Allocation

Constructor calls are allocation:

```
; interp : -> void
(define (interp)
  (type-case CFAE fae-reg
    ...
    [cfun (body-expr)
          (begin
            (set! v-reg (closureV body-expr sc-reg))
            (continue))]
    ...))

; continue : -> void
(define (continue k v)
  ...
  [addSecondK (r sc k)
              (begin
                (set! fae-reg r)
                (set! sc-reg sc)
                (set! k-reg (doAddK v-reg k))
                (interp))]
  ...)
```

Deallocation

Where does **free** go?

```
; continue : -> void
(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! fae-reg (closureV-body fun-val))
            (set! sc-reg (cons v-reg
                               (closureV-sc 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 `letcc`, this free is fine, because the continuation can't be referenced anywhere else
- A continuation record is always freed as `(free k-reg)`, which is why most languages use a stack

Deallocation

```
[doAppK (fun-val k)
        (begin
          (set! fae-reg (closureV-body fun-val))
          (set! sc-reg (cons v-reg
                             (closureV-sc fun-val)))
          (set! k-reg k)
          (free fun-val) ; ???
          (interp))]
```

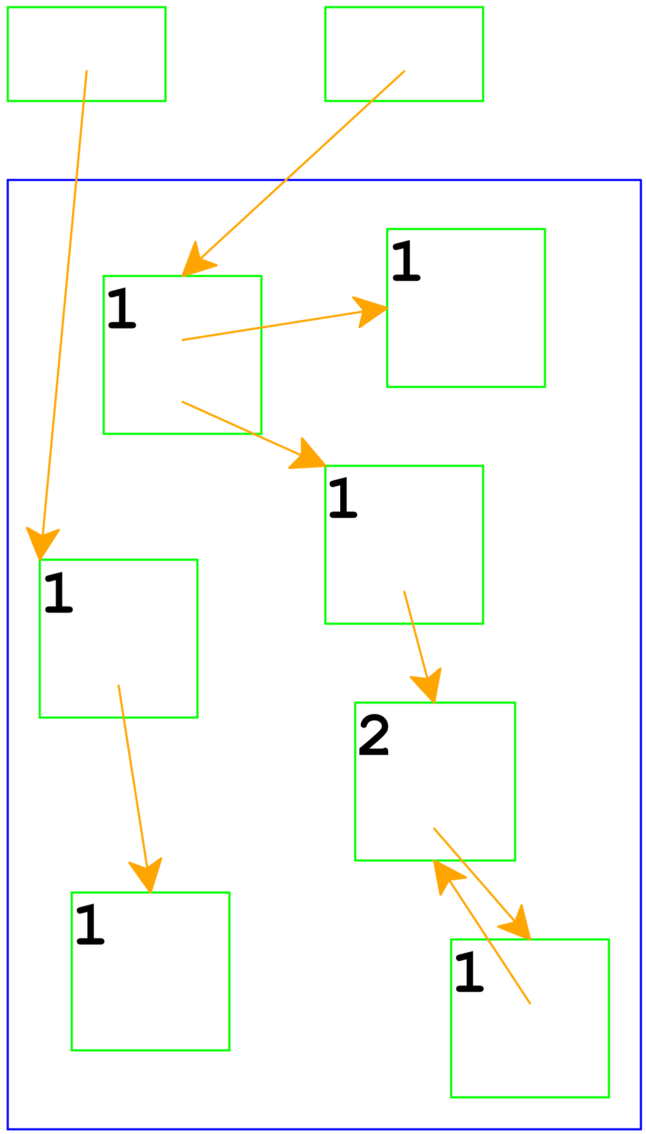
- This free is *not* ok, because the closure might be kept in a substitution somewhere
- Need to free only if no one else is using it...

Reference Counting

Reference counting: a way to know whether a record has other users

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

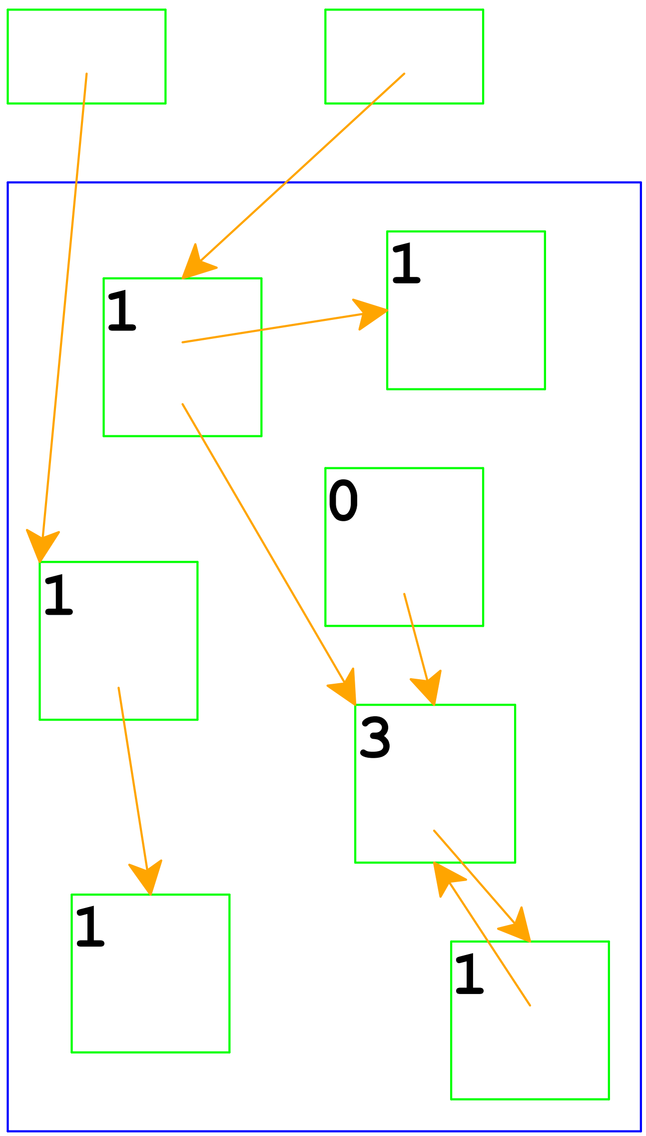
Reference Counting



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

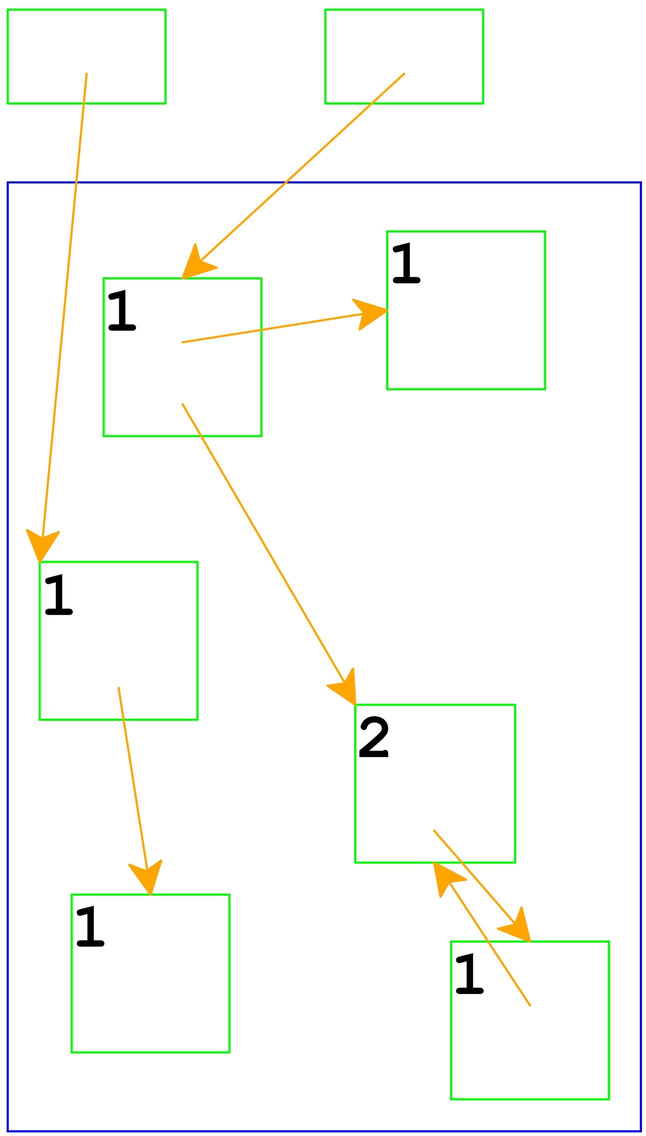
Boxes in the blue area are allocated with **`malloc`**

Reference Counting



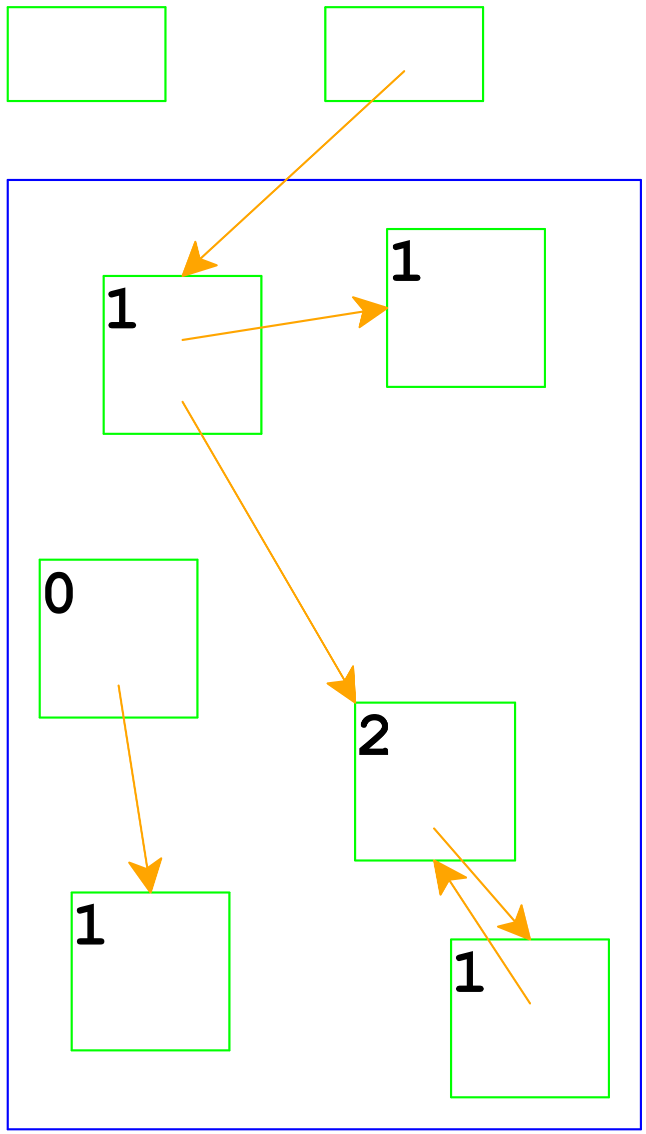
Adjust counts when a pointer is changed...

