Part I

Allocation

Constructor calls are allocation:

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

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

Deallocation

Where does **free** go?

```
(define (continue)
  ...
  [doAddK (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

```
[doAddK (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`**

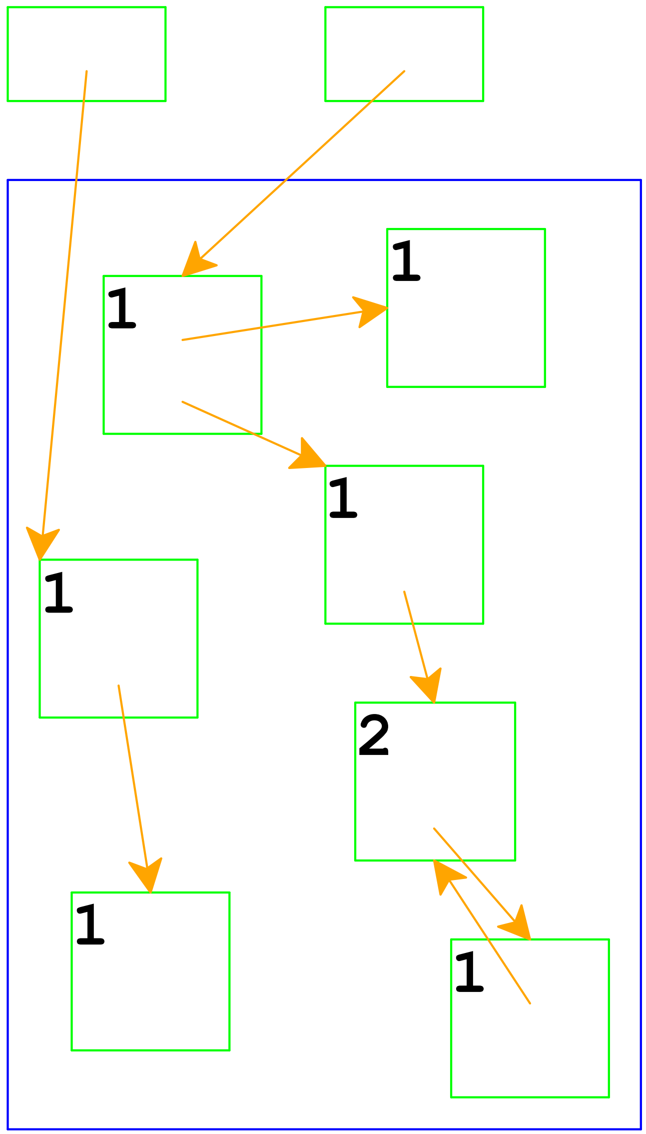
Part 2

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

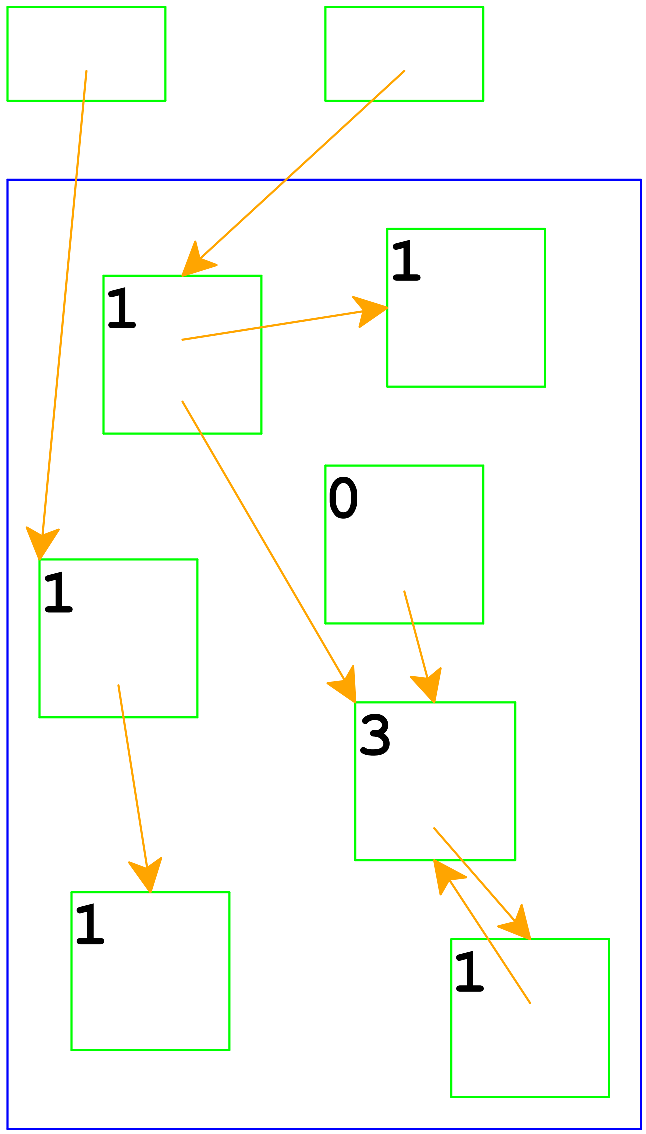
Reference Counting



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

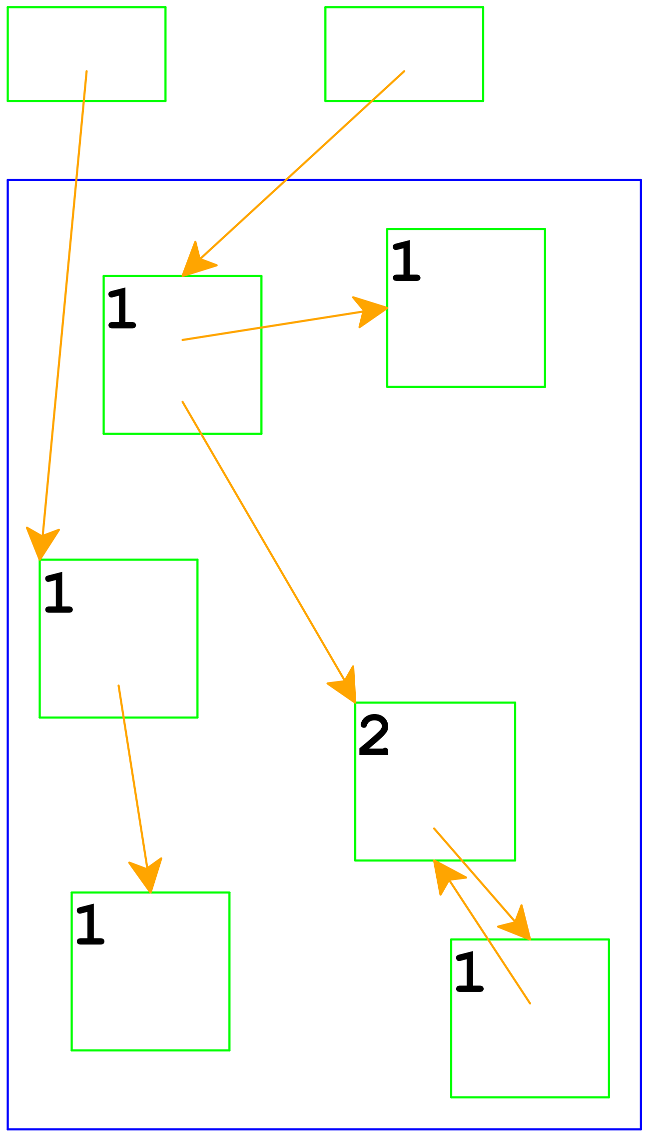
Boxes in the blue area are allocated with **`malloc`**

Reference Counting



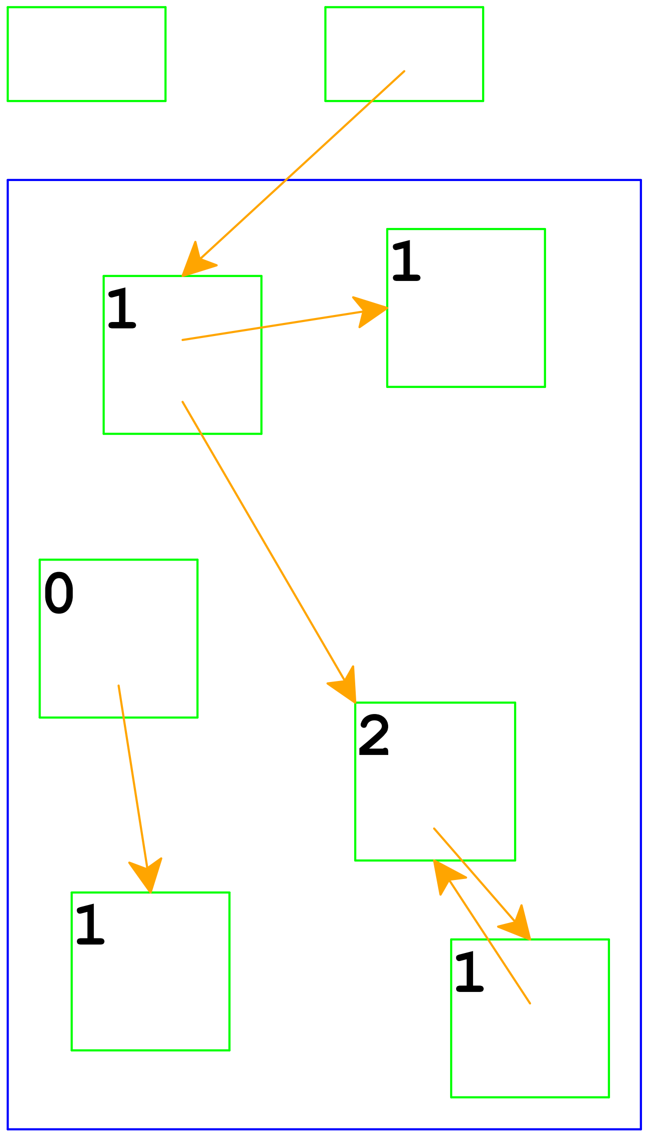
Adjust counts when a pointer is changed...

Reference Counting



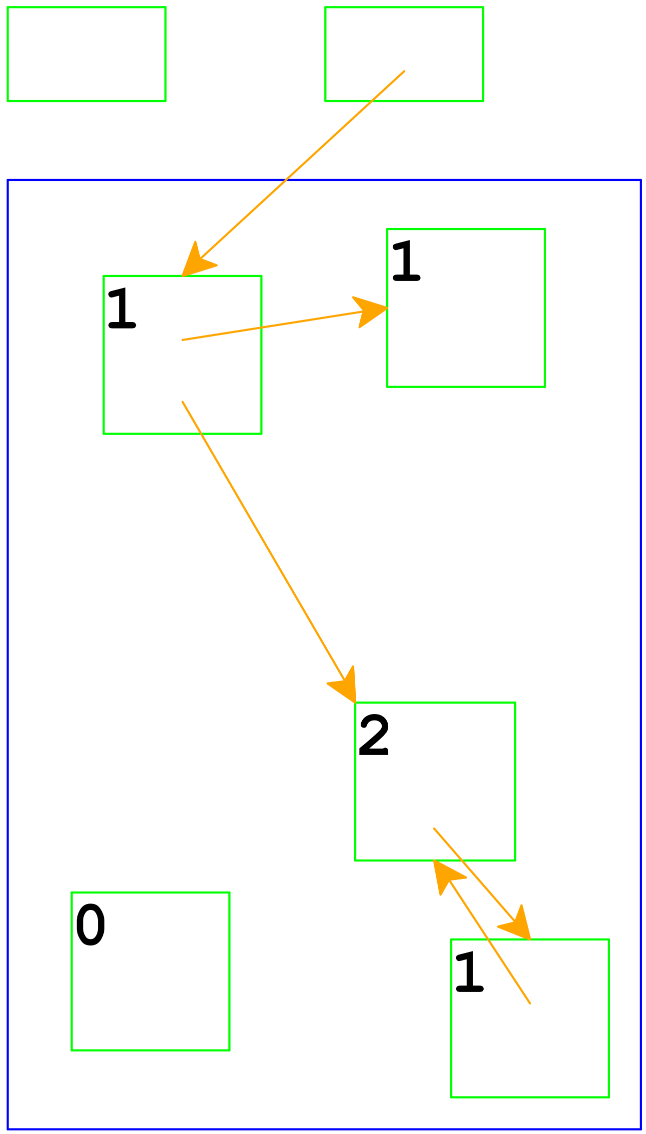
... freeing an object if its count goes to 0

