Dynamic Memory Allocation

We have discussed two kinds of memory allocation:

- **Static allocation**
  - Global variables
  - Static local or global variables
- **Dynamic allocation**
  - Automatic variables
  - Manually allocated memory

We covered automatic variables in depth, now it’s time for manual allocations!
The Dynamic Allocator

The interface to the dynamic allocator is `malloc() et al.`

However, the underlying mechanism is more complex.

The operating system kernel provides only large allocations.

Its minimum allocation on x86-64 is typically 4 KB.

The dynamic allocator must efficiently parcel out these allocations.
The OS heap occupies the memory above the BSS.

To the OS, it is **one large block of memory**.

The dynamic allocator must manage it.

The OS provides **one tool** for this: the **system break**.
Managing the System Break

The **system break** marks the boundary of the heap. It is the address of the first byte that *isn’t* on the heap.

It can be moved with two system calls:

- `brk()`: set the break to an address
- `sbrk()`: move the break a relative number of bytes

A **dynamic allocator** can use this to **request memory from the OS**.
The `sbrk()` system call moves the system break:

```c
void *sbrk(intptr_t increment);
```

It returns the old location of the system break.

A positive break value expands the heap.

This means `sbrk()` works a little bit like `malloc`:

```c
void *mem = sbrk(size);
```
The original Unix allocator required explicit sizes: both allocating and freeing memory took a size.

The `malloc()` allocator does not.

This means that it must store that size somewhere!

There are many allocation strategies with different solutions to this problem.
**Metadata**

Metadata\(^1\) is stored for heap allocations.

This metadata allows for:

- Identifying available memory on the heap
- Determining the size of allocated memory for `free()`
- Locating regions of memory that make up the heap
- …

How this metadata is stored and managed can vary.

\(^1\)Metadata is data about data.
Allocation Blocks

Assume that the dynamic allocator allocates blocks of memory.

Each block contains:

- Any metadata that is required for the allocator
- Memory available to the user to serve an allocation

The set of all of these blocks makes up the heap.
Explicit Metadata

When *explicit metadata* is in use, the block might contain:

- An integer containing the **size** of the block
- A flag indicating whether it is **free** or **in use**

This data is stored **adjacent to, or nearby**, the user memory:

![Heap Block Diagram](image-url)
Free Lists

A common allocation management technique is:

- Blocks containing **explicit sizes**
- Free blocks placed on a **linked list**

Sometimes allocated blocks may also be on a list.

When the user asks for memory, **available memory** is located on this list.
Sharing Space

Sometimes metadata is required *only when a block is free*.

This metadata can be stored *inside the application memory portion of the block*.

Since the block is *not in use*, this memory is *available*.

This reduces the *overhead* of free memory blocks.
Allocators have \textit{overhead}.

This is \textit{extra memory used only by the allocator}.

It is important to minimize this overhead.

There are two primary sources of overhead:

- Metadata
- Fragmentation
Fragmentation

Fragmentation is space used by the allocator that is not useful to the application.

Sometimes metadata is included in fragmentation.

There are two kinds of fragmentation:

- **Internal**: unused memory inside a heap block
- **External**: unused memory between heap blocks
Internal Fragmentation

Internal fragmentation is like packing in a structure.

It is memory that is required by the allocator, but not useful.

It often arises because allocator blocks either:

- Must be aligned
- Have limited possible sizes

For example: an allocator only creates blocks of size $2^k$, but the user asks for $2^k - 1$ bytes of memory.
External Fragmentation

External fragmentation is due to user allocation patterns.

The allocator has free blocks, but they are not suitable.

What if:
- this is the entire heap
- the user wants a 64B block?
Let’s explore some of these concepts in diagrams.
Summary

- The OS notion of the heap is **very simplistic**.
- The **dynamic allocator** has to manage the heap.
- **Metadata** is required for management.
- The heap can become **fragmented**:
  - **Internal** fragmentation is inside heap blocks.
  - **External** fragmentation is between heap blocks.
References I

Required Readings

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