Memory Allocation in C

C Programming and Software Tools

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The Easy Way

- Java (JVM) automatically allocates and reclaims memory for you, e.g...

Removed object is implicitly reclaimed (garbage collected) when there are no longer any references to it

```
public class LinkedList {
    ...
    public void addFirst (Object obj) {
        Node newNode = new Node();
        newNode.data = ...;
        newNode.next = first;
        first = newNode;
    }
    public Object removeFirst() {
        if (first == null)
            throw new emptyException();
        Object obj = first.data;
        first = first.next;
        return obj;
    }
...
}
```

The Harder Way

C requires you to manually allocate and reclaim memory, e.g...

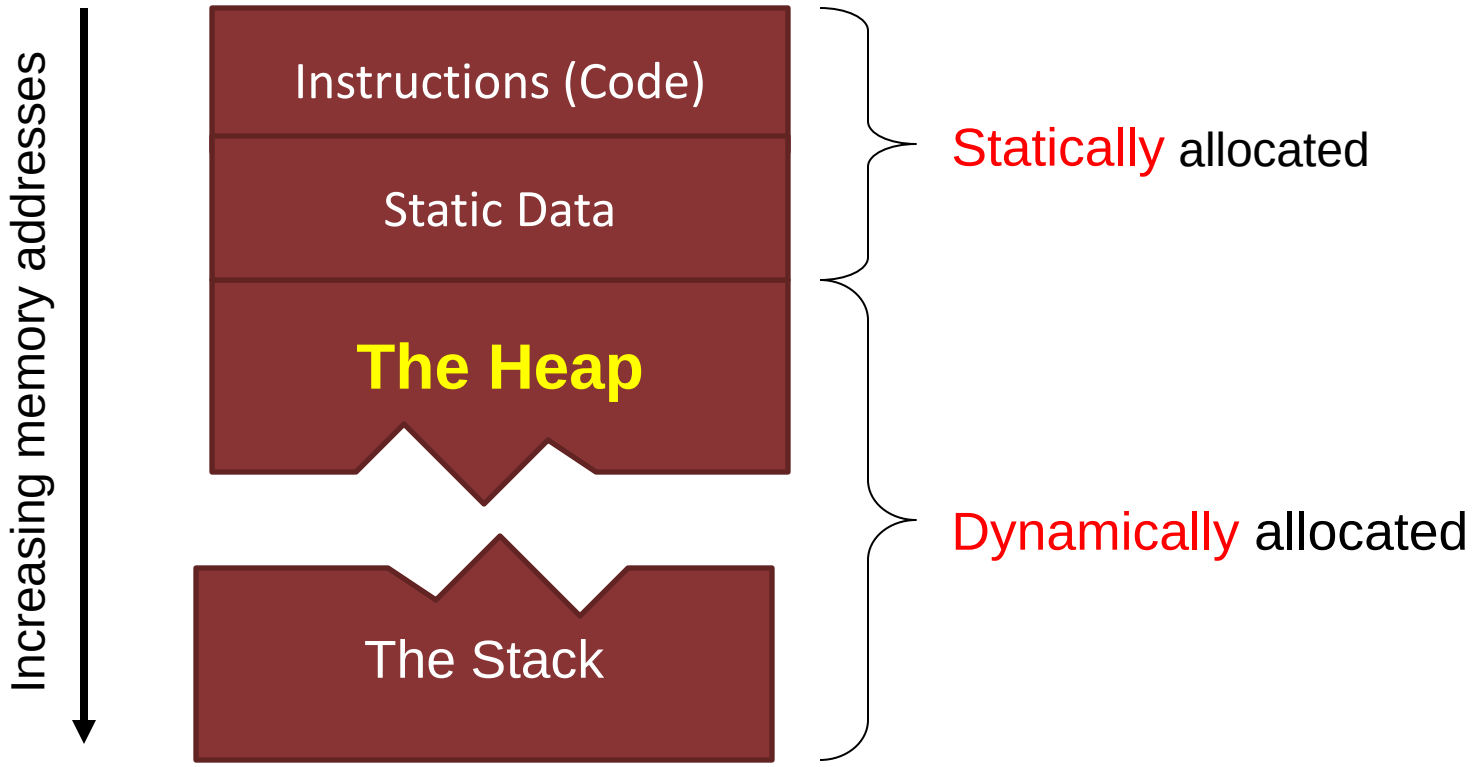
```
void addFirst (Object obj) {
    Node * newNode =
         (Node *) malloc (sizeof(Node));
    assert( newNode != NULL );
    newNode->data = ...;
    newNode->next = first;
    first = newNode;
}

Object removeFirst() {
    assert (first != NULL);
    Node * old = first;
    Object obj = first->data;
    first = first->next;
    free (old);
    return obj;
}
```

