Princeton University

Computer Science 217: Introduction to Programming Systems

Dynamic Memory Management

Goals of this Lecture

Help you learn about:

- The need for dynamic* memory mgmt (DMM)
- Implementing DMM using the heap section
- Implementing DMM using virtual memory

* During program execution

System-Level Functions Covered

As noted in the ***Processes and Exceptions*** lecture…

Linux system-level functions for **dynamic memory management (DMM)**

Function	Description
brk()	Move the program break, thus changing the amount of memory allocated to the HEAP
sbrk()	(Variant of previous)
mmap()	Map a virtual memory page
munmap()	Unmap a virtual memory page

Agenda

The need for DMM

DMM using the heap section

DMM system 1: Minimal implementation

DMM system 2: Pad implementation

Fragmentation

DMM system 3: List implementation

DMM system 4: Doubly-linked list implementation

DMM system 5: Bins implementation

DMM using virtual memory

DMM system 6: VM implementation

Why Allocate Memory Dynamically?

Why **allocate** memory dynamically?

Problem

- Unknown object size
  - E.g. unknown element count in array
  - E.g. unknown node count in linked list or tree
- How much memory to allocate?

Solution 1

- Guess (i.e., fixed size buffers. i.e., problems!)

Solution 2

- Allocate memory dynamically

Why Free Memory Dynamically?

Why **free** memory dynamically?

Problem

- Program should use little memory, i.e.
- Program should **map** few pages of virtual memory
  - Mapping unnecessary VM pages bloats page tables, wastes memory/disk space

Solution

- Free dynamically allocated memory that is no longer needed

Option A: Automatic Freeing

Run-time system frees unneeded memory

- Java, Python, …
- **Garbage collection**

Pros:

- Easy for programmer

Cons:

- Hard to reason about
- Performed constantly => overhead
- Performed periodically => unexpected pauses

```
Car c;
Plane p;
...
c = new Car();
p = new Plane();
...
c = new Car();
...
```

Original Car object can’t be accessed

Option B: Manual Freeing

Programmer frees unneeded memory

- C, C++ raw pointers, Objective-C, …

Pros

- Less overhead
- No unexpected pauses

Cons

- More complex for programmer
- Opens possibility of memory-related bugs
  - Dereferences of dangling pointers, double frees, memory leaks

Option A vs. Option B

Implications…

If you can, use an automatic-freeing language

- Such as Java or Python

If you must, use a manual-freeing language

- Such as C
- For OS kernels, device drivers, garbage collectors, dynamic memory managers, real-time applications, …

We'll focus on **manual** freeing

Standard C DMM Functions

Standard C DMM functions:

```
void *malloc(size_t size);
void  free(void *ptr);
void *calloc(size_t nmemb, size_t size);
void *realloc(void *ptr, size_t size);
```

Collectively define a **dynamic memory manager**

We’ll focus on **`malloc()`** and **`free()`**

Goals for DMM

Goals for effective DMM:

- **Time** efficiency
  - Allocating and freeing memory should be fast
- **Space** efficiency
  - Program should use little memory

Note

- Easy to reduce time **or** space
- Hard to reduce time **and** space

Implementing malloc() and free()

Question:

- How to implement **`malloc()`** and **`free()`**?
- How to implement a DMM system?

Answer 1 (familiar):

- Use the heap section of memory
- We'll focus on this now

Answer 2 (advanced):

- Make use of a virtual memory concept…

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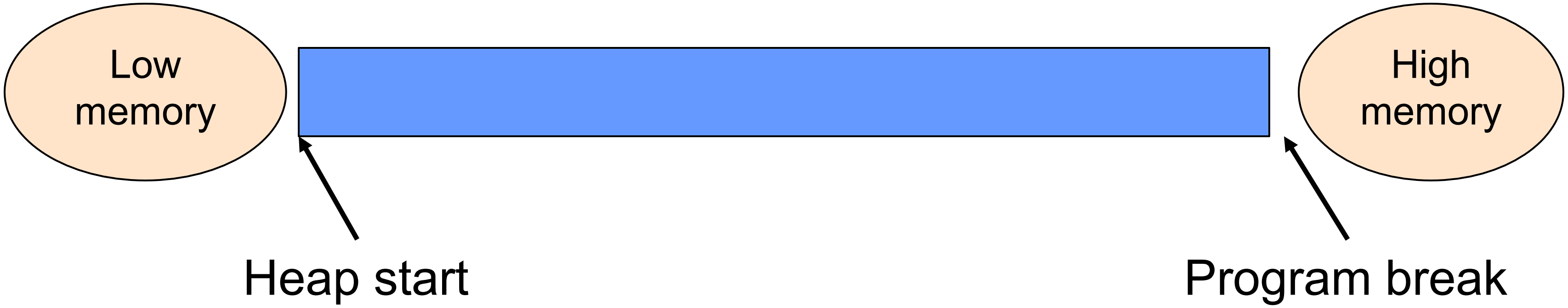
DMM using virtual memory

DMM system 6: VM implementation

The Heap Section of Memory



Supported by Unix/Linux, MS Windows, …

Heap start is stable

Program break points to end

At process start-up, heap start == program break

Can grow dynamically

- By moving program break to higher address
- Thereby (indirectly) mapping pages of virtual mem

Can shrink dynamically

- By moving program break to lower address
- Thereby (indirectly) unmapping pages of virtual mem

Unix Heap Management

Unix system-level functions for heap mgmt:

```
int brk(void *p);
```

- Move the program break to address **`p`**
- Return 0 if successful and -1 otherwise

```
void *sbrk(intptr_t n);
```

- (Deprecated) Increment the program break by **`n`** bytes, **`n ≠ 0`**
  - Return ptr to memory if successful and (void*)(–1) otherwise
  - Buggy, unreliable implementation in case of overflow
- **If `n` is 0, then return the current location of the program break**

Note: minimal interface (good!)

Agenda

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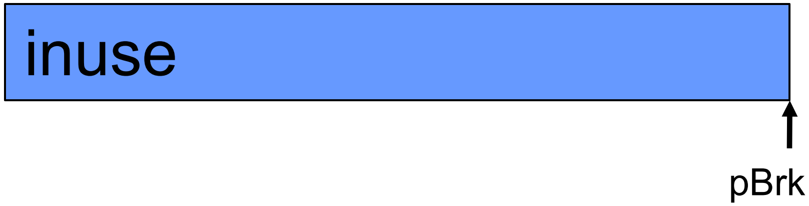
DMM using virtual memory

DMM system 6: VM implementation

Minimal Impl

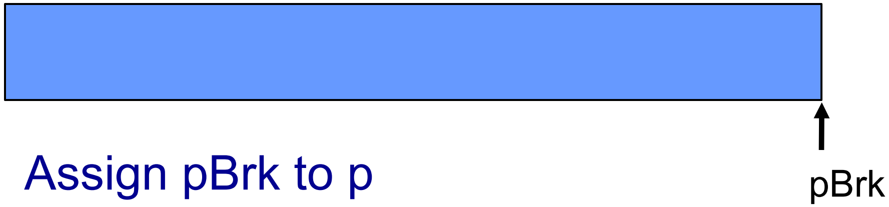
Data structures



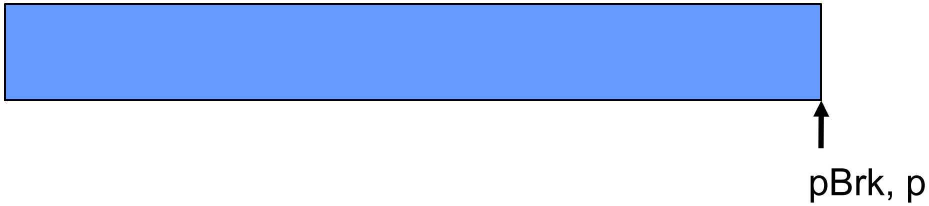
- **`pBrk`**: address of end of heap (i.e. the program break)

Algorithms (by examples)…

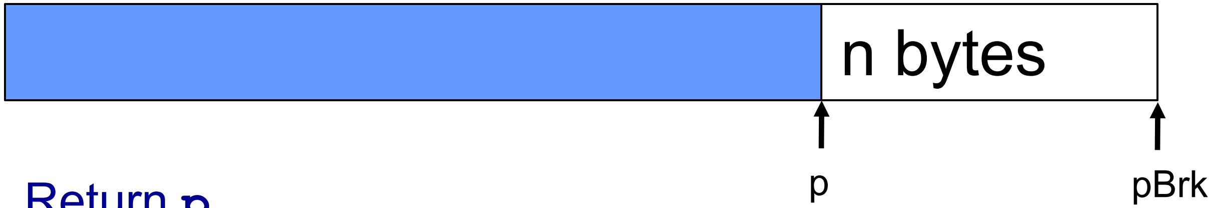
Minimal Impl malloc(n) Example



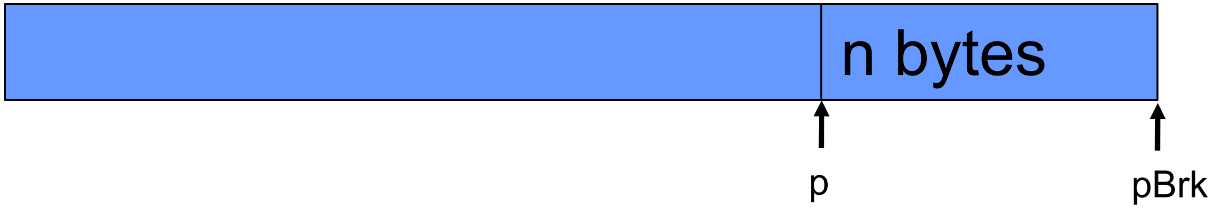
Assign pBrk to p



Call **`brk(p+n)`** to increase heap size, change pBrk



Return **`p`**



Minimal Impl free(p) Example

Do nothing!

Minimal Impl

```
void *malloc(size_t n)
{   static char *pBrk;
    char *p = pBrk;
    if (pBrk == NULL)
       p = pBrk = sbrk(0);
    if (brk(p + n) == -1)
       return NULL;
    pBrk = p + n;
    return p;
}
```

```
void free(void *p)
{
}
```

Minimal Impl Performance

Performance (general case)

- **Time**: bad
  - One system call per `malloc()`
- **Space**: bad
  - Each call of `malloc()` extends heap size
  - No reuse of freed chunks

Priority problem

- `malloc()` executes a system call each time

Solution

- Redesign `malloc()` so it does fewer system calls
- Maintain a pad at the end of the heap…

Agenda

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DMM system 4: Doubly-linked list implementation

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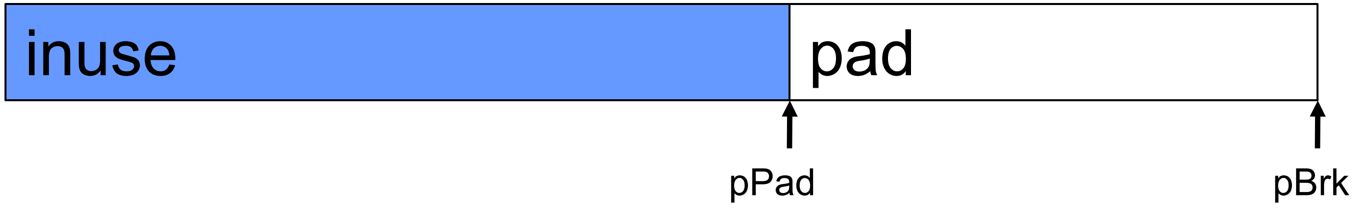
DMM using virtual memory

DMM system 6: VM implementation

Pad Impl

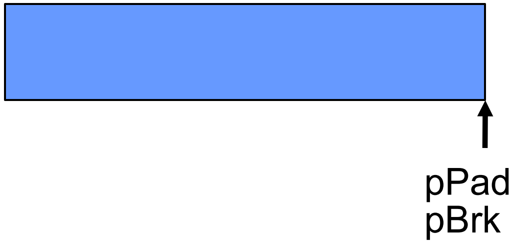
Data structures



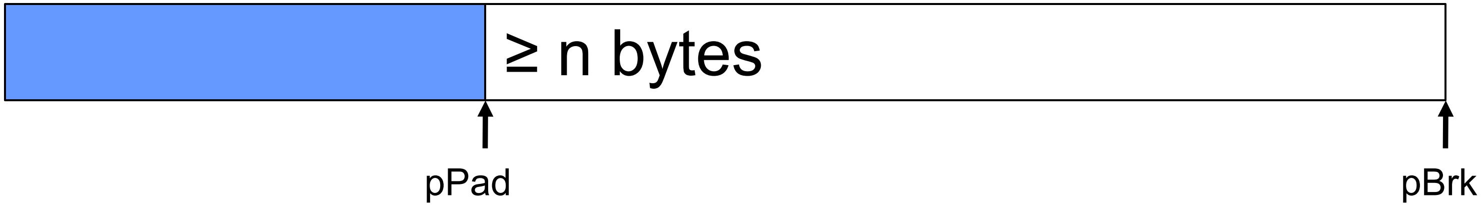
- **`pBrk`**: address of end of heap (i.e. the program break)
- **`pPad`**: address of beginning of pad

Algorithms (by examples)…

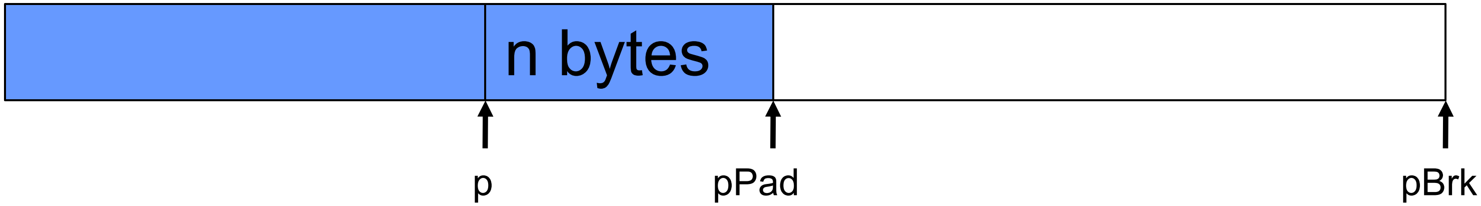
Pad Impl malloc(n) Example 0



Are there at least **`n`** bytes between **`pPad`** and **`pBrk`**? **No**!
Call **`brk()`** to allocate (more than) enough additional memory