Reference Counting



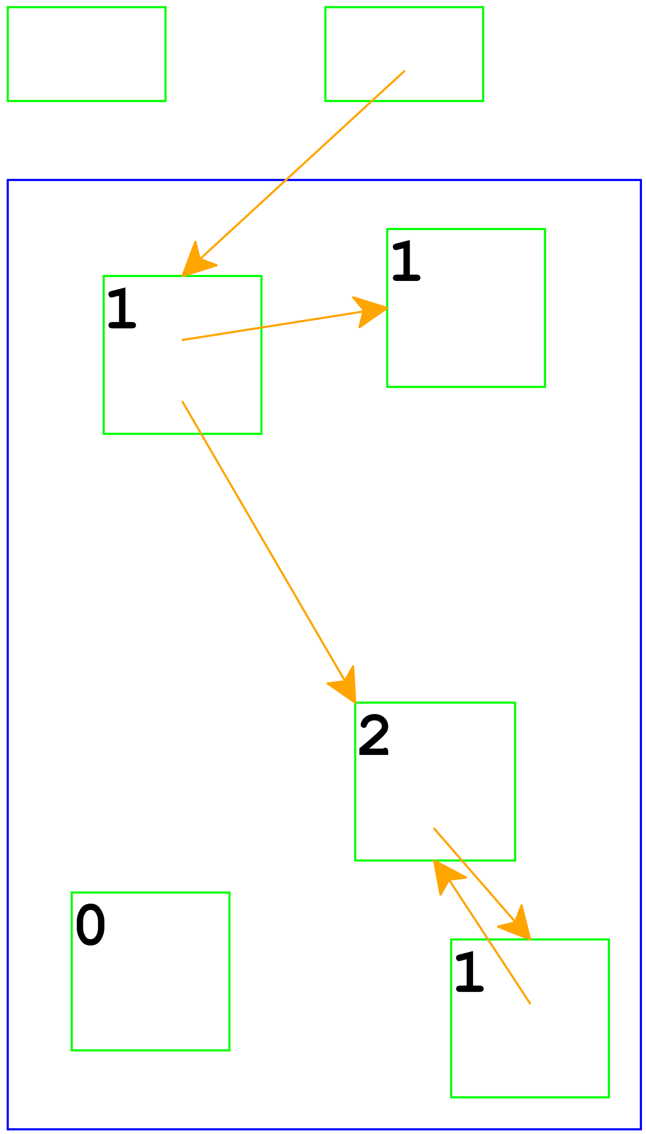
... freeing a record if its count goes to 0

Reference Counting



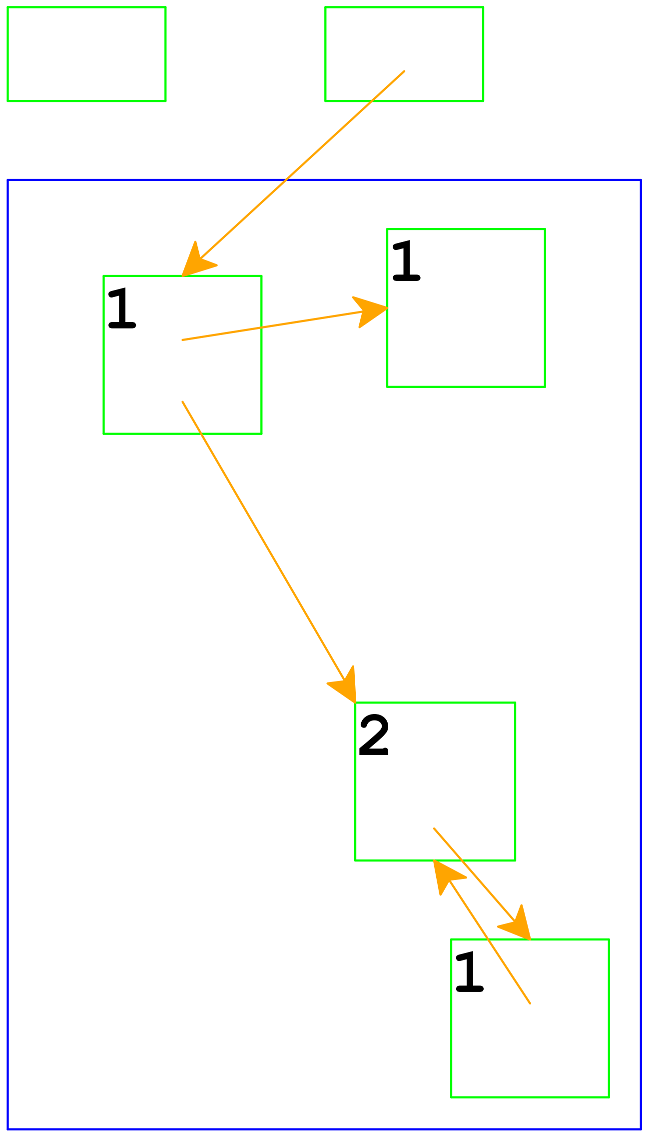
Same if the pointer is in a register

Reference Counting



Adjust counts after frees, too...

Reference Counting

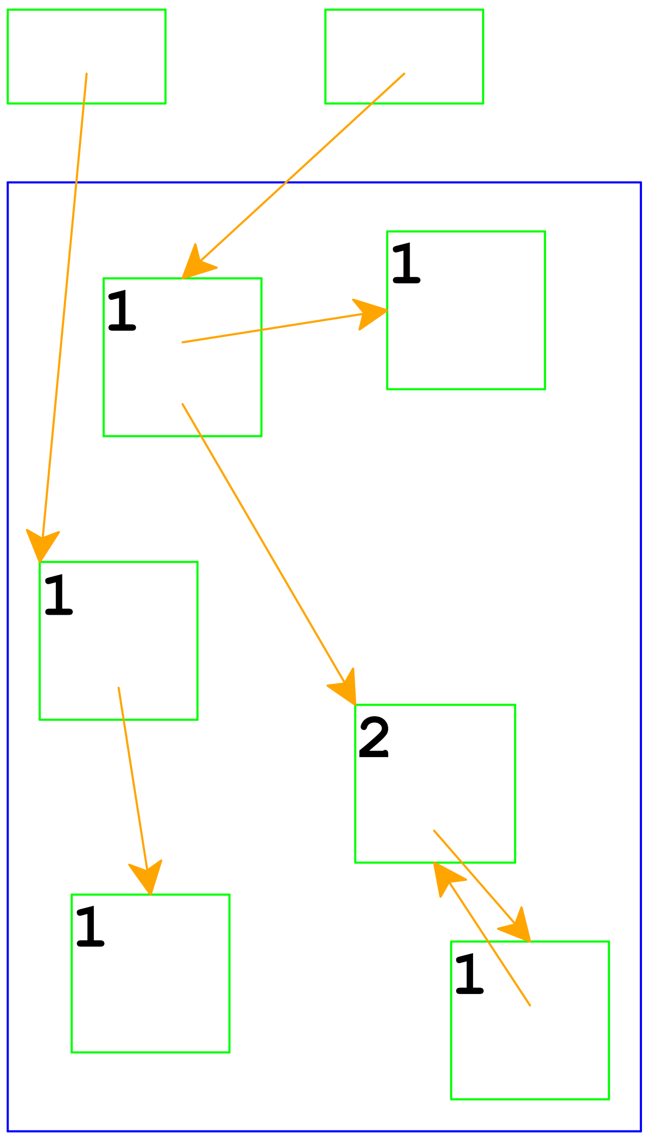


... which can trigger more frees

Reference Counting in FAE

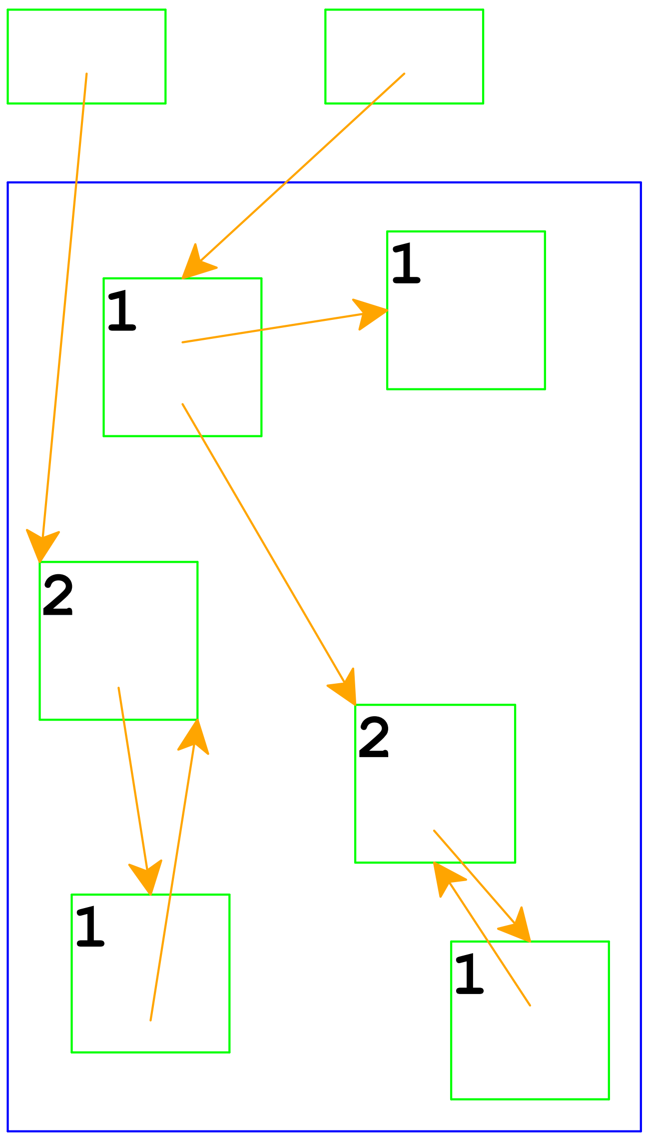
```
...
[cfun (body-expr)
      (begin
        (ref- v-reg)
        (set! v-reg (closureV body-expr sc-reg))
        (ref+ v-reg)
        (continue))]
...
[doAppK (fun-val k)
        (begin
          (set! fae-reg (closureV-body fun-val)) ; code is static
          (ref- sc-reg)
          (set! sc-reg (cons v-reg (closureV-sc fun-val)))
          (ref+ sc-reg) ; => ref+ on v-reg and closure's sc
          (ref+ k)
          (ref- k-reg) ; => ref- on fun-val and k
          (set! k-reg k)
          (interp))]
```

Reference Counting And Cycles



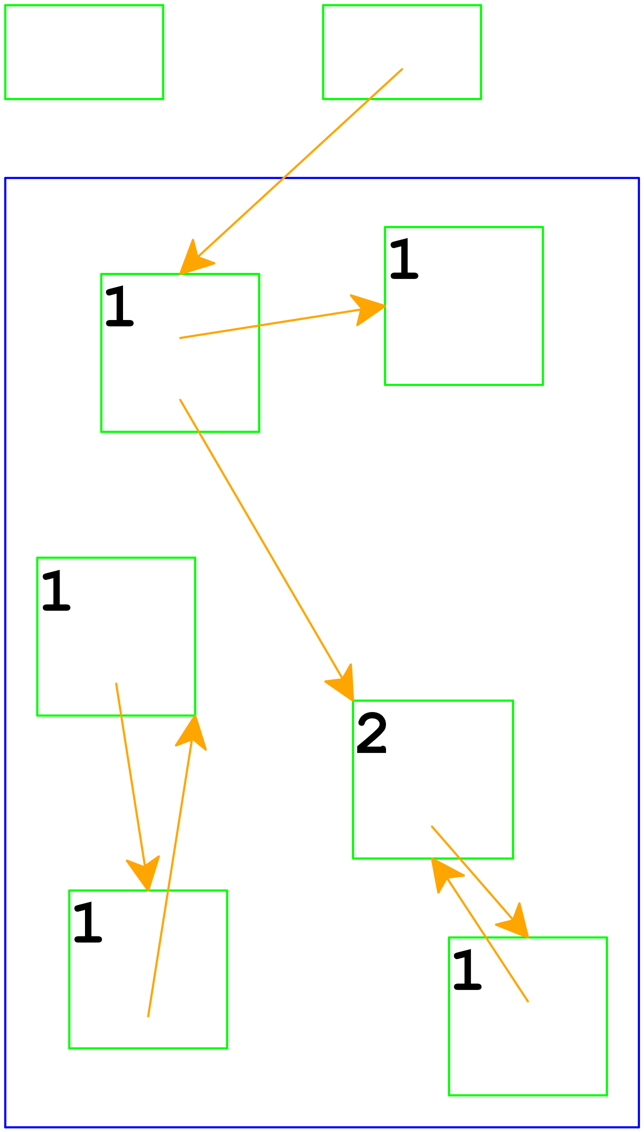
An assignment can create a cycle...

