

Princeton University
Computer Science 217: Introduction to Programming Systems

Dynamic Memory Management

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Agenda

The need for DMM

- DMM using the heap section
- DMMgr 1: Minimal implementation
- DMMgr 2: Pad implementation
- Fragmentation
- DMMgr 3: List implementation
- DMMgr 4: Doubly-linked list implementation
- DMMgr 5: Bins implementation
- DMM using virtual memory
- DMMgr 6: VM implementation

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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

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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

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Option A: Automatic Freeing

Run-time system frees unneeded memory

- Java, Python, ...
- Garbage collection**

Pros:

- Easy for programmer

Cons:

- 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++, 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 or 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 nmem, size_t size);
void *realloc(void *ptr, size_t size);
```

Collectively define a **dynamic memory manager (DMMgr)**

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
 - Pgm 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 DMMgr?

Answer 1:

- Use the heap section of memory

Answer 2:

- (Later in this lecture)

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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);
```

- Increment the program break by *n* bytes
- If *n* is 0, then return the current location of the program break
- Return 0 if successful and (void*)(-1) otherwise
- Beware: should call only with argument 0 – buggy implementation in the case of overflow

Note: minimal interface (good!)

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Agenda

The need for DMM

DMM using the heap section

DMMgr 1: Minimal implementation

DMMgr 2: Pad implementation

Fragmentation

DMMgr 3: List implementation

DMMgr 4: Doubly-linked list implementation

DMMgr 5: Bins implementation

DMM using virtual memory

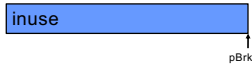
DMMgr 6: VM implementation

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Minimal Impl

Data structures



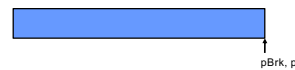
- **pBrk**: address of end of heap (i.e. the program break)

Algorithms (by examples)...

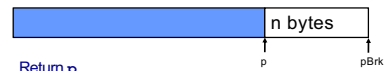
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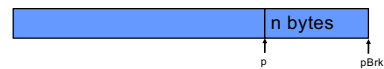
Minimal Impl malloc(n) Example



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



Return **p**

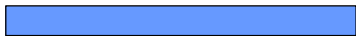


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Minimal Impl free(p) Example

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

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What's Wrong?

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 1

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 malloc(n) Example 2

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

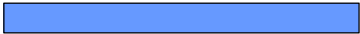
Set `pBrk` to new program break

Proceed as previously!

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Pad Impl free(p) Example

Do nothing!



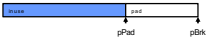
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Pad Impl

```

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

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What's Wrong?

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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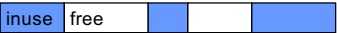
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Fragmentation

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



DMMgr must be concerned about **fragmentation**...

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Internal Fragmentation

Internal fragmentation: waste **within** chunks

100 bytes

Client asks for 90 bytes
DMMgr provides chunk of size 100 bytes
10 bytes wasted

Generally
Program asks for n bytes
DMMgr provides chunk of size n+Δ bytes
Δ bytes wasted
Space efficiency =>
DMMgr should reduce internal fragmentation

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External Fragmentation

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

100 bytes 50 bytes

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

Generally
Program asks for n bytes
n bytes are available, but not contiguously
DMMgr must extend size of heap to satisfy request
Space efficiency =>
DMMgr should reduce external fragmentation

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DMMgr Desired Behavior Demo

```
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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DMMgr Desired Behavior Demo

```
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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DMMgr Desired Behavior Demo

```
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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DMMgr Desired Behavior Demo

```
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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DMMgr Desired Behavior Demo

External fragmentation occurred

```

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);

```

0
Heap
Stack
0xfffffff

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DMMgr Desired Behavior Demo

```

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);

```

0
Heap
Stack
0xfffffff

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DMMgr Desired Behavior Demo

DMMgr coalesced two 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);

```

0
Heap
Stack
0xfffffff

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DMMgr Desired Behavior Demo

DMMgr reused previously freed chunk

```

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);

```

0
Heap
Stack
0xfffffff

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DMMgr Desired Behavior Demo

```

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);

```

0
Heap
Stack
0xfffffff

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DMMgr Desired Behavior Demo

```

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);

```

0
Heap
Stack
0xfffffff

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DMMgr Desired Behavior Demo

```

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);

```

0xaaaaaaaa

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DMMgr Desired Behavior Demo

DMMgr 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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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: free(p) Example

Free list

Free list

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

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

Free list

Free list

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.)