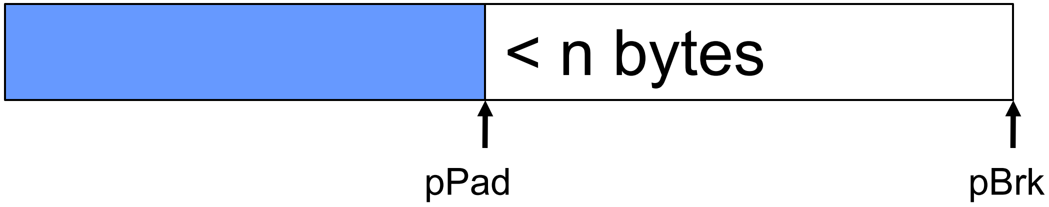


Set **`pBrk`** to new program break

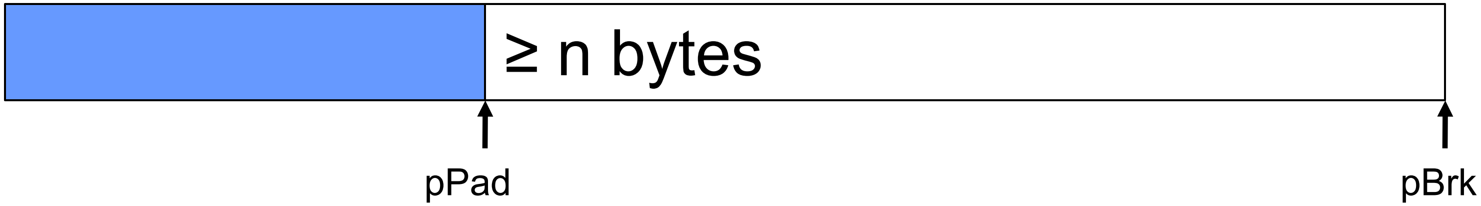


Save **`pPad`** as **`p`**; add **`n`** to **`pPad`**; return **`p`**

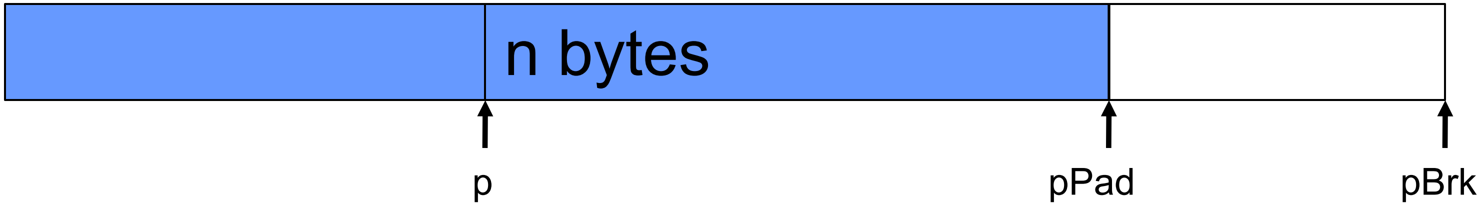
Pad Impl malloc(n) Example 1



Are there at least **n** bytes between **pPad** and **pBrk**? **No**!
Call **brk()** to allocate (more than) enough additional memory

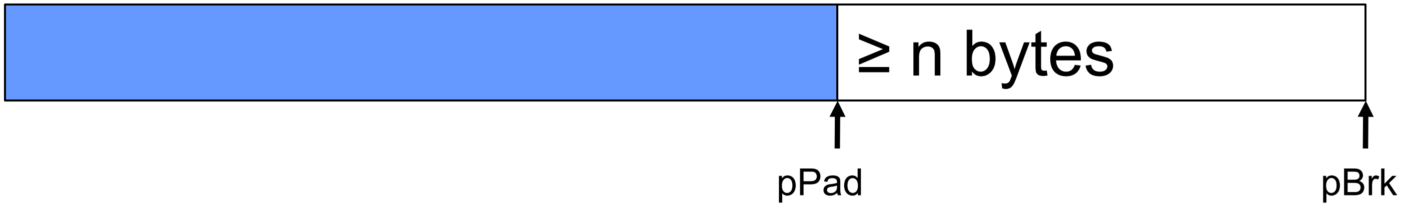


Set **pBrk** to new program break

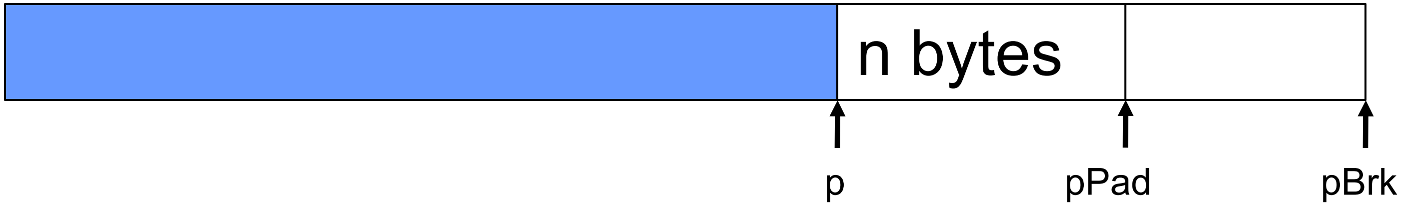


Save **pPad** as **p**; add **n** to **pPad**; return **p**

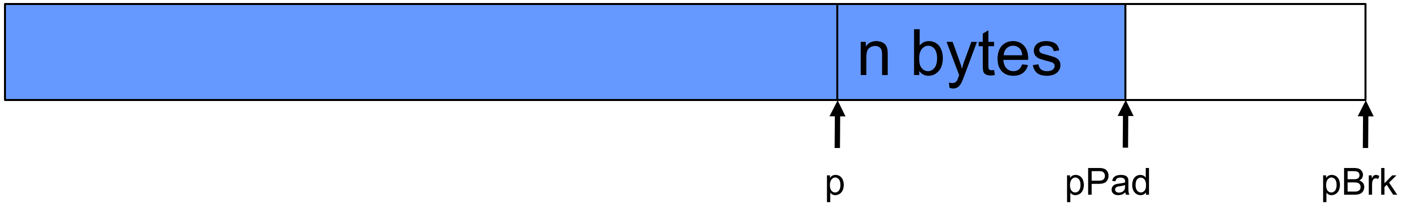
Pad Impl malloc(n) Example 2



Are there at least **`n`** bytes between **`pPad`** and **`pBrk`**? **Yes**!
Save **`pPad`** as **`p`**; add **`n`** to **`pPad`**

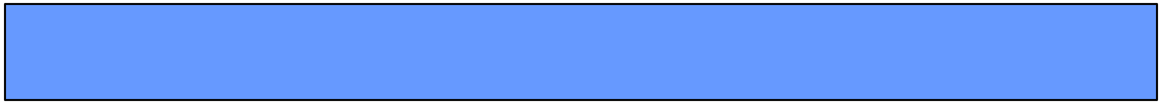


Return **`p`**



Pad Impl free(p) Example

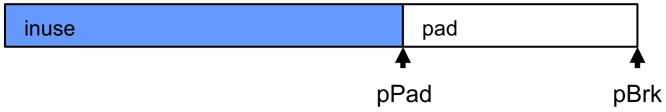
Do nothing!



Pad Impl

```
void *malloc(size_t n)
{  enum {MIN_ALLOC = 8192};
   static char *pPad = NULL;
   static char *pBrk = NULL;
   char *p;
   if (pBrk == NULL)
      pPad = pBrk = sbrk(0);
   if (pPad + n > pBrk) /* move pBrk */
   {  char *pNewBrk =
         max(pPad + n, pBrk + MIN_ALLOC);
      if (brk(pNewBrk) == -1) return NULL;
      pBrk = pNewBrk;
   }
   p = pPad;
   pPad += n;
   return p;
}
```

```
void free(void *p)
{
}
```



Pad Impl Performance

Performance (general case)

- **Time**: good
  - `malloc()` calls `sbrk()` initially
  - `malloc()` calls `brk()` infrequently thereafter
- **Space**: bad
  - No reuse of freed chunks

Priority problem

- `malloc()` doesn't reuse freed chunks

Solution

- `free()` marks freed chunks as "free"
- `malloc()` uses marked chunks whenever possible
- `malloc()` extends size of heap only when necessary

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Fragmentation

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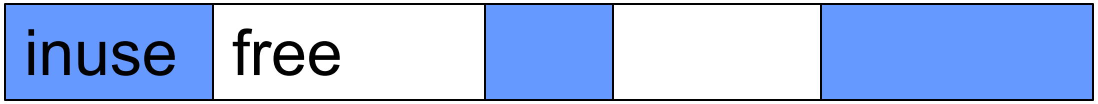
DMM system 6: VM implementation

Fragmentation

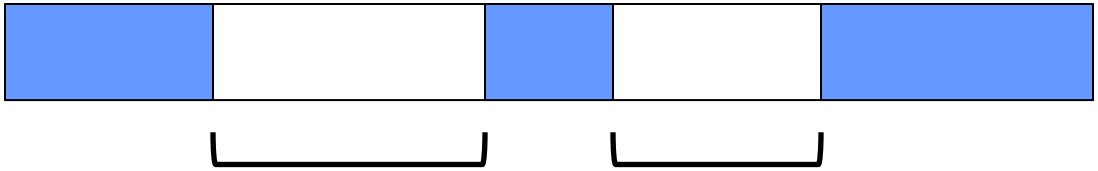
At any given time, some heap memory chunks are in use, some are marked "free"



DMM system must be concerned about **fragmentation**…

External Fragmentation

External fragmentation: waste because of **non-contiguous** chunks



Client asks for 150 bytes
150 bytes are available, but not contiguously
DMM system must extend size of heap

Generally

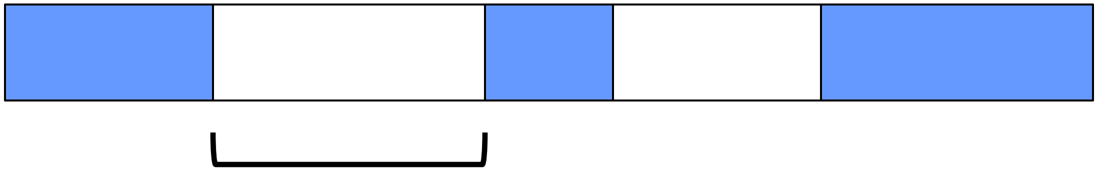
- Program asks for n bytes
- n bytes are available, but not contiguously
- DMM system must extend size of heap to satisfy request

Space efficiency =>

- DMM system should reduce external fragmentation

Internal Fragmentation

Internal fragmentation: waste **within** chunks



100 bytes

Client asks for 98 bytes
DMM system provides chunk of size 100 bytes
2 bytes wasted

Generally

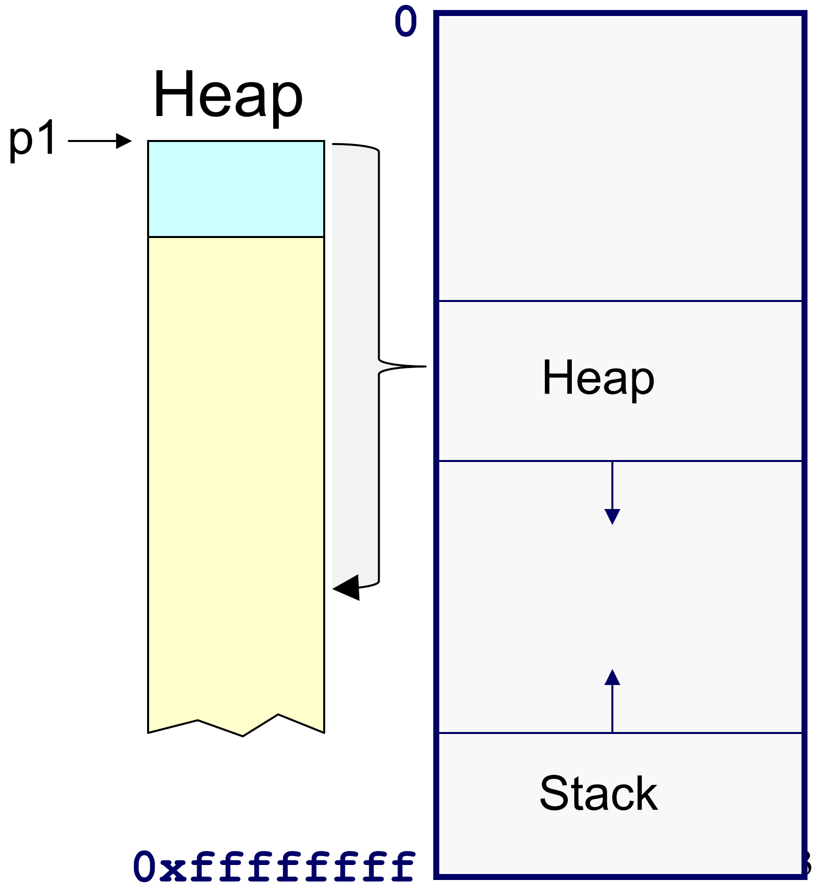
- Program asks for n bytes
- DMM system provides chunk of size n+Δ bytes
- Δ bytes wasted

