Interpreter with Continuations

```
(define (eval-expression exp env cont)
  (cases expression exp
    (lit-exp (datum)
      (apply-cont cont datum))
    (var-exp (id)
      (apply-cont cont (apply-env env id)))
    (proc-exp (id body-exp)
      (apply-cont cont
                  (closure id body-exp env)))
    ...))

(define (apply-cont cont val)
  (cases continuation cont
    (done-cont () val)
    ...))
```

Continuations and Gotos

```
(define (eval-expression exp env cont)
 (cases exp ...
  (proc-exp (id body-exp)
    (apply-cont cont
                (closure id body-exp env)))

=>

;; registers:
(define EXP ...) (define CONT ...) ...

(define (eval-expression)
 (cases EXP ...
  (proc-exp (id body-exp)
    (set! VAL (closure id body-exp ENV))
    ;; CONT stays the same
    (apply-cont)) ; "goto"
```

Continuations and Gotos

```
(define (eval-expression exp env cont)
 (cases exp...
  (app-exp (rator rand)
    (eval-expression
     rator env
     (app-arg-cont rand env cont)))

=>

(define (eval-expression)
 (cases EXP ...
  (app-exp (rator rand)
    (set! EXP rator)
    ;; ENV stays the same
    (set! CONT (app-arg-cont rand ENV CONT))
    (eval-expression)) ; "goto"
```

Continuations and Gotos

- Registers and gotos explain why the following program never generates a stack overflow:

```
let f = proc(f) proc(n) ((f f) n)
 in ((f f) 0)
```

- So, can we compute arbitrarily deep recursions?

```
let f = proc(f)
          proc(n)
            if n then +(1, ((f f) -(n, 1)))
              else 0
 in ((f f) 1000000000)
```

No...

Allocation

- We've avoided stack allocation
- But we still have to allocate
  - continuation records
  - closures
  - environment records

Allocation

- Where do we call **`malloc`**?

```
(define (eval-expression)
 (cases EXP ...
  (proc-exp (id body-exp)
    (set! VAL (closure id body-exp ENV))
    ;; CONT stays the same
    (apply-cont))
  (app-exp (rator rand)
    (set! EXP rator)
    ;; ENV stays the same
    (set! CONT (app-arg-cont rand ENV CONT))
    (eval-expression))
  ...
```

Allocation

- Where do we call **`malloc`**?

```
(define (eval-expression)
 (cases EXP ...
  (proc-exp (id body-exp)
    (set! VAL (closure id body-exp ENV))
    ;; CONT stays the same
    (apply-cont))
  (app-exp (rator rand)
    (set! EXP rator)
    ;; ENV stays the same
    (set! CONT (app-arg-cont rand ENV CONT))
    (eval-expression))
  ...
```

Exposing Allocation

```
(define (closure id body env)
  (let ([v (malloc 4)])
    (mem-set! v 0 closure-tag)
    (mem-set! v 1 id)
    (mem-set! v 2 body)
    (mem-set! v 3 env)
    v))

(define (closure? v)
  (= (mem-ref v 0) closure-tag))

(define (closure->id v)
  (mem-ref v 1))
...
```

Memory Allocator

```
(define memory (make-vector 200))
(define allocated 0)

(define (malloc size)
  (let ([result allocated])
    (set! allocated (+ allocated size))
    result))

(define (mem-set! a n v)
  (vector-set! memory (+ a n) v))

(define (mem-ref a n)
  (vector-ref memory (+ a n)))
```

Exposing Allocation

- Use of **`malloc`** explains why the following program runs out of memory:

```
let f = proc(f)
          proc(n)
            if n then +(1, ((f f) -(n, 1)))
                 else 0
 in ((f f) 1000000000)
```

- Each call to (**f f**) extends the continuation
- Eventually, the continuation fills all memory

Exposing Allocation

- Does the following program run forever?

let f = **proc**(**f**) **proc**(**n**) ((**f f**) **n**)
in ((**f f**) 0)

- Each call to (**f f**)
  - creates an extended environment
  - creates a new closure

We need ***deallocation***

Deallocation

- Where do we call **free**?

```
(define (apply-cont)
  (cond ...
   [(app-cont? CONT)
    (let ([rator (app-cont->rator CONT)]
          [old-cont (app-cont->cont CONT)])
      (set! EXP (closure->body rator))
      (set! ENV (extend-env
                 (closure->id rator)
                 VAL
                 (closure->env rator)))
      (set! CONT old-cont))
    (eval-expression)]
  ...
```

Deallocation

- Where do we call **free**?

```
(define (apply-cont)
  (cond ...
   [(app-cont? CONT)
    (let ([rator (app-cont->rator CONT)]
          [old-cont (app-cont->cont CONT)])
      (set! EXP (closure->body rator))
      (set! ENV (extend-env
                 (closure->id rator)
                 VAL
                 (closure->env rator)))
      (free CONT) ;; unless letcc'd!
      (set! CONT old-cont))
    (eval-expression)]
  ...
```

Deallocation

- Where do we call **free**?

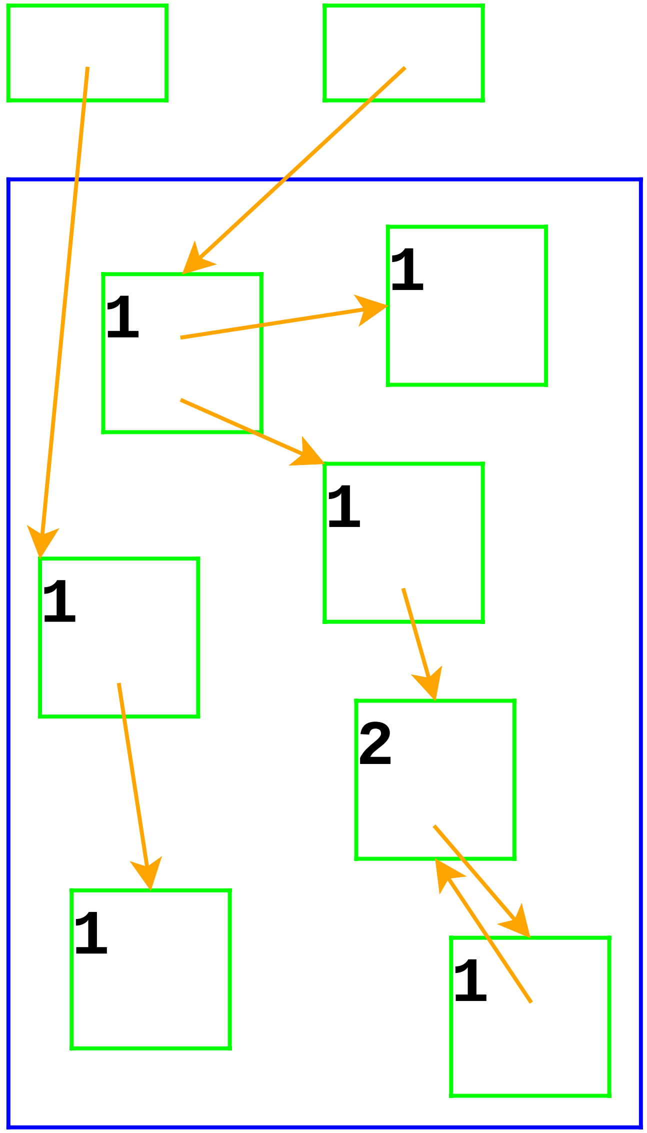
```
(define (apply-cont)
  (cond ...
   [(app-cont? CONT)
    (let ([rator (app-cont->rator CONT)]
          [old-cont (app-cont->cont CONT)])
      (set! EXP (closure->body rator))
      (free ENV) ;; unless in a closure!
      (set! ENV (extend-env
                 (closure->id rator)
                 VAL
                 (closure->env rator)))
      (set! CONT old-cont))
    (eval-expression)]
  ...
```

Reference Counting

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

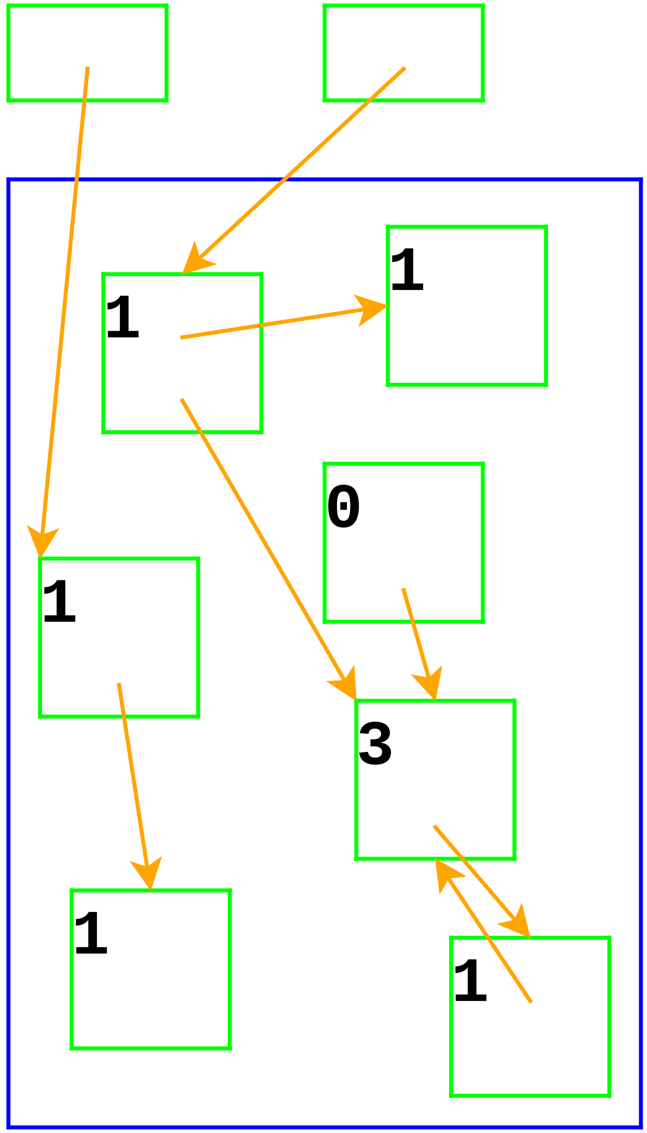
- Attatch a count to every record, start at 0
- When installing a pointer to a record (into a register, or another record), increment its count
- When replacing a pointer to a record, decrement its count
- When a count is decremented to 0, decrement counts for other records referenced by the record,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

Reference Counting



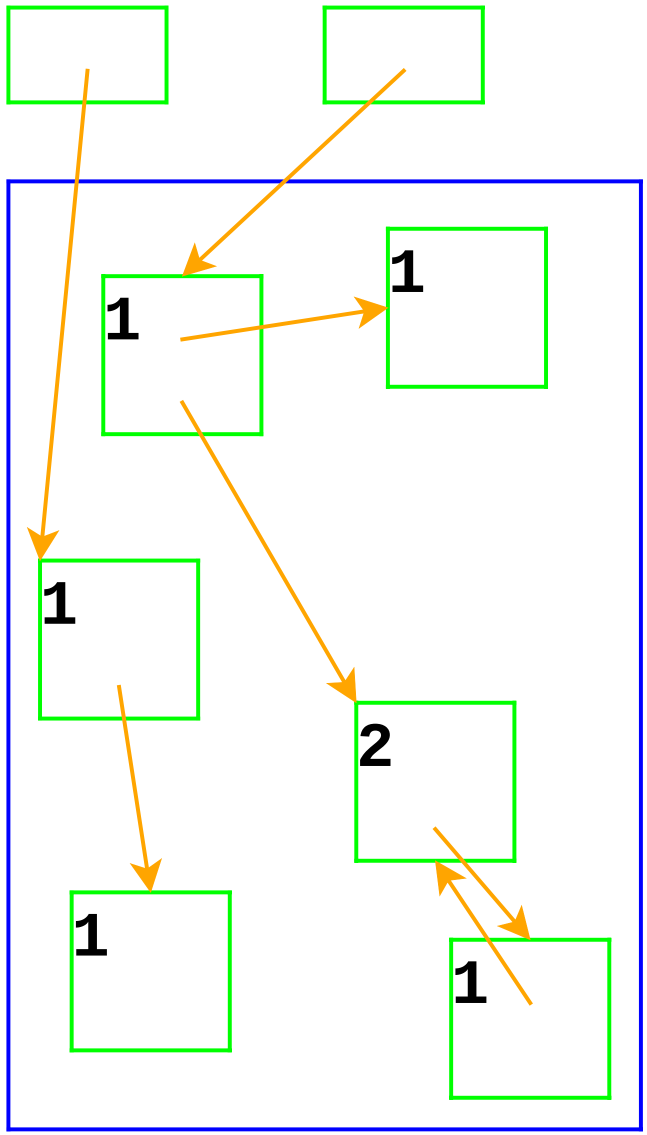
- Top boxes are the registers **`ENV`**, **`CONT`**, etc.
- Boxes in the blue area are allocated with **`malloc`**

