Memory Management in C

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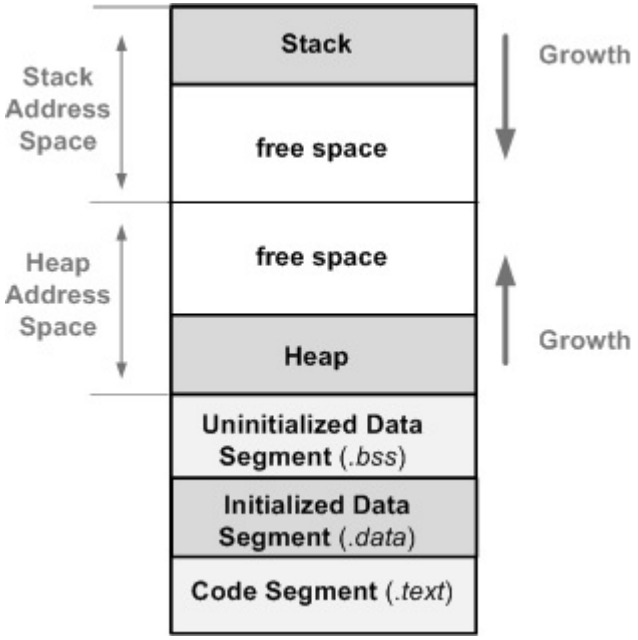
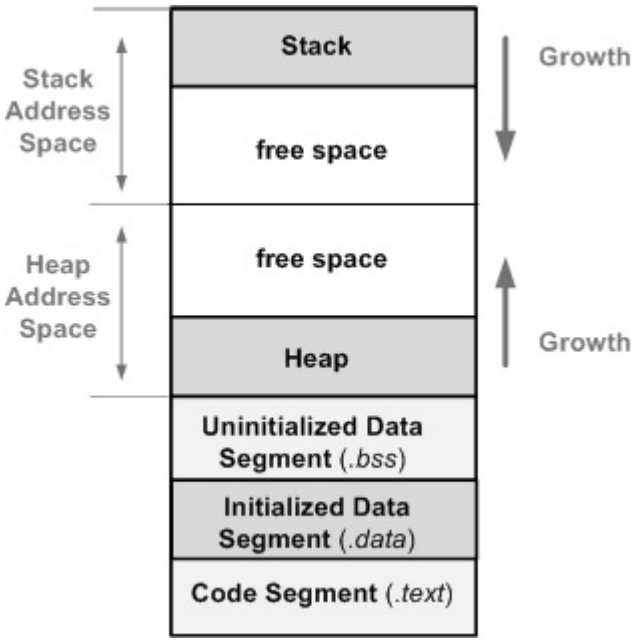
Recall: Memory Layout

- Stack growing downward
  - Function arguments
  - Return addresses
  - Local variables
- Heap growing upward
  - For dynamic demands
- .bss for global/static initially being zero
- .data for global/static with initial values
- .text for machine code



Why Bother?

- Different lifespans of variable
  - global/static: entire execution period
  - local/args/RA: within the function
  - dynamic: undeterminable
- Smaller program size
  - Many global/static start as zero, wasteful if stored explicitly
- Portable to non-von Neumann
  - e.g., separate devices for code, var, const



An Example: .bss vs .data

```
yitro@RM-server ~/tmp/disc3 07:58
[526] $ cat layout.c
int a = 1, b = 0, c;
int main() {
    int d;
    static int e = 1, f = 0, g;
    return 0;
}
yitro@RM-server ~/tmp/disc3 07:58
[527] $ objdump --syms a.out | grep '\.bss\|\.data'
0000000000004024 l     O .bss   0000000000000004              g.2
0000000000004028 l     O .bss   0000000000000004              f.1
0000000000004014 l     O .data  0000000000000004              e.0
0000000000004000  w      .data  0000000000000000              data_start
000000000000401c g     O .bss   0000000000000004              b
0000000000004018 g       .data  0000000000000000              _edata
0000000000004000 g       .data  0000000000000000              __data_start
0000000000004008 g     O .data  0000000000000000              .hidden __dso_handle
0000000000004030 g       .bss   0000000000000000              _end
0000000000004020 g     O .bss   0000000000000004              c
0000000000004010 g     O .data  0000000000000004              a
0000000000004018 g       .bss   0000000000000000              __bss_start
0000000000004018 g     O .data  0000000000000000              .hidden __TMC_END__
```

Out-of-range!