Space efficiency =>

- DMM system should reduce internal fragmentation

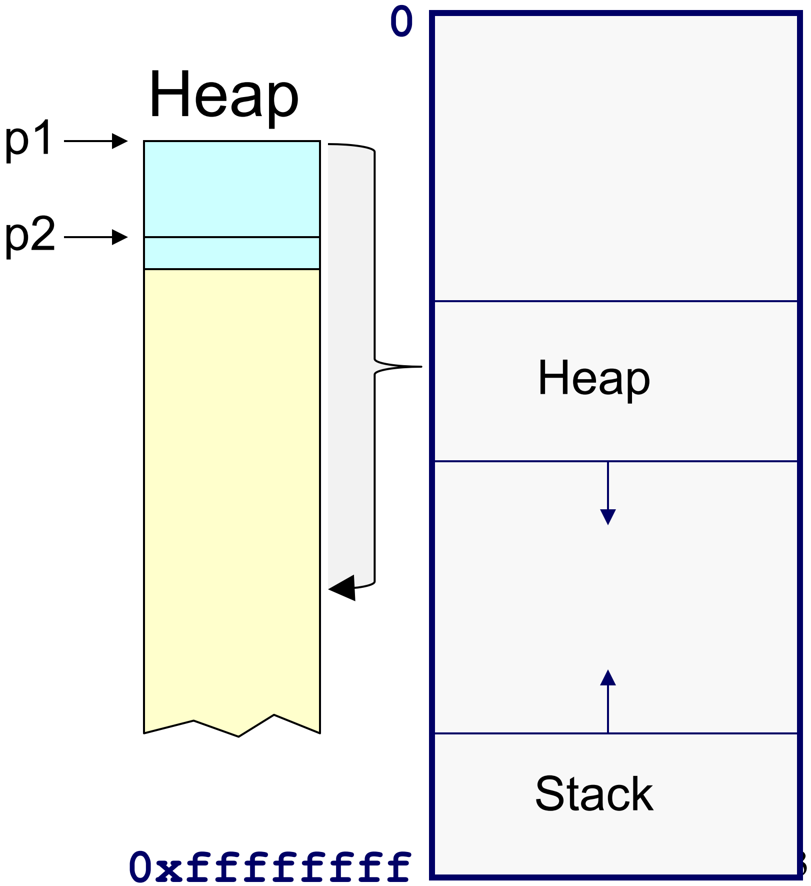
DMM Desired Behavior Demo

```
char *p1 = malloc(3);
char *p2 = malloc(1);
char *p3 = malloc(4);
free(p2);
char *p4 = malloc(8);
free(p3);
char *p5 = malloc(2);
free(p1);
free(p4);
free(p5);
```



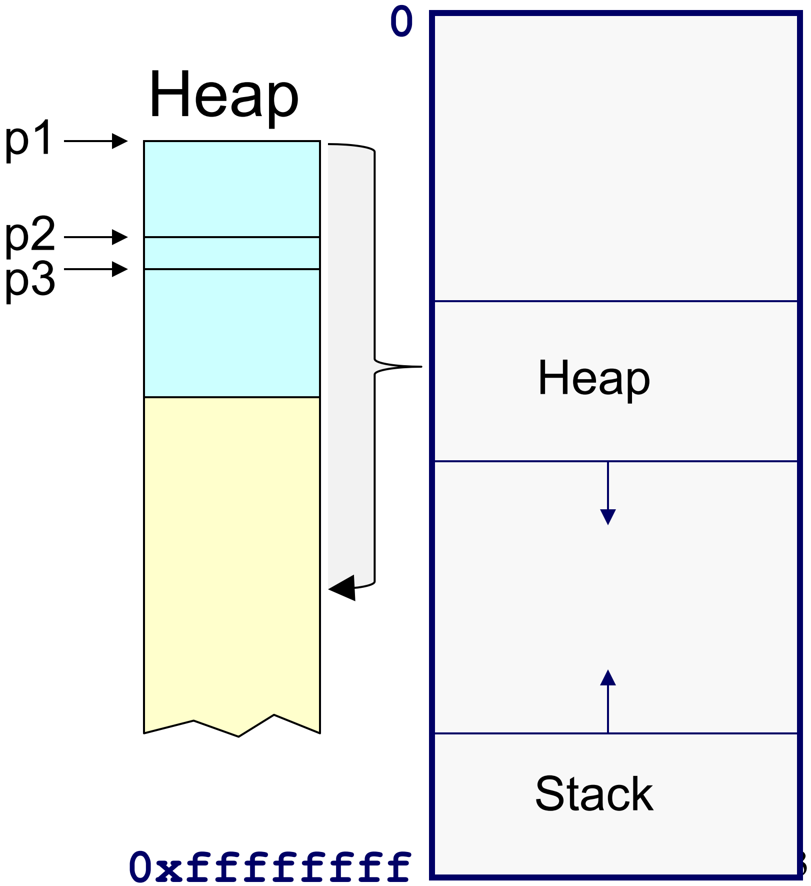
DMM Desired Behavior Demo

```
char *p1 = malloc(3);
char *p2 = malloc(1);
char *p3 = malloc(4);
free(p2);
char *p4 = malloc(8);
free(p3);
char *p5 = malloc(2);
free(p1);
free(p4);
free(p5);
```



DMM Desired Behavior Demo

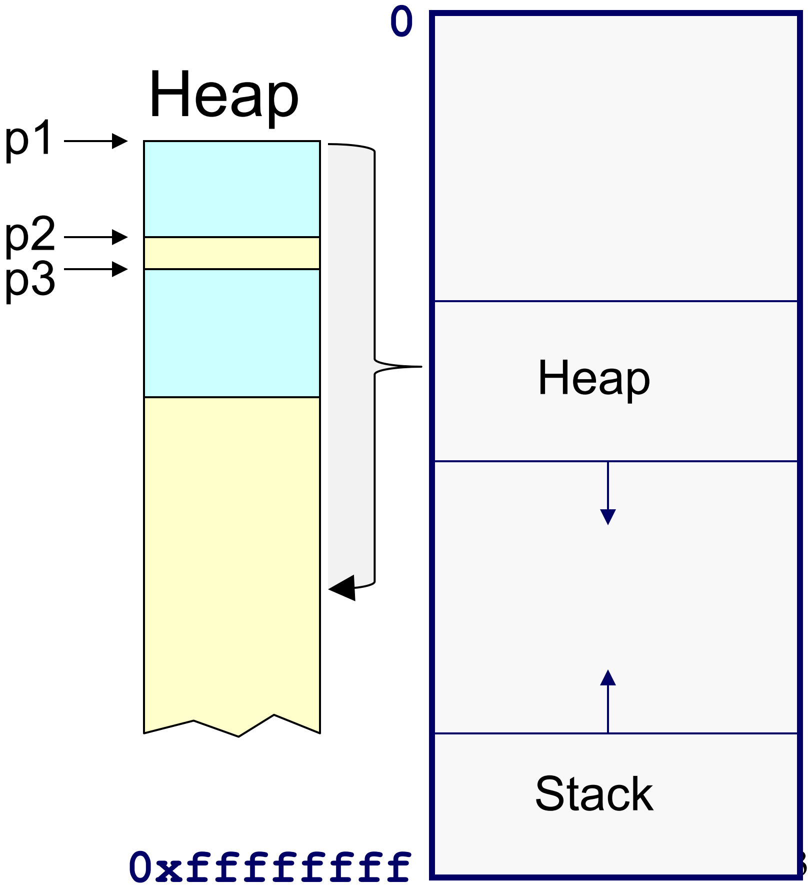
```
char *p1 = malloc(3);
char *p2 = malloc(1);
char *p3 = malloc(4);
free(p2);
char *p4 = malloc(8);
free(p3);
char *p5 = malloc(2);
free(p1);
free(p4);
free(p5);
```



DMM Desired Behavior Demo

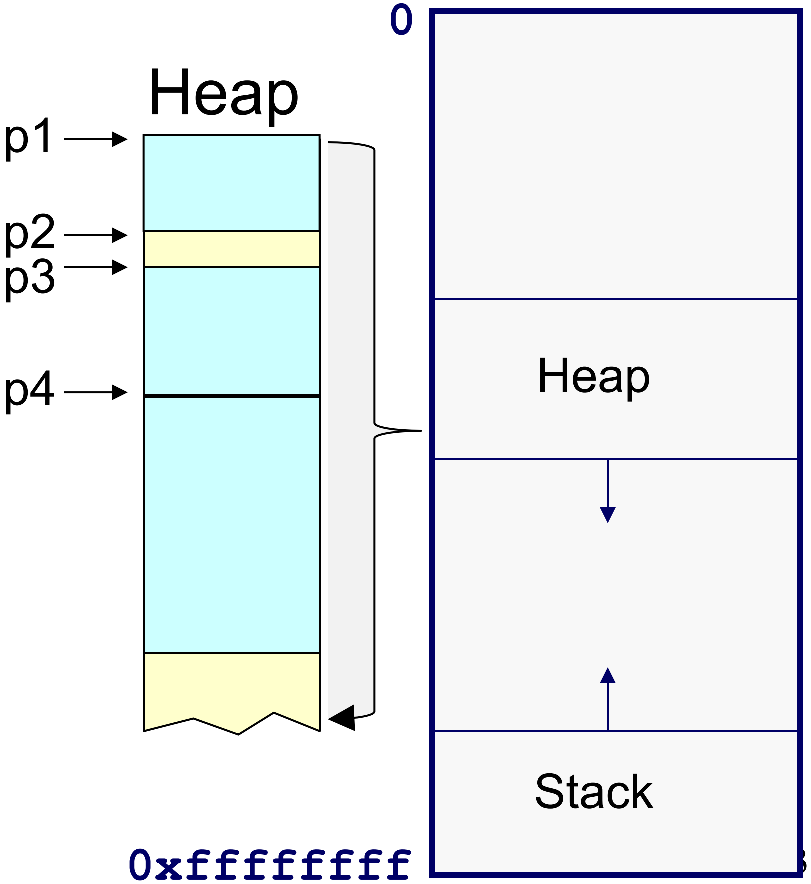
External fragmentation!

```
char *p1 = malloc(3);
char *p2 = malloc(1);
char *p3 = malloc(4);
free(p2);
char *p4 = malloc(8);
free(p3);
char *p5 = malloc(2);
free(p1);
free(p4);
free(p5);
```



DMM Desired Behavior Demo

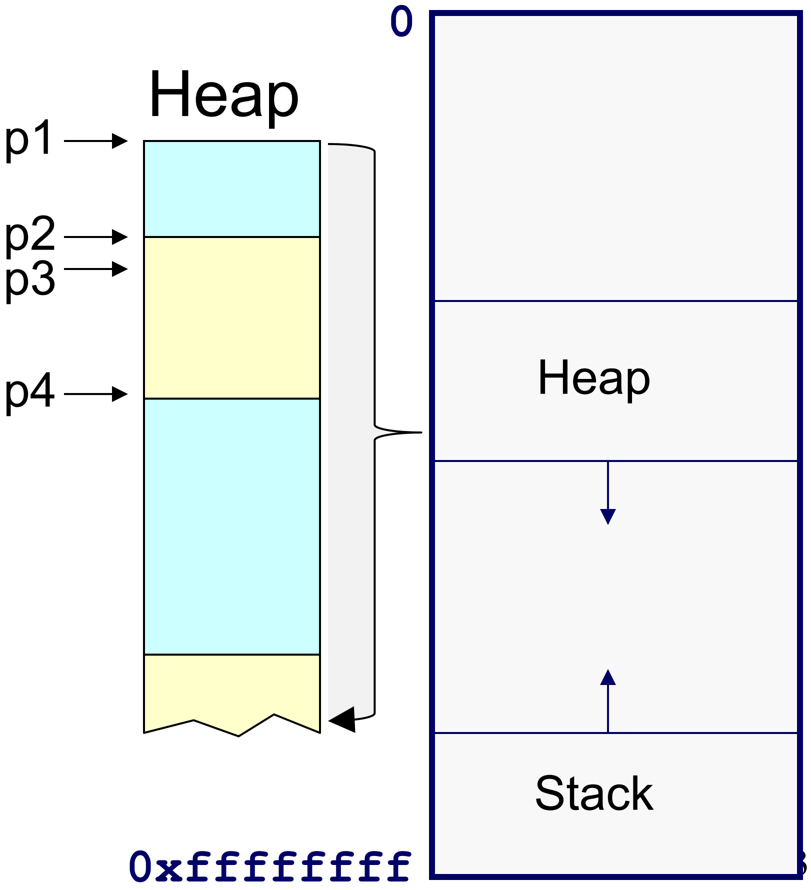
```
char *p1 = malloc(3);
char *p2 = malloc(1);
char *p3 = malloc(4);
free(p2);
char *p4 = malloc(8);
free(p3);
char *p5 = malloc(2);
free(p1);
free(p4);
free(p5);
```



DMM Desired Behavior Demo

DMM system coalesced two free chunks

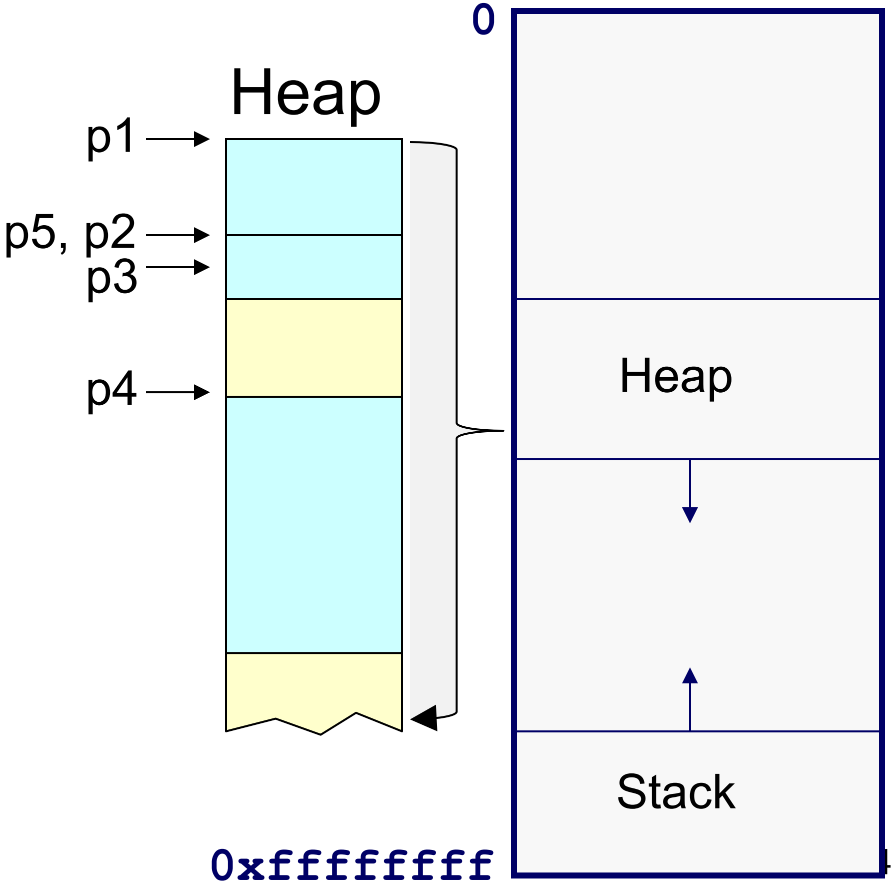
```
char *p1 = malloc(3);
char *p2 = malloc(1);
char *p3 = malloc(4);
free(p2);
char *p4 = malloc(8);
free(p3);
char *p5 = malloc(2);
free(p1);
free(p4);
free(p5);
```