Reference Counting



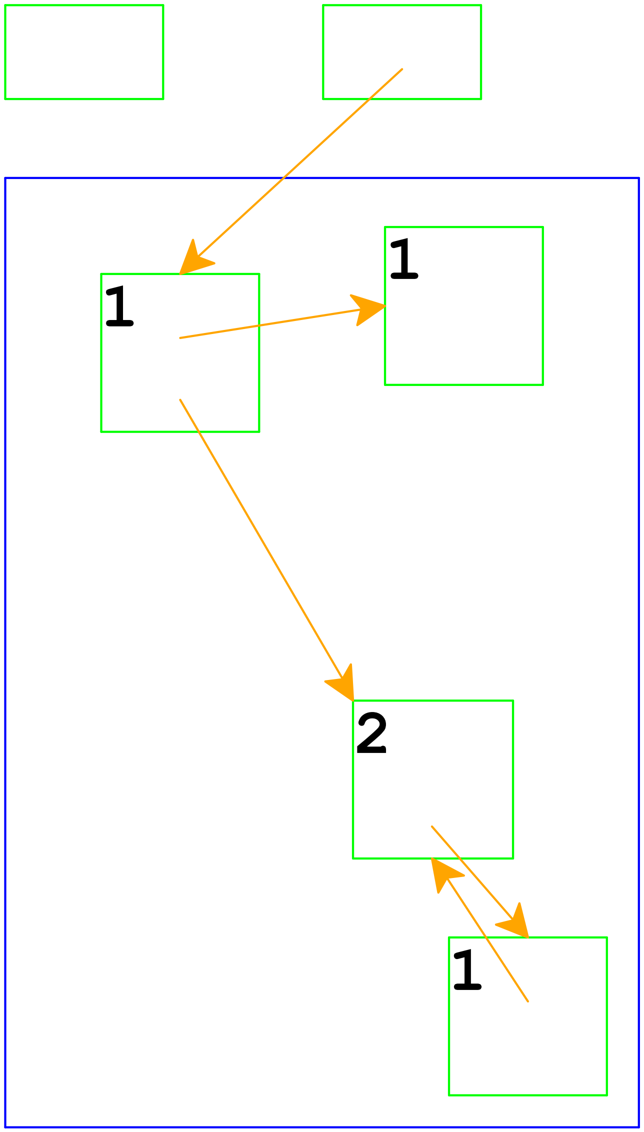
Same if the pointer is in a register

Reference Counting



Adjust counts after frees, too...

