CS 31: Introduction to Computer Systems

14-15: Arrays and Pointers

March 21-26

SWARTHMORE COLLEGE

Announcements

- Everything up to Lab 5 graded
  - Check Github repos for comments
  - Check Gradesource for grades
- Midterm debrief last 15 minutes
- Final Exam Time Posted:
  - May 12 9 – 12pm SCI 199
- Please choose partners for Lab 7!

Data Collections in C

- Many complex data types out there (CS 35)

- C has a few simple ones built-in:
  - Arrays
  - Structures (`struct`)
  - Strings (arrays of characters)

- Often combined in practice, e.g.:
  - An array of structs
  - A struct containing strings

Today

- Accessing *things* via an offset
  - Arrays, Structs, Unions

- How complex structures are stored in memory
  - Multi-dimensional arrays & Structs

So far: Primitive Data Types

- We’ve been using ints, floats, chars, pointers

- Simple to place these in memory:
  - They have an unambiguous size
  - They fit inside a register*
  - The hardware can operate on them directly

(*There are special registers for floats and doubles that use the IEEE floating point format.)

Composite Data Types

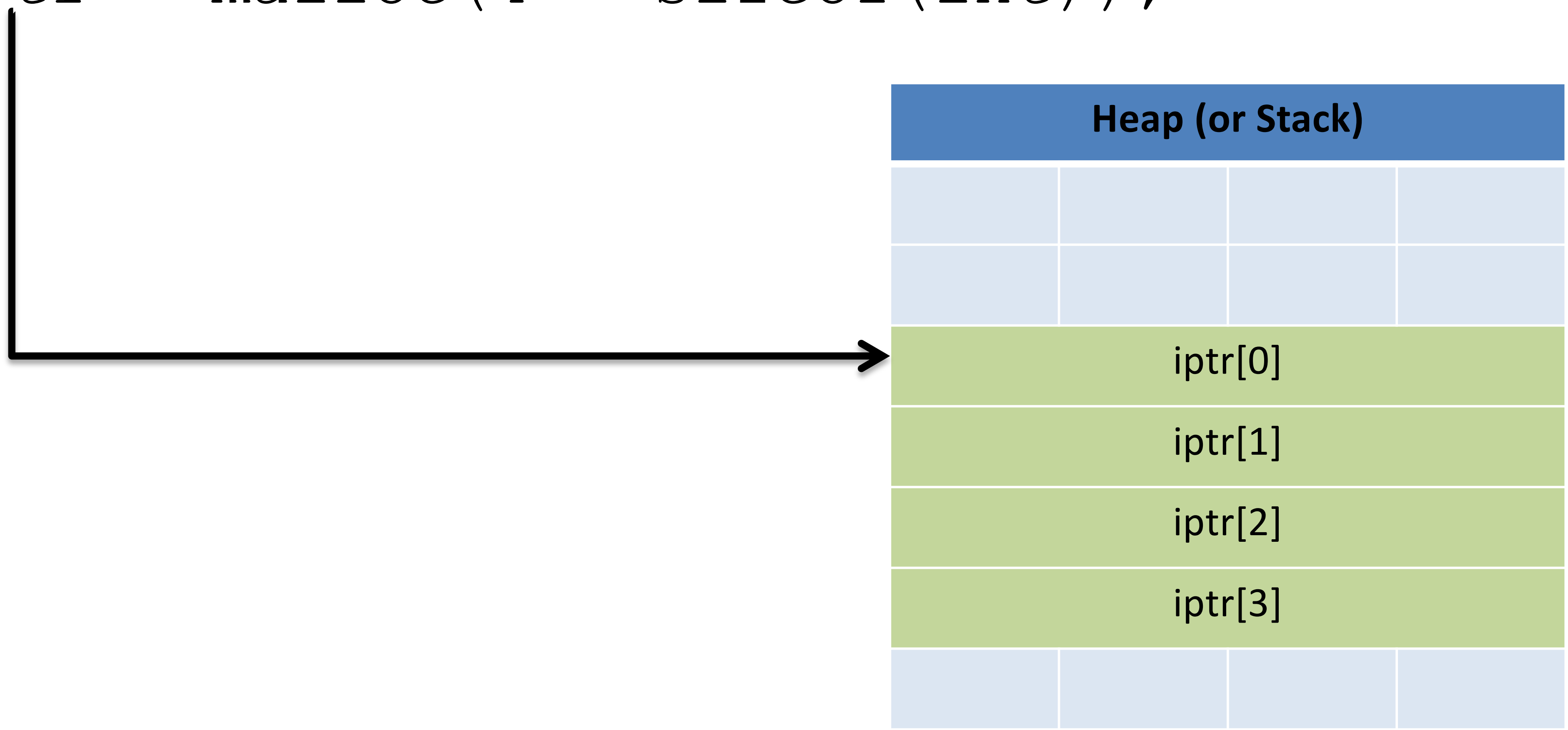
- Combination of one or more existing types into a new type. (e.g., an array of *multiple* ints, or a struct)