DMM Desired Behavior Demo

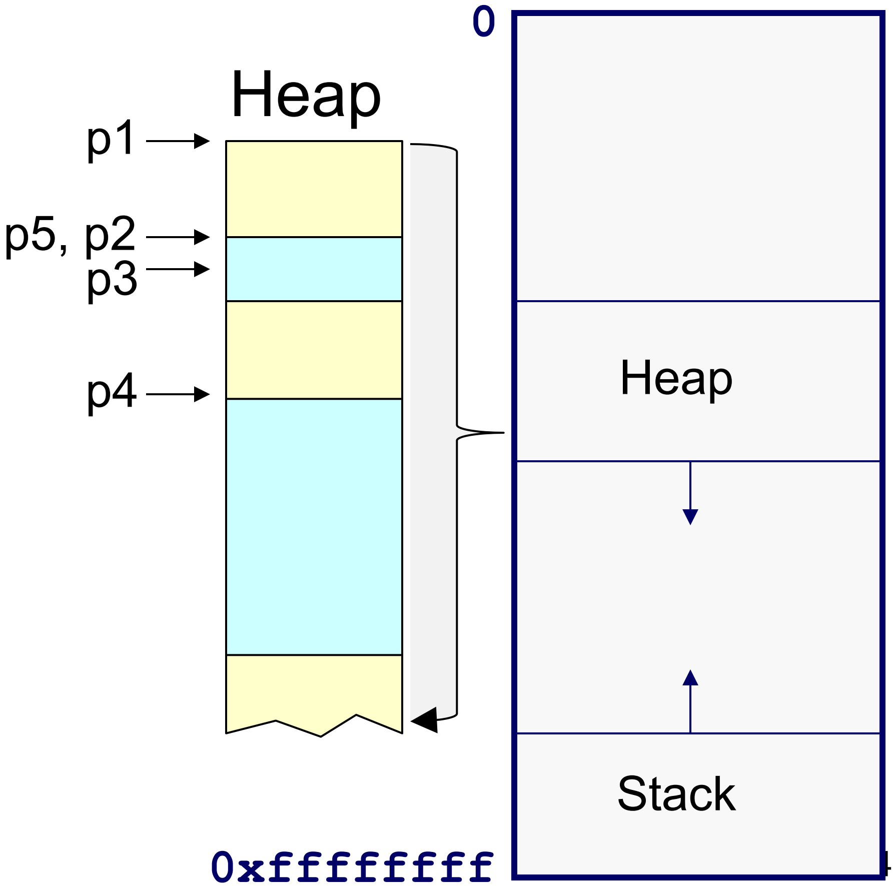
DMM system reused previously freed chunk

```
char *p1 = malloc(3);
char *p2 = malloc(1);
char *p3 = malloc(4);
free(p2);
char *p4 = malloc(8);
free(p3);
char *p5 = malloc(2);
free(p1);
free(p4);
free(p5);
```



DMM Desired Behavior Demo

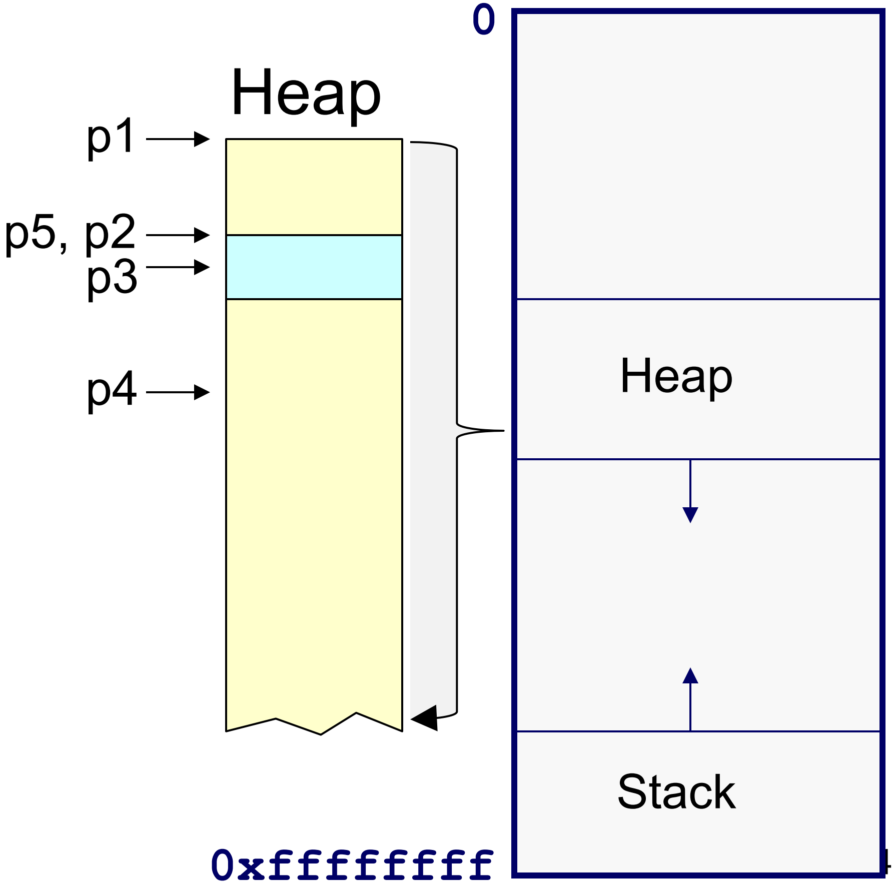
```
char *p1 = malloc(3);
char *p2 = malloc(1);
char *p3 = malloc(4);
free(p2);
char *p4 = malloc(8);
free(p3);
char *p5 = malloc(2);
free(p1);
free(p4);
free(p5);
```



DMM Desired Behavior Demo

DMM system coalesced two (three!) free chunks

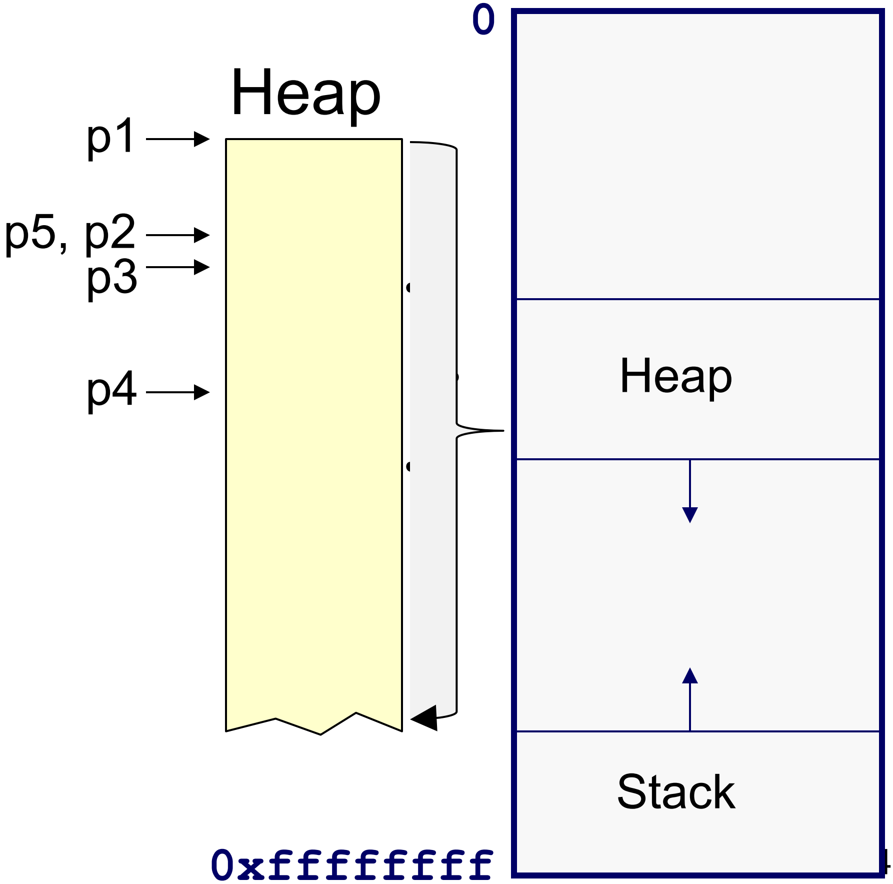
```
char *p1 = malloc(3);
char *p2 = malloc(1);
char *p3 = malloc(4);
free(p2);
char *p4 = malloc(8);
free(p3);
char *p5 = malloc(2);
free(p1);
free(p4);
free(p5);
```



DMM Desired Behavior Demo

DMM system coalesced two (three!) free chunks

```
char *p1 = malloc(3);
char *p2 = malloc(1);
char *p3 = malloc(4);
free(p2);
char *p4 = malloc(6);
free(p3);
char *p5 = malloc(2);
free(p1);
free(p4);
free(p5);
```



DMM Desired Behavior Demo

DMM system cannot:

- Reorder requests
  - Client may allocate & free in arbitrary order
  - Any allocation may request arbitrary number of bytes
- Move memory chunks to improve performance
  - Client stores addresses
  - Moving a memory chunk would invalidate client pointer!

Some external fragmentation is unavoidable

Agenda

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DMM system 2: Pad implementation

Fragmentation

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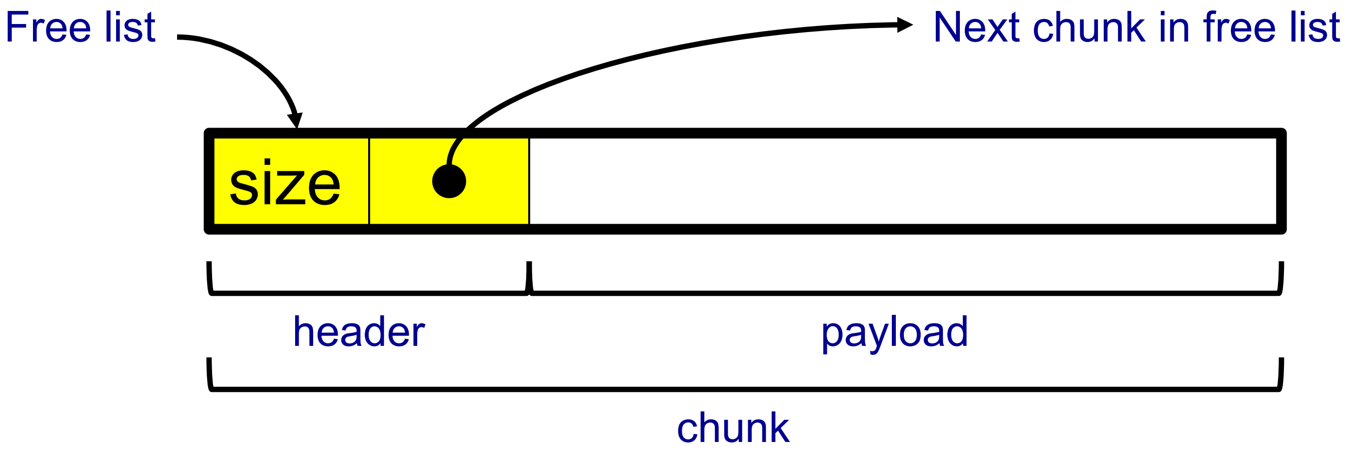
DMM system 5: Bins implementation

