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CS61C

Great Ideas in Computer Architecture

(a.k.a. Machine Structures)

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Memory (Mis)Management

内存管理

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What gets printed?

sizeof()

sizeof(): compile-time operator; gives size in **bytes** (of type or variable).

字节

```
// for this exercise, assume
// shorts are 16b, pointers are 32b
void mystery(short arr[], int len) {
  printf("%d ", len);
  printf("%d\n", sizeof(arr));
}

int main() {
  short nums[] = {1, 2, 3, 99, 100};
  printf("%d ", sizeof(nums));
  mystery(nums, sizeof(nums)/sizeof(short));
  return 0;
}
```

↑ pointer

total size = 10

A. 10 5 10
B. 10 5 4
C. 80 5 80
D. 80 5 32
E. Other

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What gets printed?

`sizeof()`: compile-time operator; gives size in bytes (of type or variable).

```
// for this exercise, assume
// shorts are 16b, pointers are 32b
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  printf("%d ", len);
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int main() {
  short nums[] = {1, 2, 3, 99, 100};
  printf("%d ", sizeof(nums));
  mystery(nums, sizeof(nums)/sizeof(short));
  return 0;
}
```

Array has decayed to a pointer

In array's declared scope, total array size.

In array's declared scope, # elements in array.

A. 10 5 10
B. 10 5 4
C. 80 5 80
D. 80 5 32
E. Other

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Memory Locations

- Memory Locations
- The Stack
- The Heap
- Linked List Example
- When Memory Goes Bad
- Implementing Memory Management

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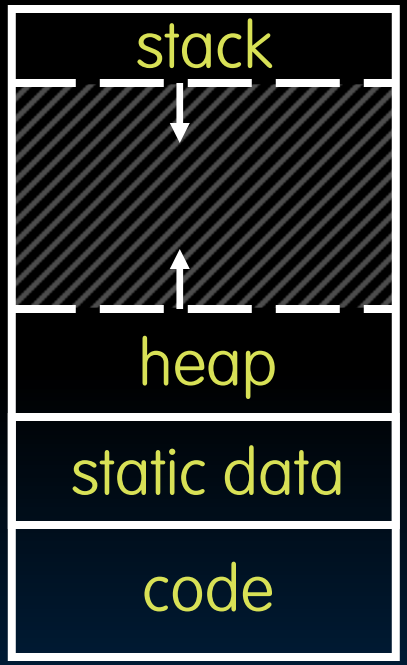
C Program Address Space 地址空间

- **A program's address space contains 4 regions:**
  - **Stack**: local variables inside functions, grows downward
  - **Heap**: space requested for pointers via `malloc()`; resizes dynamically, grows upward 动态调整
  - **Static Data**: variables declared outside main, does not grow or shrink
  - **Code (aka Text)**: loaded when program starts, does not change
  - `0x00000000` chunk is unwriteable/unreadable so you that crash on `NULL` pointer access
- **Programming in C requires knowing where objects are in memory, otherwise things don't work as expected.**
  - By contrast, Java hides location of objects.



For now, OS somehow prevents accesses between stack and heap (gray hash lines). Wait for virtual memory!

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Where are variables allocated?

- If declared outside a function (global), allocated in "static" storage.
- If declared inside function (local), allocated on the "stack" and freed when function returns.
  - NB: `main()` is a function
- For both these memory types, the management is automatic.
  - You don't need to worry about deallocating when you are no longer using them.
  - But a variable **does not exist anymore** once a function ends!

```
int myGlobal;
main() {
   int myTemp;
}
```

static Data
Stack

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The Stack

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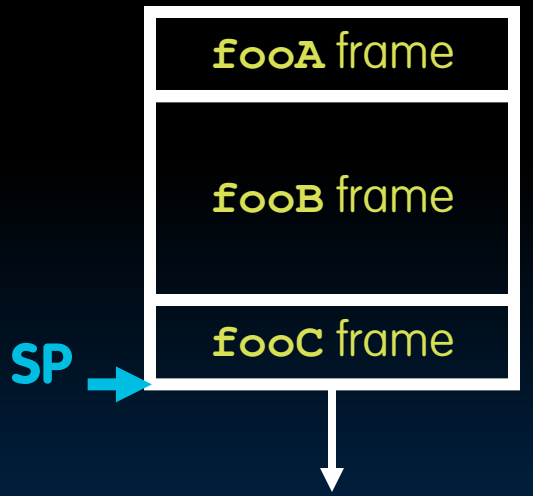
The Stack

