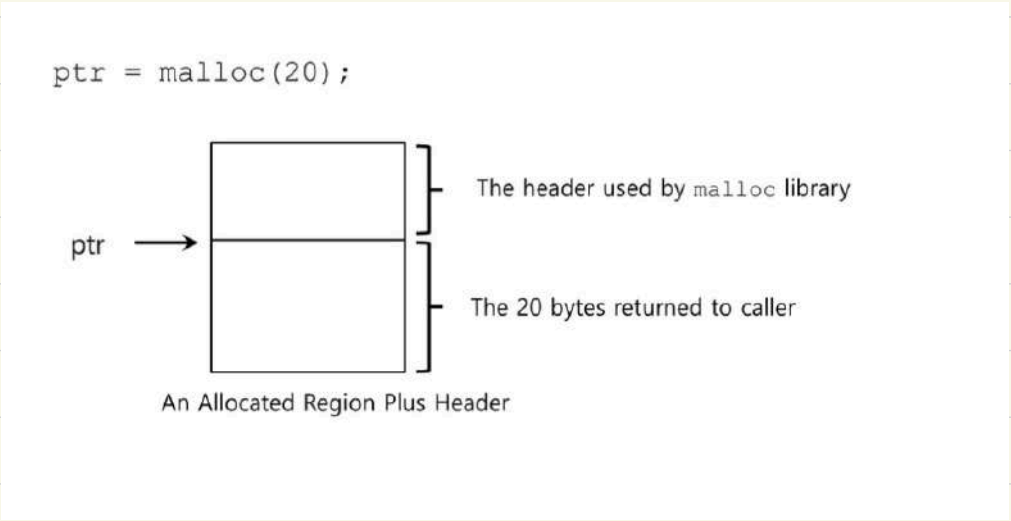
Recall that the interface to free(void *ptr) does not take a size parameter.

Then, how does the library know the size of the memory region that will be back into free list?

↳ most allocators store extra information in a header block.

* The size for free region is the size of the header + size of the space allocated to the user.

i.e., if a user request N bytes, the library searches for a free chunk of size N + the size of the header.



What are the contents of the header?

* size of the allocated region
* "magic number", for additional integrity checking,

etc..

```
typedef struct {
        int size;
        int magic;
} header_t;
```

What exactly happens when user calls free(ptr)?

* The library uses the following to figure out where the header begins?

```
void free(void *ptr) {
        header_t *hptr = (void *)ptr - sizeof(header_t);
. . .
}
```

* Library then determine whether the magic number matches the expected value as a sanity check.
  magic number mismatch → error reported!

* Calculate the total size of the newly-freed region.
  size of region + size of the header.

NOTE:

How magic number helps in debugging?

* Detecting double frees

free(*ptr)

→ magic number matches and gets updated

free(*ptr)

→ allocator sees a different magic number and reports double free

Also can be used to detect,

* invalid frees
* detecting memory corruption
* Buffer overflows, etc.-

Embedding a free list

In a typical list → for allocating a new node → call malloc().

but what about free list? → need to build it inside the free space itself.

* Description of a node of the list.

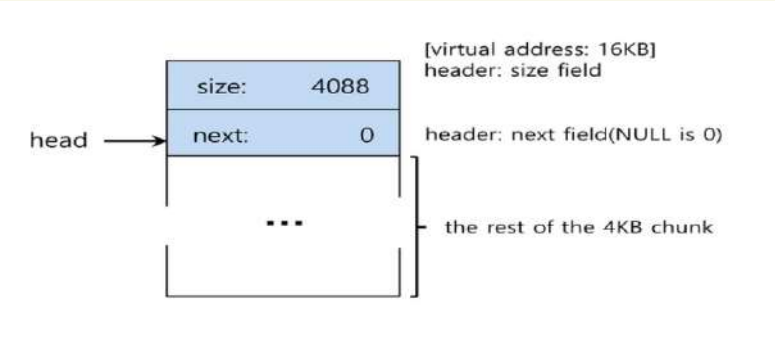
```
typedef struct __node_t {
        int size;
        struct __node_t *next;
} nodet_t;
```

* The process starts with some initial heap space from the kernel.

