Dynamic Memory Allocation

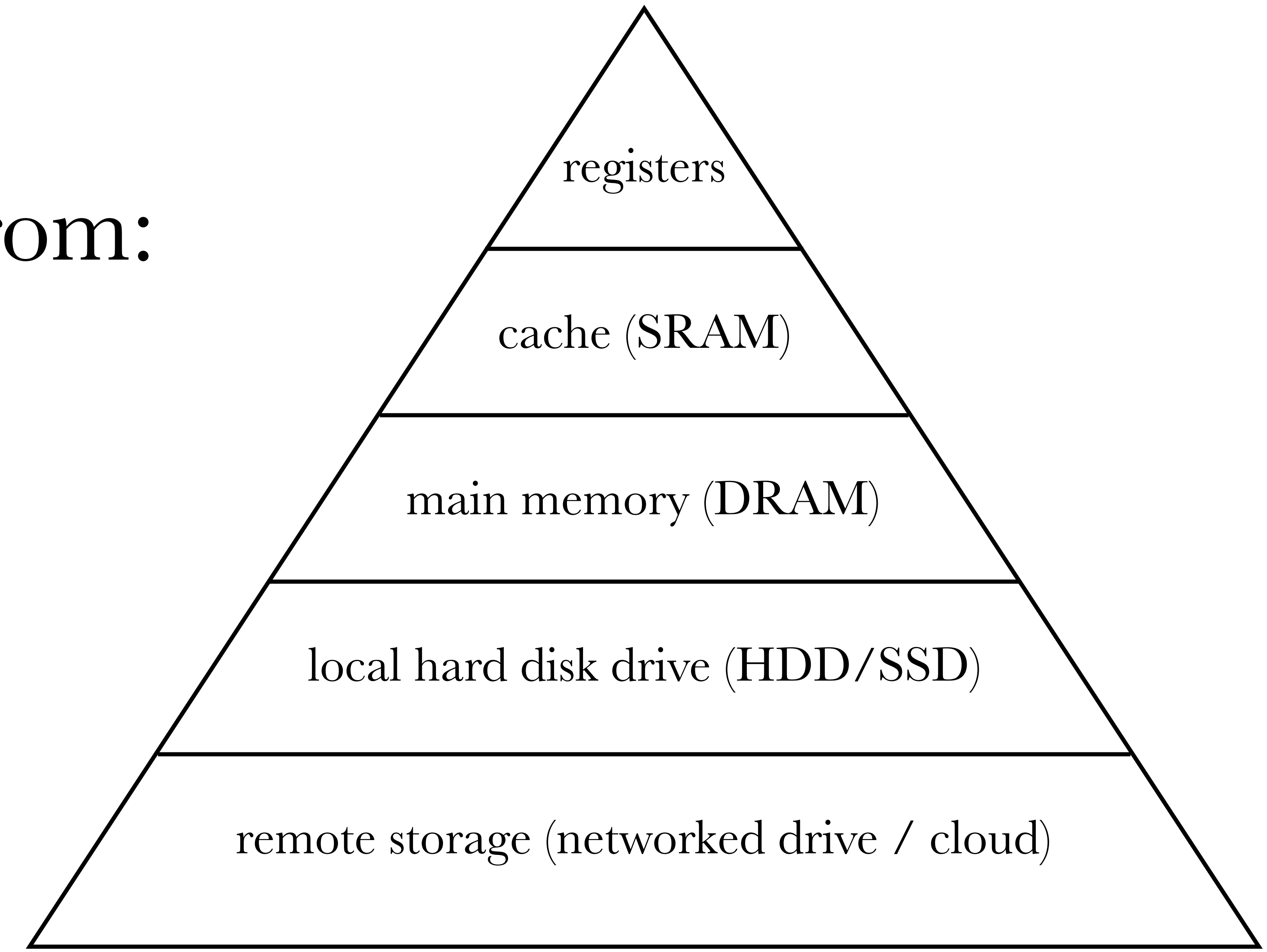
Science | Computer Science

CS 351: Systems Programming

Michael Saelee <lee@iit.edu>

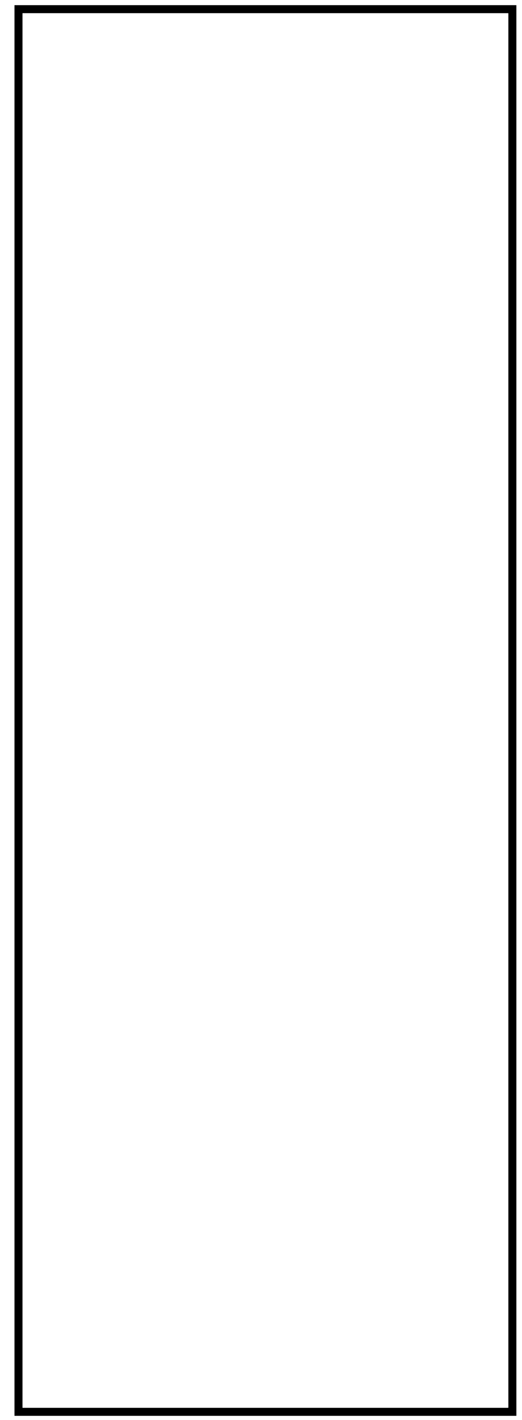
IIT College of Science
ILLINOIS INSTITUTE OF TECHNOLOGY

from:



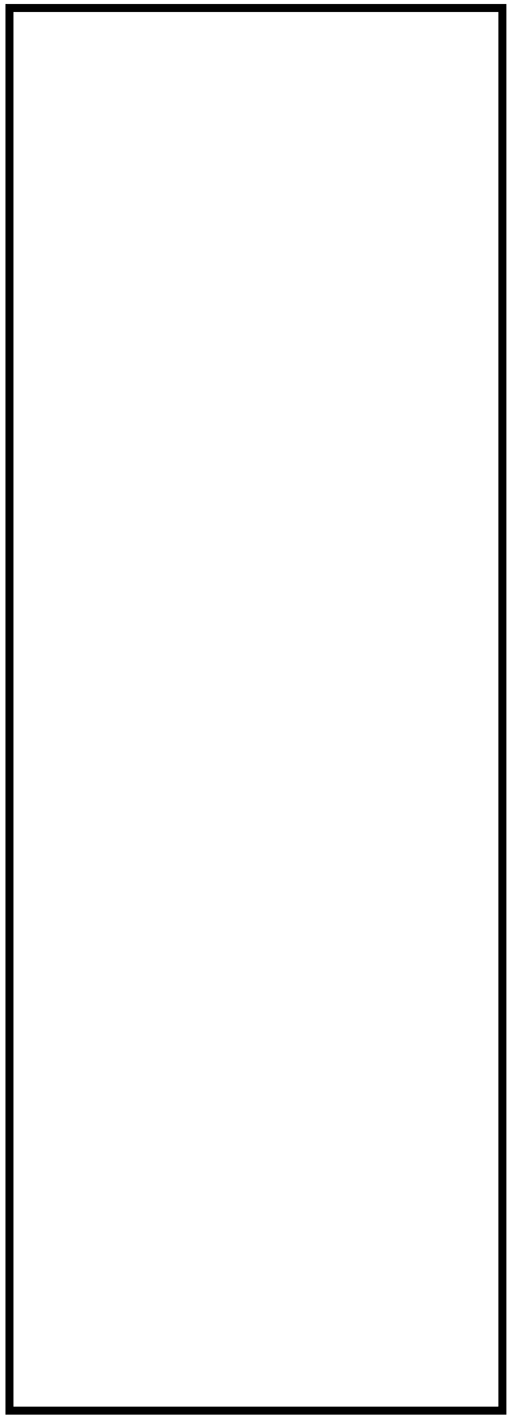
The Memory Hierarchy

we now have:



Virtual Memory

now what?



- code, global variables, jump tables, etc.
- allocated at fork/exec
- lifetime: *permanent*

Static Data

The *Stack*

- function activation records
  - local vars, arguments, return values
- lifetime: *LIFO*

pages allocated as needed
(up to preset stack limit)

explicitly requested from the kernel

- for ***dynamic allocation***
- lifetime: *arbitrary*!

