

Freeing memory is a pain

- Need to decide on a protocol (who frees what?)
- Pollutes interfaces
- Errors hard to track down

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- Need to decide on a protocol (who frees what?)
- Pollutes interfaces
- Errors hard to track down
- ... but lets try an example anyway (fire isn't hot until it burns **me**)

Freeing memory is a pain

```
; (listof any) -> (listof any[no-cons])
(define (remove-pairs l)
  (cond
    [(empty? l) '()]
    [else
     (if (cons? (first l))
         (remove-pairs (rest l))
         (cons (first l)
               (remove-pairs (rest l)))))]))
```

Freeing memory is a pain

```
; (listof any) -> (listof any[no-cons])
(define (remove-pairs l)
  (cond
    [(empty? l) '()]
    [else
     (begin
       (free! (first l))
       (if (cons? (first l))
           (remove-pairs (rest l))
           (cons (first l)
                 (remove-pairs (rest l))))))]))
```

Freeing memory is a pain

```
; (listof any) -> (listof any[no-cons])
(define (remove-pairs l)
  (cond
    [(empty? l) '()]
    [else
     (begin
       (free! (first l))          ; frees too much
       (if (cons? (first l))
           (remove-pairs (rest l))
           (cons (first l)
                 (remove-pairs (rest l))))))]))
```

Freeing memory is a pain

```
; (listof any) -> (listof any[no-cons])
(define (remove-pairs l)
  (cond
    [(empty? l) '()]
    [else
     (begin
       (free! (first l))           ; frees too much
       (if (cons? (first l))      ; .. and too little
           (remove-pairs (rest l))
           (cons (first l)
                 (remove-pairs (rest l))))))]))
```

Freeing memory is a pain

```
; (listof any) -> (listof any[no-cons])
(define (remove-pairs l)
  (cond
    [(empty? l) '()]
    [else
     (begin
      (free! l)
      (if (cons? (first l))
          (begin (free! (first l))
                  (remove-pairs (rest l)))
          (cons (first l)
                 (remove-pairs (rest l))))))]))
```

Freeing memory is a pain

```
; (listof any) -> (listof any[no-cons])
(define (remove-pairs l)
  (cond
    [(empty? l) '()]
    [else
     (begin
       (free! l) ; frees too soon
       (if (cons? (first l))
           (begin (free! (first l))
                  (remove-pairs (rest l)))
           (cons (first l)
                  (remove-pairs (rest l))))))]))
```


Freeing memory is a pain

```
; (listof any) -> (listof any[no-cons])
(define (remove-pairs l)
  (cond
    [(empty? l) '()]
    [else
     (let ([ans
            (if (cons? (first l))
                (begin (free! (first l))
                       (remove-pairs (rest l)))
                (cons (first l)
                      (remove-pairs (rest l)))))]
       (free! l)
       ans))]))
```

Freeing memory is a pain

```
; (listof any) -> (listof any[no-cons])
(define (remove-pairs l)
  (cond
    [(empty? l) '()]
    [else
     (let ([ans
            (if (cons? (first l))
                (begin (free! (first l))
                       (remove-pairs (rest l)))
                (cons (first l)
                      (remove-pairs (rest l)))))]
       (free! l) ; broke tail recursion!
       ans))]))
```

Freeing memory is a pain

```
; (listof any) -> (listof any[no-cons])
(define (remove-pairs l)
  (begin0 (remove-pairs/real l)
          (cleanup l)))

(define (cleanup l)
  (cond [(empty? l) (void)]
        [else
         (when (cons? (first l)) (free! (first l)))
         (let ([next (rest l)])
           (free! l)
           (cleanup next))]))

; the original function
(define (remove-pairs/real l) ...)
```

Automatic storage management

The PL has its own implementation of allocation; why not freeing too?

When can we free an object?

- When we can guarantee that it won't be used again in the computation

Automatic storage management

The PL has its own implementation of allocation; why not freeing too?

When can we free an object?

