Garbage Collection

David Bremner

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Automatic memory management

- PLAI2 chapter 11
- Garbage Collection Handbook
- https://docs.racket-lang.org/plai/gc2-collector.html
- https://docs.racket-lang.org/plai/gc2-mutator.html

The argument for automatic storage management

Manual is hard 2253 / 2263 / C programming in general

Manual is error prone Both security bugs and memory leaks are common with manually managed storage.

When can we automatically free an object

- When we can guarantee that it won't be used again in the computation (ground truth).
- this is too hard.

Two conservative approximations

Reference counting when number of references reaches zero (leave for later)

Garbage collection when an object is not reachable from *roots*

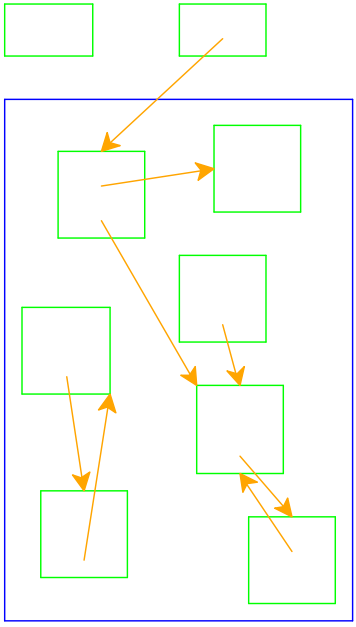
Garbage Collection

- Values reachable directly (without pointers) are live (the roots) E.g., values on the stack and in registers
- 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

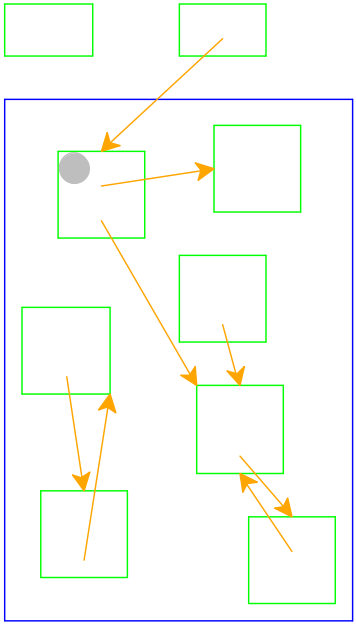
- Color all records white
- Color records referenced by roots gray
- Repeat until there are no gray records:
  - Pick a gray record, r
  - For each white record that r points to, make it gray
  - Color r black
- Deallocate all white records

Garbage Collection



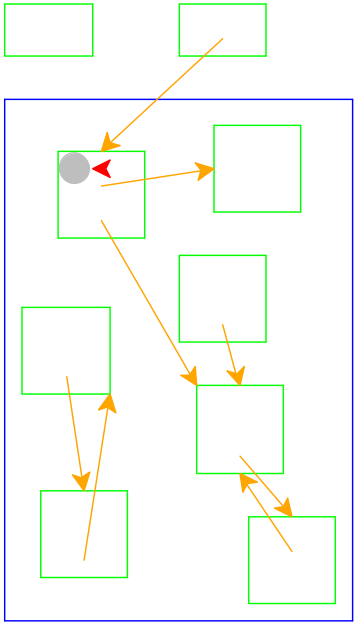
- All records are marked white

Garbage Collection



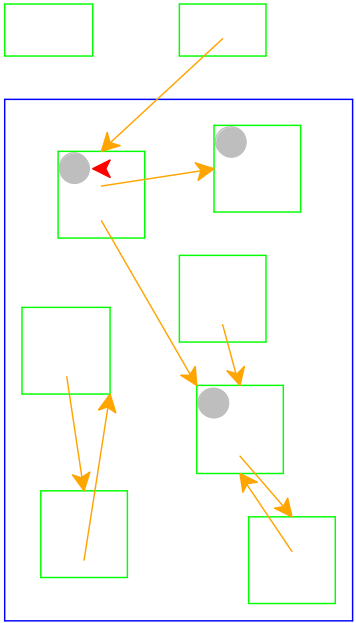
- Mark records referenced by registers as gray

Garbage Collection



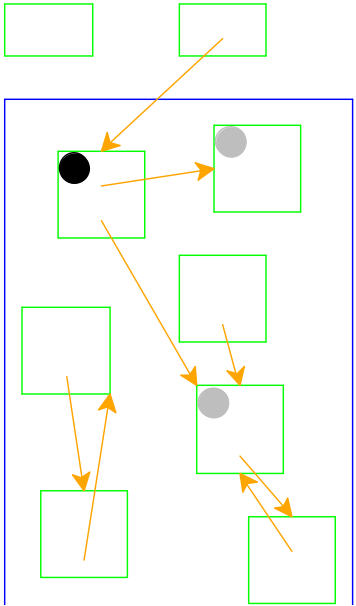
- Need to pick a gray record
- Red arrow indicates the chosen record

