Memory Allocation I

Computer Operating Systems, Fall 2025

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Sana Manesh

Logistics

- Milestone 1 is due this week, Nov 21st
  - Keep your TA in the loop for when you'd like to schedule the demonstration of your work.
  - Also, you may meet with TAs for Milestone 1 after Friday.
    - The # of late days has to do with the most recent modification of your code.

- Recitation 9: Led by Yemisi & Joy

- No Class or Recitastion, Nov 25th and Nov 27th for Thanksgiving Break.
  - Office Hours Subject to Change.
  - Mine will be online, Wednesday Nov 26th

Logistics

- ***Apply to be a TA for this course!***
  - https://www.cis.upenn.edu/ta-information/
- Here's the timeline!
  - Application due Nov 30th
  - You'll hear back by Dec 4th
  - Interviews conducted Dec 8th – 10th
  - Offers sometime on Dec 10th

- If you have any ideas for how to make the course better, would like to make an impact on a course, and would like to support students as they navigate PennOS; consider applying!

Administrivia

- Final Exam; December 11th
  - Same format as the Midterm!
  - Last course day is December 4th
  - Final Exam Review December 4th @ Recitation
- PennOS Due Friday, July 25th

Administrivia

- Some notes:
  - Reminder, you instead of just doing:

```
lseek(FAT_FD, offset, SEEK_SET);
write(FAT_FD, contents, size);
```

  you may need to do:

```
lseek(FAT_FD, offset, SEEK_SET);
write(FAT_FD, contents, size);
lseek(FAT_FD, offset, SEEK_SET);
write(FAT_FD, contents, size);
```

  - With the description of `setitimer()`, it just says that sigalarm is delivered to the process, not necessarily the calling thread. To make sure siglaram goes to the scheduler, you may want to make it so that all threads (spthread or otherwise) that aren't the scheduler call something like: **`pthread_sigmask(SIG_BLOCK, SIGALARM)`**
    - Which will block SIGALARM in that thread.

Administrivia

- If you are having issues with the scheduler not running you can try running
  - **`strace -e 'trace=!all' ./bin/pennos`**
  - You may have to install strace: **`sudo apt install strace`**
  - This will print out every time a signal is sent to your pennos
  - (Usual fix is the pthread_sigmask thing on the previous slide)

Lecture Outline

- **Stack & Heap w/ Free-lists**
- Memory Alignment
- Fragmentation
- Leaks

Stack & Heap

- Hopefully you are familiar with the stack and the heap,
  - Quick refresher now though

- Stack:
  - Where local variables & information for local functions are stored (return address, etc).
  - Grows whenever you call a function. pushes a “stack frame” for each function call.

- Heap:
  - Dynamically allocated data stored here. Usually done when data needs to exist beyond the scope it is allocated in, or the size is not known at compile time

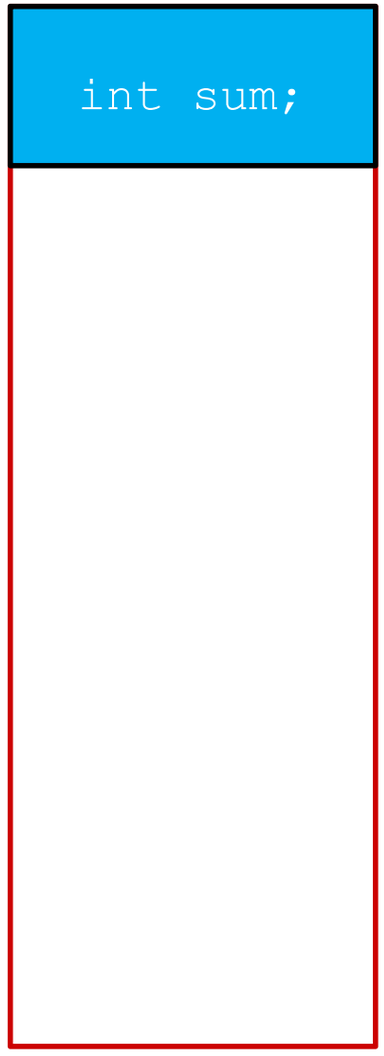
Stack Example:

Stack frame for main is created when CPU starts executing it

```c
#include <stdio.h>
#include <stdlib.h>

int sum(int n) {
  int sum = 0;
  for (int i = 0; i < n; i++) {
    sum += i;
  }
  return sum;
}

int main() {
  int sum = sum(3);
  printf("sum: %d\n", sum);
  return EXIT_SUCCESS;
}
```



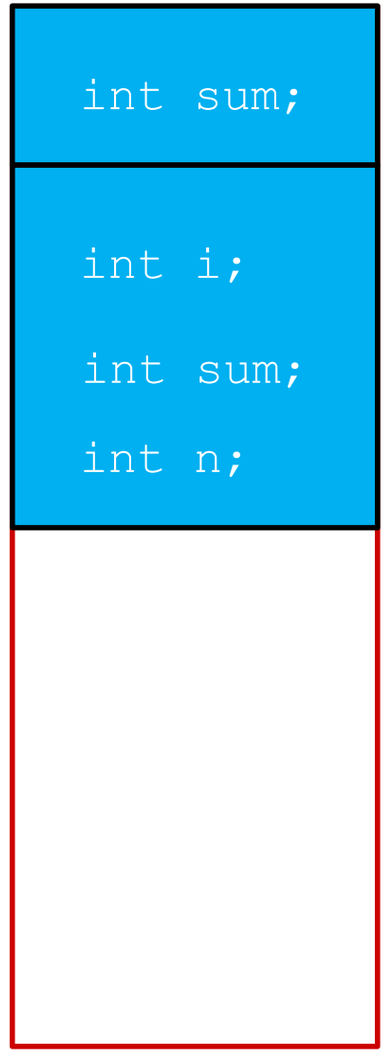
Stack frame for `main()`

Stack Example:

```c
#include <stdio.h>
#include <stdlib.h>

int sum(int n) {
  int sum = 0;
  for (int i = 0; i < n; i++) {
    sum += i;
  }
  return sum;
}

int main() {
  int sum = sum(3);
  printf("sum: %d\n", sum);
  return EXIT_SUCCESS;
}
```