DMM using virtual memory

DMM system 6: VM implementation

List Impl

Data structures



Free list contains all free chunks

In order by mem addr

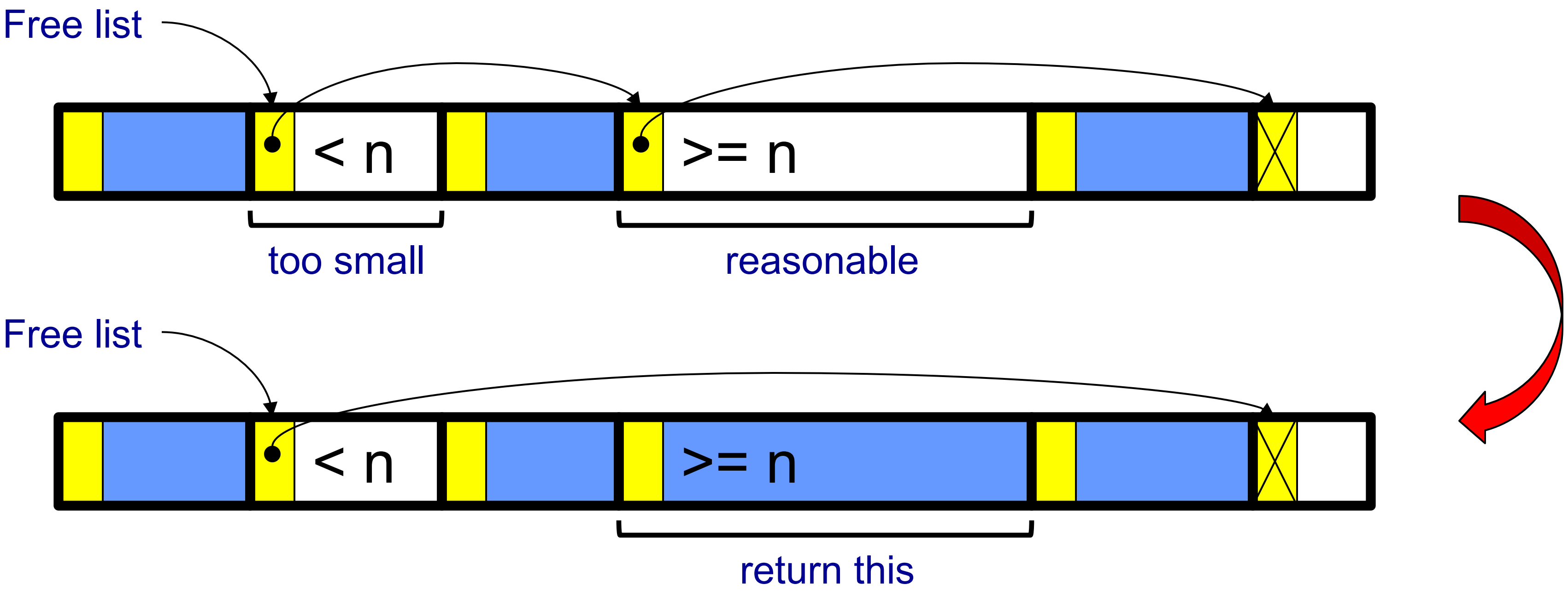
Each chunk contains header & payload

Payload is used by client

Header contains chunk size & (if free) addr of next chunk in free list

Algorithms (by examples)…

List Impl: malloc(n) Example 1



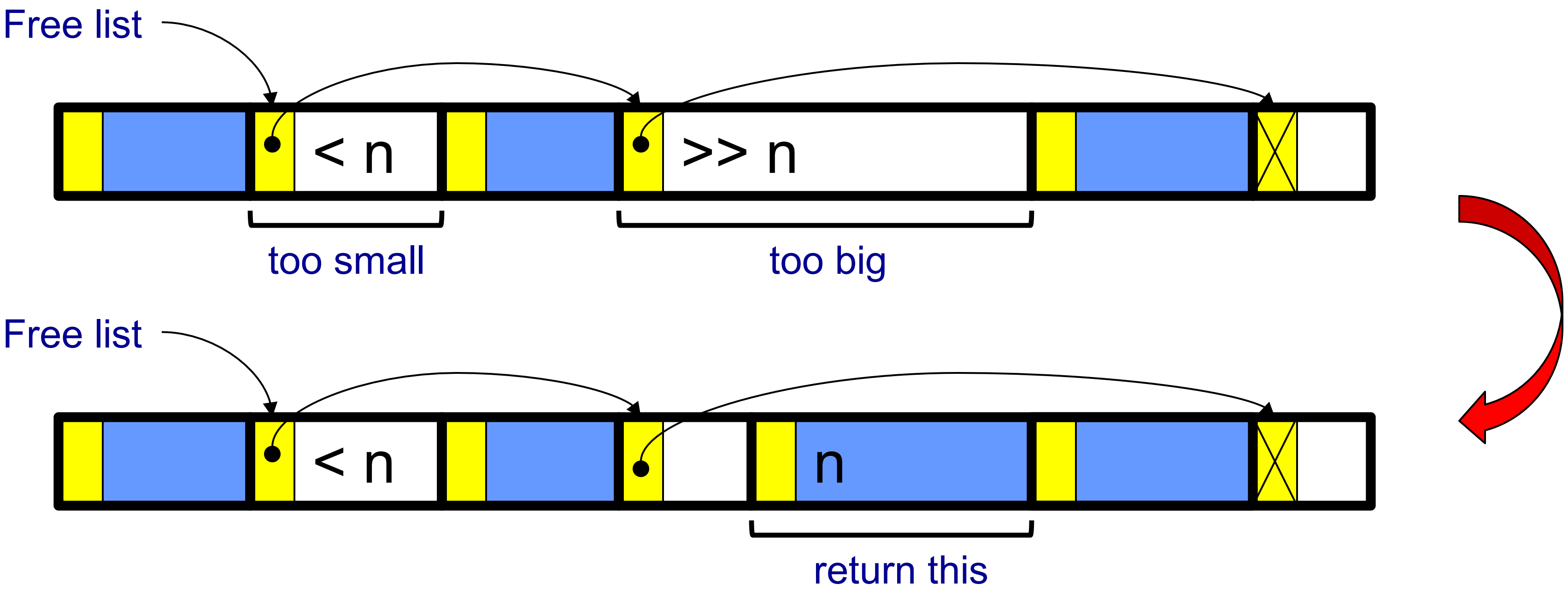
Search list for big-enough chunk

Note: **first-fit** (not **best-fit**) strategy

Found & reasonable size =>

Remove from list and return payload

List Impl: malloc(n) Example 2



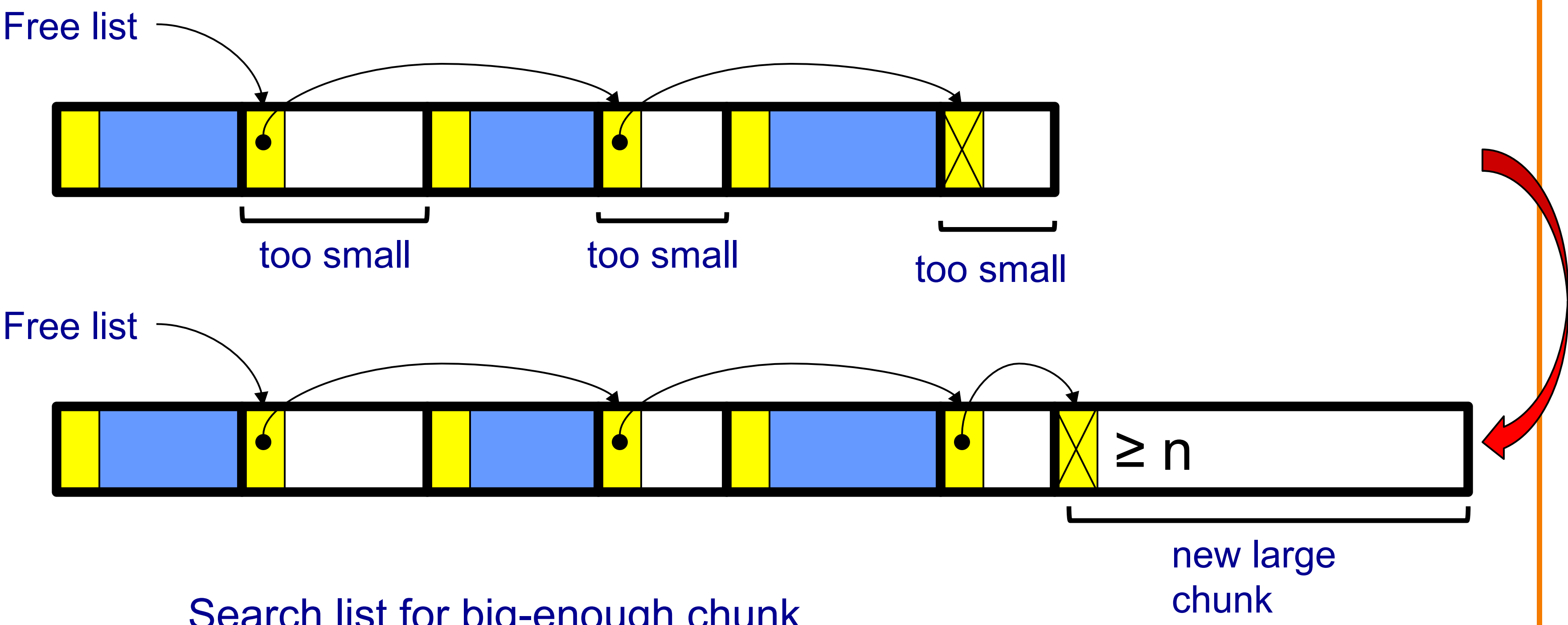
Search list for big-enough chunk

Found & too big =>

Split chunk, return payload of tail end

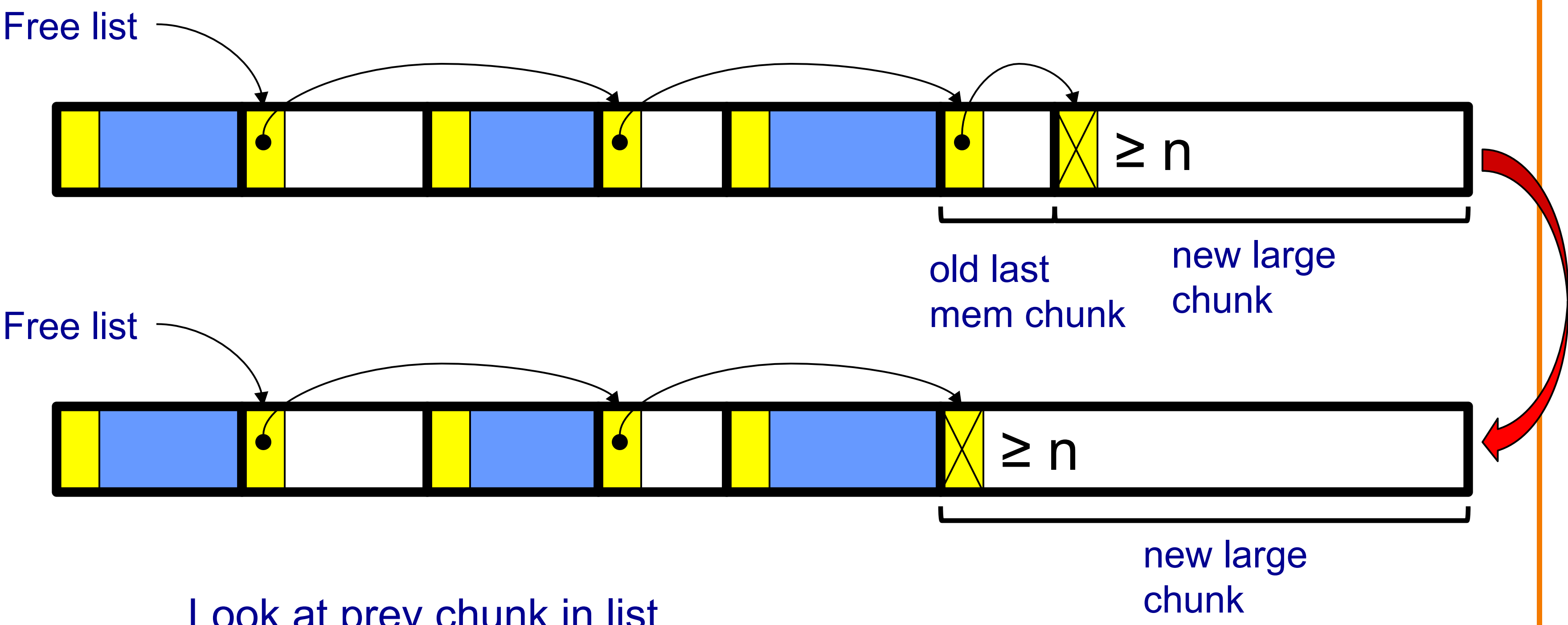
Note: Need not change links

List Impl: malloc(n) Example 3



Search list for big-enough chunk
None found =>
    Call **`brk()`** to increase heap size
    Insert new chunk at end of list
(Not finished yet!)

List Impl: malloc(n) Example 3 (cont.)



Look at prev chunk in list

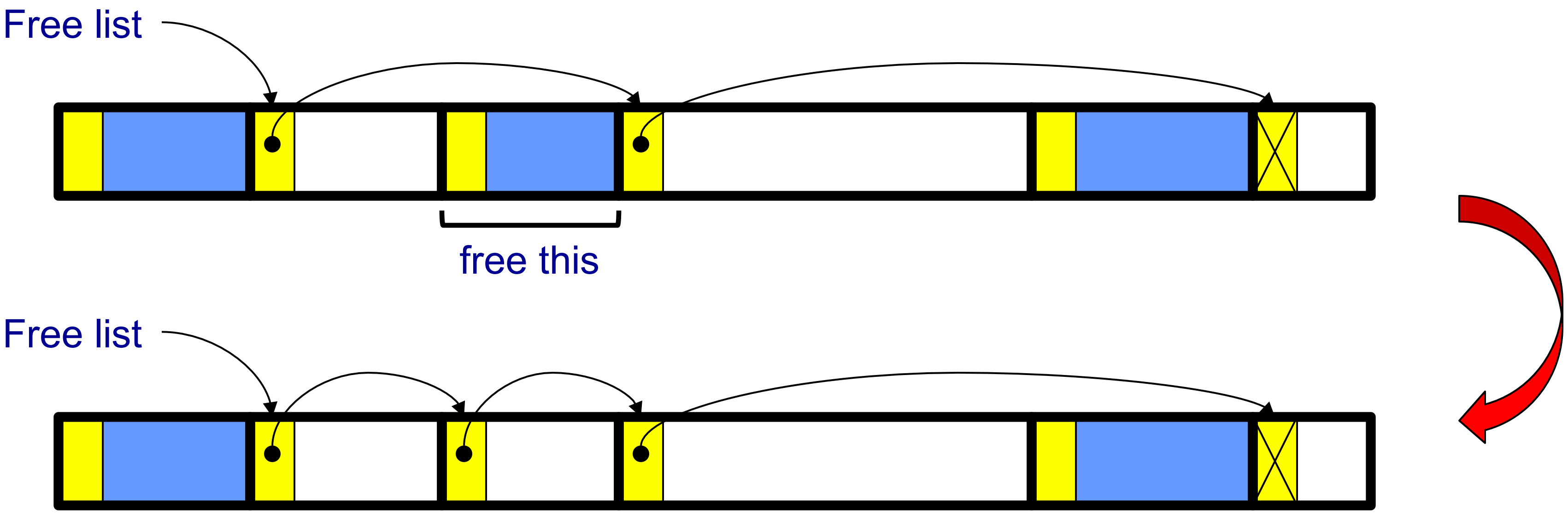
Next chunk memory == next chunk in list =>

- Remove both chunks from list
- Coalesce
- Insert chunk into list

Then proceed to use the new chunk, as before

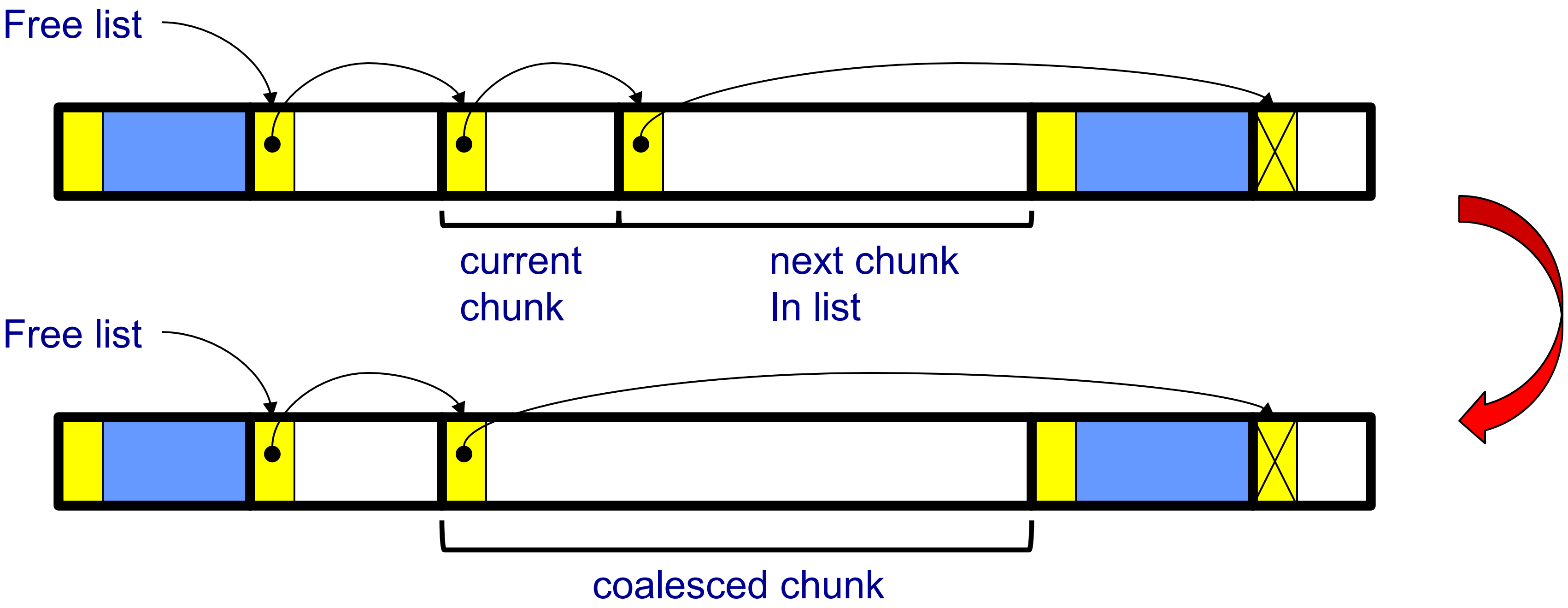
(Finished!)