Garbage Collection



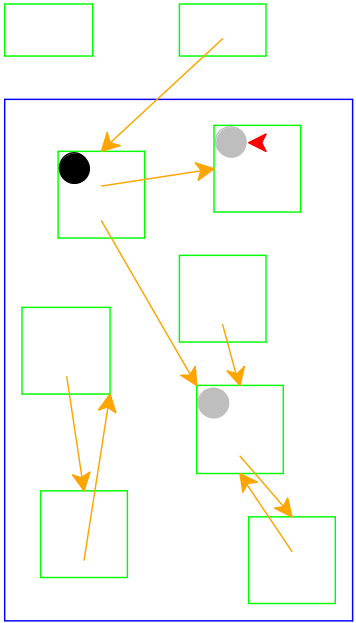
Mark white records referenced by chosen record as gray

Garbage Collection



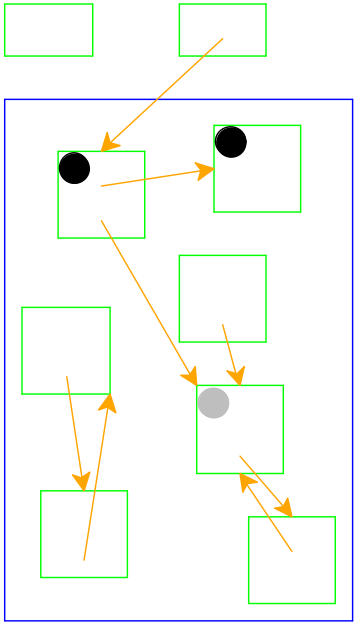
Mark chosen record black

Garbage Collection



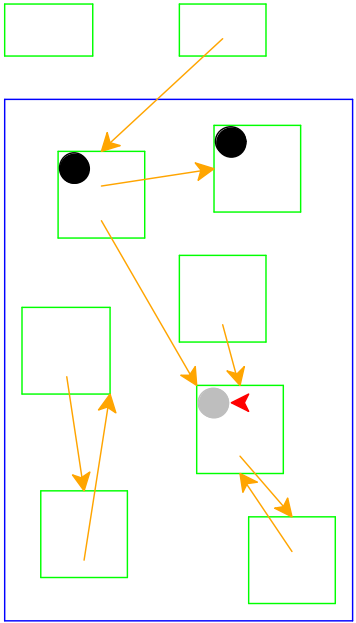
Start again: pick a gray record

Garbage Collection



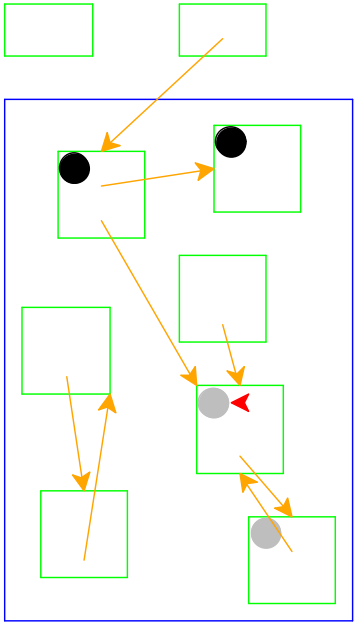
No referenced records; mark black

Garbage Collection



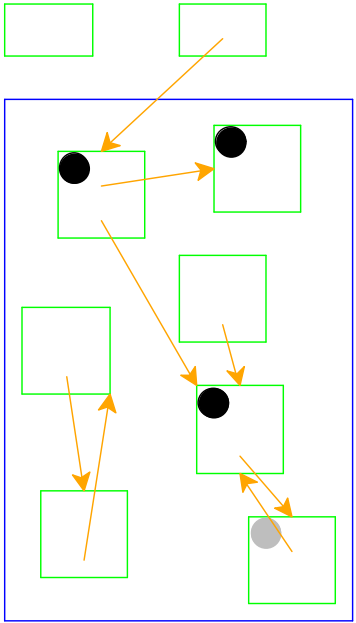
Start again: pick a gray record

Garbage Collection



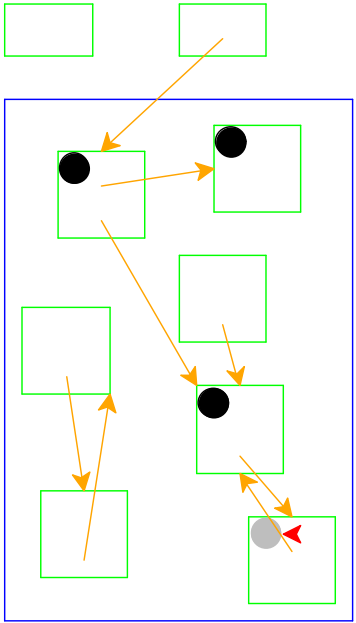
Mark white records referenced by chosen record as gray