Stack frame for `main()`

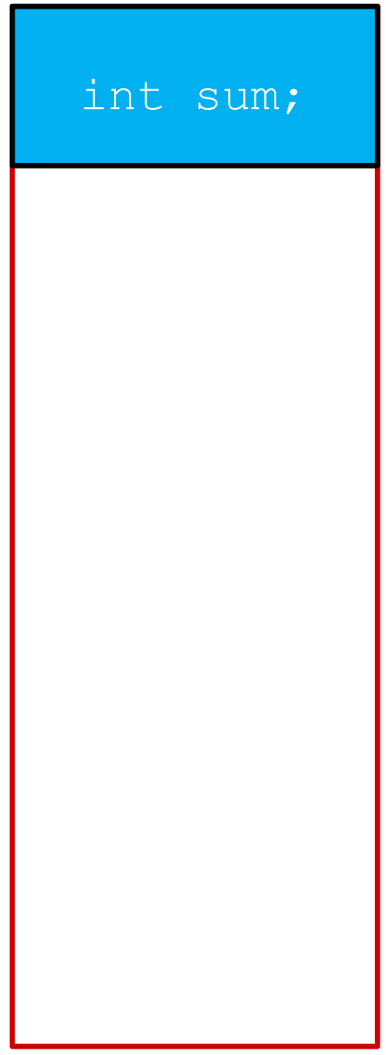
Stack frame for `sum()`

Stack Example 1:

```c
#include <stdio.h>
#include <stdlib.h>

int sum(int n) {
  int sum = 0;
  for (int i = 0; i < n; i++) {
    sum += i;
  }
  return sum;
}

int main() {
  int sum = sum(3);
  printf("sum: %d\n", sum);
  return EXIT_SUCCESS;
}
```

Stack frame for `main()`

`sum()`'s stack frame goes away after **`sum()`** returns.

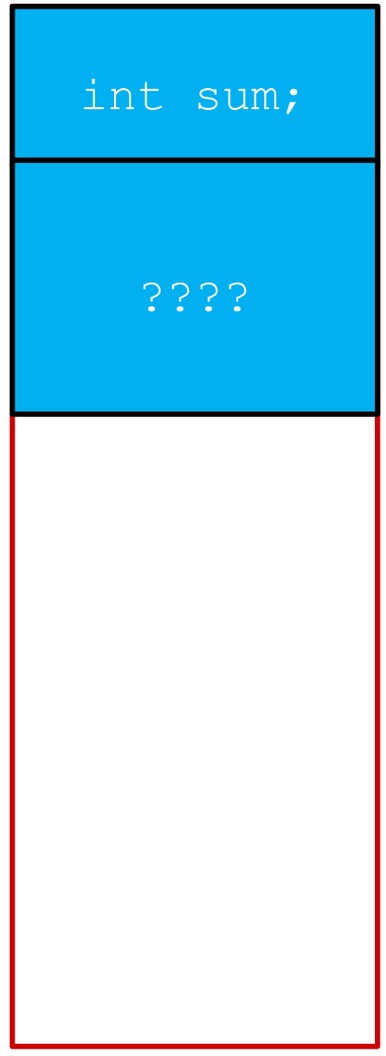
`main()`'s stack frame is now top of the stack and we keep executing **`main()`**

Stack Example:

```c
#include <stdio.h>
#include <stdlib.h>

int sum(int n) {
  int sum = 0;
  for (int i = 0; i < n; i++) {
    sum += i;
  }
  return sum;
}

int main() {
  int sum = sum(3);
  printf("sum: %d\n", sum);
  return EXIT_SUCCESS;
}
```



Stack frame for `main()`

Stack frame for `printf()`

Stack

- Grows, but has a static max size
  - Can find the default size limit with the command `ulimit -a`
    (May be a different command in different shells and/or linux versions. Works in bash on Ubuntu though)
  - Can also be found at runtime with `getrlimit(3)`

- Max Size of a stack can be changed
  - at run time with `setrlimit(3)`
  - At compilation time for some systems (not on Linux it seems)
  - (or at the creation of a thread, more on threads next lecture)

The Heap

- The Heap is a large pool of available memory to use for Dynamic allocation
- This pool of memory is kept track of with a small data structure indicating which portions have been allocated, and which portions are currently available.
- **`malloc`**:
  - searches for a large enough unused block of memory
  - marks the memory as allocated.
  - Returns a pointer to the beginning of that memory
- **`free`**:
  - Takes in a pointer to a previously allocated address
  - Marks the memory as free to use.

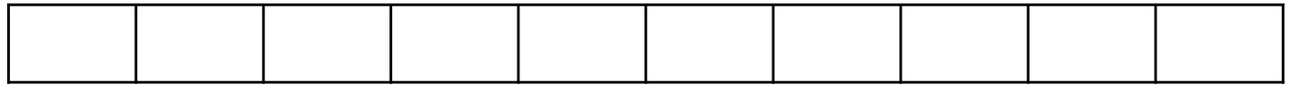
Dynamic Memory Example (Naïve)

- When we allocate data on the heap we get the guarantee that the data is contiguous within an allocation

```c
#include <stdlib.h>

int main() {
  char* ptr = malloc(4*sizeof(char));
  char* ptr2 = malloc(6*sizeof(int));
  ...              // do stuff with ptr
  free(ptr);
  free(ptr2);
}
```

- Heap:



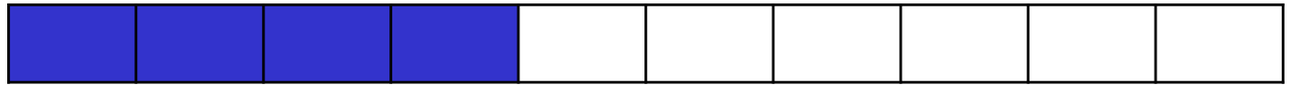
Dynamic Memory Example (Naïve)

