Linked data structures

CS 211

Winter 2020

Initial code setup

The code in this course is available online. To download a copy of this lecture into your Unix shell account:

```
% cd cs211
% curl $URL211/lec/07linked.tgz | tar zxvk
⋮
% cd 07linked
```

Preliminaries

Two views on `malloc` and `free`

The client/C view:

- `malloc(n)` gives you an *abstract reference* to a shiny, new, never-before-seen object of n bytes.
- `free(p)` destroys the object `*p`, never to be seen again.

Two views on `malloc` and `free`

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The implementation/machine view:

- `malloc(n)` searches a huuuge array of bytes for an unused section of size n, makes a note that the section is now used, and returns its address.
- `free(p)` marks the section that p refers to unused again.

asan is a memory debugger

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int main() { int i = 6; int x[i]; x[i] = 17; }
% cc -o oops oops.c -fsanitize=address
% ./oops
% valgrind ./oops
…
==============================================================
==98261==ERROR: AddressSanitizer: dynamic-stack-buffer-over
n address 0x7ffee68a9ff8 at pc 0x000109355eb4 bp 0x7ffee68a
p 0x7ffee68a9fa8
WRITE of size 4 at 0x7ffee68a9ff8 thread T0
    #0 0x109355eb3 in main (oops:x86_64+0x100000eb3)
    #1 0x7fff6d6d47fc in start (libdyld.dylib:x86_64+0x1a7f

Address 0x7ffee68a9ff8 is located in stack of thread T0
SUMMARY: AddressSanitizer: dynamic-stack-buffer-overflow (o
_64+0x100000eb3) in main
Shadow bytes around the buggy address:
  0x1fffdcd153a0: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
```

The main event

How can we deal with growing data?

- `malloc` returns a fixed-sized array

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- `malloc` returns a fixed-sized array
- So how does, say, `read_line` work?
- It reallocates and copies as needed

Simplification of `read_line`

```
char* read_line(void)
{
    size_t cap   = 0;
    size_t size  = 0;
    char* buffer = NULL;

    for (;;) {
        if (size + 1 > cap) {
            cap    = cap? (2 * cap) : CAPACITY0;
            buffer = realloc_or_die(buffer, cap);
        }

        int c = getchar();

        if (c == EOF || c == '\n') {
            buffer[size] = '\0';
            return buffer;
        } else buffer[size++] = (char) c;
    }
}
```

The real, slightly more efficient read_line

```
char* read_line(void)
{
    int c = getchar();
    if (c == EOF) return NULL;

    size_t cap   = CAPACITY0;
    size_t size  = 0;
    char* buffer = realloc_or_die(NULL, cap);

    for (;;) {
        if (c == EOF || c == '\n') {
            buffer[size] = '\0';
            return buffer;
        } else buffer[size++] = (char) c;

        c = getchar();

        if (size + 1 > cap) {
            cap   *= 2;
            buffer = realloc_or_die(buffer, cap);
        }
    }
}
```

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But it's not smooth, and it's not very flexible, so there's an alternative: Instead of one big allocation, lots of small allocations, pointing to each other.

Remember this?

```
; length : [List-of X] -> Nat
; Finds the length of a list.
(define (length lst)
  (if (empty? lst)
    0
    (+ 1 (length (rest lst)))))
```

Remember this?

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; length : [List-of X] -> Nat
; Finds the length of a list.
(define (length lst)
  (if (empty? lst)
    0
    (+ 1 (length (rest lst)))))

(length (cons 2 (cons 3 (cons 4 '()))))
```

Here’s how it works*

```
struct cons_pair
{
    int car;
    struct cons_pair* cdr;
};
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In `cons.h`:

```
typedef struct cons_pair* list_t;
```

In `cons.c`:

```
struct cons_pair
{
    int car;
    list_t cdr;
};
```

cons == malloc + initialization

```
#include <stdlib.h>

list_t cons(int first, list_t rest)
{
    list_t result = malloc(sizeof *result);
    if (result == NULL) … bail out …;

    result->car = first;
    result->cdr = rest;
    return result;
}
```

empty = NULL*

```
const list_t empty = NULL;
```

Using cons and empty

```c
#include "cons.h"

int main()
{
    list_t m = cons(2, cons(3, cons(4, empty)));
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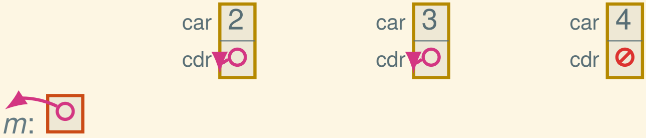
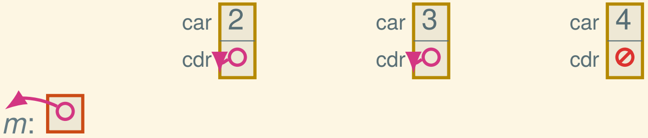


Using cons and empty

```
#include "cons.h"

int main()
{
    list_t m = cons(2, cons(3, cons(4, empty)));
    // Now what?
```



We need predicates and selectors

```
bool is_empty(list_t lst) { return lst == NULL; }

bool is_cons(list_t lst) { return lst != NULL; }

int first(list_t lst)
{
    assert( lst );
    return lst->car;
}

list_t rest(list_t lst)
{
    assert( lst );
    return lst->cdr;
}
```

