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)))

=>

(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

- Explains why the following program never generates a stack overflow:

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

- So we can 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

- 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 still 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

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** ?

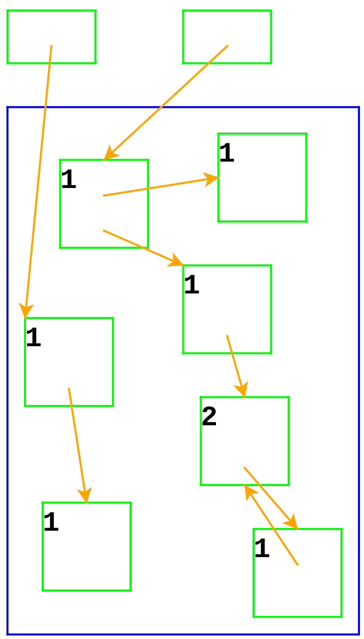
```
(define (apply-cont)
  (cond ...
   [(app-cont? CONT)
    (let ([rator (app-cont->rator CONT)]
          [old-cont (app-cont->cont CONT)])
      (set! EXP (closure->body rator))
      (free ENV) ;; unless in a closure!
      (set! ENV (extend-env
                 (closure->id rator)
            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

Reference Counting

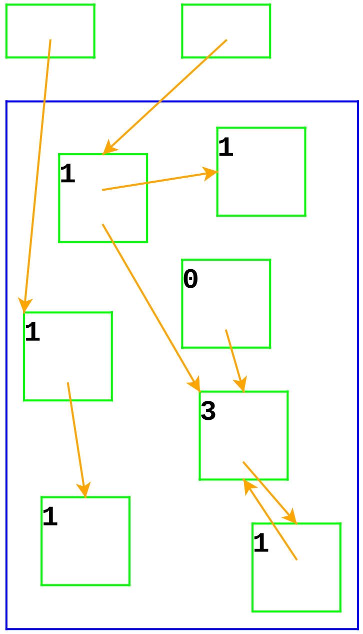