- When we allocate data on the heap we get the guarantee that the data is contiguous within an allocation

```c
#include <stdlib.h>

int main() {
  char* ptr = malloc(4*sizeof(char));
  char* ptr2 = malloc(6*sizeof(int));
  ...              // do stuff with ptr
  free(ptr);
  free(ptr2);
}
```

- Heap:



Dynamic Memory Example (Naïve)

- When we allocate data on the heap we get the guarantee that the data is contiguous within an allocation

```c
#include <stdlib.h>

int main() {
  char* ptr = malloc(4*sizeof(char));
  char* ptr2 = malloc(6*sizeof(int));
  ...              // do stuff with ptr
  free(ptr);
  free(ptr2);
}
```

- Heap:

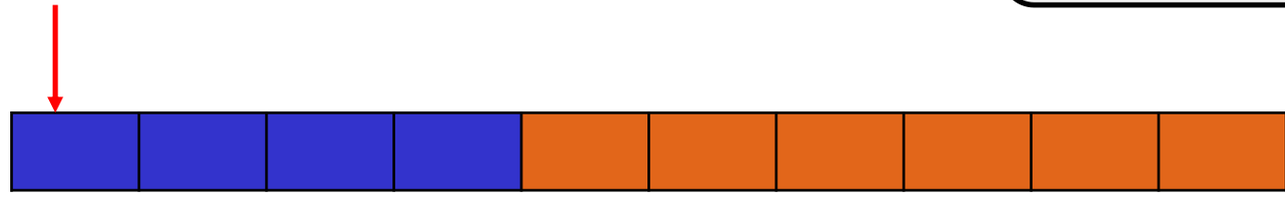
Dynamic Memory Example (Naïve)

- When we allocate data on the heap we get the guarantee that the data is contiguous within an allocation

```c
#include <stdlib.h>

int main() {
  char* ptr = malloc(4*sizeof(char));
  char* ptr2 = malloc(6*sizeof(int));
  ...              // do stuff with ptr
  free(ptr);
  free(ptr2);
}
```

- Heap:



How do we know how much to deallocate?

How do we mark the memory as “free”?

When we allocate next, how do we know where we could allocate from?

Free Lists

- One way that malloc can be implemented is by maintaining an implicit list of the space available and space allocated.
- Before each chunk of allocated/free memory, we'll also have this metadata:

```
// this is simplified
// not what malloc really does
struct alloc_info {
  alloc_info* prev;
  alloc_info* next;
  bool allocated;
  size_t size;
};
```

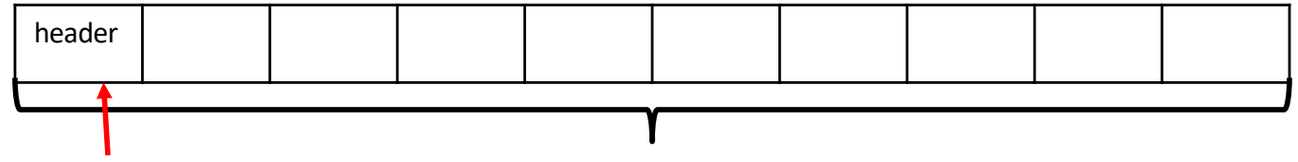
Dynamic Memory Example

```
#include <stdlib.h>

int main() {
  char* ptr = malloc(4*sizeof(char));
  char* ptr2 = malloc(6*sizeof(int));
  ...              // do stuff with ptr
  free(ptr);
  free(ptr2);
}
```

This diagram is not to scale

- free_list ->




```
{
 NULL,
 NULL,
 false,
 1000
}
```

The metadata is at the beginning of the chunk of memory

Dynamic Memory Example

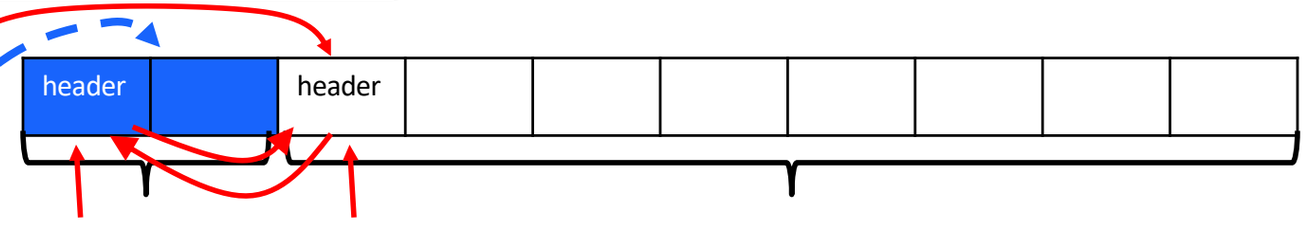
```c
#include <stdlib.h>

int main() {
  char* ptr = malloc(4*sizeof(char));
  char* ptr2 = malloc(6*sizeof(int));
  ...              // do stuff with ptr
  free(ptr);
  free(ptr2);
}
```

Free chunks can be split to allocate blocks of specific size

Malloc gets a pointer to just after the metadata

- free_list



malloc return value

```
{
 NULL,
 0x…,
 true,
 4
}
```

```
{
 0x…,
 NULL,
 false,
 972
}
```