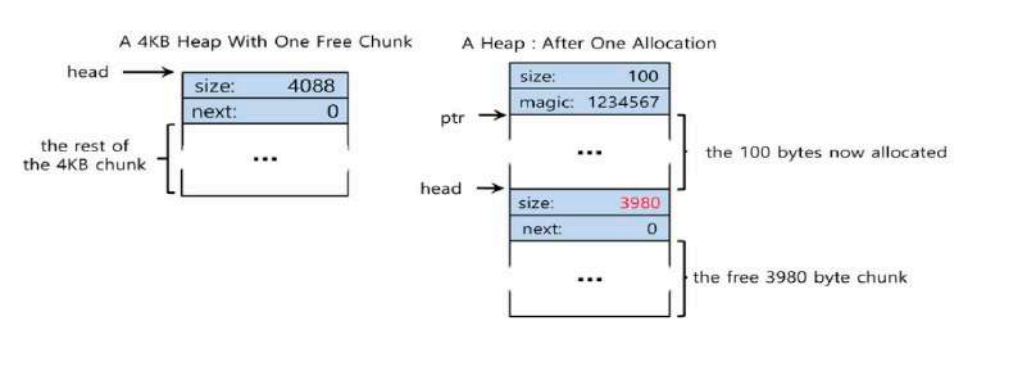
- assume that the heap is built via an mmap() system call.

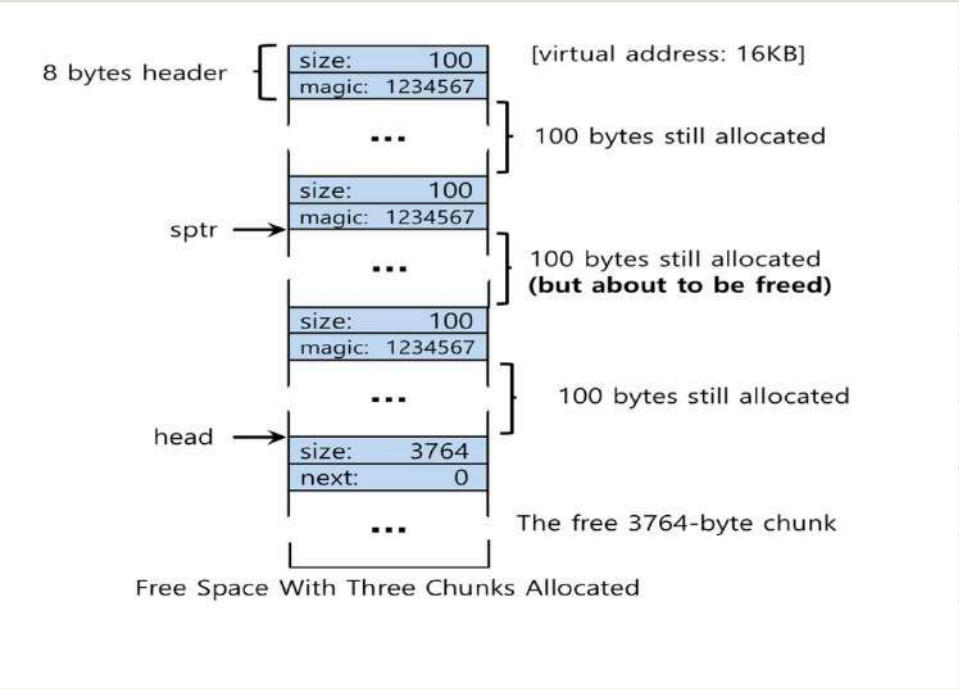
```
// mmap() returns a pointer to a chunk of free space
node_t *head = mmap(NULL, 4096, PROT_READ|PROT_WRITE,
                                MAP_ANON|MAP_PRIVATE, -1, 0);
head->size = 4096 - sizeof(node_t);
head->next = NULL;
```