Reference counting: a way to know whether a record has other users

- Attatch a count to every record, start at 0
- When installing a pointer to a record (into a regsiter, 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

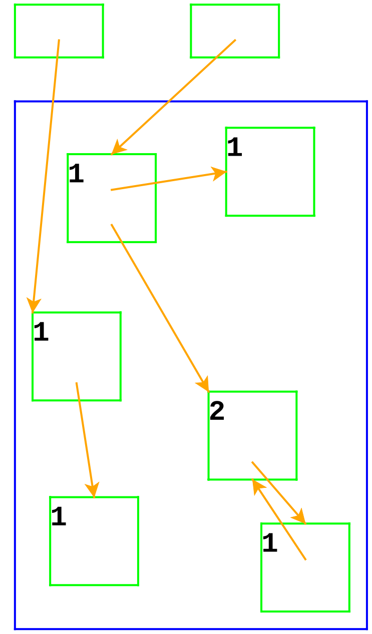
Reference Counting



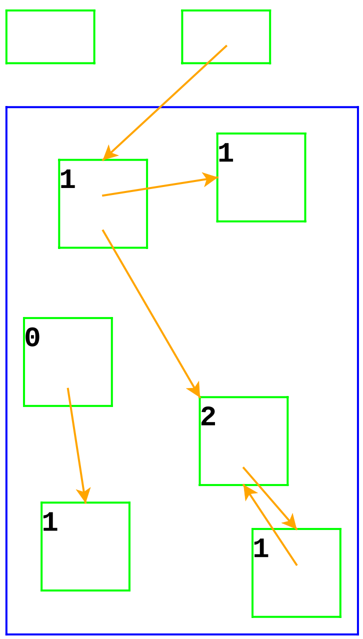
Reference Counting



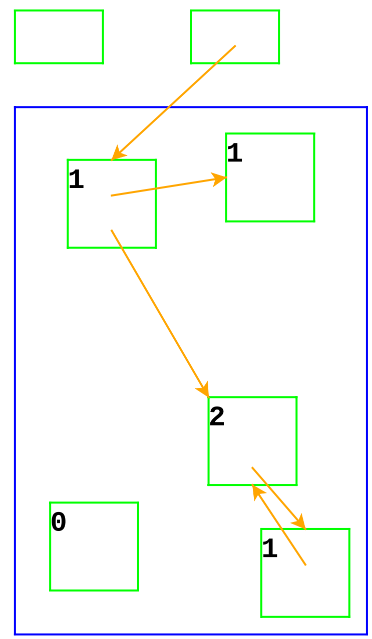
Reference Counting



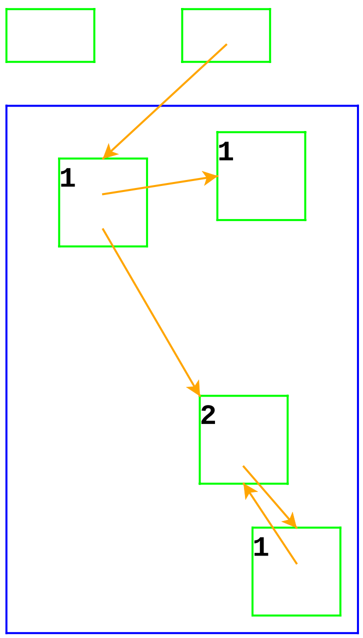
Reference Counting



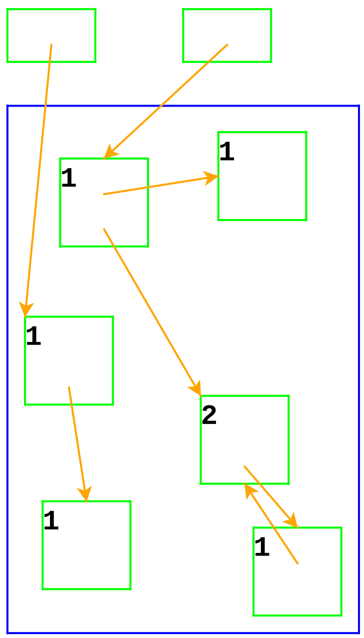