List Impl: free(p) Example



Search list for proper insertion spot
Insert chunk into list
(Not finished yet!)

List Impl: free(p) Example (cont.)



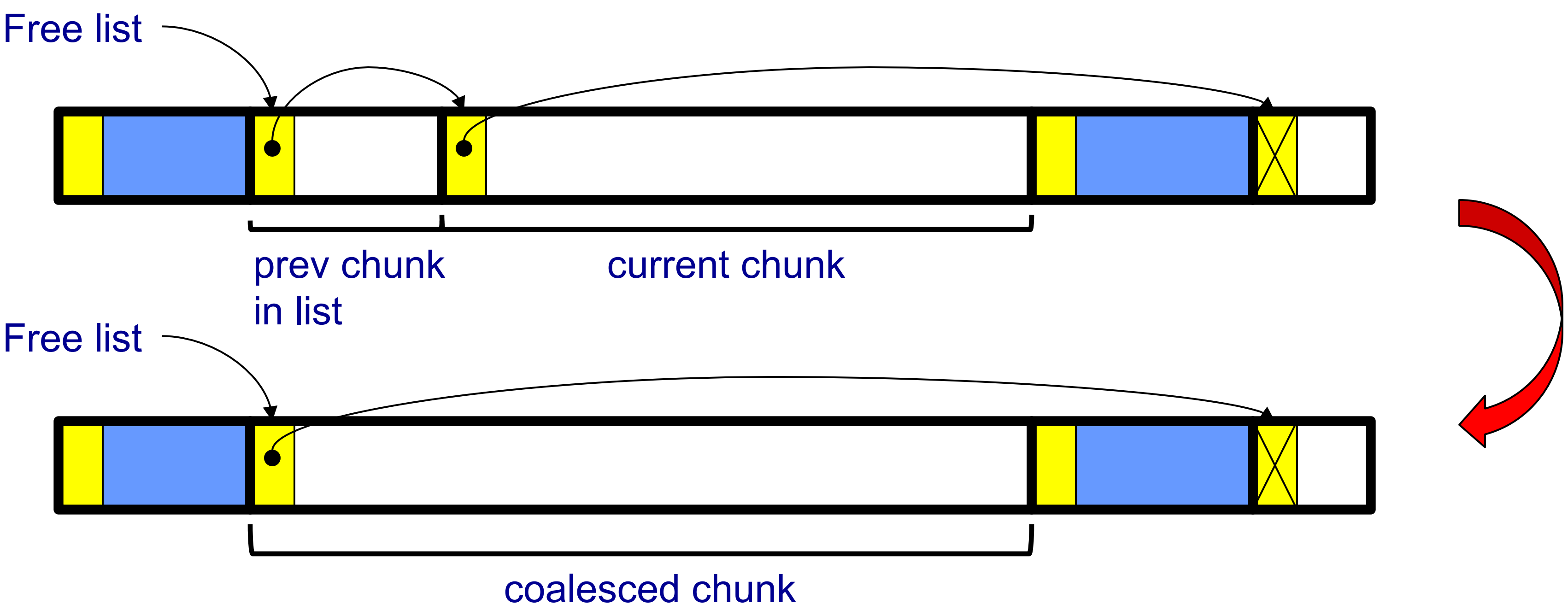
Look at current chunk

Next chunk in memory == next chunk in list =>

- Remove both chunks from list
- Coalesce
- Insert chunk into list

(Not finished yet!)

List Impl: free(p) Example (cont.)



Look at prev chunk in list
Next in memory == next in list =>
    Remove both chunks from list
    Coalesce
    Insert chunk into list
(Finished!)

List Impl

Algorithms (see precepts for more precision)

`malloc(n)`

- Search free list for big-enough chunk
- Chunk found & reasonable size => remove, use
- Chunk found & too big => split, use tail end
- Chunk not found => increase heap size, create new chunk
- New chunk reasonable size => remove, use
- New chunk too big => split, use tail end

`free(p)`

- Search free list for proper insertion spot
- Insert chunk into free list
- Next chunk in memory also free => remove both, coalesce, insert
- Prev chunk in memory free => remove both, coalesce, insert

iClicker Question

Q: How fast is `free()` in the List implementation?

A. O(1), always with a small constant

B. O(1), usually but not always with a small constant

C. O(1), often with a large constant

D. Even worse than that…

List Impl Performance

Space

- Some internal & external fragmentation is unavoidable
- Headers are overhead
- Overall: good

Time: `malloc()`

- Must search free list for big-enough chunk
- Bad: O(n)
- But often acceptable

Time: `free()`

- Must search free list for insertion spot
- Bad: O(n)
- Often **very** bad

Solution

- Remove ordering invariant
- Use a doubly linked list

Agenda

The need for DMM

DMM using the heap section

DMM system 1: Minimal implementation

DMM system 2: Pad implementation

Fragmentation

DMM system 3: List implementation

DMM system 4: Doubly-linked list implementation

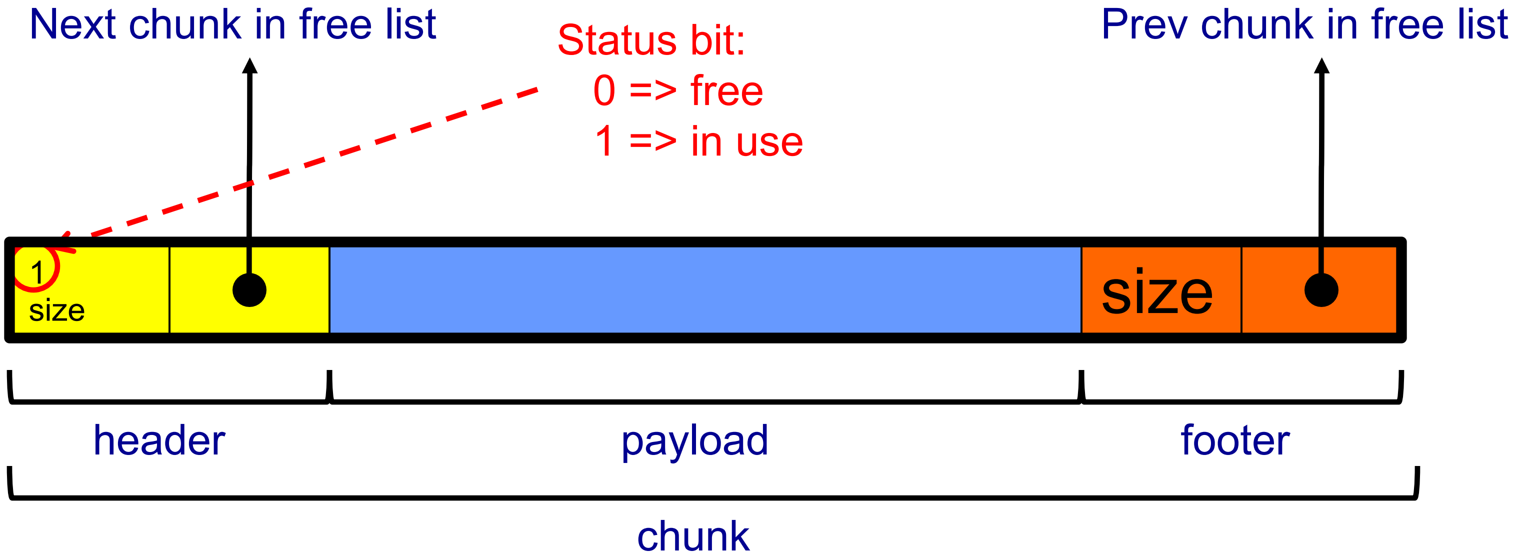
DMM system 5: Bins implementation

DMM using virtual memory

DMM system 6: VM implementation

Doubly-Linked List Impl

Data structures



Free list is doubly-linked

Each chunk contains header, payload, footer

Payload is used by client

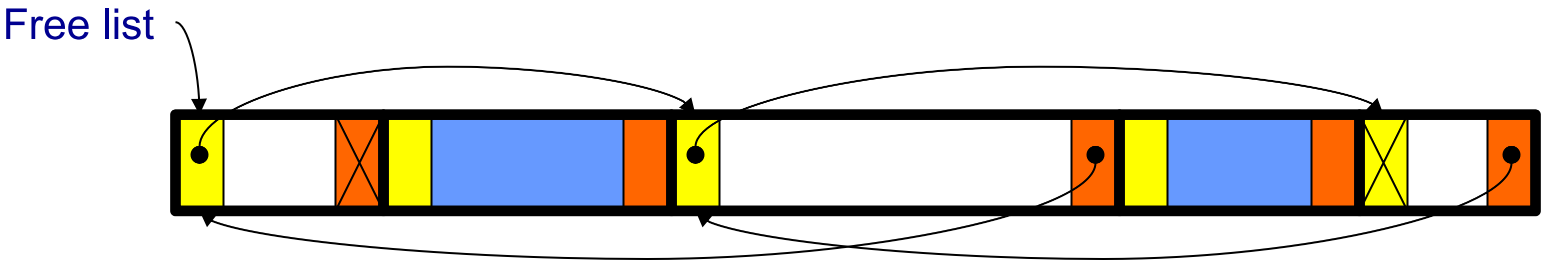
Header contains status bit, chunk size, & (if free) addr of next chunk in list

Footer contains redundant(?) chunk size & (if free) addr of prev chunk in list

Free list is unordered

Doubly-Linked List Impl

Typical heap during program execution:



Doubly-Linked List Impl

Algorithms (see precepts for more precision)

`malloc(n)`

- Search free list for big-enough chunk
- Chunk found & reasonable size => remove, set status, use
- Chunk found & too big => remove, split, insert tail, set status, use front
- Chunk not found => increase heap size, create new chunk, insert
- New chunk reasonable size => remove, set status, use
- New chunk too big => remove, split, insert tail, set status, use front

Doubly-Linked List Impl

Algorithms (see precepts for more precision)

`free(p)`

- Set status
- ~~Search free list for proper insertion spot~~
- Insert chunk into free list
- Next chunk in memory also free => remove both, coalesce, insert
- Prev chunk in memory free => remove both, coalesce, insert

Doubly-Linked List Impl Performance

Consider sub-algorithms of `free()`…

Set status bit

Insert chunk into free list

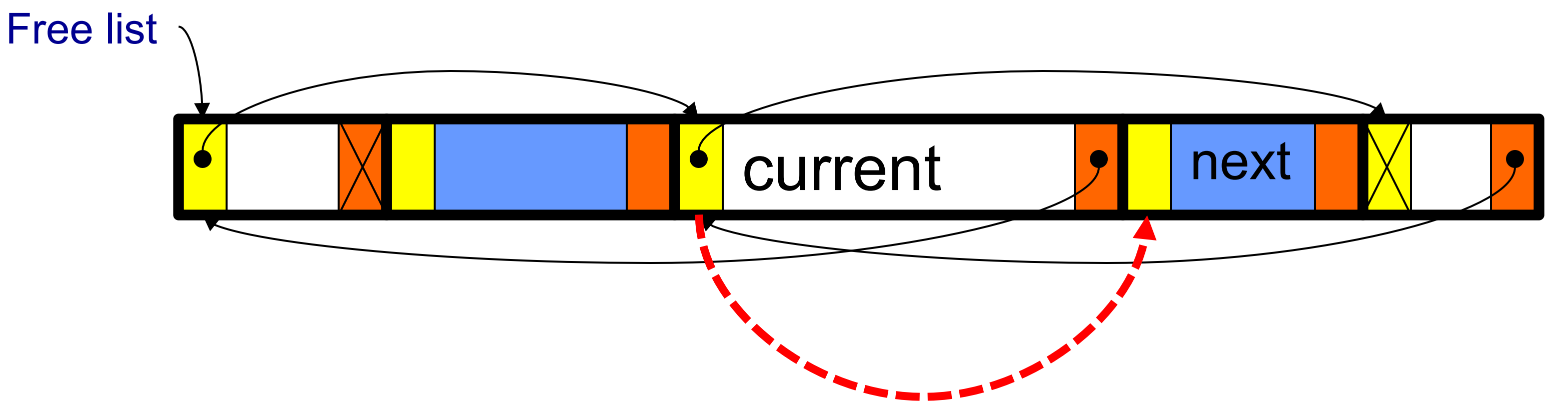
- **Linked list version**: slow
  - Traverse list to find proper spot
- **Doubly-linked list version**: fast
  - Insert at front!

Doubly-Linked List Impl Performance

Consider sub-algorithms of `free()`...