Reference Counting



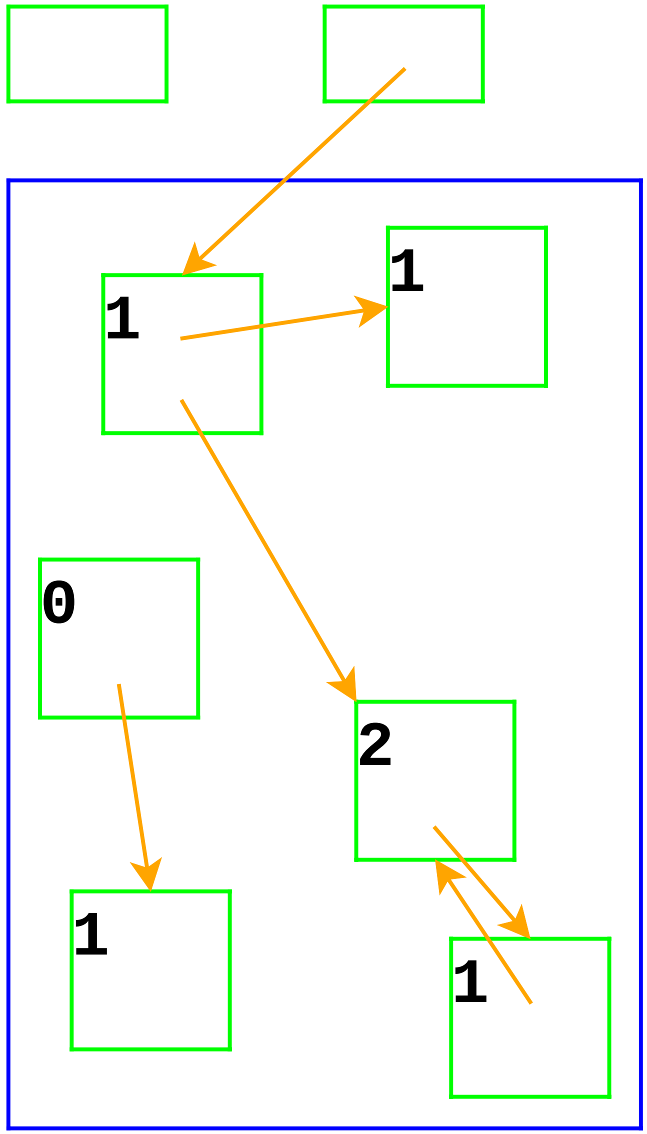
- Adjust counts when a pointer is changed...

Reference Counting



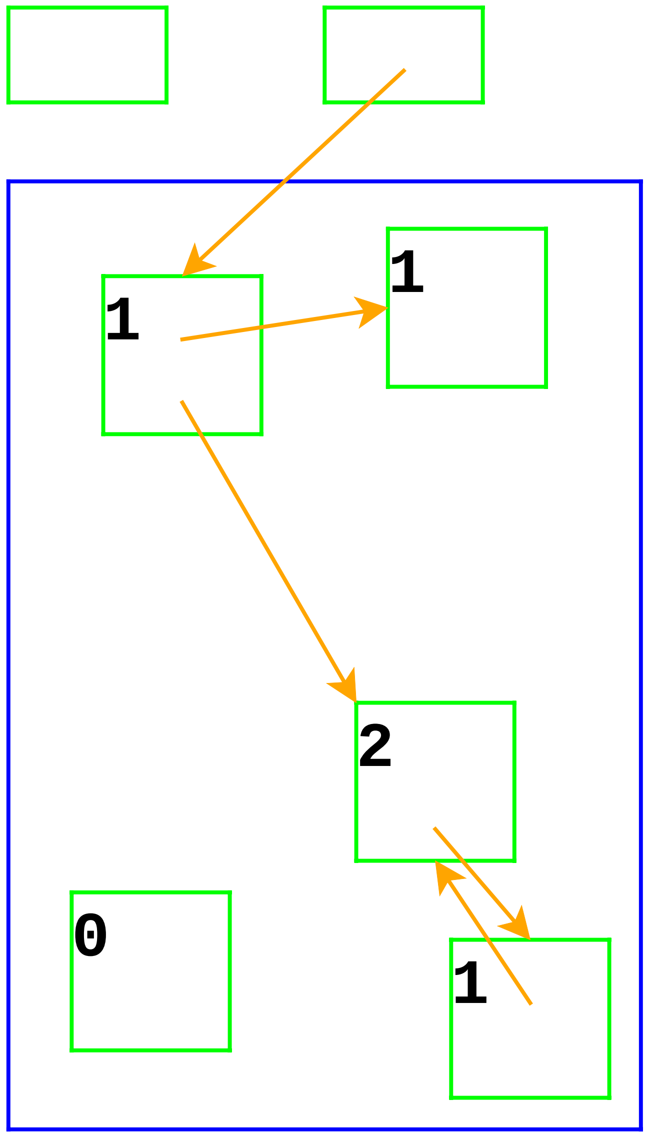
- ... freeing a record if its count goes to 0

Reference Counting



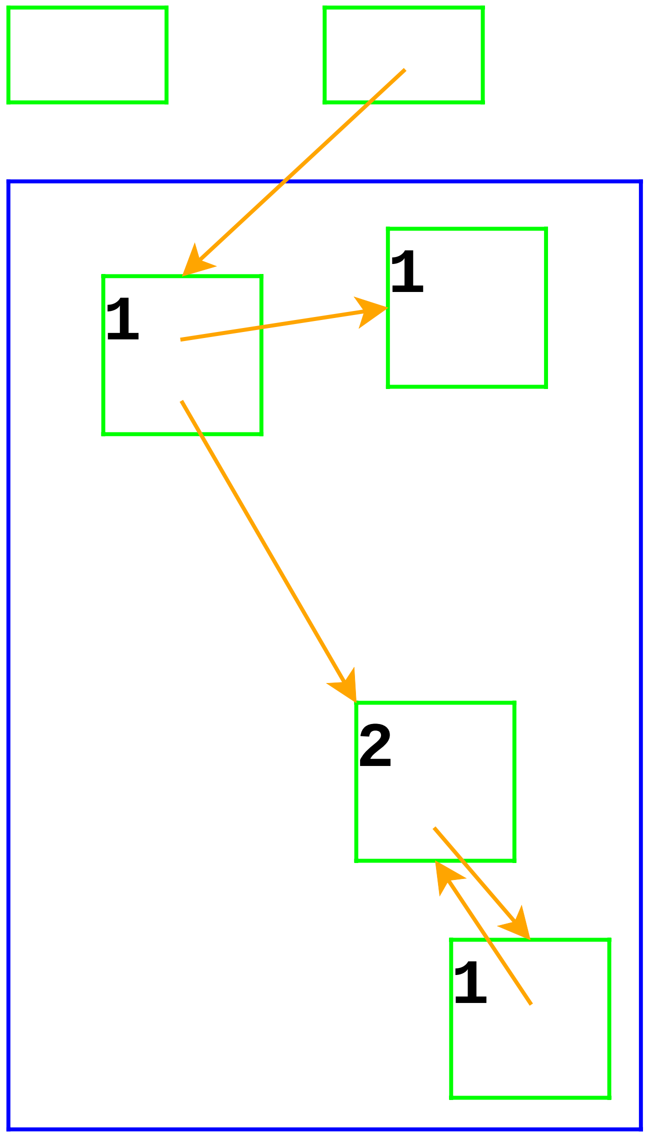
- Same if the pointer is in a register

Reference Counting



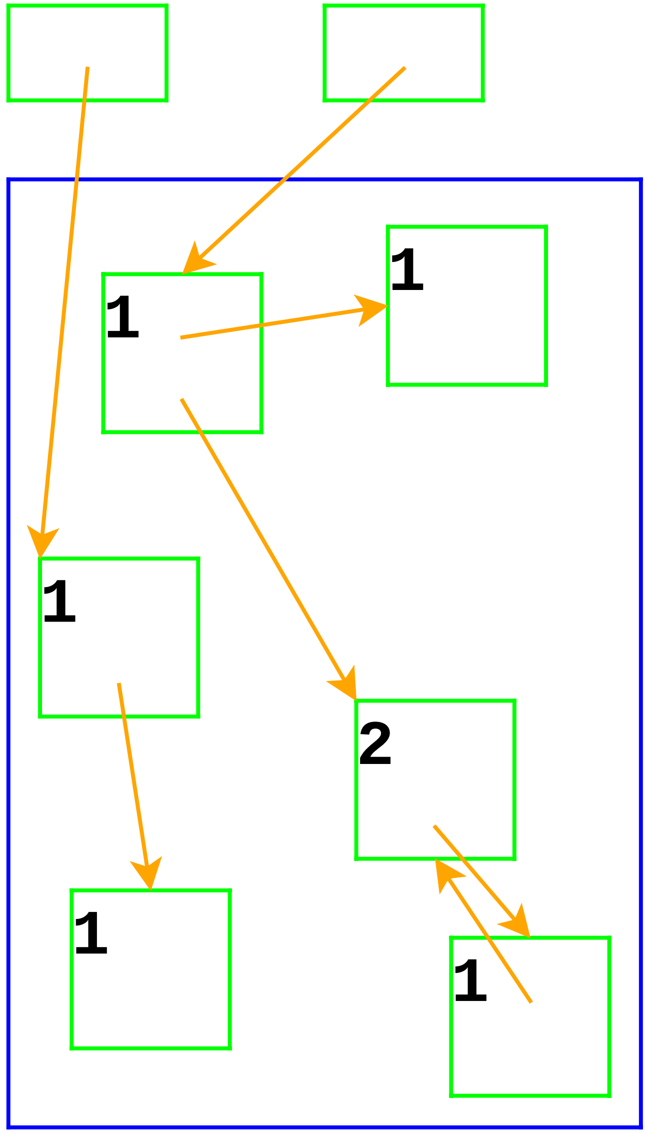
- Adjust counts after frees, too...

