Understanding Memory Management

Dipesh Kafle

Prerequisites

Memory Layout

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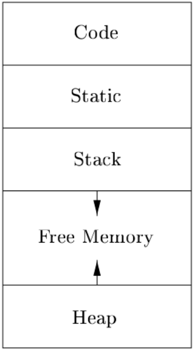

Figure 1: A rough classification of program's memory segments

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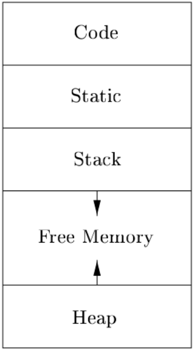

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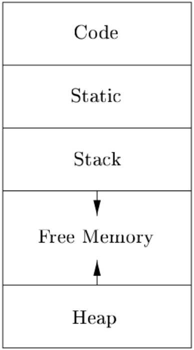

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- What are all these things ??

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```
const char* s = "Lorem Ipsum something something";
int main(){
  const char* string_arr[] = {"Made", "with", "love",
    "by", "Delta", "Force"};
  return 0;
}
```

All the strings used in the above code segment are stored in static section, while the instructions generated for the program will be in code section.

Stack and Stack Allocation

- The stack will store things such as local variables, return address from a function call, etc.

Stack and Stack Allocation(continued)

```c
int main(){
// All of this is
// doing stack
   allocation
  int a = 10;
  int b = 20;
  int arr[2] = {1,2};
  return 0;
}
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Stack and Stack Allocation(continued)

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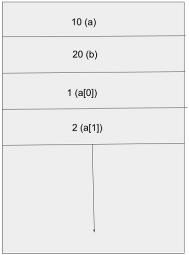

Figure 2: Stack Layout for above code

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```c
int* f(int n){
  return malloc(n*sizeof(int));
}
int main(){
    int n ;
    scanf("%d", &n);
    int *arr = f(n); // arr is heap allocated,returned from call to f
    free(arr); //Since, we're good programmers, we'll free the memory as
      ↪  well.
}
```

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- `free(p)` : return heap memory to the operating system

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- If it's done incorrectly, the program can crash or slow down.
- There are different techniques for managing heap memory.

What is this scope thing??

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```
// NOTE: This function won't compile
int f(){ // scope '1 starts
    int a = 10;
    { // scope '2 starts
       int b = 20;
       { // scope '3 stars
           int c = 50;
       } // scope '3 ends
    } // scope '2 ends

    if(a == 10){ // scope '4 starts
      int c = 30;
    } // scope '4 ends
    else { // scope '5 starts
       int c = 90;
    } // scope '5 ends
    return b; // This fails because it's not in scope
} // scope '1 ends
```

What is this scope thing?? (continued)

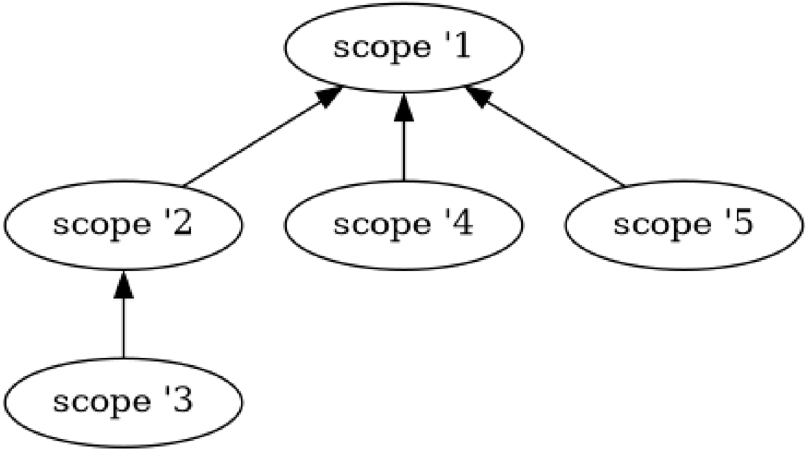

Figure 3: Pictorial representation of scope heirarchy

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Important terminology

- **Memory Leak**: It happens when you ask the operating system for memory but don't return it back.

Ways to manage memory

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- Automatic Memory Management: Languages such as Python, Java, Go, JavaScript, Swift, etc have this.