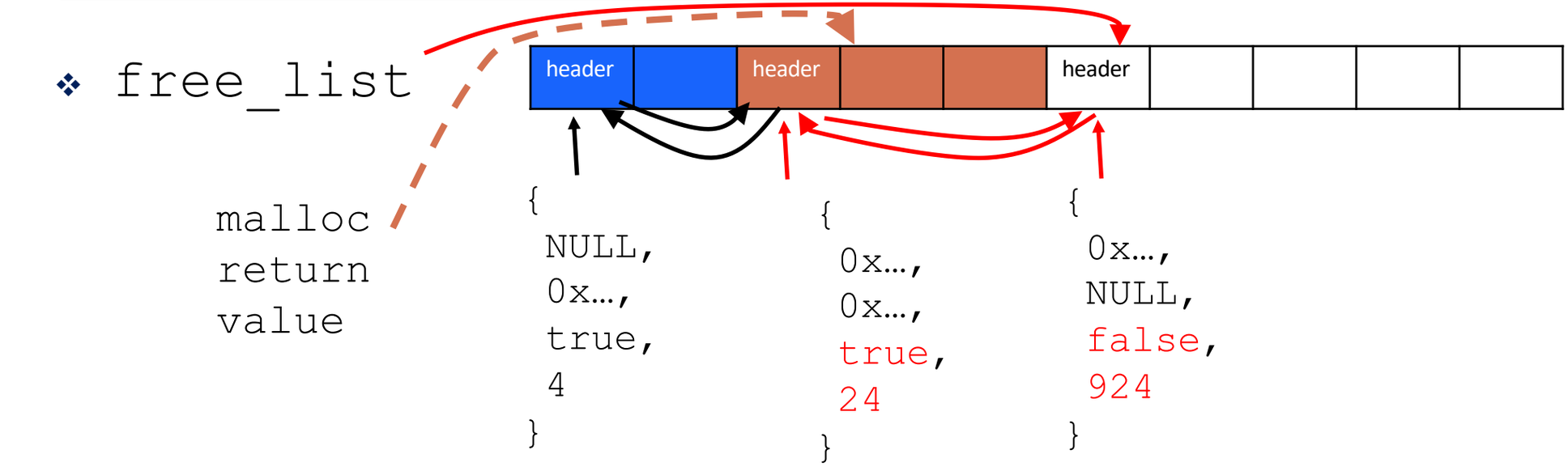
free_list points to first free chunk

Dynamic Memory Example

```
#include <stdlib.h>

int main() {
  char* ptr = malloc(4*sizeof(char));
  char* ptr2 = malloc(6*sizeof(int));
  ...              // do stuff with ptr
  free(ptr);
  free(ptr2);
}
```

- free_list

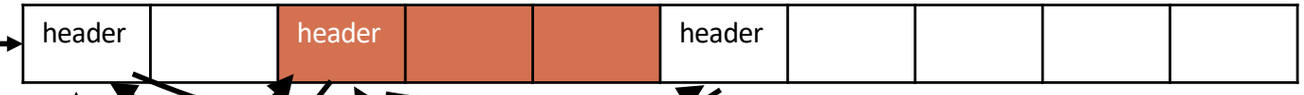


Dynamic Memory Example

```c
#include <stdlib.h>

int main() {
  char* ptr = malloc(4*sizeof(char));
  char* ptr2 = malloc(6*sizeof(int));
  ...              // do stuff with ptr
  free(ptr);
  free(ptr2);
}
```

- free_list




```
{
 NULL,
 0x…,
 false,
 4
}
```

```
{
 0x…,
 0x…,
 true,
 24
}
```

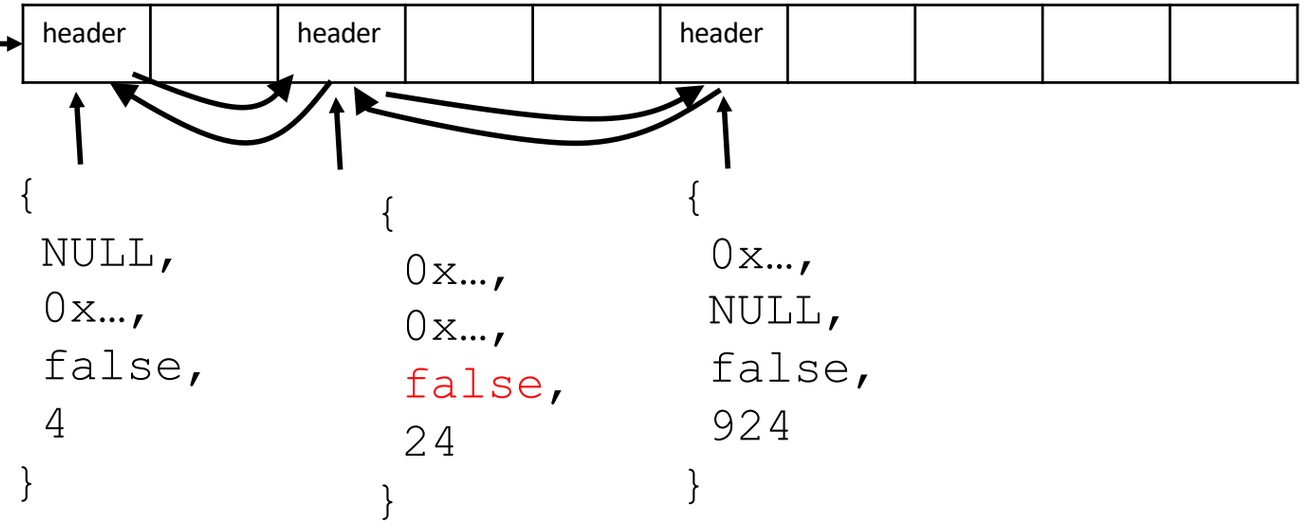
```
{
 0x…,
 NULL,
 false,
 924
}
```

Dynamic Memory Example

```c
#include <stdlib.h>

int main() {
  char* ptr = malloc(4*sizeof(char));
  char* ptr2 = malloc(6*sizeof(int));
  ...              // do stuff with ptr
  free(ptr);
  free(ptr2);
}
```