- Bad in global/static
  - Secretly corrupt nearby variables
- Worse in heap
  - Secretly corrupt who-knows-where vars
  - May corrupt heap management
    - If allocation records are kept in heap
- Worst in stack!
  - Secretly corrupt nearby variables, arguments, callers' arguments, and even return addresses

```
yitro@RM-server ~/tmp/disc3 08:54
[558] $ cat global-overrun.c
#include <stdio.h>
int a[1] = {5}, b = 6;
int main() {
  a[1] = 0;
  printf("%d\n", b);
  return 0;
}
yitro@RM-server ~/tmp/disc3 08:54
[559] $ gcc global-overrun.c && ./a.out
0
```

```
yitro@RM-server ~/tmp/disc3 08:49
[553] $ cat stack-overrun.c
#include <stdio.h>
#include <stdlib.h>
void g() { puts("Surprise!"); exit(1); }
void f() { void(*a[1])(); a[3] = g; }
int main() { f(); return 0; }
yitro@RM-server ~/tmp/disc3 08:49
[554] $ gcc stack-overrun.c && ./a.out
Surprise!
```

Side Note: Undefined Behaviors

- “Out-of-range array subscripting is an undefined behavior.”
- What is UB?

- Myth: Programs with UB always die ugly.
- Consequence of undefined behaviors is undefined
  - Might just work as if there are no UB.
  - Might start/stop working because of one added/removed printf()
  - Might work on Windows, fail on Linux and fail differently on Mac OS
    - Windows is much more tolerant to memory-related UB than Linux

Management: .bss and .data

- Allocated and associated at compile-time
- Die with the process
- Not freed/reclaimed at all

Management: Stack

- Managed implicitly by compiler
  - Allocated on demand and reclaimed on leaving scope
  - Allocations are calculated at compile-time
- Generally, in a consistent manner, except:
  - Variadic functions, e.g., scanf() and printf()
    - Indefinite number of arguments
    - Callers explicitly provide hints, e.g. format strings
    - Goes wrong on incorrect hints
  - Variable Length Array (VLA) “int a[n];”
    - Hard to use safely! Starting from C11, only optionally supported.

Related Issues: Stack

- Local variables are uninitialized by default
  - Their values depend on the trashes left in stack
    - May from other processes or even OS
    - Some OS intentionally fills stack with special values to aid debugging
  - Mitigation: Always initialize at definition
- Local variables are reclaimed on leaving scope
  - Using them outside (e.g., returned as pointer) is UB
  - Mitigation: Don’t do it. Enforce with warning options.

Management: Heap

- Managed explicitly by programmer
  - Allocate using malloc(), calloc()
  - Reclaim using free()
  - Reallocate using realloc() to change size
- calloc() fills the allocated space with zero
  and catches multiplication overflow in C11

Related Issues: Heap

- Use after freed
  - Access the piece of memory already freed
  - If allocated to others, data will be corrupted
    - Random crimes are hard to investigate
  - Mitigation: Set a freed pointer to NULL
- Double free
  - Free an already freed allocation
  - Mitigation: Set a freed pointer to NULL
    - Fact: Freeing NULL is well defined as doing nothing.
  - Or just let it die?