Manual Memory Management

Scenarios where you can go wrong

```
// NOTE: this is a dumb example to show where things can go wrong,
// I don't actually write code like this
int* allocate_and_throw_exn(int n){
   int *arr = malloc(n*sizeof(int));
   if (n < 10){
       throw runtime_error("n < 10");
   }
   return arr;
}
int main(){
    try {
        auto *arr = allocate_and_throw_exn(2);
        free(arr);
    } catch(const std::runtime_error &e){
        cout << "Error:" <<e.what() << endl;
    }
}
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Scenarios where you can go wrong

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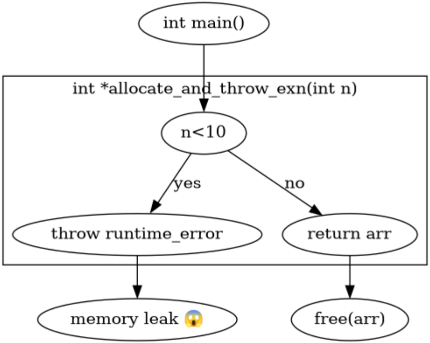

Figure 4: Flow for the leaking code

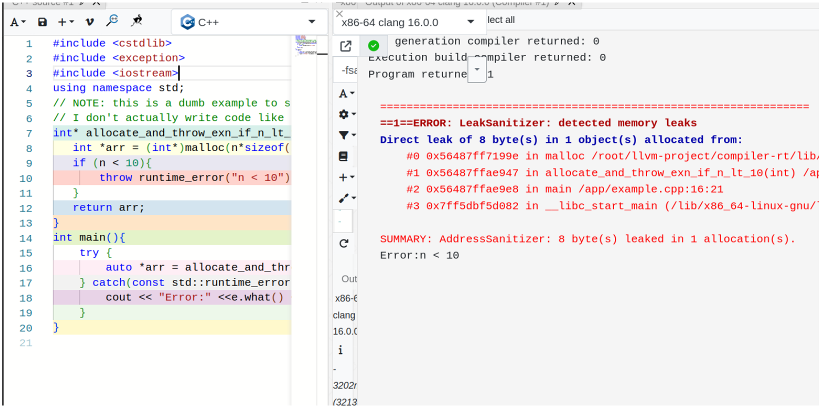

Figure 5: Memory Leak Detected by address sanitizer

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- DON'T WRITE DUMB CODE LIKE I DID
- More high level language(than C) like C++, Rust provide us with smart ways to manage memory
- They come built-in with smart pointer types like `unique_ptr` (C++)

Fixing the code with smart pointer

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     }
}
```

```
# FIXED CODE
std::unique_ptr<int[]> allocate_and_throw_exn(int n){
    auto arr = std::unique_ptr<int[]>(new int[n]);
    if (n < 10){
        throw runtime_error("n < 10");
    }
    return arr;
}
int main(){
     try {
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```

What the hell just happened??

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- C++ uses `destructors` to run code when an object goes out of scope. (due to RAII in C++)

What is RAII in C++?

RAII can be summarized as follows:

- encapsulate each resource into a class, where
  - the constructor acquires the resource and establishes all class invariants or throws an exception if that cannot be done,
  - the destructor releases the resource and never throws exceptions;

Figure 6: RAII

Destructors In Action

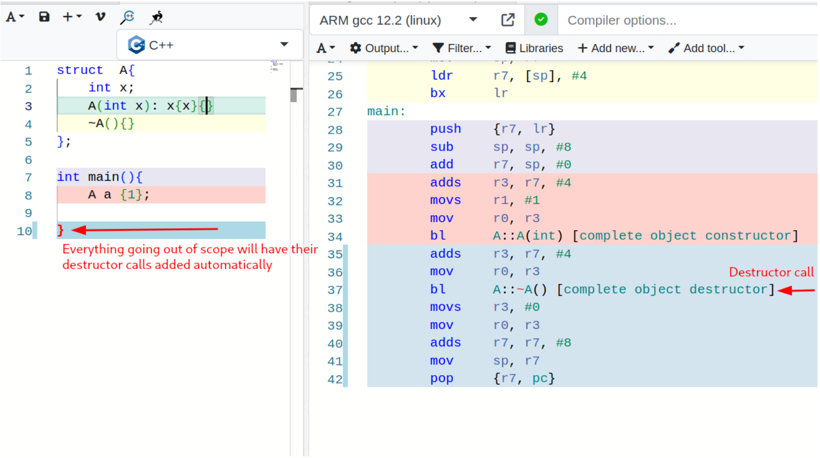

Figure 7: Destructor call added automatically

Let’s make our own unique_ptr

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```cpp
#include <iostream>
using namespace std;
class int_ptr{
    int* x ;
public:
    int_ptr(int x): x{new int(x)}{}
    ~int_ptr(){
        delete x;
    }
    int& operator*(){
        return *x;
    }
};
int main(){
    int_ptr one(1);
    cout << *one << endl;
}
```

Figure 8: int_ptr working without any leaks

Is unique_ptr the only smart pointer??

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NO

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- A `unix file descriptor`

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- A `unix file descriptor`
- A file descriptor can have multiple owners. It should only be freed when all the owners go out of scope.

