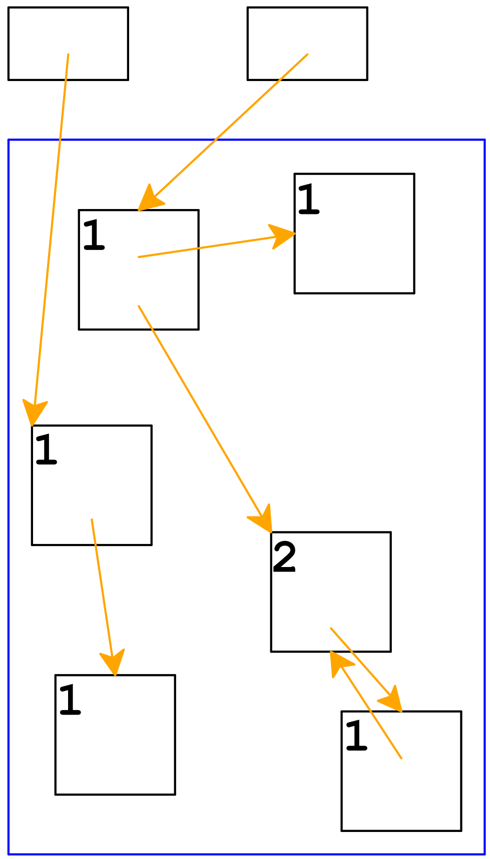
Boxes in the blue area are allocated with **`malloc`**

# Reference Counting



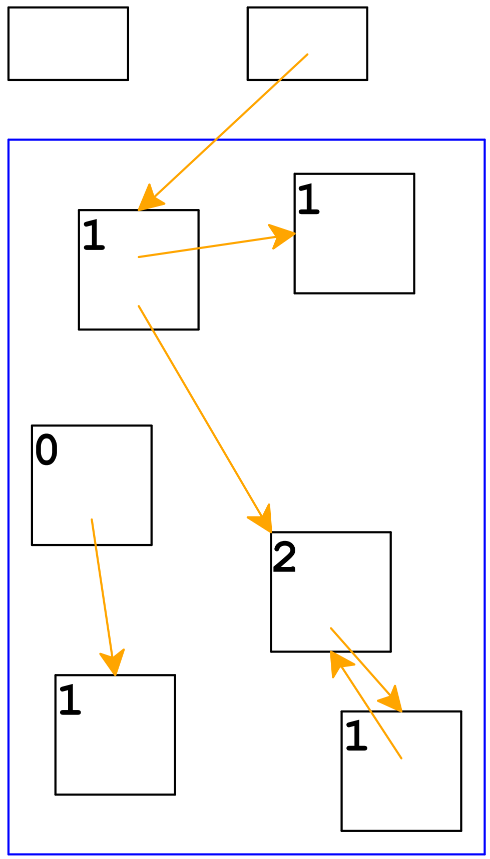

Adjust counts when a pointer is changed...

# Reference Counting



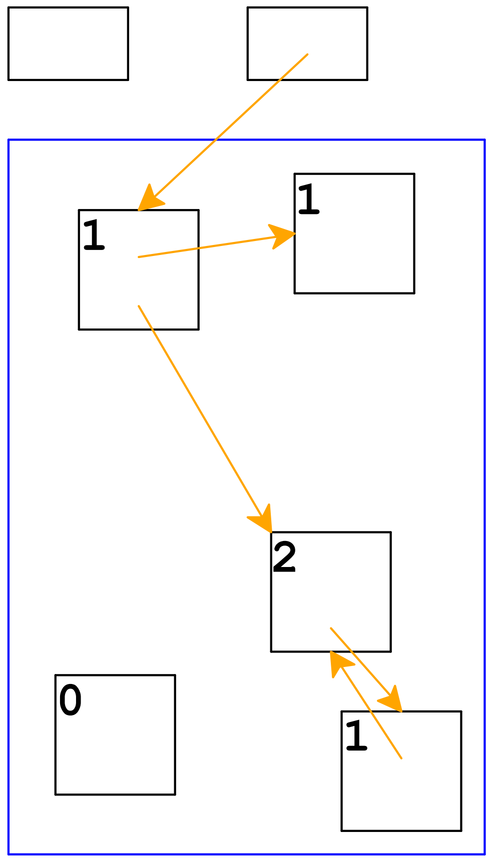

... freeing an object if its count goes to 0

# Reference Counting



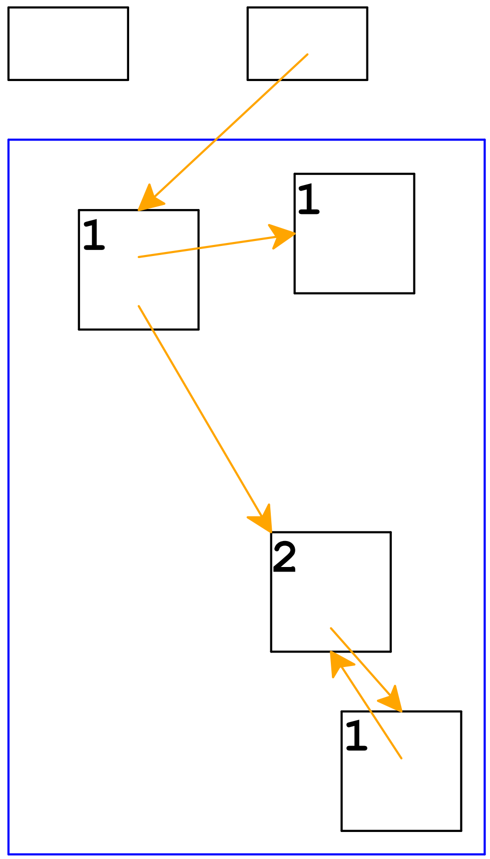

Same if the pointer is in a register

# Reference Counting




Adjust counts after frees, too...

# Reference Counting

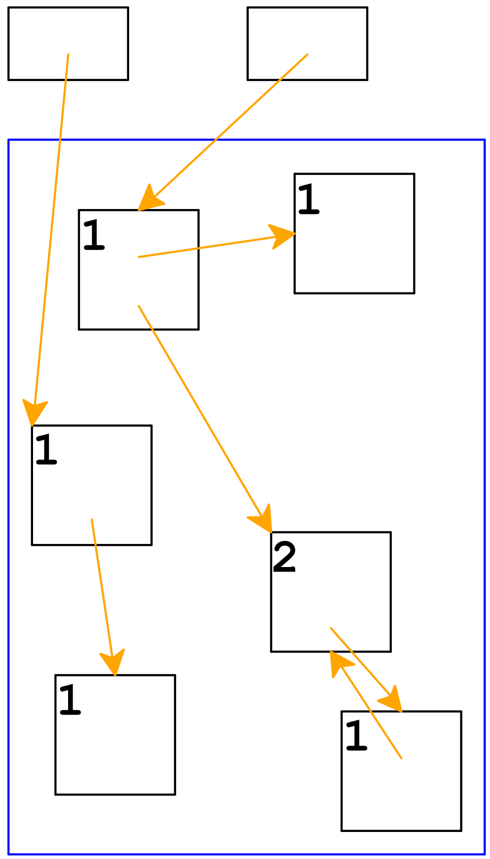



... which can trigger more frees

# Reference Counting in an Interpreter

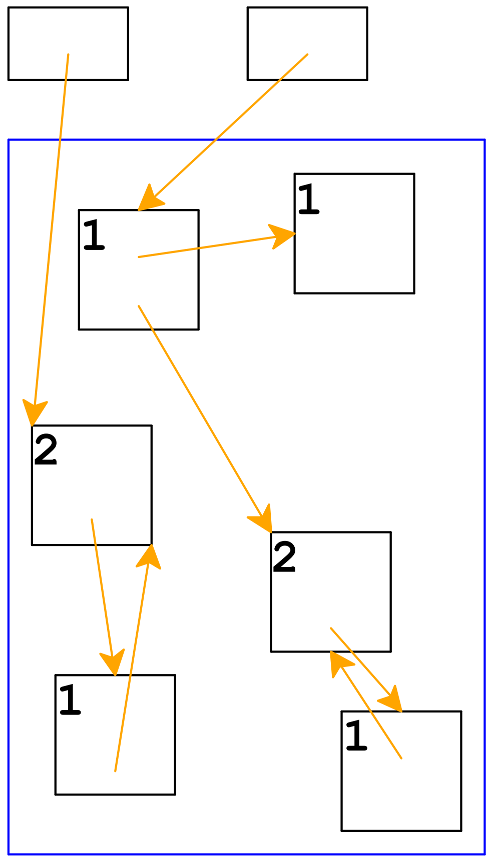
```
...
[(lamE body-expr)
 (begin
   (ref- v-reg)
   (set! v-reg
         ; must ref+ env:
         (closV body-expr env-reg))
   (ref+ v-reg)
   (continue))]
...
[(doAppK fun-val k)
 (begin
   (set! expr-reg (closV-body fun-val)) ; code is static
   (ref- env-reg)
   (set! env-reg
         ; must ref+ each arg:
         (cons v-reg (closV-env fun-val)))
   (ref+ env-reg) ; => ref+ on v-reg
   (ref+ k)
   (ref- k-reg) ; => ref- on fun-val and k
   (set! k-reg k)
   (interp))]
```