- Every time a function is called, a new "stack frame" is allocated on the stack.
- Stack frame includes:
  - Return "instruction" address (who called me?)
  - Arguments
  - Space for other local variables
- Stack frames contiguous blocks of memory; stack pointer indicates start of stack frame.
- When function ends, stack frame is tossed off the stack; frees memory for future stack frames.
- Later, we'll cover details for RISC-V processor.

```
fooA() { fooB(); }
fooB() { fooC(); }
fooC() { … }
```



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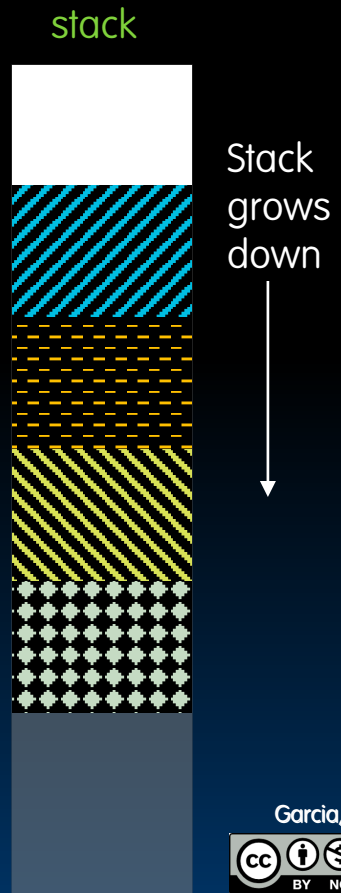
The Stack is Last In, First Out (LIFO)

```
int main ()
{ a(0);  …
}
  void a (int m)
  { b(1);
  }
    void b (int n)
    { c(2);
    }
      void c (int o)
      { d(3);
      }
        void d (int p)
        {
        }
```

Last in First Out



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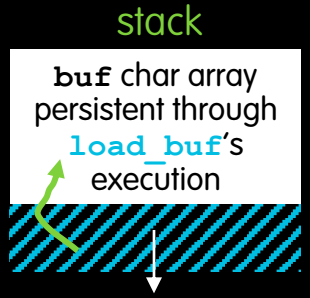
Passing Pointers into the Stack

It is fine to pass a pointer to stack space further down.

```
#define BUFLEN 256
int main() {
    …
    char buf[BUFLEN];
    load_buf(buf, BUFLEN);
    …
}
```

buf is pointer

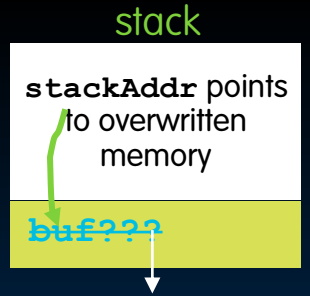


However, it is catastrophically bad to return a pointer to something in the stack!

