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

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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

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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

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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()`

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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

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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 system 6: VM implementation

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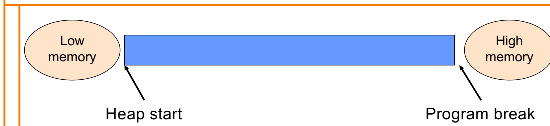
The Heap Section of Memory



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

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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!)

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Minimal Impl

Data structures

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

Algorithms (by examples)…

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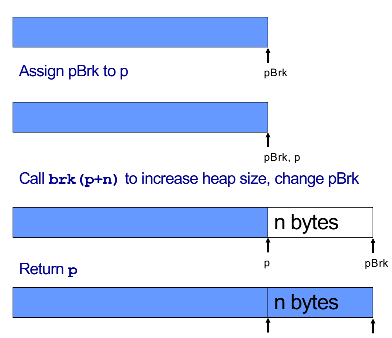
Minimal Impl malloc(n) Example



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Minimal Impl free(p) Example

Do nothing!

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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)
{
}
```

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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…

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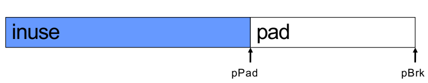
Pad Impl

Data structures



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

Algorithms (by examples)…

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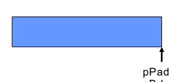
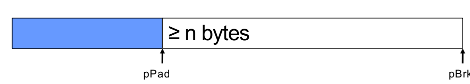
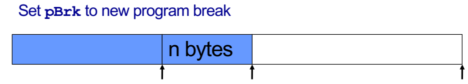
Pad Impl malloc(n) Example 0



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`

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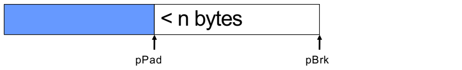
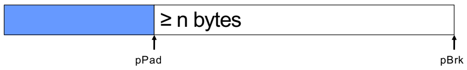
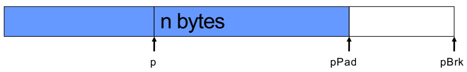
Pad Impl malloc(n) Example 1



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**

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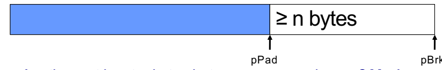
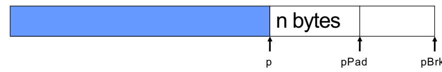
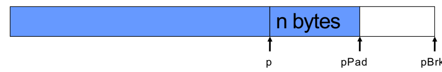
Pad Impl malloc(n) Example 2



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



Return **p**



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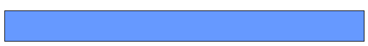
Pad Impl free(p) Example

Do nothing!



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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)
{
}
```

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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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Agenda

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Fragmentation
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DMM system 5: Bins implementation
DMM using virtual memory
DMM system 6: VM implementation

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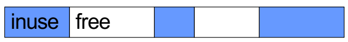
Fragmentation

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



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

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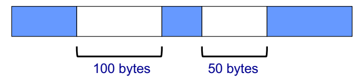
External Fragmentation

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

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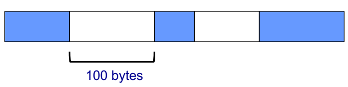
Internal Fragmentation

Internal fragmentation: waste **within** chunks



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

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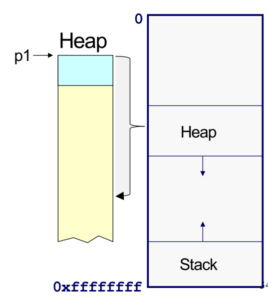
DMM Desired Behavior Demo

```
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);
```



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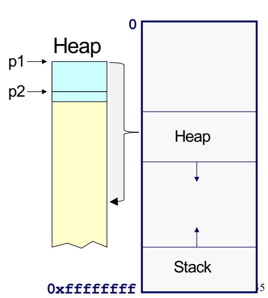
DMM Desired Behavior Demo

```
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);
```