Garbage Collection



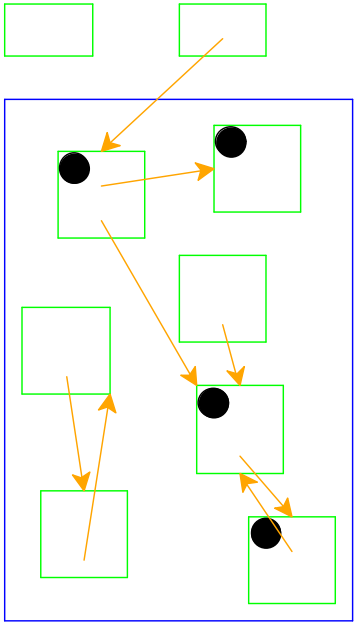
Mark chosen record black

Garbage Collection



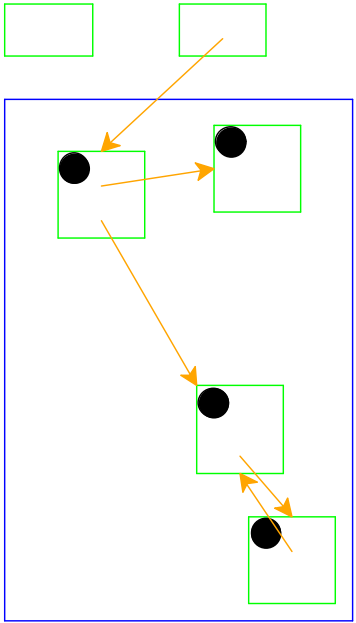
Start again: pick a gray record

Garbage Collection



No referenced white records; mark black

Garbage Collection



- No more gray records; deallocate white records
- Cycles do not break garbage collection (spoiler re: Reference counting)

Mutators and Collectors(s)

Programs divided into two parts

collector manages the heap, allocates memory, collects garbage to free space

mutator asks the collector for memory, does the work the program is supposed to do

- from now on mostly used for test cases

collector API called by mutator

- Allocate a number,
- Allocate a pair,
- Give me the first element of that pair, ...

PLAI GC language(s)

Two languages

- `#lang plai/gc2/collector`
- `#lang plai/gc2/mutator`

Collectors implement a specific API

- See the docs: search for `init-allocator`

Collectors use an API provided by the collector language

- See the docs: search for `heap-ref`

PLAI GC language(s)

Two languages

- `#lang plai/gc2/collector`, `#lang plai/gc2/mutator`

The mutator language transforms mutators to

- keep track of roots
- make allocations explicit
- use the collector API

Mutators are (mostly) regular PLAI (racket) programs

- No need to use the (low-level) collector API directly!

Heap Model

- Like Lectures 10 - 11, but with symbols for tags.
- Heap is a vector of values
- Collector and mutator language are dynamically typed, allowing non-homogeneous heap.
- All values need to be allocated in the heap
- All values need to be tagged (to remember their type)

Atomic and compound values

- Atomic values include, numbers, symbols, booleans, and the empty list.
- Conceptually these fit in one cell; this is somewhat of a lie.
- Compound values include pairs and closures

Roots and compound values

Mutator creates roots to avoid race condition.

cons-ex

```
(define (cons-test)
    (cons 1 2))

(define the-cons (cons-test))
```

- i.e. 1 and 2 are on the heap, but nothing references them until the cons is allocated.

