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 ***Exceptions and Processes*** lecture…

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

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

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

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

Why Allocate Memory Dynamically?

Why **allocate** memory dynamically?

Problem
- Number of objects needed not known in advance
  (e.g., how many elements of linked list or tree?)
- Unknown object size
  (e.g., how large should the array be, in hash table?)

How much memory to allocate?

Solution 1
- Guess!

Solution 2
- Allocate memory dynamically

Why Free Memory Dynamically?

Why **free** memory dynamically?

Problem

- Pgm should use little memory, i.e.
- Pgm 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 1: Automatic Freeing

Run-time system frees unneeded memory

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

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

Original Car object can't be accessed

Pros:

- Easy for programmer
- Fewer bugs
- Simpler interfaces between modules
- Fewer bugs

Cons:

- Performed constantly ⇒ overhead
- Performed periodically ⇒ unexpected pauses

(these days, high-performance garbage collectors minimize overhead and pause latency)

Option 2: 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

Conclusion:

Program in a safe, garbage-collected language!

(not in C)

Use unsafe languages with manual memory management (such as C)

only for low-level programs where the overhead or latency of garbage collection is intolerable

such as: OS kernels,
device drivers,
garbage collectors,
memory managers

All right then, let's see how manual memory management works in C

C memory allocation library

Standard C dynamic-memory-management 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 (DMMgr)**

We'll focus on `malloc()` and `free()`

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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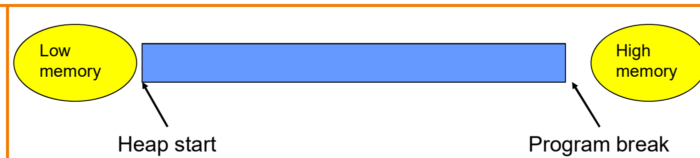
The Heap Section of Memory



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

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
- Return *previous break* if successful and (void*)-1 otherwise
- [therefore] **If `n` is 0, return the current location of the program break**
- **Beware: On Linux has a known bug (overflow not handled); should call only with argument 0.**

Note: minimal interface (good!)

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Minimal Impl

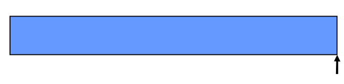
Data structures

- One word: remember the current value of program break

Algorithms (by examples)…

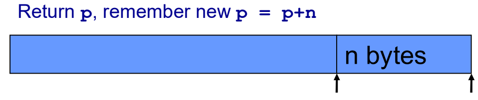
Minimal Impl malloc(n) Example

Remember the current program break (p) (initialize using `sbrk(0)`)



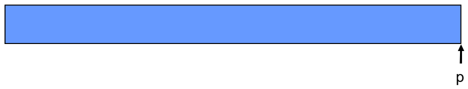
Call `brk(p+n)` to increase heap size

Return `p`, remember new `p = p+n`



Minimal Impl free(p) Example

Do nothing!