- Memory will be overwritten when other functions are called!
- So your data would no longer exist…and writes can overwrite key pointers, causing crashes!

```
char *make_buf() {
    char buf[50];
    return buf;
}

int main(){
    …
    char *stackAddr = \
       make_buf();
    foo();
    …
}
```



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The Heap

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动态

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What is the Heap? 动态内存

- **The heap is dynamic memory – memory that can be allocated, resized, and freed during program runtime.**
  - Where Java `new` command allocates memory
  - Useful for persistent memory across function calls
  - But biggest source of pointer bugs, memory leaks, …
- **Large pool of memory, not allocated in contiguous order**
  - Back-to-back requests for heap memory *could* result in blocks very far apart
- **In C, specify number of bytes of memory explicitly to allocate item**
  - `malloc()`: Allocates raw, uninitialized memory from heap
  - `free()`: Frees memory on heap
  - `realloc()`: Resizes previously allocated heap blocks to new size
  - Unlike the stack, memory gets reused only when programmer **explicitly** cleans up

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void *malloc(size_t n)

- **Allocates a block of uninitialized memory:**
  - `size_t n` is an unsigned integer type big enough to "count" memory bytes.
  - Returns `void *` pointer to block of memory on heap.
  - A return of NULL indicates no more memory (**always** check for it!!!)
- **To allocate a struct:**

```
typedef struct { ... } TreeNode;
TreeNode *tp = (TreeNode *) malloc(sizeof(TreeNode));
```

give size in bytes

Typecast casts return value from type `(void *)` to `(TreeNode *)`

`sizeof(type)` gives size in bytes.

- **To allocate an array of 20 `int`s:**

```
int *ptr = (int *) malloc(20*sizeof(int));
```

  - Many years ago ints used to be 16b. Now, 32b or 64b…

Assuming size of objects can lead to misleading, unportable code. Use `sizeof()`!

a pointer pointing at one integer which is the first one!

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void free(void *ptr)

- **Dynamically frees heap memory**
  - `ptr` is a pointer containing an address originally returned by `malloc()/realloc()`.

```
int *ptr = (int *) malloc (sizeof(int)*20);
...
free(ptr); // implicit typecast to (void *)
```

- **When you free memory, be sure to pass the original address returned from `malloc()`. Otherwise, crash (or worse!)**

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void *realloc(void *ptr, size_t size)

- **Resize a previously allocated block at `ptr` to a new size.**
  - Returns new address of the memory block.
    - In doing so, it may need to copy all data to a new location.
  - `realloc(NULL, size); // behaves like malloc`
  - `realloc(ptr, 0); // behaves like free, deallocates heap block`
- **Remember: Always check for return `NULL`, which would mean you've run out of memory!**

```
int *ip; ip = (int *) malloc(10*sizeof(int));
… … …                    /* check for NULL */
ip = (int *) realloc(ip, 20*sizeof(int));
/* contents of first 10 elements retained */
… … …                    /* check for NULL */
realloc(ip,0);           /* equivalent to free(ip); */
```

that's it

from 0 to Sth

expand the memory

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Linked List Example

- Memory Locations
- The Stack
- The Heap
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- Implementing Memory Management

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Linked List Example

```
   # include <string.h>
   int main() {
1    struct Node *head = NULL;
2    add_to_front(&head, "abc");
     …  // free nodes, strings here…
   }
   void add_to_front(struct Node **head_ptr, char *data) {
3    struct Node *node = (struct Node *) malloc(sizeof(struct Node));
4    node->data = (char *) malloc(strlen(data) + 1); // extra byte!
5    strcpy(node->data, data);  // strcpy also copies null terminator
6    node->next = *head_ptr;
7    *head_ptr = node;
   }
```

```
struct Node {
  char *data;
  struct Node *next;
};
```

the address of pointer

strcpy(,)