Reference Counting

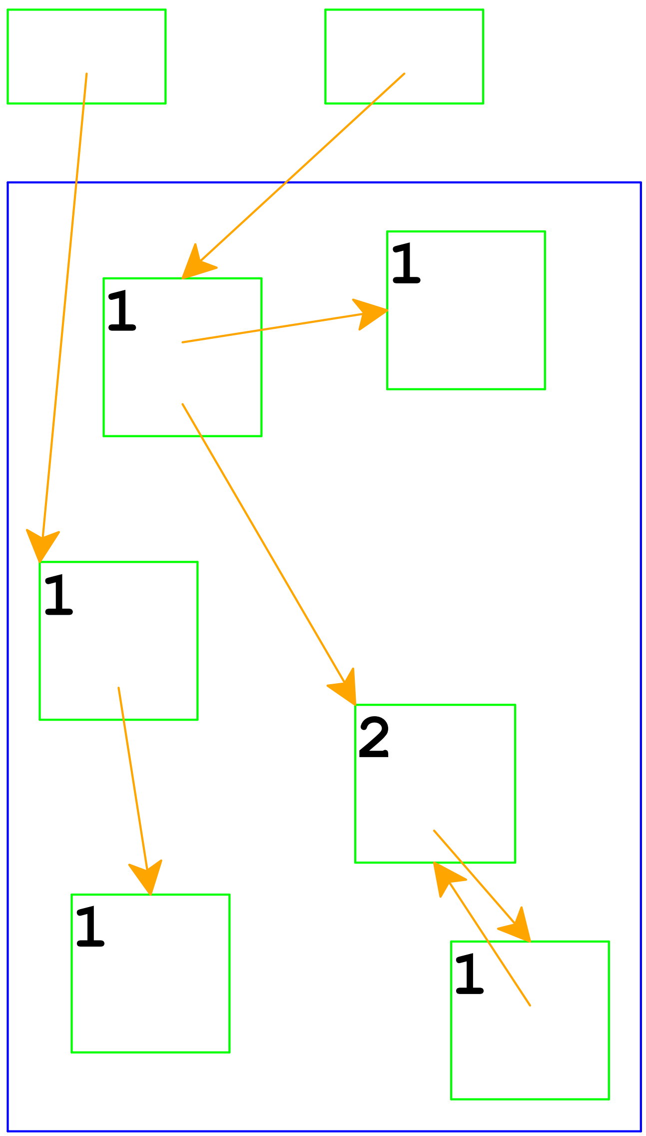


... which can trigger more frees

Reference Counting in an Interpreter

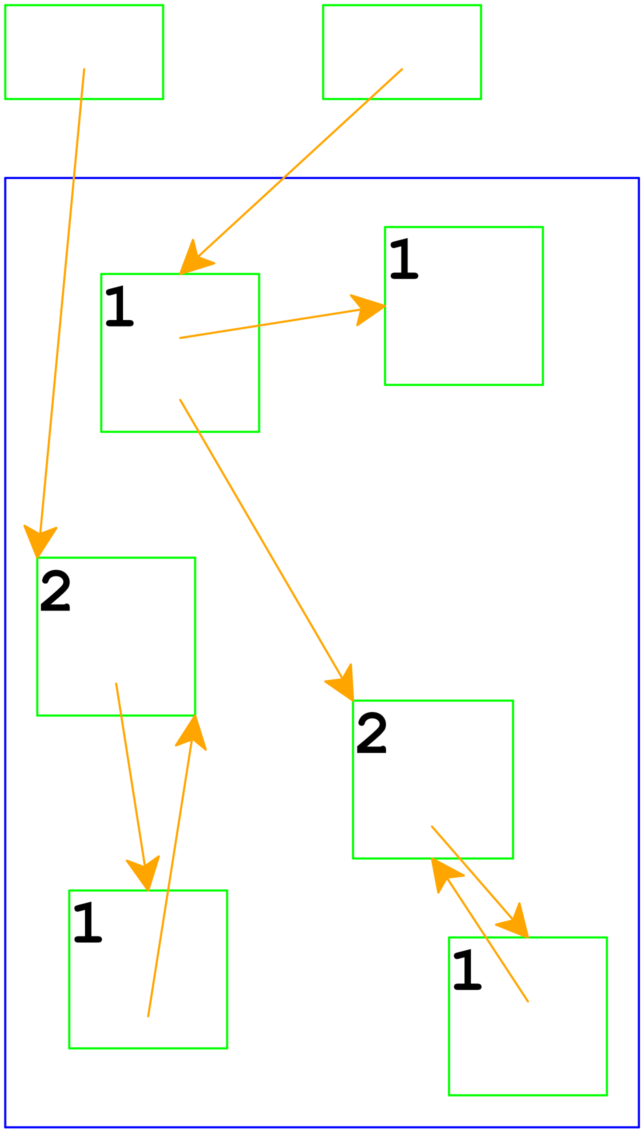
```
...
[lamC (body-expr)
      (begin
        (ref- v-reg)
        (set! v-reg
              ; must ref+ env:
              (closV body-expr env-reg))
        (ref+ v-reg)
        (continue))]
...
[doAppK (fun-val k)
        (begin
          (set! fae-reg (closV-body fun-val)) ; code is static
          (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



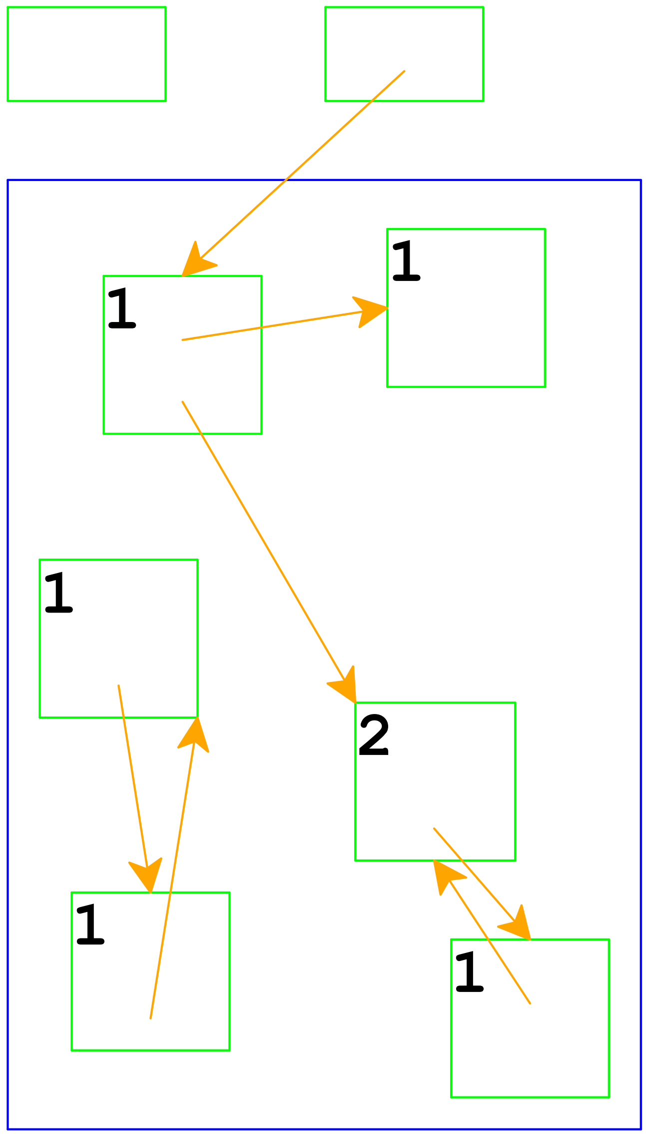
An assignment can create a cycle...