Minimal Impl

Algorithms

```
static void *current_break;

void *malloc(size_t n)
{   char *p = current_break;
    if (!p) p=(char *)sbrk(0);
    if (brk(p+n) == -1)
       return NULL;
    current_break = p+n;
    return (void*)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

What's Wrong?

Problem

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

Solution

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

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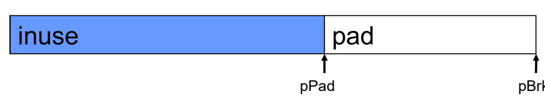
Pad Impl

Data structures

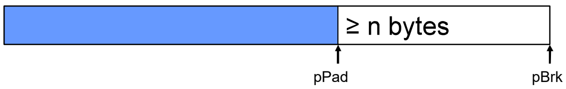


- `pBrk`: address of end of heap (i.e. the program break)
- `pPad`: address of beginning of pad

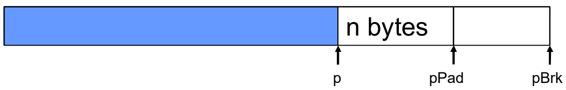
```
char *pPad = NULL;
char *pBrk = NULL;
```

Algorithms (by examples)…

Pad Impl malloc(n) Example 1

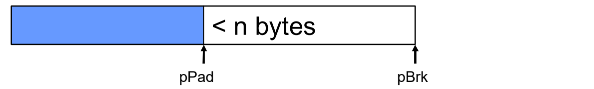


Are there at least **n** bytes between **pPad** and **pBrk**? **Yes**!
Save **pPad** as **p**; add **n** to **pPad**

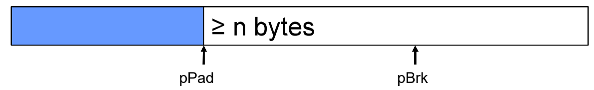


Return **p**

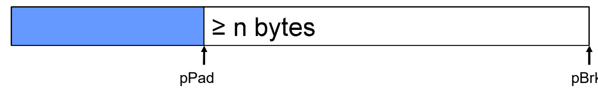
Pad Impl malloc(n) Example 2



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



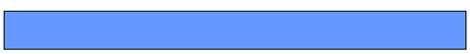
Set **pBrk** to new program break



Proceed as previously!

Pad Impl free(p) Example

Do nothing!



Pad Impl

Algorithms

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

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

Agenda

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DMMgr 5: Bins implementation

DMM using virtual memory

DMMgr 6: VM implementation

Fragmentation

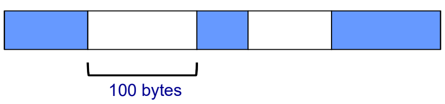
At any given time, some heap memory chunks are in use, some are marked “free”

DMMgr must be concerned about **fragmentation**…

Internal Fragmentation

Internal fragmentation: waste **within** chunks

Example



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

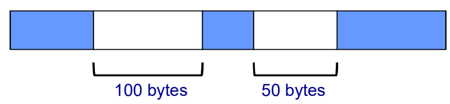
Space efficiency ⇒

- DMMgr should reduce internal fragmentation

External Fragmentation

External fragmentation: waste **between** chunks

Example



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 ⇒

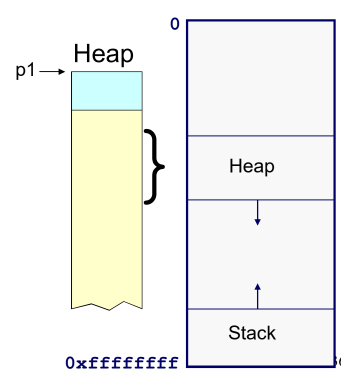
- DMMgr should reduce external fragmentation

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);
```


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);
```



DMMgr Desired Behavior Demo

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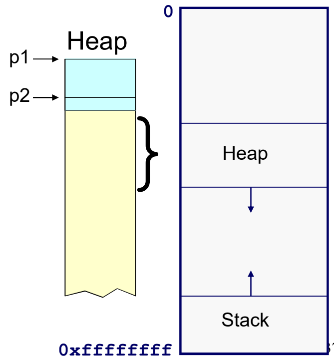
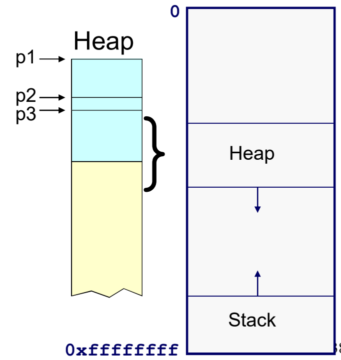



DMMgr Desired Behavior Demo

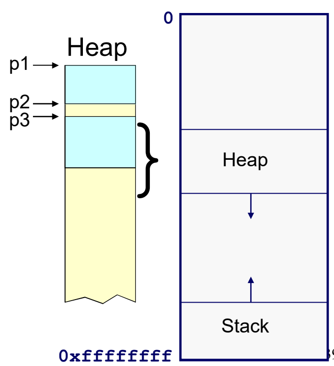
```
char *p1 = malloc(3);
char *p2 = malloc(1);
char *p3 = malloc(4);
free(p2);
char *p4 = malloc(6);
free(p3);
char *p5 = malloc(2);
free(p1);
free(p4);
free(p5);
```



DMMgr Desired Behavior Demo

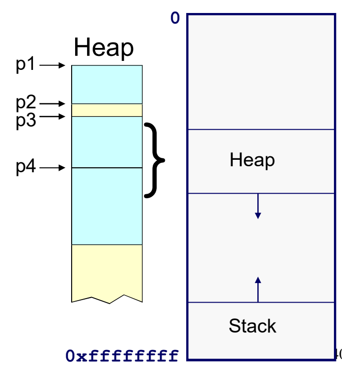
External fragmentation occurred