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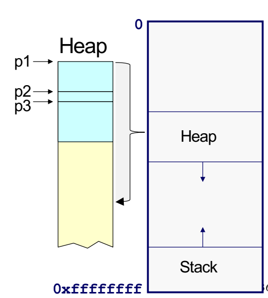
DMM Desired Behavior Demo

```
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);
```



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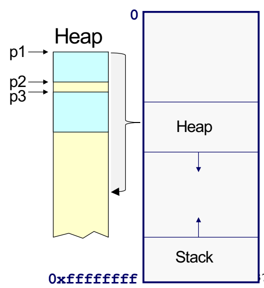
DMM Desired Behavior Demo

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);
```



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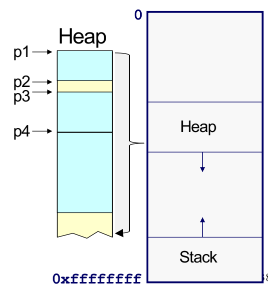
DMM Desired Behavior Demo

```
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);
```



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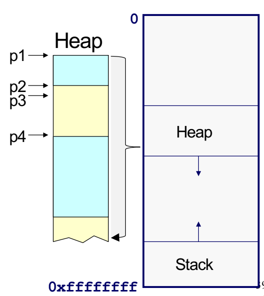
DMM Desired Behavior Demo

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);
```



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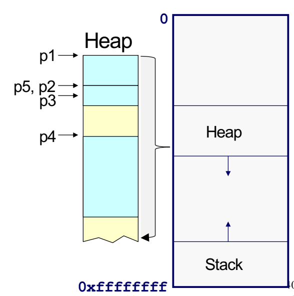
DMM Desired Behavior Demo

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);
```



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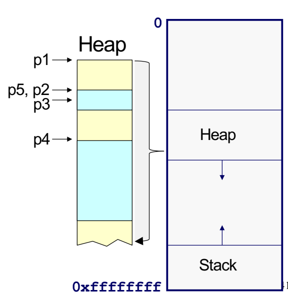
DMM Desired Behavior Demo

```
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);
```



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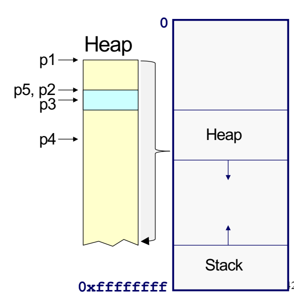
DMM Desired Behavior Demo

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);
```



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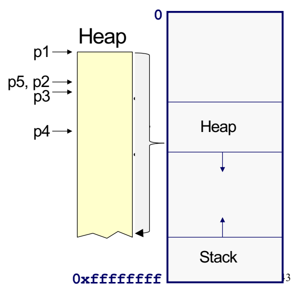
DMM Desired Behavior Demo