Reference Counting And Cycles



Adding a reference increments a count

Reference Counting And Cycles



Lower-left records are inaccessible, but not deallocated

In general, cycles break reference counting

Garbage Collection

Garbage collection: a way to know whether a record is *accessible*

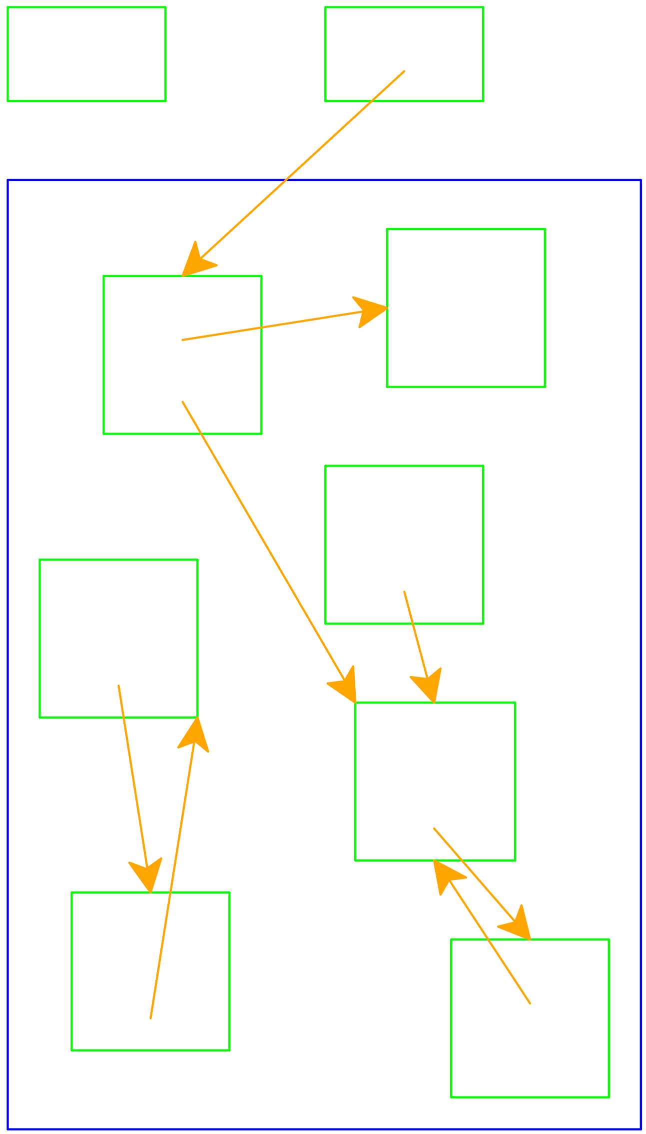
- A record referenced by a register is ***live***
- A record referenced by a live record is also live
- A program can only possibly use live records, because there is no way to get to other records

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

Garbage Collection Algorithm

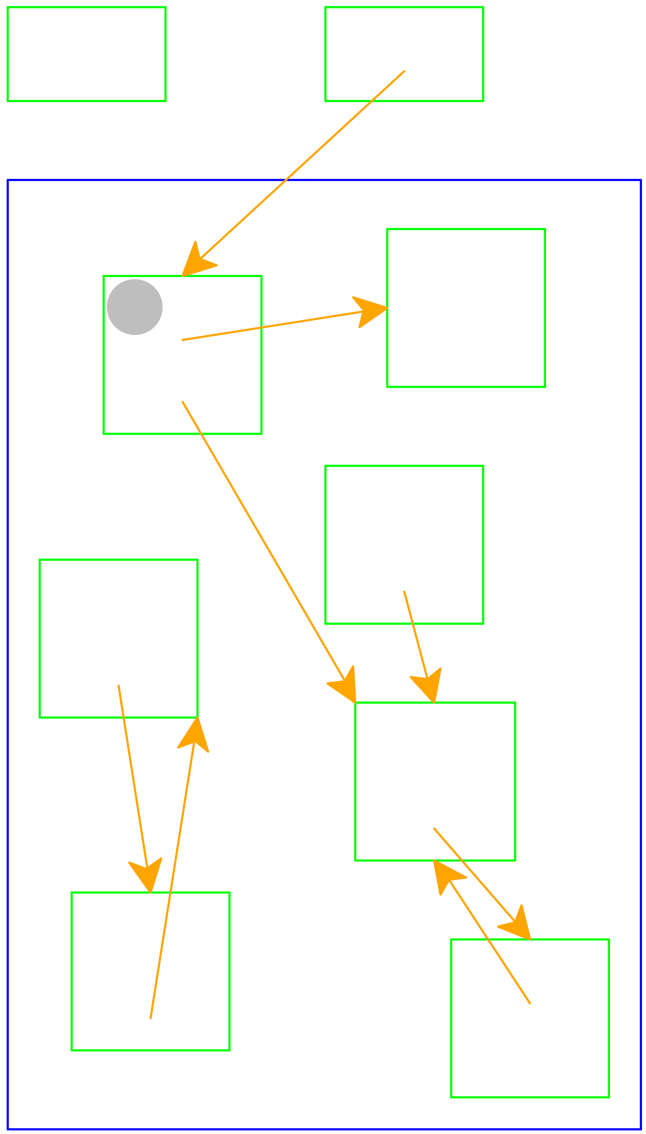