```
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);
```



DMMgr Desired Behavior Demo

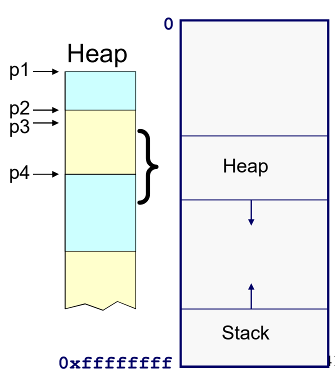
```
char *p1 = malloc(3);
char *p2 = malloc(1);
char *p3 = malloc(4);
free(p2);
char *p4 = malloc(6);
free(p3);
char *p5 = malloc(2);
free(p1);
free(p4);
free(p5);
```



DMMgr Desired Behavior Demo

DMMgr coalesced two free chunks

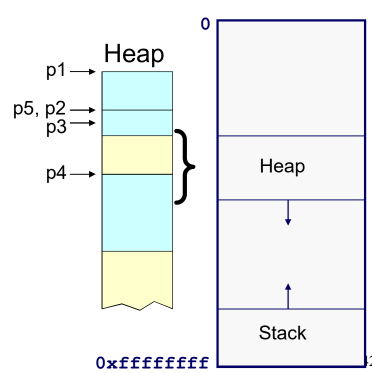
```
char *p1 = malloc(3);
char *p2 = malloc(1);
char *p3 = malloc(4);
free(p2);
char *p4 = malloc(6);
free(p3);
char *p5 = malloc(2);
free(p1);
free(p4);
free(p5);
```



DMMgr Desired Behavior Demo

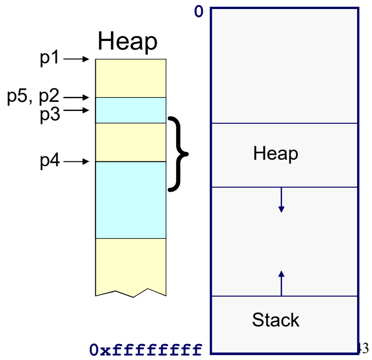
DMMgr reused previously freed chunk

```
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);
```



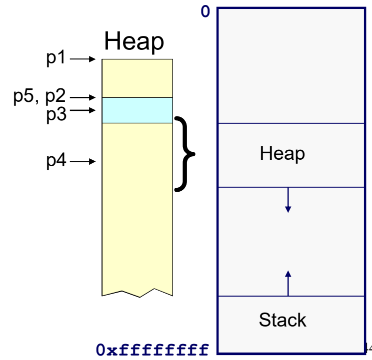
DMMgr Desired Behavior Demo

```
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);
```



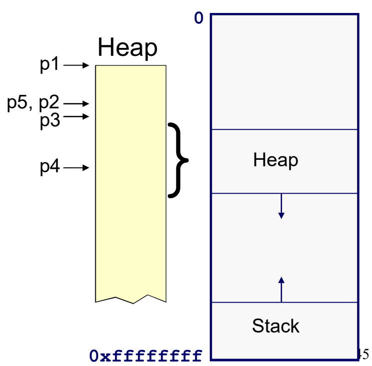
DMMgr Desired Behavior Demo

```
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);
```



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);     ⇦
```



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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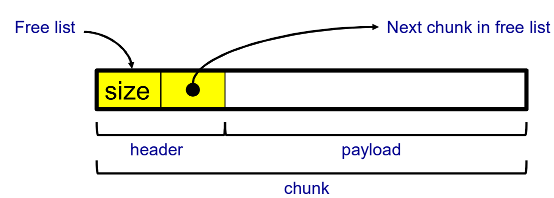
DMM using virtual memory

