Princeton University
Computer Science 217: Introduction to Programming Systems

Dynamic Memory Management

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Review from Last Time

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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 (DMMgr)**

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

And **time** and **space** efficiency!

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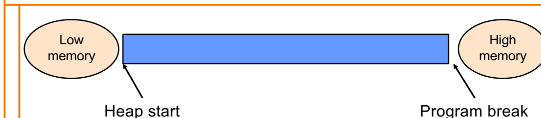
The Heap Section of Memory



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
Can shrink dynamically

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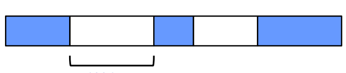
Internal Fragmentation

Internal fragmentation: waste **within** chunks



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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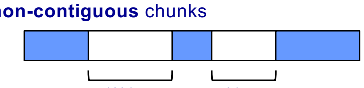
External Fragmentation

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



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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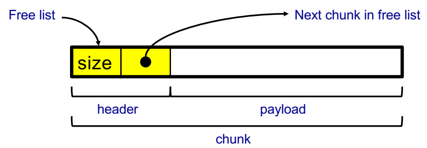
List Impl: Baseline for Asgt 6

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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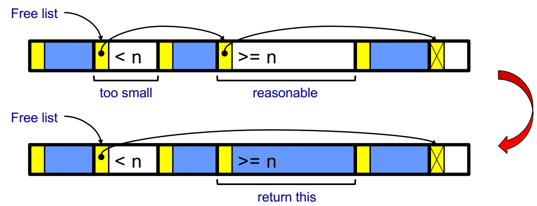
List Impl: malloc(n) Example 1



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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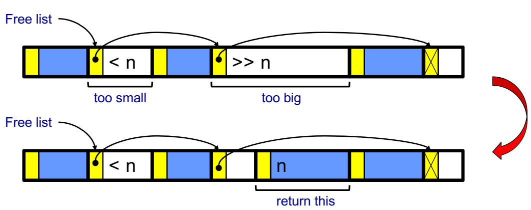
List Impl: malloc(n) Example 2



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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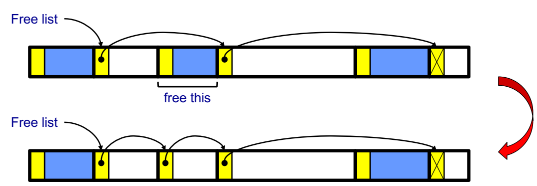
List Impl: free(p) Example



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

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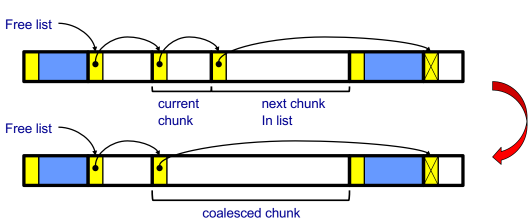
List Impl: free(p) Example (cont.)



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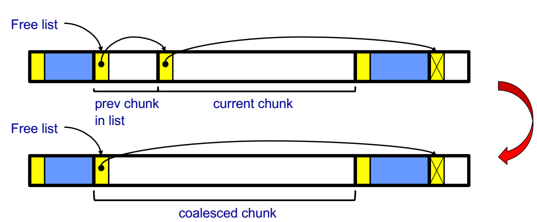
List Impl: free(p) Example (cont.)



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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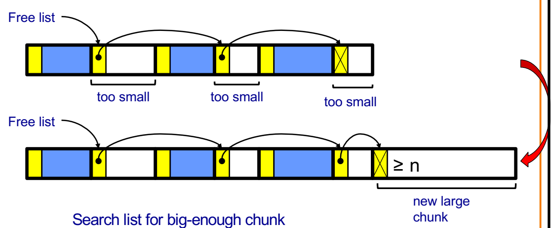
List Impl: malloc(n) Example 3



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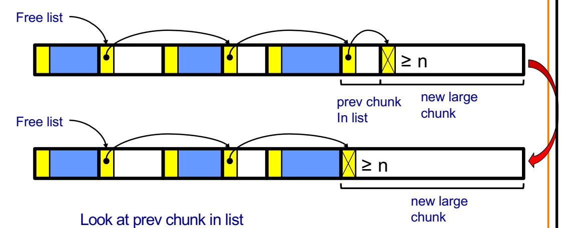
List Impl: malloc(n) Example 3 (cont.)