- When we can guarantee that it won't be used again in the computation
- ... when it isn't reachable; this is garbage collection

Garbage Collection

Garbage collection: a way to know whether a record is *live* i.e., accessible

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- Values on the stack & in registers are live (the roots)
- 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

Garbage Collection

Garbage collection: a way to know whether a record is *live* i.e., accessible

- Values on the stack & in registers are live (the roots)
- 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

Time to write a garbage collector

- Two new languages: `#lang plai/gc2/mutator` for writing programs to be collected, and `#lang plai/gc2/collector` for writing collectors
- Collector interface, see section 2 of the PLAI docs (search for `init-allocator`)

Rules of the game

- All values are allocated (we have no type information!)
- Atomic values (fit in one cell in memory) include numbers (a lie), symbols (a less bad lie), booleans, and the empty list
- Compound values (require multiple cells in memory) include pairs and closures

A non-collecting collector

- Put the allocation pointer at address 0
- Allocate all constants in the heap, tag them with `'flat'`
- Allocate all pairs in the heap, tag them with `'pair'`
- Allocate all closures in the heap, tag them with `'proc'`

A non-collecting collector

```
#lang plai/gc2/collector
```

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

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

A non-collecting collector, cotd

```
(define (gc:flat? addr)
  (equal? (heap-ref addr) 'flat))

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

(define (gc:deref addr)
  (if (gc:flat? addr)
      (heap-ref (+ addr 1))
      (error 'gc:deref
             "expected a flat value, got addr ~s"
             addr)))
```

A non-collecting collector, cotd

```
(define (gc:cons hd tl)
  (define addr (alloc 3))
  (heap-set! addr 'cons)
  (heap-set! (+ addr 1) (read-root hd))
  (heap-set! (+ addr 2) (read-root tl))
  addr)
```

```
(define (gc:cons? pr)
  (equal? (heap-ref pr)
          'cons))
```

A non-collecting collector, cotd

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

(define (gc:rest addr)
  (chk-pair addr 'gc:rest)
  (heap-ref (+ addr 2)))

(define (chk-pair pr who)
  (unless (gc:cons? pr)
    (error who
           "expected a pair, got addr ~a"
           pr)))
```

A non-collecting collector, cotd

```
(define (gc:set-first! addr nv)
  (chk-pair addr 'gc:set-first!)
  (heap-set! (+ addr 1) nv))
```

```
(define (gc:set-rest! addr nv)
  (chk-pair addr 'gc:set-rest!)
  (heap-set! (+ addr 2) nv))
```


A non-collecting collector, cotd

```
(define (gc:closure code-ptr free-vars)
  (define fv-count (length free-vars))
  (define addr (alloc (+ fv-count 2)))
  (heap-set! addr 'proc)
  (heap-set! (+ addr 1) code-ptr)
  (for ([i (in-naturals)]
        [r (in-list free-vars)])
    (heap-set! (+ addr 2 i)
                (read-root r)))
  addr)
```

A non-collecting collector, cotd

```
(define (gc:closure? loc)
  (equal? (heap-ref loc) 'proc))
(define (ensure-closure loc)
  (unless (gc:closure? loc)
    (error 'gc
           "expected a closure @ loc ~a"
           loc)))
(define (gc:closure-code-ptr loc)
  (ensure-closure loc)
  (heap-ref (+ loc 1)))
(define (gc:closure-env-ref loc i)
  (ensure-closure loc)
  (heap-ref (+ loc 2 i)))
```

Testing a collector

We can use **with-heap** to test a collector. The expression

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

expects **h-expr** to evaluate to a vector and then it uses that vector as the memory that **heap-ref** and **heap-set!** refer to while evaluating the **body-exprs**.

Testing our non-collecting collector

```
(let ([h (vector 'x 'x 'x 'x 'x)])  
  (test (with-heap h  
          (init-allocator)  
          (gc:alloc-flat #f)  
          h)  
        (vector 3 'flat #f 'x 'x)))
```

Testing our non-collecting collector

```
(define (make-simple-root n)
  (define b (box n))
  (make-root 'simple-root
             (λ () (unbox b))
             (λ (n) (set-box! b n))))