- Color all records ***white***
- Color records referenced by registers ***gray***
- Repeat until there are no gray records:
  - Pick a gray record, *r*
  - For each white record that *r* points to, make it gray
  - Color *r* ***black***
- Deallocate all white records

Garbage Collection



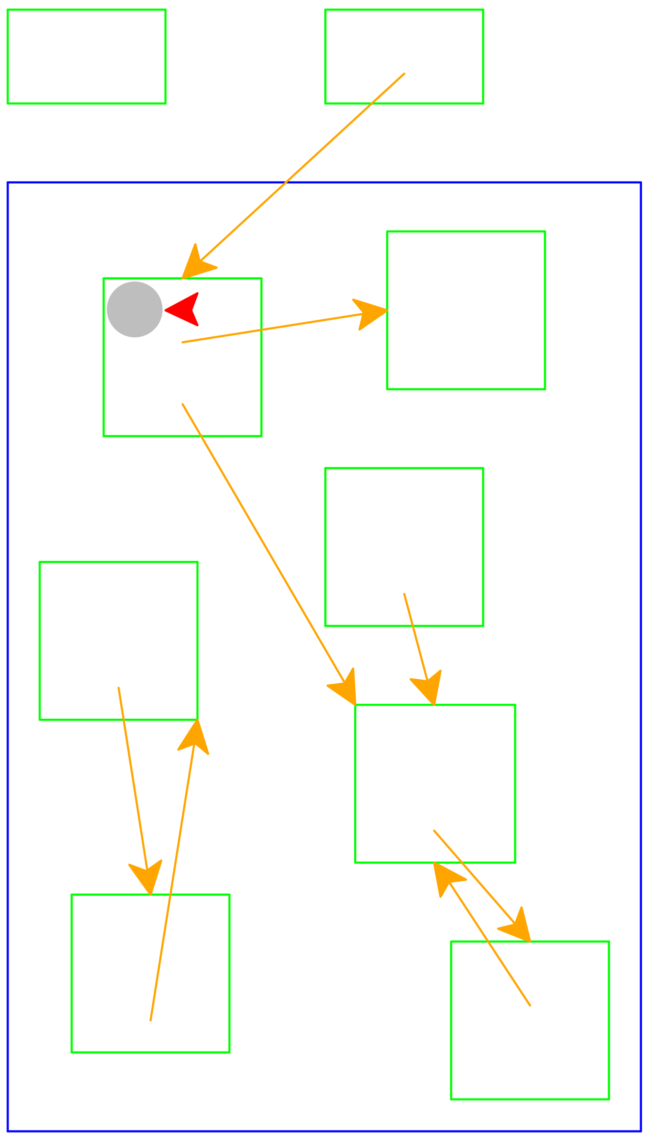
All records are marked white

Garbage Collection



Mark records referenced by registers as gray

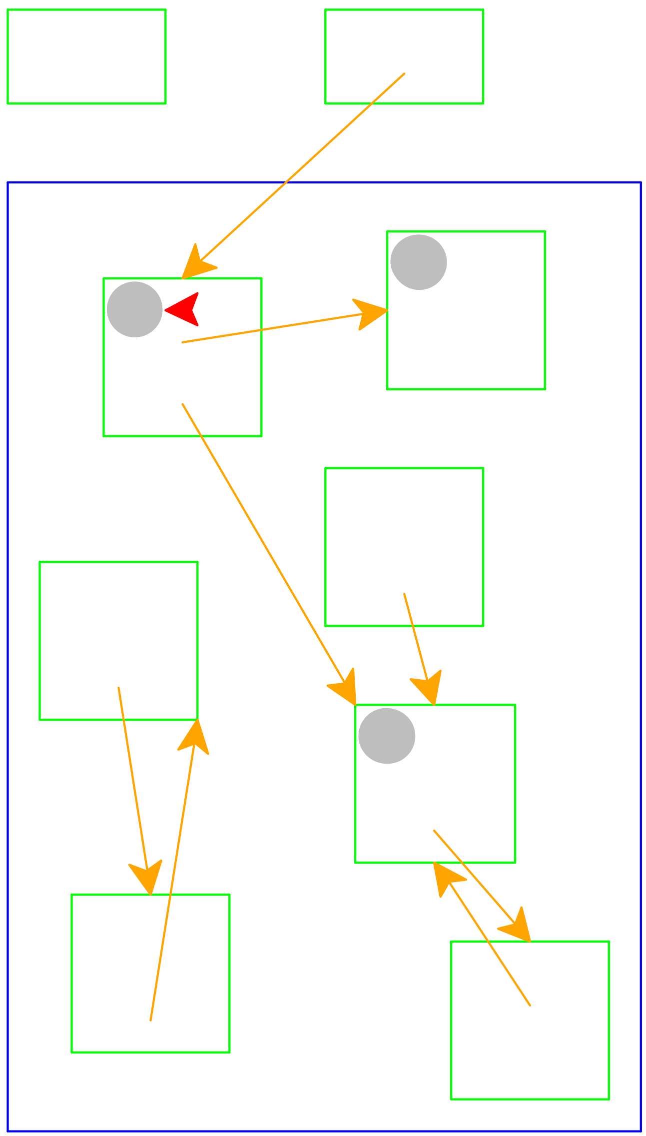
Garbage Collection



Need to pick a gray record

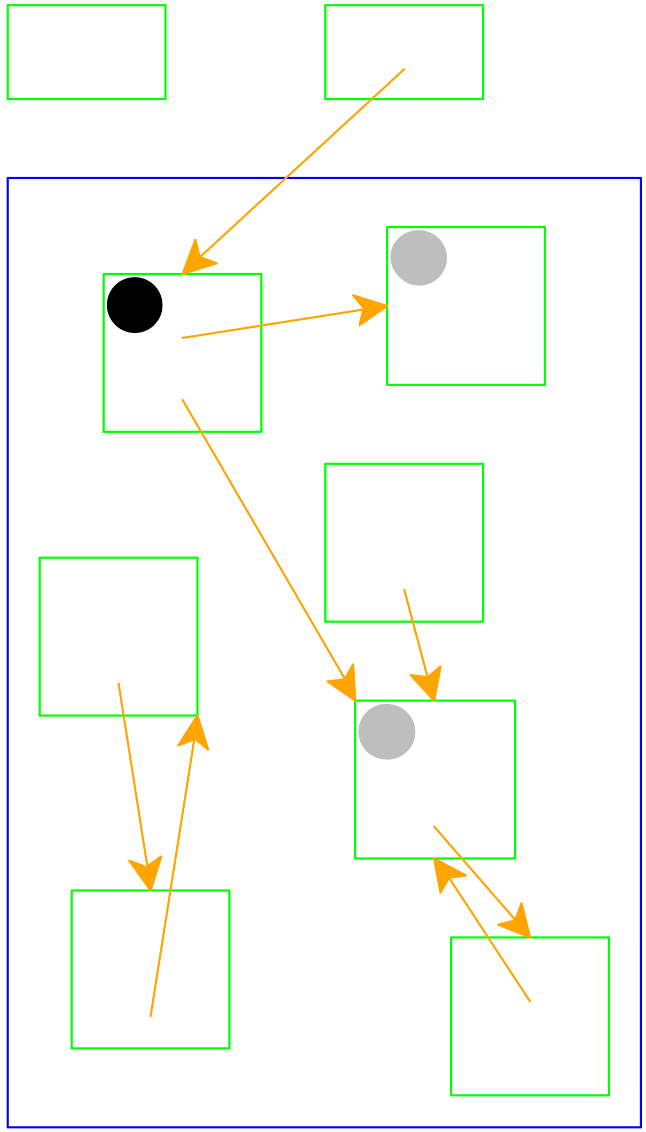
Red arrow indicates the chosen record

Garbage Collection



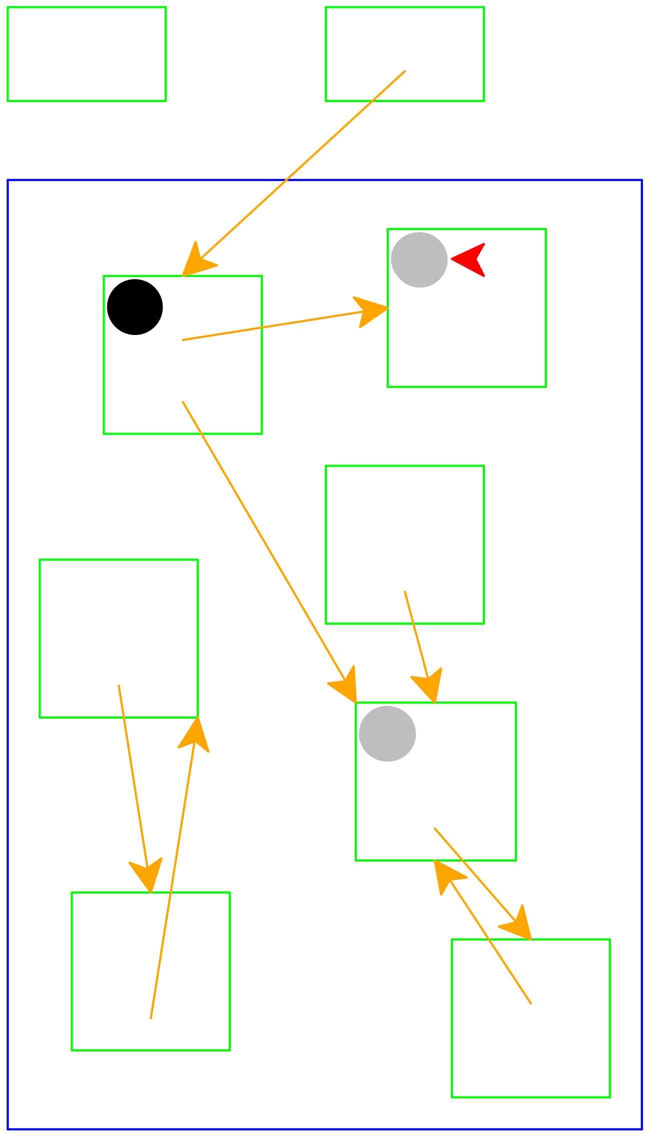