Reference Counting



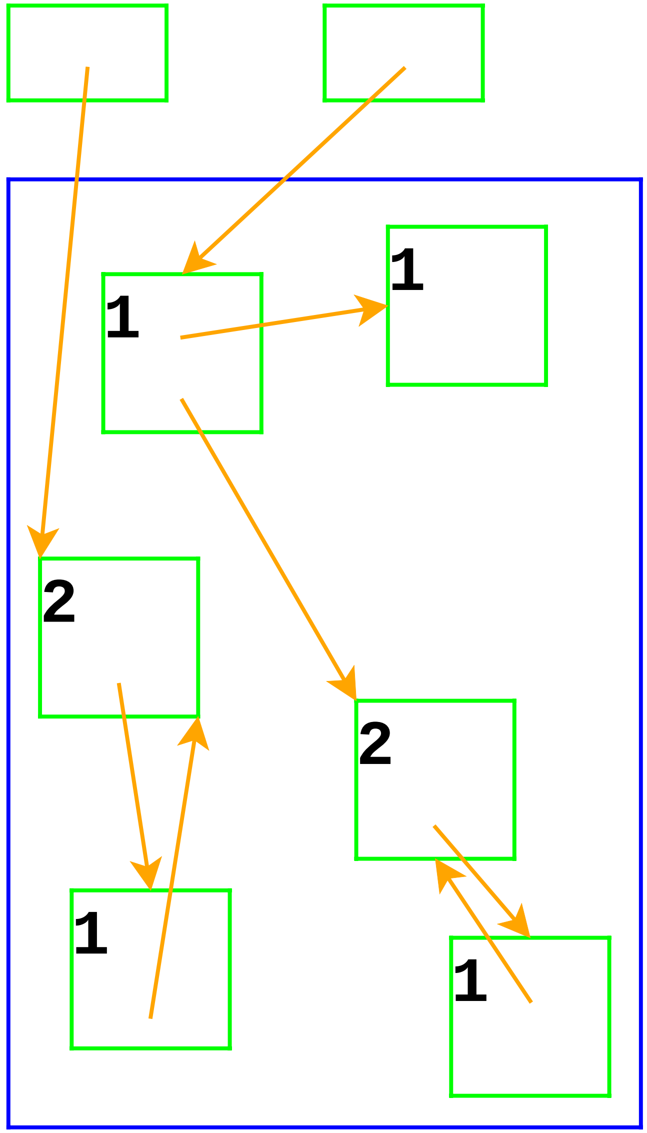
- ... which can trigger more frees

Reference Counting



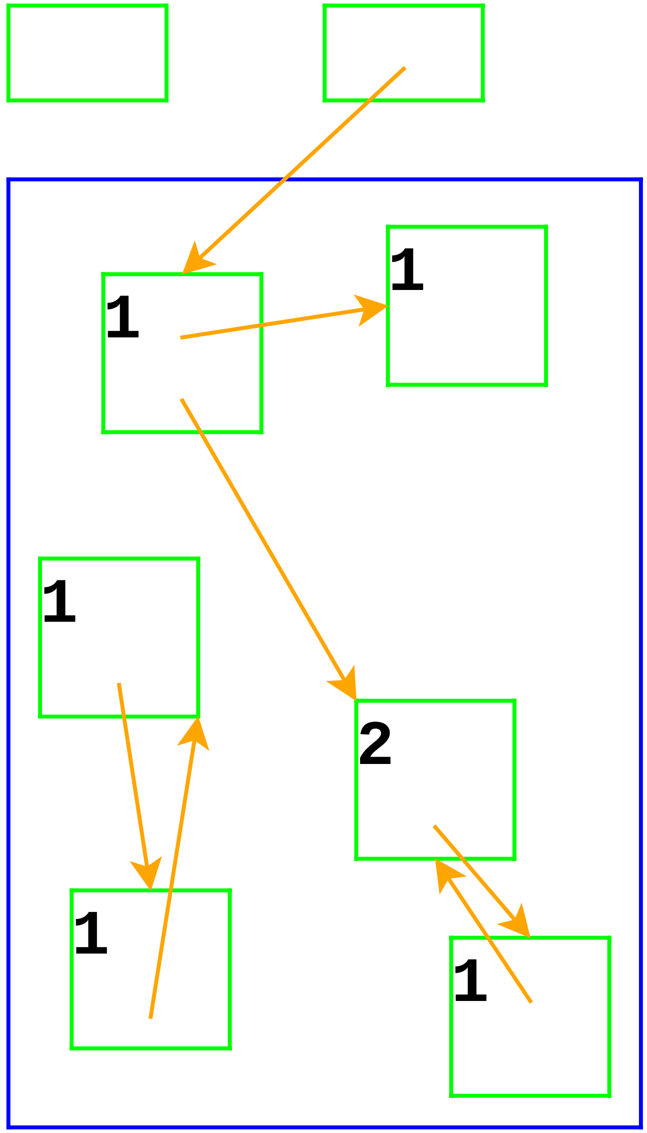
- Another example

Reference Counting



- Adding a reference increments a count

Reference Counting



- 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*

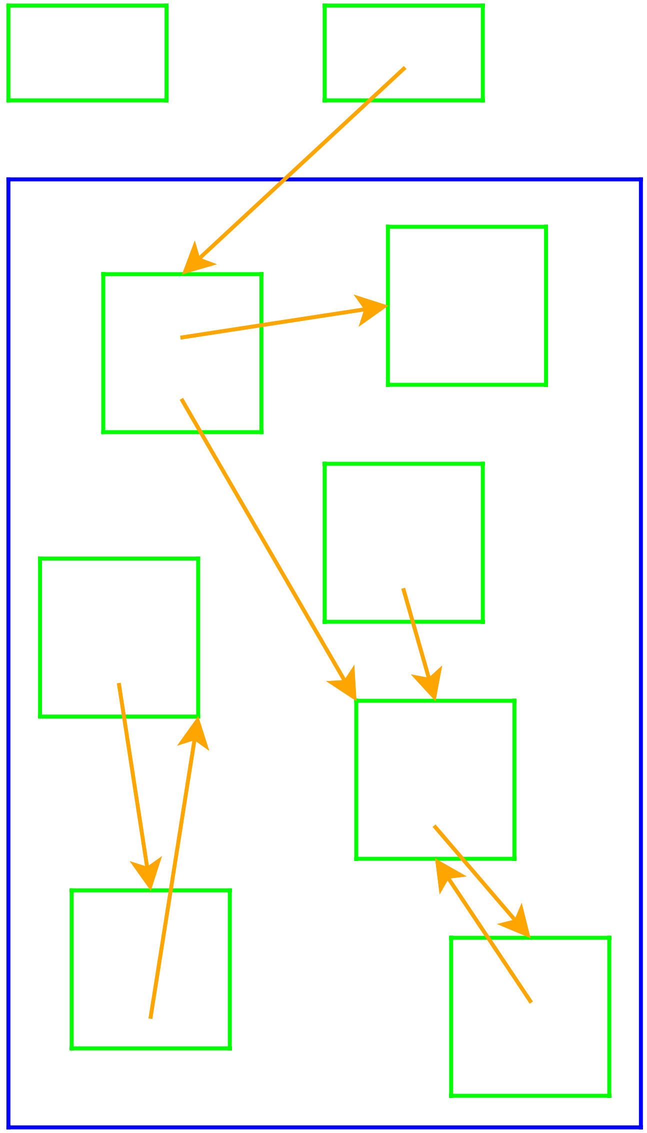
- A record referenced by a register is ***live***
- A record referenced by a live record is also live
- A program can only possibly use live records, because there is no way to get to other records

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

Garbage Collection Algorithm

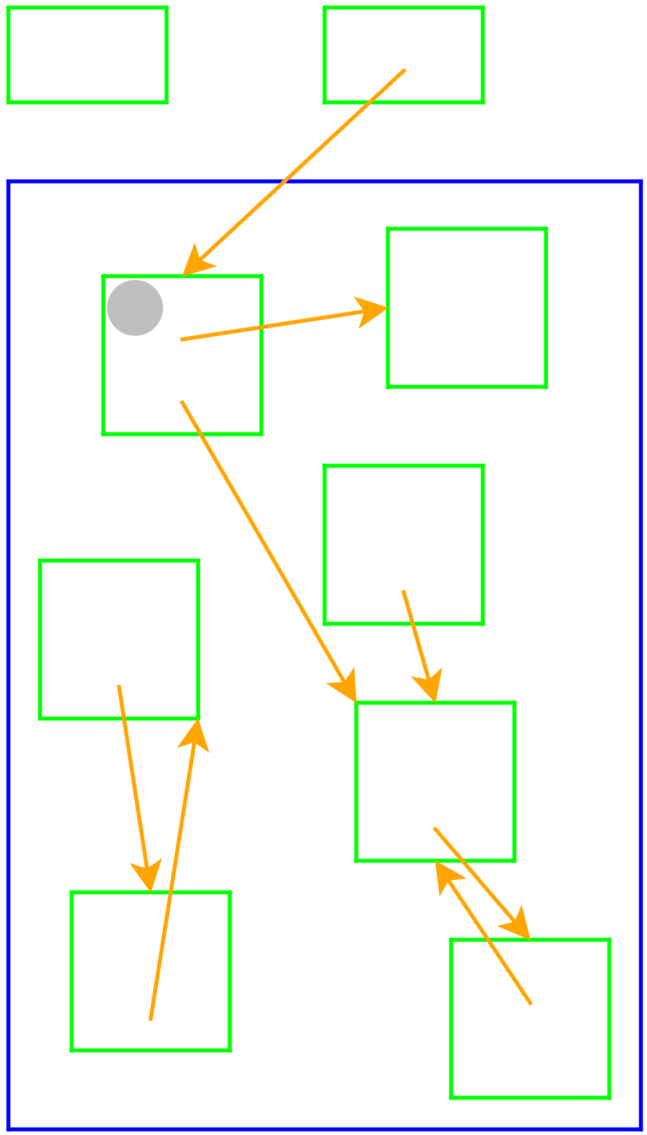
- Color all records ***white***
- Color records referenced by registers ***gray***
- Repeat until there are no gray records:
  - Pick a gray record, *r*
  - For each white record that *r* points to, make it gray
  - Color *r* ***black***
- Deallocate all white records

Garbage Collection



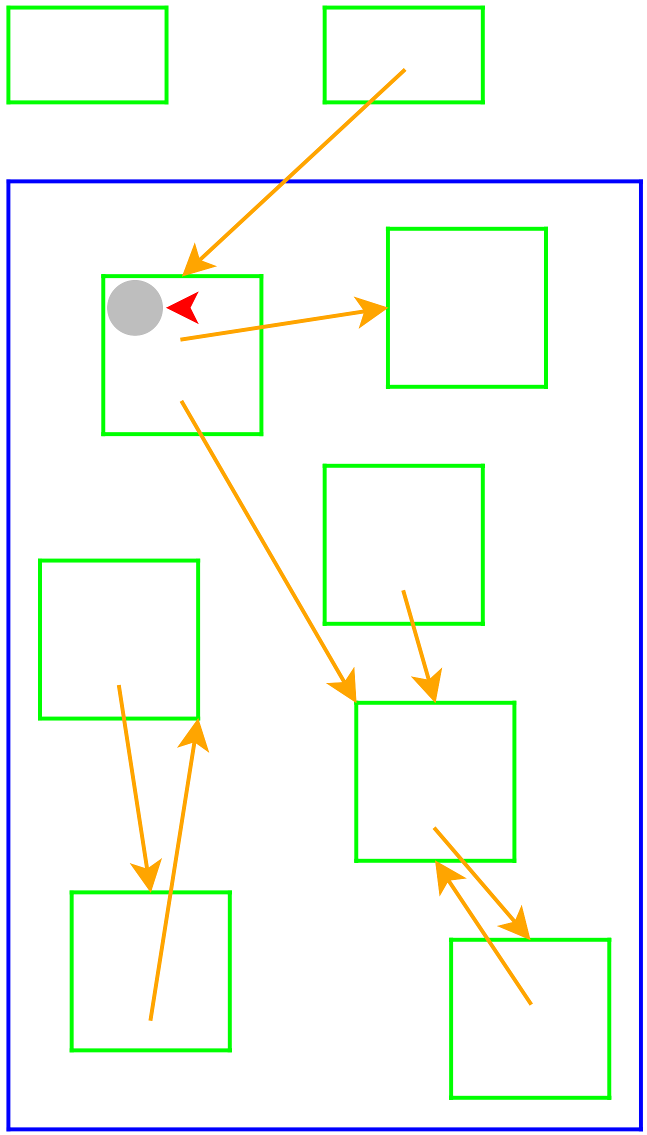
- All records are marked white

Garbage Collection



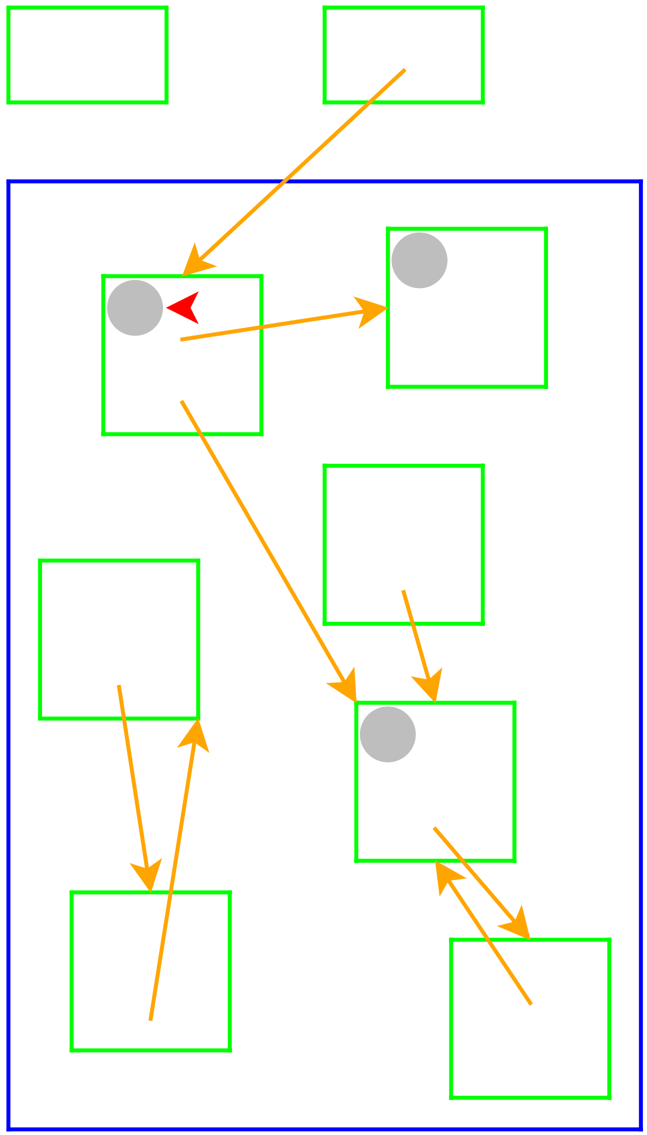
- Mark records referenced by registers as gray