# Reference Counting And Cycles



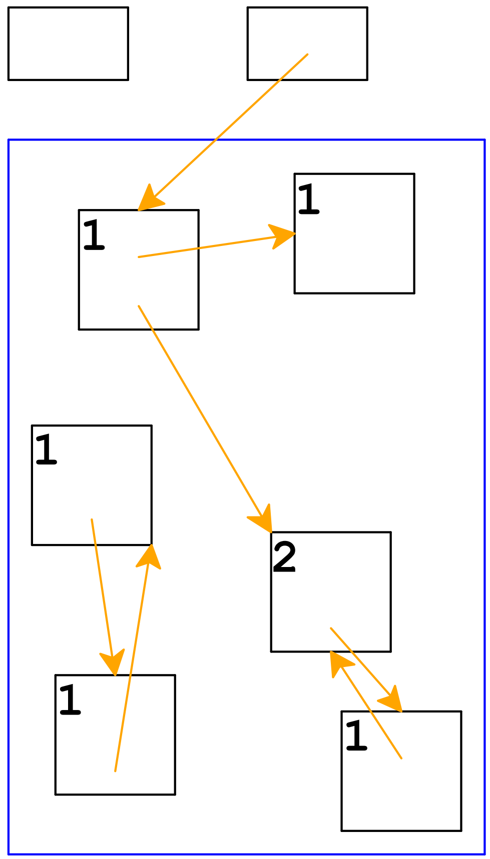

An assignment can create a cycle...

# Reference Counting And Cycles




Adding a reference increments a count

# Reference Counting And Cycles




Lower-left objects are inaccessible, but not deallocated

In general, cycles break reference counting

# Part 3

# Garbage Collection

***Garbage collection:*** a way to know whether an object is *accessible*

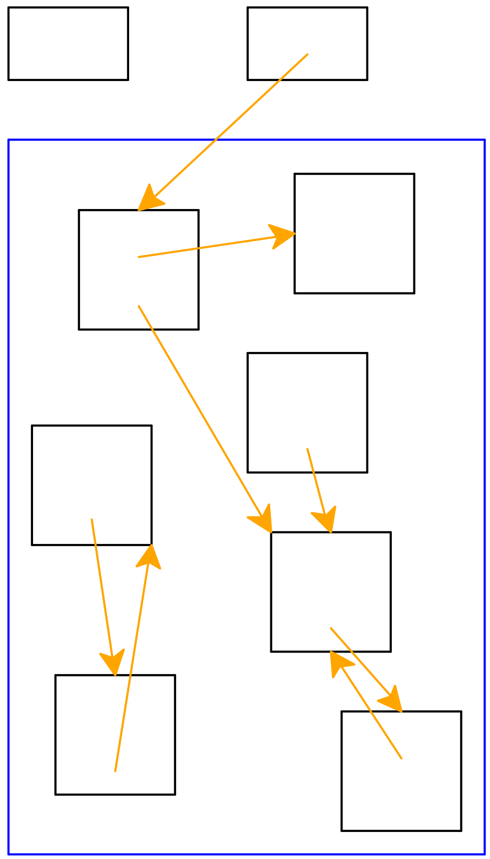
- An object referenced by a register is ***live***
- An object referenced by a live object is also live
- A program can only possibly use live objects, because there is no way to get to other objects

- A garbage collector frees all objects that are not live
- Allocate until we run out of memory, then run a garbage collector to get more space

# Garbage Collection Algorithm

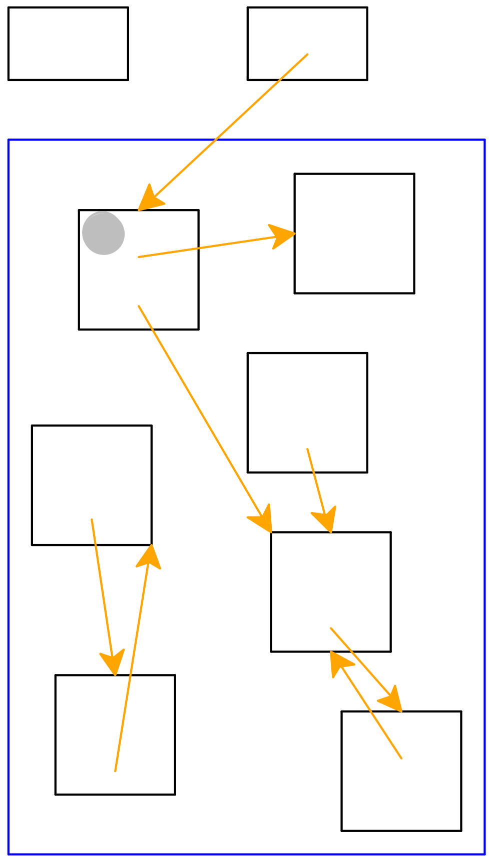
- Color all objects ***white***
- Color objects referenced by registers ***gray***
- Repeat until there are no gray objects:
  - Pick a gray object, *r*
  - For each white object that *r* points to, make it gray
  - Color *r* ***black***
- Deallocate all white objects