The *Heap*

- starts out empty
- **`brk`** pointer marks top of the heap

← `brk`

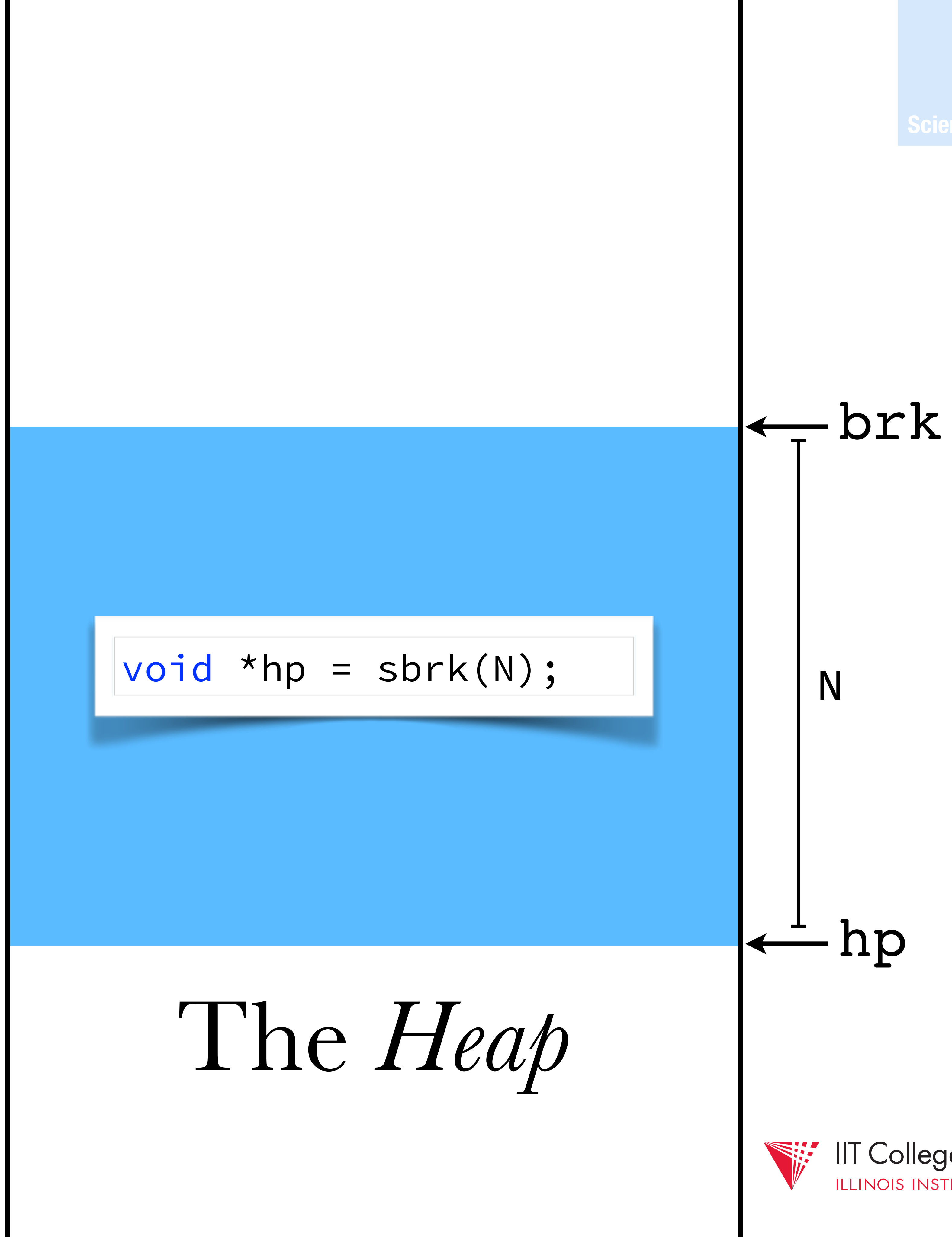
The *Heap*

heap mgmt syscall:

```c
void *sbrk(int inc);    /* increments brk by inc,
                           returns old brk value */
```

brk

The *Heap*

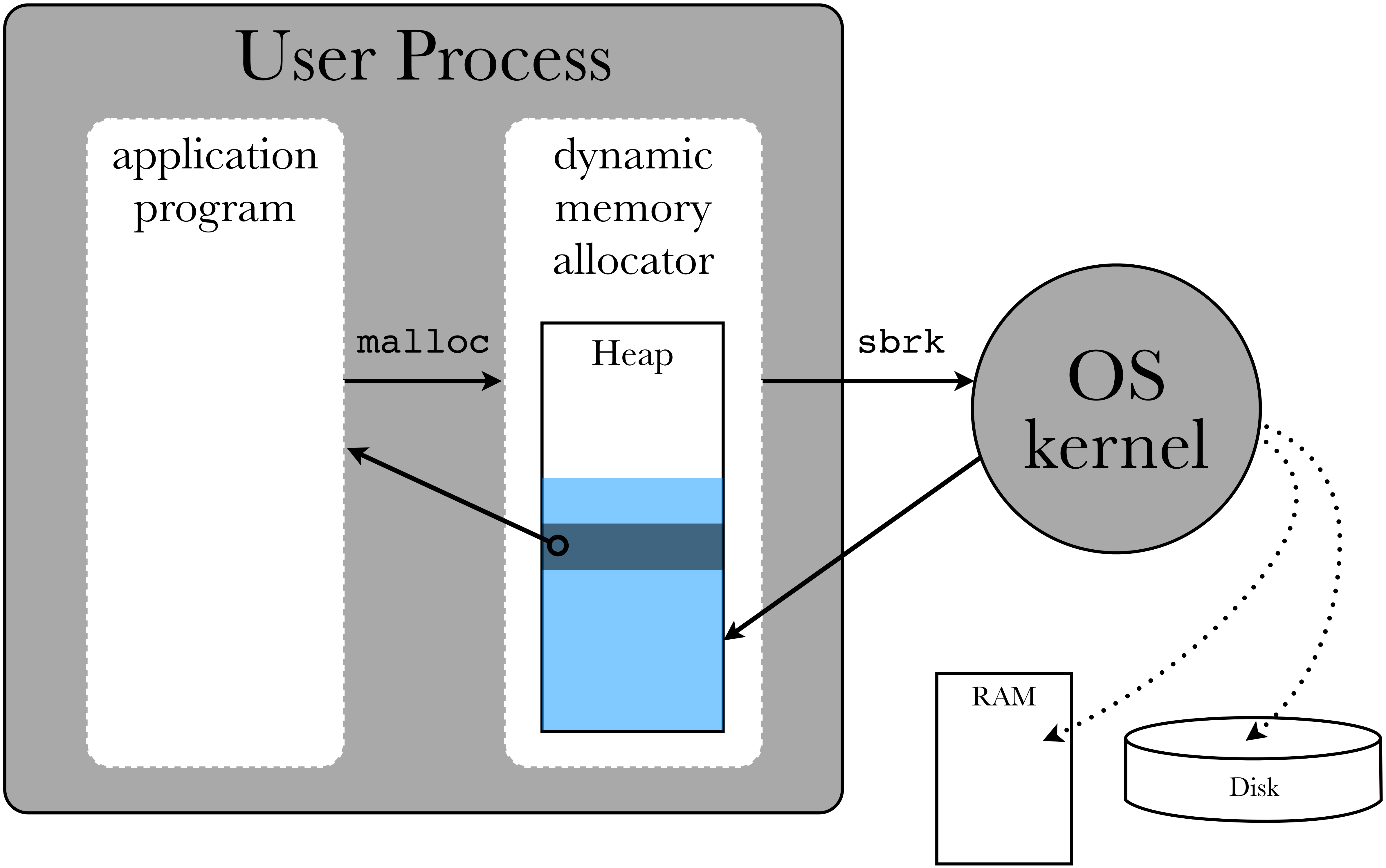

void *hp = sbrk(N);
brk
N
hp
The Heap

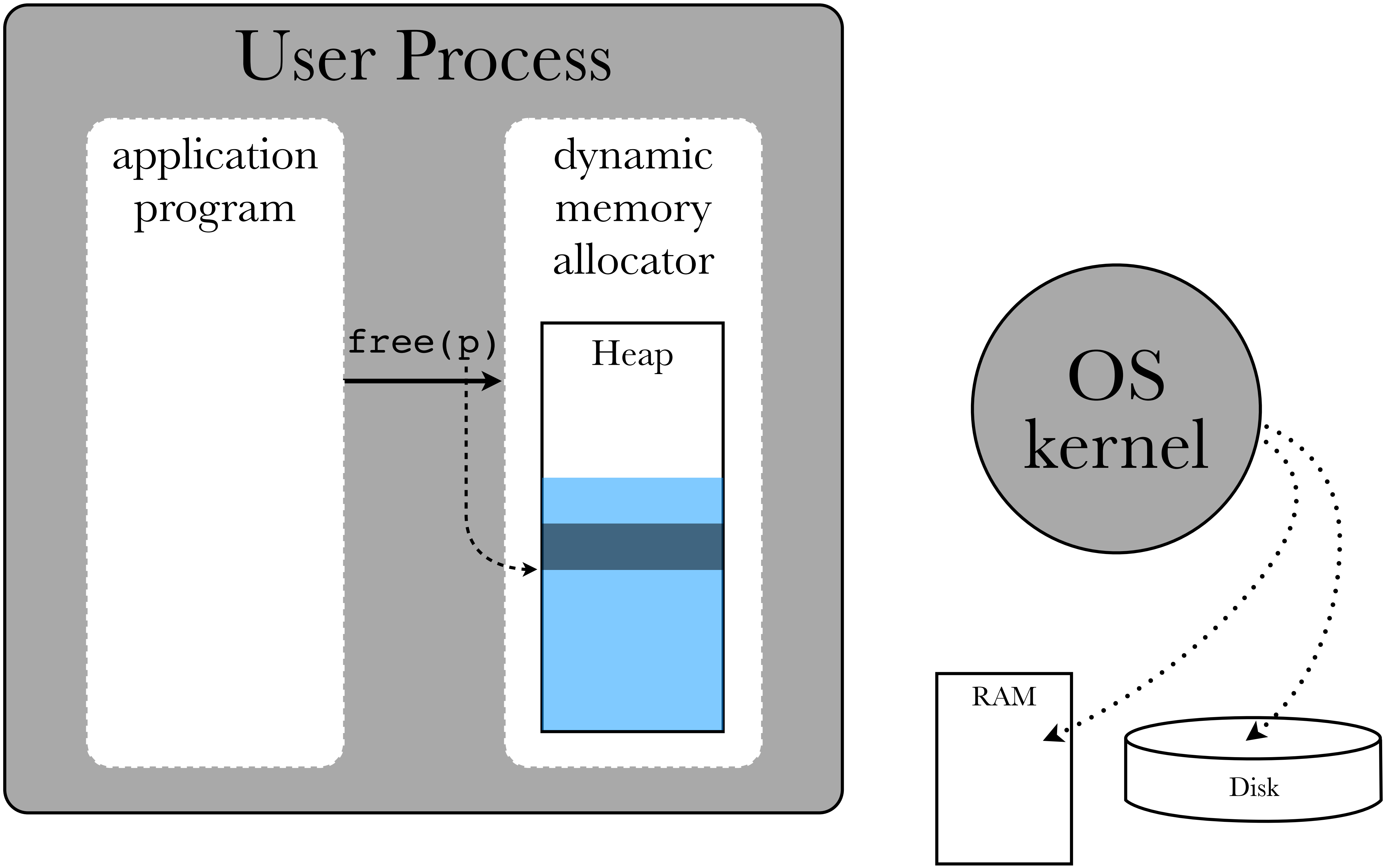
after the kernel allocates heap space for a process, it is *up to the process* to *manage* it!