String copy function

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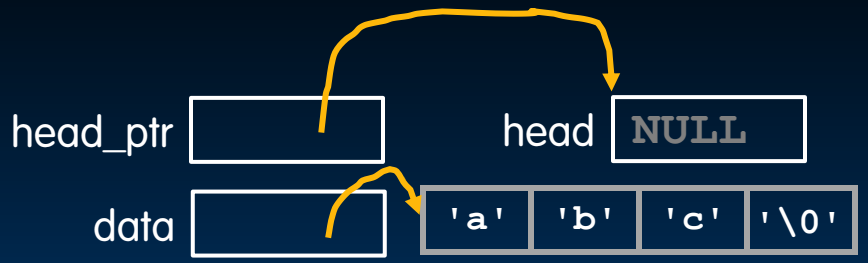
Linked List Example

```
   # include <string.h>
   int main() {
1    struct Node *head = NULL;
2    add_to_front(&head, "abc");
     …  // free nodes, strings here…
   }
   void add_to_front(struct Node **head_ptr, char *data) {
3    struct Node *node = (struct Node *) malloc(sizeof(struct Node));
4    node->data = (char *) malloc(strlen(data) + 1); // extra byte!
5    strcpy(node->data, data);  // strcpy also copies null terminator
6    node->next = *head_ptr;
7    *head_ptr = node;
   }
```

```
struct Node {
  char *data;
  struct Node *next;
};
```



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Linked List Example

```
# include <string.h>
int main() {
1   struct Node *head = NULL;
2   add_to_front(&head, "abc");
    …  // free nodes, strings here…
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void add_to_front(struct Node **head_ptr, char *data) {
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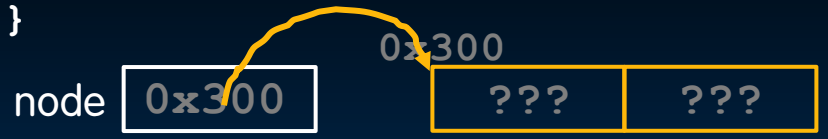
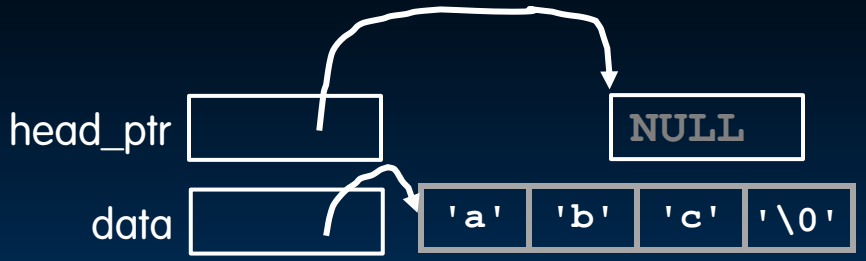
5   strcpy(node->data, data);  // strcpy also copies null terminator
6   node->next = *head_ptr;
7   *head_ptr = node;
}
```

```
struct Node {
  char *data;
  struct Node *next;
};
```





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Linked List Example

```
# include <string.h>
int main() {
1   struct Node *head = NULL;
2   add_to_front(&head, "abc");
    …  // free nodes, strings here…
}
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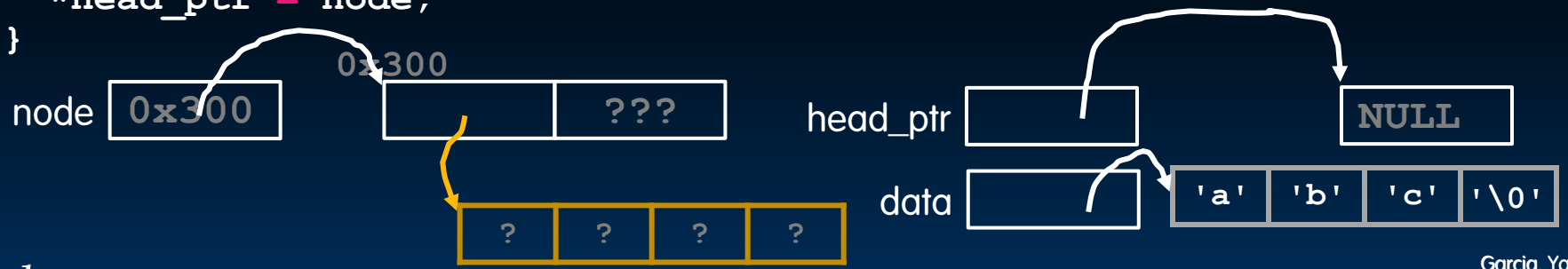
4   node->data = (char *) malloc(strlen(data) + 1); // extra byte!
5   strcpy(node->data, data);  // strcpy also copies null terminator
6   node->next = *head_ptr;
7   *head_ptr = node;
}
```

```
struct Node {
  char *data;
  struct Node *next;
};
```



