# Linked data structures

EECS 211

Winter 2019

# Initial code setup

```
$ cd eecs211
$ curl $URL211/lec/07linked.tgz | tar zx
…
$ 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`

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.

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.

# `valgrind(1)` is a memory debugger

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$
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$ valgrind ./oops
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# valgrind(1) is a memory debugger

```
$ cat oops.c
#include <stdlib.h>
int main() { malloc(211); }
$ cc -o oops oops.c
$ ./oops
$ valgrind ./oops
…
==25879== HEAP SUMMARY:
==25879==     in use at exit: 211 bytes in 1 blocks
==25879==   total heap usage: 1 allocs, 0 frees, 211 bytes
==25879==
==25879== LEAK SUMMARY:
==25879==    definitely lost: 211 bytes in 1 blocks
==25879==    indirectly lost: 0 bytes in 0 blocks
==25879==      possibly lost: 0 bytes in 0 blocks
==25879==    still reachable: 0 bytes in 0 blocks
==25879==         suppressed: 0 bytes in 0 blocks
==26289== Rerun with --leak-check=full to see details of le
…
```

## The main event

# How can we deal with growing data?

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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

```c
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);
        }
    }
}
```

# The alternative

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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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typedef struct cons_pair* list_t;


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};
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# Here's how it works*

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

```
#include "cons.h"

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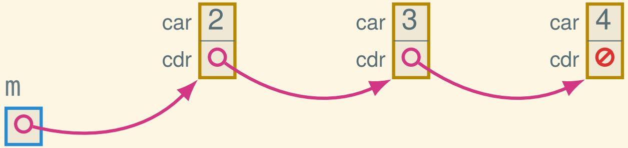
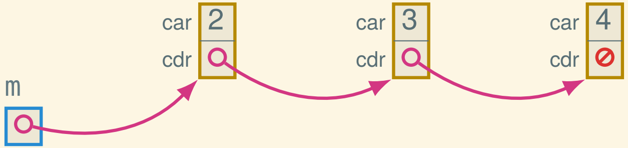


# Using cons and empty

```
#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?

```
#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

```
#include "cons.h"

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

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

# 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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Back to cons.c…

```
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?

```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);
}
```

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 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:
list_t cons(int first, list_t rest);

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

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bool is_empty(list_t lst), is_cons(list_t lst);
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// Borrows `lst` and returns borrowed sub-part:
list_t rest(list_t lst);
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// Takes ownership of `lst` (and all it points to):
void uncons_all(list_t lst);
```

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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);
    return lst->cdr;    //UB!
}
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```
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;
}
```

# 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

```
#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);
}
```

# 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);
}
```

– Next time: RAII –

# Notes

* Lies