# Garbage Collection



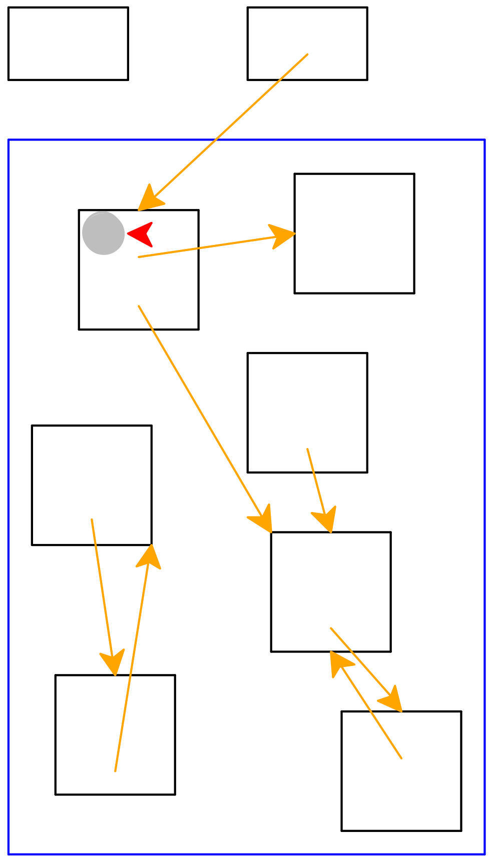
All objects are marked white

# Garbage Collection



Mark objects referenced by registers as gray

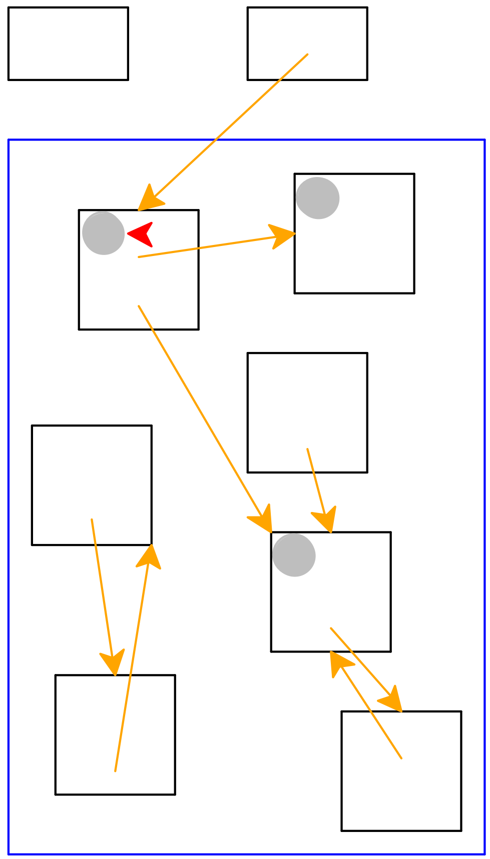
# Garbage Collection



Need to pick a gray object

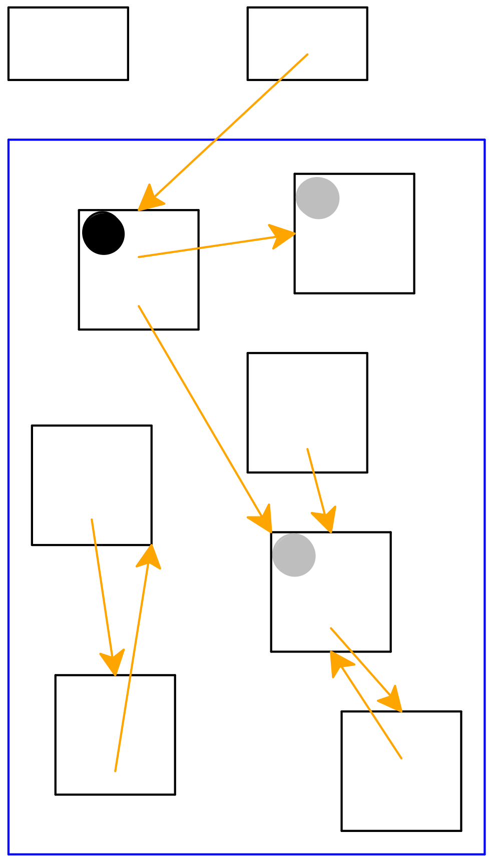
Red arrow indicates the chosen object

# Garbage Collection



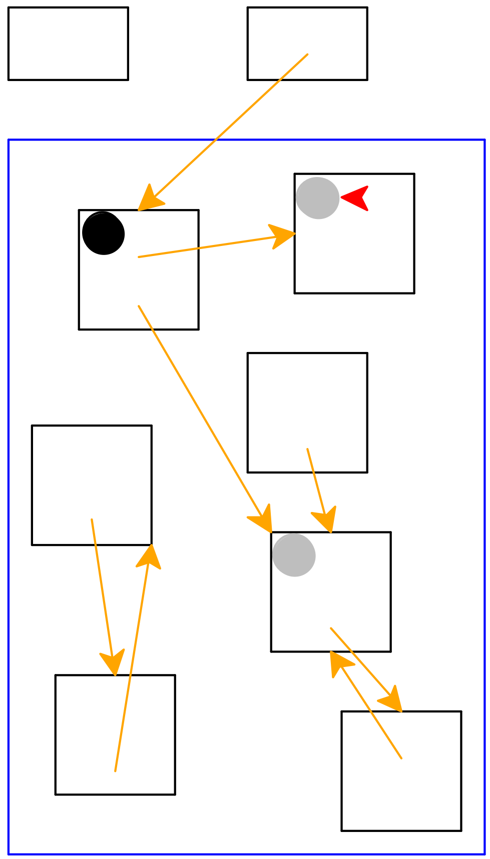
Mark white objects referenced by chosen object as gray

# Garbage Collection



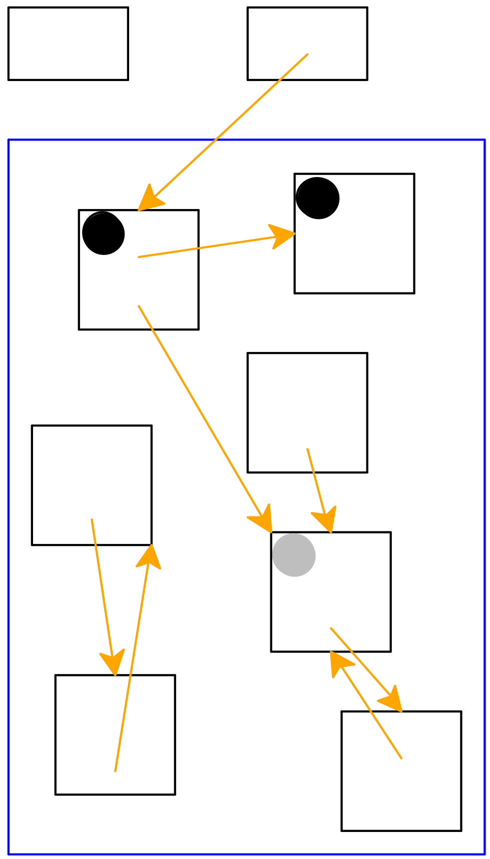
Mark chosen object black

# Garbage Collection



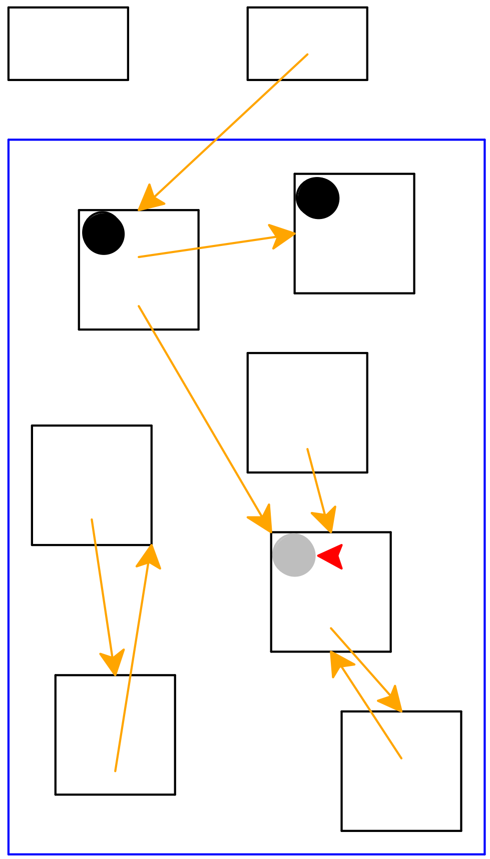
Start again: pick a gray object

# Garbage Collection



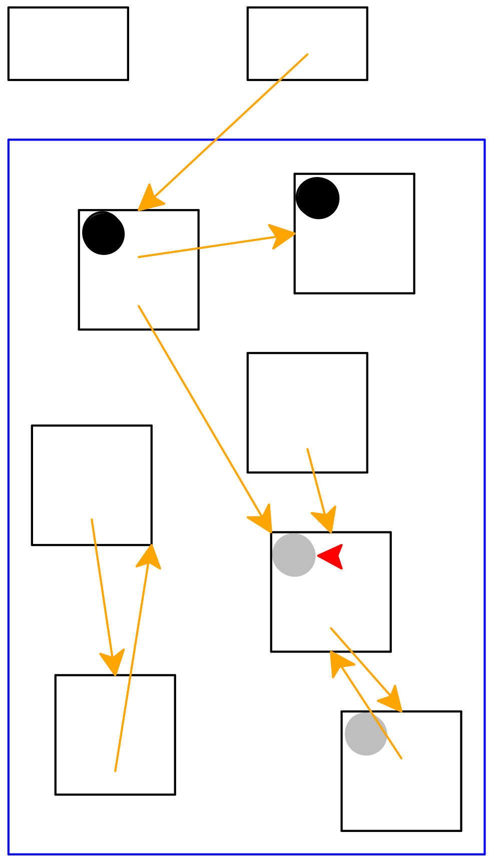
No referenced objects; mark black

# Garbage Collection



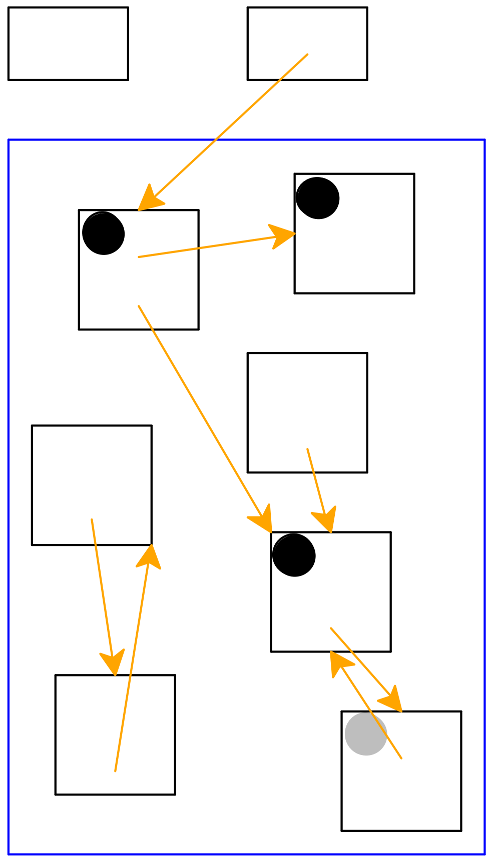
Start again: pick a gray object

# Garbage Collection



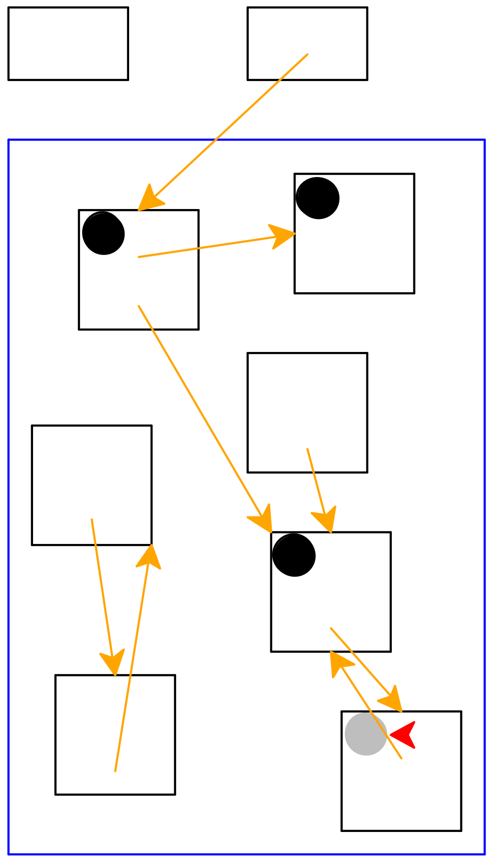
Mark white objects referenced by chosen object as gray