Garbage Collection



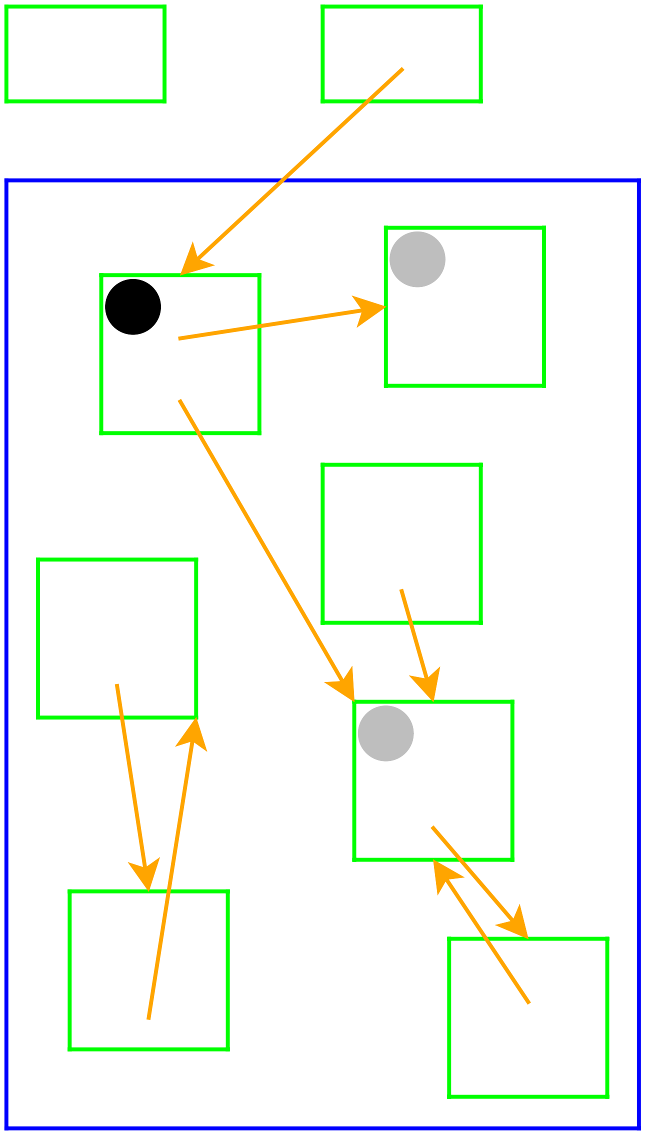
- Need to pick a gray record
- Red arrow indicates the chosen record

Garbage Collection



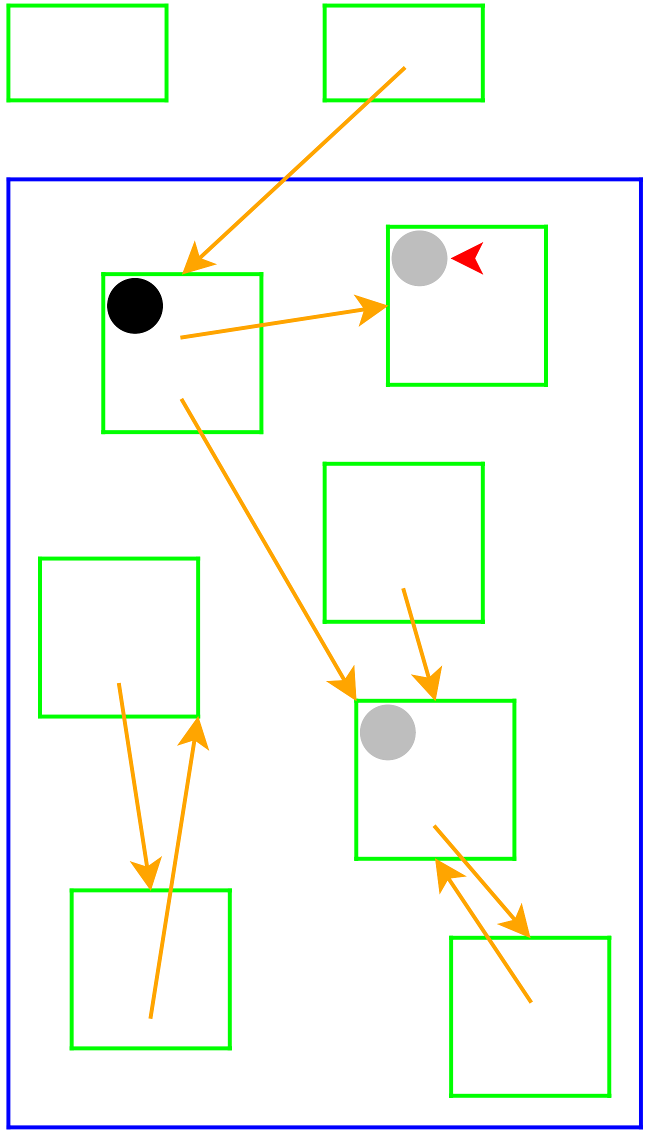
- Mark white records referenced by chosen record as gray