Programmer explicitly indicates there are no more references to the removed object

Memory Layout of a Program

- The heap is an area of *virtual memory* available for dynamic (runtime) memory allocation



Why Dynamic Memory Allocation?

- Don't know how much data will need to be stored until runtime; choices?

Choice 1: Declare static array of maximum size that could possibly occur

```
#define MAXCLASSSIZE 500
struct student { …definition here… };
struct student students[MAXCLASSSIZE];

int i = 0;
while (more_students  && (i < MAXCLASSSIZE))
   readstudents (students[i++]);
```

Why Dynamic … (cont'd)

Choice 2: Declare dynamic (auto) array of specific size needed, at run time

```
int main (void) {
   int maxnum;
   printf("Number of students in class? \n");
   scanf("%d", &maxnum);
   struct student students[maxnum];

   int i = 0;
   while (more_students  && (i < maxnum))
      readstudents (students[i++]);
}
```

Why Dynamic… (cont'd)

Choice 3: Allocate memory dynamically using a standard library function (**malloc** or **calloc**)

```
#include <stdio.h>
#include <stdlib.h>
…
int main(void) {
    struct student *sp;
    while (more_students) {
        sp = (struct student *)
            calloc (num, sizeof(struct student));
        if (sp != NULL)
            readstudents (sp);
    }
}
```

The `sizeof` Operator

- Not a function call; a C operator
  - returns number of bytes required by a data type
- Return value is of predefined type `size_t`

```
#include <stdlib.h>
size_t tsz1, tsz2, tsz3;
int a;
float b[100];
struct student { …definition here… } st;

tsz1 = sizeof (a);   /* 4 */
tsz2 = sizeof (b);   /* ? */
tsz3 = sizeof (st); /* ? */
```

what are these sizes?

The `calloc()` Standard Library Function

Syntax:

```
void * calloc (size_t num, size_t sz)
```

Generic pointer, must be cast to type of result
(Sometimes optional on modern compilers)

OS allocates (**`num * sz`**) bytes of contiguous storage (all bytes initialized to zeros)

```
struct student * students;
students = (struct student *)
     calloc (num, sizeof(struct student));
int * ip;
ip = (int *) calloc (1, sizeof (int));
char *cp;
cp = (char *) calloc (1000, sizeof (char));
```

`calloc()` (cont'd)

- Return value is starting address of the storage allocated
- If not enough memory available, returns **`NULL`**
  - Could also be a unique pointer that could be passed to free()
  - always check for this error

☠ *common source of bugs* ☠
failure to check return value

```
cp = (char *) calloc (1000, sizeof (char));
if (cp == NULL) {
   printf("Cannot allocate memory; exiting\n");
   exit (-1);
}
```

The `malloc()` Std. Lib. Function

- Syntax: `void * malloc (size_t sz)`
- OS allocates `sz` bytes of contiguous storage
  - (uninitialized)
- Returns starting address of storage
  - If size is 0, returns NULL or unique pointer that can be freed

☠ *common source of bugs* ☠
malloc() does not initialize memory

```
students = (struct student *)
      malloc ( num * sizeof(struct student));
ip = (int *) malloc (sizeof (int));
cp = (char *) malloc ( 1000 * sizeof (char));
```

The `realloc()` Std. Lib. Function

- Syntax: `void * realloc(void * ptr, size_t sz)`
- Grows or shrinks allocated memory
  - `ptr` must be dynamically allocated
  - Growing memory doesn't initialize new bytes
  - If can't expand, returns `NULL`
    - Old memory is unchanged
  - If `ptr` is `NULL`, behaves like malloc
  - If `sz` is `NULL`, behaves like free
  - Memory shrinks in place
  - Memory may NOT grow in place
    - If not enough space, will move to new location and copy contents
    - Old memory is freed
    - Update all pointers!!!