Reference Counting



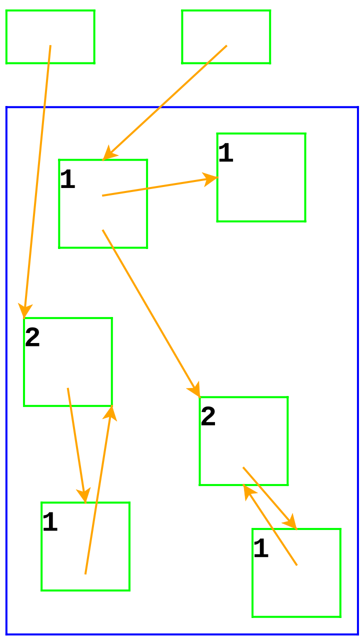
Reference Counting



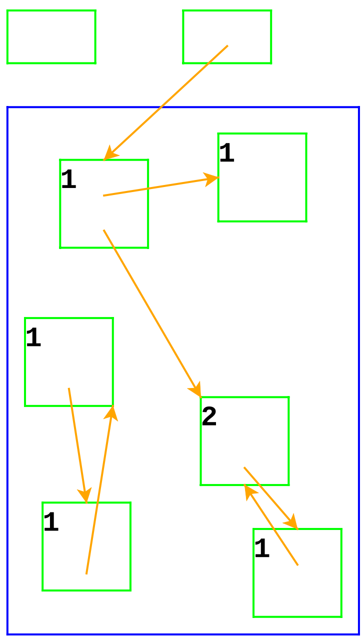
Reference Counting



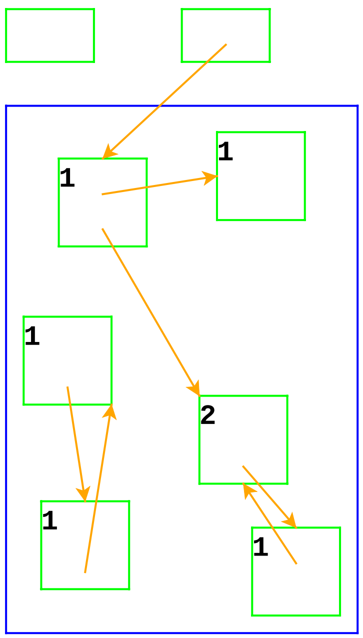
Reference Counting



Reference Counting



Reference Counting and Cycles



- Pointer cycles break reference counting

Garbage Collection

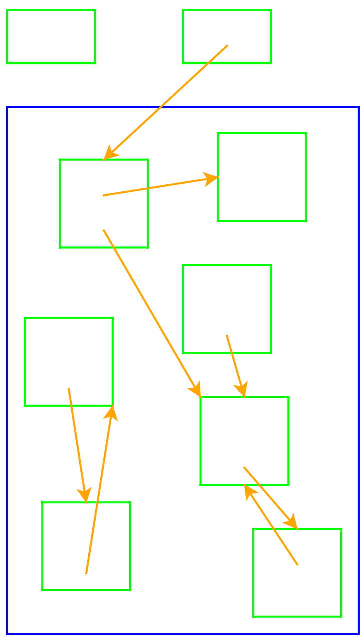
Garbage collection: a way to know whether a record has *any* users

- 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

