

CSE 220: Systems Programming

Dynamic Memory Allocation

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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.

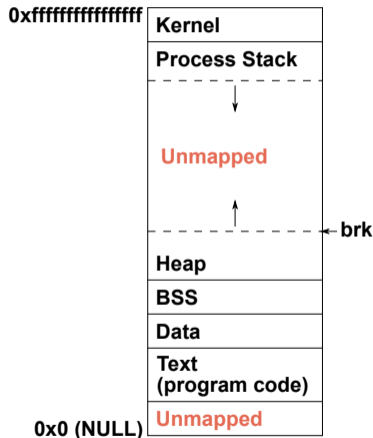
The System Break

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 break represents the **address of the last byte** of 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

This is the **primary mechanism** a dynamic allocator uses to **request memory from the OS**. ¶

sbrk()

The sbrk() system call **moves the system break**:

```
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:

```
void *mem = sbrk(size);
```

Allocation API

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

Metadata¹ 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.

¹Metadata is data about data.

Explicit vs. Implicit Metadata

Metadata can be stored **explicitly** or **implicitly**.

Explicit metadata is **data stored in memory** that describes other data.

Implicit metadata is **data recoverable from other information**.

For example:

- The **location** of something in memory
- The **size** of something
- ...

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

Implicit Metadata

When **implicit metadata** is in use, a block might contain only user memory.

In this case, the allocator must **find the metadata**.

Often this is from a computation on the **location of the block**.

The text contains an example of an **implicit list structure**.

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.

Overhead

Allocators have **overhead**.

This is **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:

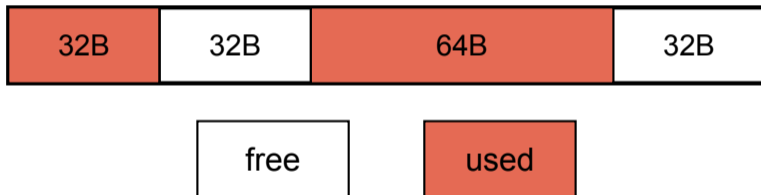
- Must be aligned
- Have limited possible sizes

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?**

Exploration

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

- [1] Randal E. Bryant and David R. O'Hallaron. *Computer Science: A Programmer's Perspective*. Third Edition. Chapter 9: 9.9, 9.11. Pearson, 2016.

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