	0	1	2	3	4	5	6	7	8	9
0	10	'clos	cons-tes	'flat	1	'flat	2	'cons	3	5
10	#f	#f	#f	#f	#f	#f	#f	#f	#f	#f

A non-collecting collector

- Put the allocation pointer at address 0 (visible)
- Allocate all constants in the heap, tag them with 'flat
- Allocate all conses in the heap, tag them with 'cons
- Allocate all closures in the heap, tag them with 'clos

Low level allocation

```
(define (init-allocator)
  (heap-set! 0 1))

(define (malloc n)
  (define addr (heap-ref 0))
  (unless (<= (+ addr n) (heap-size))
    (error 'allocator "out of memory"))
  (heap-set! 0 (+ addr n))
  addr)
```

	0	1	2	3	4	5	6	7	8	9
0	10	'clos	cons-tes	'flat	1	'flat	2	'cons	3	5
10	#f	#f	#f	#f	#f	#f	#f	#f	#f	#f

Atomic values

```
(define (gc:alloc-flat x)
  (define addr (malloc 2))
  (heap-set! addr 'flat)
  (heap-set! (+ addr 1) x)
  addr)

(define (gc:deref addr)
  (unless (equal? (heap-ref addr) 'flat)
    (error 'gc:deref "not a flat at ~a" addr))
  (heap-ref (+ addr 1)))
```

	0	1	2	3	4	5	6	7	8	9
0	10	'clos	cons-tes	'flat	1	'flat	2	'cons	3	5
10	#f	#f	#f	#f	#f	#f	#f	#f	#f	#f

Allocating pairs

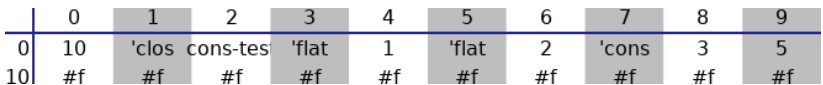
```
(define (gc:cons f r)
  (define addr (malloc 3))
  (heap-set! addr 'cons)
  (heap-set! (+ addr 1) (read-root f))
  (heap-set! (+ addr 2) (read-root r))
  addr)
```

	0	1	2	3	4	5	6	7	8	9
0	10	'clos	cons-tes	'flat	1	'flat	2	'cons	3	5
10	#f	#f	#f	#f	#f	#f	#f	#f	#f	#f

Accessing pairs

```
(define (gc:first addr)
  (check-pair addr)
  (heap-ref (+ addr 1)))

(define (gc:rest addr)
  (check-pair addr)
  (heap-ref (+ addr 2)))
```



Allocating closures 1/2

closure-ex

```
(let ([x 100]
      [y 1000])
  (lambda () (+ x y)))
```

	0	1	2	3	4	5	6	7	8	9
0	9	'flat	100	'flat	1000	'clos	#<proc>	1	3	#f
10	#f	#f	#f	#f	#f	#f	#f	#f	#f	#f

Allocating closures 2/2

```
(define (gc:closure code-pointer free-vars)
  (define addr (malloc (+ 2 (length free-vars))))
  (heap-set! addr 'clos)
  (heap-set! (+ addr 1) code-pointer)
  (for ([i (in-range 0 (length free-vars))]
        [v (in-list free-vars)])
    (heap-set! (+ addr 2 i)
               (read-root v)))
  addr)
```

	0	1	2	3	4	5	6	7	8	9
0	9	'flat	100	'flat	1000	'clos	#<proc>	1	3	#f
10	#f	#f	#f	#f	#f	#f	#f	#f	#f	#f

Testing a collector without a mutator

```
(with-heap h-expr body-exprs ...)
```

- `h-expr` must evaluate to a vector
- that vector is used for `heap-ref` and `heap-set!`
- `body-exprs` can (must) use the collector API.

Testing the non-collecting collector

null-gc

```
(module+ test
  (with-heap (vector 'x 'x 'x 'x 'x)
    (init-allocator)
    (gc:alloc-flat #f)
    (test (current-heap) (vector 3 'flat #f 'x 'x))))
```

Testing our non-collecting collector

null-gc

```
(module+ test
  (with-heap (vector 'x 'x 'x 'x 'x 'x 'x 'x 'x)
    (init-allocator)
    (gc:cons
     (simple-root (gc:alloc-flat #f))
     (simple-root (gc:alloc-flat #t)))
    (test (current-heap)
          (vector 8 'flat #f 'flat #t 'cons 1 3 'x))))
```

Testing with mutator programs

cons2

```
(allocator-setup "null-gc.rkt" 20) ; heap size

(define c1 (cons 2 (cons 3 empty)))
(define c2 (cons 1 c1))

(test/location=? (rest c2) c1) ; point to same location

(test/value=? (rest c1) '(3)) ; produce same value
```

	0	1	2	3	4	5	6	7	8	9
0	18	'flat	2	'flat	3	'flat	empty	'cons	3	5
10	'cons	1	7	'flat	1	'cons	13	10	#f	#f

Our friend fib

fib

```
(allocator-setup "null-gc.rkt" 160)
(define (fib n)
  (cond
    [(<= n 1) 1]
    [else (+ (fib (- n 1)) (fib (- n 2)))]))

(fib 5)
```