Garbage Collection



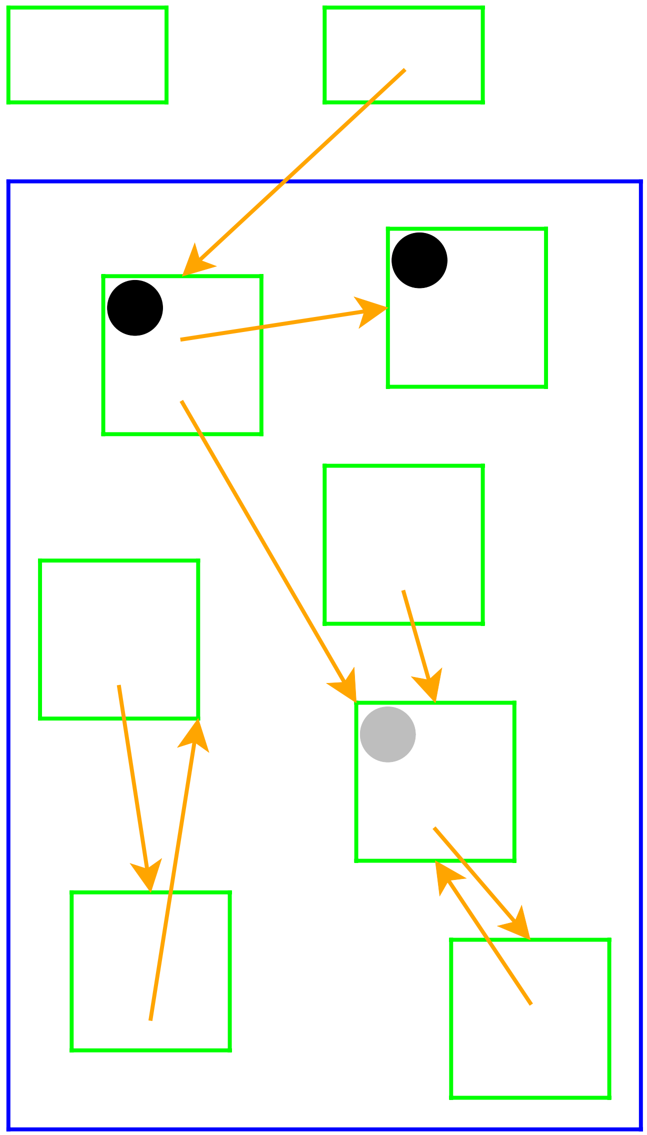
- Mark chosen record black

Garbage Collection



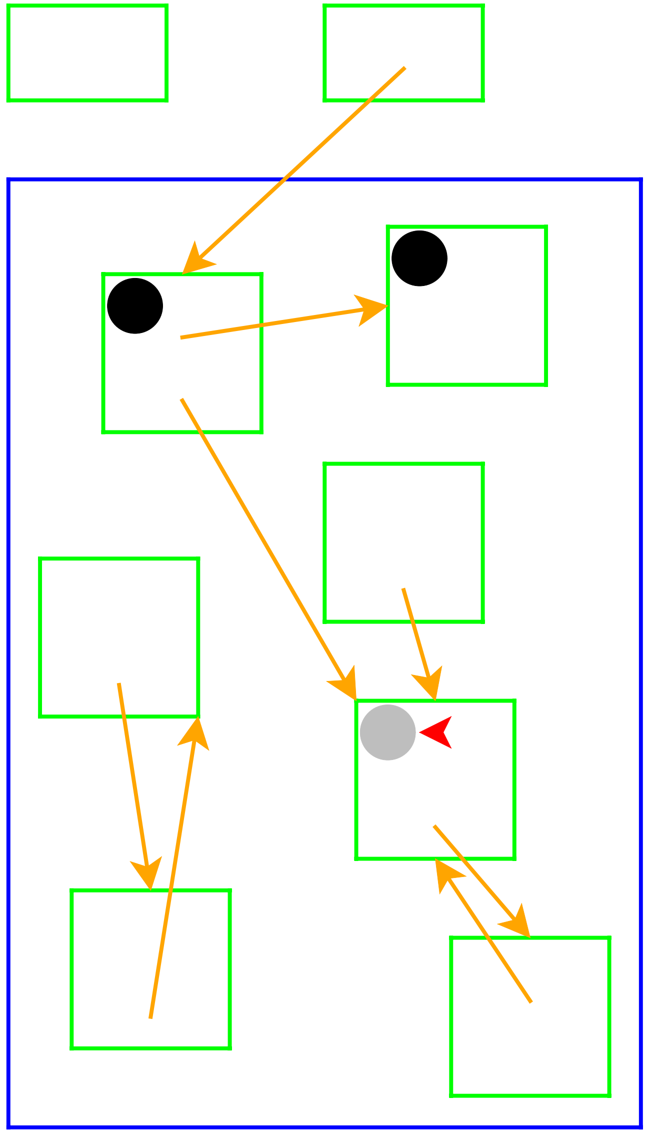
- Start again: pick a gray record

Garbage Collection



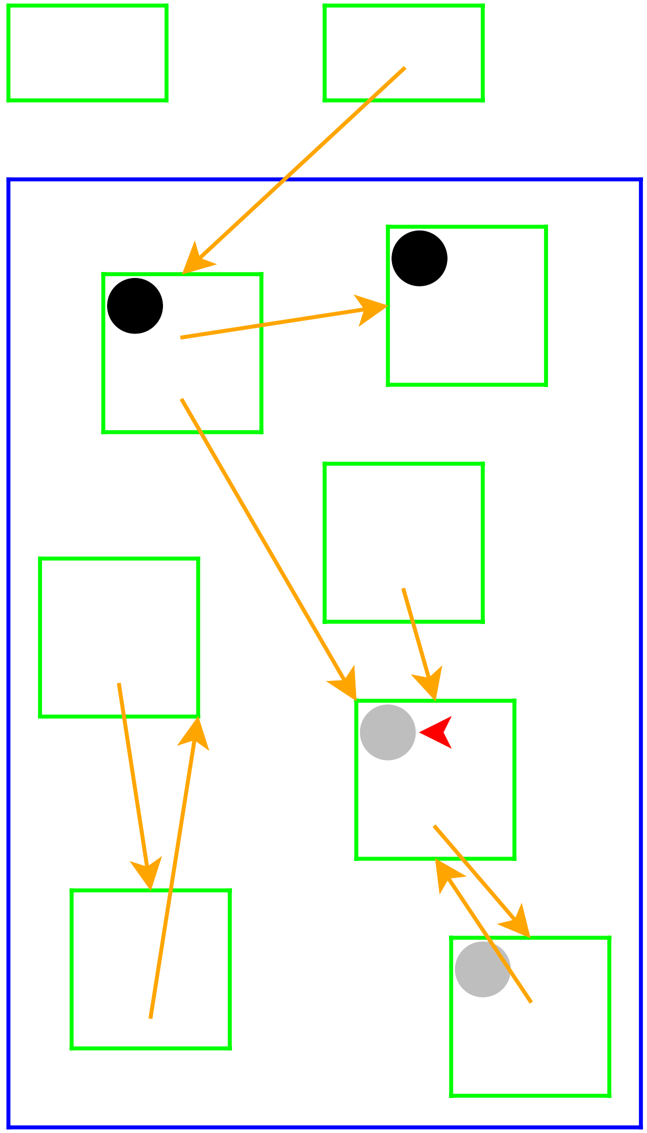
- No referenced records; mark black

Garbage Collection



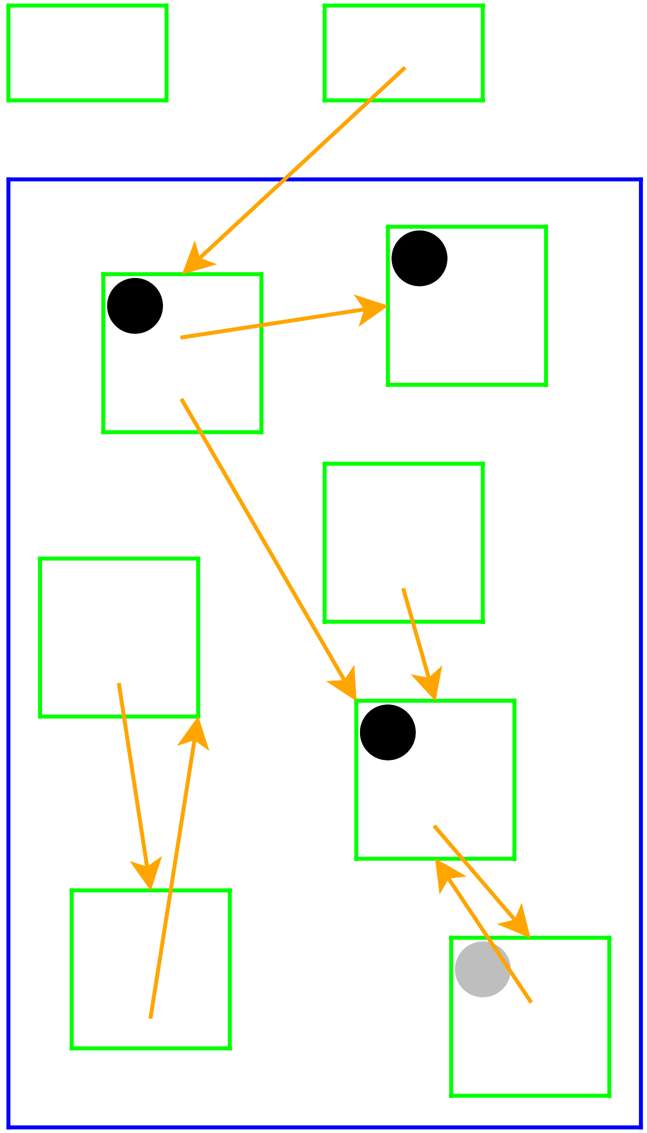
- Start again: pick a gray record

Garbage Collection



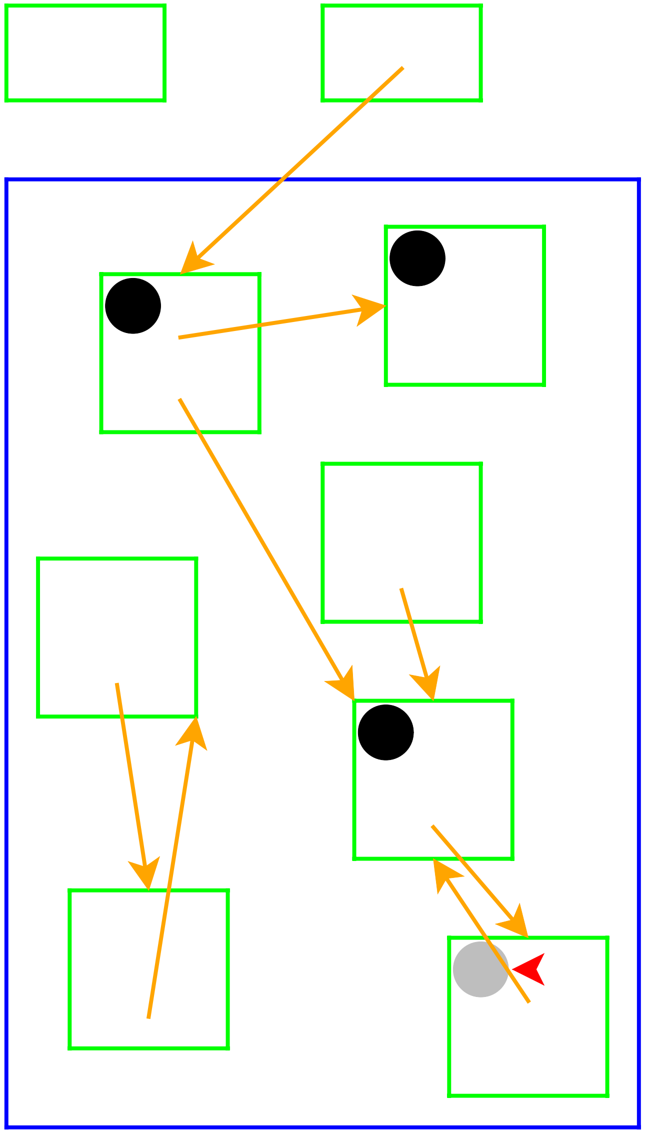
- Mark white records referenced by chosen record as gray

Garbage Collection



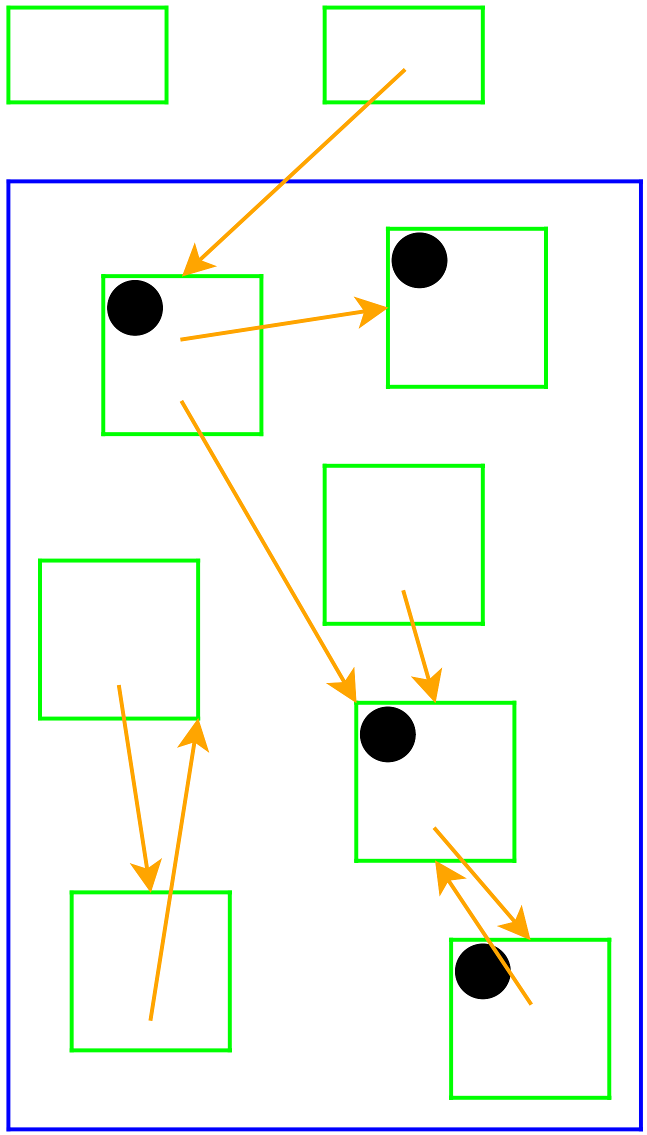
- Mark chosen record black

Garbage Collection



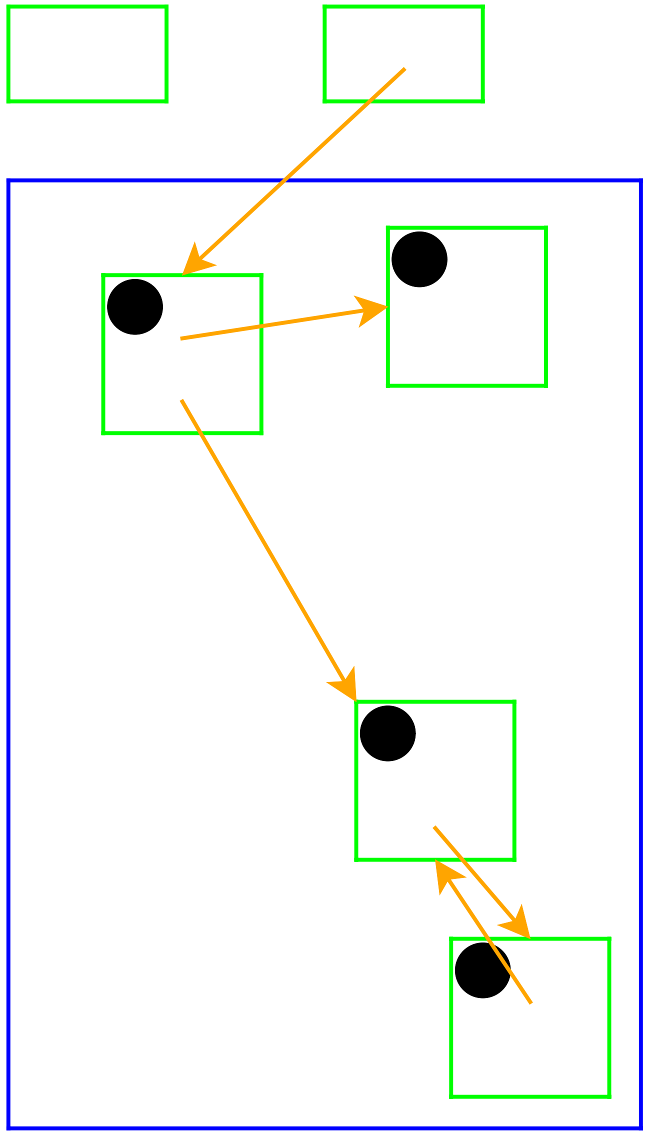
- Start again: pick a gray record

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***

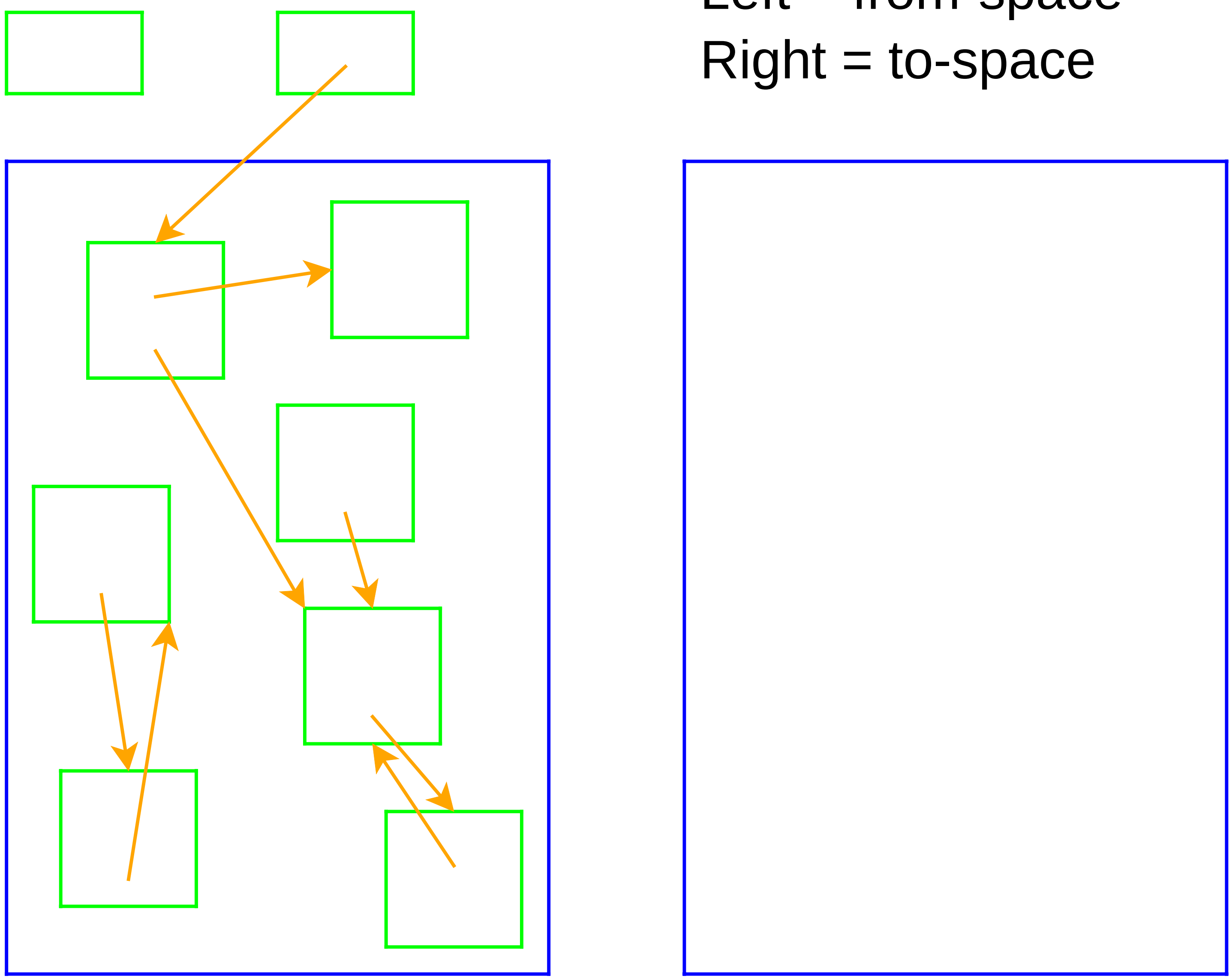
Collector:

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

Two-Space Collection

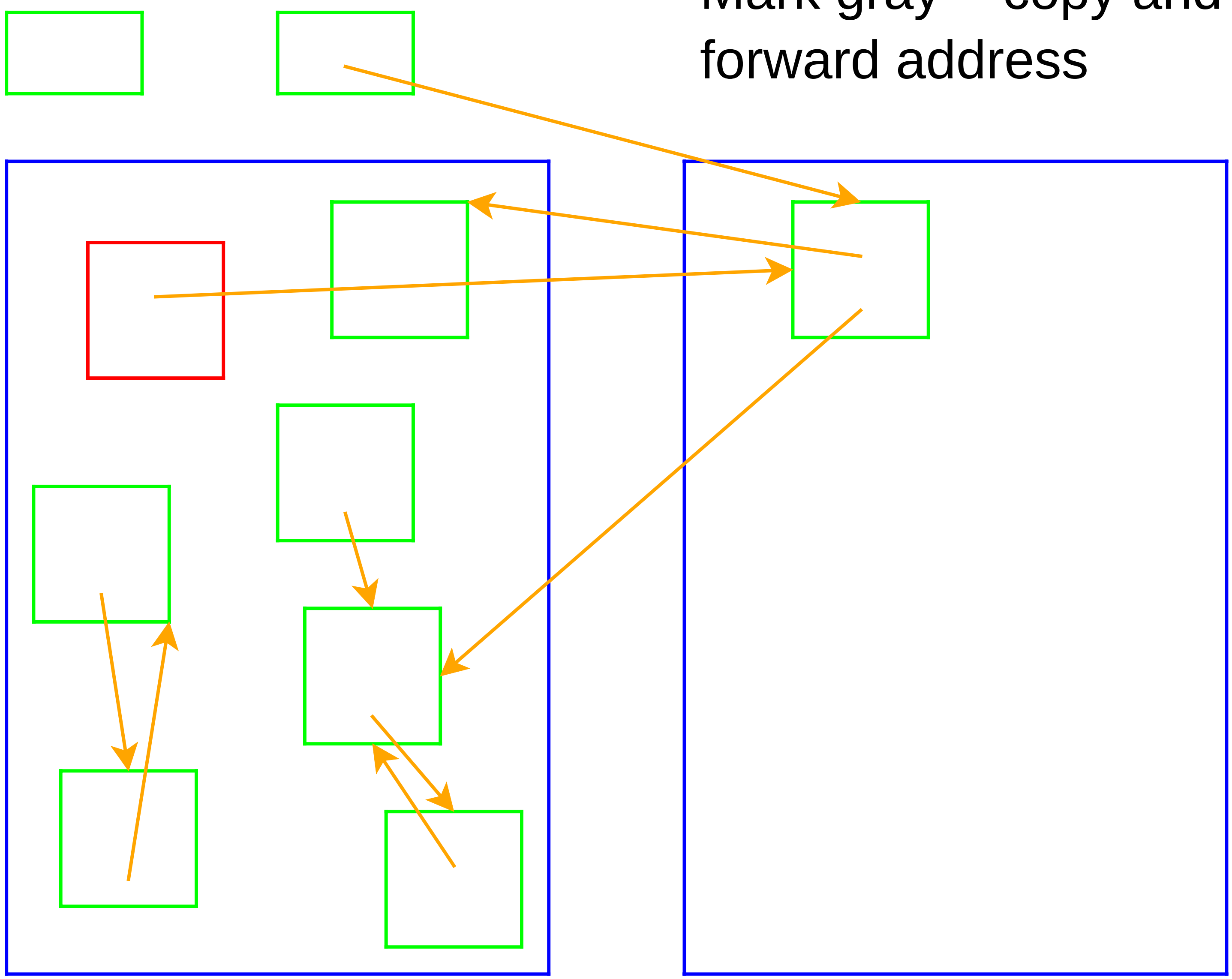
Left = from-space

Right = to-space



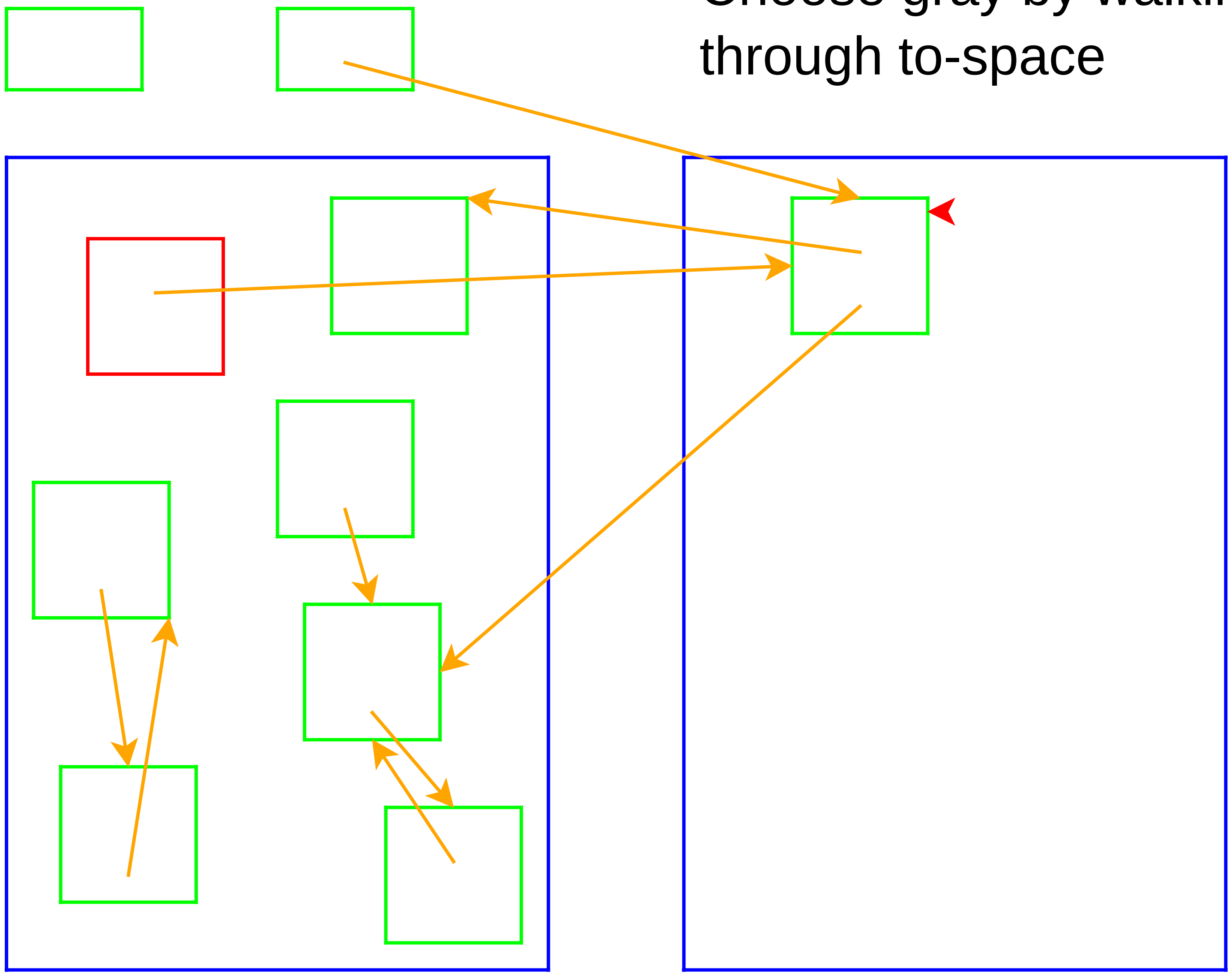
Two-Space Collection

Mark gray = copy and leave forward address



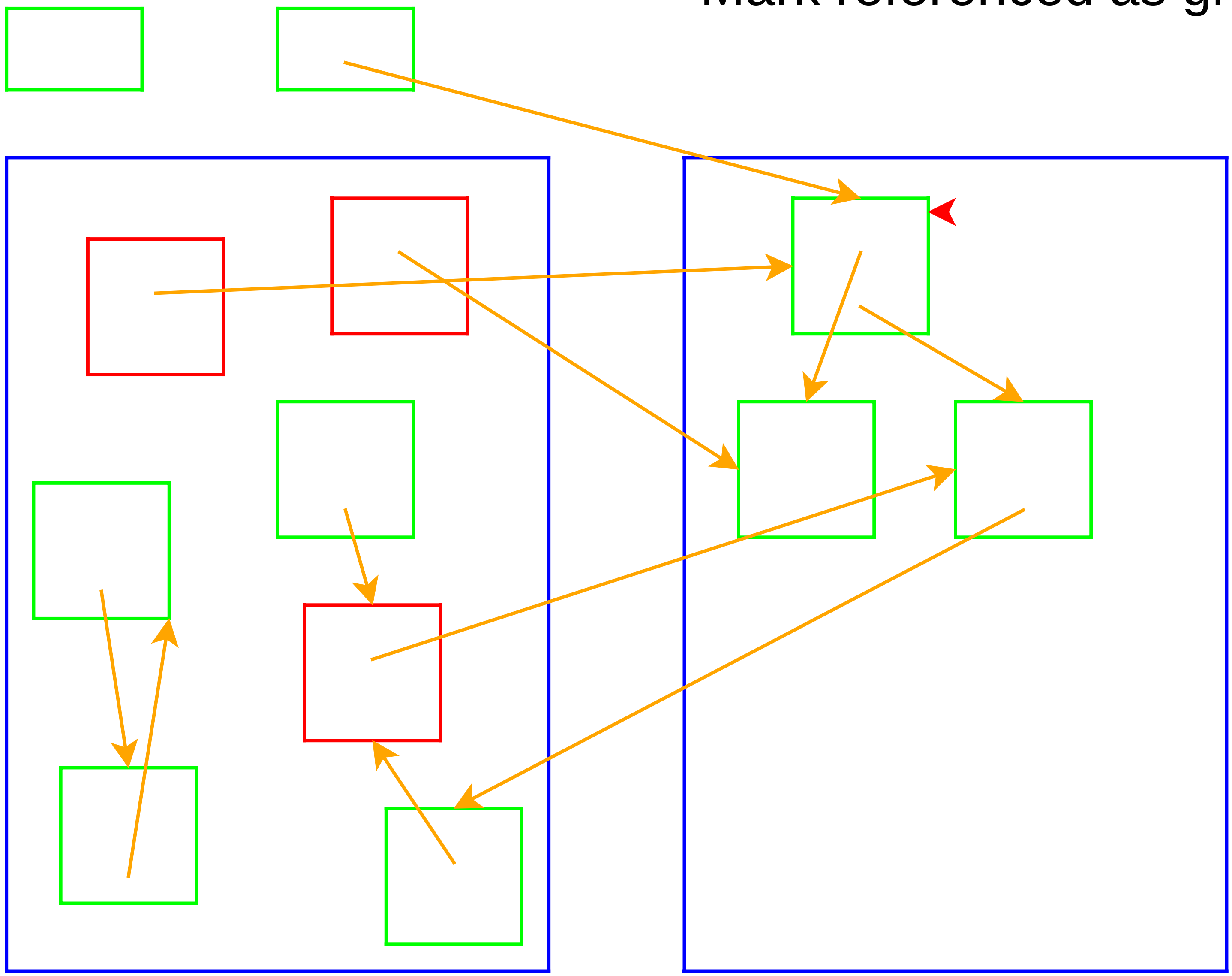
Two-Space Collection

Choose gray by walking through to-space



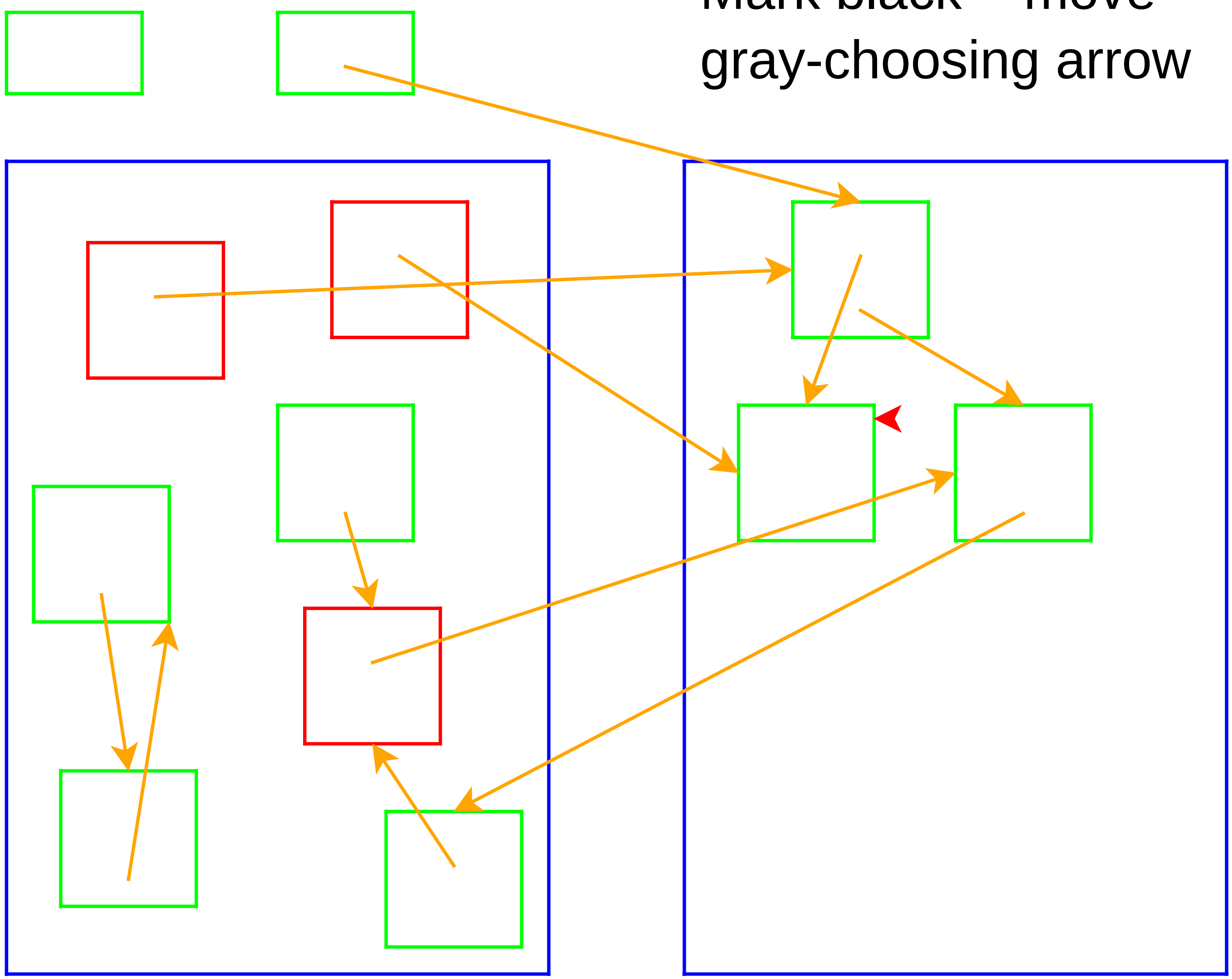
Two-Space Collection