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 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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Agenda

DMMgr 4: Doubly-linked list implementation

DMMgr 5: Bins implementation

DMM using virtual memory

DMMgr 6: VM implementation

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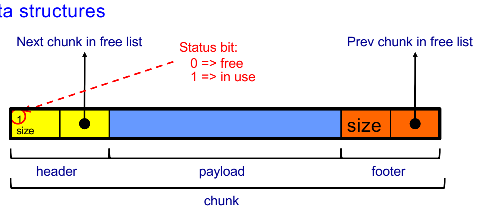
Doubly-Linked List Impl

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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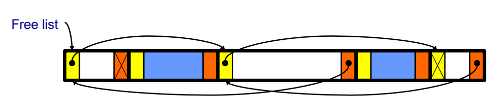
Doubly-Linked List Impl

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()`** …

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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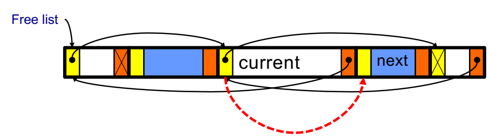
Doubly-Linked List Impl Performance

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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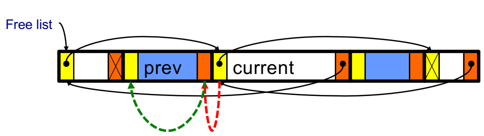
Doubly-Linked List Impl Performance

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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Agenda

DMMgr 4: Doubly-linked list implementation

DMMgr 5: Bins implementation

DMM using virtual memory

DMMgr 6: VM implementation

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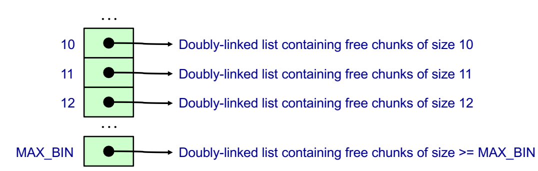
Bins Impl

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()`
- ???

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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

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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Agenda

DMMgr 4: Doubly-linked list implementation

DMMgr 5: Bins implementation

DMM using virtual memory

DMMgr 6: VM implementation

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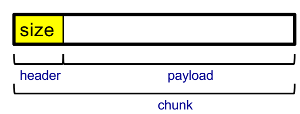
VM Mapping Impl

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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iClicker Question

Q: When is coalescing most useful?

A. Always

B. When most of the program's objects are the same size

C. When the program simultaneously uses objects of different sizes

D. When the program allocates many objects of size A, then frees most of them, then allocates many objects of size B

E. Never

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Appendix: Additional Approaches

Some additional approaches to dynamic memory mgmt…

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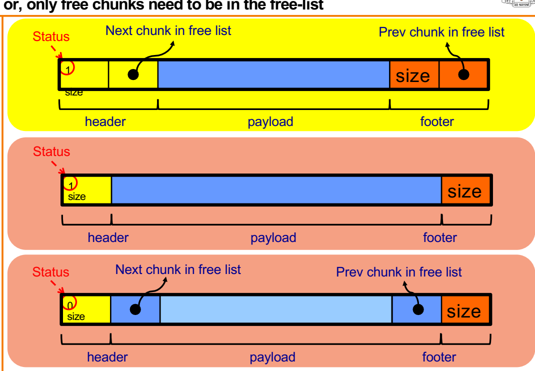
Using payload space for management

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



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This trick is NOT part of assignment 6!

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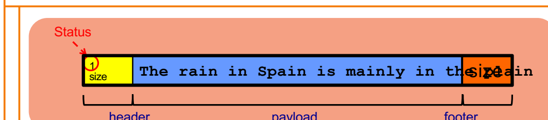
Another use for the extra size field: error checking




```
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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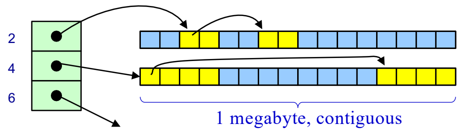
Segregated metadata



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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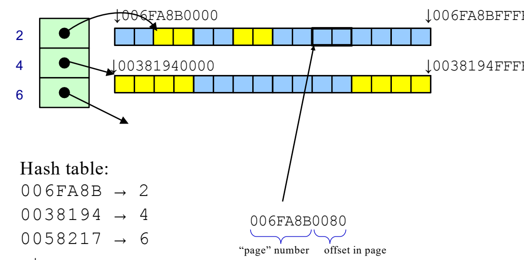
How free() finds the size



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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~~ 16, if payload overlapped with header bytes overhead per object	☺ 0 bytes overhead per object
☺ coalescing, *might* reduce fragmentation	☹ no coalescing

There’s no “one best memory allocator”

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