Free list

Free list

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: malloc(n) Example 3

Free list

Free list

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.)

Free list

Free list

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

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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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()

- ???

 iClicker Question coming up . . .

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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

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What's Wrong?

Problem

- `free()` must traverse (long) free list, so can be (very) slow

Solution

- Use a doubly linked list...

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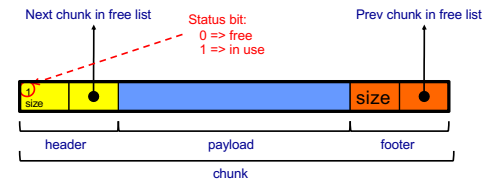
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Doubly-Linked List Impl

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 ()** ...

Insert chunk into free list

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

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

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

Fetch prev chunk's size from its footer
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

Observation:

- All sub-algorithms of `free()` are fast
- `free()` is fast!

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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

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What's Wrong?

Problem

- `malloc()` must traverse doubly-linked list, so can be slow

Solution

- Use multiple doubly-linked lists (bins)...

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Bins Impl

Data structures

10 → Doubly-linked list containing free chunks of size 10

11 → Doubly-linked list containing free chunks of size 11

12 → Doubly-linked list containing free chunks of size 12

... →

MAX_BIN → Doubly-linked list containing free chunks of size \geq 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)

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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 \Rightarrow remove, set status, use
- Chunk found & too big \Rightarrow remove, split, insert tail, set status, use front
- Chunk not found \Rightarrow increase heap size, create new chunk
- New chunk reasonable size \Rightarrow remove, set status, use
- New chunk too big \Rightarrow 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 \Rightarrow remove both, coalesce, insert
- Prev chunk in memory free \Rightarrow 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()

- ???

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iClicker Question

Q: How fast is `free()` in the Bins 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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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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DMMgr 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 Wrong?



Observations

- Heap mgr might want to free memory chunks by **unmapping** them rather than **marking** them
 - Minimizes virtual page count
- Heap mgr 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 heap mgr unmap memory effectively?

Solution

- Don't use the heap!

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What's Wrong?



Reprising a previous slide...

Question:

- How to implement `malloc()` and `free()`?
- How to implement a DMMgr?

Answer 1:

- Use the heap section of memory

Answer 2:

- Make use of virtual memory concept...

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Agenda

- The need for DMM
- DMM using the heap section
- DMMgr 1: Minimal implementation
- DMMgr 2: Pad implementation
- Fragmentation
- DMMgr 3: List implementation
- DMMgr 4: Doubly-linked list implementation
- DMMgr 5: Bins implementation
- DMM using virtual memory**
- DMMgr 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 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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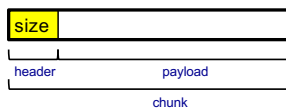


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VM Mapping Impl

Data structures



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



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VM Mapping Impl

Algorithms

```
void *mmap(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()` unmmaps (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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iClicker Question

Q: When is coalescing most useful?

- Always
- When most of the program's objects are the same size
- When the program simultaneously uses objects of different sizes
- When the program allocates many objects of size A, then frees most of them, then allocates many objects of size B
- Never

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Appendix: Additional Approaches



Some additional approaches to dynamic memory mgmt...

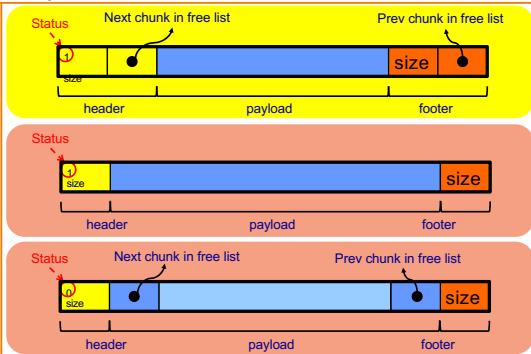
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Using payload space for management



or, only free chunks need to be in the free-list



This trick is NOT part of assignment 6!

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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

Alternative: selective splitting

- Split only when remainder is above some threshold

Pro

- Reduces external fragmentation

Con

- Increases internal fragmentation

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Deferred Coalescing

Observation

- Previous implementations do coalescing 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
- Elaboration...

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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

- 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!

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.

006FA8B0080
 "page" number offset in page

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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 <small>16, if payload overlapped with header</small>	⊕ 0 bytes overhead per object
⊕ coalescing, <i>might</i> reduce fragmentation	⊖ no coalescing

There's no "one best memory allocator"

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