Mark referenced as gray



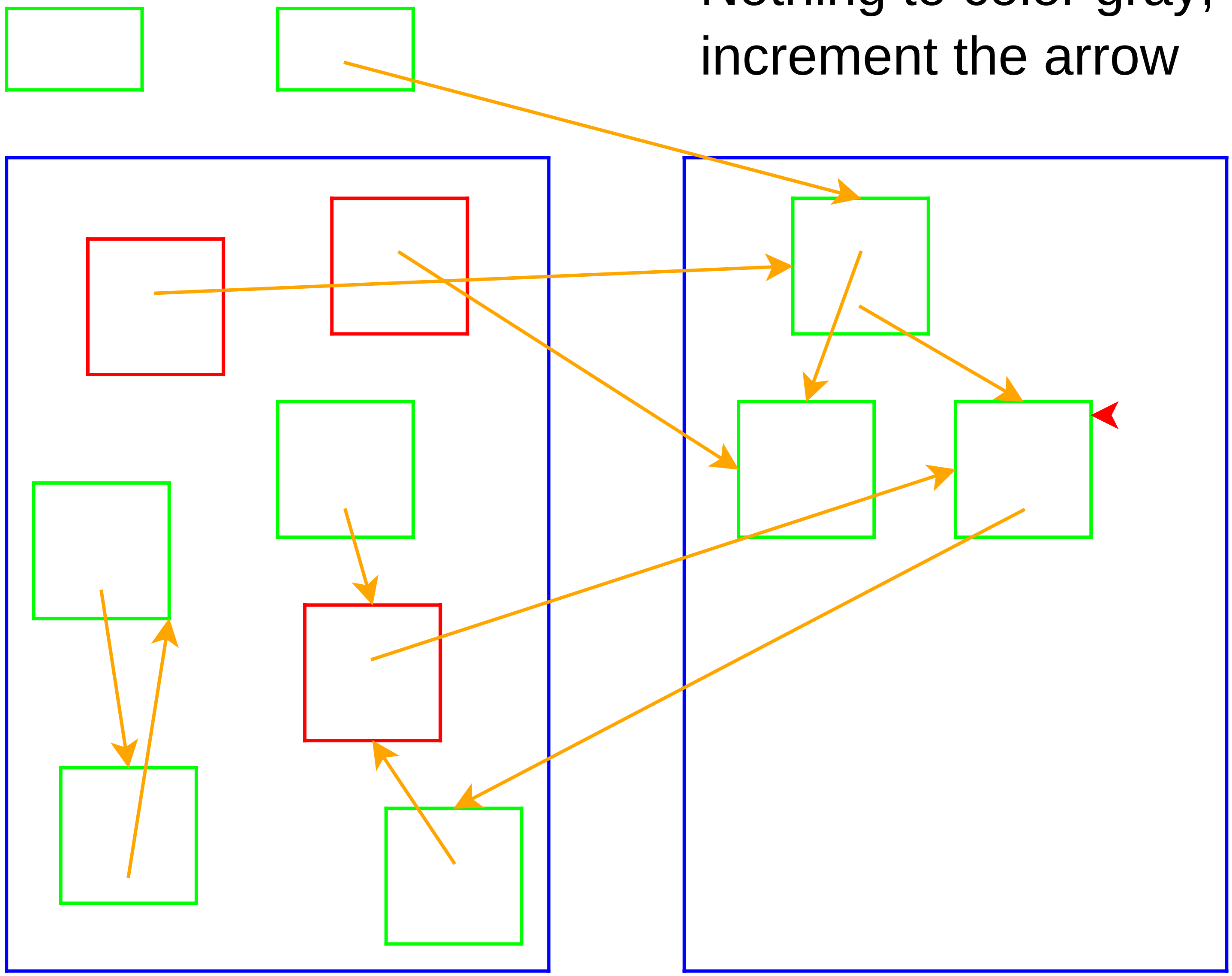
Two-Space Collection

Mark black = move
gray-choosing arrow



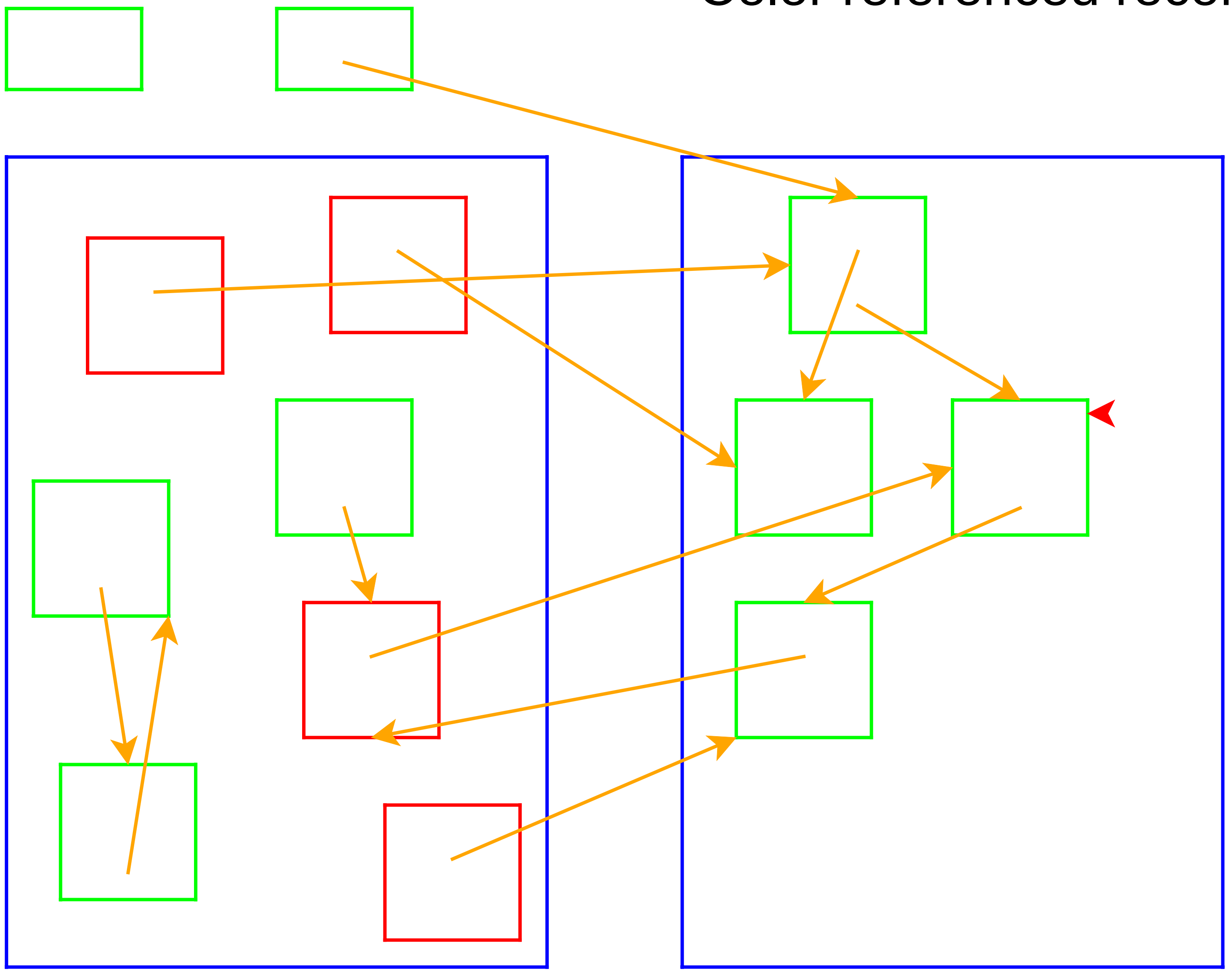
Two-Space Collection

Nothing to color gray;
increment the arrow



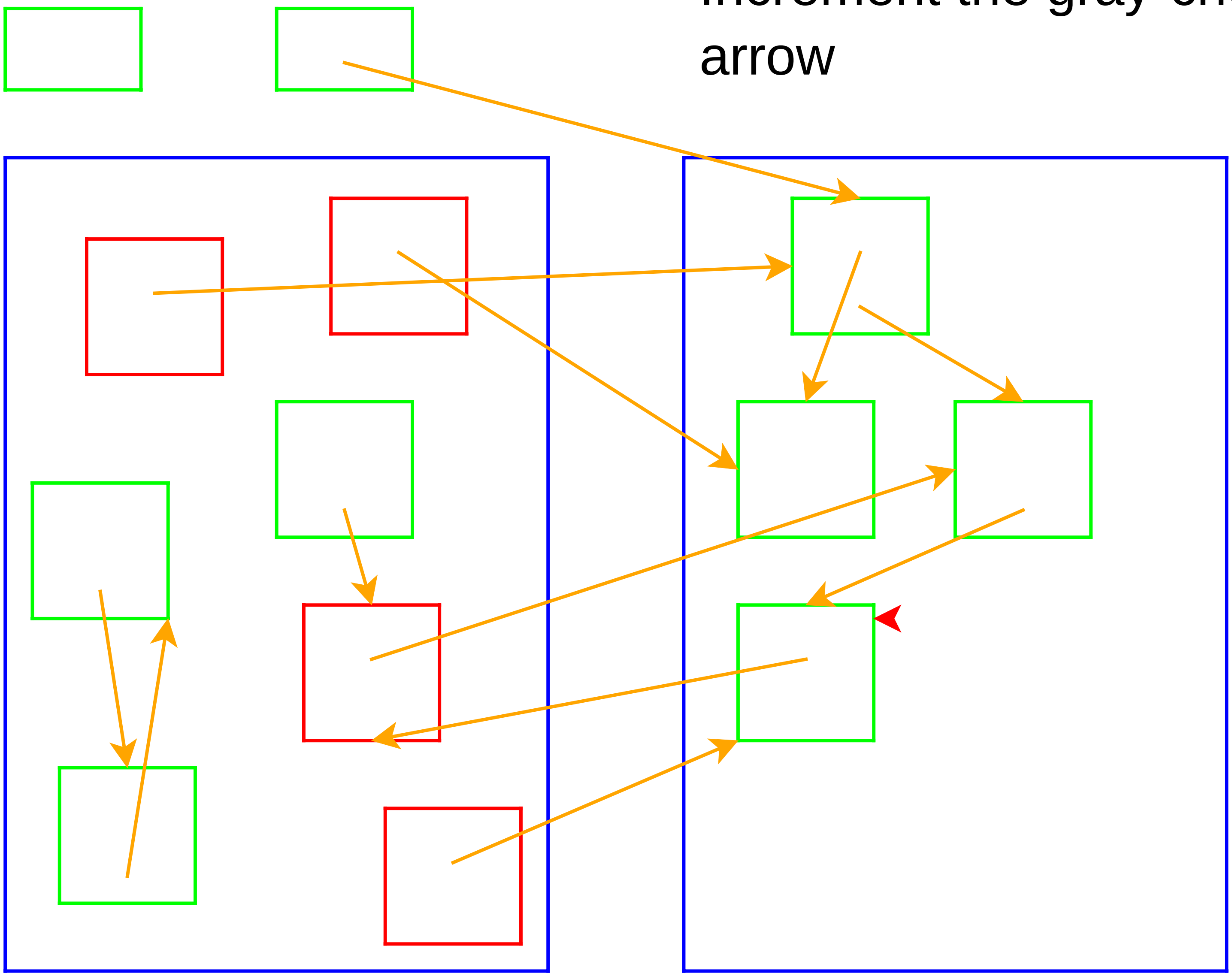
Two-Space Collection

Color referenced record gray



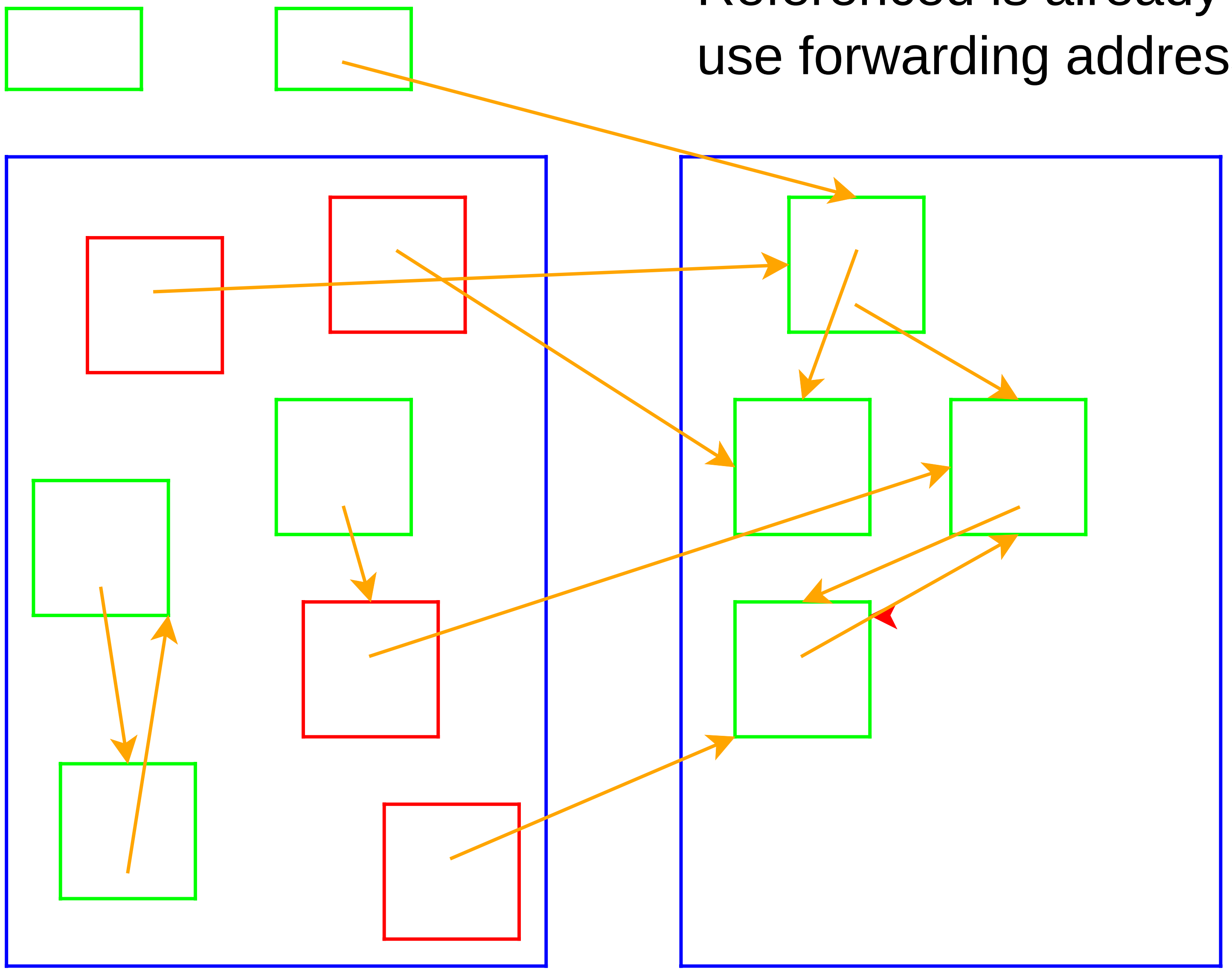
Two-Space Collection

Increment the gray-choosing arrow



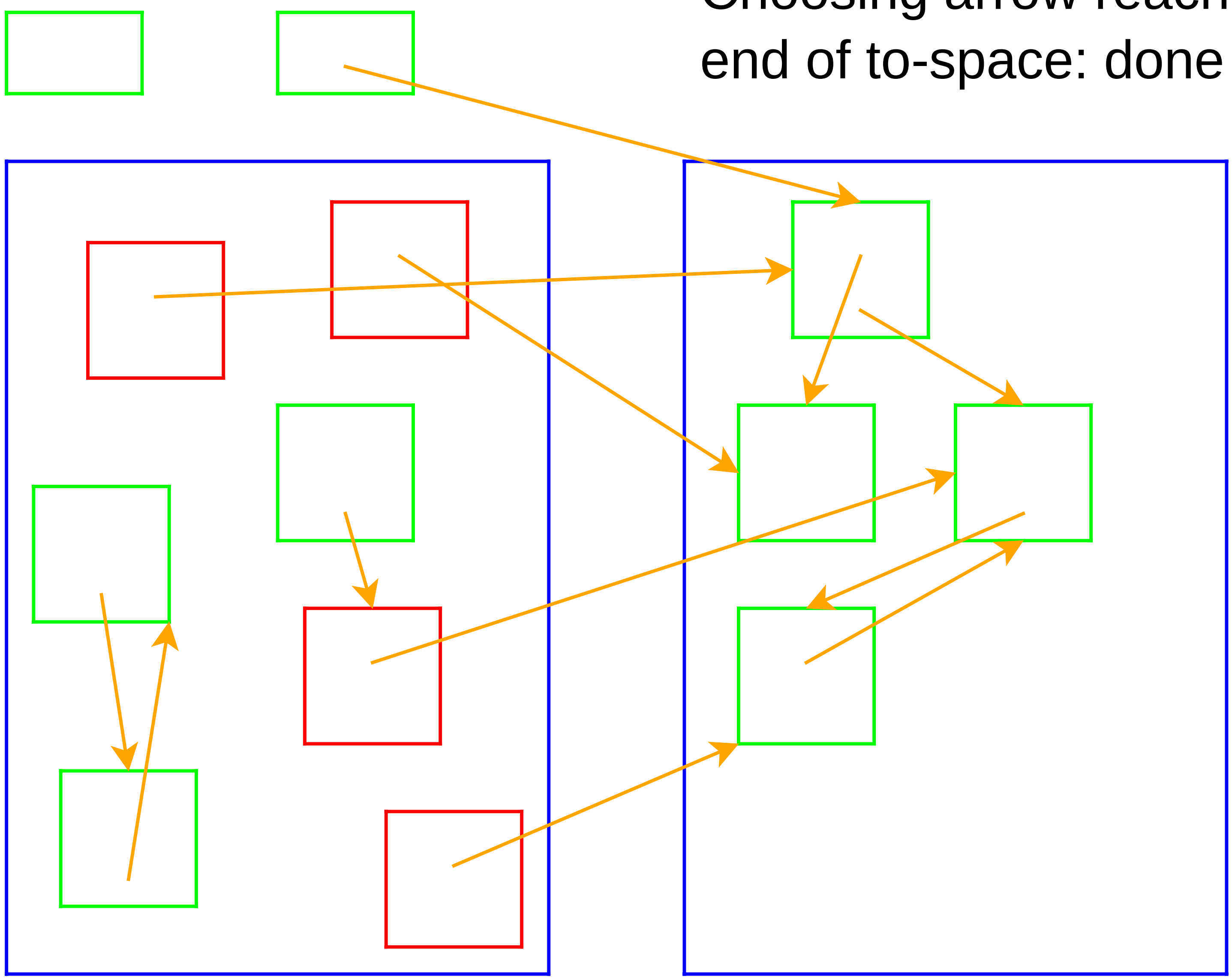