Mark white records referenced by chosen record as gray

Garbage Collection



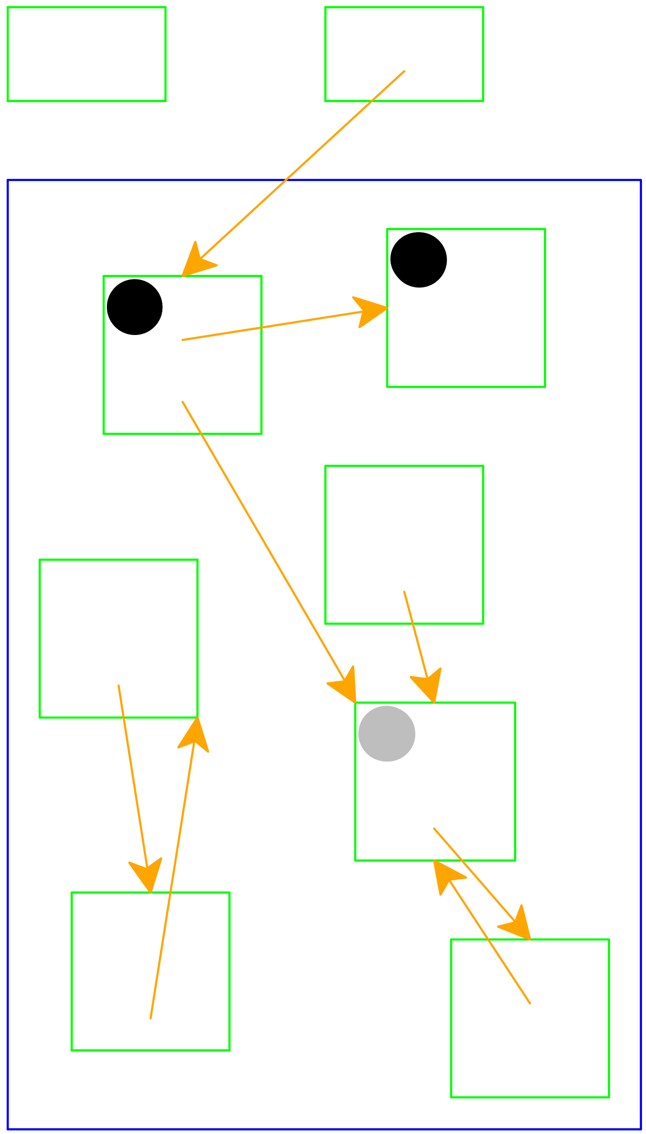
Mark chosen record black

Garbage Collection



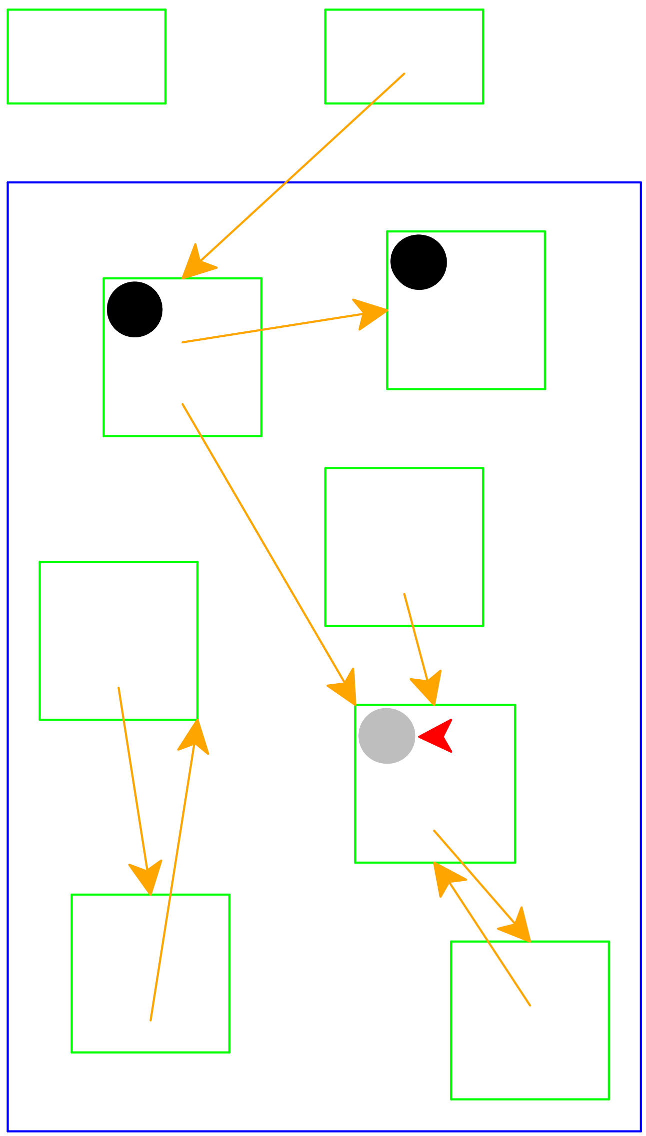
Start again: pick a gray record

Garbage Collection



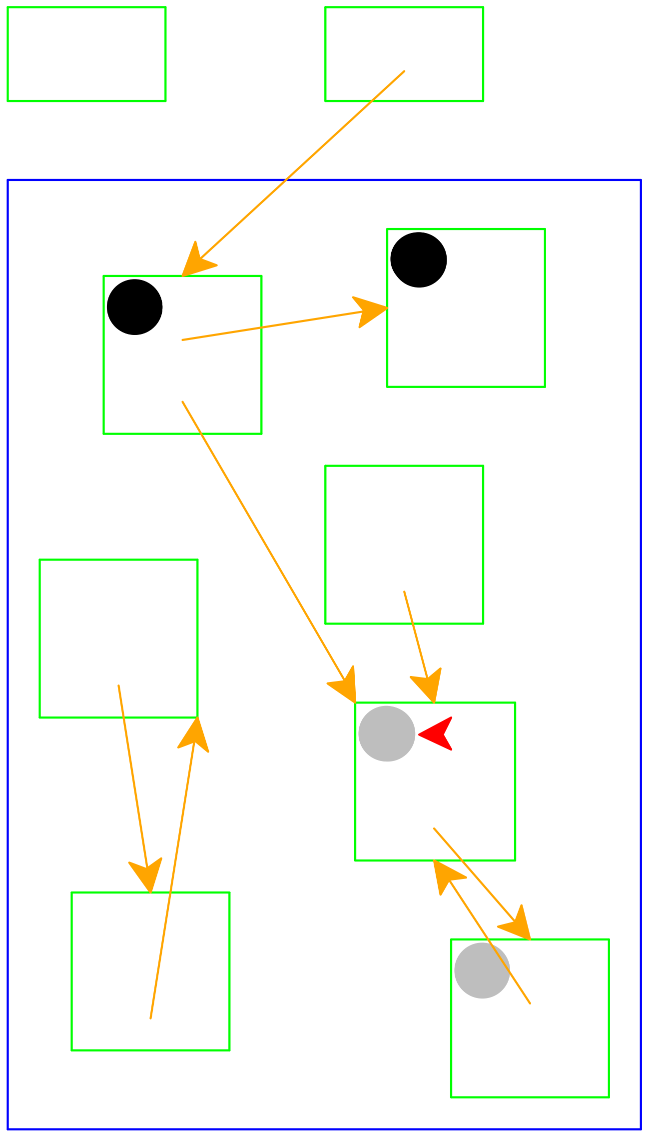
No referenced records; mark black

Garbage Collection



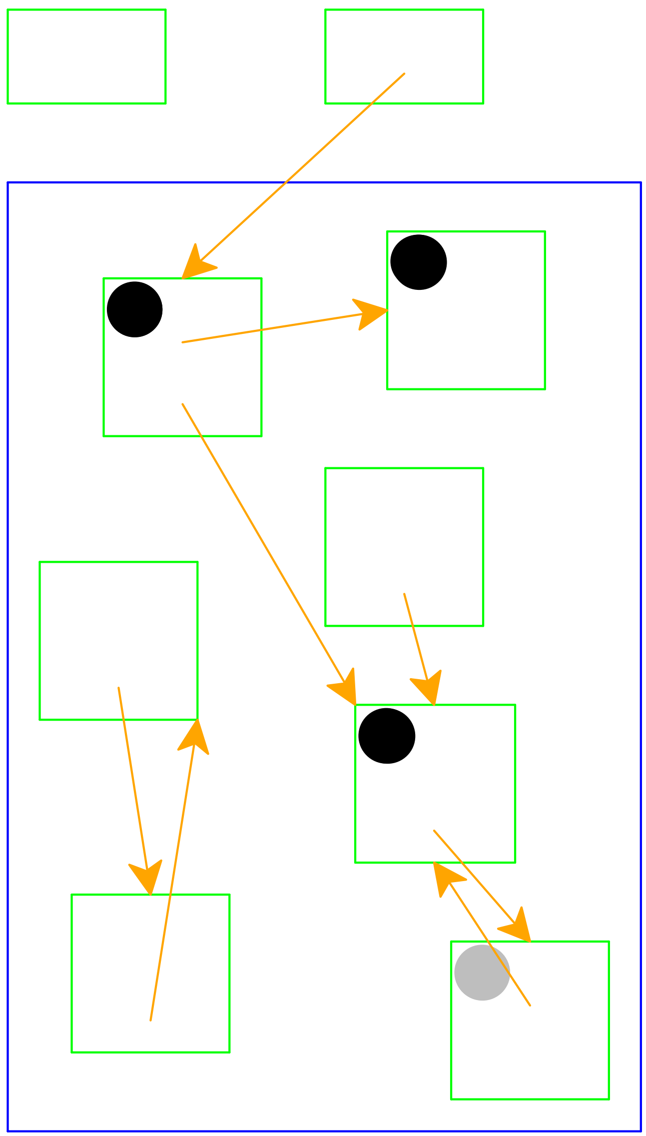
Start again: pick a gray record

Garbage Collection



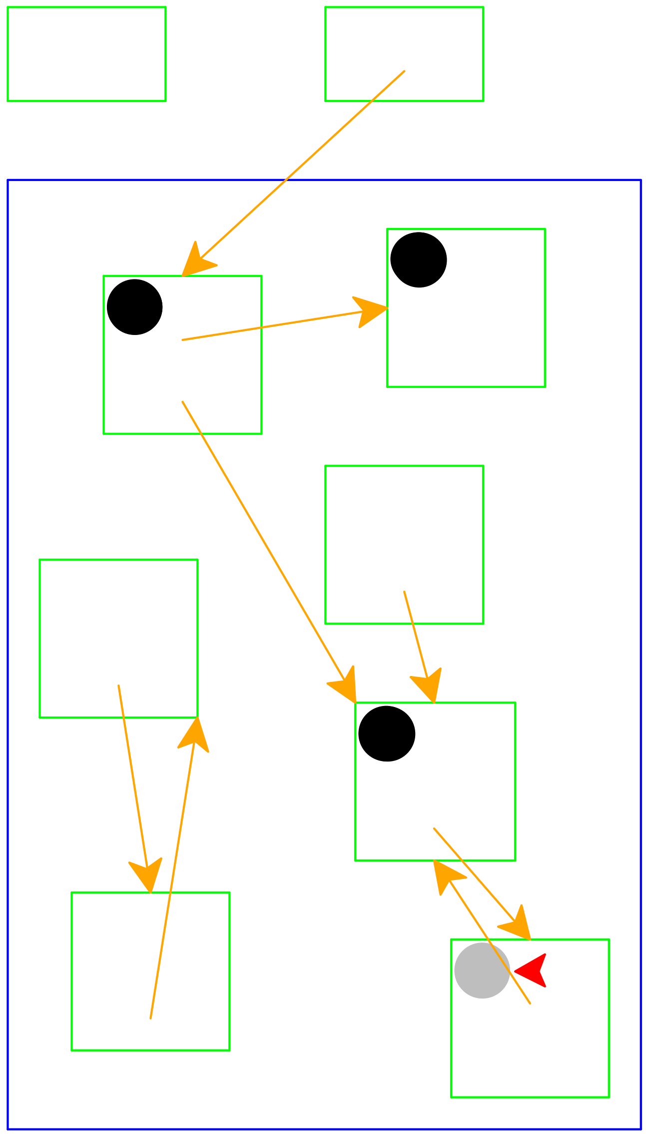
Mark white records referenced by chosen record as gray

Garbage Collection



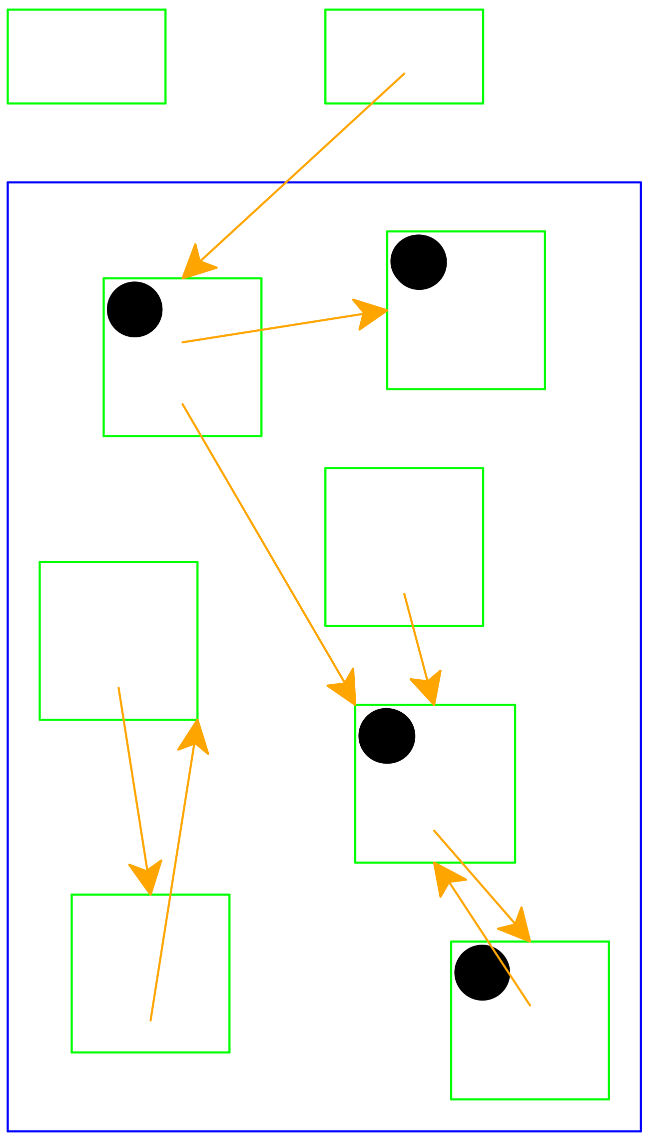
Mark chosen record black

Garbage Collection