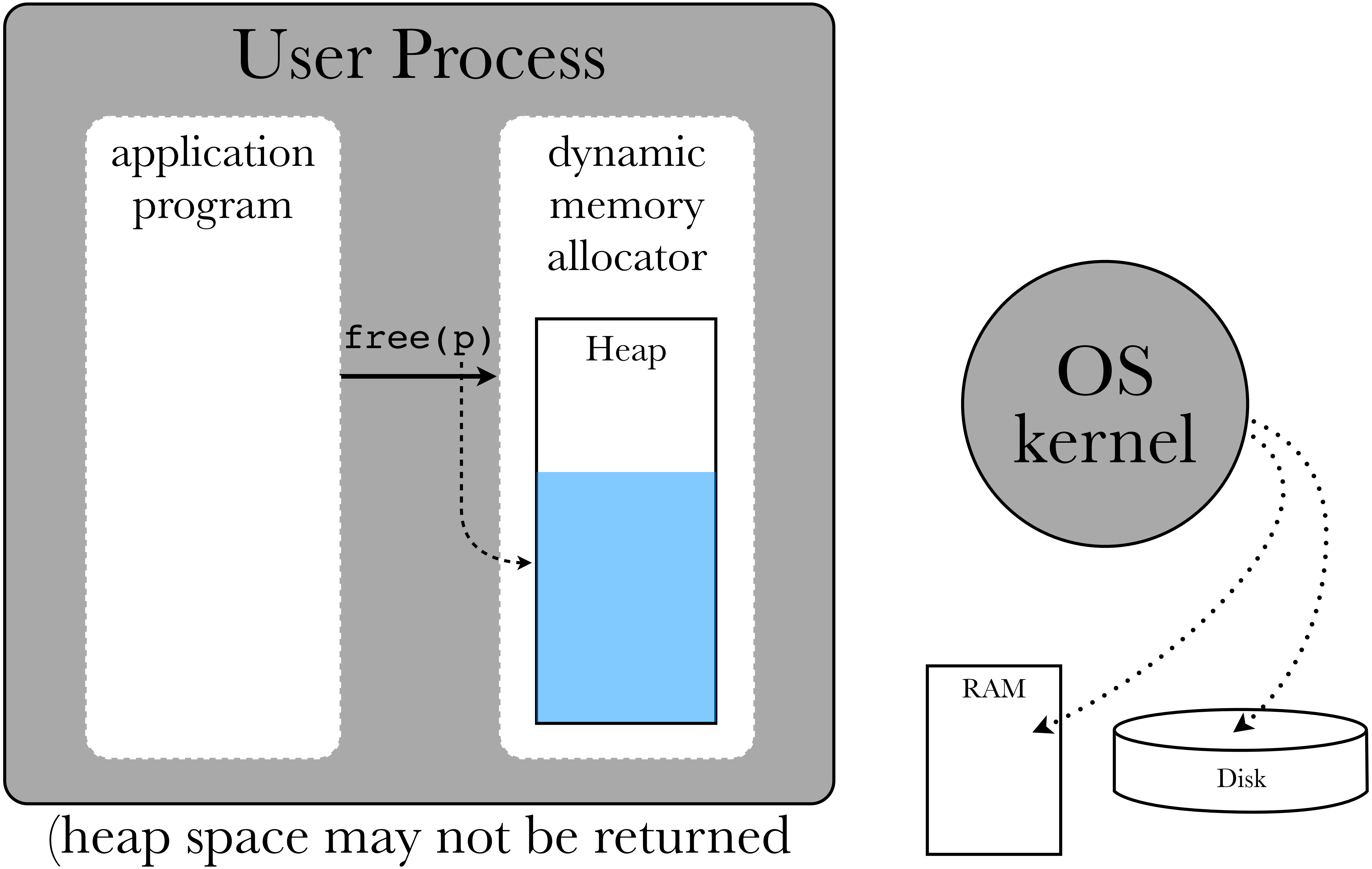
"manage" = tracking memory in use,
tracking memory not in use,
reusing unused memory

job of the *dynamic memory allocator*

— typically included as a user-level library and/or language runtime feature


User Process
application program
malloc
dynamic memory allocator
Heap
sbrk
OS kernel
RAM
Disk


User Process
application program
dynamic memory allocator
free(p)
Heap
OS kernel
RAM
Disk



(heap space may not be returned to the kernel!)

the DMA constructs a *user-level* abstraction (re-usable “blocks” of memory) *on top of* a *kernel-level* one (virtual memory) the user-level implementation must make good use of the underlying infrastructure (the memory hierarchy) e.g., the DMA should:

- maintain data alignment
- maximize throughput of requests
- help maximize memory utilization
- leverage locality

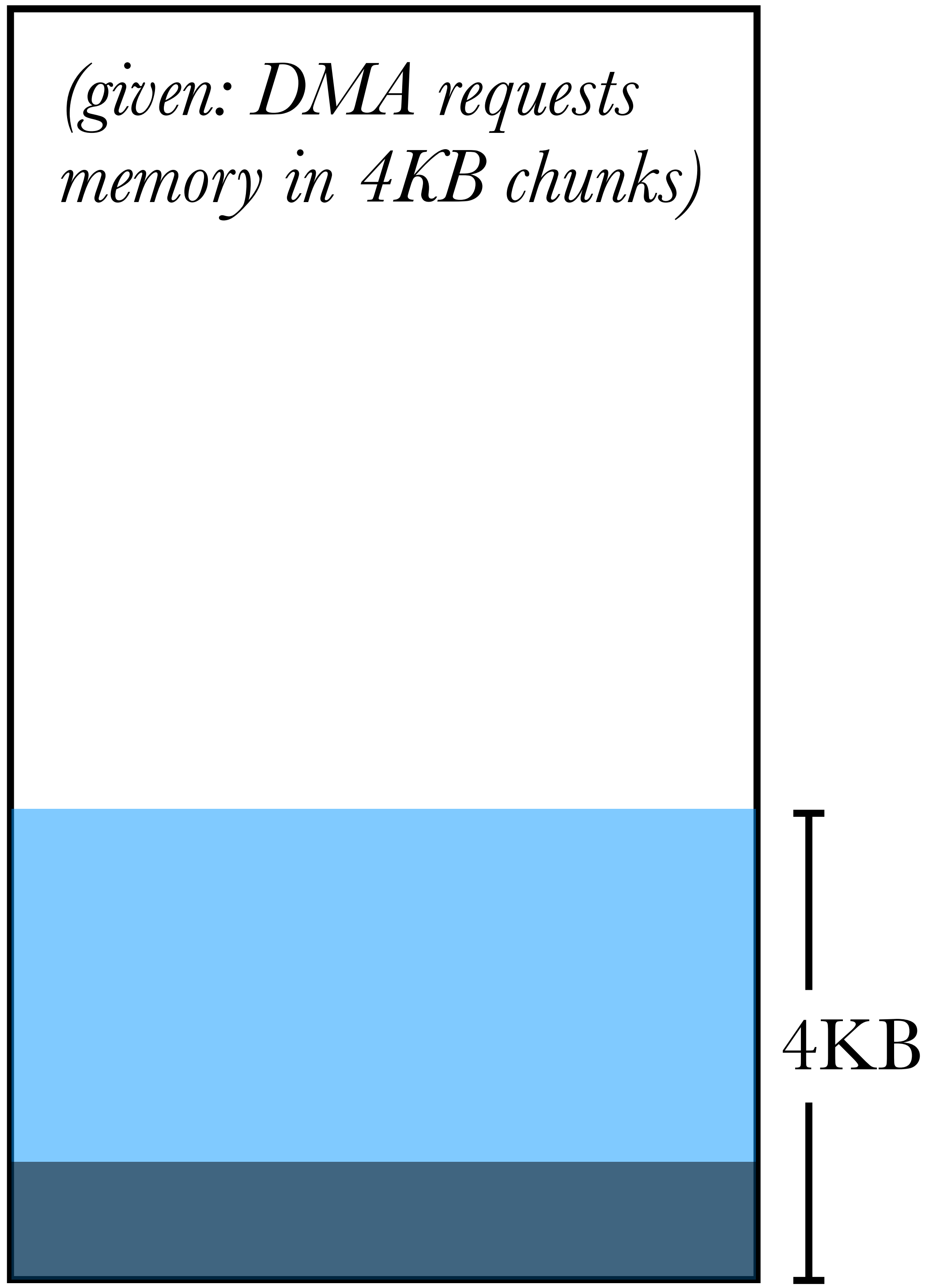
how to quantify this?

utilization = fraction of memory in use

- "in use" is a relative concept
- for DMA, "in use" = amount of memory actually requested by user (aka *payload*)
  - vs. heap space obtained via `sbrk`