Two-Space Collection

Referenced is already copied,
use forwarding address



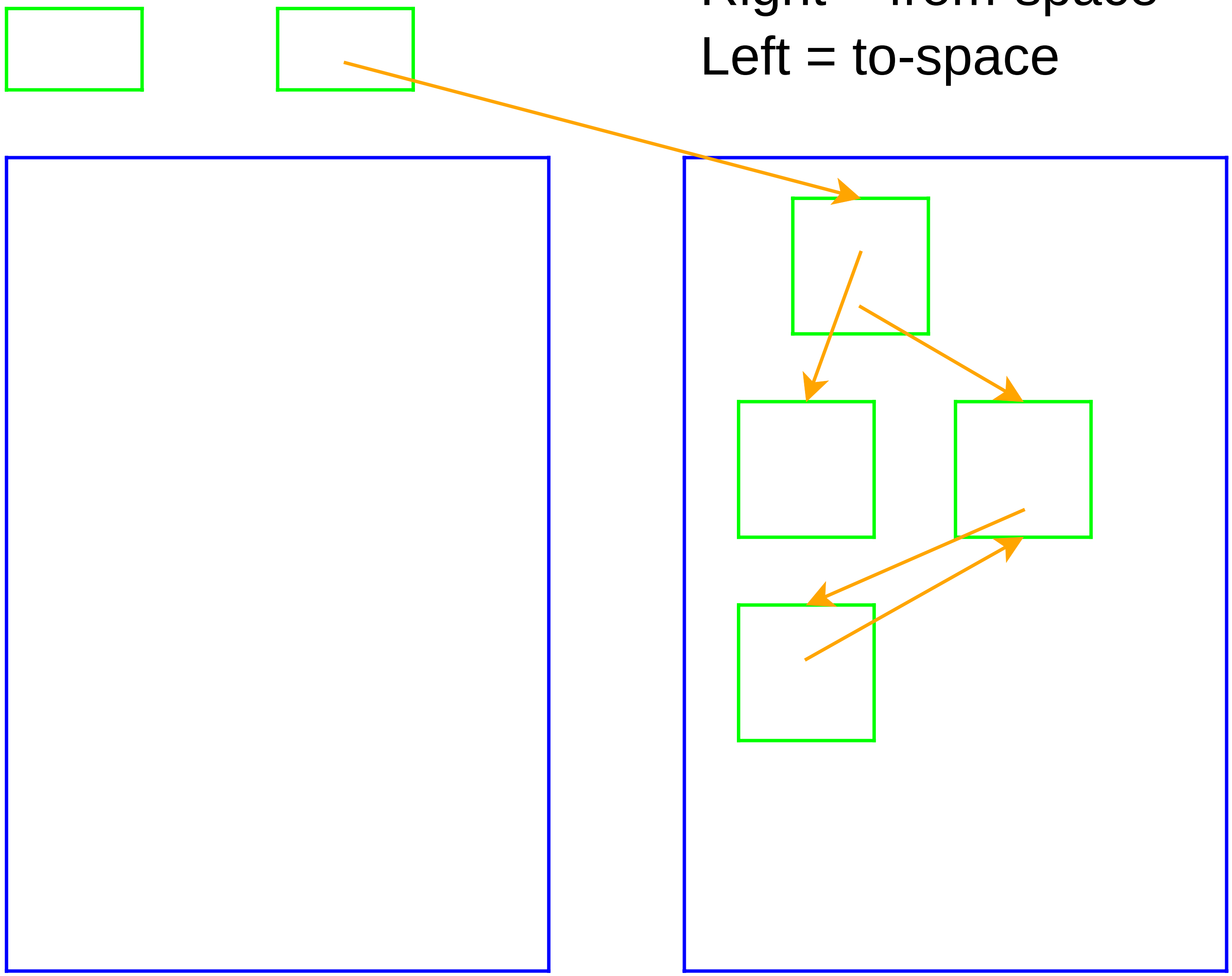
Two-Space Collection

Choosing arrow reaches the end of to-space: done



Two-Space Collection

Right = from-space
Left = to-space



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
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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
								^					