- Example: a queue
  - Might need a value (int) plus a link to the next item (pointer)

```
struct queue_node{
  int value;
  struct queue_node *next;
}
```

Recall: Arrays in Memory

```
int *iptr = NULL;
iptr = malloc(4 * sizeof(int));
```



Recall: Assembly While Loop

```
  movl $0 eax //return value
  movl $0 edx //loop counter
loop:
  addl (%ecx), %eax
  addl $4, %ecx
  addl $1, %edx
  cmpl $5, %edx
  jne loop
```

Using (*dereferencing*) the memory address to access memory at that location.

ecx was a pointer to the beginning of the array. Manipulating the pointer to point to something else.

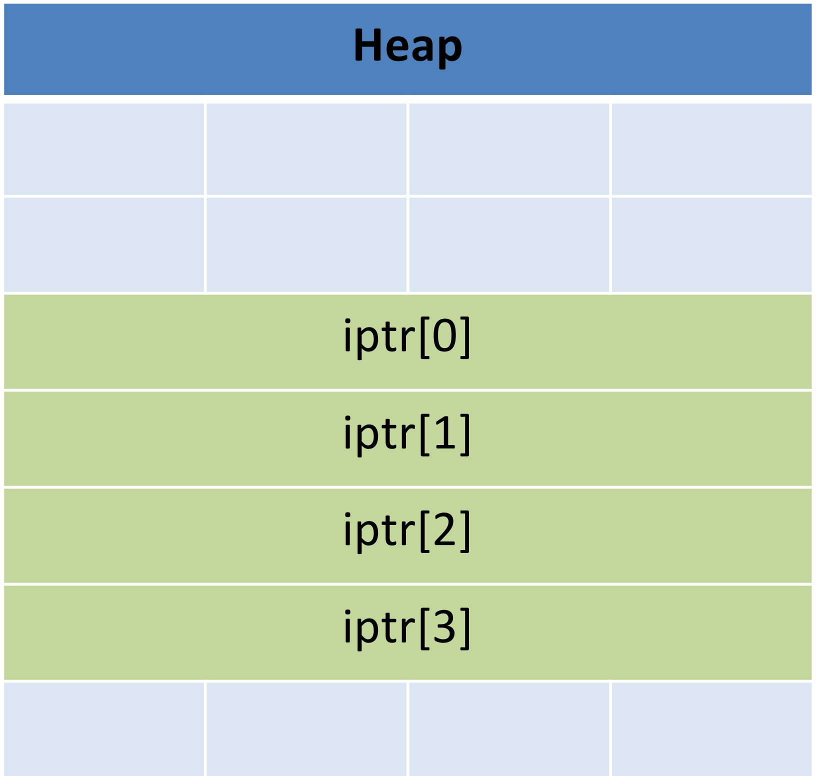
Note: This did NOT read or write the memory that is pointed to.

Pointer Manipulation: Necessary?

- Previous example: advance %ecx to point to next item in array.

```
iptr = malloc(…);
sum = 0;
while (i < 4) {
   sum += *iptr;
   iptr += 1;
   i += 1;
}
```