DMMgr 6: VM implementation

List Impl

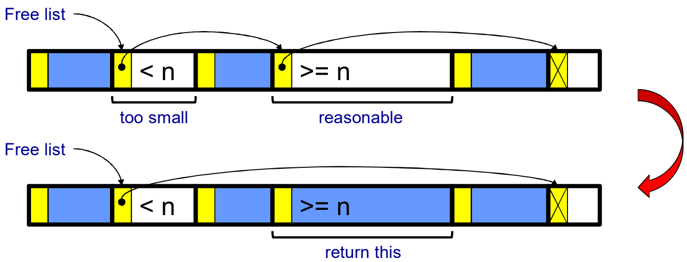
Data structures



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

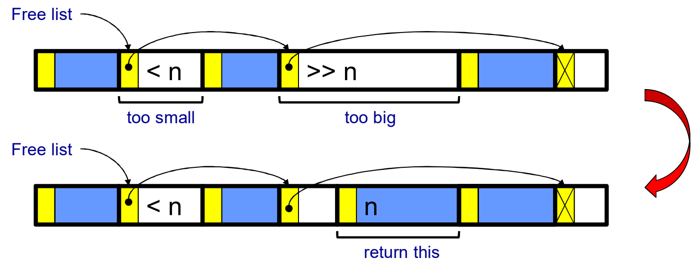
Algorithms (by examples)…

List Impl: malloc(n) Example 1



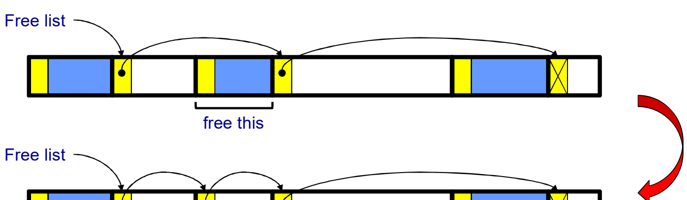
Search list for big-enough chunk
    Note: **first-fit** (not **best-fit**) strategy
Found & reasonable size ⇒
    Remove from list and return payload

List Impl: malloc(n) Example 2



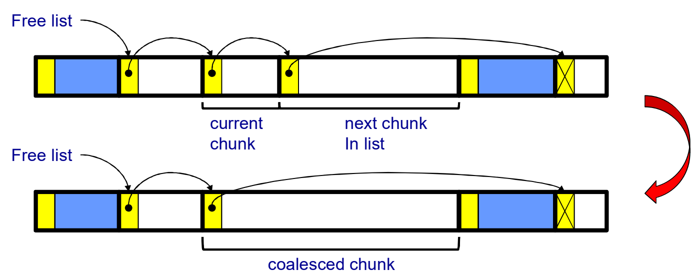
Search list for big-enough chunk
Found & too big ⇒
    Split chunk, return payload of tail end
    Note: Need not change links

List Impl: free(p) Example



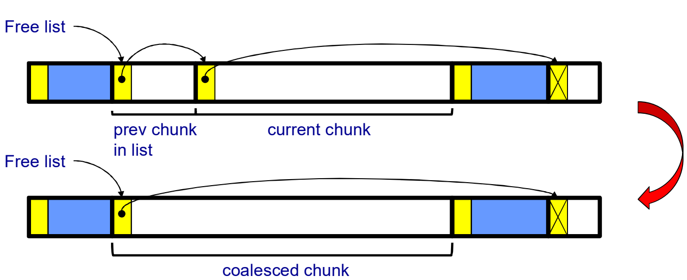
Search list for proper insertion spot
Insert chunk into list
(Not finished yet!)

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



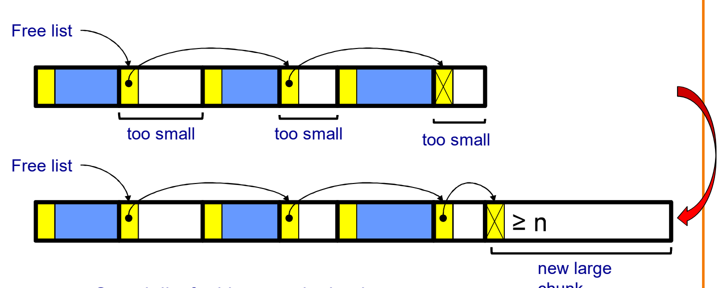
Look at current chunk
Next chunk in memory == next chunk in list ⇒
    Remove both chunks from list
    Coalesce
    Insert chunk into list
(Not finished yet!)

