The Adventures of Malloc and New
Lecture 3: Oh, Say Can You C

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MIT CSAIL

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Homework notes

Programs must:

• Compile and run (with instructions) to receive a ✓.
• Compile and run, passing tests, to receive a ✓+.

Lecture plan

The more I C, the less I see. –Unknown.

1. Review of main concepts from previous lectures.
2. Fancier memory examples.
3. Closer look at GCC.
4. Style and tips.
5. Why C?
Review: stack and heap

Figure by MIT OpenCourseWare.

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The Adventures of Malloc and New
Review: when to use pointers

- When you have to allocate memory on heap. (When is this?)
- When passing a parameter whose value you want to allow the other function to change.
- Also for efficiency—to avoid copying data structures.
Buggy field access

```c
int * i = NULL;
*i = 3;
```

Segmentation fault!

```c
struct pair {
    int first;
    int second;
};

struct pair* pp = NULL;
pp->first = 1;
```

Segmentation fault!
Buggy free

```
struct pair* pp = malloc(sizeof(struct pair));
pp = NULL;
free(pp);
```

Memory leak!

```
int* i = NULL;
free(i);
```

Nothing bad happens! Freeing NULL does nothing.
Buggy example

```c
int* get_array(int* len) {
    *len = 3;
    return vals;
}

int main() {
    int len, i;
    int* arr = get_array(&len);
    for (i = 0; i < len; +i) {
        printf("%d\n", arr[i]);
    }
    return 0;
}
```

Returns address of local (statically allocated) variable. (Should get warning!)

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Buggy scope continued...

Buggy output

1
32607
-1527611392

Correct program

```c
int* get_array(int* len) {
  *len = 3;
  int* vals = malloc(sizeof(int) * 3);
  arr[0] = 1; arr[1] = 2; arr[2] = 3;
  return arr;
}
```
Buggy initialization

```c
struct pair* pp;
int i = pp->first;
```

*Maybe a segmentation fault...*
In-place linked list reversal

```c
Element *reverse(Element *old_list) {
    Element *new_list = NULL;

    while (old_list != NULL) {
        // Remove element from old list.
        Element *element = old_list;
        old_list = old_list->next;

        // Insert element in new list.
        element->next = new_list;
        new_list = element;
    }

    return new_list;
}
```

Courtesy of Lawrence Kesteloot. Used with permission. Please see [http://www.teamten.com/lawrence/writings/reverse_a_linked_list.html](http://www.teamten.com/lawrence/writings/reverse_a_linked_list.html).
Constant time insert into a circular singly-linked list

- Circular linked list: last node has a pointer to the first node.
- Given a pointer to a node–can’t change that pointer!
- Want to insert a node before the current one–can we do that in constant time?

Figure by MIT OpenCourseWare.
A closer look at the GCC compilation process

Preprocessor
Translation of # directives.

- Translates all macros (#DEFINE's) into inline C code.
- Takes #include files and inserts them into the code.
  - Get redefinition error if structs etc. are defined more than once!
  - Use ifndef directive to define things only if they have not been defined.

```c
#define __HEADER_NAME 
/* Header code here. */
#endif
```
Aside: #define

Compiler directive.

```c
#define DEFINED_CONSTANT 3

#define increment(x) (x+1)
```
Parsing and translation
Translates to assembly, performing optimizations.

Assembler
Translates assembly to machine instructions.

Linking

- **Static.** For each function called by the program, the assembly to that function is included directly in the executable, allowing function calls to directly address code.

- **Dynamic.** Function calls call a Procedure Linkage Table, which contains the proper addresses of the mapped memory.
## Some helpful compiler options

<table>
<thead>
<tr>
<th>Enforcements and warnings</th>
</tr>
</thead>
<tbody>
<tr>
<td>-ansi</td>
</tr>
<tr>
<td>-pedantic</td>
</tr>
<tr>
<td>-Wall</td>
</tr>
<tr>
<td>-W</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Compilation/output</th>
</tr>
</thead>
<tbody>
<tr>
<td>-c</td>
</tr>
<tr>
<td>-S</td>
</tr>
<tr>
<td>-E</td>
</tr>
<tr>
<td>-o [file]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Profiling</th>
</tr>
</thead>
<tbody>
<tr>
<td>-pg</td>
</tr>
</tbody>
</table>
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gcc pi.c -E

```c
long F=00,OO=00;
main() {F_OO(); printf("%1.3f\n", 4.*F/OO/OO);} F_OO()
{
    F-->00 || F--OO--;F-->00 || F--OO--;F-->00
    || F--OO--;F-->00 || F--OO--;
    F-->00 || F--OO--;F-->00 || F--OO--;F-->00 || F--
    OO--;F-->00 || F--OO--;F-->00 || F--OO--;F
    -->00 || F--OO--;F-->00 || F--OO--;F-->00 ||
    F--OO--;F-->00 || F--OO--;F-->00 || F--OO
    --;F-->00 || F--OO--;F-->00 || F--OO--;F-->00
    || F--OO--;F-->00 || F--OO--;F-->00 || F--OO--;
    F-->00 || F--OO--;F-->00 || F--OO--;F-->00 ||
    F--OO--;F-->00 || F--OO--;F-->00 || F--OO
    --;F-->00 || F--OO--;F-->00 || F--OO--;F-->00 ||
    F--OO--;F-->00 || F--OO--;F-->00 || F--OO--;
    F--->00 || F--OO--;F-->00 || F--OO--;F-->00 ||
    F--OO--;F-->00 || F--OO--;F-->00 || F--OO
    --;F-->00 || F--OO--;F-->00 || F--OO--;F-->00 ||
    F--OO--;F-->00 || F--OO--;F-->00 || F--OO--;
}
```