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Linked List Example

```
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int main() {
1   struct Node *head = NULL;
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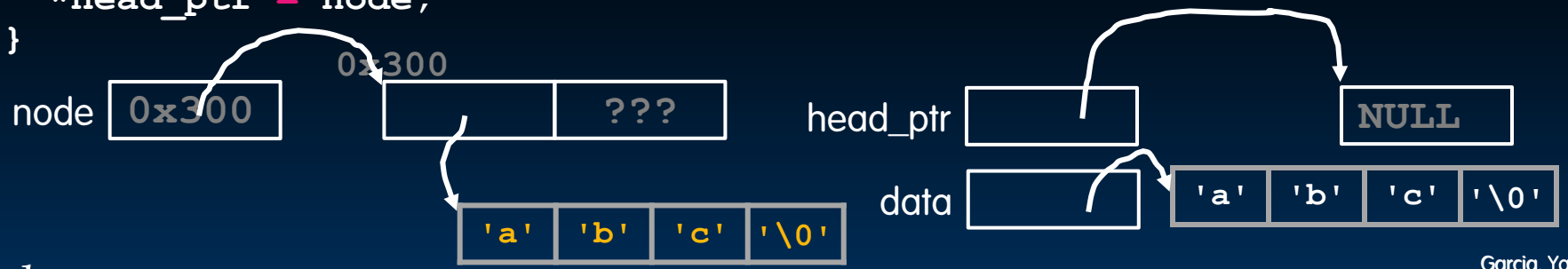
5   strcpy(node->data, data);  // strcpy also copies null terminator
6   node->next = *head_ptr;
7   *head_ptr = node;
}
```

```
struct Node {
  char *data;
  struct Node *next;
};
```



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Linked List Example

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1   struct Node *head = NULL;
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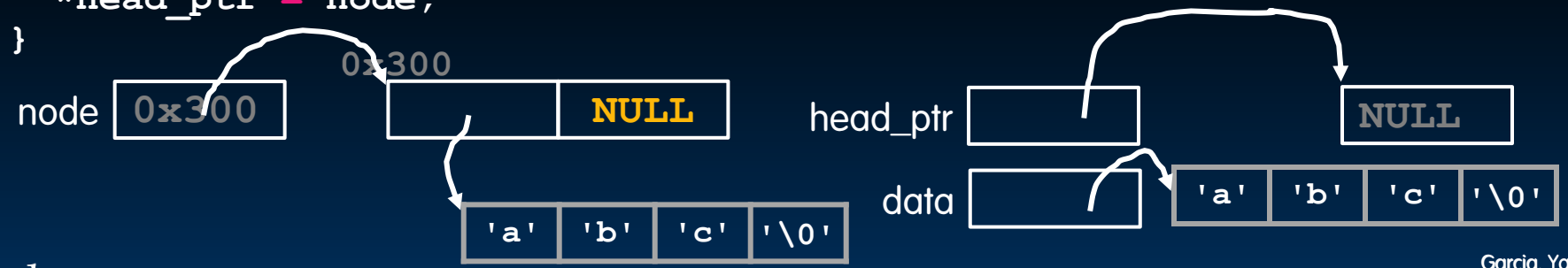
4   node->data = (char *) malloc(strlen(data) + 1); // extra byte!
5   strcpy(node->data, data);  // strcpy also copies null terminator
6   node->next = *head_ptr;
7   *head_ptr = node;
}
```

```
struct Node {
  char *data;
  struct Node *next;
};
```



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Linked List Example