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



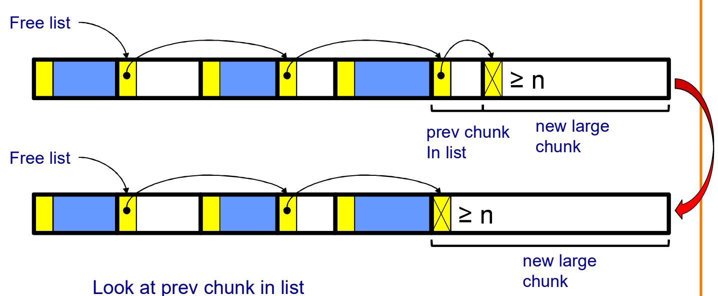
Look at prev chunk in list
Next in memory == next in list ⇒
    Remove both chunks from list
    Coalesce
    Insert chunk into list
(Finished!)

List Impl: 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

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

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

Princeton University
Computer Science 217: Introduction to Programming Systems

Dynamic Memory Management,

continued

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

Pad Impl Performance

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

Unsorted-list-no-coalesce performance

Space

Time: **`malloc()`**

Time: **`free()`**

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

What’s Wrong?

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

Solution
- Use a doubly linked list…

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

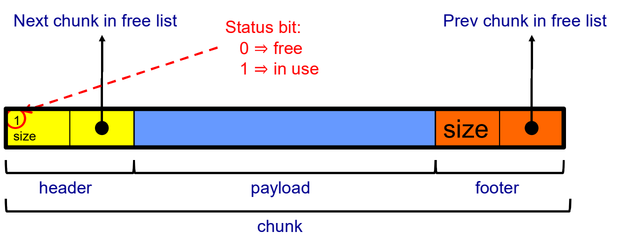
DMMgr 5: Bins implementation

DMM using virtual memory

DMMgr 6: VM implementation

doubly linked List Impl

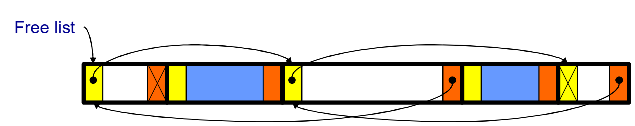
Data structures



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()` …

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

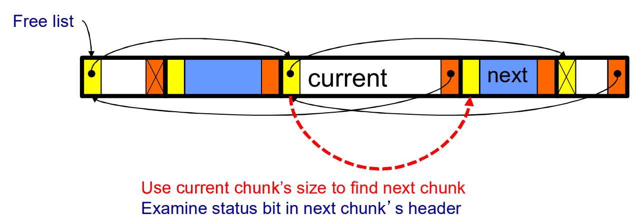
- **Linked list version**: slow
  - Traverse list to find prev chunk in list
- **doubly linked list version**: fast
  - Use backward pointer of current chunk to find prev chunk in list