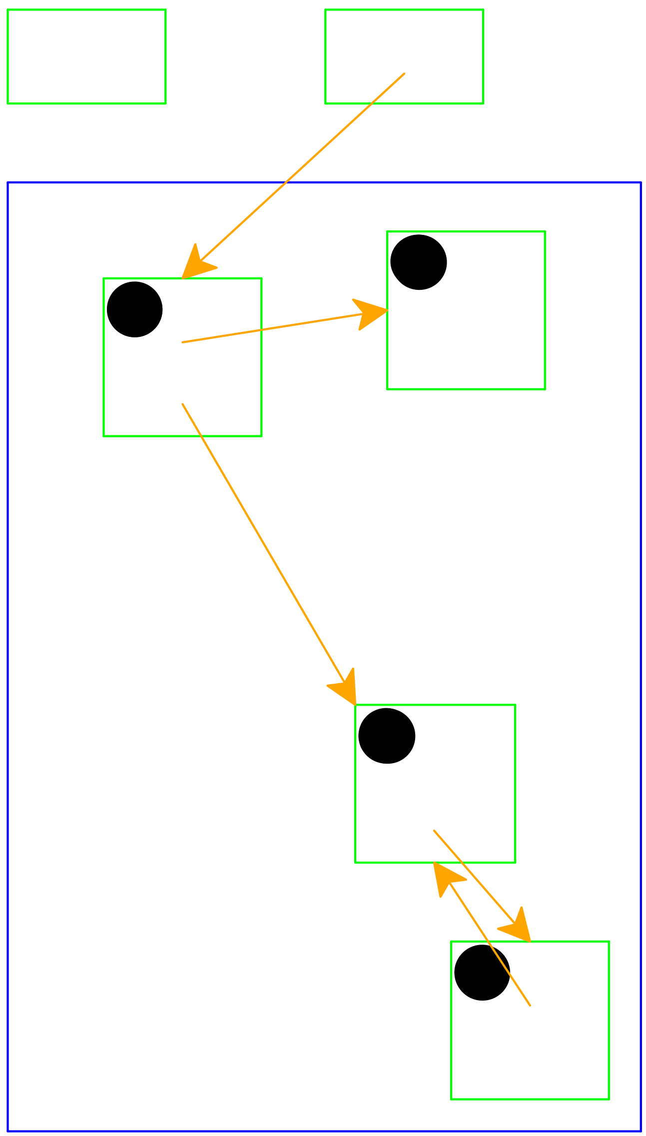
Start again: pick a gray record

Garbage Collection



No referenced white records; mark black

Garbage Collection



No more gray records; deallocate white records

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

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***

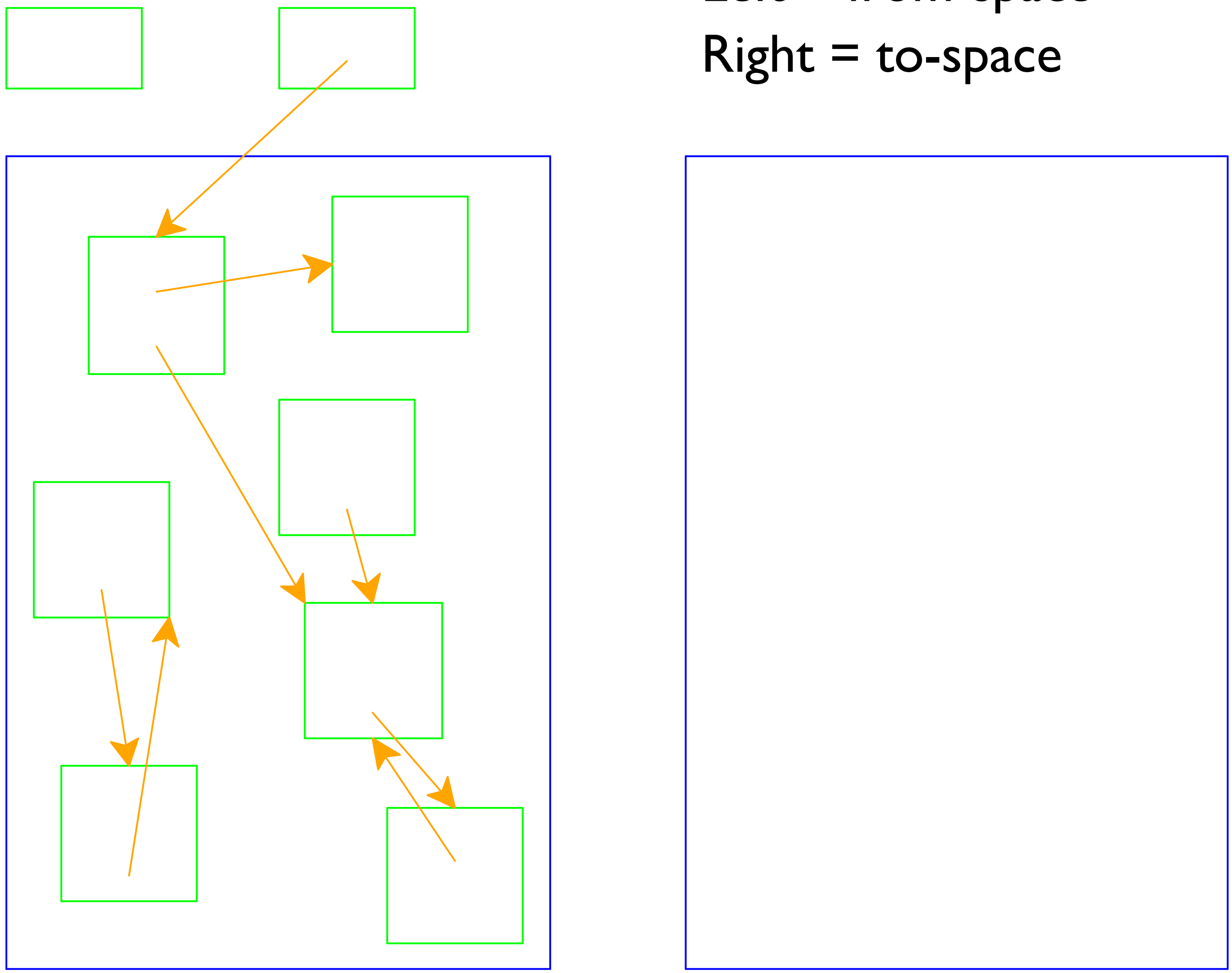
Collector:

- Starts by swapping ***to-space*** and ***from-space***
- Coloring gray $\Rightarrow$ copy from ***from-space*** to ***to-space***
- Choosing a gray record $\Rightarrow$ walk once though the new ***to-space***, update pointers

Two-Space Collection

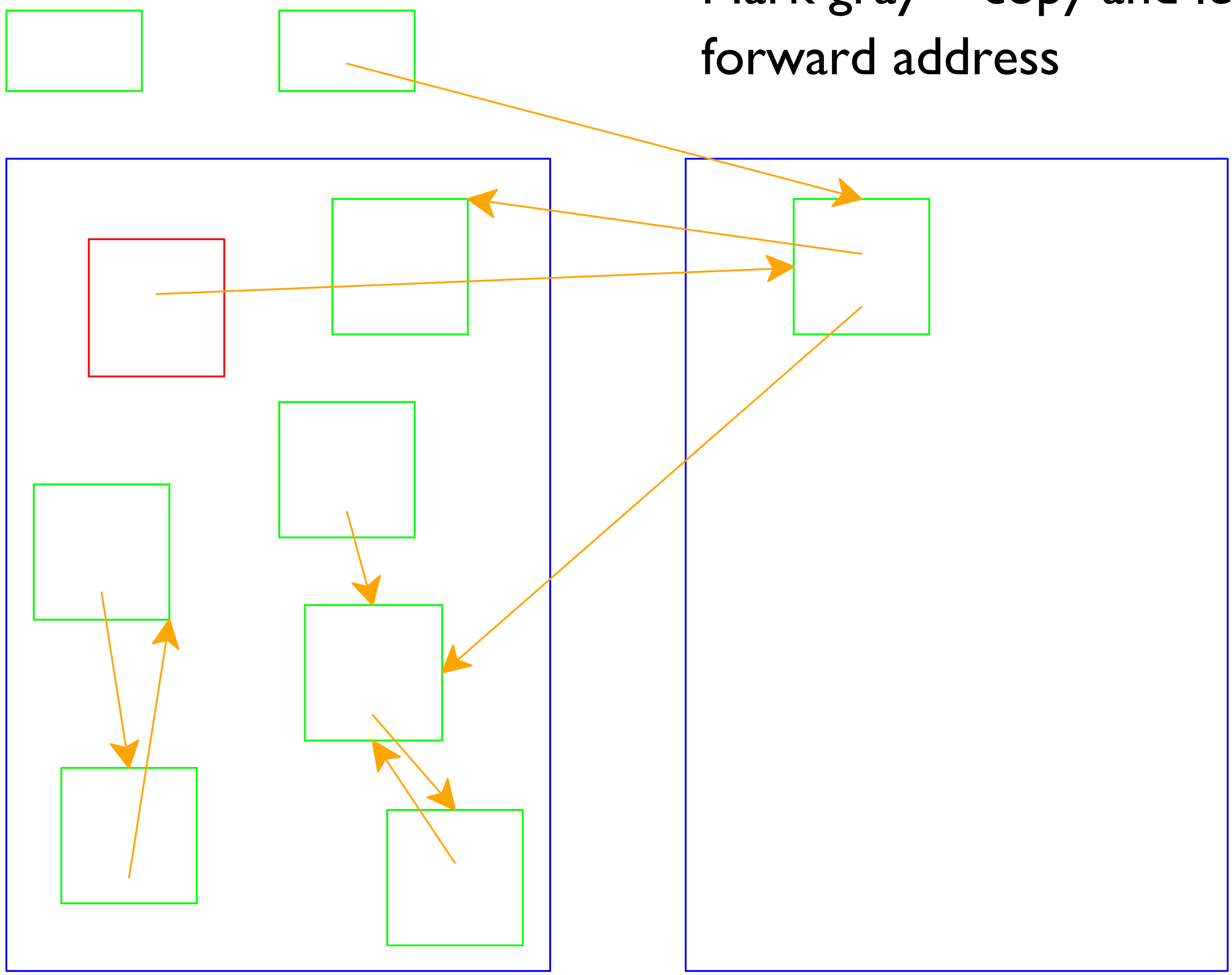