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But, we'll do it still(for the purpose of this talk)

File Descriptors (continued)

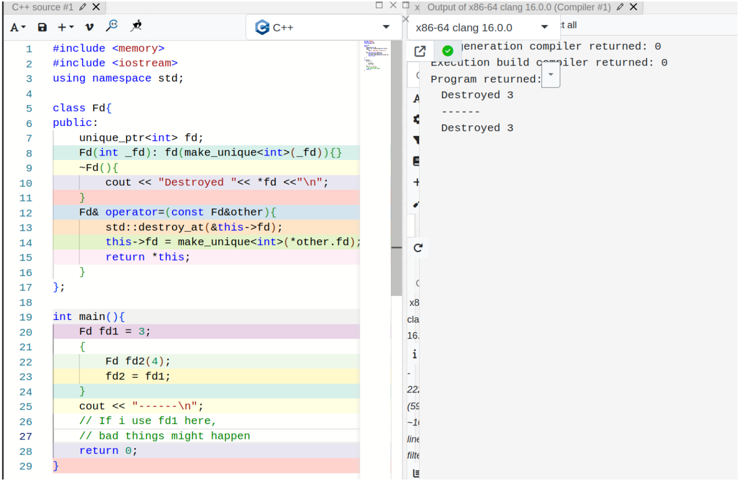
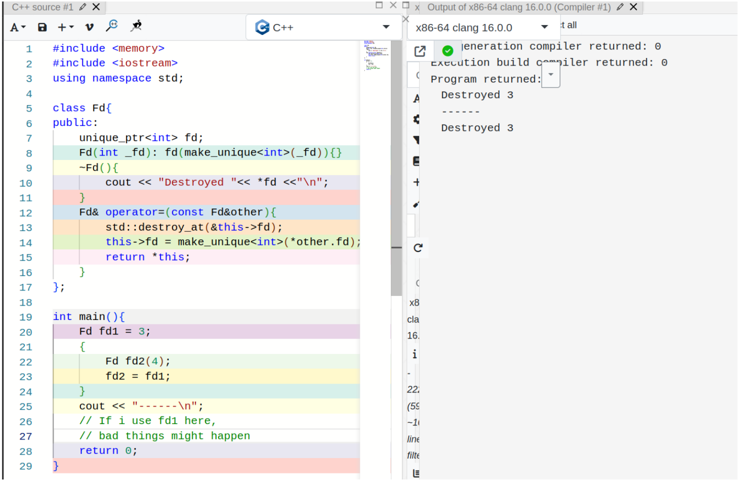


Figure 9: File Descriptor with unique_ptr

File Descriptors (continued)



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Not possible to model this correctly

Another classic example (why only unique_ptr isn't enough?)

- SPMC(Single Producer Multiple Consumer) and MPMC(Multiple Producer Multiple Consumer) problem

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- Requires multiple owners for producer end as well as the consumer end

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- Every allocated pointer has a reference count associated with it
- Every copy leads to reference count increment.
- Every time a reference of the pointer goes out of scope, reference count is decremented by 1.
- When the reference count goes to 0, it is safe to `free` the object.

C++'s shared_ptr type

- It is a `reference-counted pointer`, manages the `reference count` elegantly with assignment operator overload, copy constructor overload, destructors, etc.

Let’s solve our file descriptor issue

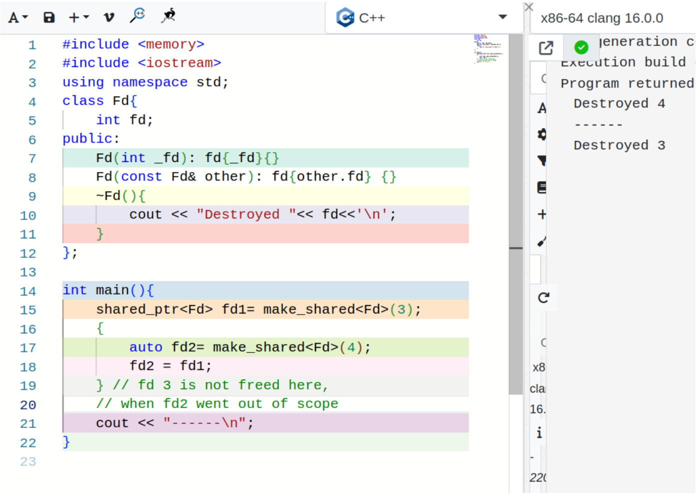

Figure 11: File Descriptor with shared_pointer

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- A pointer is reachable $\Rightarrow$ There's a root somewhere(in stack, register, static, etc.) from where we can transitively access the pointer.