- free_list



Dynamic Memory Example

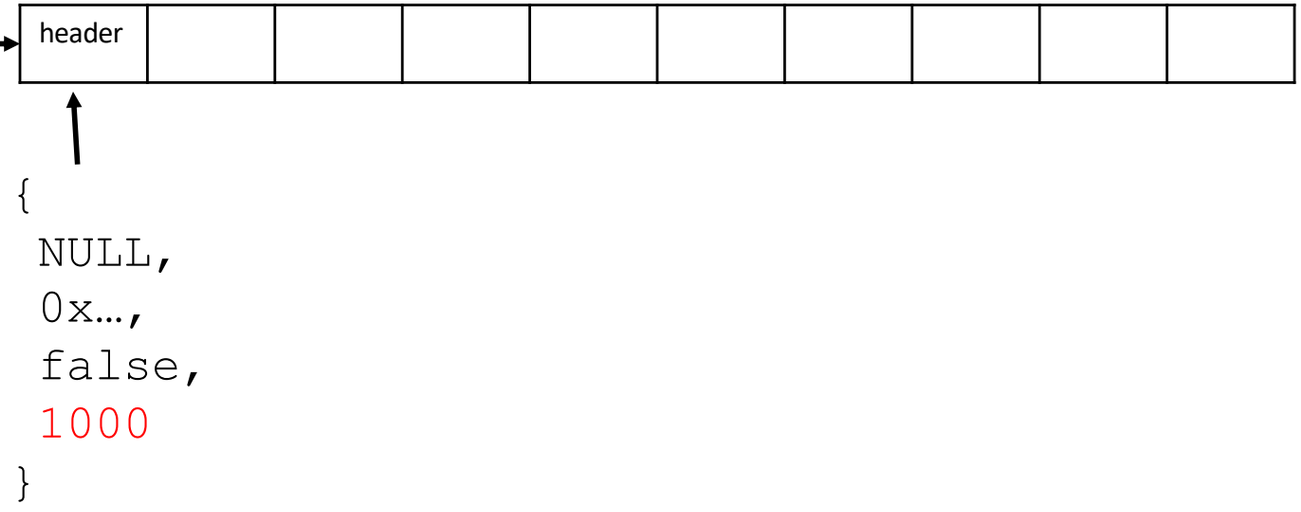
```c
#include <stdlib.h>

int main() {
  char* ptr = malloc(4*sizeof(char));
  char* ptr2 = malloc(6*sizeof(int));
  ...              // do stuff with ptr
  free(ptr);
  free(ptr2);
}
```

Once a block has been freed, we can try to "coalesce" it with their neighbors

The first free couldn't be coalesced, only neighbor was allocated

- free_list



Heap

- `malloc()` and `free()` are not system calls, they are implemented as part of the C std library
  - `malloc()` and `free()` will sometimes internally invoke system calls to expand the heap if needed
  - Instead, these functions just manipulate memory already given to the process, marking some as free and some as allocated

- System calls used by `malloc()` and `free()`:
  - `brk()` and `sbrk()`
    - Used to grow/shrink the data segment of memory
  - `mmap()`, `munmap()`
    - creates / or destroys a mapping in virtual address space

Memory Allocation Has a Cost

- There is a reason we had “Unnecessary Memory Allocation” in the style guide.
- Memory Allocation is not an O(1) operation

- It takes time to:
  - Search for a block size that is big enough
  - Coalesce / free memory
  - Grow the heap if needed
  - In multithreaded applications, locks need to be acquired!

Poll Everywhere

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- How many memory allocations occur in each piece of code?
  - Assume vector resizes will double capacity
  - std::vector is an arraylist in C++
    std::list is a linked list in C++

```
int main() {
  vector nums {4, 8};  // size and capacity == 2
  nums.push_back(5);
  nums.push_back(9);
  nums.push_back(5);
  nums.push_back(0);
}
```

```
int main() {
  list nums {4, 8};
  nums.push_back(5);
  nums.push_back(9);
  nums.push_back(5);
  nums.push_back(0);
}
```

Minimizing Allocations

- As we saw previously, memory allocations require time, sometimes a lot of time to compute.

- If performance is our goal, we should minimize the number of allocations we make.

- This can include
  - Making references instead of copies
  - Using functions like `vector::reserve(size_t new capacity)`
    - In C++
    - Java arraylist lets you specify capacity in the constructor.
  - Using move semantics

Lecture Outline

- Stack & Heap w/ Free-lists
- **Memory Alignment**
- Fragmentation
- Leaks

Poll Everywhere

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- What do you think sizeof(alloc_info) is on our 64-bit machines? (how many bytes is it)
- Assume size_t is 4 bytes.

```
// this is simplified
// not what malloc really does
struct alloc_info {
  alloc_info* prev;
  alloc_info* next;
  bool allocated;
  size_t size;
};
```

Memory Alignment

- In memory, data isn't always just crammed together.
- Hardware likes it so that if we are dealing with a 4-byte type, then that variable is stored at an address that is a multiple of 4 bytes.
  - Same with types that are 8, 2, 1-byte etc.

- This isn't always the case, but our software and hardware tries to make this the case.

Back to Poll:

- How big is this struct?

```
// this is simplified
// not what malloc really does
struct alloc_info {
  alloc_info* prev;
  alloc_info* next;
  bool allocated;
  size_t size;
};
```

Back to Poll: (Naïve answer)

- How big is this struct?
  - prev
  - next
  - allocated
  - size

```
// this is simplified
// not what malloc really does
struct alloc_info {
  alloc_info* prev;
  alloc_info* next;
  bool allocated;
  size_t size;
};
```

Back to Poll: (Fragmentation answer)

- How big is this struct?
  - prev
  - next
  - allocated
  - size

```
// this is simplified
// not what malloc really does
struct alloc_info {
  alloc_info* prev;
  alloc_info* next;
  bool allocated;
  size_t size;
};
```

Fragmentation: Struct Size

- C structs will also try to be a multiple of its biggest member.
  So in our example, we want to make sure that the struct size is a multiple of 8

```
// this is simplified
// not what malloc really does
struct alloc_info {
  alloc_info* prev;
  alloc_info* next;
  bool allocated;
  size_t size;
};
```

- Given this struct foo: what is the size of the struct?
  What is the optimal size of the struct we could have
  if we rearranged the fields and still respected alignment?

```
struct foo {
  bool allocated;
  uint32_t size;
  bool flag;
  uint16_t bleg;
};
```

Calculating Offsets and Packing Structs

- `offsetof(struct mystruct, struct_member)`
- The macro **offsetof** expands to an integral constant expression, the value of which is the offset, in bytes, from the beginning of the struct of specified type to its specified member, ***including padding bits if any.***

```
struct __attribute__((packed)) mystruct {
        char a;
        int c;
        char b;
};
```

- *Using the attribute packed allows you to pack structs tightly together without any padding in GNU C.*
- ***There are other ways to do this as well, such as #pragma pack(1)***

Lecture Outline

- Stack & Heap w/ Free-lists
- Memory Alignment
- **Fragmentation**
- Leaks

Fragmentation

- Fragmentation: when storage is used inefficiently, which can hurt performance and ability to allocate things.