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Build systems: a quick flavor of `make`

- Way to manage compilation for large systems.
- Automatically determines which parts of large programs need to be recompiled.
- Simple makefile consists of rules of the following form:
  ```
  target ... : prerequisites ...
  command
  ...
  ...
  ```
- Build system by running `make` from command line.
A simple C makefile

**Makefile**
This uses the implicit rules GNU Make defines for compiling C.

CC=gcc
CFLAGS=-Wall
main: main.o hello_fn.o
clean:
    rm -f main main.o hello_fn.o

**Compiling with make**

```
$ make
gcc -Wall  -c  -o main.o  main.c
gcc -Wall  -c  -o hello_fn.o  hello_fn.c
gcc   main.o hello_fn.o   -o main
$ ./main
"Hello world!"
```
**Profiling: gprof**

1. Compile with the profiling option.
   
   ```
   gcc single_linked_list.c test_sll.c -o sll -pg
   ```

2. Run the program—this will produce a file gmon.out (unless otherwise specified) containing profiling information.
   
   ```
   ./sll
   ```

3. Run gprof on the binary to get the profiling information. (Can suppress/select specific functions.)
   
   ```
   gprof sll > profile_output.txt
   ```
Sample profiling output

Flat profile

<table>
<thead>
<tr>
<th>% cumulative</th>
<th>time</th>
<th>seconds</th>
<th>self</th>
<th>seconds</th>
<th>calls</th>
<th>self</th>
<th>total</th>
<th>name</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>6</td>
<td>0.00</td>
<td>0.00</td>
<td>print_sll</td>
</tr>
<tr>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>5</td>
<td>0.00</td>
<td>0.00</td>
<td>make_node</td>
</tr>
<tr>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>4</td>
<td>0.00</td>
<td>0.00</td>
<td>insert_val</td>
</tr>
<tr>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>delete_val</td>
</tr>
</tbody>
</table>

Call tree
Also shows more detailed call tree information, sorted by total amount of time spent in each function and its children.
War stories

Figure: With great power comes great responsibility.

Courtesy of xkcd.com. Comic is available here: http://xkcd.com/229/

- Linker woes—why you want namespaces.
- You can link anything!
Write principled code in C

I will not be a lemming and follow the crowd over the cliff and into the C. –John (Jack) Beidler
Array indexing

Recall that an array of size $n$ with objects of type $t$ is just a block of memory of size $\text{sizeof}(t) \times n$.

<table>
<thead>
<tr>
<th>Element</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pointer</strong> (arr*)</td>
<td>*arr</td>
<td>*(arr+1)</td>
<td>*(arr+2)</td>
<td>*(arr + $n + 1$)</td>
</tr>
</tbody>
</table>
Style guidelines

- Test for equality with the constant on the left-hand side.
  ```c
  if (3 == x) /* rather than (x == 3) { 
  ...
  }
  ```

- Initialize pointers to NULL.
  ```c
  int* p = NULL;
  int* q;  /* Initialized, q will point to junk. */
  ```

- Use pre-increment unless post-increment is necessary.
  ```c
  ++i;   /* Pre-increment. */
  i++;   /* Post-increment. */
  ```
Where is the overhead?

In memory-managed languages

- **Garbage collection**—figuring out what can be garbage collected and reclaiming that memory.
- Overhead from GC’s *conservative* approximations of what is still in use.
- Reducing object allocation mitigates this problem.

In C

- Each **allocation** takes time because the allocator has to search for a piece of sufficiently large memory each time.
- Reducing the number of allocations mitigates this problem.
C is not just for thrill-seekers

Speed

- Slowdowns from compiling from higher-level languages.
- Personal anecdote: randomized simulations (C vs. Python).

Memory

- Memory overhead (20%+) necessary for garbage collection.
- Personal anecdote: 400x speedup from reducing object creation in OCaml program.

Access to dangerous, low-level parts of system

- Accessing hardware devices as memory.
- Mucking with the registers (stack pointer).
Until tomorrow... 

Homework (due Saturday)

- Rewrite the binary search tree assignment using an array.
- Please submit a .zip or .tar.gz file prefaced by [username].hw[number].
- More details on the course website.

Questions?

- The course staff will be available after class.