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

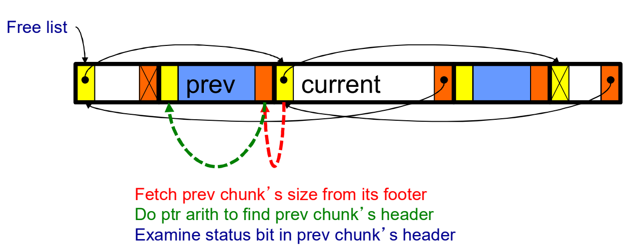


doubly linked List Impl Performance

Consider sub-algorithms of `free()` …

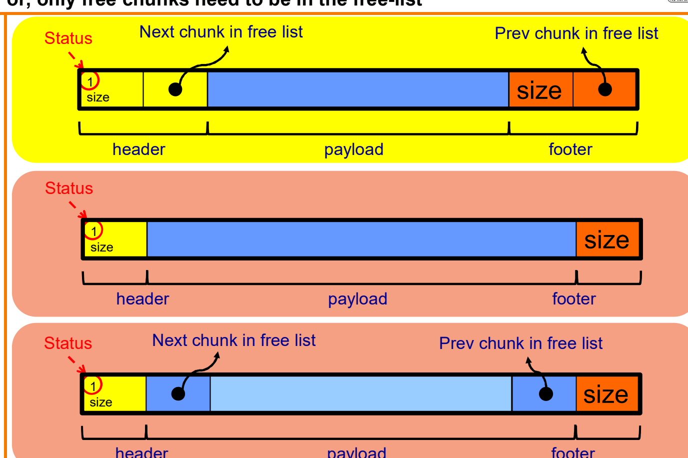
Determine if prev chunk in memory is free

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



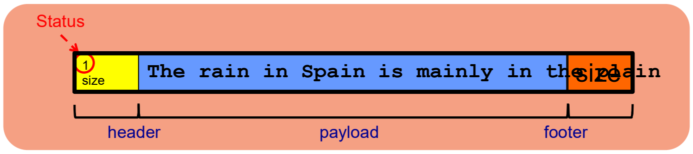
Using payload space for management

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



This trick is NOT part of assignment 6!

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);
```


doubly linked List Impl Performance

Observation:

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

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

doubly linked List Impl Performance
with use-payload-space-for-management

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

What's Wrong?

Problem

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

Solution

- Use multiple doubly linked lists (bins)…

Agenda

The need for DMM

DMM using the heap section

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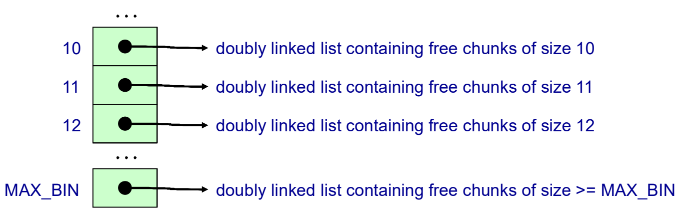
DMMgr 5: Bins implementation

DMM using virtual memory

DMMgr 6: VM implementation

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)

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 internal 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**: very good: O(1)

Time: `free()`
- Very good: O(1)

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)

Agenda

The need for DMM

DMM using the heap section

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Fragmentation

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DMMgr 5: Bins implementation

DMM using virtual memory

DMMgr 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 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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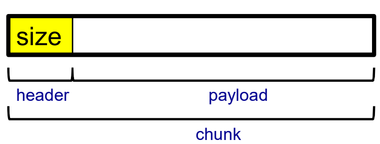
DMMgr 5: Bins implementation

DMM using virtual memory

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

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


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: **bad**
- For large chunks
  - **`free()`** unmaps (large) chunks of memory, and so shrinks page table
  - Overall: **good**

The GNU Implementation

Observation

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

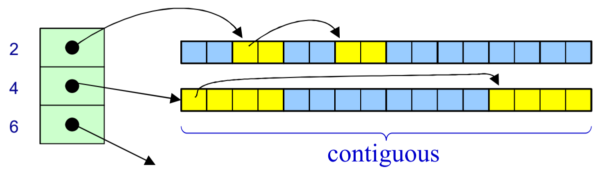
Question

- 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()`**)

Segregated metadata

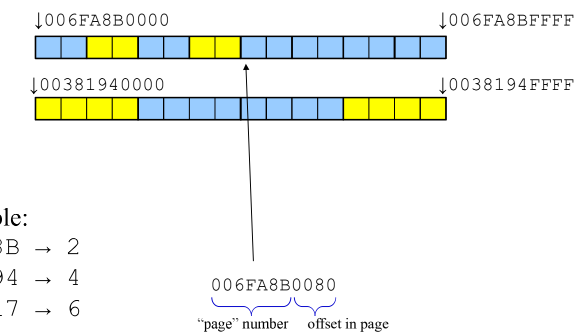


Data layout: no "size" field, no header at all!

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

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, O(1)
- No coalescing, fragmentation may occur, possibly bad

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

Summary

The need for dynamic memory management
- 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