```
# include <string.h>
int main() {
  struct Node *head = NULL;
1 add_to_front(&head, "abc");
2 … // free nodes, strings here…
}
void add_to_front(struct Node **head_ptr, char *data) {
3   struct Node *node = (struct Node *) malloc(sizeof(struct Node));
4   node->data = (char *) malloc(strlen(data) + 1); // extra byte!
5   strcpy(node->data, data);  // strcpy also copies null terminator
6   node->next = *head_ptr;
7   *head_ptr = node;
}
```

```
struct Node {
  char *data;
  struct Node *next;
};
```

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Linked List Example

```
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int main() {
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5   strcpy(node->data, data);  // strcpy also copies null terminator
6   node->next = *head_ptr;
7   *head_ptr = node;
}
```

```
struct Node {
  char *data;
  struct Node *next;
};
```

Check out the lecture code in the drive!

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When Memory Goes Bad

- Memory Locations
- The Stack
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Working with Memory

code and static data never change

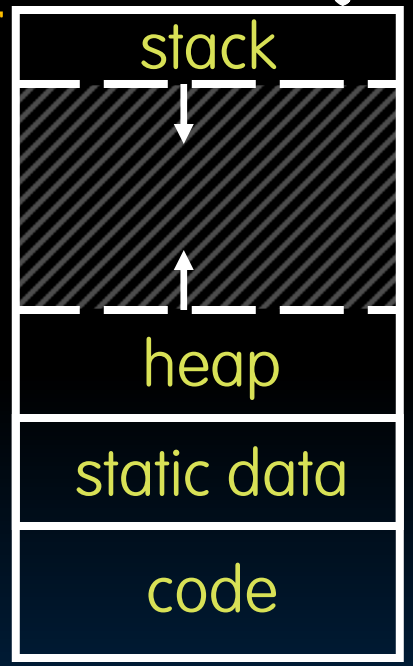
Code, Static storage are easy:

- They never grow or shrink.

Stack space is also easy:

先进后出

- Stack frames are created and destroyed in LIFO order.
- Just avoid "**dangling references**": pointers to deallocated variables (e.g., from old stack frames).



⚠ **Working with the heap is tricky:**

- Memory can be allocated / deallocated at any time!
- "**Memory leak**": If you forget to deallocate memory — Your program will eventually run out of memory
- "**Use after free**": If you use data after calling free
- "**Double free**": If you call free 2x on same memory — Possible crash or exploitable vulnerability

overflow

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Failure to `free()`

- **The runtime does not check for the programmer's failure to manage memory.**
  - Memory is so performance-critical that there just isn't time to do this.
  - Usual result: you corrupt the memory allocator's internal structure, and you find out much later in a totally unrelated part of your code!
- **Memory leak: Failure to `free()` allocated memory**
  - 🙃 Initial symptoms. Nothing…
    - Until you hit a critical point, memory leaks aren't actually a problem
  - 📈 …Later symptoms: performance drops off a cliff…
    - Memory hierarchy behavior tends to be great just up until it isn't, then it hits several cliffs
  - 😈 …and then your program is killed off!
    - Because the operating system (OS) says "no" when you ask for more memory

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Use after Free

- **"Dangling reference"**
  When you keep using a pointer, even after it has been deallocated

- **Reads after the free may be corrupted!**
  - If something else takes over that memory, your program will probably read the wrong information!
- **Writes corrupt other data!**
  - Uh oh… Your program crashes later!

```
struct foo *f;
…
f = malloc(sizeof(struct foo));
…
free(f);
…
bar(f->a); // !!!
```

mother-fucker

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Double-Free...

```
struct foo *f = (struct foo *) malloc(10*sizeof(struct foo));
...
free(f);
...
free(f); // !!!
```

f doesn't exist any more.

- May cause either a use-after-`free` (because something else called `malloc()` and got that data) or corrupt heap data (because you are no longer freeing a pointer tracked by `malloc`)

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Forgetting `realloc()` Can Move Data

- "Dangling reference"
- Remember, when you `realloc` it can copy data to a different part of the heap.