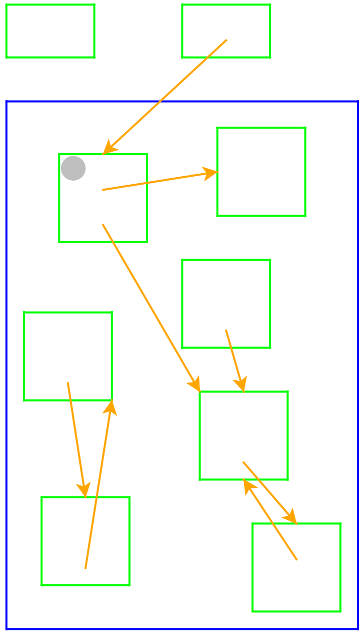
Garbage Collection Algorithm

- 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

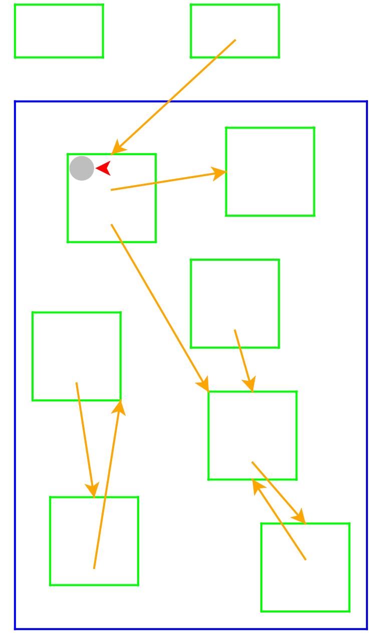
Garbage Collection



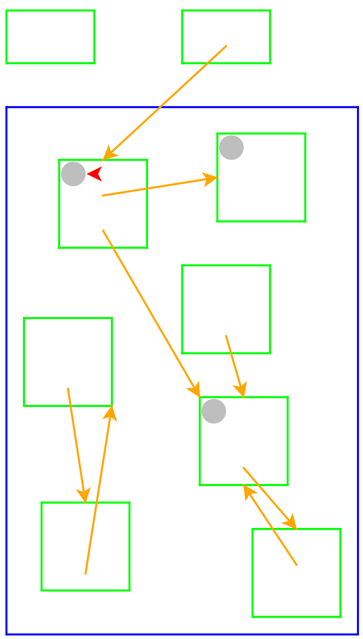
Garbage Collection



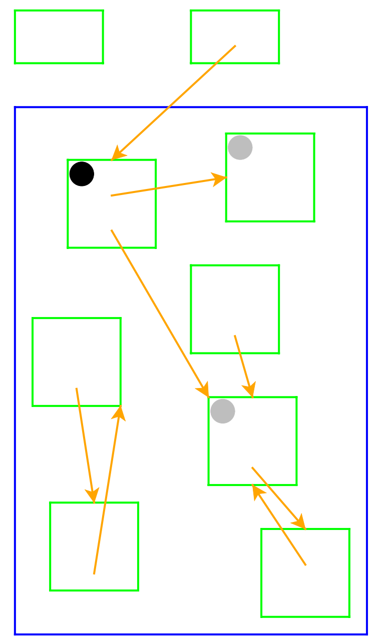
Garbage Collection



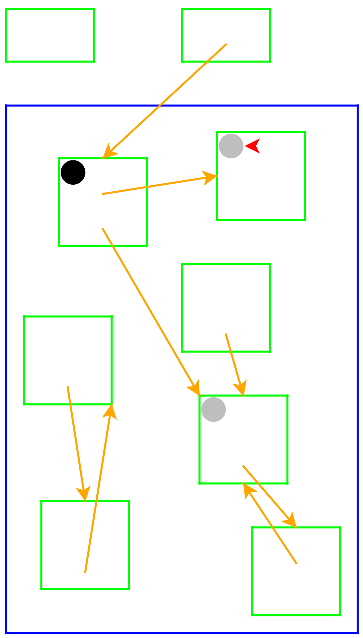
Garbage Collection



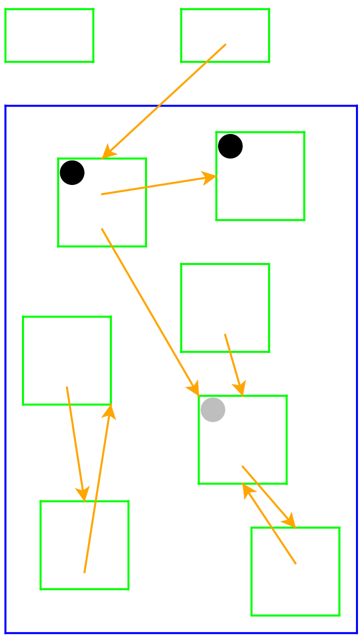
Garbage Collection



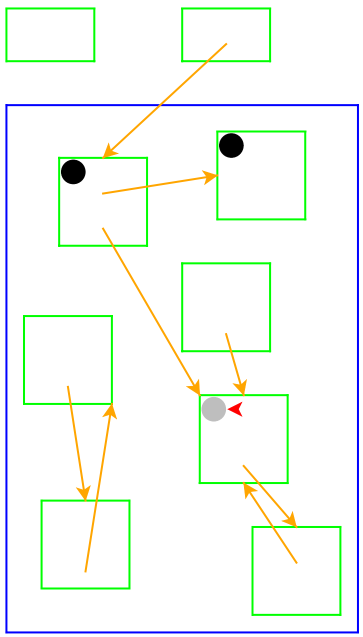