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*

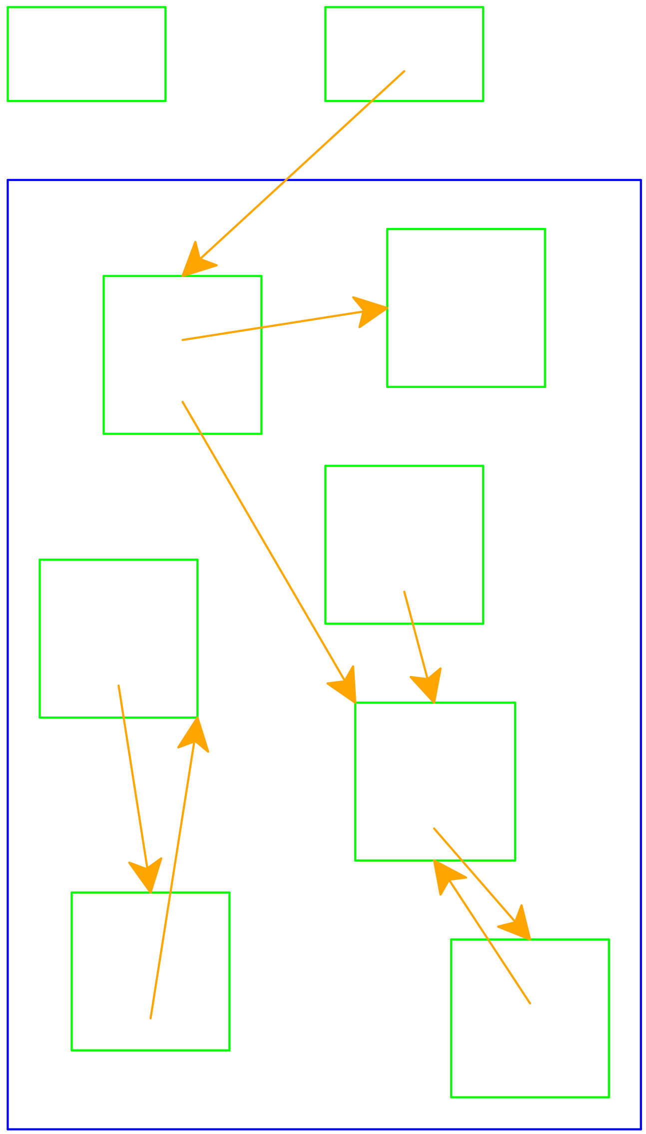
- An object referenced by a register is ***live***
- An object referenced by a live object is also live
- A program can only possibly use live objects, because there is no way to get to other objects

- 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

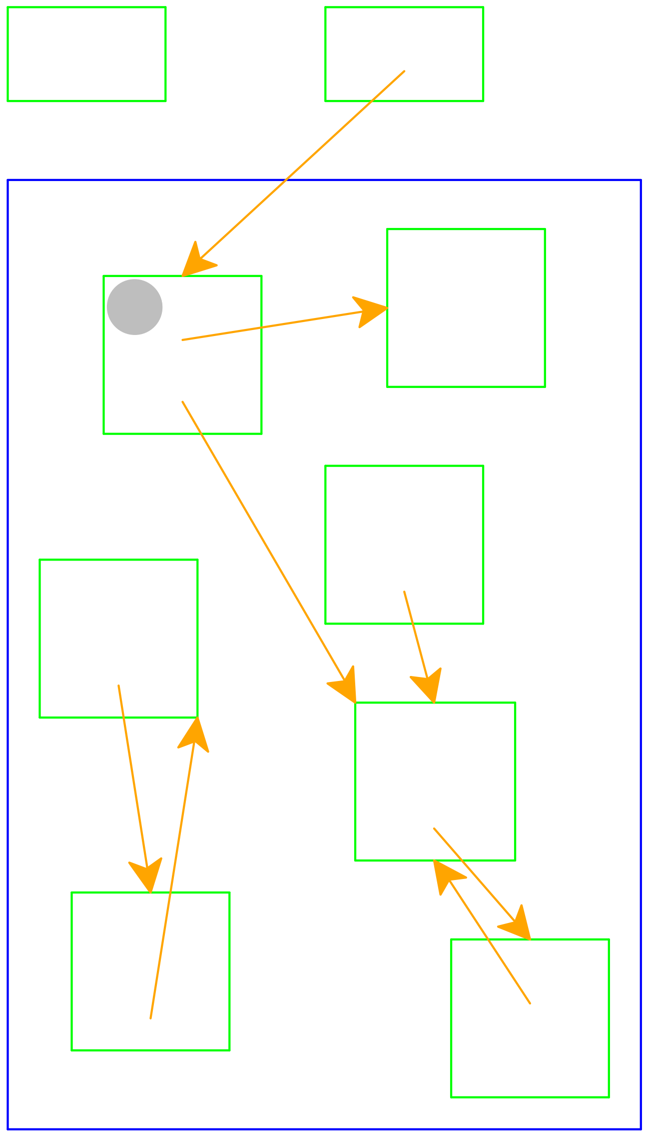
- Color all objects ***white***
- Color objects referenced by registers ***gray***
- Repeat until there are no gray objects:
    - Pick a gray object, *r*
    - For each white object that *r* points to, make it gray