```
int *nums;
nums = malloc(10*sizeof(int));
…
int *g = nums;
…
nums = realloc(nums,
         20*sizeof(int));

// g could now point
// to invalid memory
```

```
int *nums;
nums = malloc(10*sizeof(int));
…
// forget to update nums
// on realloc call
realloc(nums, 20*sizeof(int));

// nums could now point
// to invalid memory,
// and we could have potentially
lost a pointer to a new block
```

- Reads may be corrupted, and writes may corrupt other pieces of memory.

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Faulty Heap Management

How many memory management errors are in this code?

```
void free_mem_x() {
  int fnh[3];
  ...
  free(fnh);
}

void free_mem_y() {
  int *fum = malloc(4*sizeof(int));
  free(fum+1);
  ...
  free(fum);
  ...
  free(fum);
}
```

A. 1
B. 2
C. 3
D. 0
E. Other

When poll is active, respond at **pollev.com/yanl**

Text **YANL** to **22333** once to join

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Respond at **pollev.com/yanl**

Text **YANL** to **22333** once to join, then **A, B, C, D, or E**

How many memory management errors are in this code?

1	**A**
2	**B**
3	**C**
0	**D**
Other	**E**

Powered by Poll Everywhere

Start the presentation to see live content. For screen share software, share the entire screen. Get help at **pollev.com/app**

Faulty Heap Management

How many memory management errors are in this code?