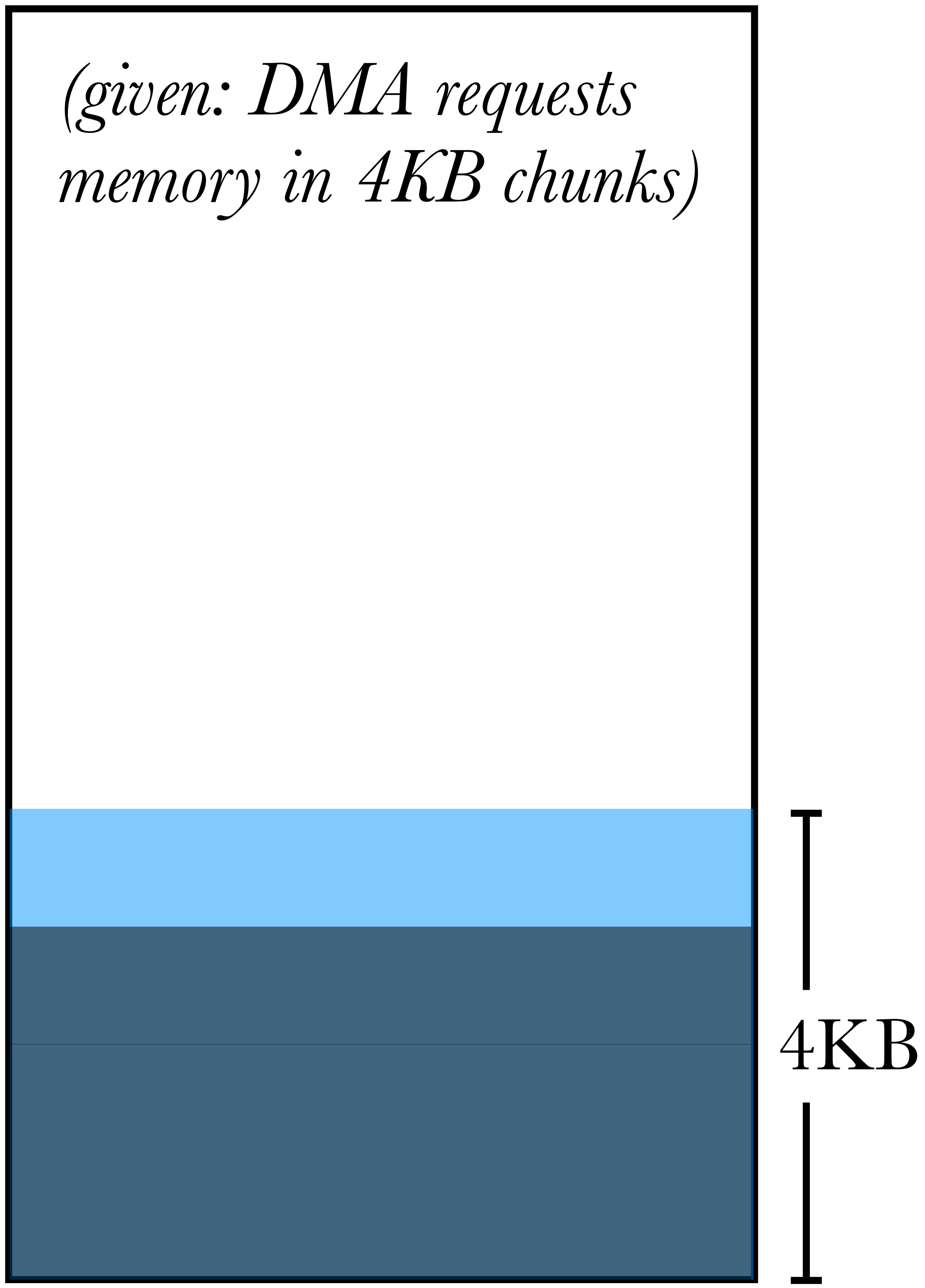
```
p1 = malloc(1024);
// util = 1K/4K = 25%
```

Heap

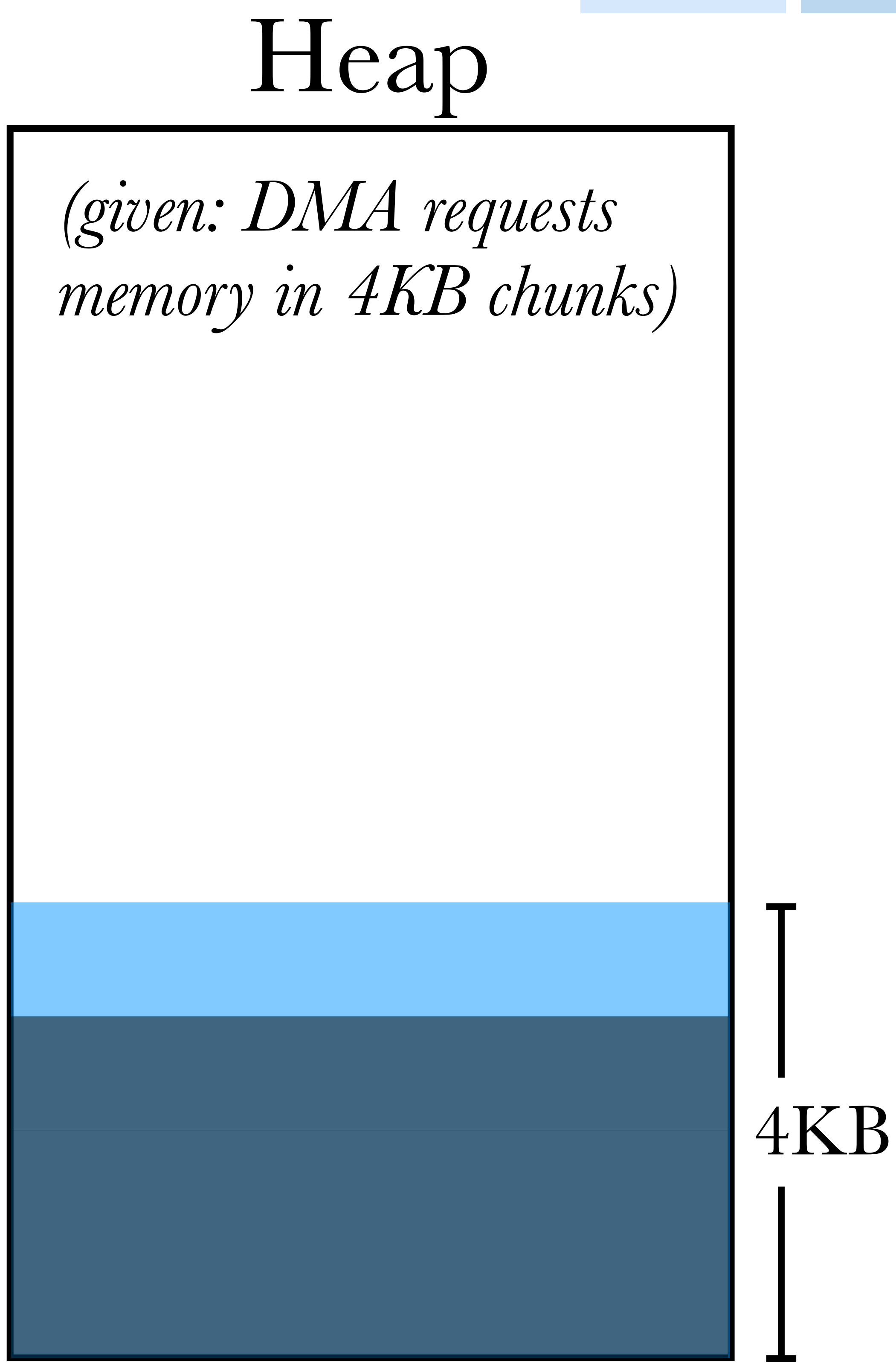


```
p1 = malloc(1024);
// util = 1K/4K = 25%
p2 = malloc(2048);
// util = 3K/4K = 75%
```