Related Issues: Heap

- Memory leak
  - Inaccessible allocated pieces not freed
    - Mainly due to address lost
      - Carelessly overwritten in an assignment
      - The variable holding the address reached end-of-life
  - Mitigation:
    - Think twice when assigning to a pointer
    - Do cleanup at every exits of the scope
    - Reclaim the associated resources before freeing a heap variable

Side Note: Warning Options

- Controlling for what the compiler should warn you
- E.g., -Wall -Wpedantic –Werror -Wno-unused-result

Side Note: Warning Options

- Pros
  - Second chances to notice things stupid.
  - Timely remainders of things you might not fully know
  - Sincere hints for improvement in coding style
- Cons
  - Too wordy and anxious when overly enabled
    - Complaining even common daily practices
      - Comparing int and size_t
      - Unused function results, including printf()’s

Valgrind --tool=memcheck

Detecting

- Illegal memory access
  - Overrunning, underrunning, use-after-freed
- Use of uninitialized values
- Double free of heap blocks
- Fishy size parameter to allocation function
- Memory leaks
- …

Illegal Access

```
int *f(void) { int a; return &a; }
int main() { *f() = 1; return 0; }

==78779== Invalid write of size 4
==78779==    at 0x10918C: main (in /home/yitro/tmp/disc3/valgrind/a.out)
==78779==  Address 0x0 is not stack'd, malloc'd or (recently) free'd
```

Use of Uninitialized

```
int y = 0;
int main() {
  int x;
  if (x == 42) y += 8;
  return y; }

==11956== Conditional jump or move depends on uninitialised value(s)
==11956==    at 0x109135: main (in /home/yitro/tmp/disc3/valgrind/a.out)
```

Illegal Free

```
#include <stdlib.h>
int main() { void *buf = malloc(0); free(buf), free(buf); }

==16354== Invalid free() / delete / delete[] / realloc()
==16354==    at 0x484495F: free (vg_replace_malloc.c:989)
==16354==    by 0x10919A: main (in /home/yitro/tmp/disc3/valgrind/a.out)
==16354==  Address 0x4a31040 is 0 bytes after a block of size 0 free'd
==16354==    at 0x484495F: free (vg_replace_malloc.c:989)
==16354==    by 0x10918E: main (in /home/yitro/tmp/disc3/valgrind/a.out)
==16354==  Block was alloc'd at
==16354==    at 0x4841878: malloc (vg_replace_malloc.c:446)
==16354==    by 0x10917E: main (in /home/yitro/tmp/disc3/valgrind/a.out)
```

Fishy Size

```
#include <stdlib.h>
void main() { malloc(-1); }


==28552== Argument 'size' of function malloc has a fishy (possibly
negative) value: -1
==28552==    at 0x4841878: malloc (vg_replace_malloc.c:446)
==28552==    by 0x10915C: main (in /home/yitro/tmp/disc3/valgrind/a.out)
```

Memory Leaks --leak-check

```
#include <stdlib.h>
void f(void) {
  char  *c = malloc(10);
  char **b = malloc(9);
  *b = c;
}

char *g(void) {
  char  *d = malloc(11);
  return d + 1;
}
```

```
char **a;

int main() {
  f();
  a = malloc(8);
  *a = g();
  return 0;
}
```

Memory Leaks --leak-check

```
==34098== LEAK SUMMARY:
==34098==    definitely lost: 9 bytes in 1 blocks
==34098==    indirectly lost: 10 bytes in 1 blocks
==34098==      possibly lost: 11 bytes in 1 blocks
==34098==    still reachable: 8 bytes in 1 blocks
==34098==         suppressed: 0 bytes in 0 blocks
```

Memory Leaks --leak-check=full

```
==34098== 11 bytes in 1 blocks are possibly lost in loss record 3 of 4
==34098==    at 0x4841878: malloc (vg_replace_malloc.c:446)
==34098==    by 0x109194: g (in /home/yitro/tmp/disc3/valgrind/a.out)
==34098==    by 0x1091D1: main (in /home/yitro/tmp/disc3/valgrind/a.out)
==34098==
==34098== 19 (9 direct, 10 indirect) bytes in 1 blocks are definitely
lost in loss record 4 of 4
==34098==    at 0x4841878: malloc (vg_replace_malloc.c:446)
==34098==    by 0x10916C: f (in /home/yitro/tmp/disc3/valgrind/a.out)
==34098==    by 0x1091B4: main (in /home/yitro/tmp/disc3/valgrind/a.out)
```