The `free()` Standard Library Function

- Syntax: `void free (void * ptr)`
  - no way to check for errors!
  - `ptr` must have been previously allocated by `malloc()` or `calloc()`
  - no need to specify amount of memory to be freed; why not?
- Frees (for other uses) memory previously allocated

```
free(students);
free (ip);
free (cp);
```

☠ *common source of bugs* ☠
failure to free unused memory

Why bother freeing up memory?

Dynamic memory function summary

- **`void *malloc(size_t size);`**
  - Give me **`size`** bytes, don't initialize them
- **`void *calloc(size_t nmemb, size_t size);`**
  - Give me **`nmemb*size`** bytes, initialize them to 0
- **`void *realloc(void *ptr, size_t size);`**
  - Take this pointer and make the space it refers to bigger/smaller (moving it if necessary).
- **`void free(void *ptr);`**
  - I'm done using the memory here, you can have it back.

Dynamic Memory Allocation Mistakes

- These bugs can really be hard to find and fix
  - may run for hours before the bug pops up, and in a place that appears to have no relationship to the actual cause of the error

☠ common source of bugs ☠

Mistake M1: Invalid Pointers

- Problems?

```
int i, j, result;
result = scanf ("%d %d", i, &j);
```

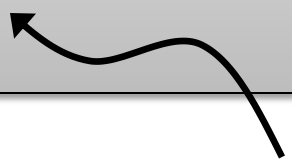
```
char *ptr;
…
ptr = 'A';
…
*ptr = 'B';
```

☠ common source of bugs ☠

Invalid Pointers (cont'd)

- Problems?

```
int * f( void )
{
    int val;
    …
    return &val;
}
```



why is this a problem?

☠ common source of bugs ☠

Invalid Pointers (cont'd)

- Problems? Fix?

```
…dynamically allocate and construct a linked list…
…
/* now list is no longer needed,
 * free memory
 */
for (p = head; p != NULL; p = p->next)
    free(p);
```

why is this a problem?

☠ common source of bugs ☠

M2: Not Initializing Memory

- Problems?

```
int * sumptr;
int ival[100] = { …initial values here… };
int i;

sumptr = (int *) malloc ( sizeof(int) );

for (i = 0; i < 100; i++)
   *sumptr += ival[i];
```

☠ common source of bugs ☠

M3: Stack Buffer Overflows

```
void bufoverflow (void)
{
    char buf[64];

    gets(buf);
    return;
}
```

- Problems?
- One of the biggest sources of security problems

M4: Writing Past End of Dyn. Allocated Memory

☠ common source of bugs ☠

```
int i, sz;
int *ip, *jp;

scanf ("%d", &sz);
ip = (int *) calloc (sz, sizeof(int));
…check for errors here…

jp = ip;
for (i = 0; i <= sz; i++)
   scanf ("%d", jp++);
```

why is this a problem?

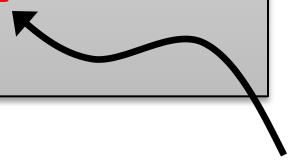
☠ common source of bugs ☠

M5: Freeing Unallocated Memory

Problems?

```
int i;
int *ip;

ip = &i;
…
free(ip);
```



why is this a problem?