Garbage Collection



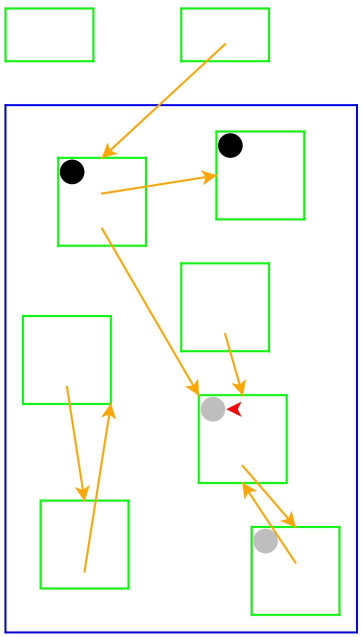
Garbage Collection



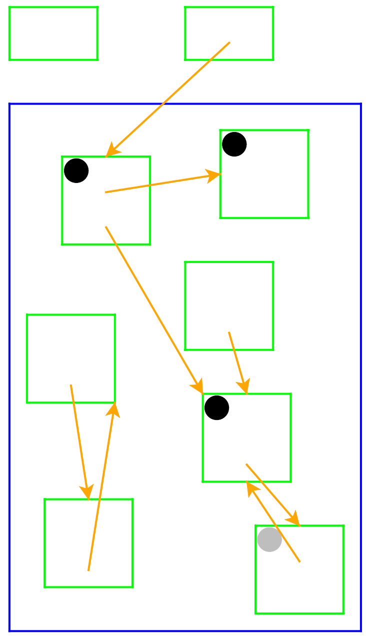
Garbage Collection



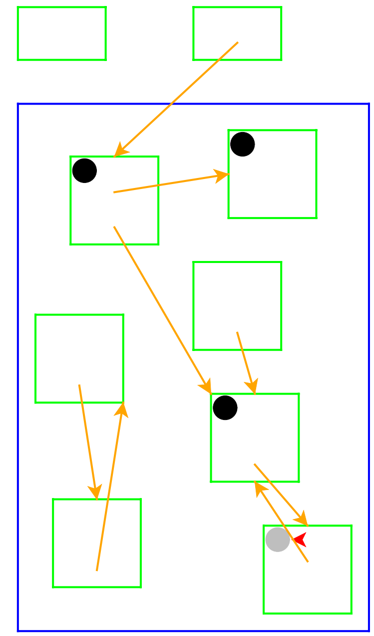
Garbage Collection



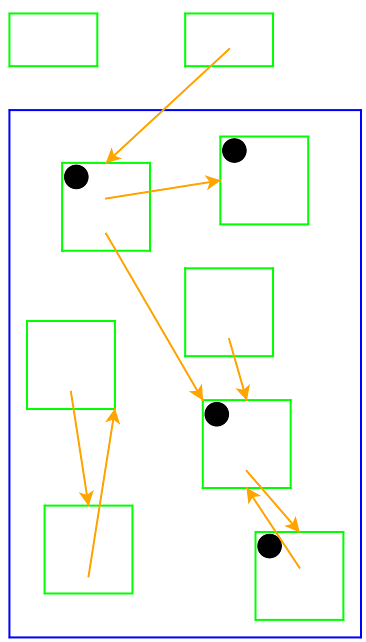
Garbage Collection



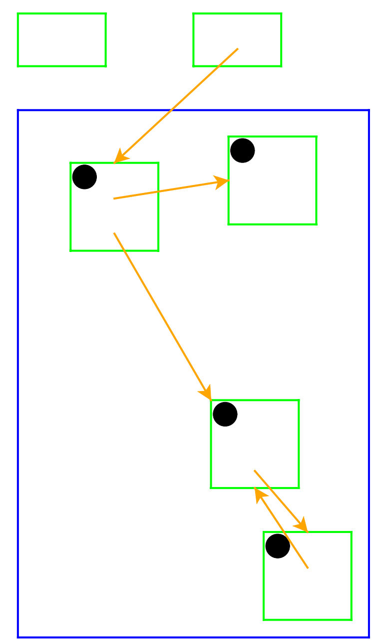
Garbage Collection



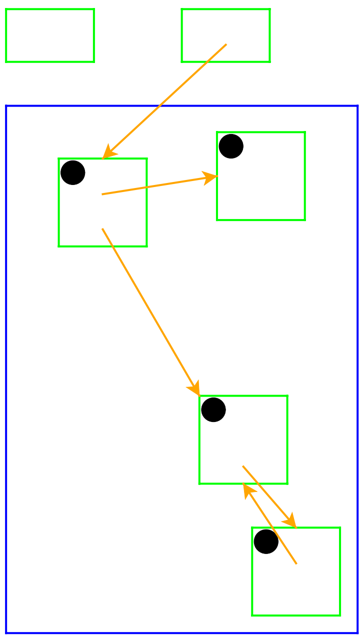
Garbage Collection



Garbage Collection



Garbage Collection and Cycles



- Pointer cycles ***do not*** break garbage collection