* Now the status of the list is →



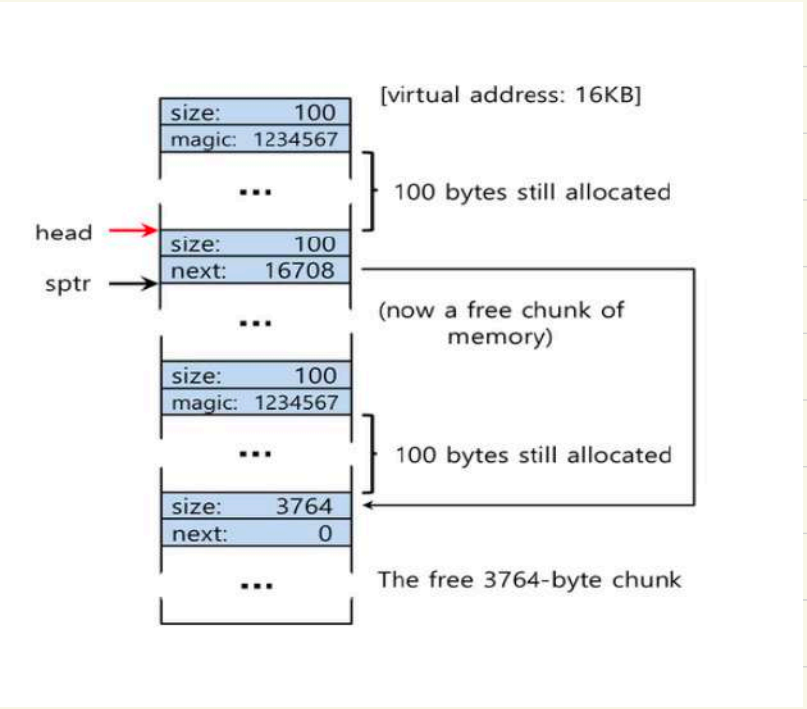
* a request for 100 bytes by *ptr = malloc(100)
  - allocating 108 bytes out of the existing one free chunk.
  - shrinking the one free chunk to 3980 (4088 − 108)



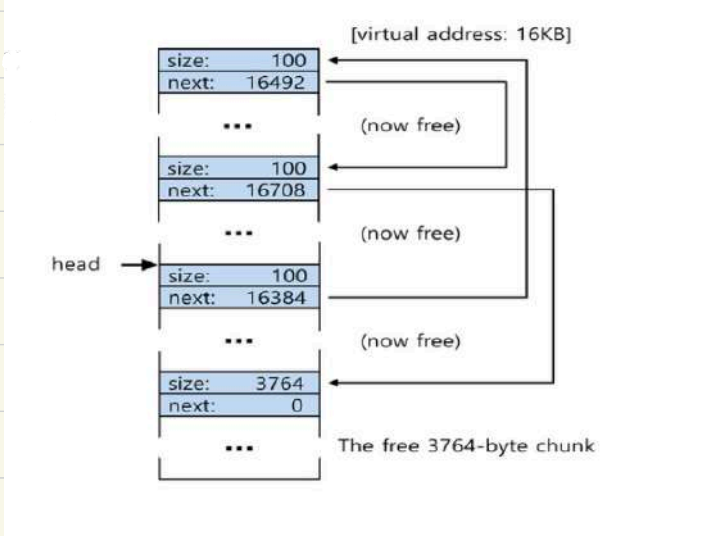


* eg.- free(sptr)

- the 100 bytes chunks is back into the free list
- the free list will start with a small chunk and the list header will point the small chunk.



* Assume that last two in-use chunks are also freed.



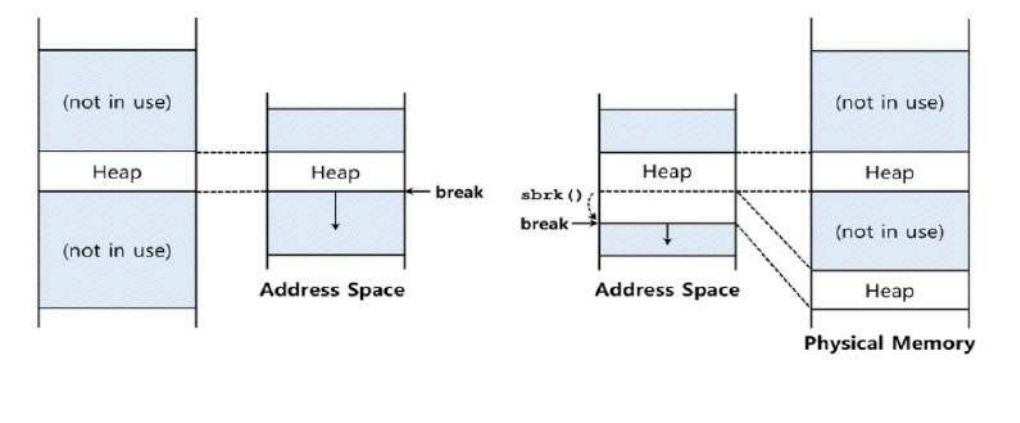
→ External fragmentation occurs

- coalescing is needed in the list.