```
void free_mem_x() {
  int fnh[3];
  ...
  free(fnh);
}

void free_mem_y() {
  int *fum = malloc(4*sizeof(int));
  free(fum+1);
  ...
  free(fum);
  ...
  free(fum);
  }
```

fnh is not allocated in heap

free() on stack-allocated memory

free() on memory that isn't the pointer from malloc

"fum+1" is not allocated by malloc()

Double free()

free() for twice

A. 1
B. 2
C. 3
D. 0
E. Other

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Valgrind to the rescue!!!

- **Valgrind slows down your program by an order of magnitude, but…**
  - It adds a tons of checks designed to catch most (but not all) memory errors
    - Memory leaks
    - Misuse of free
    - Writing over the end of arrays
- **Tools like Valgrind are absolutely essential for debugging C code.**

Check out Lab 02!

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Implementing Memory Management

- Memory Locations
- The Stack
- The Heap
- Linked List Example
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Material not tested. Recording:
https://www.youtube.com/watch?v=Sq5tSeWfnGY

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Heap Management Requirements

- Want `malloc()` and `free()` to run quickly
- Want minimal memory overhead
- Want to avoid fragmentation*, 分裂
  when most of our free memory is in many small chunks
  - In this case, we might have many free bytes but not be able to satisfy a large request since the free bytes are not contiguous in memory.

* This is technically external fragmentation

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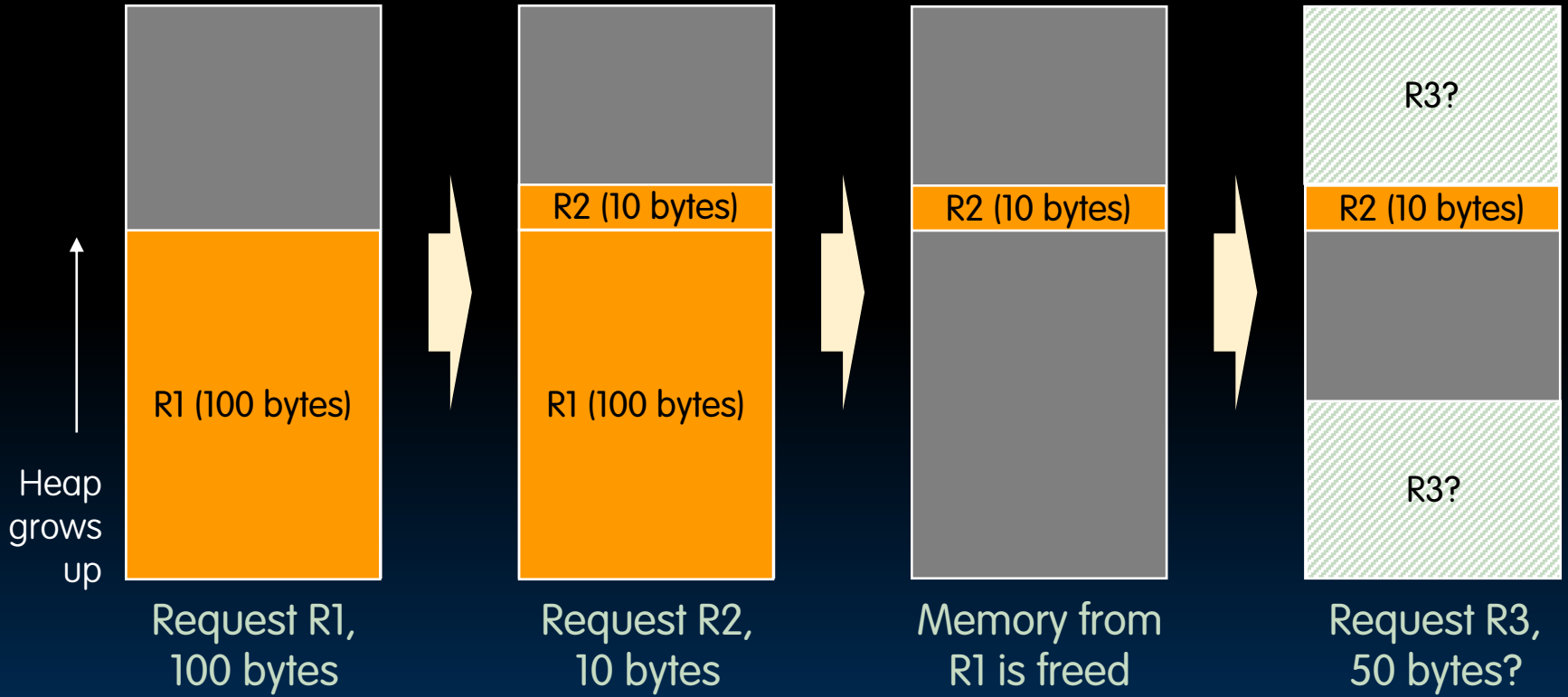
Heap Management Example



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K&R Malloc/Free Implementation

- **From Section 8.7 of K&R**
  - Code in the book uses some C language features we haven't discussed and is written in a very terse style; don't worry if you can't decipher the code
- **Each block of memory is preceded by a header that has two fields:**
  - size of the block, and
  - a pointer to the next block
- **All free blocks are kept in a circular linked list.**
- **In an allocated block, the header's pointer field is unused.**

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K&R Malloc/Free Implementation

- `malloc()` searches the free list for a block that is big enough. If none is found, more memory is requested from the operating system. If what it gets can't satisfy the request, it fails.
- `free()` checks if the blocks adjacent to the freed block are also free.
  - If so, adjacent free blocks are merged (**coalesced**) into a single, larger free block.
  - Otherwise, freed block is just added to the free list.

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Choosing a block in `malloc()`

- **If there are multiple free blocks of memory that are big enough for some request, how do we choose which one to use?**
  - **best-fit**: choose the smallest block that is big enough for the request.
  - **first-fit**: choose the first block we see that is big enough.
  - **next-fit**: like first-fit, but remember where we finished searching and resume searching from there.

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And in Conclusion…

- **C has 3 pools of memory**
  - Static storage: global variable storage, basically permanent, entire program run
  - The Stack: local variable storage, parameters, return address
  - The Heap (dynamic storage): malloc() grabs space from here, free() returns it.
- **Heap data is biggest source of bugs in C code**
- **`malloc()` handles free heap space with freelist. Take CS162 for more!**

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