Heap

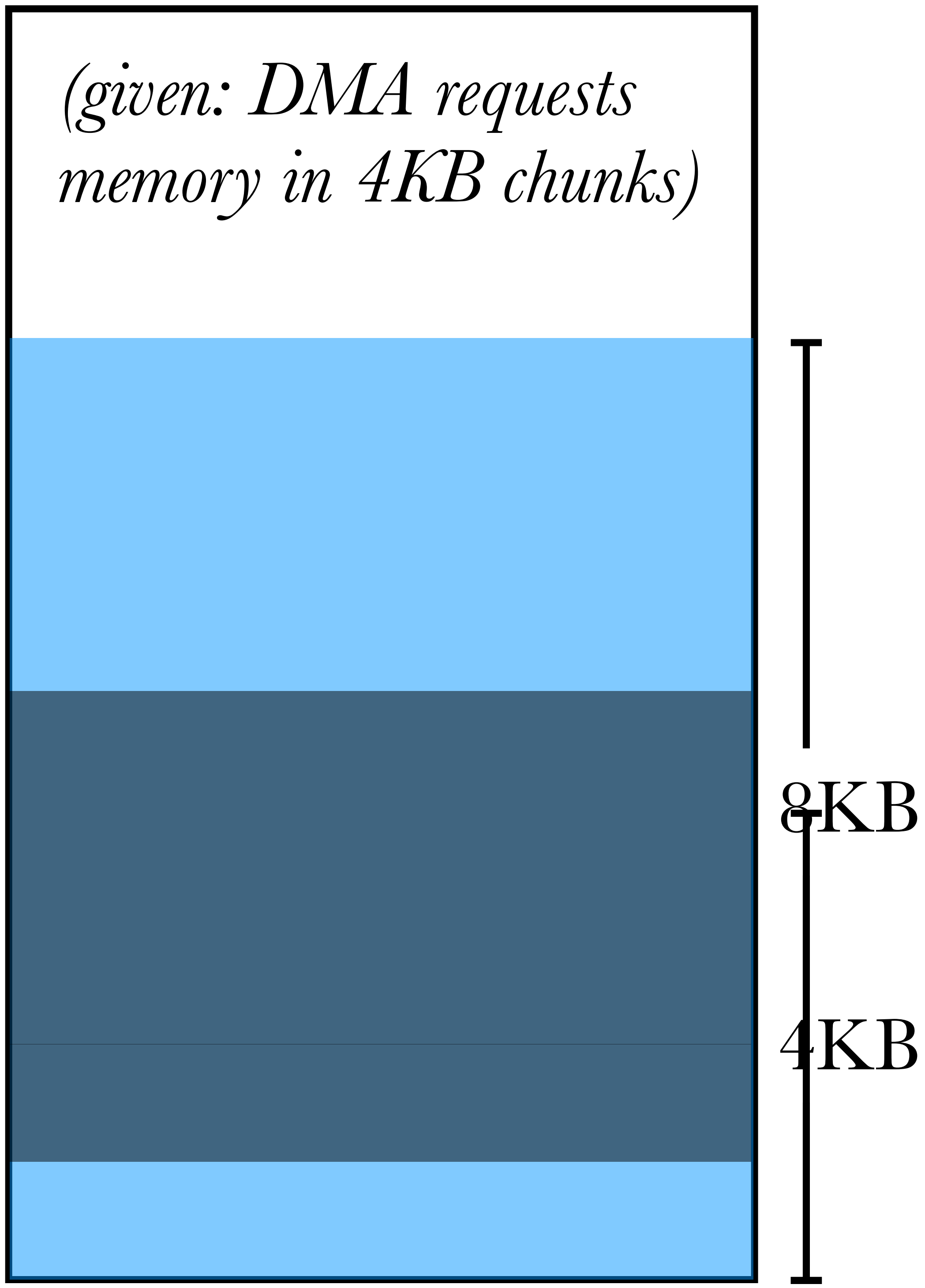


```
p1 = malloc(1024);
// util = 1K/4K = 25%
p2 = malloc(2048);
// util = 3K/4K = 75%
free(p1);
// util = 2K/4K = 50%
```



```
p1 = malloc(1024);
// util = 1K/4K = 25%
p2 = malloc(2048);
// util = 3K/4K = 75%
free(p1);
// util = 2K/4K = 50%
p3 = malloc(2048);
// util = 4K/8K = 50%
```

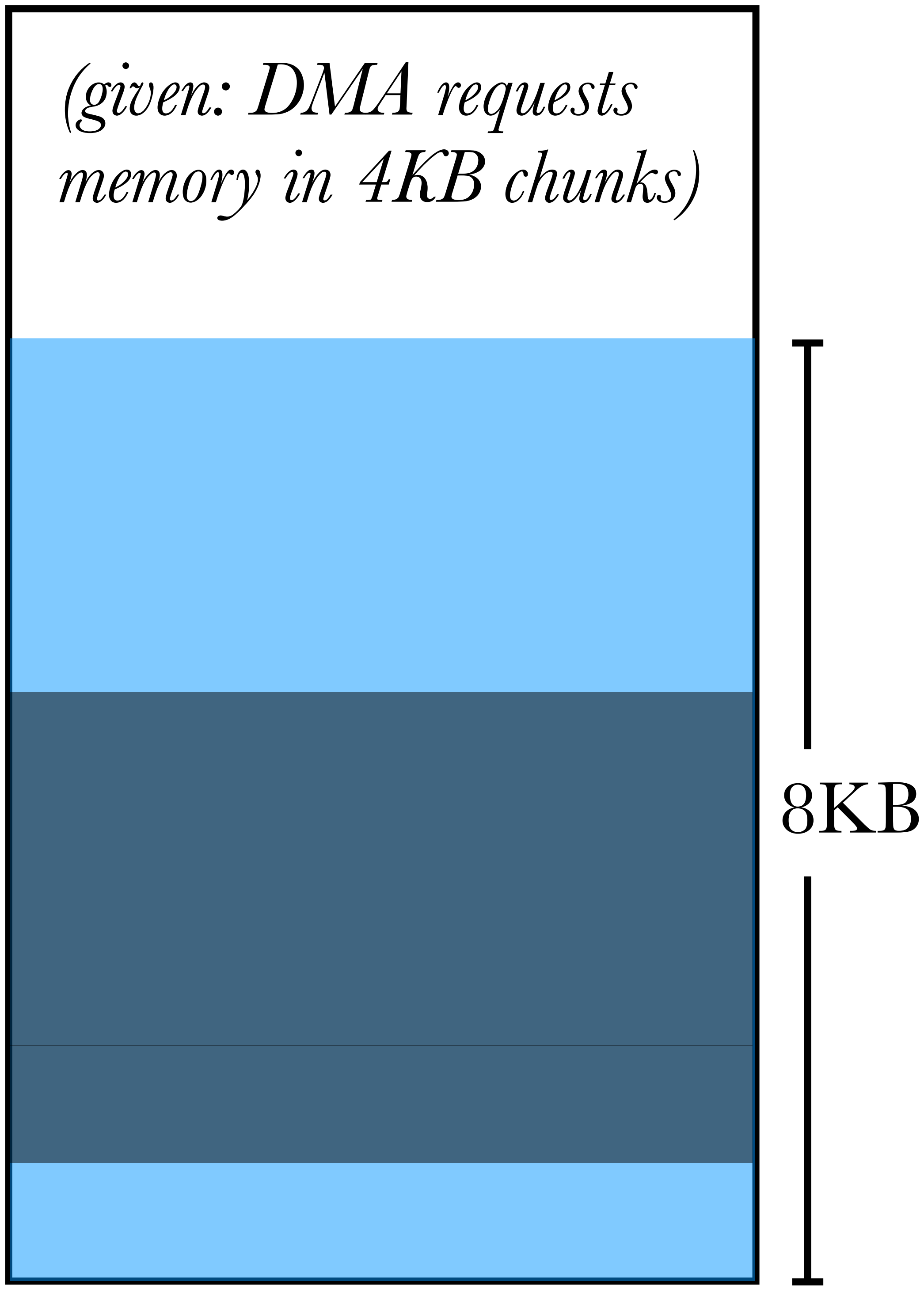
Heap



```
p1 = malloc(1024);
// util = 1K/4K = 25%
p2 = malloc(2048);
// util = 3K/4K = 75%
free(p1);
// util = 2K/4K = 50%
p3 = malloc(2048);
// util = 4K/8K = 50%
free(p3);
// util = 2K/8K = 25%
free(p2);
// util =  0/8K =  0%

// all non-leaking
// programs end in 0%
```

Heap



makes no sense to measure utilization *at the end* of process execution,

and it makes no sense to *arbitrarily* measure utilization *during* execution instead, measure *peak memory utilization*

- ratio between *maximum aggregate payload* and *maximum heap size*
- "high water mark" measure
- assuming the heap never shrinks, *end heap size = max heap size*

```
p1 = malloc(1024);
// util = 1K/4K = 25%
p2 = malloc(2048);
// util = 3K/4K = 75%
free(p1);
// util = 2K/4K = 50%
p3 = malloc(2048);
// util = 4K/8K = 50%
free(p3);
// util = 2K/8K = 25%
free(p2);
// util =  0/8K =  0%

// all non-leaking
// programs end in 0%
```

- max agg. payload = 4K
- max heap size = 8K
- peak memory util = 50%

aggregate payload

```
p1 = malloc(100);    // 100
p2 = malloc(200);    // 300
free(p1);            // 200
p3 = malloc(300);    // 500
free(p2);            // 300
p4 = malloc(100);    // 400
p5 = malloc(200);    // 600
free(p3);            // 300
p6 = malloc(100);    // 400
p7 = malloc(300);    // 700
free(p4);            // 600
free(p5);            // 400
p8 = malloc(200);    // 600

// measured heap size
// at end is 1K
```

peak memory util

$$= 700 \;/\; 1024$$

$$\approx 68\%$$

utilization is affected by *memory fragmentation*

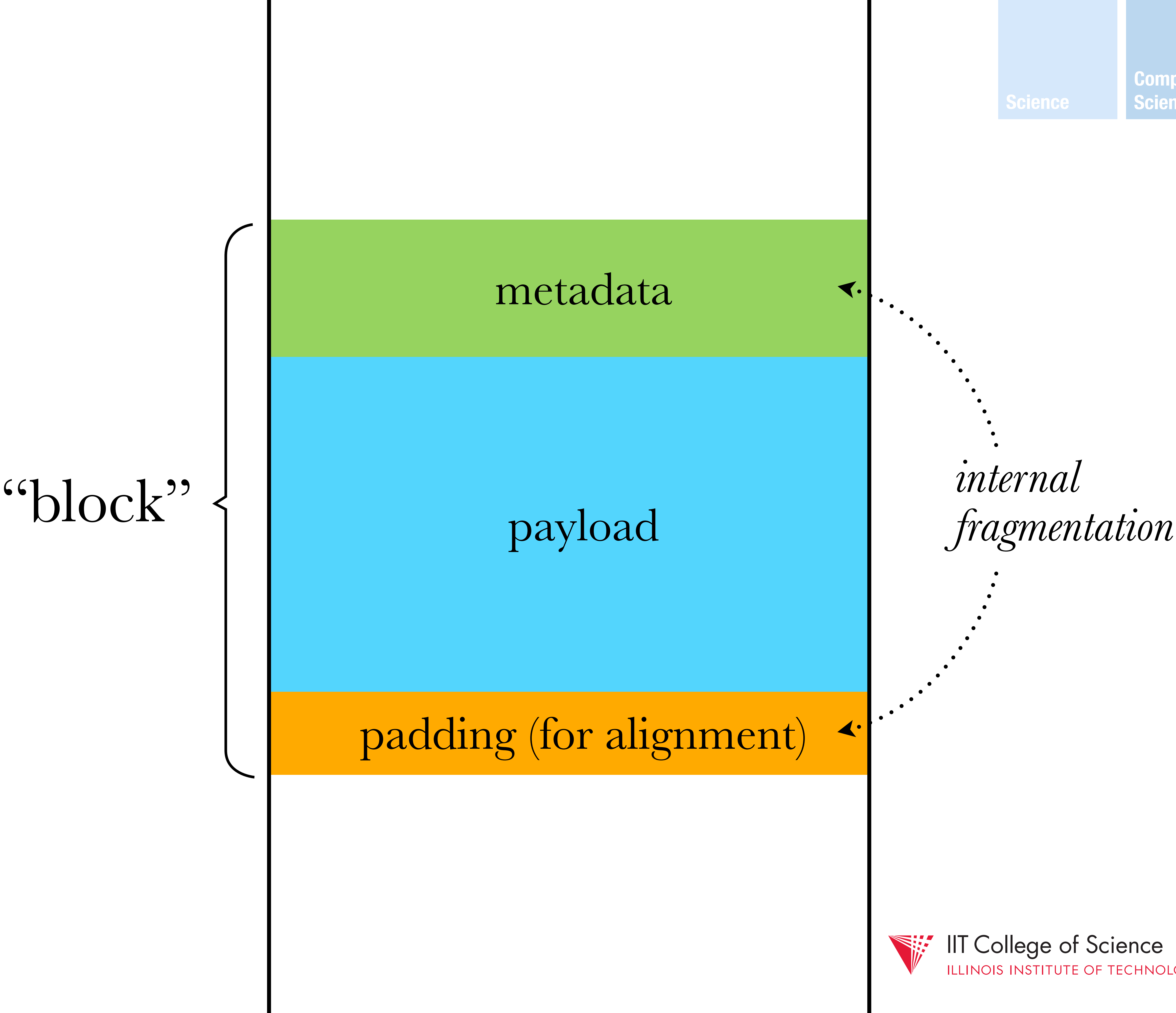
two forms:

1. *internal* fragmentation
2. *external* fragmentation

when allocating blocks of memory, it is convenient to make them *self-describing*

i.e., store metadata alongside blocks with size, allocation status, etc.

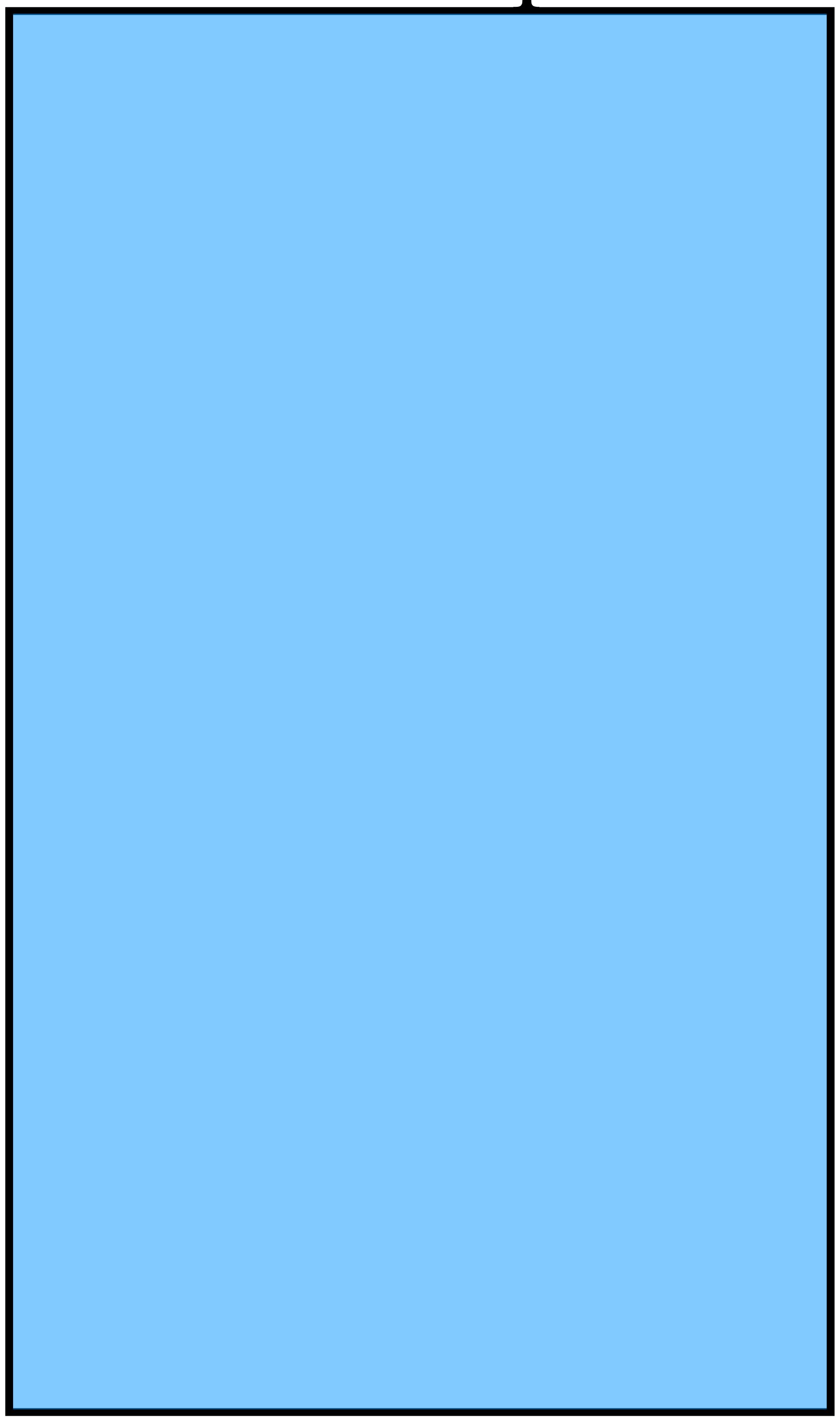
allocator must also adhere to alignment requirements (to help optimize cache/memory fetches)


"block"
metadata
payload
padding (for alignment)
internal fragmentation

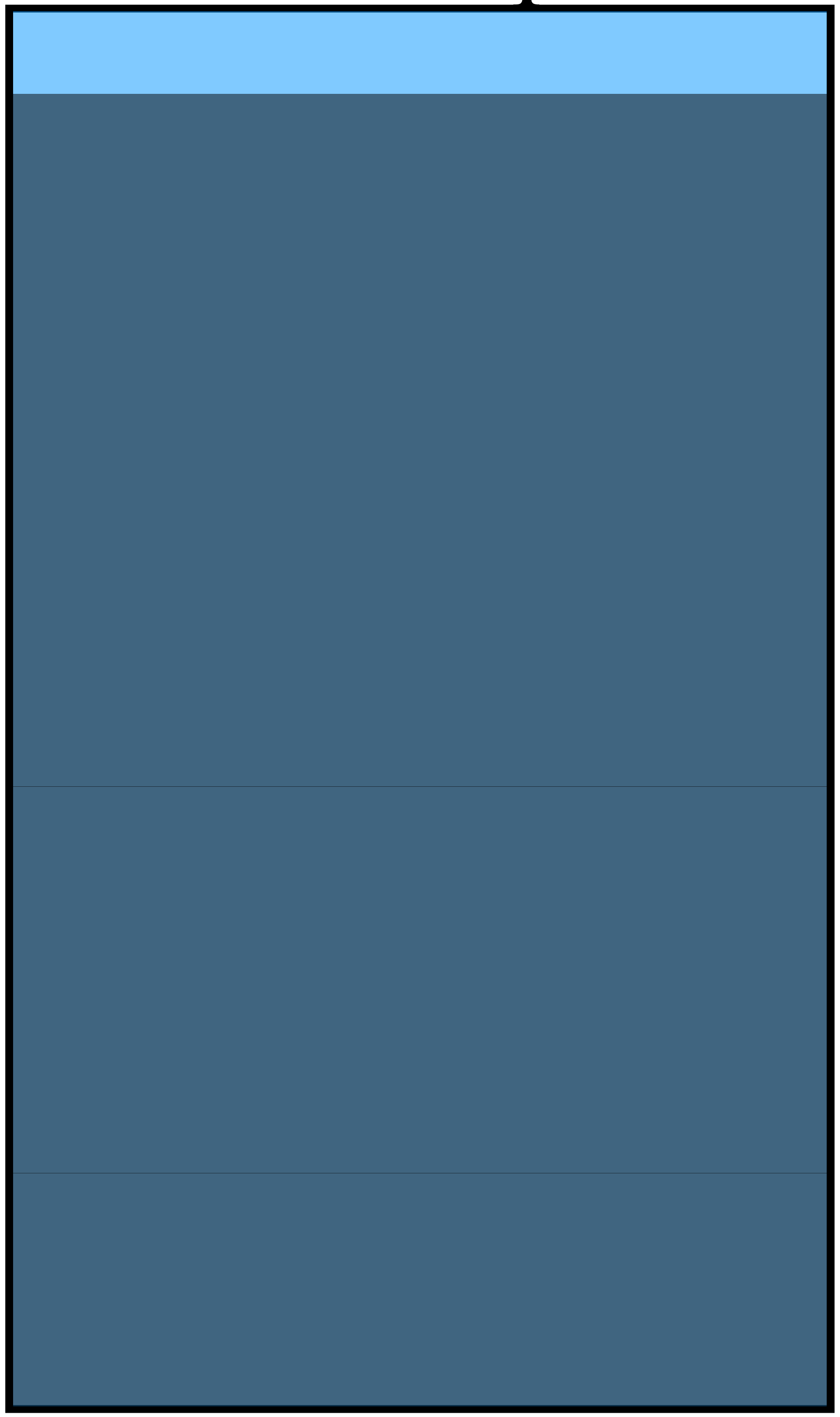
amount of internal fragmentation is *easy to predict*, as it's based on *pre-determined* factors