    - Color *r* ***black***
- Deallocate all white objects

Garbage Collection



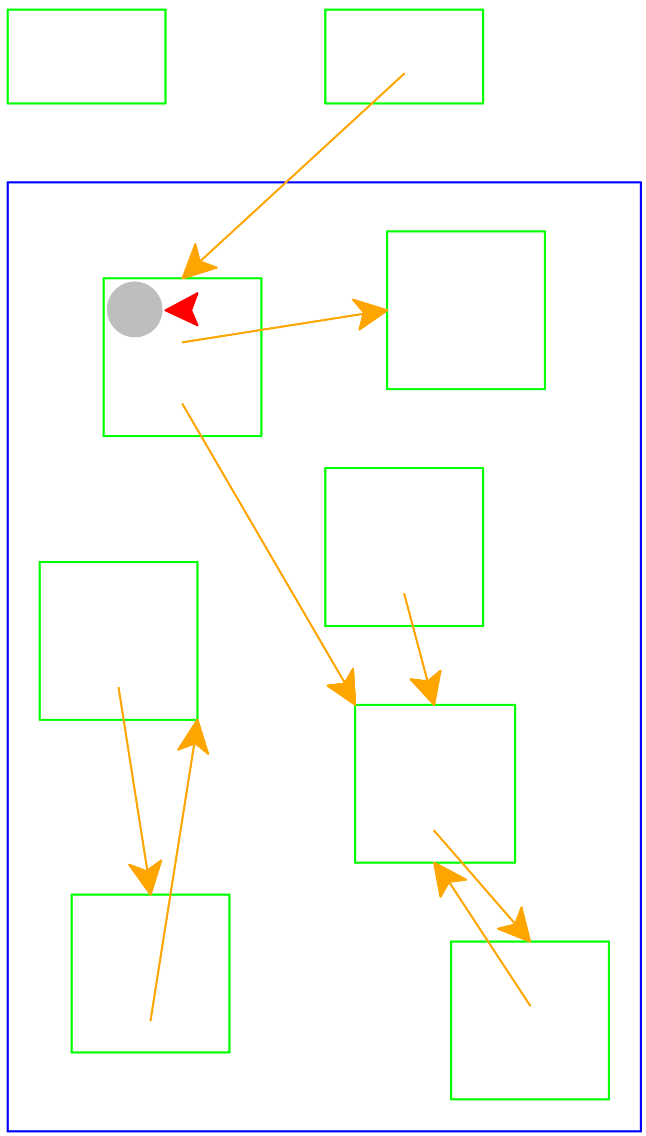
All objects are marked white

Garbage Collection



Mark objects referenced by registers as gray

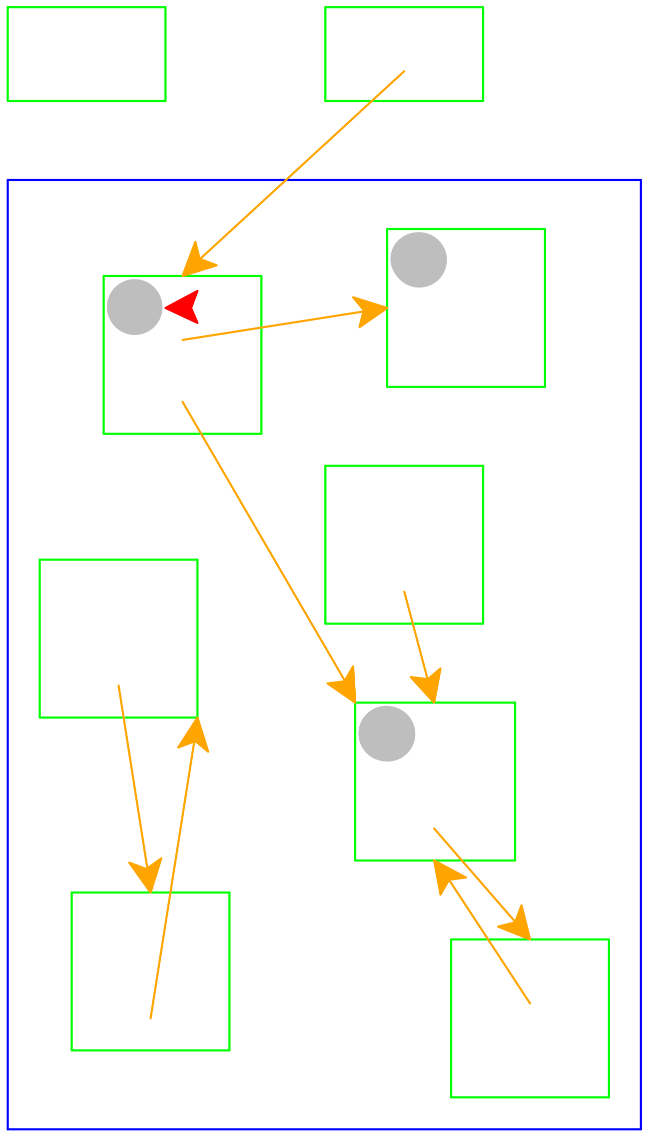
Garbage Collection



Need to pick a gray object

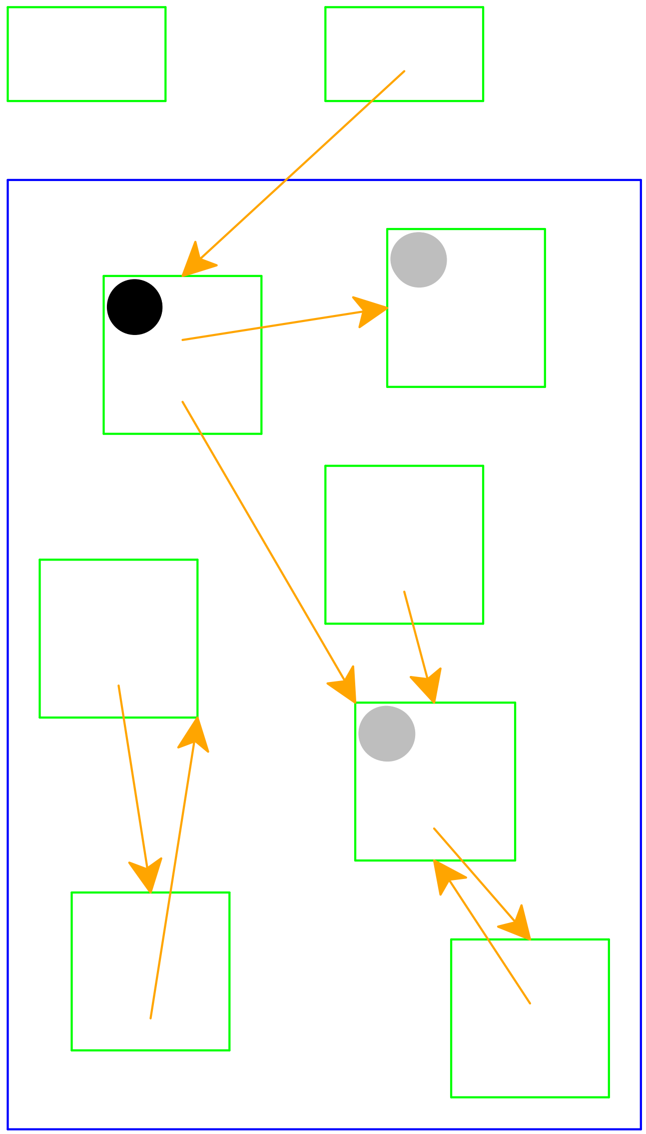
Red arrow indicates the chosen object

Garbage Collection



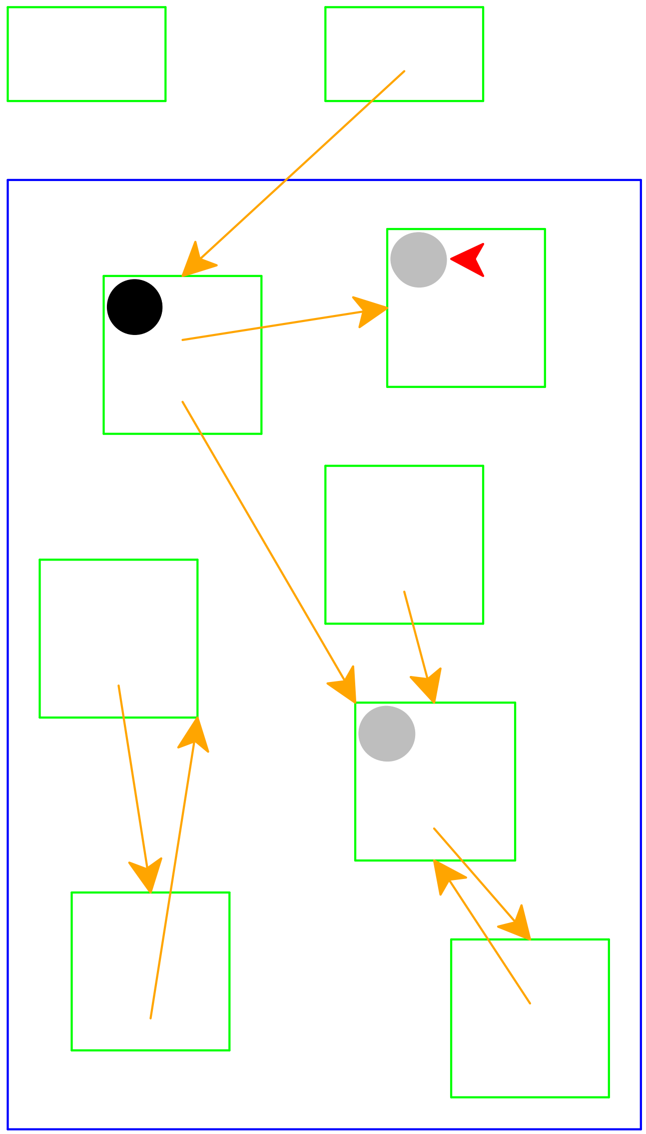
Mark white objects referenced by chosen object as gray

Garbage Collection



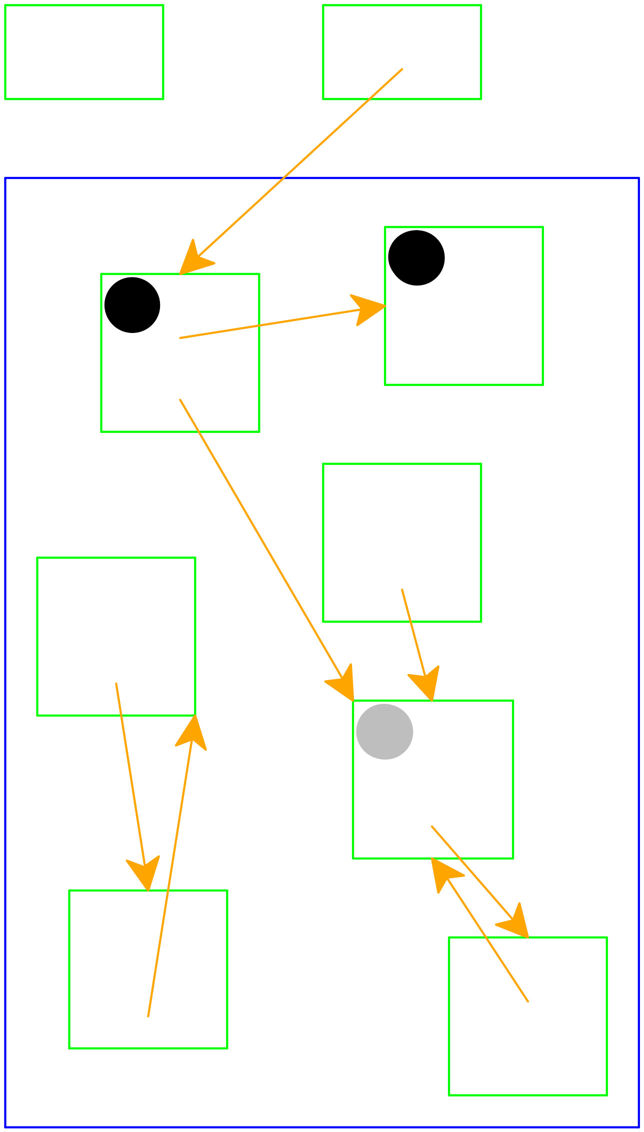
Mark chosen object black

Garbage Collection