☠ common source of bugs ☠

Freeing Unallocated …(cont'd)

- Problems?

```
int *ip;

ip = (int *) calloc (1000, sizeof(int));
…
free(ip);
…
free(ip);
```

☠ common source of bugs ☠

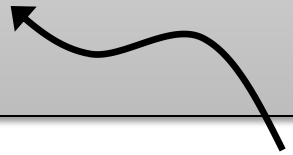
M6: Memory Leaks

- Allocated memory is referenced using pointer returned by allocation
- If you lose pointers (free them, change to another address), you can no longer reference or free allocated memory
- Common problem in large, long-running programs (think: servers)
  - over time, memory footprint of program gets bigger, bigger, …

☠ common source of bugs ☠

M6: Memory Leaks

```
void leak (int n)
{
    int * xp;
    xp = (int *) malloc (n * sizeof(int));
    …memory is used and then no longer needed…
    return;
}
```



why is this a problem?

M6: Memory Leaks

- Valgrind – software tool for detecting memory leaks on actual program executions
  - Compile with –g option
  - Arguments: --leak-check=yes

```
% gcc –Wall –std=c99 –g program.c –o program
% valgrind –leak-check=yes ./program
```

```
==15703== Memcheck, a memory error detector
==15703== Copyright (C) 2002-2012, and GNU GPL'd, by Julian Seward et al.
==15703== Using Valgrind-3.8.1 and LibVEX; rerun with -h for copyright info
==15703== Command: ./memory
==15703==
==15703== Invalid write of size 1
==15703==    at 0x40055E: f (memory.c:9)
==15703==    by 0x40058E: main (memory.c:15)
==15703==  Address 0x4c41043 is 0 bytes after a block of size 3 alloc'd
==15703==    at 0x4A0577B: calloc (vg_replace_malloc.c:593)
==15703==    by 0x400523: f (memory.c:6)
==15703==    by 0x40058E: main (memory.c:15)
==15703==
==15703== Invalid read of size 1
==15703==    at 0x3AF5C480AC: vfprintf (in /lib64/libc-2.12.so)
==15703==    by 0x3AF5C4F409: printf (in /lib64/libc-2.12.so)
==15703==    by 0x400579: f (memory.c:10)
==15703==    by 0x40058E: main (memory.c:15)
==15703==  Address 0x4c41043 is 0 bytes after a block of size 3 alloc'd
==15703==    at 0x4A0577B: calloc (vg_replace_malloc.c:593)
==15703==    by 0x400523: f (memory.c:6)
==15703==    by 0x40058E: main (memory.c:15)
==15703==
String = abc
==15703==
==15703== HEAP SUMMARY:
==15703==     in use at exit: 3 bytes in 1 blocks
==15703==   total heap usage: 1 allocs, 0 frees, 3 bytes allocated
==15703==
==15703== 3 bytes in 1 blocks are definitely lost in loss record 1 of 1
==15703==    at 0x4A0577B: calloc (vg_replace_malloc.c:593)
==15703==    by 0x400523: f (memory.c:6)
==15703==    by 0x40058E: main (memory.c:15)
==15703==
==15703== LEAK SUMMARY:
==15703==    definitely lost: 3 bytes in 1 blocks
==15703==    indirectly lost: 0 bytes in 0 blocks
==15703==      possibly lost: 0 bytes in 0 blocks
==15703==    still reachable: 0 bytes in 0 blocks
==15703==         suppressed: 0 bytes in 0 blocks
==15703==
==15703== For counts of detected and suppressed errors, rerun with: -v
==15703== ERROR SUMMARY: 3 errors from 3 contexts (suppressed: 6 from 6)
```

Garbage Collection

- Some language run-time systems free up unused memory automatically for the programmer
  - accomplished through "reachability analysis”

Java

```
Student st = new Student("John Smith");
…
st = null; // space for student st is
           // automatically reclaimed
```

Exercise 18a:

Crash ideone

- Write a program that allocates memory infinitely, 1kB at a time.
- Print a counter for each allocation.
- See how much you can allocate before ideone kills it.
- Don’t run it on a shared NCSU system!

Reminder: Go to course web page for link to exercise form.
Paste code into ideone.com and submit the link.