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);
```



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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

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DMM using virtual memory

DMM system 6: VM implementation

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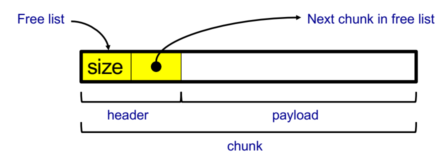
List Impl

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)…

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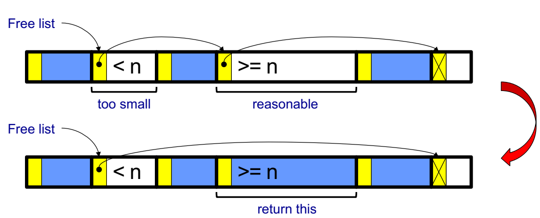
List Impl: malloc(n) Example 1



Search list for big-enough chunk
Note: **first-fit** (not **best-fit**) strategy
Found & reasonable size =>
Remove from list and return payload

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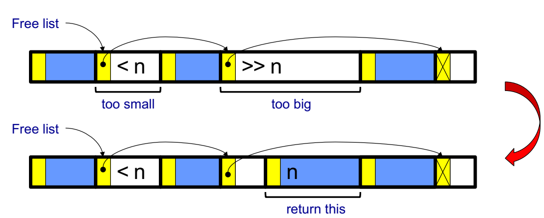
List Impl: malloc(n) Example 2



Search list for big-enough chunk
Found & too big =>
Split chunk, return payload of tail end
Note: Need not change links

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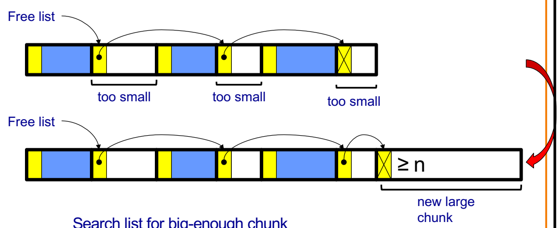
List Impl: malloc(n) Example 3



Search list for big-enough chunk
None found =>
- Call `brk()` to increase heap size
- Insert new chunk at end of list

(Not finished yet!)

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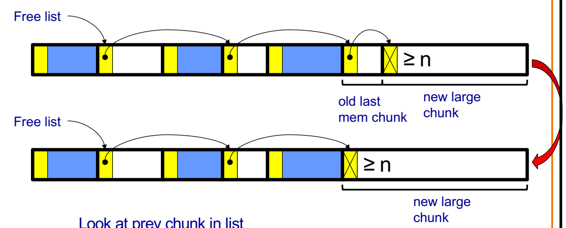
List Impl: malloc(n) Example 3 (cont.)



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!)

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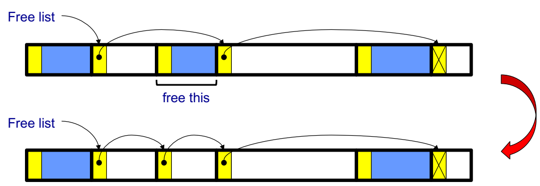
List Impl: free(p) Example



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

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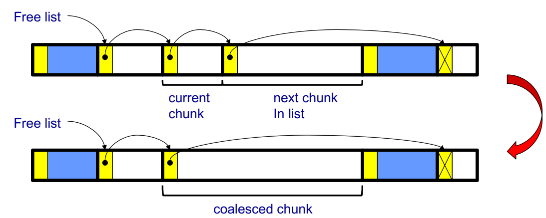
List Impl: free(p) Example (cont.)



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!)

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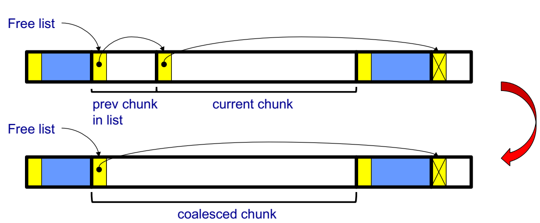
List Impl: free(p) Example (cont.)



Look at prev chunk in list
Next in memory == next in list =>
- Remove both chunks from list
- Coalesce
- Insert chunk into list

(Finished!)

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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

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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…

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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

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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

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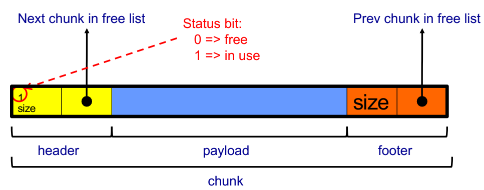
Doubly-Linked List Impl

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

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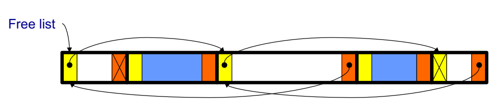
Doubly-Linked List Impl

Typical heap during program execution:



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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

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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

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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!

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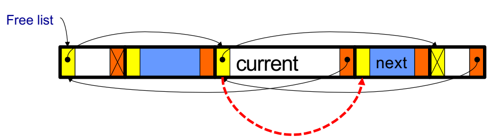
Doubly-Linked List Impl Performance

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

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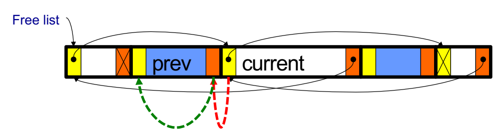
Doubly-Linked List Impl Performance

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

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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

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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"

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Agenda

The need for DMM

DMM using the heap section

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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

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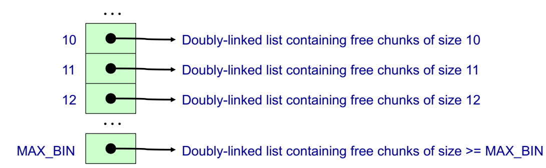
Bins Impl

Data structures



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)

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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

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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

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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)

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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!

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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

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Agenda

The need for DMM

DMM using the heap section

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DMM using virtual memory

DMM system 6: VM implementation

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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

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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

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Agenda

The need for DMM

DMM using the heap section

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DMM system 3: List implementation

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DMM system 5: Bins implementation

DMM using virtual memory

DMM system 6: VM implementation

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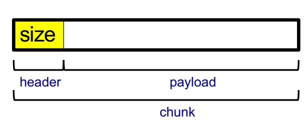
VM Mapping Impl

Data structures



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

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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);
}
```