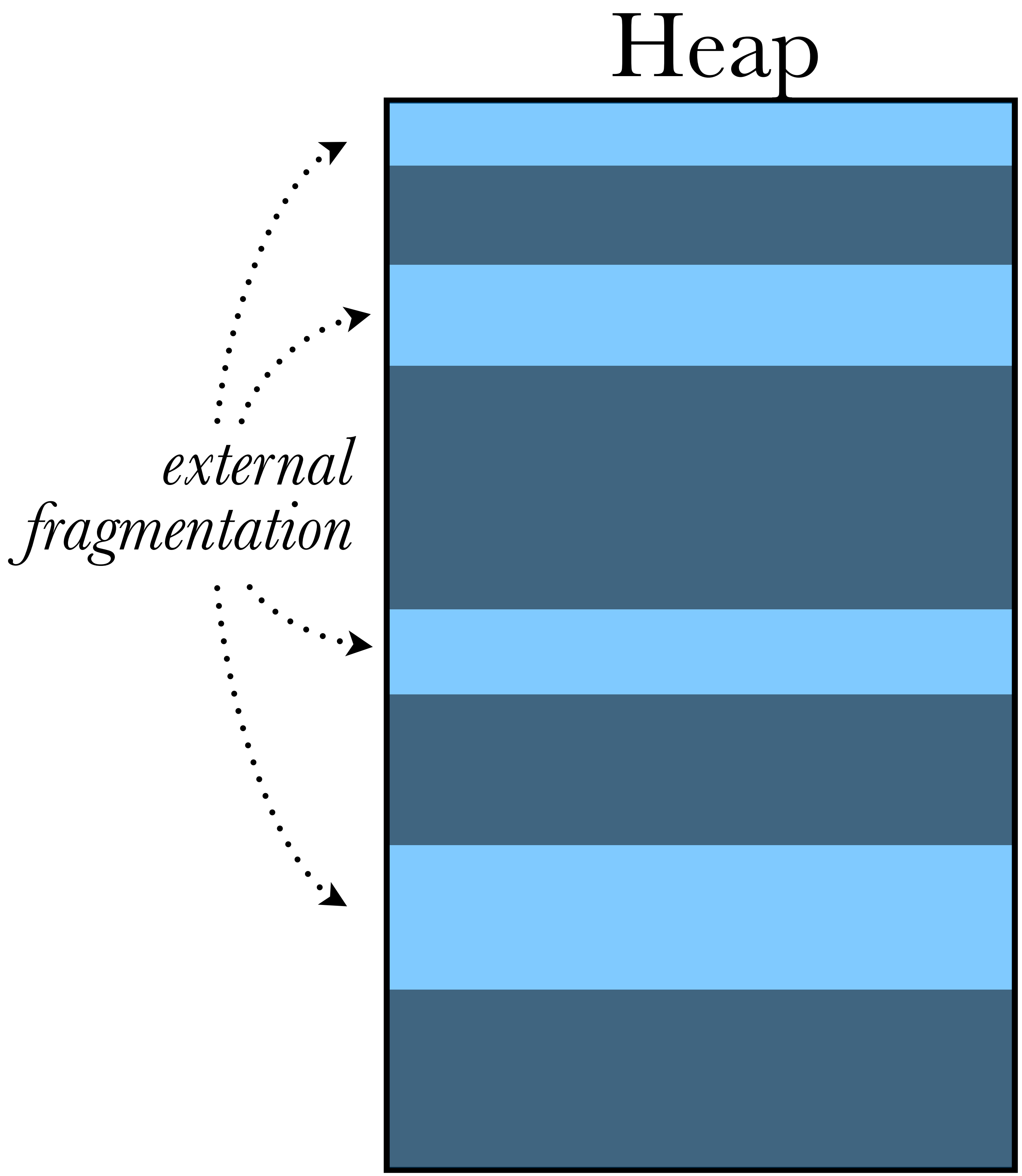
- metadata = fixed amount
- k-byte alignment → max $k-1$ padding