(let ([h (vector 'x 'x 'x 'x 'x 'x 'x 'x 'x 'x)])
  (test (with-heap
         h
         (init-allocator)
         (gc:cons
          (make-simple-root (gc:alloc-flat #f))
          (make-simple-root (gc:alloc-flat #t)))
         h)
        (vector 8 'flat #f 'flat #t 'cons 1 3 'x)))
; (Of course, this is not enough testing.)
```

We can also use random testing to generate mutators.

A `plai` library generates code that makes interesting heap structures (randomly), and then makes up a traversal of them.

The next three slides give three example random mutators and the calls into the library that generated them.

Random mutators

```
#lang racket
```

```
(require plai/random-mutator)
```

```
(save-random-mutator "tmp.rkt" "mygc.rkt" #:gc2? #t)
```

```
#lang plai/gc2/mutator
(allocator-setup "mygc.rkt" 200)
(define (build-one)
  (let* ((x0 'x)
        (x1 (cons #f #f))
        (x2 (cons x1 #f))
        (x3
         (lambda (x)
           (if (= x 0)
               x0
               (if (= x 1)
                   x2
                   (if (= x 2) x2 (if (= x 3) x2 (if (= x 4) x1 x2)))))))
        (x4
         (lambda (x)
           (if (= x 0)
               x1
               (if (= x 1)
                   x0
                   (if (= x 2)
                       x1
                       (if (= x 3)
                           x2
                           (if (= x 4)
                               x1
                               (if (= x 5)
                                   x2
                                   (if (= x 6)
                                       x3
                                       (if (= x 7) x0 (if (= x 8) x0 x3)))))))))))
        (x5 (lambda (x) (if (= x 0) x3 x0)))
        (x6 (lambda (x) x1)))
    (set-first! x1 x4)
    (set-rest! x1 x2)
    (set-rest! x2 x5)
    x4))
(define (traverse-one x4)
  (symbol=? 'x ((rest ((first ((first ((first (x4 4)) 0)) 0)) 3)) 1)))
(define (trigger-gc n)
  (if (zero? n) 0 (begin (cons n n) (trigger-gc (- n 1)))))
(define (loop i)
  (if (zero? i)
      'passed
      (let ((obj (build-one)))
        (trigger-gc 200)
        (if (traverse-one obj) (loop (- i 1)) 'failed))))
(loop 200)
```

Random mutators

```
#lang racket
(require plai/random-mutator)
(save-random-mutator "tmp.rkt" "mygc.rkt" #:gc2? #t)

#lang plai/gc2/mutator
(allocator-setup "mygc.rkt" 200)
(define (build-one) (let* ((x0 0)) x0))
(define (traverse-one x0) (= 0 x0))
(define (trigger-gc n)
  (if (zero? n) 0 (begin (cons n n) (trigger-gc (- n 1)))))
(define (loop i)
  (if (zero? i)
      'passed
      (let ((obj (build-one)))
        (trigger-gc 200)
        (if (traverse-one obj) (loop (- i 1)) 'failed))))
(loop 200)
```


Random mutators

```
#lang racket
```

```
(require plai/random-mutator)
```

```
(save-random-mutator "tmp.rkt" "mygc.rkt" #:gc2? #t)
```

```
#lang plai/gc2/mutator
(allocator-setup "mygc.rkt" 200)
(define (build-one)
  (let* ((x0 empty)
        (x1
         (lambda (x)
           (if (= x 0)
               x0
               (if (= x 1)
                   x0
                   (if (= x 2)
                       x0
                       (if (= x 3)
                           x0
                           (if (= x 4)
                               x0
                               (if (= x 5)
                                   x0
                                   (if (= x 6) x0 (if (= x 7) x0 x0))))))))))
        (x1))
    (define (traverse-one x1) (empty? (x1 0)))
    (define (trigger-gc n)
      (if (zero? n) 0 (begin (cons n n) (trigger-gc (- n 1)))))
    (define (loop i)
      (if (zero? i)
          'passed
          (let ((obj (build-one)))
            (trigger-gc 200)
            (if (traverse-one obj) (loop (- i 1)) 'failed))))
    (loop 200)
```