Left = from-space

Right = to-space



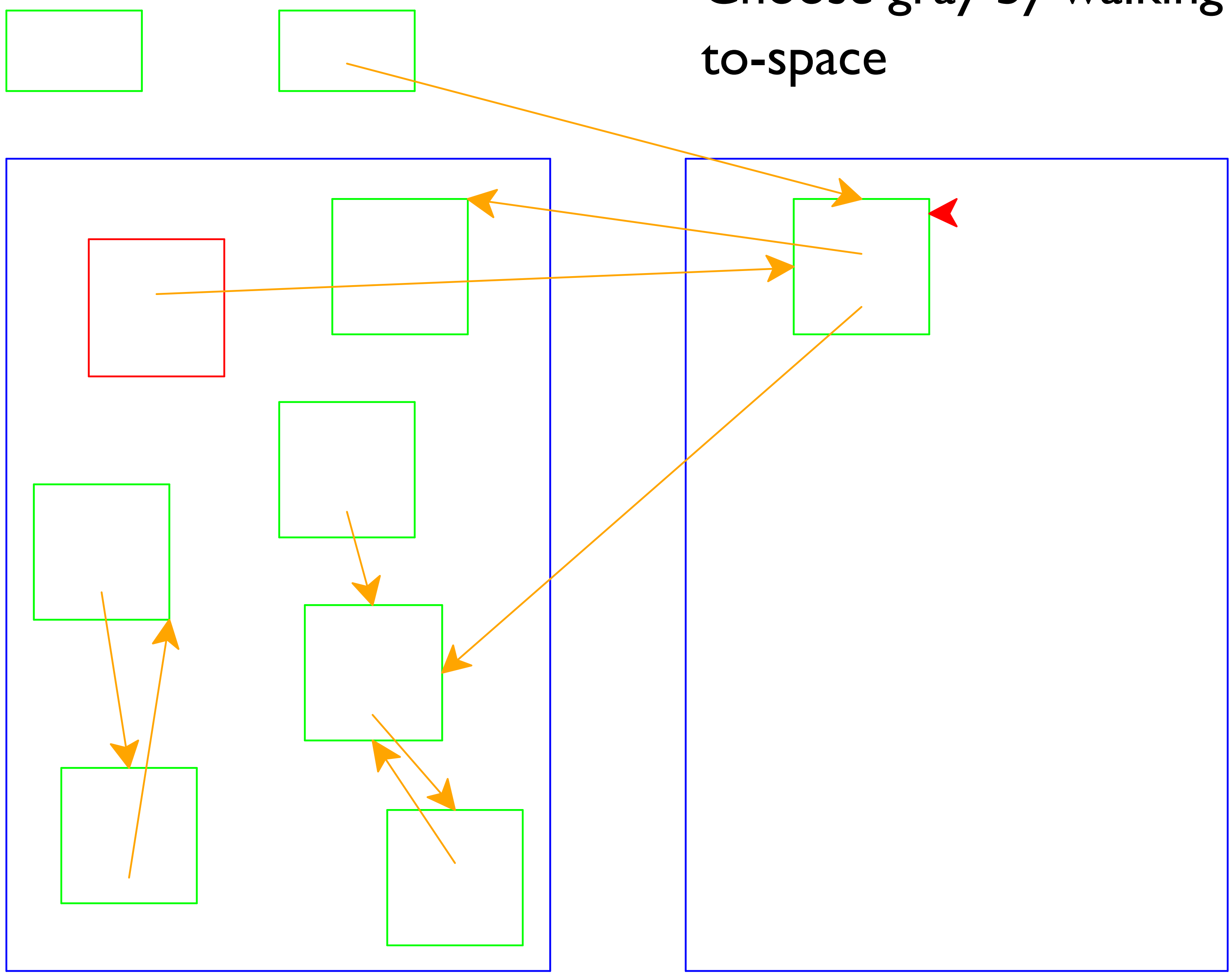
Two-Space Collection

Mark gray = copy and leave forward address



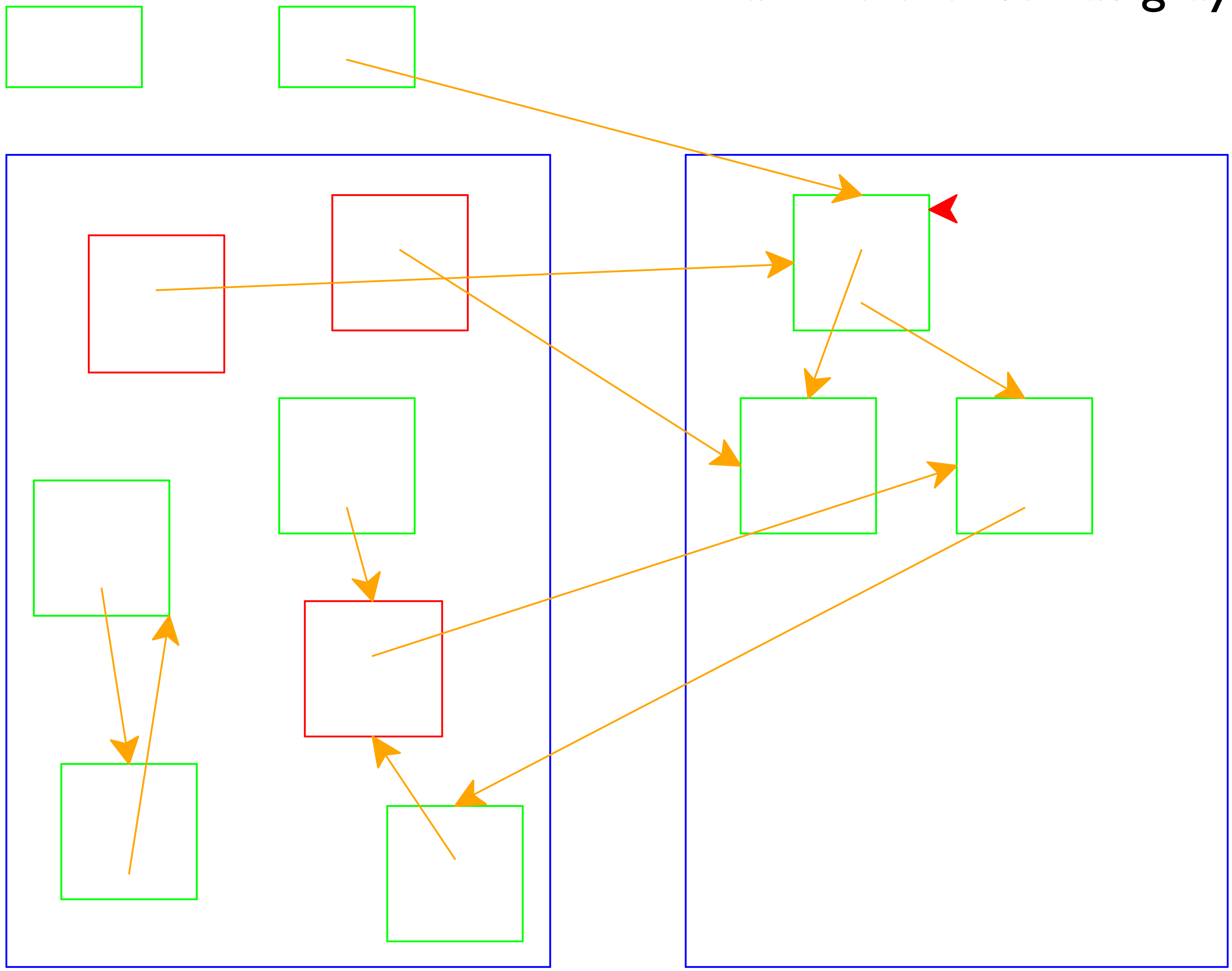
Two-Space Collection

Choose gray by walking through to-space



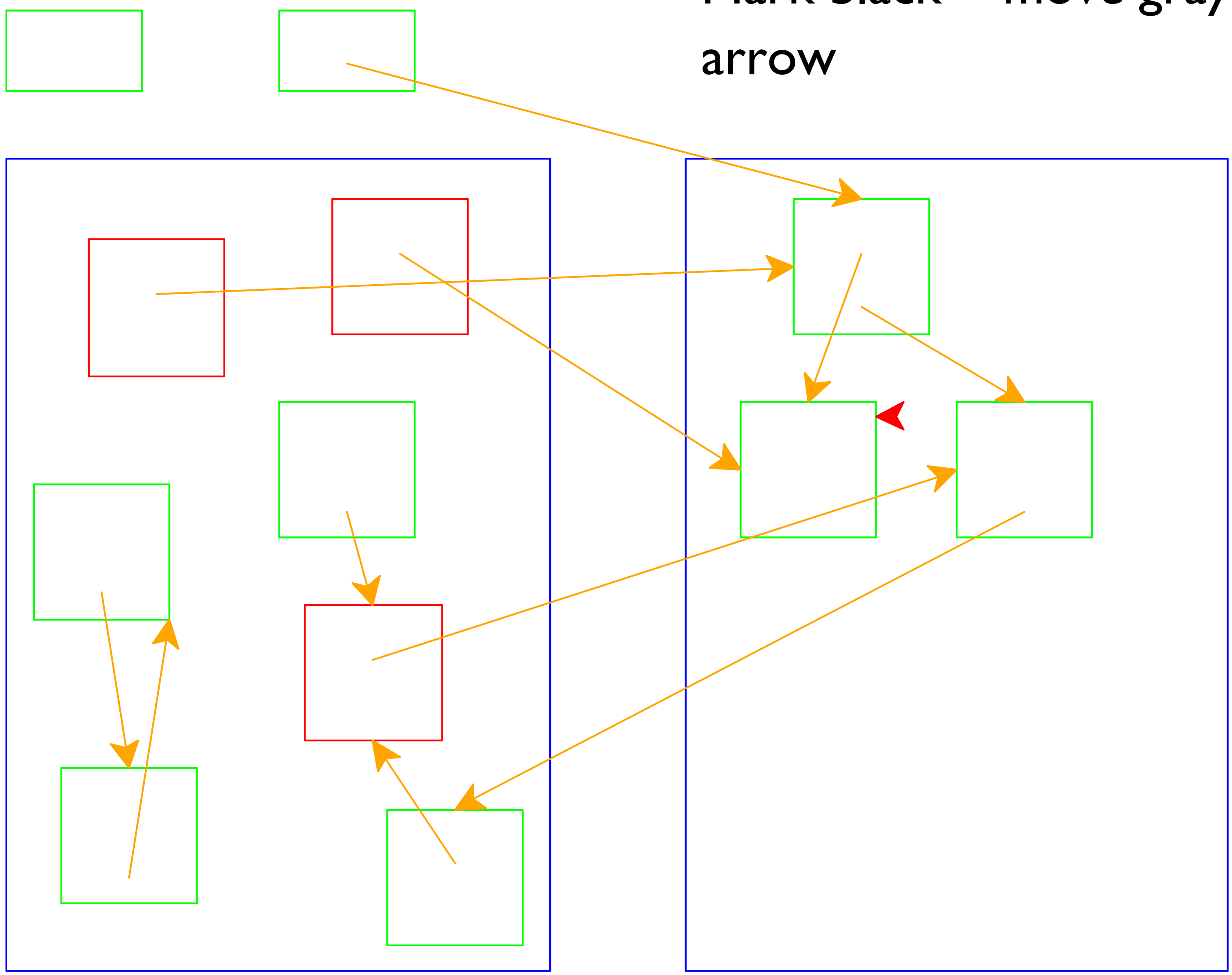
Two-Space Collection

Mark referenced as gray



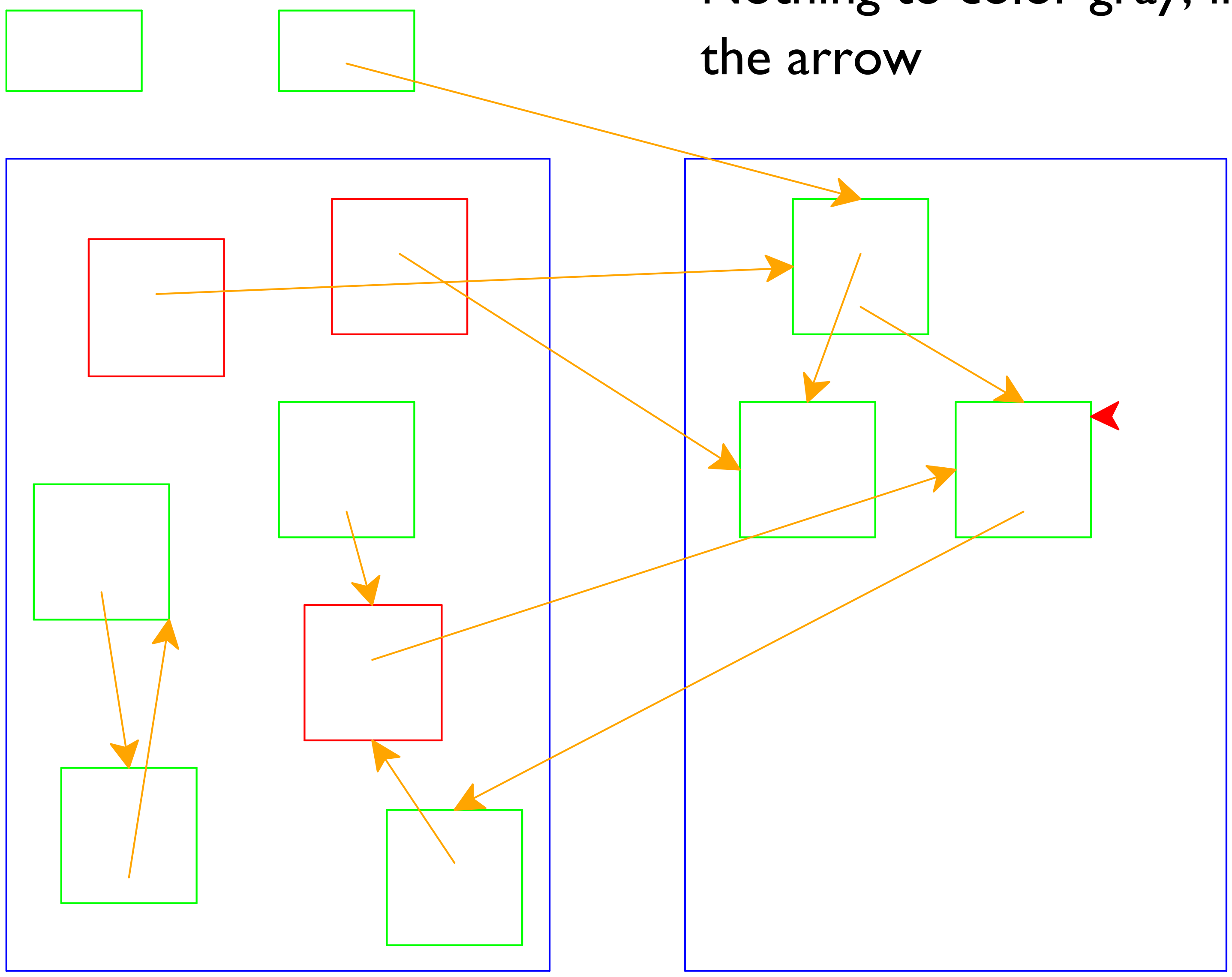
Two-Space Collection

Mark black = move gray-choosing arrow



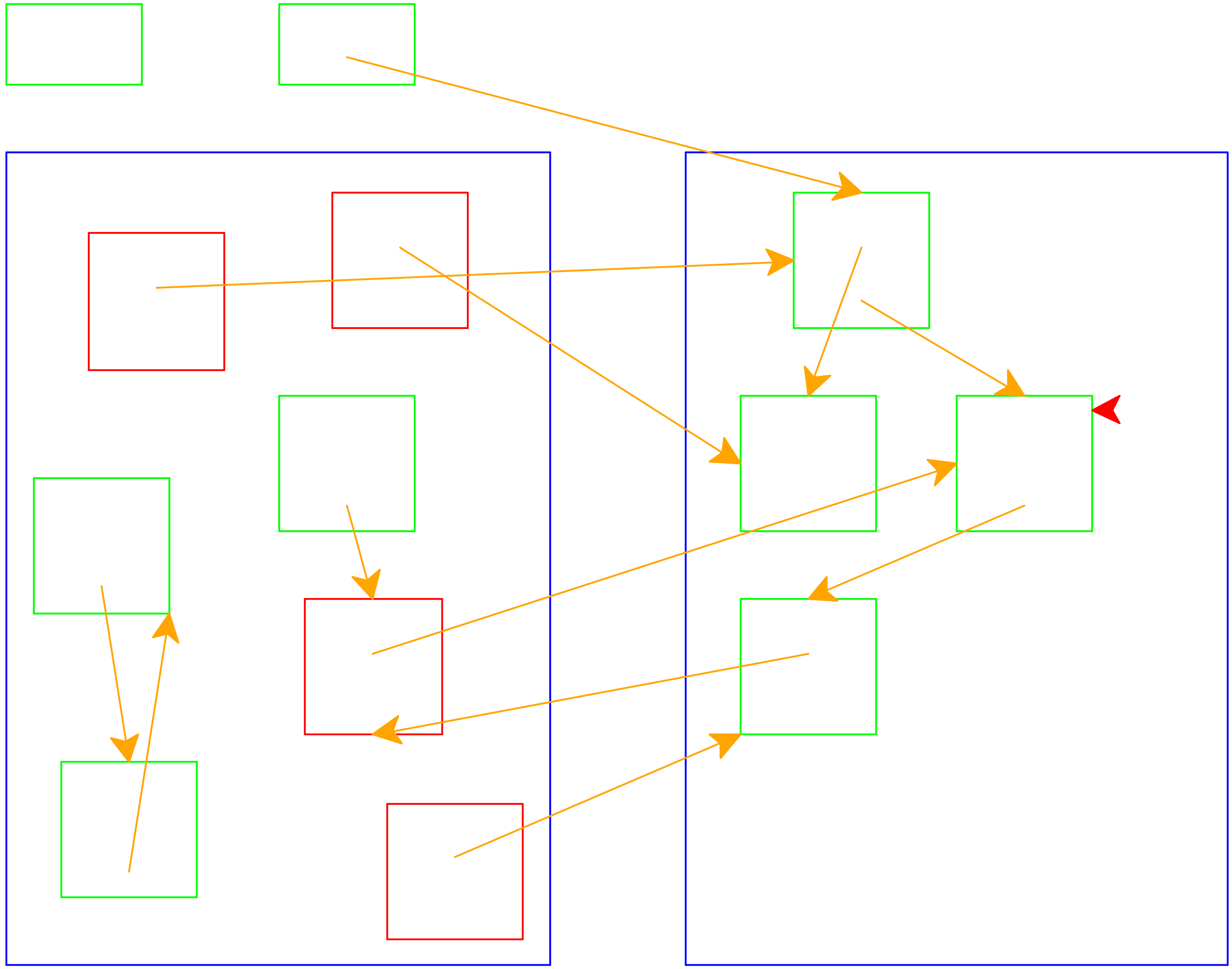
Two-Space Collection

Nothing to color gray; increment the arrow



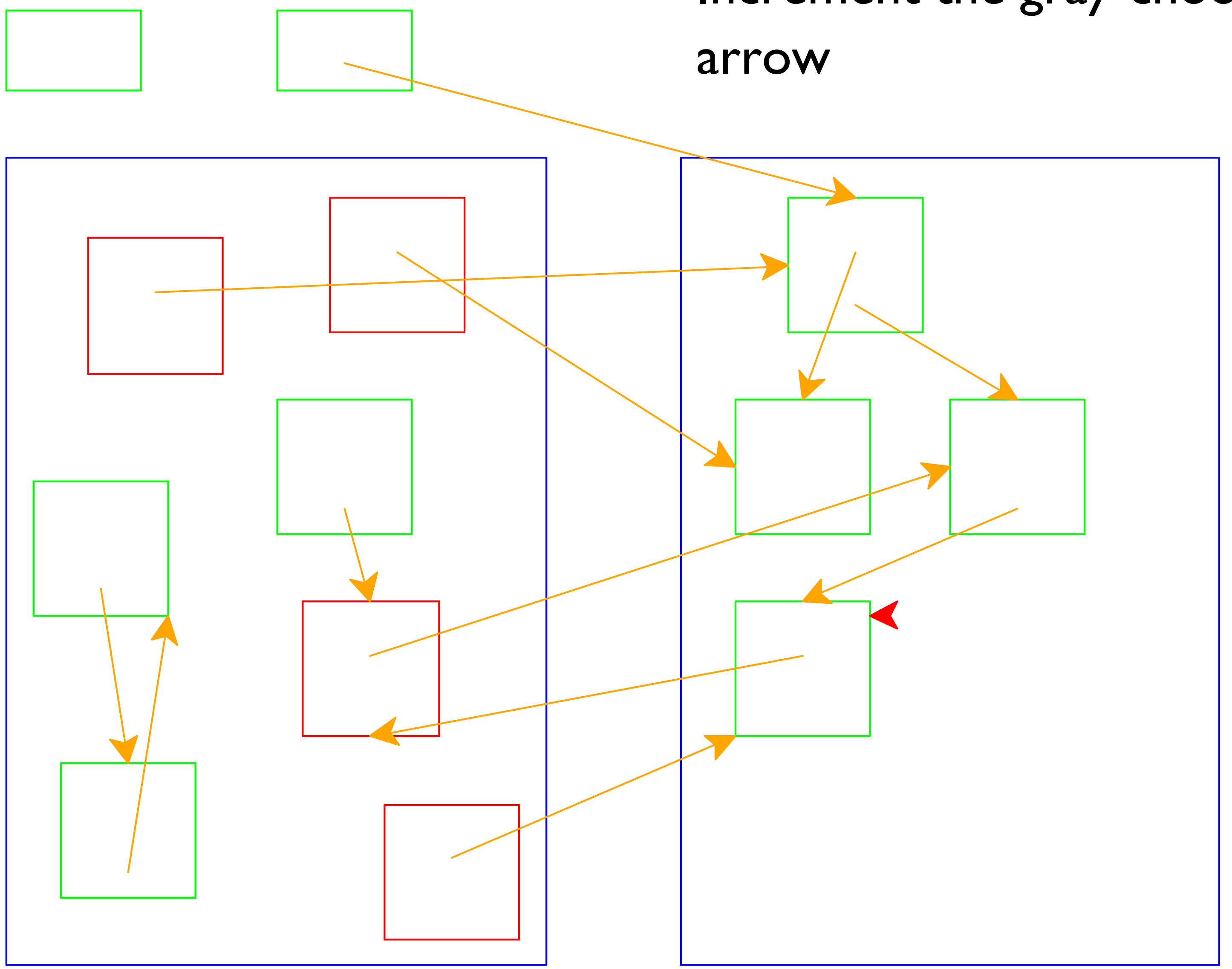
Two-Space Collection

Color referenced record gray



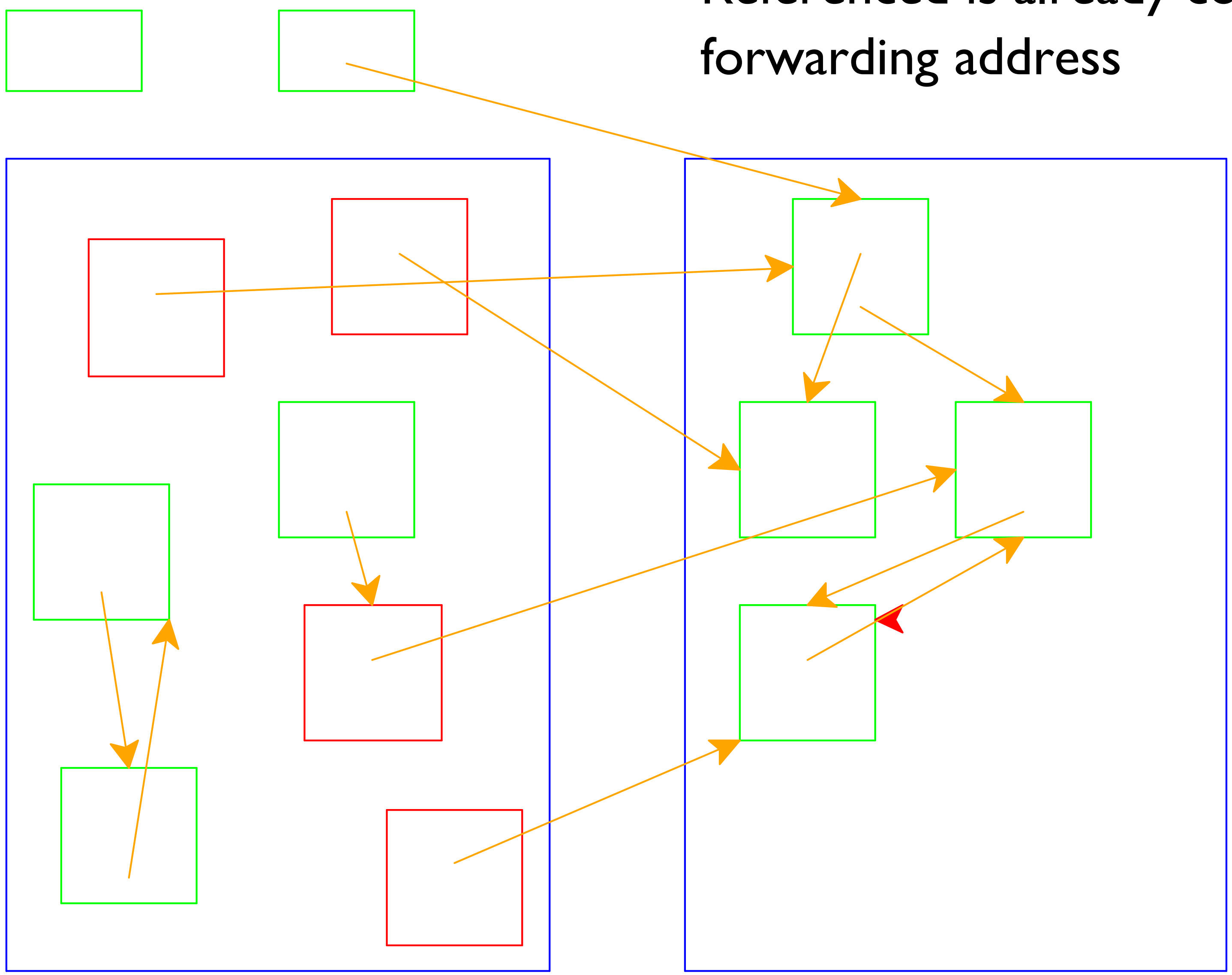