  Specifically, when there is something that prevents "unused" memory from otherwise being used

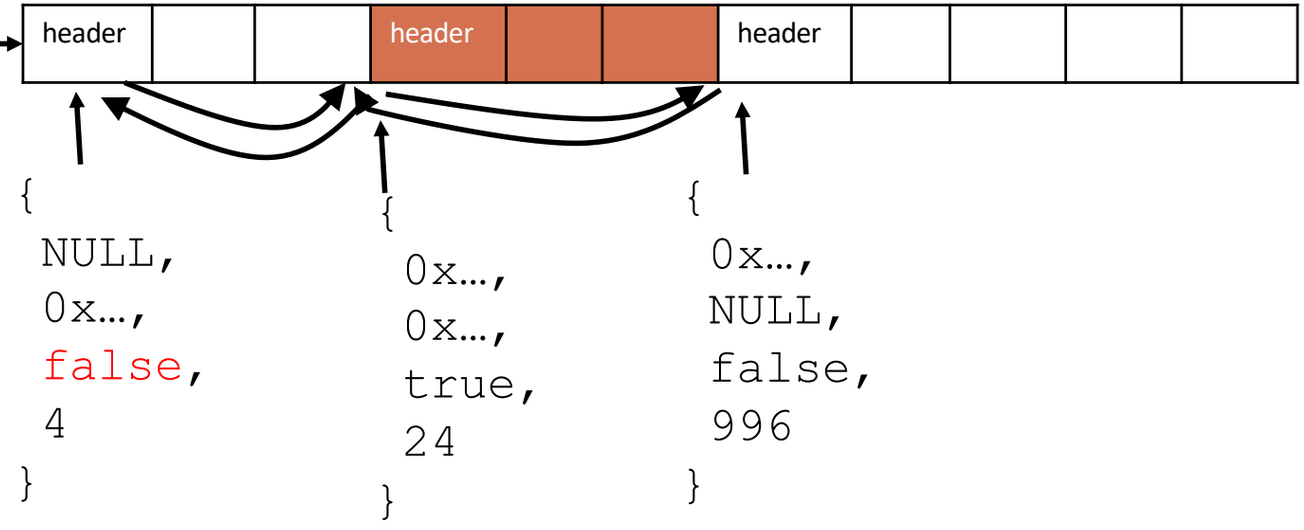
- External Fragmentation: when free memory is spread out over small portions that cannot be coalesced into a bigger block that can be used for allocation

External Fragmentation Example

```
#include <stdlib.h>

int main() {
  char* ptr = malloc(4*sizeof(char));
  char* ptr2 = malloc(6*sizeof(int));
  ...            // do stuff with ptr
  free(ptr);
  ptr = malloc(2*sizeof(char));
  ...
}
```

- free_list

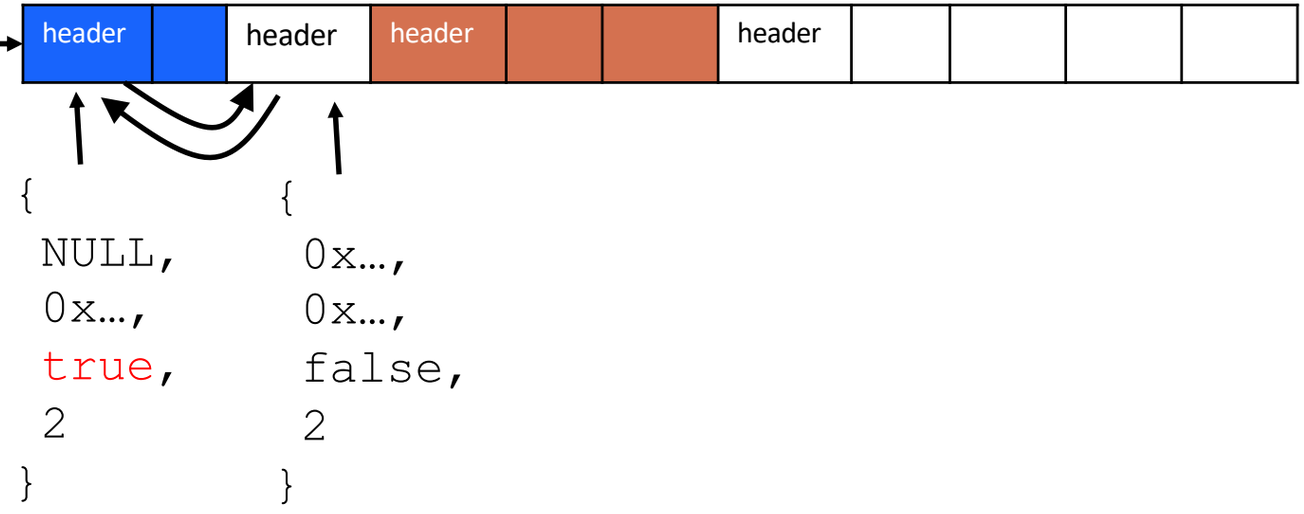


External Fragmentation Example

```
#include <stdlib.h>

int main() {
  char* ptr = malloc(4*sizeof(char));
  char* ptr2 = malloc(6*sizeof(int));
  ...              // do stuff with ptr
  free(ptr);
  ptr = malloc(2*sizeof(char));
  ...
}
```

- free_list



External Fragmentation Example

```c
#include <stdlib.h>

int main() {
  char* ptr = malloc(4*sizeof(char));
  char* ptr2 = malloc(6*sizeof(int));
  ...            // do stuff with ptr
  free(ptr);
  ptr = malloc(2*sizeof(char));
  ...
}
```

After some more series of allocations and frees (not shown), we get this:

Let's say `malloc(4)` gets called (trying to allocate 4 bytes) what happens?