# Garbage Collection



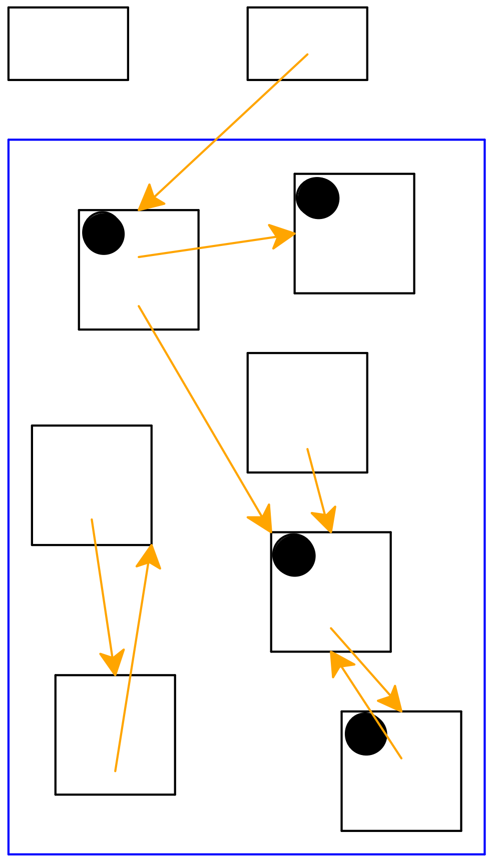
Mark chosen object black

# Garbage Collection



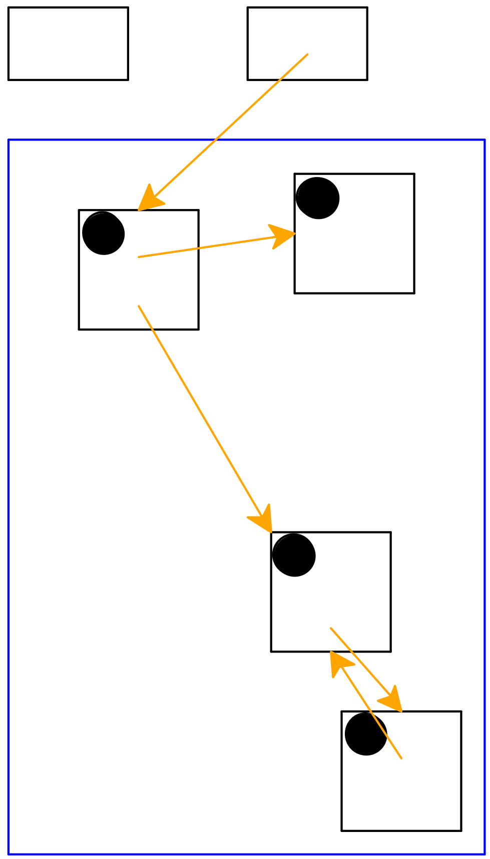
Start again: pick a gray object

# Garbage Collection



No referenced white objects;
mark black

# Garbage Collection



No more gray objects; deallocate white objects

Cycles ***do not*** break garbage collection

# Part 4

# Two-Space Copying Collectors

A ***two-space*** copying collector compacts memory as it collects, making allocation easier.

**Allocator:**

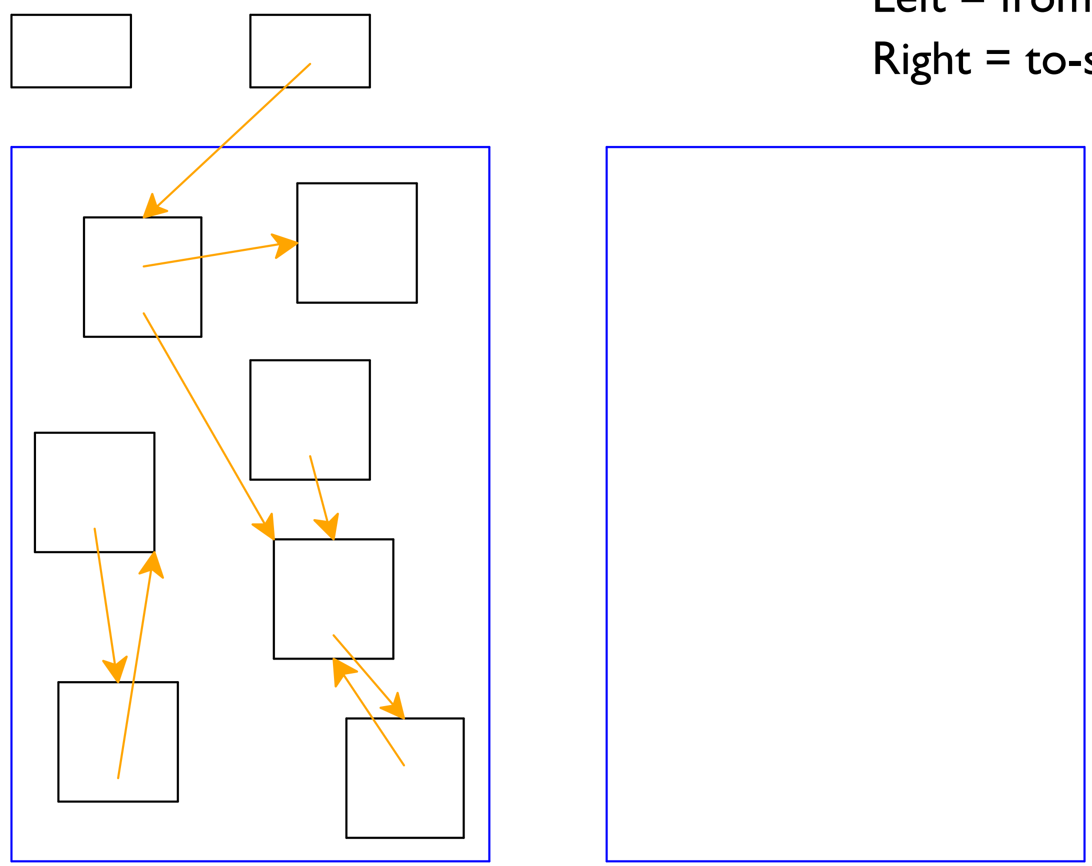
- Partitions memory into ***to-space*** and ***from-space***
- Allocates only in ***to-space***

**Collector:**

- Starts by swapping ***to-space*** and ***from-space***
- Coloring gray ⇒ copy from ***from-space*** to ***to-space***
- Choosing a gray object ⇒ walk once though the new ***to-space***, update pointers