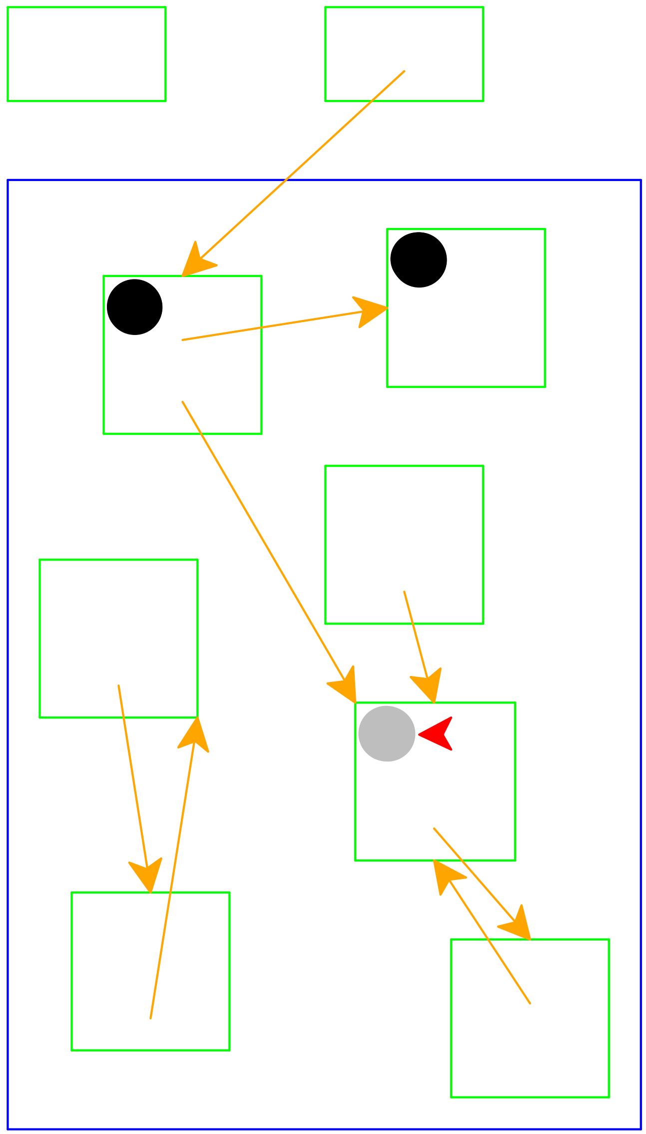
Start again: pick a gray object

Garbage Collection



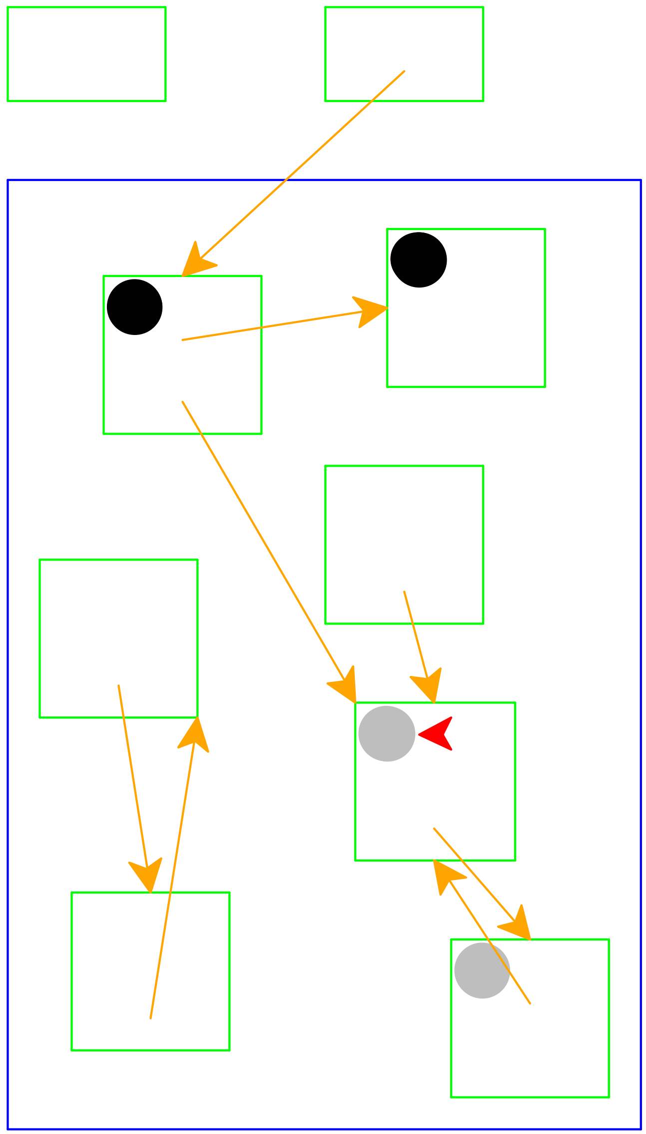
No referenced objects; mark black

Garbage Collection



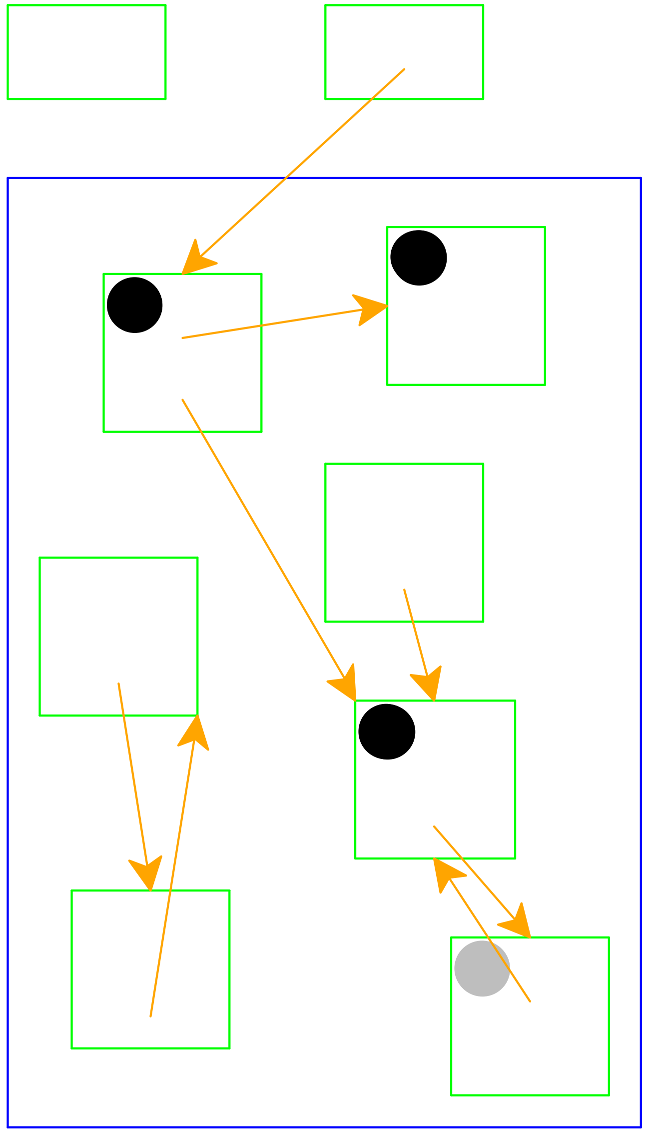
Start again: pick a gray object

Garbage Collection



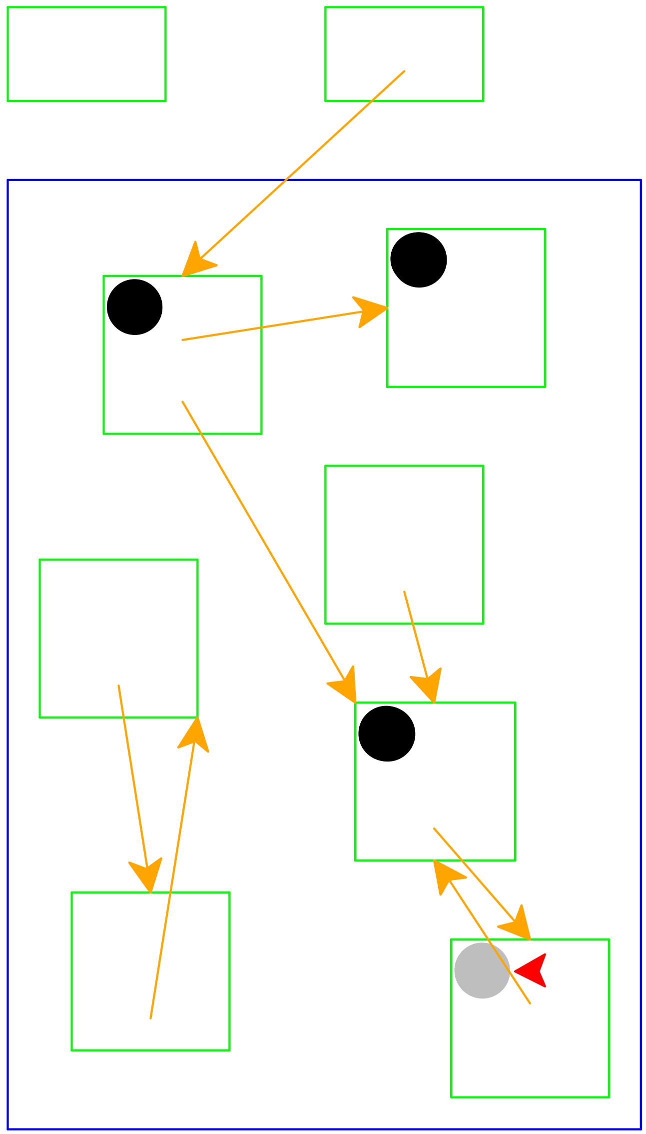
Mark white objects referenced by chosen object as gray

Garbage Collection



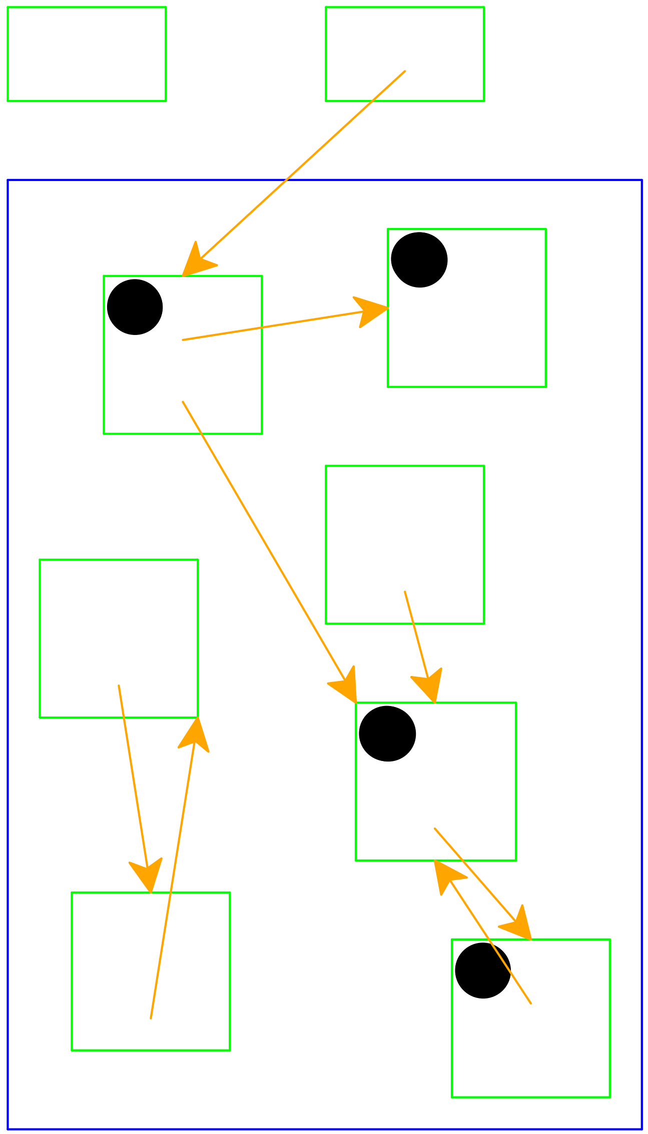
Mark chosen object black

Garbage Collection



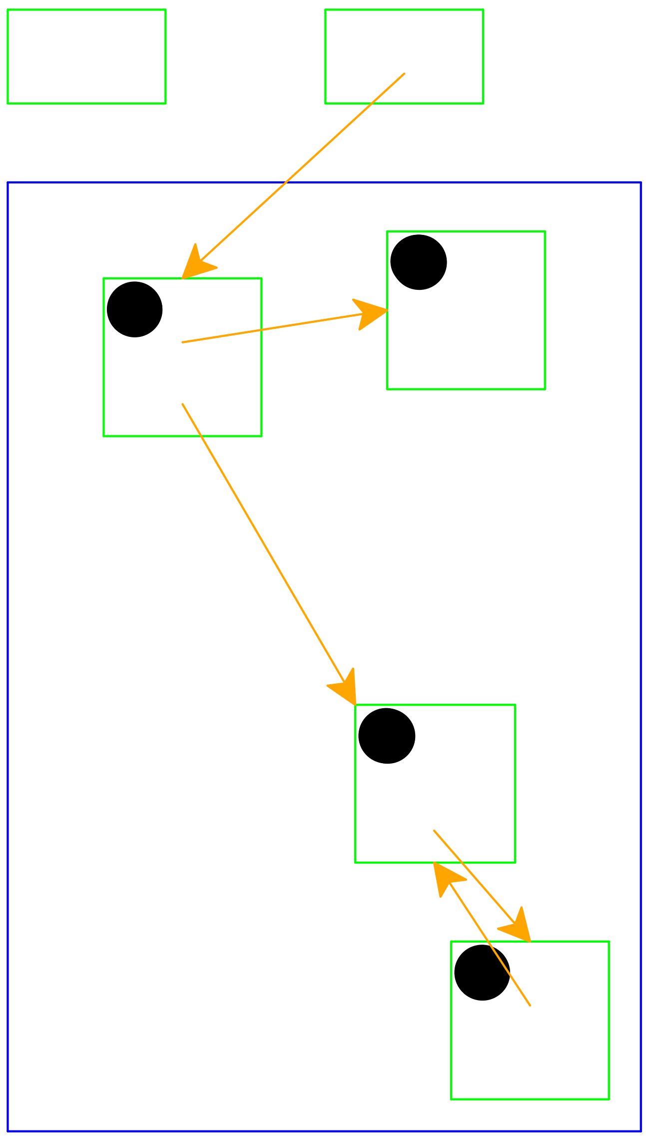
Start again: pick a gray object

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***