- free_list →


```
{
 0x…,
 0x…,
 false,
 2
}
```

```
{
 0x…,
 0x…,
 false,
 2
}
```

There are 4 bytes of free space, but they aren't next to each other and can't be coalesced into something that can be used.

Heap would need to grow to make space (if possible)

Goes without saying not to scale…

Internal Fragmentation

- Internal Fragmentation: When more space is allocated for something than is actually used. This fragmentation happens “internally” within an allocated portion, instead of “external” to one.

- What if someone calls **malloc(4096 * sizeof(char*))** and only uses the first `char*`?
  - Can be thought of internal fragmentation, not the allocator's fault though (in this use case)
- What if we allocate a struct that has empty space to meet alignment requirements?
- Sometimes we call **malloc()** and more space is allocated than needed.
  - if we allocate for 7 bytes, 8 may actually be allocated. Computer may want addresses to be aligned to a multiple of a power of 2

First Fit

- There may be multiple free blocks that can be chosen for allocation.

- The allocation policy we used in our examples is **First Fit**: find the first block of memory that is big enough
  - Start at the front of the free list, iterate till we find something big enough
  - Usually the simplest to implement

Best Fit

- **Best Fit**: another approach where instead you look for the portion of memory that is the “best” or “tightest” fit

- If allocating for 4 bytes of memory, search for the smallest block that is >= 4 bytes.

Worst Fit

- **Worst Fit**: another approach where instead you look for the portion of memory that is the "worst" fit (opposite of best fit)

- If allocating for 4 bytes of memory, search for the **largest** block that is >= 4 bytes.

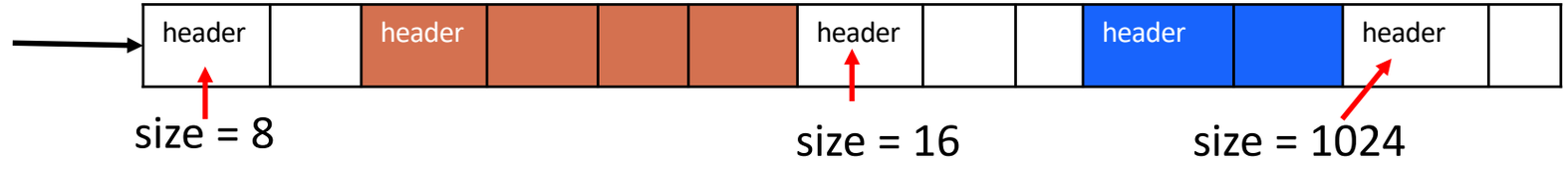
Poll Everywhere

discuss

- What is the approximate runtime of the algorithms? (e.g. O(N log(N))). What is the best/worst case?
  - First Fit
  - Best Fit
  - Worst Fit

- Lets say we call `malloc(4 bytes)`. Which block is allocated in this example if we choose:
  - First Fit
  - Best fit
  - Worst fit

free_list



Poll Everywhere

discuss

- It turns out that over long periods of time, worst fit can work better than best fit. Why is this the case?

Lecture Outline

- Stack & Heap w/ Free-lists
- Memory Alignment
- Fragmentation
- **Leaks**

Memory Leaks

- How do we feel about them? Good? Bad?

Memory Leaks

- The most common Memory Pitfall
- What happens if we allocate something, but don't delete it?
  - That block of memory cannot be reallocated, even if we don't use it anymore, until it is **`free`**-d
  - Is this a problem?

Memory Leaks

- The most common Memory Pitfall
- What happens if we allocate something, but don't delete it?
  - That block of memory cannot be reallocated, even if we don't use it anymore, until it is **`free`**-d
  - Is this a problem?

- If this happens enough, we run out of heap space and program may slow down and eventually crash

Memory Leaks

- The most common Memory Pitfall
- What happens if we allocate something, but don't delete it?
  - That block of memory cannot be reallocated, even if we don't use it anymore, until it is **`free`**-d
  - Is this a problem?

- What if it is a short lived program or we are about to exit the process? Do we still need to free?
  - Eh……. The OS will clean up all of memory when our process exits
    - And by "clean up", this means removing Page Table Entries for that process and allocating them for someone else.

Memory Leaks

- The most common Memory Pitfall
- What happens if we allocate something, but don't delete it?
  - That block of memory cannot be reallocated, even if we don't use it anymore, until it is **`free`**-d

- Garbage Collection
  - Automatically "frees" anything once the program has lost all references to it
  - Affects performance, but avoid memory leaks
  - Java and other "high level" languages

- RAII (Resource Acquisition Is Initialization)
  - C++ and Rust have this, it is VERY GOOD

RAII

- In C++, Rust and other languages we have RAII
  - Resource Acquisition is Initialization
  - What this really means is that in addition to a “constructor” for an object there exists a “destructor” that cleans up the object
  - The destructor is called for you when the object falls out of scope
    The destructor will free the underlying memory the vector allocated!
  - Can still cause issues, but makes it easier than C’s explicit calls to free()

```
int main() {
  vector nums {4, 8};
  nums.push_back(5);
  nums.push_back(9);
  nums.push_back(5);
  nums.push_back(0);
  // nums.~vector()   implicit destructor call
}
```

```
int main() {
  if (…) {
    vector nums {4, 8};
    nums.push_back(0);
    // nums.~vector()
  }
}
```