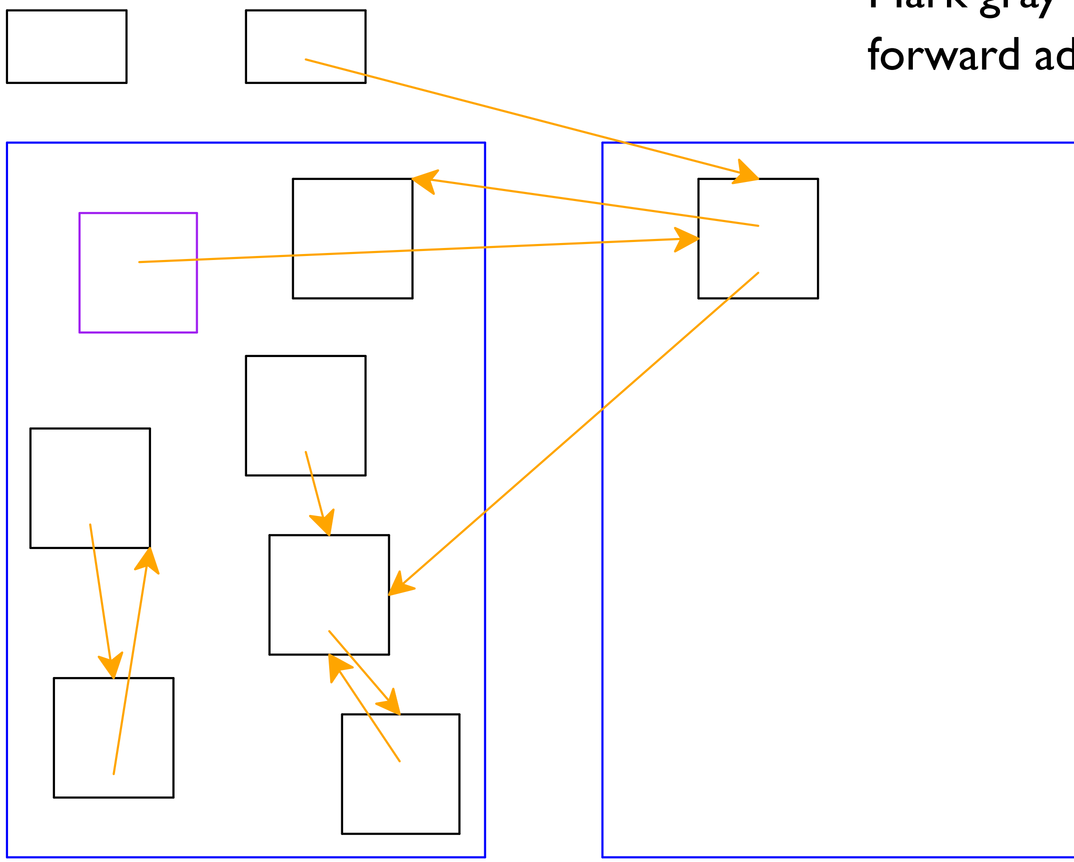
# Two-Space Collection

Left = from-space
Right = to-space

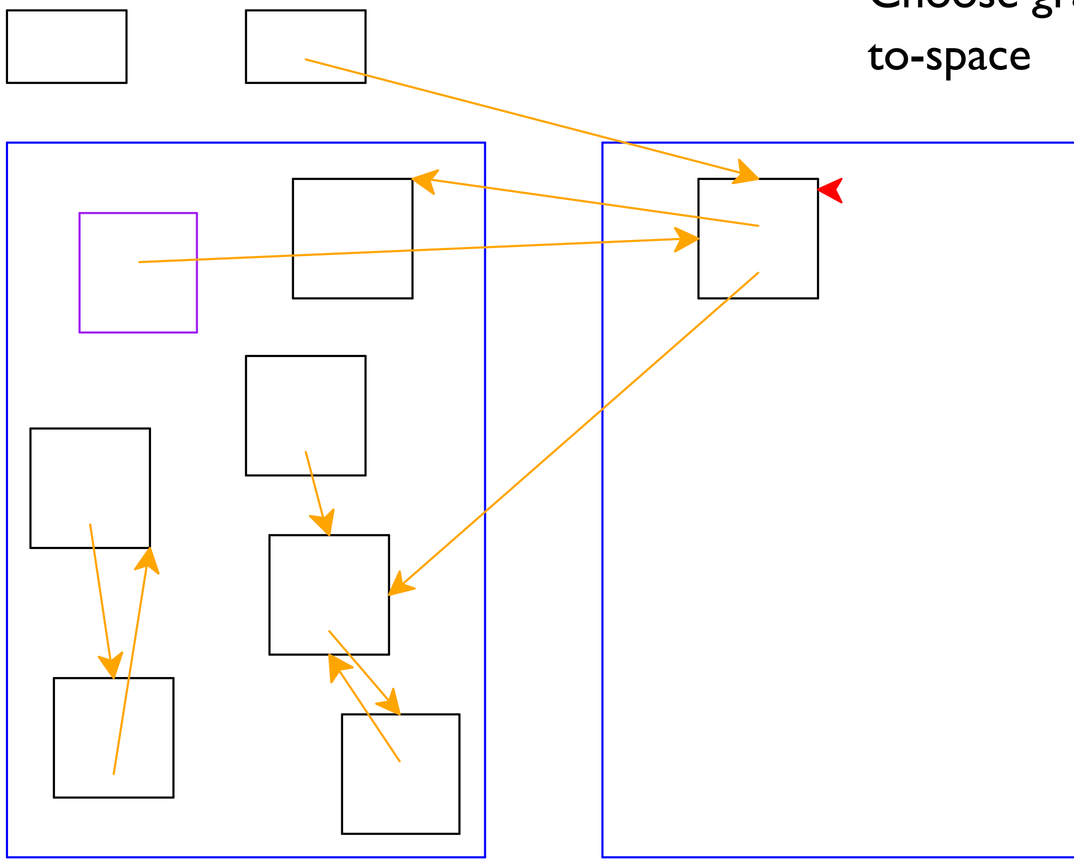


# Two-Space Collection

Mark gray = copy and leave forward address



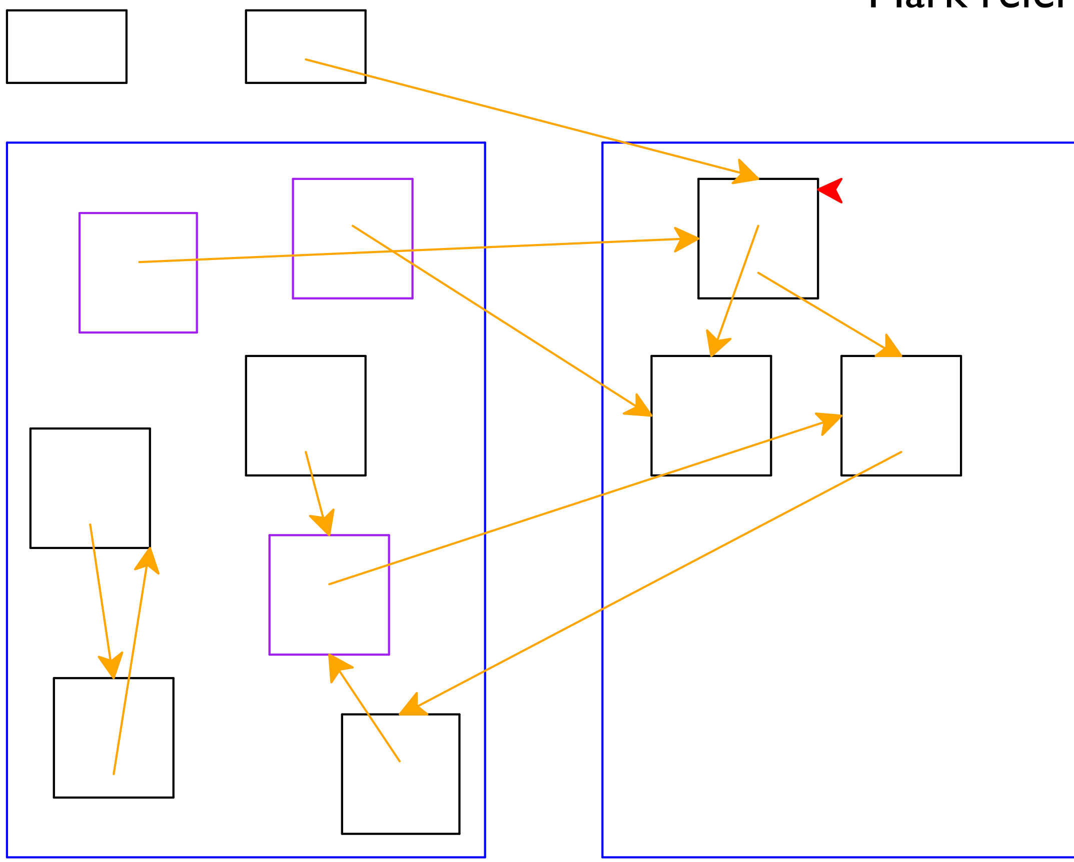
# Two-Space Collection



Choose gray by walking through to-space

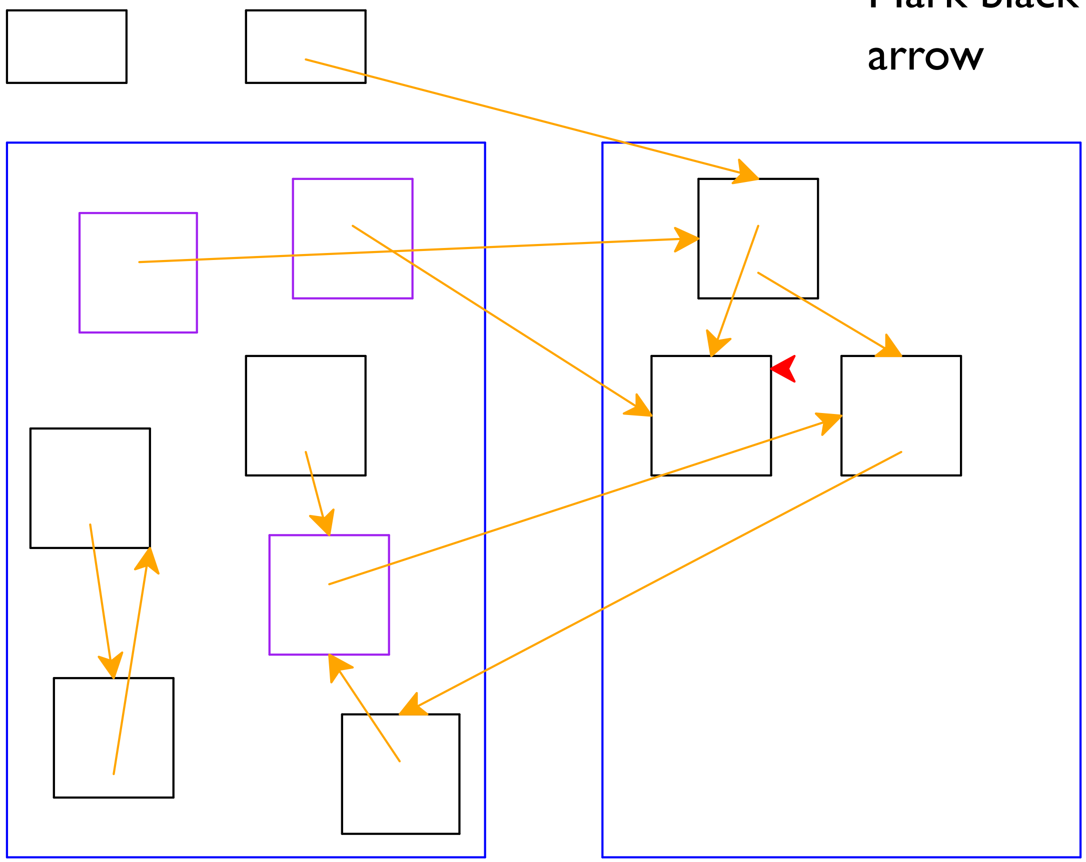
# Two-Space Collection

Mark referenced as gray



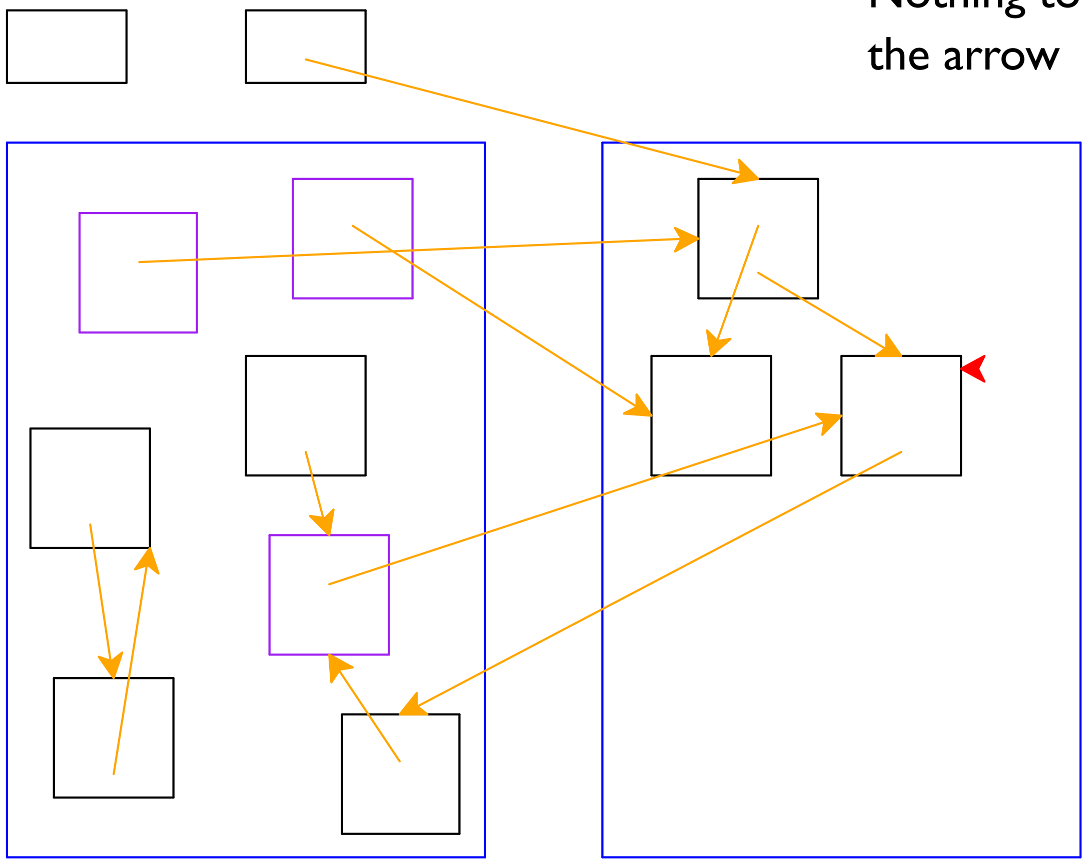
# Two-Space Collection

Mark black = move gray-choosing arrow



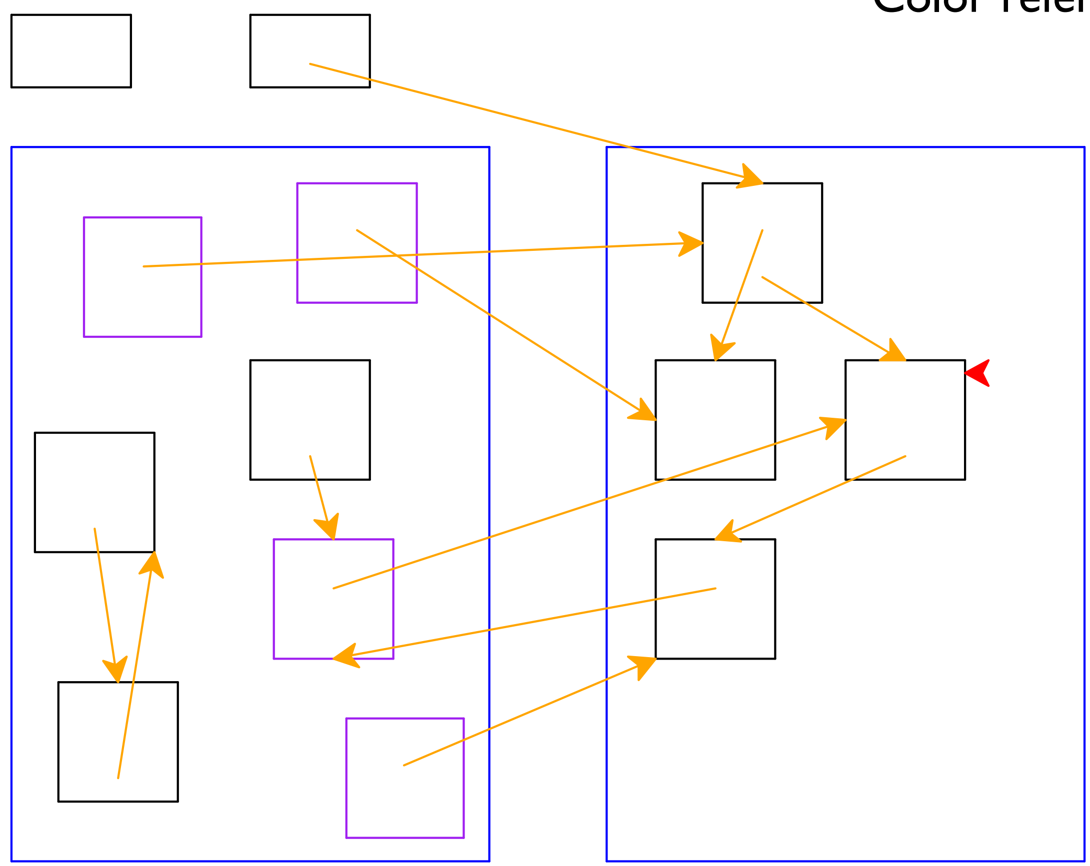
# Two-Space Collection

Nothing to color gray; increment the arrow



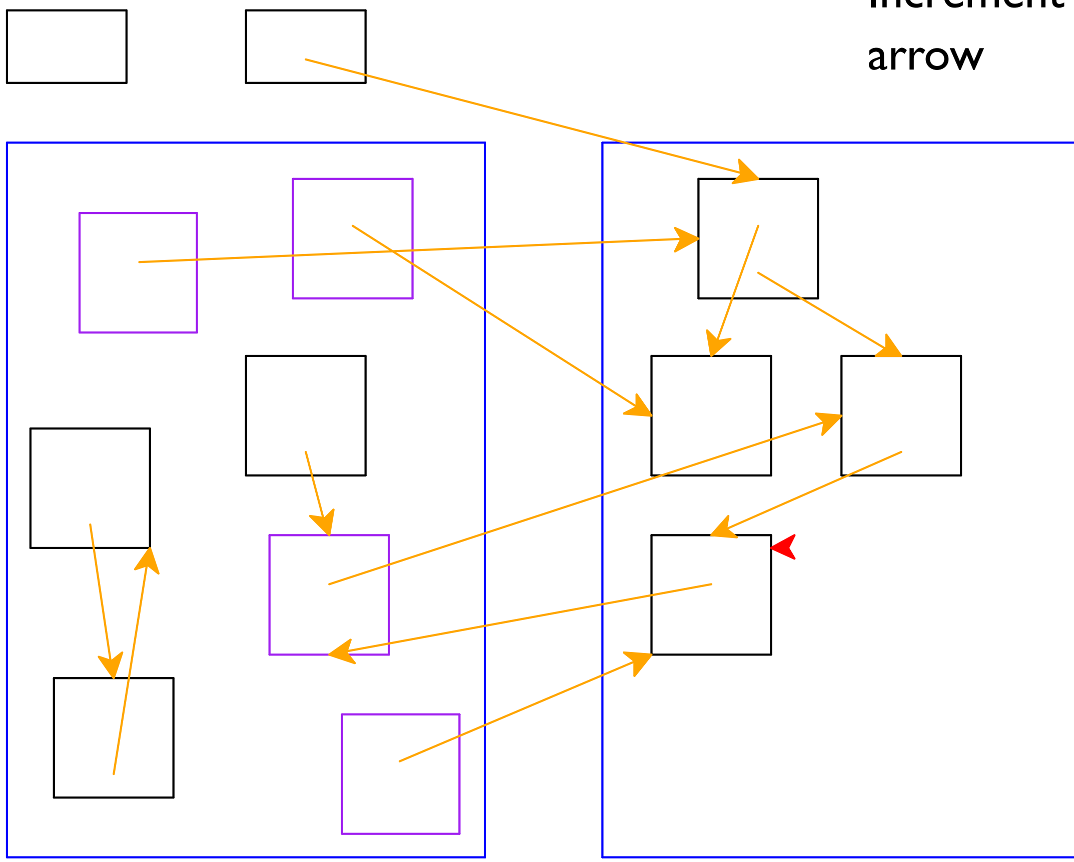
# Two-Space Collection

Color referenced object gray



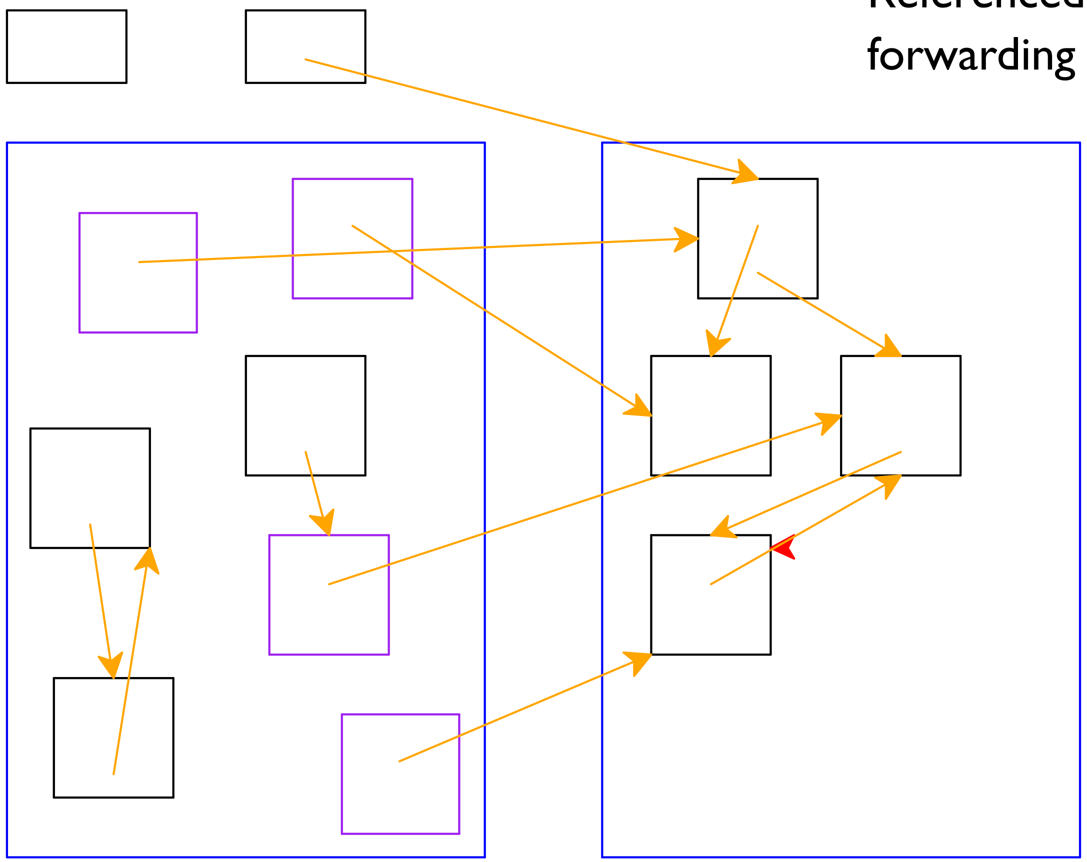
# Two-Space Collection

Increment the gray-choosing arrow



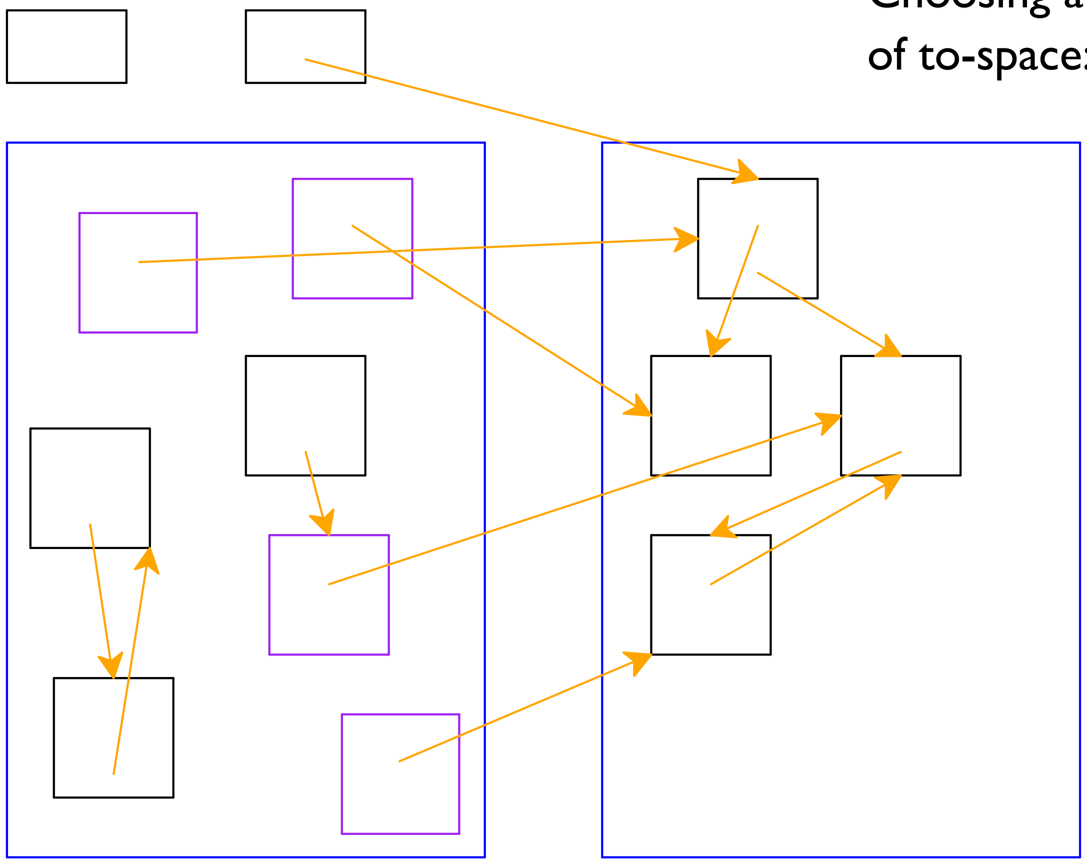
# Two-Space Collection

Referenced is already copied, use forwarding address



# Two-Space Collection

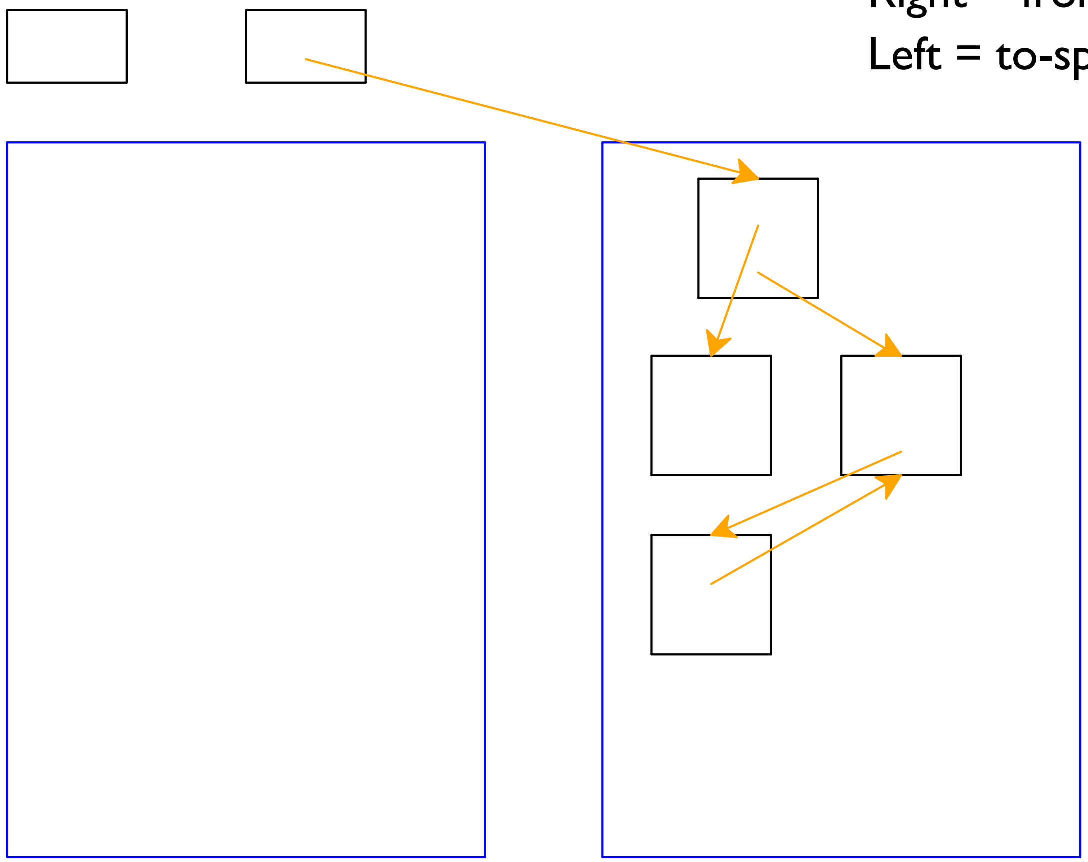
Choosing arrow reaches the end of to-space: done



# Two-Space Collection

Right = from-space

Left = to-space



# Part 5

# Two-Space Collection on Vectors

- Everything is a number:
  - Some numbers are immediate integers
  - Some numbers are pointers
- An allocated object in memory starts with a tag, followed by a sequence of pointers and immediate integers
  - The tag describes the shape

# Two-Space Vector Example

- 26-byte memory (13 bytes for each space), 2 registers