Growing the heap

Most allocators start with a small-sized heap and then request more memory from the OS when they run out.

eg: sbrk(), brk() in most UNIX systems.



Basic strategies for managing free space

An ideal allocator → fast and minimizes fragmentation.

Best fit: finds free chunks that are big or bigger than the requested size.

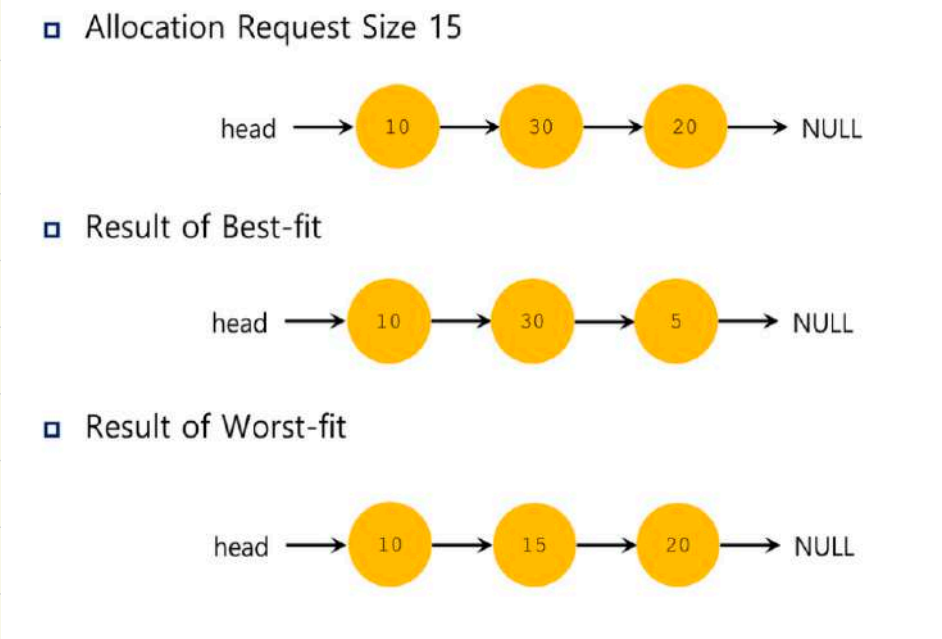
return the one that is the smallest in that group of candidates.

* reduced waste of space
* not fast, since it does an exhaustive search for the correct block.

Worst fit: finds the largest chunk and return the requested amount; keep the remaining (large) chunk on the free list.

* leaves big chunks free instead of lots of small chunks that can arise from best-fit.
* full search of free space → costly!

eg:-



first fit: finds the first block that is big enough and returns the requested amount to the user.

* faster (as there is no exhaustive search)
* pollutes the beginning of the free list with small objects.

Next fit: Instead of always starting the search from the beginning of the list, next fit algorithm keeps an extra pointer to the location within the list where one was looking last.

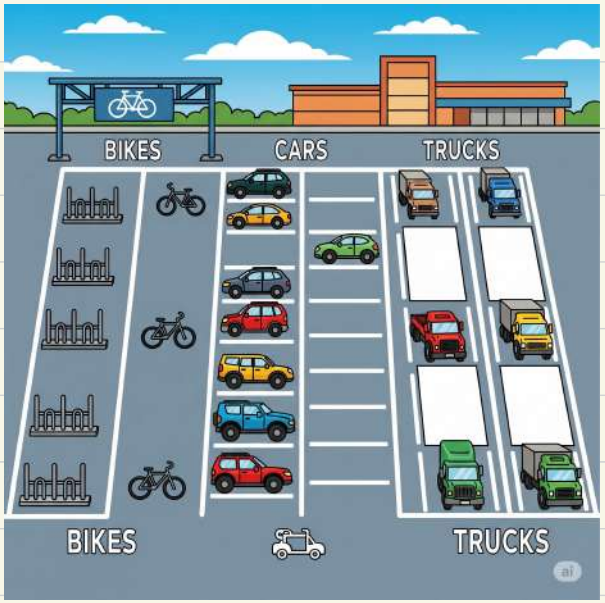
* spread the searches for free space throughout the list more uniformly.
* leaves small usable holes in the earlier parts of memory; overwise leads to external fragmentation.