Determine if next chunk in memory is free

- **Linked list version**: slow
  - Traverse free list to see if next chunk in memory is in list
- **Doubly-linked list version**: fast



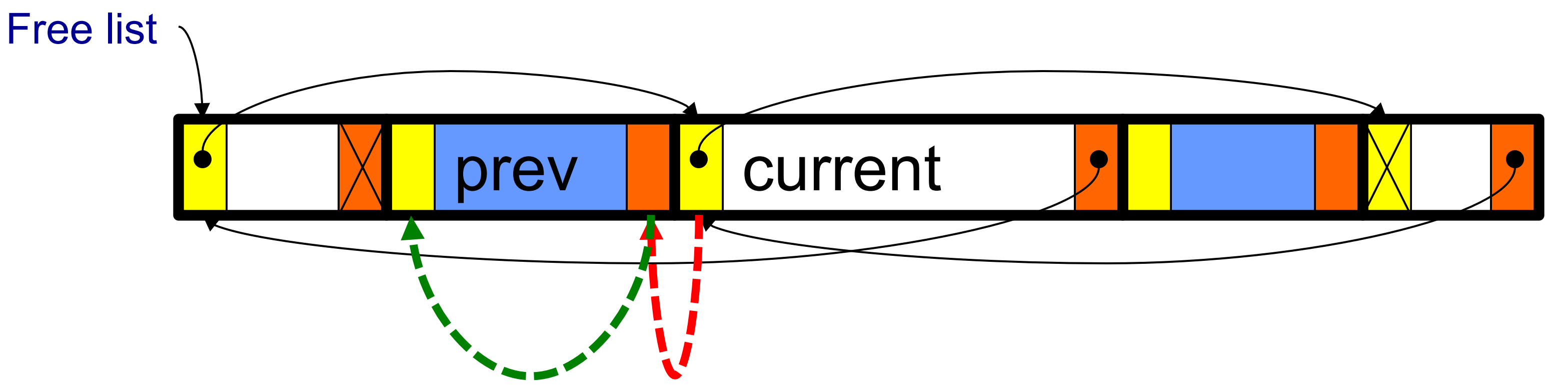
Use current chunk's size to find next chunk
Examine status bit in next chunk's header

Doubly-Linked List Impl Performance

Consider sub-algorithms of `free()`…

Determine if prev chunk in memory is free

- **Linked list version**: slow
  - Traverse free list to see if prev chunk in memory is in list
- **Doubly-linked list version**: fast



Do ptr arith to find prev chunk's footer and fetch its (not redundant!) size

Do ptr arith to find prev chunk's header

Examine status bit in prev chunk's header

Doubly-Linked List Impl Performance

Consider sub-algorithms of `free()`…

Remove chunk from free list

- **Linked list version**: slow
  - Traverse list to find prev chunk in list
- **Doubly-linked list version**: fast
  - Use backward pointer of current chunk to find prev chunk in list

Doubly-Linked List Impl Performance

Space

- Some internal & external fragmentation is unavoidable
- Headers & footers are overhead
- Overall: Good

Time: `free()`

- All steps are fast
- Good: O(1)

Time: `malloc()`

- Must search free list for big-enough chunk
- Bad: O(n)
- Often acceptable
- Subject to bad worst-case behavior
  - E.g. long free list with big chunks at end

Solution

- Use multiple lists: "bins"

Agenda

The need for DMM

DMM using the heap section

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Fragmentation

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DMM system 4: Doubly-linked list implementation

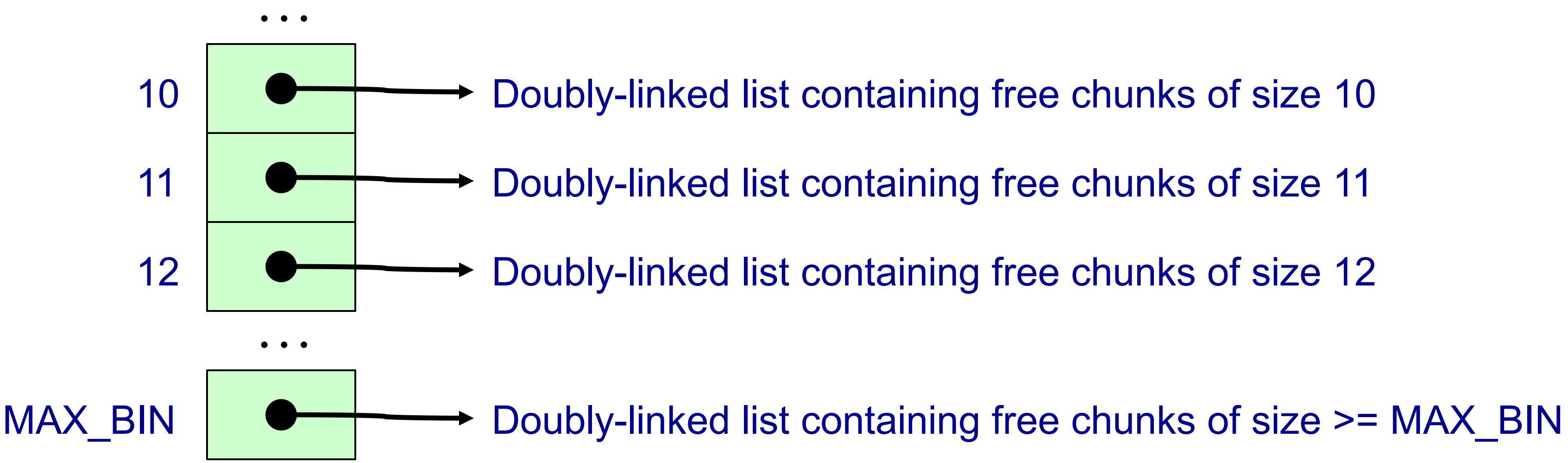
DMM system 5: Bins implementation

DMM using virtual memory

DMM system 6: VM implementation

Bins Impl

Data structures



Doubly-linked list containing free chunks of size 10

Doubly-linked list containing free chunks of size 11

Doubly-linked list containing free chunks of size 12

Doubly-linked list containing free chunks of size >= MAX_BIN

Use an array; each element is a **bin**

Each bin is a doubly-linked list of free chunks

- As in previous implementation

bin[i] contains free chunks of size i

- Exception: Final bin contains chunks of size MAX_BIN **or larger**

(More elaborate binning schemes are common)

Bins Impl

Algorithms (see precepts for more precision)

`malloc(n)`

- Search ~~free list~~ **proper bin(s)** for big-enough chunk
- Chunk found & reasonable size => remove, set status, use
- Chunk found & too big => remove, split, insert tail, set status, use front
- Chunk not found => increase heap size, create new chunk
- New chunk reasonable size => remove, set status, use
- New chunk too big => remove, split, insert tail, set status, use front

`free(p)`

- Set status
- Insert chunk into ~~free list~~ **proper bin**
- Next chunk in memory also free => remove both, coalesce, insert
- Prev chunk in memory free => remove both, coalesce, insert

Bins Impl Performance

Space

- **Pro**: For small chunks, uses **best-fit** (not **first-fit**) strategy
  - Could decrease external fragmentation and splitting
- **Con**: Some internal & external fragmentation is unavoidable
- **Con**: Headers, footers, bin array are overhead
- **Overall**: good

Time: `malloc()`

- **Pro**: Binning limits list searching
  - Search for chunk of size i begins at bin i and proceeds downward
- **Con**: Could be bad for large chunks (i.e. those in final bin)
  - Performance degrades to that of list version
- **Overall**: good O(1)

Time: `free()`

- Good: O(1) with a small constant

DMM system Impl Summary (so far)

Implementation	Space	Time
(1) Minimal	Bad	Malloc: Bad Free: Good
(2) Pad	Bad	Malloc: Good Free: Good
(3) List	Good	Malloc: Bad (but could be OK) Free: Bad
(4) Doubly-Linked List	Good	Malloc: Bad (but could be OK) Free: Good
(5) Bins	Good	Malloc: Good Free: Good

Assignment 6: Given (3), compose (4) and (5)

What’s (Still) Wrong?

Observations

- DMM system might want to free memory chunks by **unmapping** them rather than **marking** them
  - Minimizes virtual page count
- DMM system can call `brk(pBrk-n)` to decrease heap size
  - And thereby unmap heap memory
- But often memory to be unmapped is not at high end of heap!

Problem

- How can DMM system unmap memory effectively?

Solution

- Don’t use the heap!

What’s (Still) Wrong?

Reprising a previous slide…

Question:

- How to implement **`malloc()`** and **`free()`**?
- How to implement a DMM system?

Answer 1:

- Use the heap section of memory

Answer 2:

- Map a new section of memory directly
- We’ll mention this at the end of this lecture

Agenda

The need for DMM

DMM using the heap section

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DMM system 5: Bins implementation

DMM using virtual memory

DMM system 6: VM implementation

Unix VM Mapping Functions

Unix allows application programs to map/unmap VM explicitly

```
void *mmap(void *p, size_t n, int prot, int flags,
  int fd, off_t offset);
```

- Creates a new mapping in the virtual address space of the calling process
- `p`: the (approximate) starting address for the new mapping
- `n`: the length of the mapping
- If `p` is NULL, then the kernel chooses the address at which to create the mapping; this is the most portable method of creating a new mapping
- On success, returns address of the mapped area

```
int munmap(void *p, size_t n);
```

- Deletes the mappings for the specified address range

Unix VM Mapping Functions

Typical call of **`mmap()`** for allocating memory

```
p = mmap(NULL, n, PROT_READ|PROT_WRITE,
                MAP_PRIVATE|MAP_ANON, 0, 0);
```

- Asks OS to map a new read/write area of virtual memory containing **`n`** bytes
- Returns the virtual address of the new area on success, **`(void*)-1`** on failure

Typical call of **`munmap()`**

```
status = munmap(p, n);
```

- Unmaps the area of virtual memory at virtual address **`p`** consisting of **`n`** bytes
- Returns 0 on success, -1 on failure

See Bryant & O' Hallaron book and man pages for details

Agenda

The need for DMM

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DMM system 5: Bins implementation

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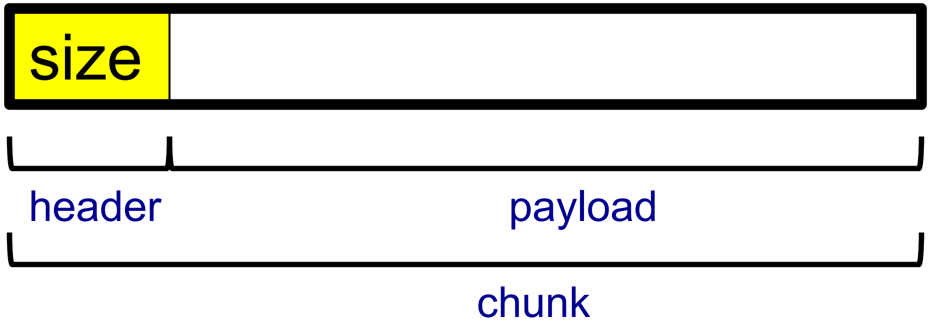
DMM system 6: VM implementation

VM Mapping Impl

Data structures



Each chunk consists of a header and payload
Each header contains size

VM Mapping Impl

Algorithms

```
void *malloc(size_t n)
{  size_t *ps;
   if (n == 0) return NULL;
   ps = mmap(NULL, n + sizeof(size_t), PROT_READ|PROT_WRITE,
             MAP_PRIVATE|MAP_ANONYMOUS, 0, 0);
   if (ps == (size_t*)-1) return NULL;
   *ps = n + sizeof(size_t);  /* Store size in header */
   ps++;  /* Move forward from header to payload */
   return (void*)ps;
}
```

```
void free(void *p)
{  size_t ps = (size_t*)p;
   if (ps == NULL) return;
   ps--;  /* Move backward from payload to header */
   munmap(ps, *ps);
}
```

VM Mapping Impl Performance

Space

- Fragmentation problem is delegated to OS
- Overall: Depends on OS

Time

- For small chunks
  - One system call (**`mmap()`**) per call of **`malloc()`**
  - One system call (**`munmap()`**) per call of **`free()`**
  - Overall: poor
- For large chunks
  - **`free()`** unmaps (large) chunks of memory, and so shrinks page table
  - Overall: maybe good!

The GNU Implementation

Observation

- **`malloc()`** and **`free()`** on ArmLab are from the **GNU** (the GNU Software Foundation)

Question

- How are GNU **`malloc()`** and **`free()`** implemented?

Answer

- For small chunks
  - Use heap (**`sbrk()`** and **`brk()`**)
  - Use bins implementation
- For large chunks
  - Use VM directly (**`mmap()`** and **`munmap()`**)

Summary

The need for DMM

- Unknown object size

DMM using the heap section

- On Unix: **`sbrk()`** and **`brk()`**
- Complicated data structures and algorithms
- Good for managing small memory chunks

DMM using virtual memory

- On Unix: **`mmap()`** and **`munmap()`**
- Good for managing large memory chunks

See Appendix for additional approaches/refinements

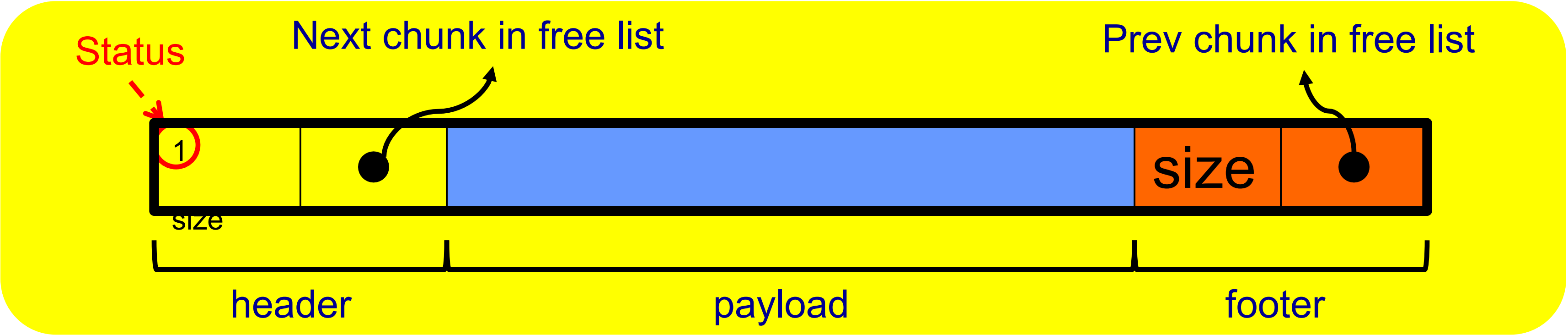
Appendix: Additional Approaches

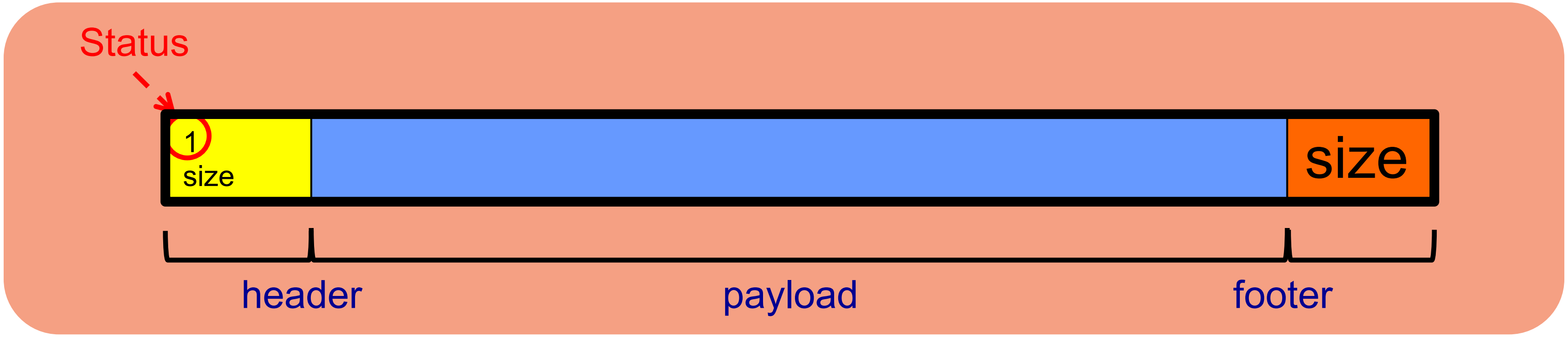
Additional approaches to dynamic memory management.