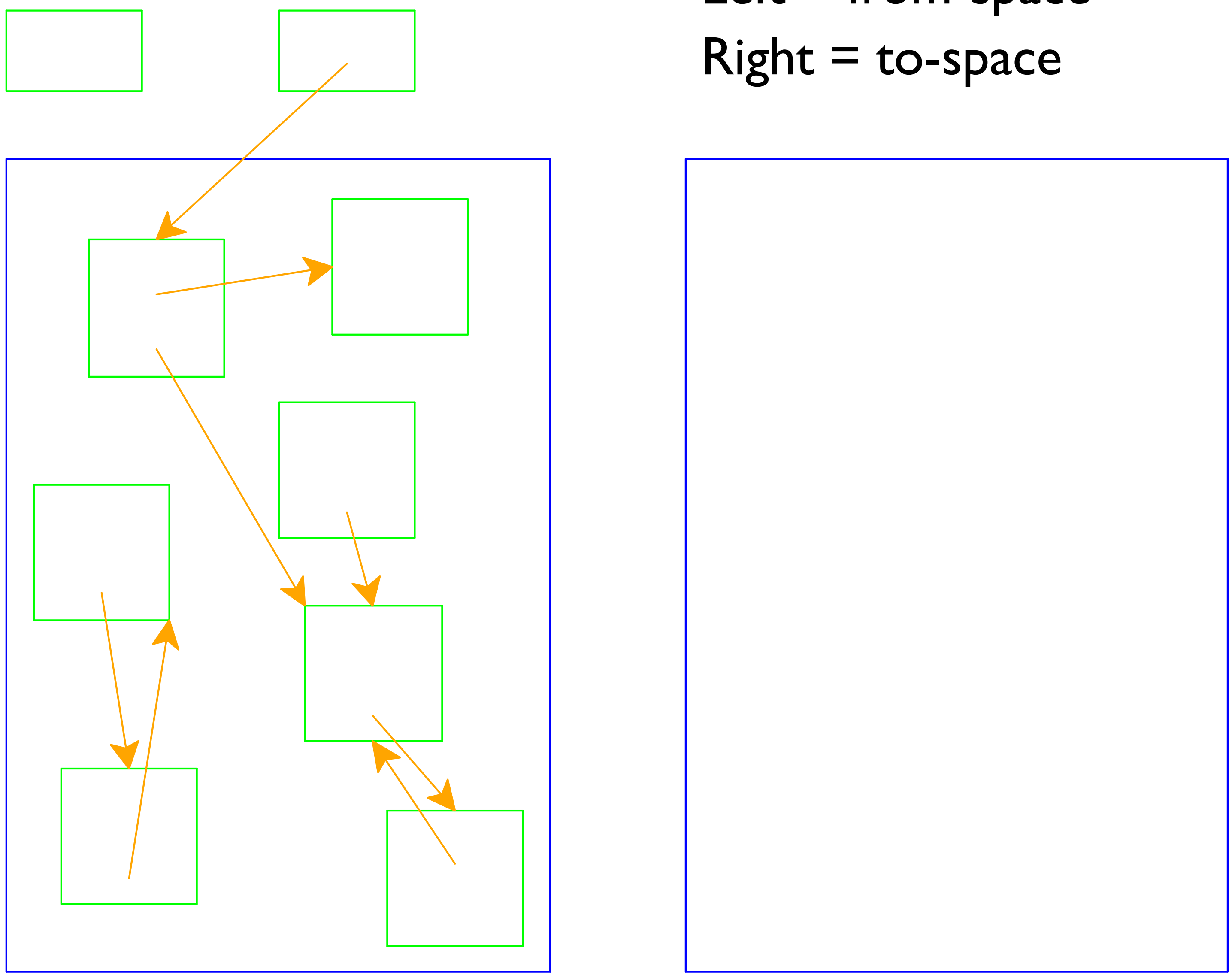
Collector:

- 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

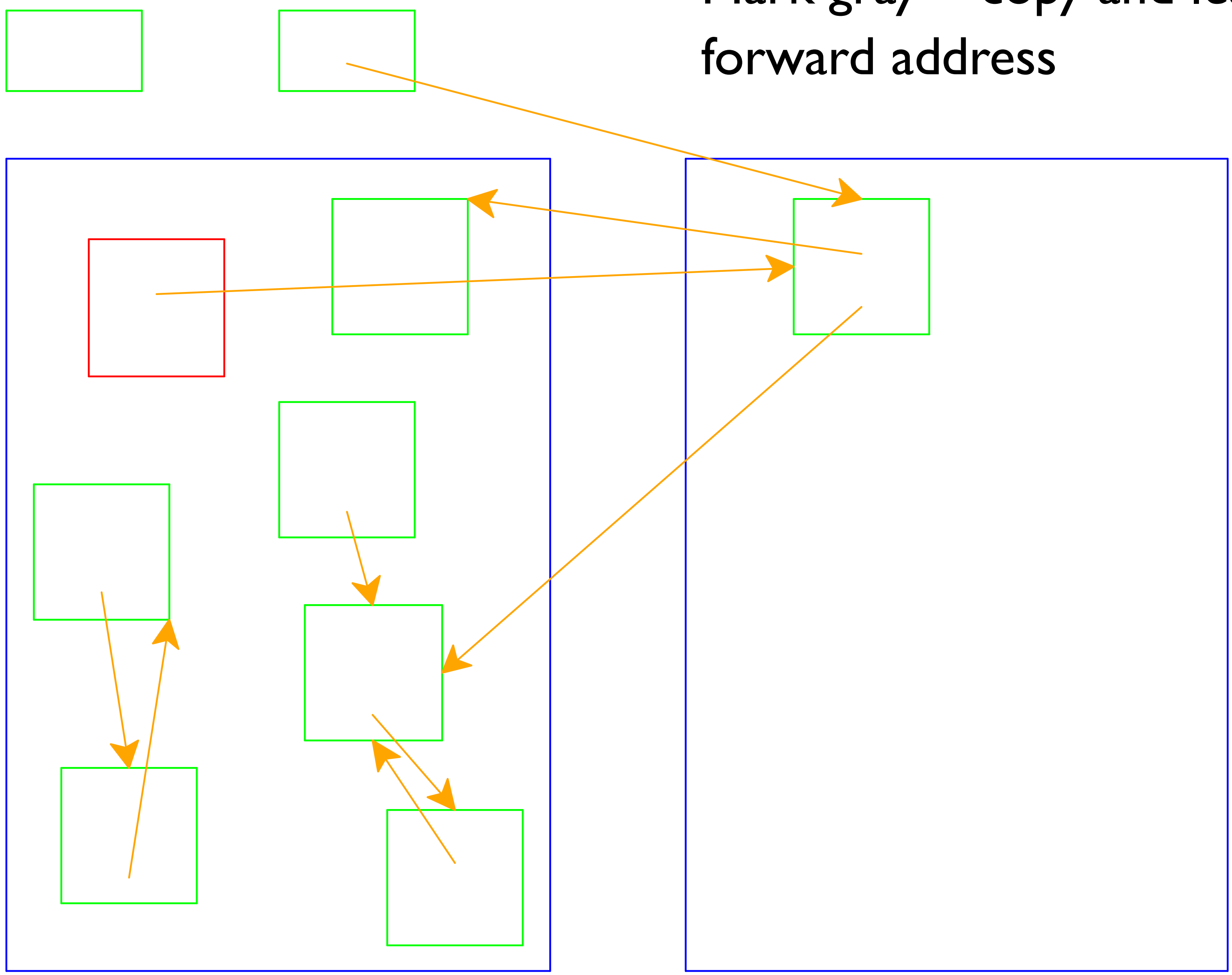
Left = from-space

Right = to-space



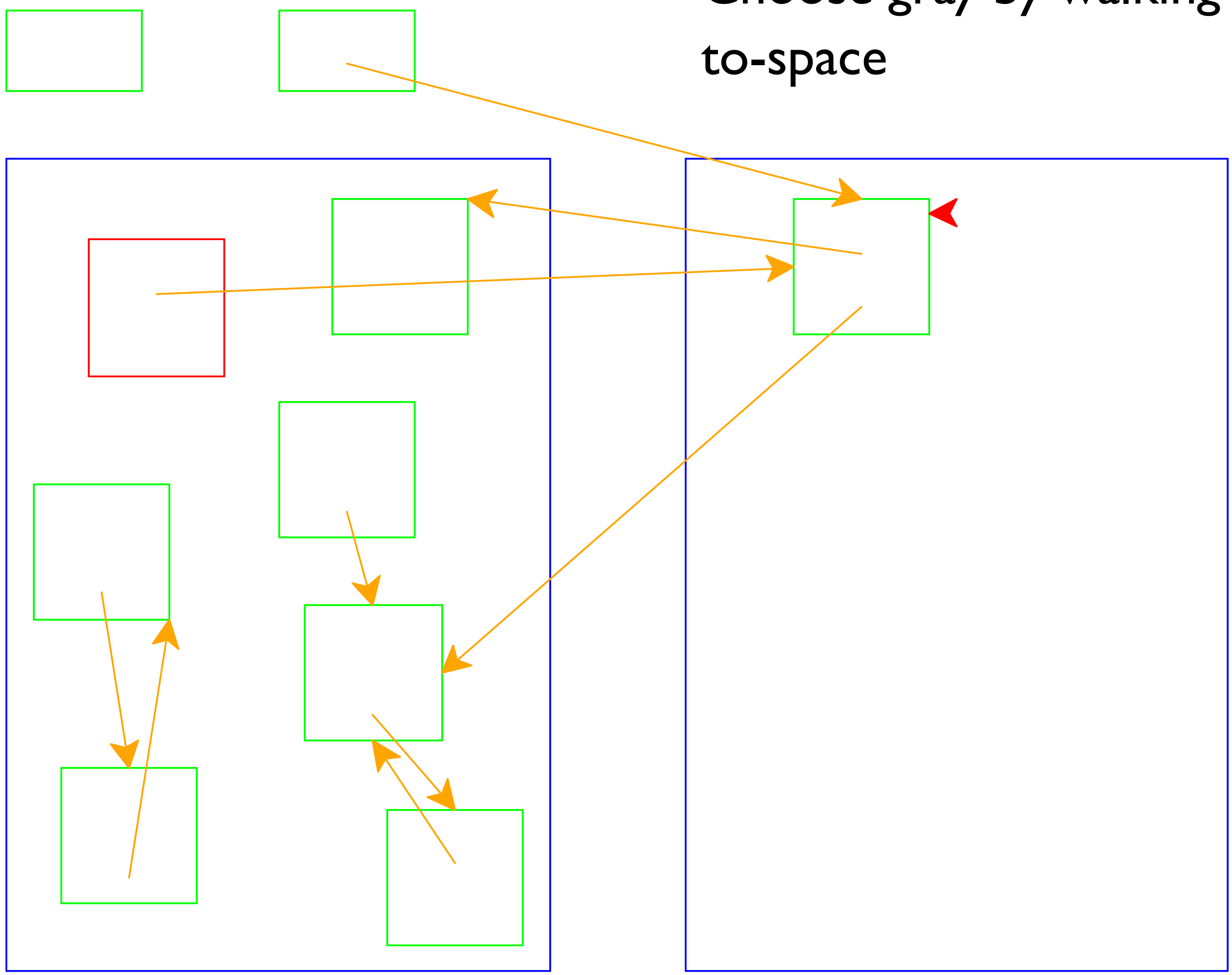
Two-Space Collection

Mark gray = copy and leave forward address



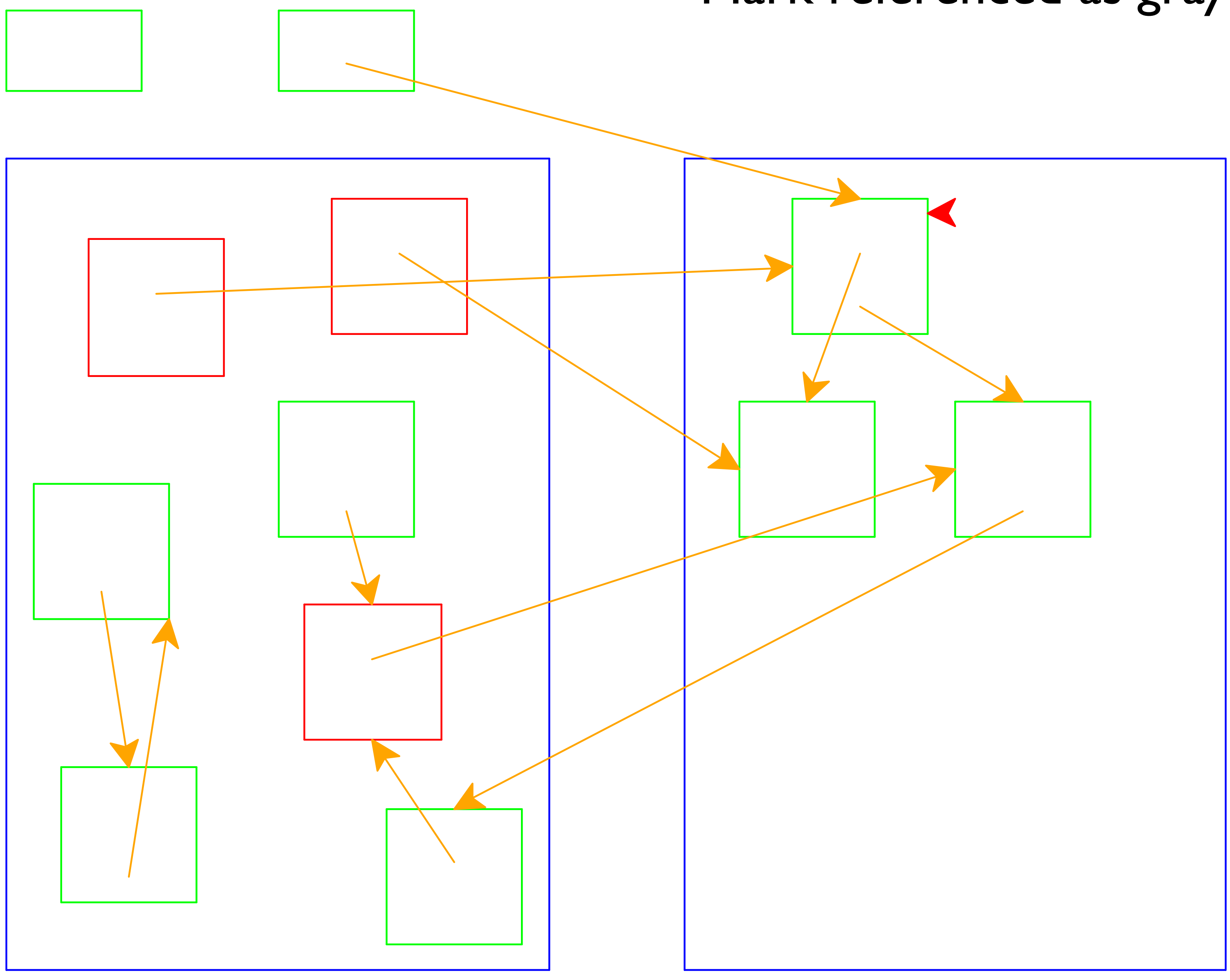
Two-Space Collection

Choose gray by walking through to-space



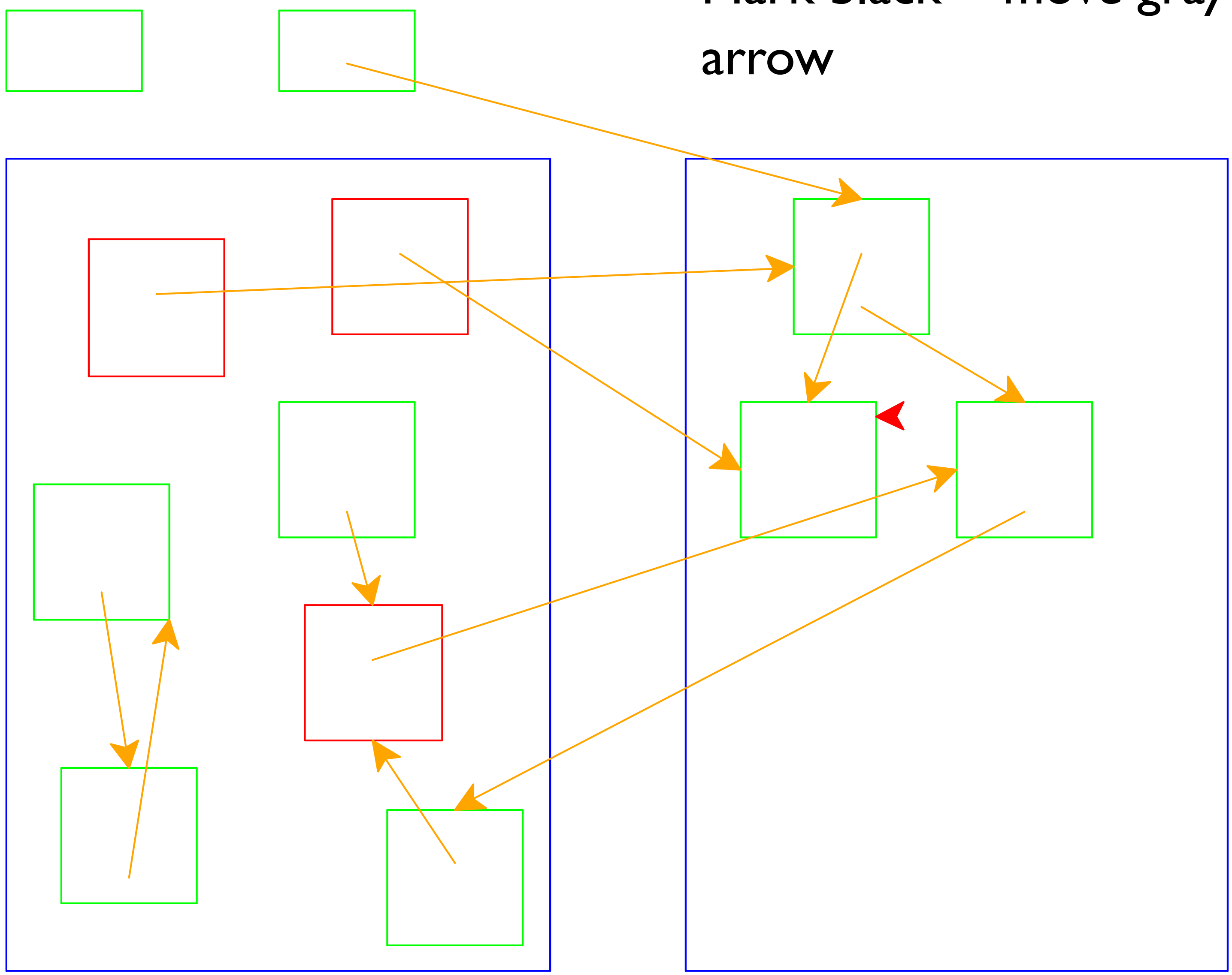
Two-Space Collection

Mark referenced as gray



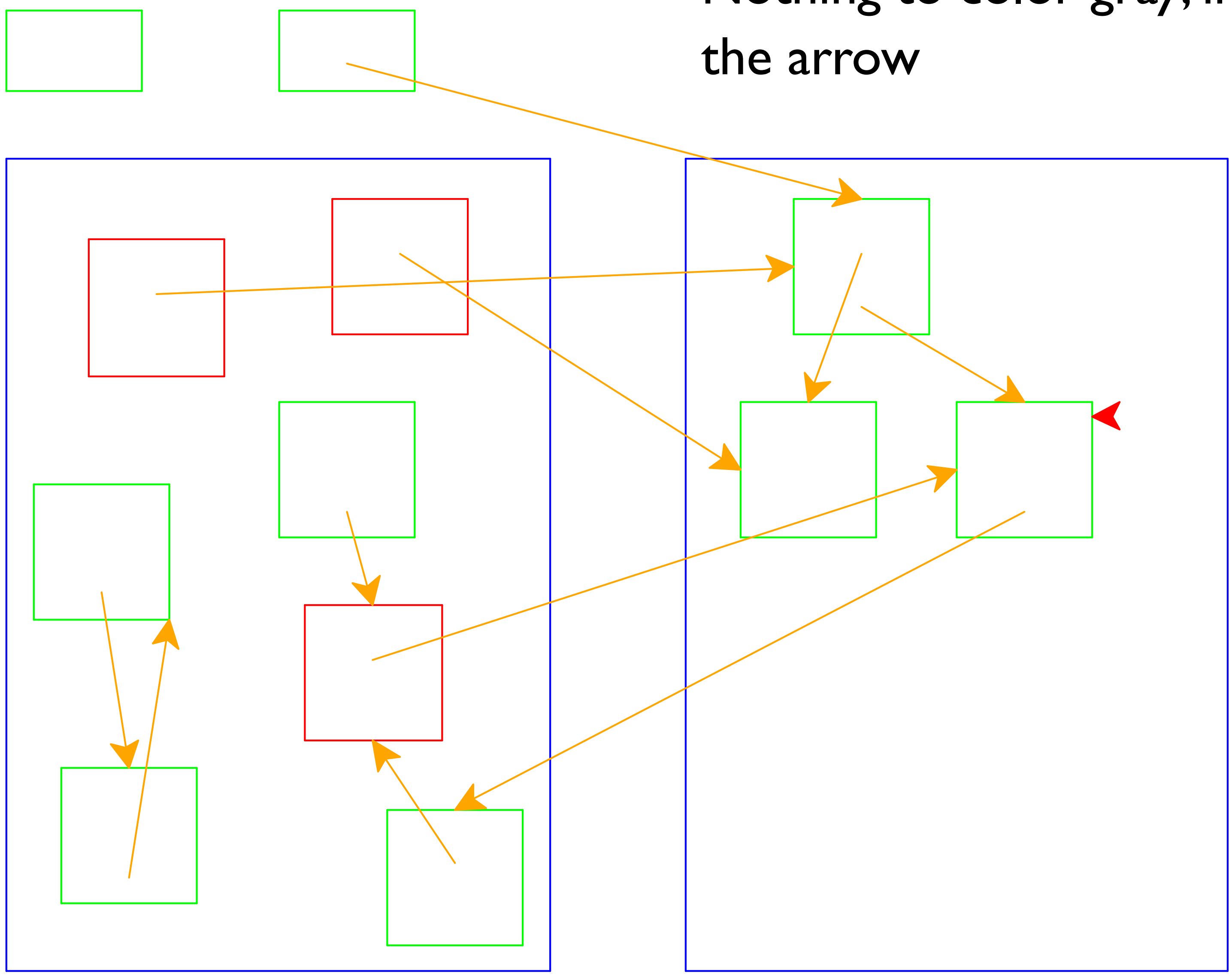
Two-Space Collection

Mark black = move gray-choosing arrow