Other approaches

Seggregated list

Some applications might have one (or a few) popular-sized request that it makes.

So, instead of keeping a single free list (which might contain free blocks of all sizes), the allocator keeps multiple free lists, each dedicated to a particular size class of memory blocks.



- This avoids having to search through lots of irrelevant blocks when looking for a free space.

simple segregation (Fixed-size classes)
- exact matches handled in size-specific regions (no internal fragmentation)
- everything else handled in a general-purpose pool.

Challenge? How much memory should one dedicate to the pool of memory that serves specialized requests of a given size, as opposed to general pool?

↳ slab allocator (originally designed for Solaris kernel)

* no static partitioning.
* Instead, for each object type/size, the allocator maintains a cache made of slabs (chunks of contiguous memory).
* If demand grows, for that size, the allocator adds more slabs dynamically.
* If demand shrinks, it can release empty slabs back to the general pool.
* Thus it automatically adapts to the workload, instead of requiring the allocator designer to guess sizes upfront.

Note that when you allocate a new object in a typical heap allocator, you need to do,

(constructor)

① Initialization: eg:- zeroing memory, setting default values, etc..
For kernel objects, this can involve non-trivial work!

Doing this every time memory is allocated adds CPU overhead, especially when many allocations happen per second.

② Destruction: freeing objects may require cleaning up fields. This too is costly if done repeatedly.

Slab allocator's solution: Pre-initialized objects.
- Slabs are created in advance with all objects pre-initialized.
i.e., when you allocate an object from the slab,
- no need to redo the initialization
- object is immediately ready for use.

Ideally when you free it
- object can optionally be reset, but the structure of the object stays intact.

To summarize, the constructor runs once per slab (when its created)
the destructor runs only if the slab is destroyed, not on every free.

Buddy allocator

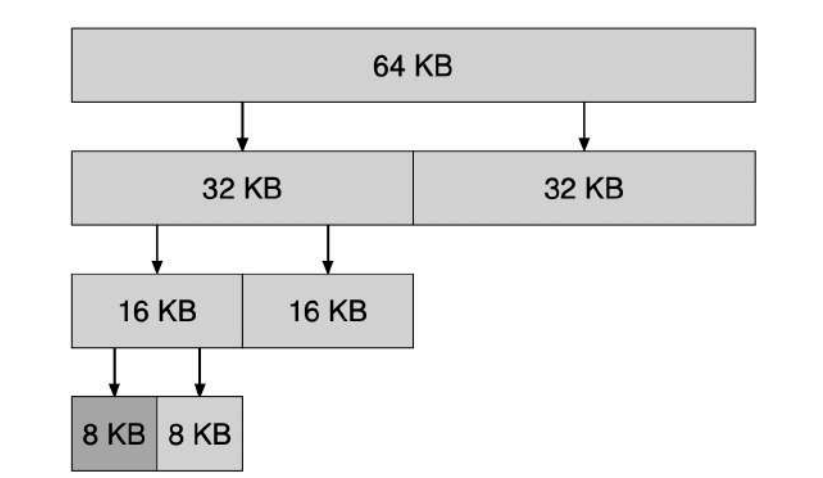
↳ an approach in which coalescing is simple.

Binary buddy allocator: free memory → big space of 2^N.

When a request comes in, the search for free space, recursively divides free space by two, until a block that is just big enough to accomodate the request is found.

eg:- free space → 64 KB; request → 7 KB block.

Left most 8 KB block gets allocated.



Internal fragmentation can happen!
(think, why?)

* When the allocated 8KB gets freed, check whether the "buddy" 8KB is free; if so, coalesce those two blocks.
continue this recursive coalescing up the tree as far as possible.
(either you restore the entire free space or find a buddy in use).

How to determine the buddy of a particular block?

If a block of size 2^k starts at address A!

Buddy address = A XOR 2^k

- XOR flips the k^{th} bit of the address

Why it works? - splitting always divides memory into halves aligned on 2^k.

- flipping the k^{th} bit moves you from one half to another.

* Buddy system relies on the property to merge blocks efficiently.
(as no search needed → just XOR)

Problem with all of the above approaches → lack of scaling
(searching the free list for a free block is slow).

↳ need to use advanced data structures
to overcome this bottle neck
like, balanced binary trees, splay trees etc...