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```
type baz = {
    x: int;
    y: int
}
type bar = {
    a:  int;
    b:  baz
}
type foo = {
    field1 : bar;
    field2: int
}
let foo_instance: foo = {
    field1 = {
        a  = 10;
        b = { x= 2 ;y= 5; };
    };
    field2= 5;
}
```

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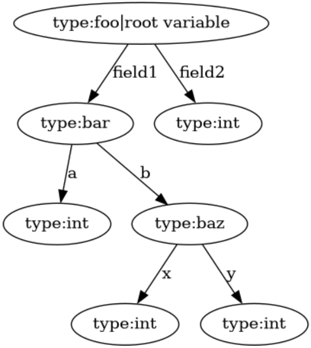

Figure 12: foo_instance variable as a graph

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- Conservative collection does not know about types of traced GC objects. It'll assume everything that's present in the stack, static and register are pointers and it'll follow it. They are inherently unsafe. Example: Boehm-Demers-Weiser conservative C/C++ Garbage Collector

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Tracing Based GC Algorithms

- Copying Collector
- Mark and Sweep Collector

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- The garbage collector then copies reachable objects to the other space.
- Roles of the semispaces are reversed when garbage collection is complete.
- While all this is happening, the whole program is stopped. (This is why it's called a stop-the-world algorithm)

Copying Collector (A visual representation)

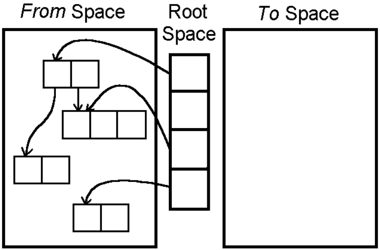
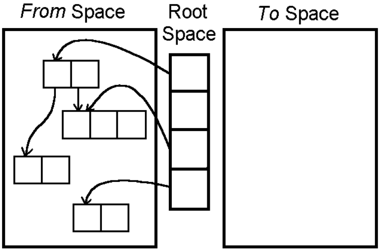


Figure 13: Before GC



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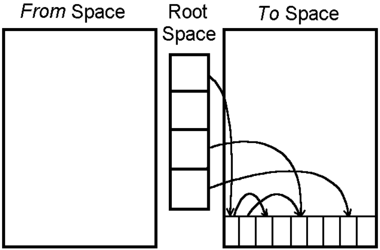

Figure 14: After GC

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Mark →responsible for marking reachable objects `Black`

Sweep →responsible for freeing all the unreachable(`White`) objects.

```
     /* marking phase */
1)   add each object referenced by the root set to list Unscanned
             and set its reached-bit to 1;
2)   while (Unscanned ≠ ∅) {
3)           remove some object o from Unscanned;
4)           for (each object o′ referenced in o) {
5)                   if (o′ is unreached; i.e., its reached-bit is 0) {
6)                           set the reached-bit of o′ to 1;
7)                           put o′ in Unscanned;
                     }
             }
     }
     /* sweeping phase */
8)   Free = ∅;
9)   for (each chunk of memory o in the heap) {
10)          if (o is unreached, i.e., its reached-bit is 0) add o to Free;
11)          else set the reached-bit of o to 0;
     }
```

Figure 15: Basic Mark and Sweep

Which is better ? (Automatic Memory Management or Manual Management)

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DEPENDS

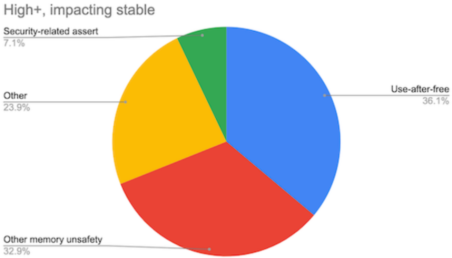
Figure 16: Segmentation Faults

Memory safety

The Chromium project finds that around 70% of our serious security bugs are memory safety problems. Our next major project is to prevent such bugs at source.

The problem

Around 70% of our high severity security bugs are memory unsafety problems (that is, mistakes with C/C++ pointers). Half of those are use-after-free bugs.



(Analysis based on 912 high or critical severity security bugs since 2015, affecting the Stable channel.)

These bugs are spread evenly across our codebase, and a high proportion of our non-security stability bugs share the same types of root cause. As well as risking our users' security, these bugs have real costs in how we fix and ship Chrome.

Figure 17: Use After Free

We frequently performed an operation we called the "gossip dance", where we'd take a node out of rotation to let it compact without taking traffic, bring it back in to pick up hints from Cassandra's hinted handoff, and then repeat until the compaction backlog was empty. We also spent a large amount of time tuning the JVM's garbage collector and heap settings, because GC pauses would cause significant latency spikes.

Figure 18: Discord Troubles(from a recent Discord Engineering Blog)

Case against Automatic Memory Management

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Figure 18: Discord Troubles(from a recent Discord Engineering Blog)

- Similar GC issues encountered by many tech giants

Advanced Topics in Memory Management

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- Advanced type system like in Rust, which help with memory safety
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- Parallel and Concurrent GC
- Generational GC
- Reducing GC pauses

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