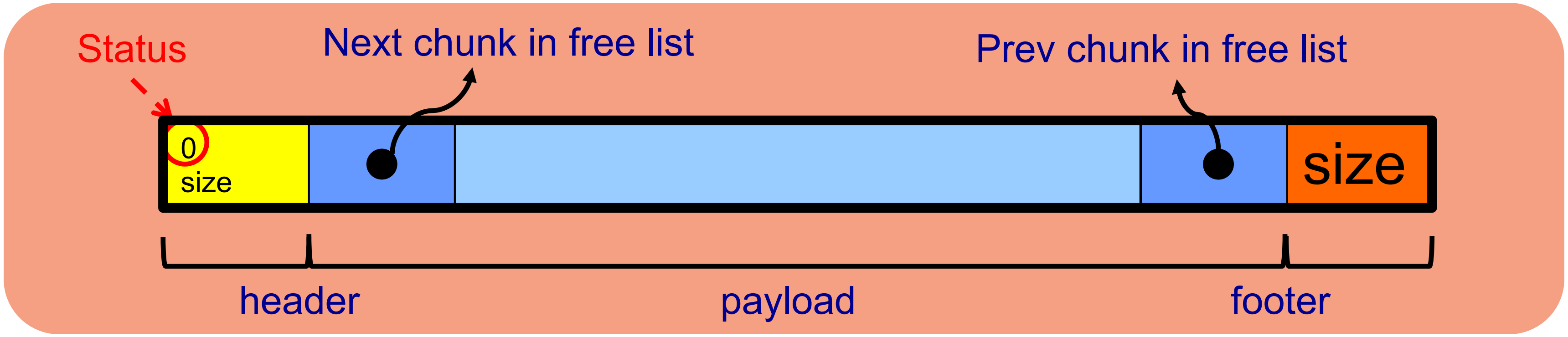
None of these are part of Assignment 6!

Using payload space for management

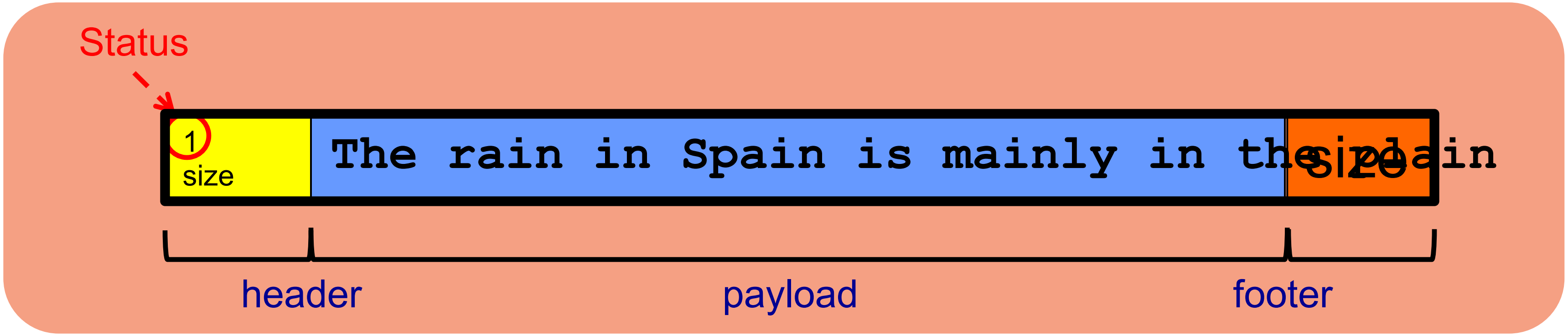
free chunks don’t have payload; in-use chunks don’t have prev/next







Another use for the extra size field: error checking



```
char *s = (char *)malloc(32);
  . . .
strcpy(s, "The rain in Spain is mainly in the plain.");
  . . .
printf("%s\n", s);
free(s);
```

Selective Splitting

Observation

- In previous implementations, **`malloc()`** splits whenever chosen chunk is too big, so long as remainder can form a chunk

Alternative: **selective splitting**

- Split only when remainder is above some higher threshold

Pro

- Reduces external fragmentation

Con

- Increases internal fragmentation

Deferred Coalescing

Observation

- Previous implementations coalesce whenever possible

Alternative: **deferred coalescing**

- Wait, and coalesce many chunks at a later time

Pro

- Handles **`malloc(n);free();malloc(n)`** sequences well

Con

- Complicates algorithms

Segregated Data

Observation

- Splitting and coalescing consume lots of overhead

Problem

- How to eliminate that overhead?

Solution: **segregated data**

- **Make use of the virtual memory concept…**
- Use bins
- Store each bin's chunks in a distinct (segregated) virtual memory page

Segregated Data

Segregated data

- Each bin contains chunks of fixed sizes
  - E.g. 32, 64, 128, …
- All chunks within a bin are from same **virtual memory** page
- **`malloc()`** never splits! Examples:
  - **`malloc(32)`** => provide 32
  - **`malloc(5)`** => provide 32
  - **`malloc(100)`** => provide 128
- **`free()`** never coalesces!
  - Free block => examine address, infer virtual memory page, infer bin, insert into that bin

Segregated Data

Pros

- Eliminates splitting and coalescing overhead
- Eliminates most meta-data; only forward links required
  - No backward links, sizes, status bits, footers

Con

- Internal fragmentation
- Some usage patterns cause excessive external fragmentation
  - E.g. Only one **`malloc(32)`** wastes all but 32 bytes of one virtual page

Segregated Meta-Data

Observations

- Meta-data (chunk sizes, status flags, links, etc.) are scattered across the heap, interspersed with user data
- Heap mgr often must traverse meta-data

Problem 1

- User error easily can corrupt meta-data

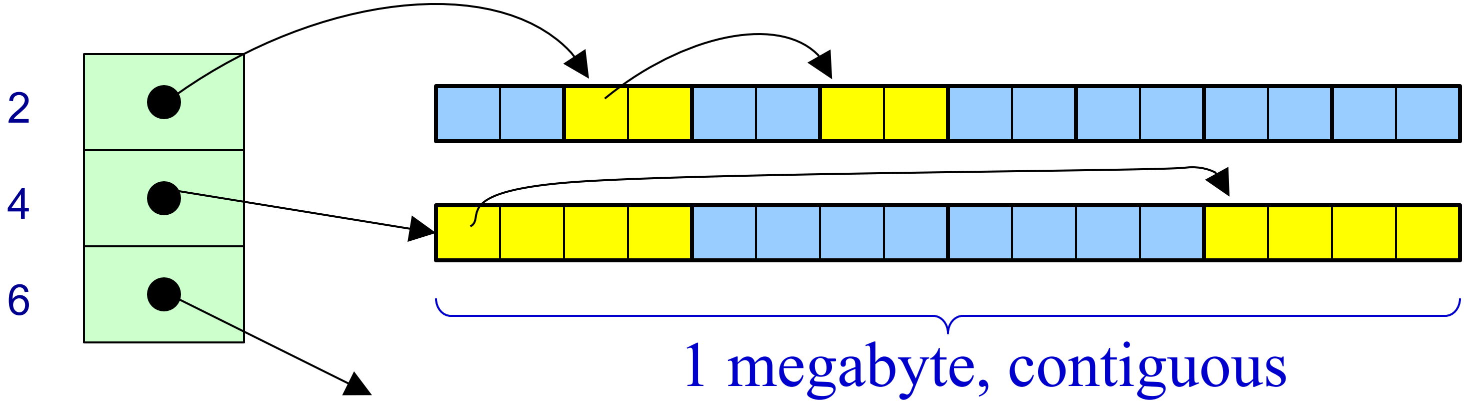
Problem 2

- Frequent traversal of meta-data can cause excessive page faults (poor locality)

Solution: **segregated meta-data**

- **Make use of the virtual memory concept…**
- Store meta-data in a distinct (segregated) virtual memory page from user data

Segregated metadata

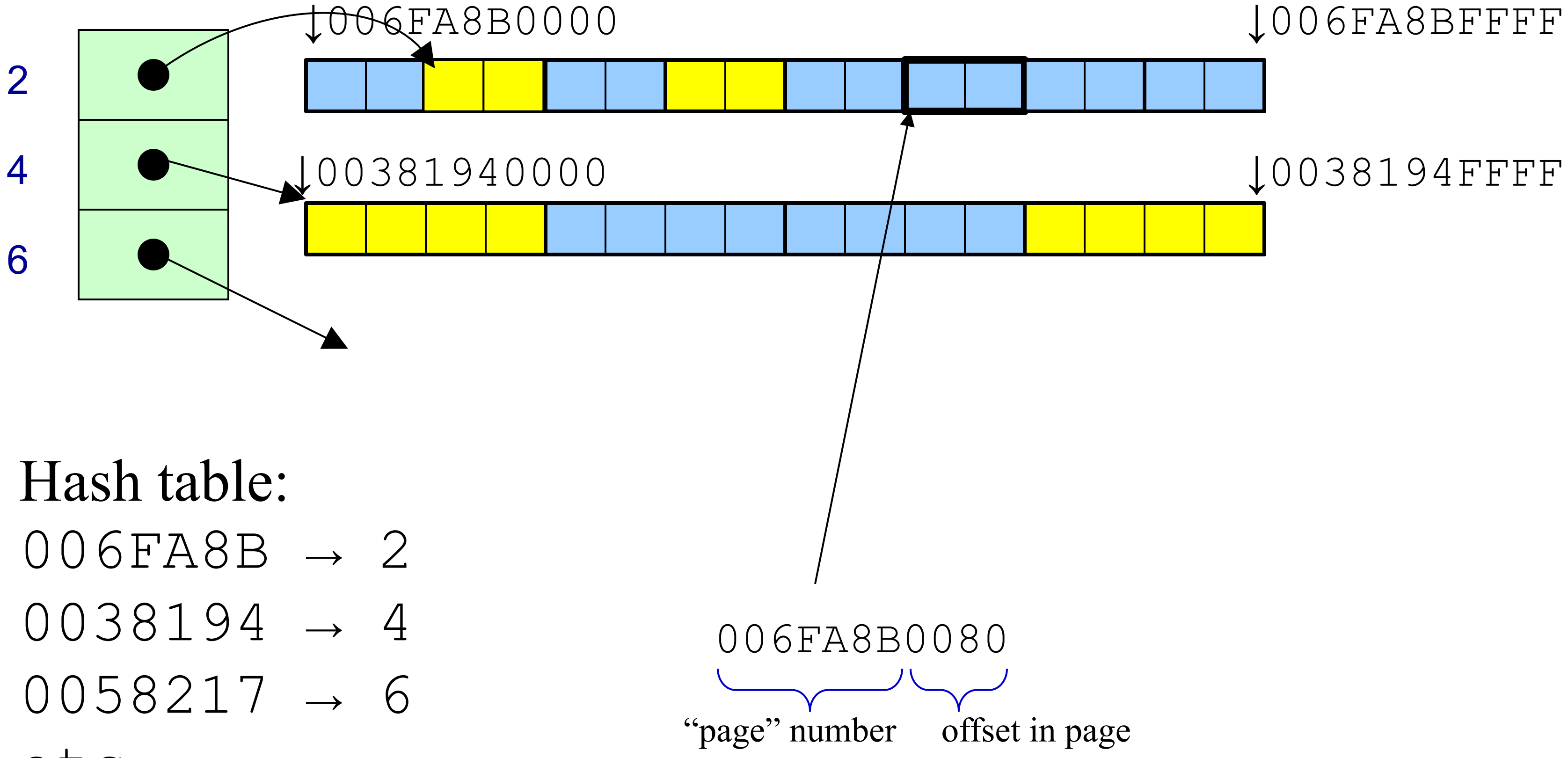


Data layout: no “size” field, no header at all!
(Payload stores pointers when not in-use.)

Malloc: look up in bins array, use first element of linked list

Free: find size (somehow), put back at head of that bin’s list

How free() finds the size



Hash table:

```
006FA8B → 2
0038194 → 4
0058217 → 6
etc.
```

Segregated metadata performance

Space

- No overhead for header: very very good,
- No coalescing, fragmentation may occur, possibly bad

Time

- malloc: very very good, O(1)
- free: hash-table lookup, good, O(1)

Trade-off

Bins+DLL+coalescing

TIME:

☺ fast malloc

☺ fast free

SPACE:

16, if payload overlapped with header

☹ ~~32~~ bytes overhead per object

☺ coalescing, *might* reduce fragmentation

Segregated metadata

TIME:

☺ *very* fast malloc

☺ fast free

SPACE:

☺ 0 bytes overhead per object

☹ no coalescing

There's no "one best memory allocator"