Two-Space Collection

Increment the gray-choosing arrow



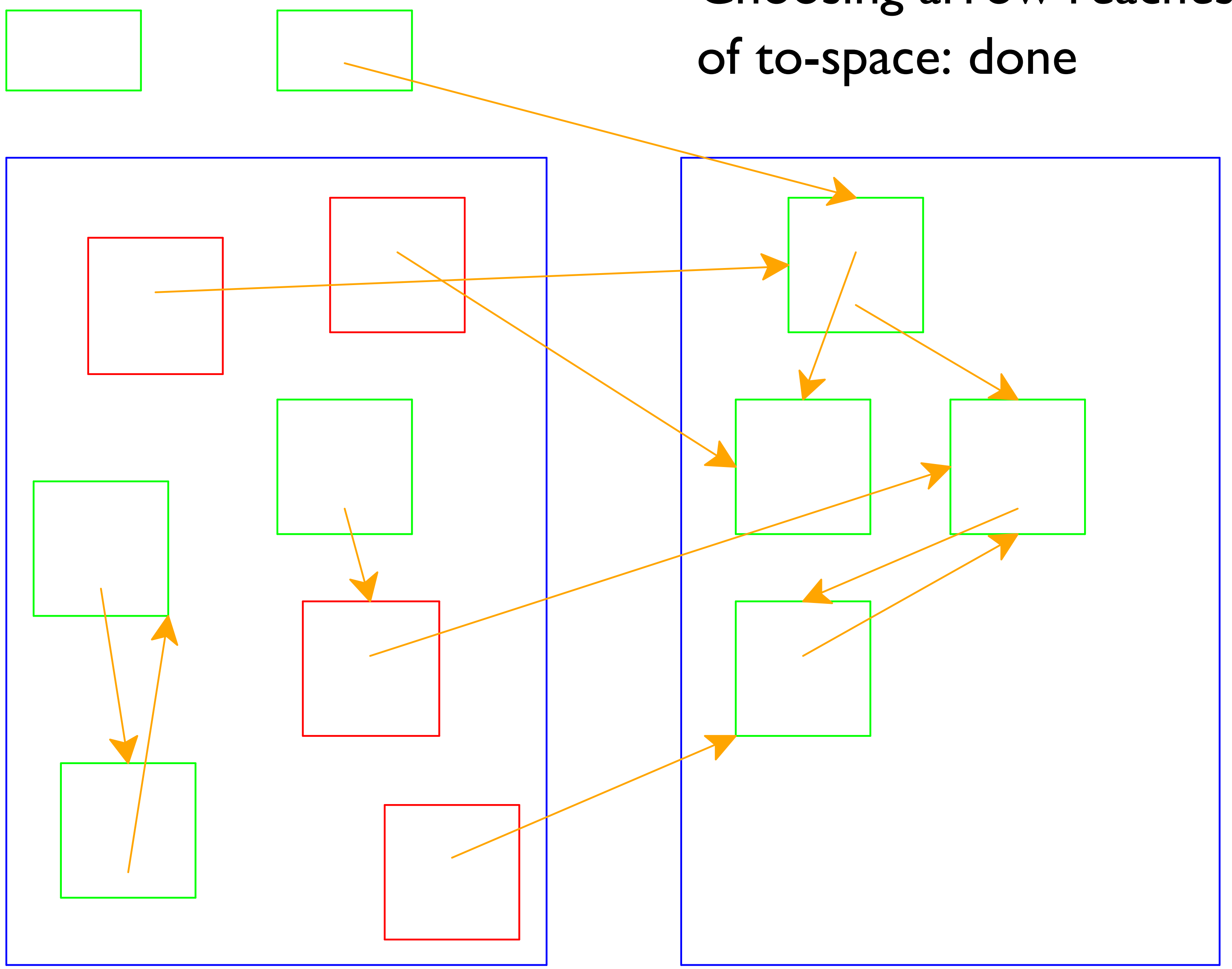
Two-Space Collection

Referenced is already copied, use forwarding address

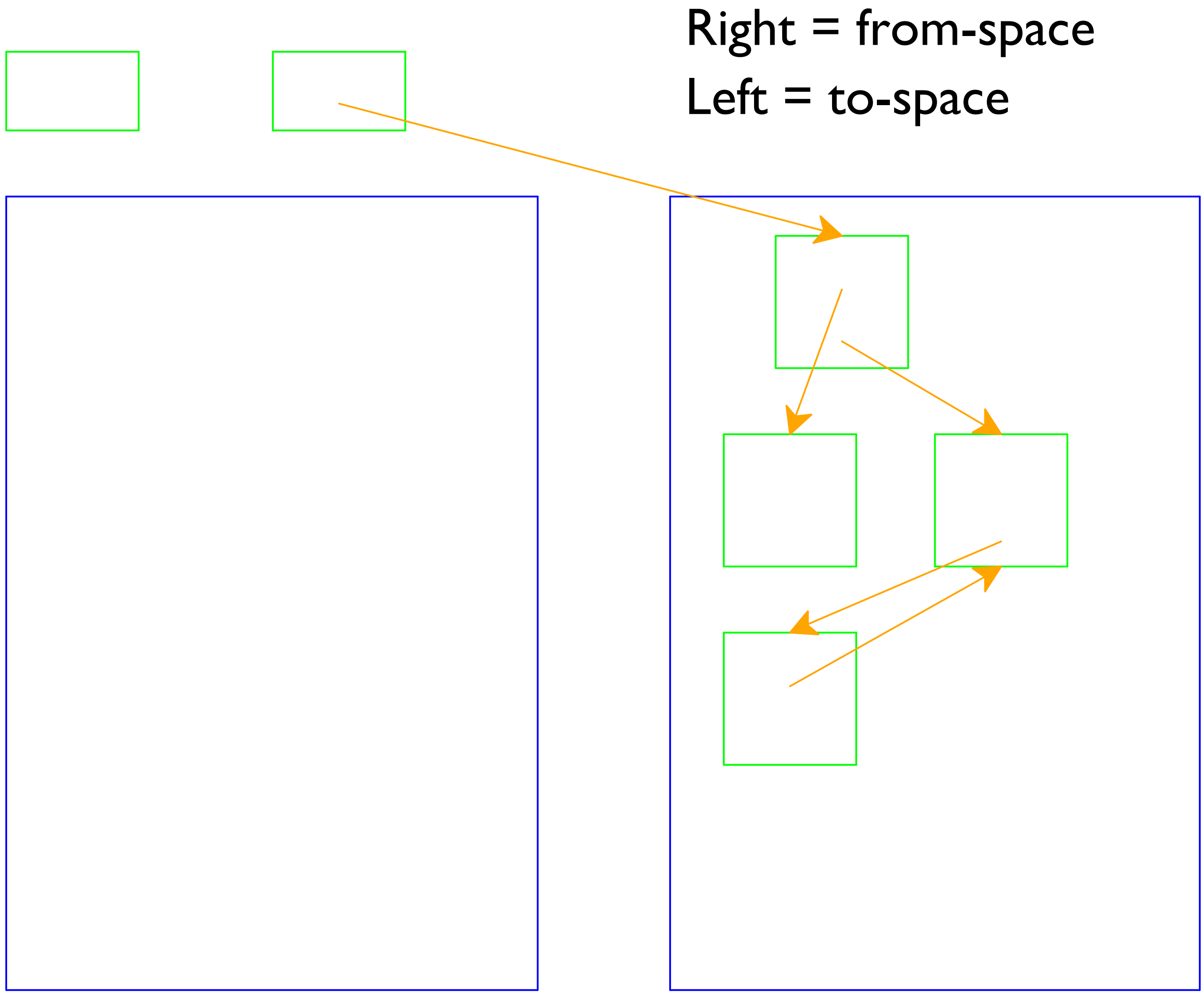


Two-Space Collection

Choosing arrow reaches the end of to-space: done



Two-Space Collection



Two-Space Collection on Vectors

- Everything is a number:
  - Some numbers are immediate integers
  - Some numbers are pointers
- An allocated record 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
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  - 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
								^					