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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!

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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()`)

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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

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Appendix: Additional Approaches

Additional approaches to dynamic memory management.

None of these are part of Assignment 6!

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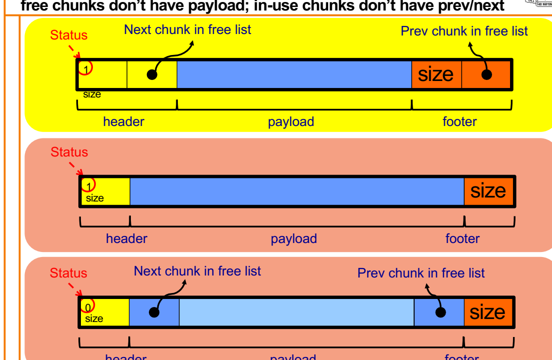
Using payload space for management

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



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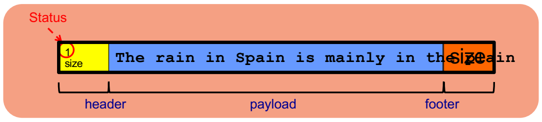
Another use for the extra size field: error checking




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

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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

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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

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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

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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

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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

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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

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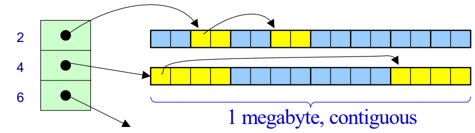
Segregated metadata



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

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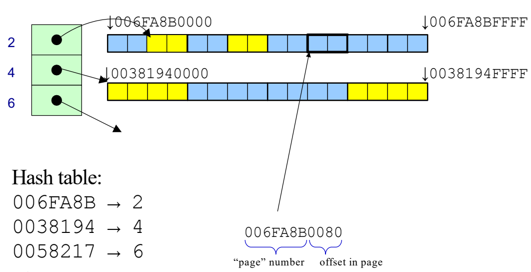
How free() finds the size



Hash table:
006FA8B → 2
0038194 → 4
0058217 → 6
etc.

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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)

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Trade-off

Bins+DLL+coalescing	**Segregated metadata**
TIME:	TIME:
☺ fast malloc	☺ *very* fast malloc
☺ fast free	☺ fast free
SPACE:	SPACE:
☹ 32 bytes overhead per object (16, if payload overlapped with header)	☺ 0 bytes overhead per object
☺ coalescing, *might* reduce fragmentation	☹ no coalescing

There's no "one best memory allocator"

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