A whole list program

```c
#include "cons.h"
#include <stdio.h>

int main()
{
    list_t m = cons(2, cons(3, cons(4, empty)));

    while (is_cons(m)) {
        printf("%d\n", first(m));
        m = rest(m);
    }
}
```

A whole list program, or is it?

```c
#include "cons.h"
#include <stdio.h>

int main()
{
    list_t m = cons(2, cons(3, cons(4, empty)));

    while (is_cons(m)) {
        printf("%d\n", first(m));
        m = rest(m);
    }
}
```

List fun, 111 style

```c
#include "cons.h"

size_t list_len(list_t lst)
{
    return is_empty(lst)
        ? 0
        : 1 + list_len(rest(lst));
}
```

List fun, 111 style

```c
#include "cons.h"

size_t list_len(list_t lst)
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    return is_empty(lst)
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}
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```scheme
(define (length lst)
  (if (empty? lst)
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    (+ 1 (length (rest lst)))))
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List fun, 211 style

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```
(define (length-acc acc lst)
  (if (empty? lst) acc
    (length-acc (+ 1 acc) (rest lst))))
(define (length lst) (length-acc 0 lst))
```

List fun, 211 style

```
(define (length-acc acc lst)
  (if (empty? lst) acc
    (length-acc (+ 1 acc) (rest lst))))
(define (length lst) (length-acc 0 lst))
```

```
size_t list_len(list_t lst)
{
    size_t result = 0;
    while (is_cons(lst)) {
        lst = rest(lst);
        ++result;
    }
    return result;
}
```

Freeing a list, recursively

Back to `cons.c`…

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```
void uncons_all(list_t lst)
{
    if (lst) {
        free(lst);
        uncons_all(lst->cdr);
    }
}

void uncons_all(list_t lst)
{
    if (lst) {
        uncons_all(lst->cdr);
        free(lst);
    }
}
```

Freeing a list, recursively

Back to `cons.c`…

```
void uncons_all(list_t lst)  //Fully broken
{
    if (lst) {
        free(lst);
        uncons_all(lst->cdr);
    }
}

void uncons_all(list_t lst)  //Semi-broken, but
{                            //go with it for now
    if (lst) {
        uncons_all(lst->cdr);
        free(lst);
    }
}
```

What's wrong with this program?

```
#include "cons.h"

int main()
{
    list_t m = cons(3, cons(4, empty));
    list_t n = rest(m);
    uncons_all(m);
    printf("%d\n", first(n));
    uncons_all(n);
}
```

What about this program?

```c
#include "cons.h"

int main()
{
    list_t m = cons(3, cons(4, empty));
    list_t n = cons(2, m);
    printf("%d\n", first(n));
    uncons_all(n);
    printf("%d\n", first(m));
    uncons_all(m);
}
```

What about this program?

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#include "cons.h"

int main()
{
    list_t m = cons(3, cons(4, empty));
    list_t n = cons(2, m);
    printf("%d\n", first(n));
    uncons_all(n);
    printf("%d\n", first(m));
    uncons_all(m);
}
```

Idea: Owners and borrowers.

Ownership protocol

- The owner of a heap-allocated object is responsible for deallocating it. (No one else may.)

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  The only way to tell which is which is to read the contract.
- Functions can also return either owned or borrowed pointers.

Ownership: Major points

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Ownership: Major points

- Every heap object has an owner.
- Owners *can and must* free the objects they own.
- Non-owners *must not* free the objects they don't own.
- Ownership is imaginary.

Ownership in `cons.h`

```
// Takes ownership of `rest`, returns owned list:
list_t cons(int first, list_t rest);
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// Takes ownership of `rest`, returns owned list:
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int first(list_t lst);
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bool is_empty(list_t lst), is_cons(list_t lst);
int first(list_t lst);

// Borrows `lst` and returns borrowed sub-part:
list_t rest(list_t lst);
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list_t rest(list_t lst);

// Takes ownership of `lst` (and all it points to):
void uncons_all(list_t lst);
```

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bool is_empty(list_t lst), is_cons(list_t lst);
int first(list_t lst);

// Borrows `lst` and returns borrowed sub-part:
list_t rest(list_t lst);

// Takes ownership of `lst` (and all it points to):
void uncons_all(list_t lst);

// Takes ownership of `lst`, and returns owned
// version of `rest(lst)`:
list_t uncons_one(list_t lst);
```

Implementations of unconsing

```
list_t uncons_one(list_t lst)
{
    free(lst);
    return lst->cdr;
}
```

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list_t uncons_one(list_t lst)
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    free(lst);
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}
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    free(lst);
    return lst->cdr;    //UB!
}

list_t uncons_one(list_t lst)
{
    list_t next = lst->cdr;
    free(lst);
    return next;
}
```

Implementations of unconsing

```
list_t uncons_one(list_t lst)
{
    free(lst);
    return lst->cdr;    //UB!
}

list_t uncons_one(list_t lst)
{
    list_t next = lst->cdr;
    free(lst);
    return next;
}

void uncons_all(list_t lst)
{
    while (lst) lst = uncons_one(lst);
}
```

The fixed program

```c
#include "cons.h"

int main()
{
    list_t m = cons(3, cons(4, empty));
    list_t n = uncons_one(m);
    printf("%d\n", first(n));
    uncons_all(n);
}
```

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```

– Next time: RAII –

Notes

* Lies