Safety C Example

- Here is an example in C where is the issue?

```
int main(int argc, char** argv) {
  int* ptr = malloc(sizeof(int));
  assert(ptr != NULL);
  *ptr = 5;

  // do stuff with ptr

  free(ptr);

  printf("%d\n", *ptr);
}
```

C++ Safety

- Here is an example in C++ where is the issue?

```
#include <iostream>
#include <vector>

using namespace std;


int main(int argc, char** argv) {
  vector<int> v {3, 4, 5};
  int* first = &v.front();

  cout << *first << endl;     // print(*first)

  v.push_back(6);

  cout << v.size() << endl;   // print(v.size())
  cout << *first << endl;     // print(*first)
}
```

C++ Safety

- Here is an example in C++ where is the issue?

```
#include <iostream>
#include <vector>

using namespace std;

int* foo() {
 vector<int> v {3, 4, 5};
 return &v[0];
}
int main(int argc, char** argv) {
  int* first = foo();
  cout << *first << endl;   // print(*first)

}
```

More Next Time ☺

- Next Time
  - Garbage Collection
  - Arena Allocators
  - Slab Allocators
  - Buddy Allocators

Poll Everywhere

pollev.com/cis5480

- How many memory allocations occur in each piece of code?
  - Assume vector resizes will double capacity
  - std::vector is an arraylist in C++
    std::list is a linked list in C++

```
int main() {
  vector nums {4, 8};  // size and capacity == 2
  nums.push_back(5);
  nums.push_back(9);
  nums.push_back(5);
  nums.push_back(0);
}
```

3

```
int main() {
  list nums {4, 8};
  nums.push_back(5);
  nums.push_back(9);
  nums.push_back(5);
  nums.push_back(0);
}
```

6

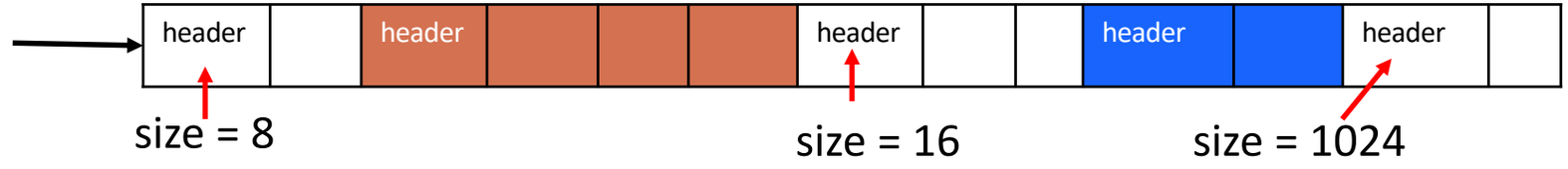
Poll Everywhere

discuss

- What is the approximate runtime of the algorithms? (e.g. O(N log(N))). What is the best/worst case?
  - First Fit best: O(1), worst: O(n)
  - Best Fit best: O(n), worst: O(n)
  - Worst Fit best: O(n), worst: O(n)

- Lets say we call `malloc(4 bytes)`. Which block is allocated in this example if we choose:
  - First Fit 8 byte chunk
  - Best fit 8 byte chunk
  - Worst fit 1024 byte chunk

free_list



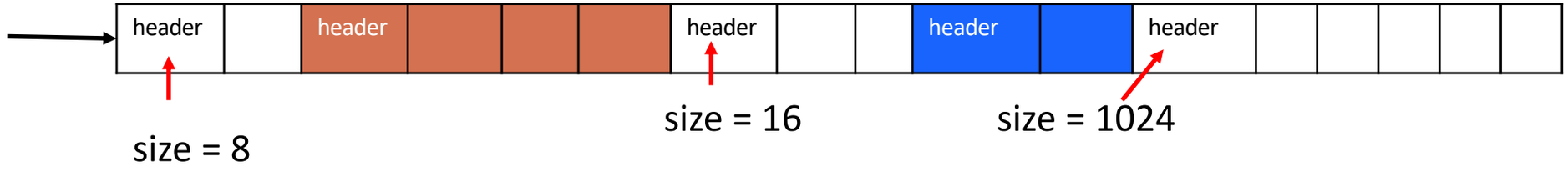
Poll Everywhere

discuss

- It turns out that over long periods of time, worst fit can work better than best fit. Why is this the case?

- Less small “leftover” fragments, fragments are bigger and easier to reuse

- In the previous example, if we allocate for size 6…



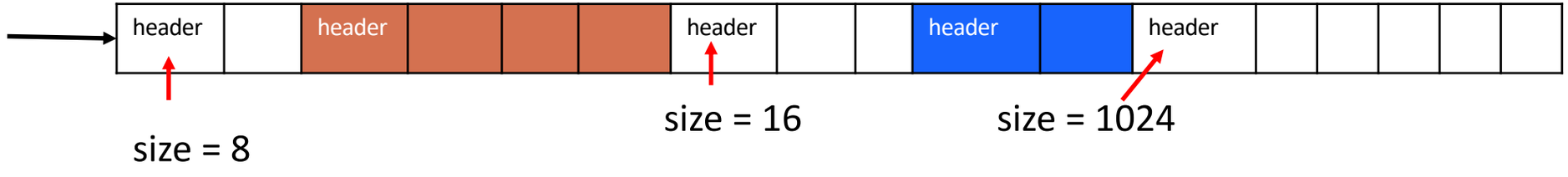
Poll Everywhere

discuss

- It turns out that over long periods of time, worst fit can work better than best fit. Why is this the case?

- Less small “leftover” fragments, fragments are bigger and easier to reuse

- In the previous example, if we allocate for size 6…
  - Best fit would allocate the size 8 free chunk leaving a size 2 chunk that is unlikely to be usable



Poll Everywhere

discuss

- It turns out that over long periods of time, worst fit can work better than best fit. Why is this the case?

- Less small “leftover” fragments, fragments are bigger and easier to reuse

- In the previous example, if we allocate for size 6…
  - Worst fit would use 1024, splitting it into 6 and 1018. 8 chunk is still usable and 1018 is still usable.