  - Tag 1: one integer
  - Tag 2: one pointer
  - Tag 3: one integer, then one pointer

Register 1: `7`    Register 2: `0`

From: `1 75 2 0 3 2 10 3 2 2 3 1 4`

# Two-Space Vector Example

- 26-byte memory (13 bytes for each space), 2 registers
  - Tag 1: one integer
  - Tag 2: one pointer
  - Tag 3: one integer, then one pointer

Register 1: **7** Register 2: **0**

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| From: | **1** | **75** | **2** | **0** | **3** | **2** | **10** | **3** | **2** | **2** | **3** | **1** | **4** |
| Addr: | **00** | **01** | **02** | **03** | **04** | **05** | **06** | **07** | **08** | **09** | **10** | **11** | **12** |

# Two-Space Vector Example

- 26-byte memory (13 bytes for each space), 2 registers
  - Tag 1: one integer
  - Tag 2: one pointer
  - Tag 3: one integer, then one pointer

Register 1: 7 Register 2: 0

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| From: | 1 | 75 | 2 | 0 | 3 | 2 | 10 | 3 | 2 | 2 | 3 | 1 | 4 |
| Addr: | 00 | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 |
| | ^ | | ^ | | ^ | | | ^ | | | ^ | | |

# Two-Space Vector Example

- 26-byte memory (13 bytes for each space), 2 registers
  - Tag 1: one integer
  - Tag 2: one pointer
  - Tag 3: one integer, then one pointer

Register 1: 7 Register 2: 0

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| From: | 1 | 75 | 2 | 0 | 3 | 2 | 10 | 3 | 2 | 2 | 3 | 1 | 4 |
| Addr: | 00 | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 |