Two-Space Copying Collectors

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

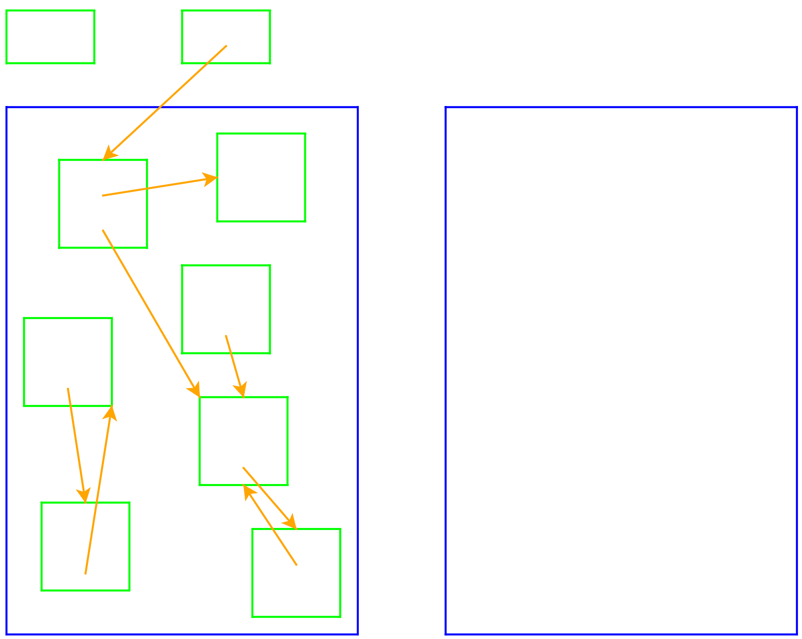
Allocator:

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

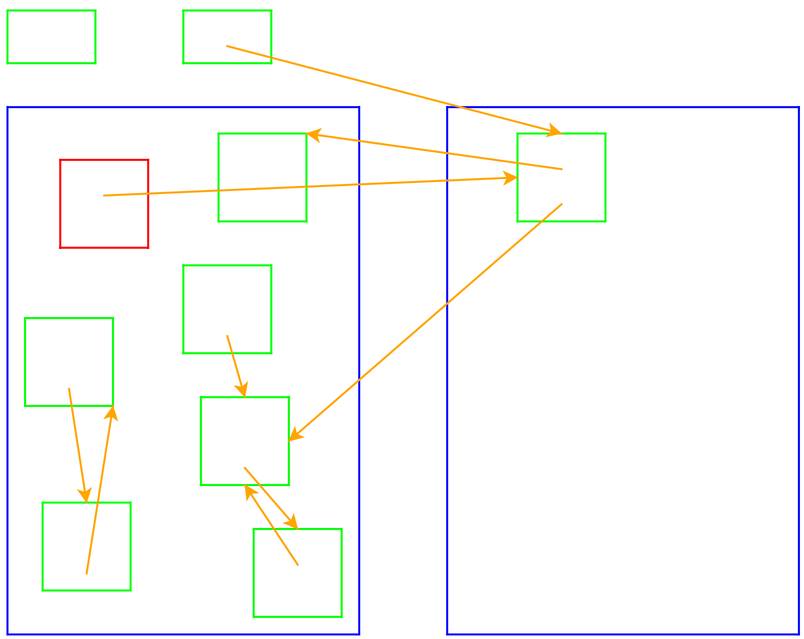
Collector:

- 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

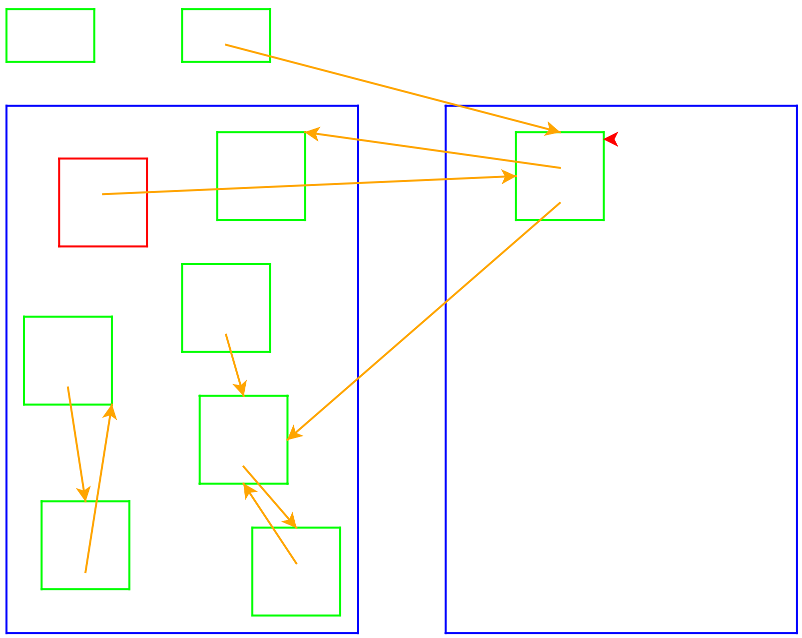
Two-Space Collection



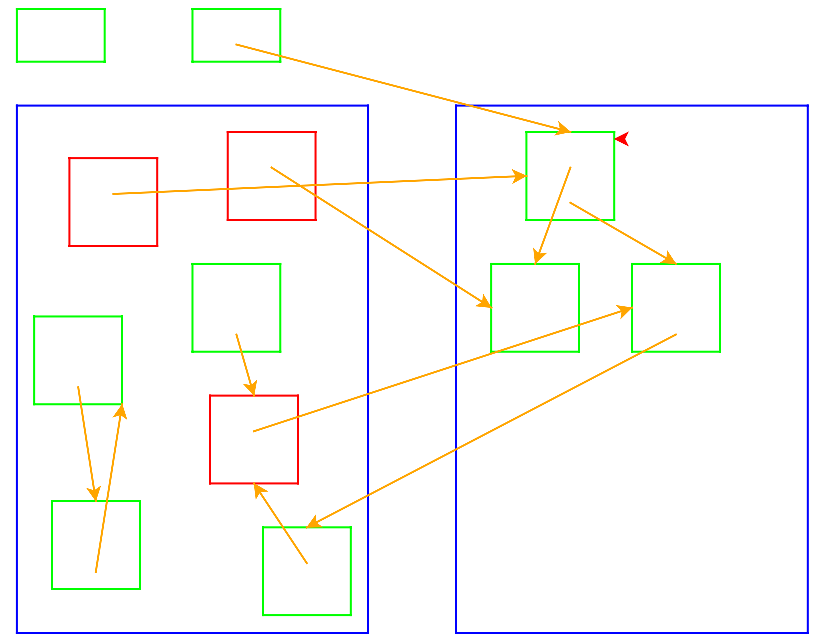
Two-Space Collection



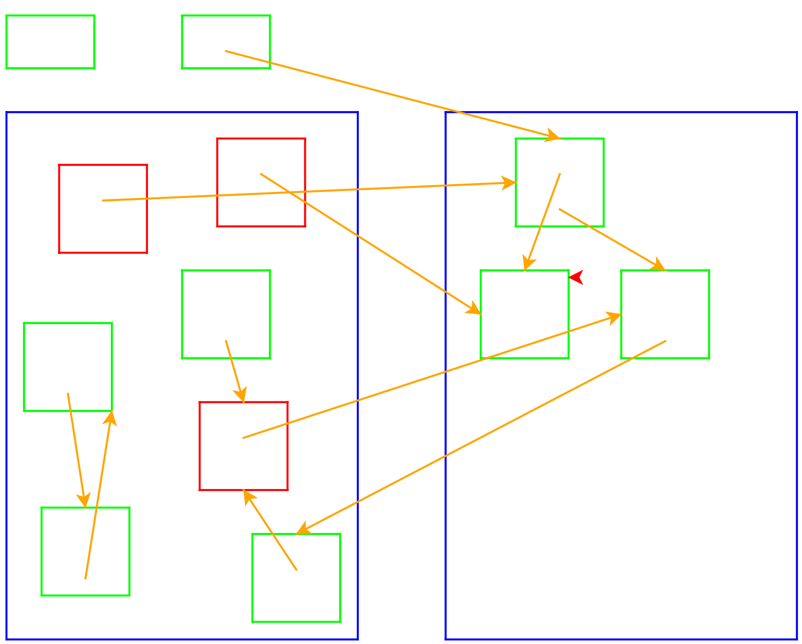