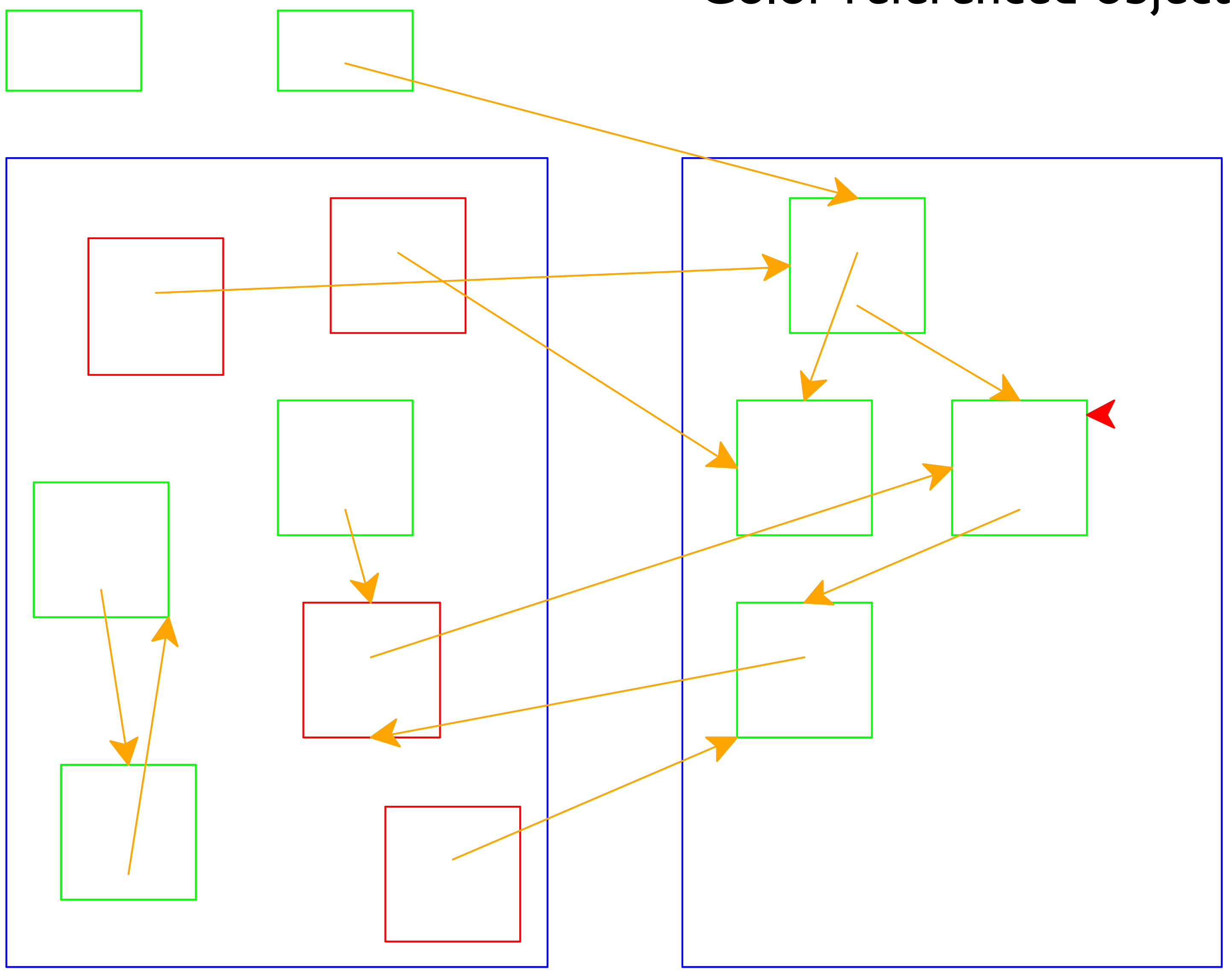
Two-Space Collection

Nothing to color gray; increment the arrow



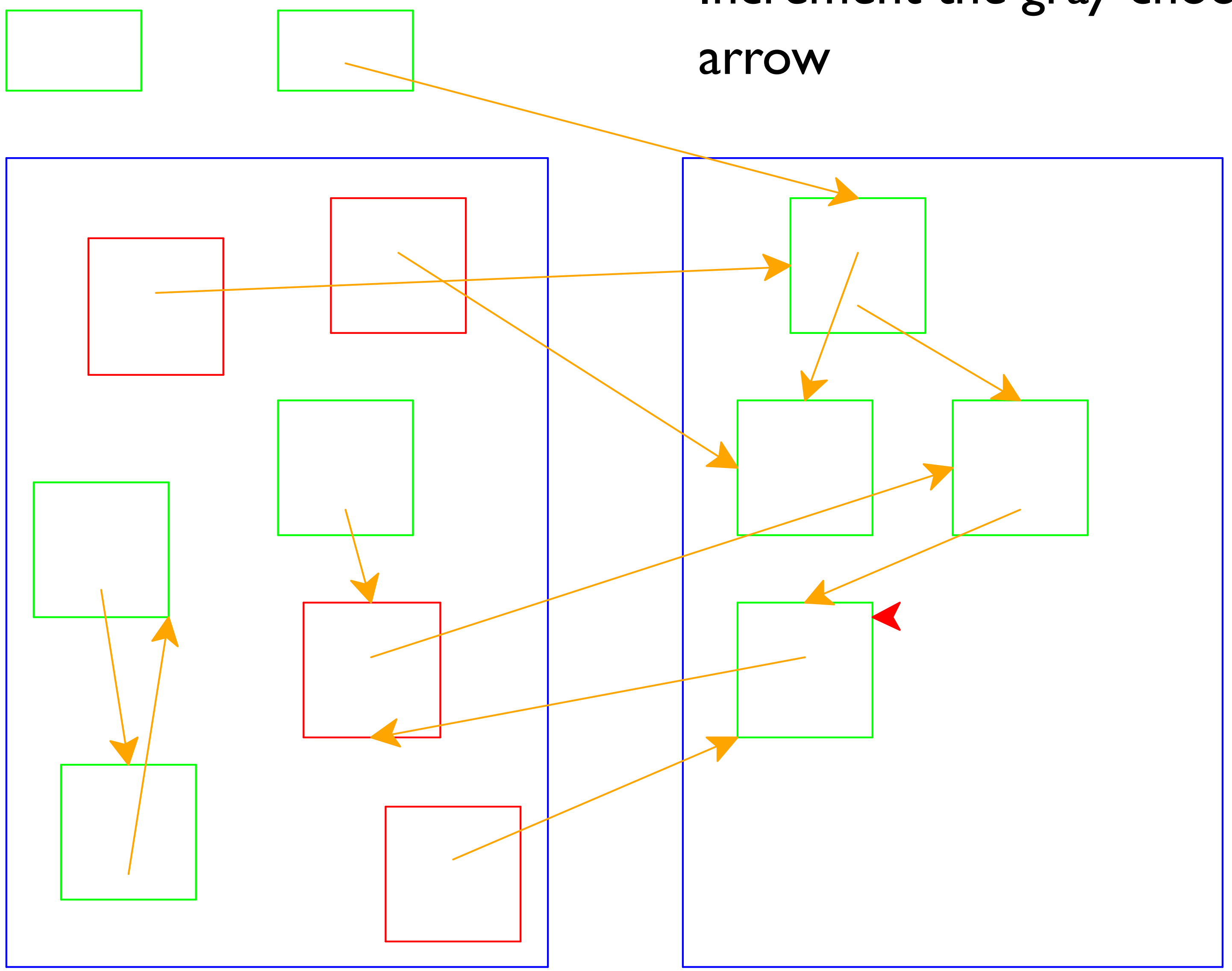
Two-Space Collection

Color referenced object gray



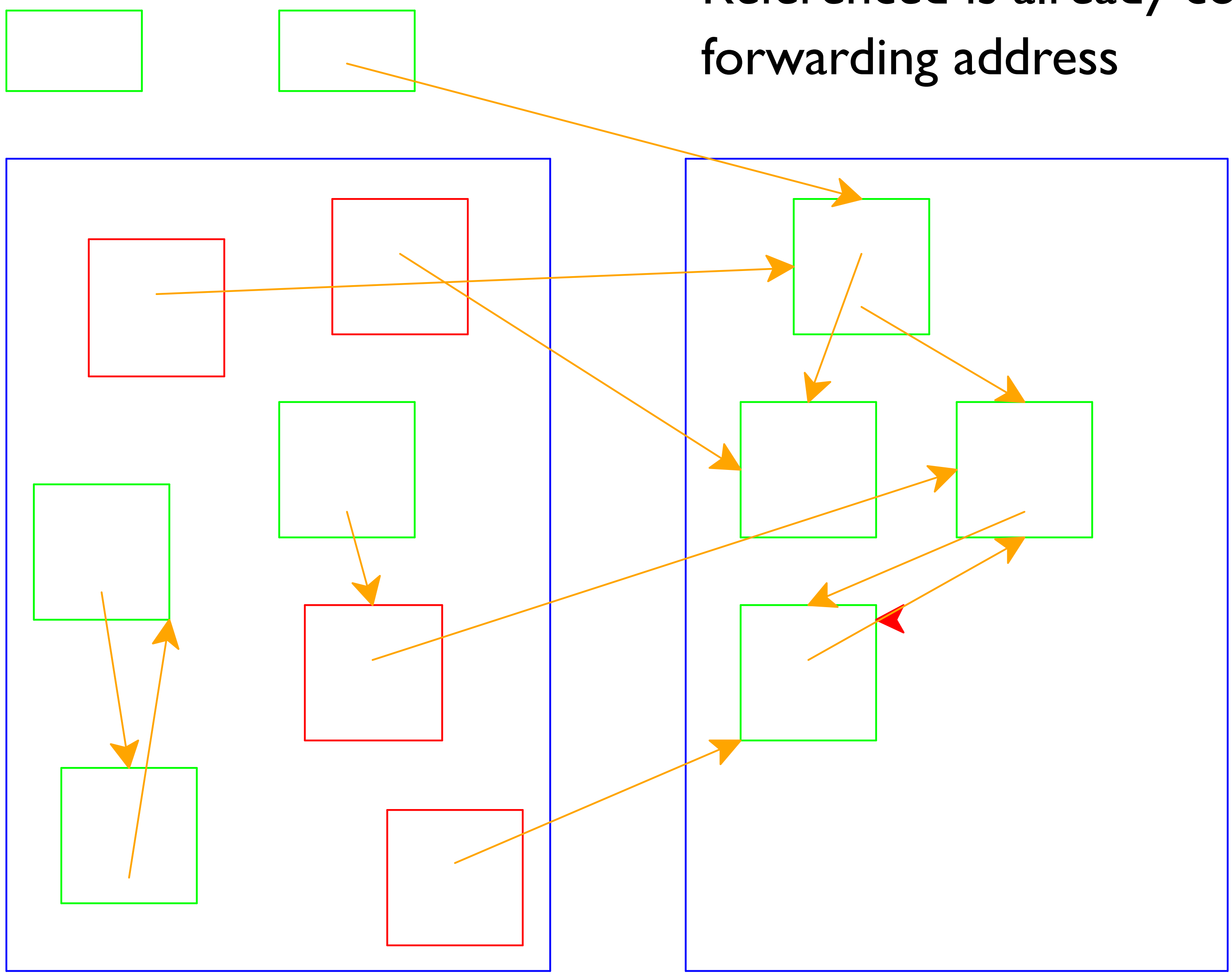
Two-Space Collection

Increment the gray-choosing arrow



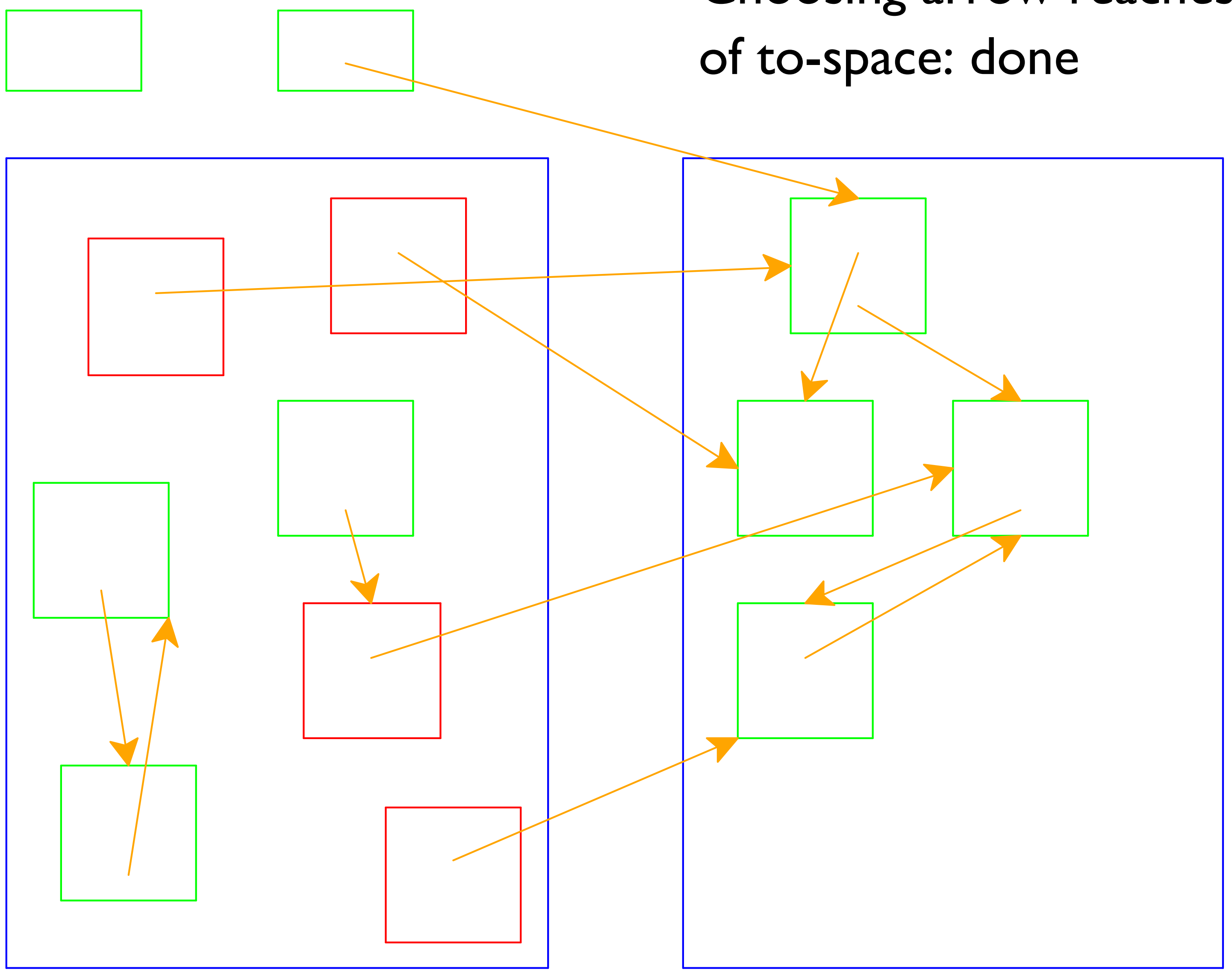
Two-Space Collection

Referenced is already copied, use forwarding address



Two-Space Collection

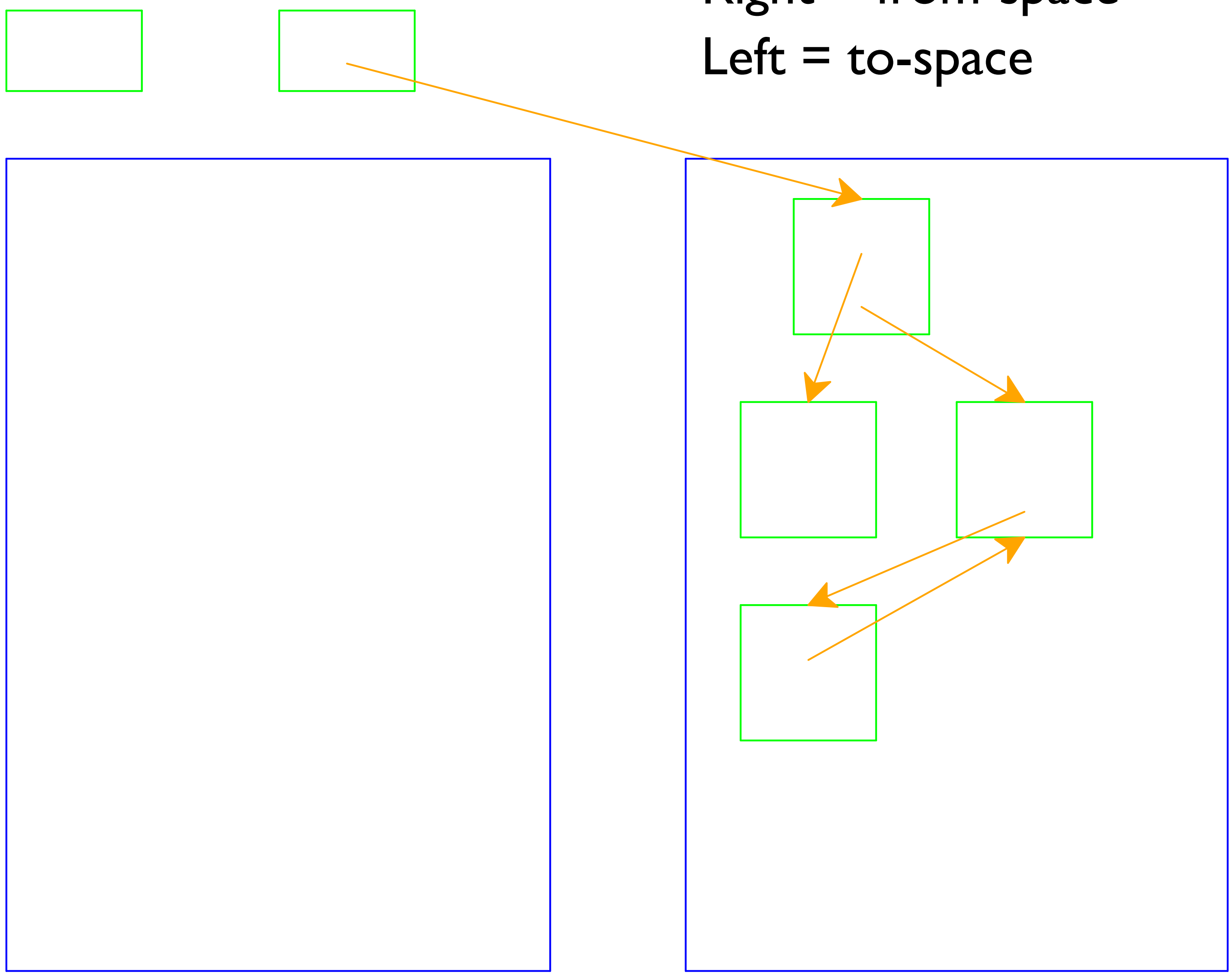
Choosing arrow reaches the end of to-space: done



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
								^					