| | ^ | | ^ | | ^ | | | ^ | | | ^ | | |
| To: | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ^ | | | | | | | | | | | | |
| | ^ | | | | | | | | | | | | |

# Two-Space Vector Example

- 26-byte memory (13 bytes for each space), 2 registers
  - Tag 1: one integer
  - Tag 2: one pointer
  - Tag 3: one integer, then one pointer

Register 1: 0 Register 2: 0

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| From: | 1 | 75 | 2 | 0 | 3 | 2 | 10 | 99 | 0 | 2 | 3 | 1 | 4 |
| Addr: | 00 | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 |
| | ^ | | ^ | | ^ | | | ^ | | | ^ | | |
| To: | 3 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ^ | | | | | | | | | | | | |
| | | | | ^ | | | | | | | | | |

# Two-Space Vector Example

- 26-byte memory (13 bytes for each space), 2 registers
  - Tag 1: one integer
  - Tag 2: one pointer
  - Tag 3: one integer, then one pointer

Register 1: 0 Register 2: 3

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| From: | 99 | 3 | 2 | 0 | 3 | 2 | 10 | 99 | 0 | 2 | 3 | 1 | 4 |
| Addr: | 00 | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 |
| | ^ | | ^ | | ^ | | | ^ | | | ^ | | |
| To: | 3 | 2 | 2 | 1 | 75 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ^ | | | | | | | | | | | | |
| | | | | | | ^ | | | | | | | |

# Two-Space Vector Example

- 26-byte memory (13 bytes for each space), 2 registers
  - Tag 1: one integer
  - Tag 2: one pointer
  - Tag 3: one integer, then one pointer

Register 1: 0 Register 2: 3