Two-Space Collection



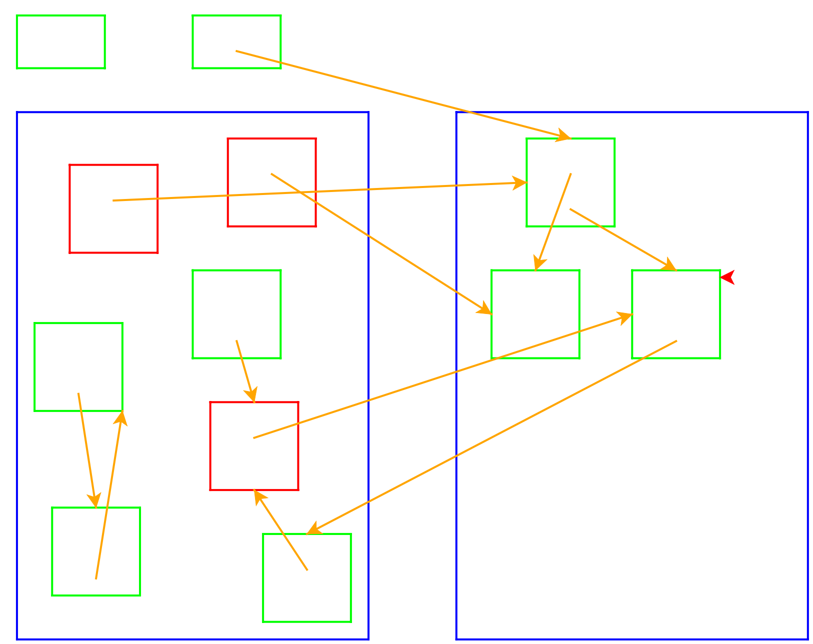
Two-Space Collection



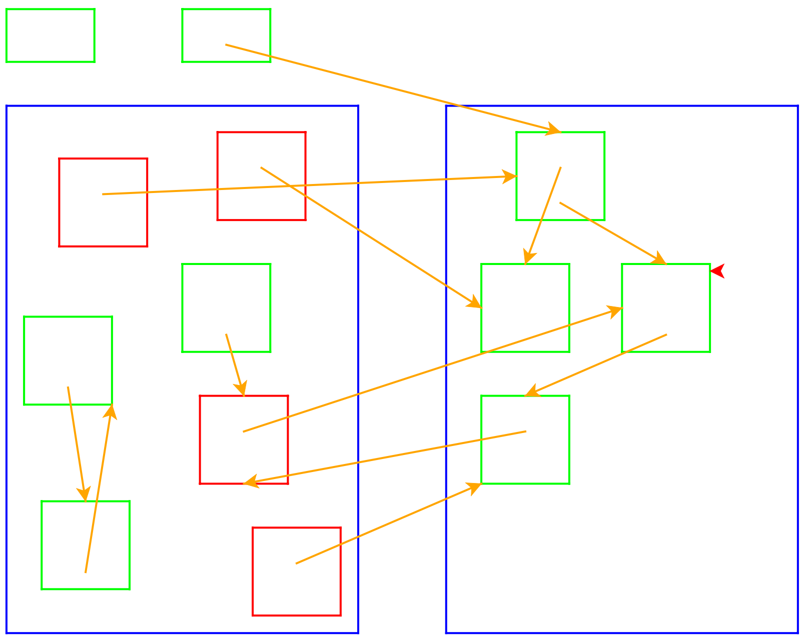
Two-Space Collection



Two-Space Collection



Two-Space Collection



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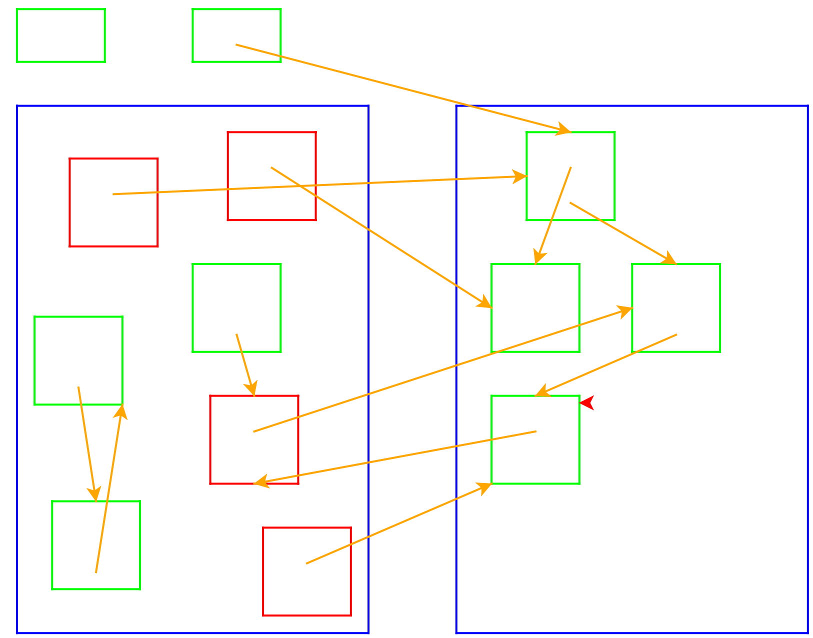

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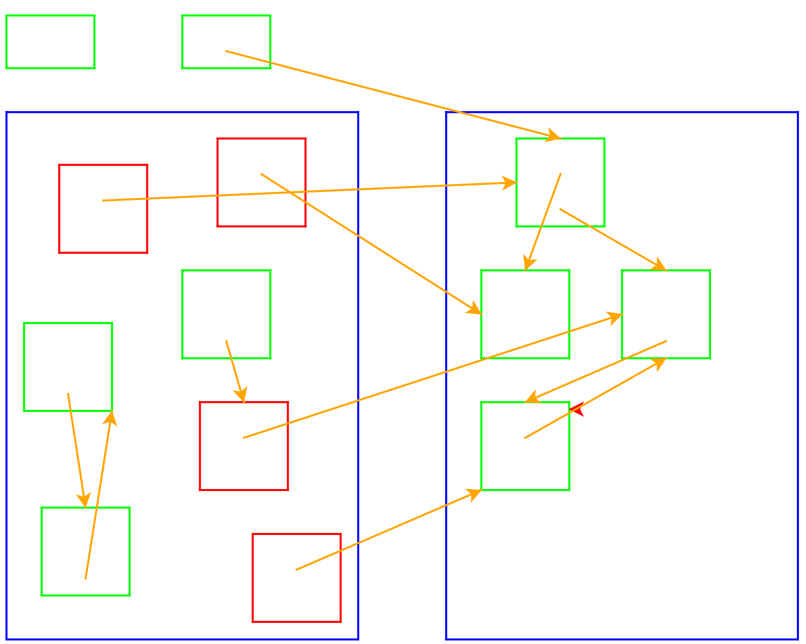
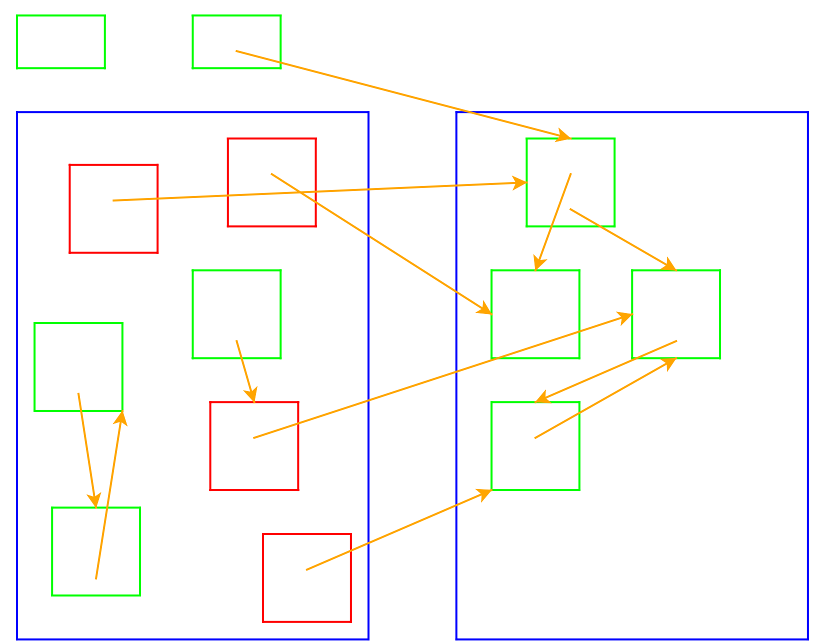


Two-Space Collection



Two-Space Collection