Heap

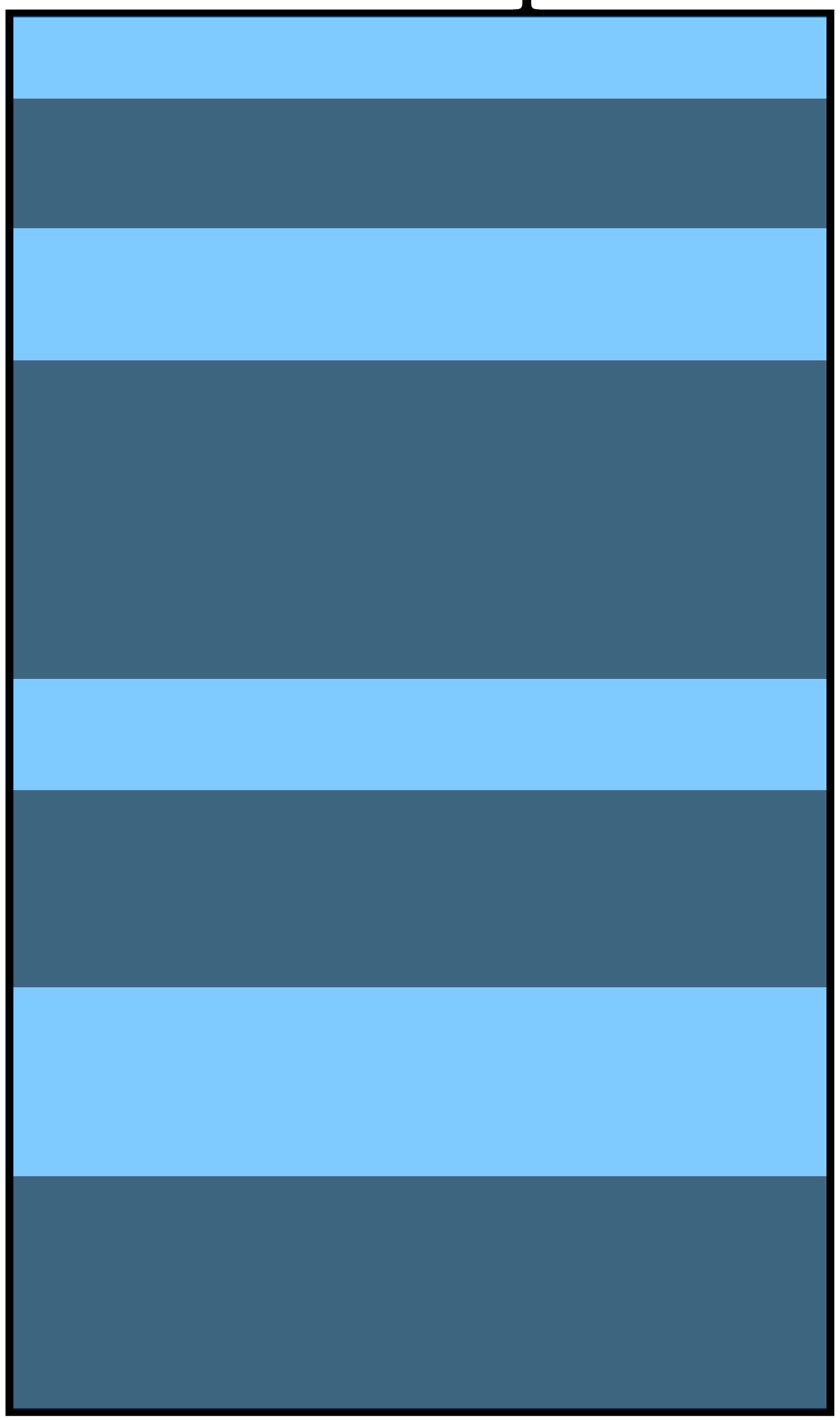


Heap



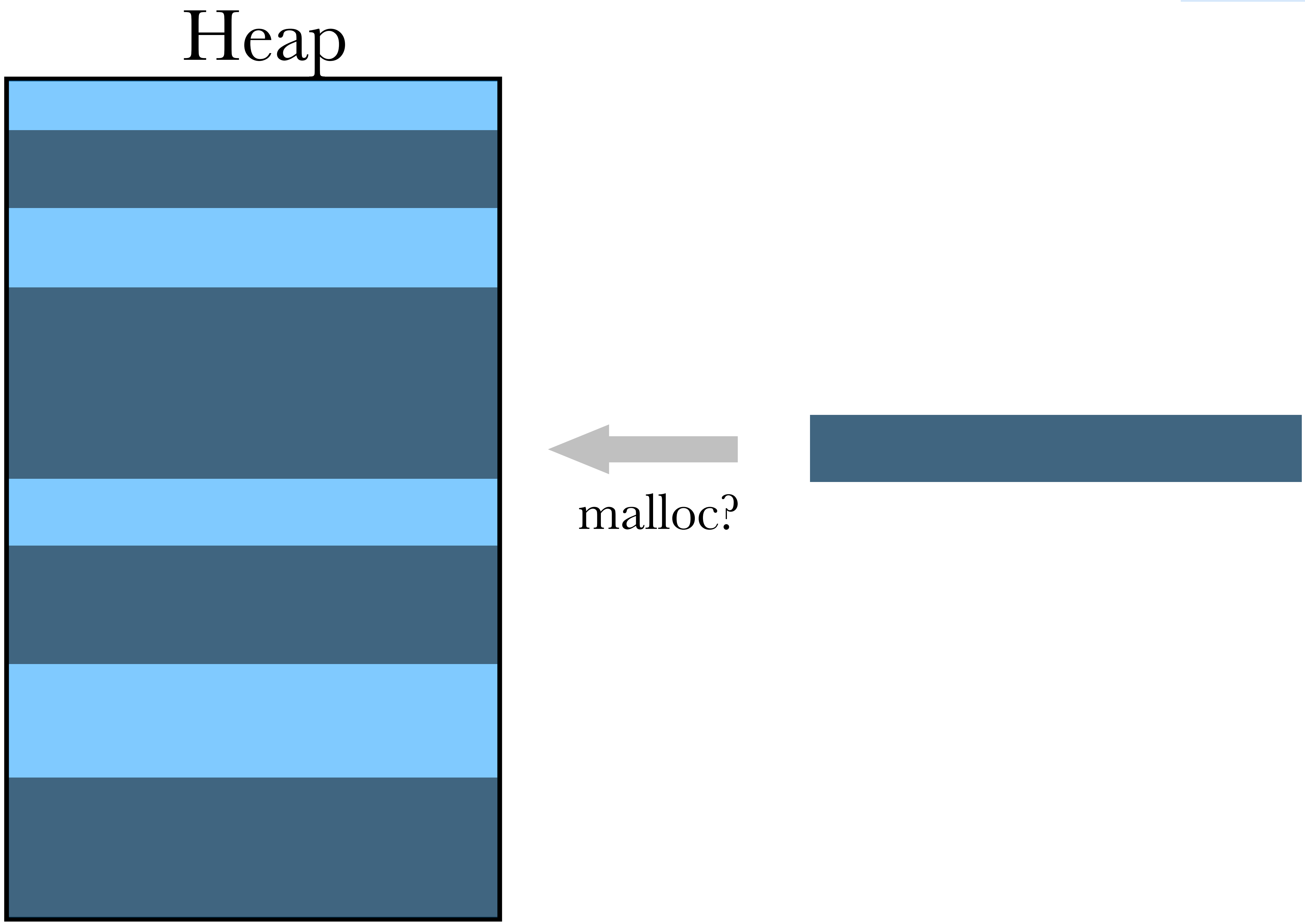

Heap
external fragmentation

Heap

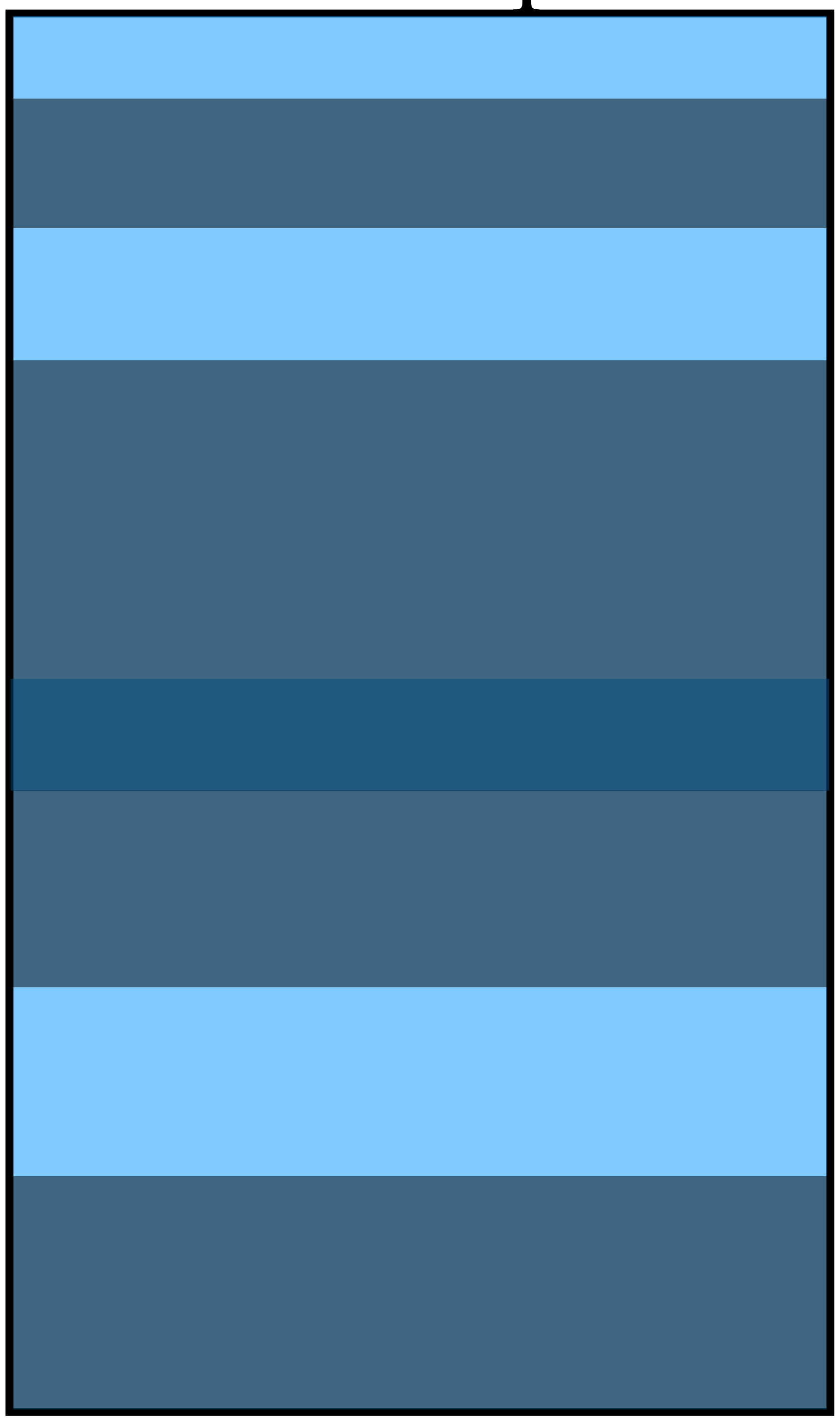


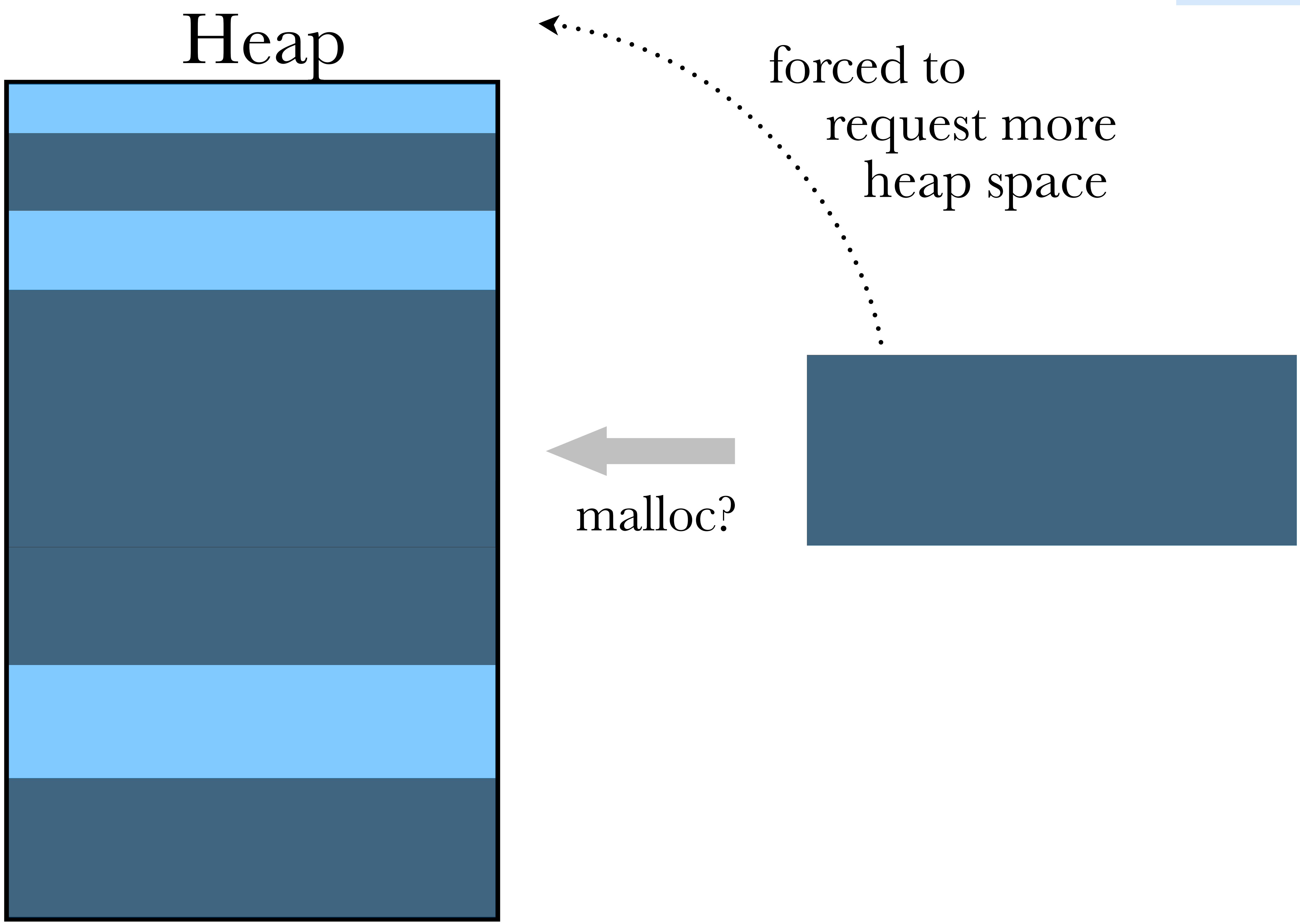
external fragmentation may affect *future* heap utilization;

i.e., by preventing free space from being re-used


Heap
malloc?

Heap




Heap
forced to
request more
heap space
malloc?

hard to predict the effect of external fragmentation on utilization

in general, we might:

- prefer fewer, larger spans of free space
- try to keep similarly sized blocks together in memory

but these recommendations are *heuristics*!

- may be defeated by pathological cases
- don't account for real-world behavior

It has been proven that for any possible allocation algorithm, there will ***always be the possibility*** *that some application program will allocate and deallocate blocks in some fashion that* ***defeats the allocator's strategy and forces it into severe fragmentation*** *... Not only are there no provably good allocation algorithms, there are proofs that* ***any allocator will be bad for some possible applications****.*

P. Wilson, M. Johnstone, M. Neely, D. Boles,

Dynamic Memory Allocation: A Survey and Critical Review