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| From: | 99 | 3 | 99 | 5 | 3 | 2 | 10 | 99 | 0 | 2 | 3 | 1 | 4 |
| Addr: | 00 | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 |
| | ^ | | ^ | | ^ | | | ^ | | | ^ | | |
| To: | 3 | 2 | 5 | 1 | 75 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | | ^ | | | | | | | | | |
| | | | | | | | | ^ | | | | | |

# Two-Space Vector Example

- 26-byte memory (13 bytes for each space), 2 registers
  - Tag 1: one integer
  - Tag 2: one pointer
  - Tag 3: one integer, then one pointer

Register 1: 0 Register 2: 3

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| From: | 99 | 3 | 99 | 5 | 3 | 2 | 10 | 99 | 0 | 2 | 3 | 1 | 4 |
| Addr: | 00 | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 |
| | ^ | | ^ | | ^ | | | ^ | | | ^ | | |
| To: | 3 | 2 | 5 | 1 | 75 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | | | | ^ | | | | | | | |
| | | | | | | | | ^ | | | | | |

# Two-Space Vector Example

- 26-byte memory (13 bytes for each space), 2 registers
  - Tag 1: one integer
  - Tag 2: one pointer
  - Tag 3: one integer, then one pointer

Register 1: 0 Register 2: 3

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| From: | 99 | 3 | 99 | 5 | 3 | 2 | 10 | 99 | 0 | 2 | 3 | 1 | 4 |
| Addr: | 00 | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 |
| | ^ | | ^ | | ^ | | | ^ | | | ^ | | |
| To: | 3 | 2 | 5 | 1 | 75 | 2 | 3 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | | | | | | ^ | | | | | |
| | | | | | | | | ^ | | | | | |