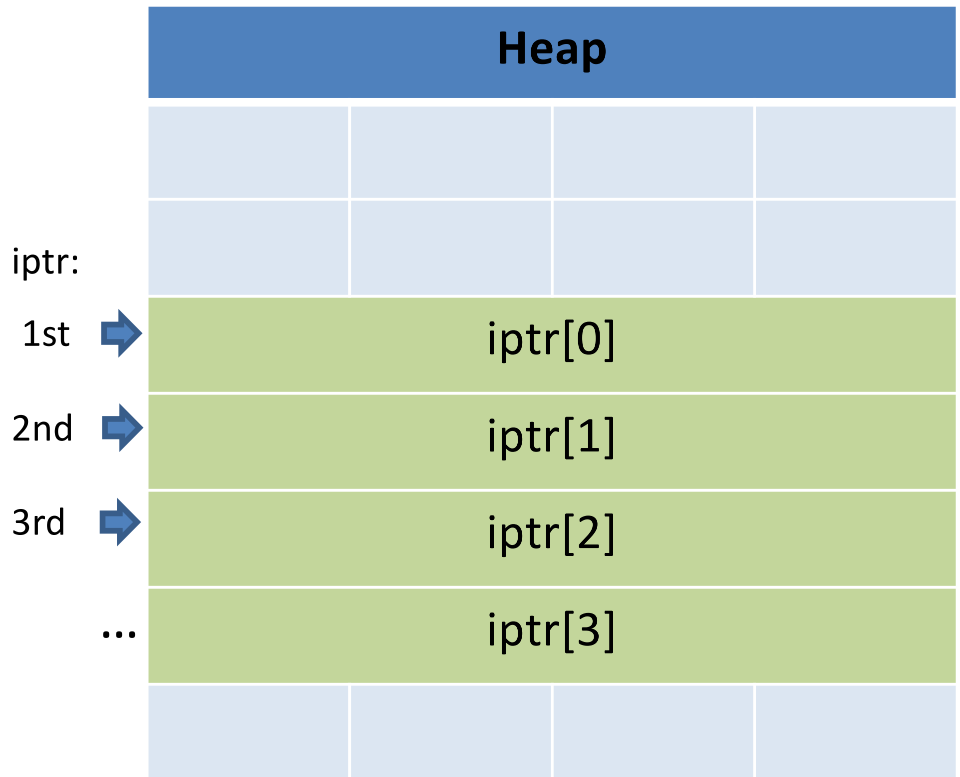
moves +1 by size of the data type!



Pointer Manipulation: Necessary?

- Previous example: advance %ecx to point to next item in array.

```
iptr = malloc(…);
sum = 0;
while (i < 4) {
   sum += *iptr;
   iptr += 1;
   i += 1;
}
```



Reminder: addition on a pointer advances by that many of the type (e.g., ints), not bytes.

Pointer Manipulation: Necessary?

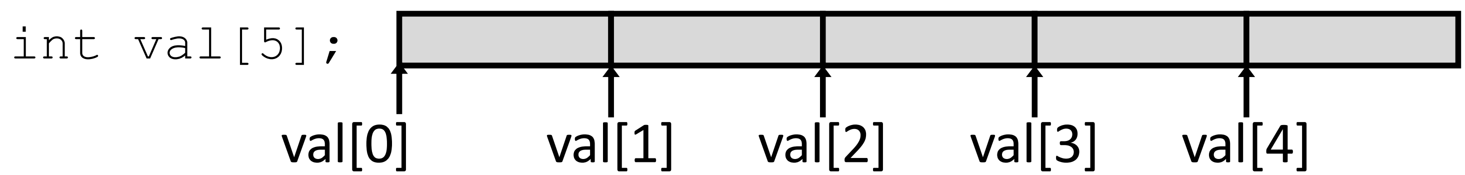
- Problem: `iptr` is changing!
- What if we wanted to free it?
- What if we wanted something like this:

```
iptr = malloc(…);
sum = 0;
while (i < 4) {
   sum += iptr[0] + iptr[i];
   ~~iptr += 1;~~
   i += 1;
}
```

Changing the pointer would be really inconvenient now!

Base + Offset

- We know that arrays act as a pointer to the first element. For bucket [N], we just skip forward N.



- "We're goofy computer scientists who count starting from zero."

Base + Offset

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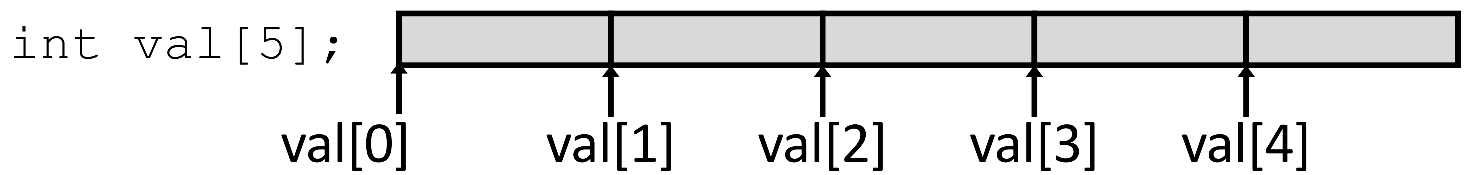
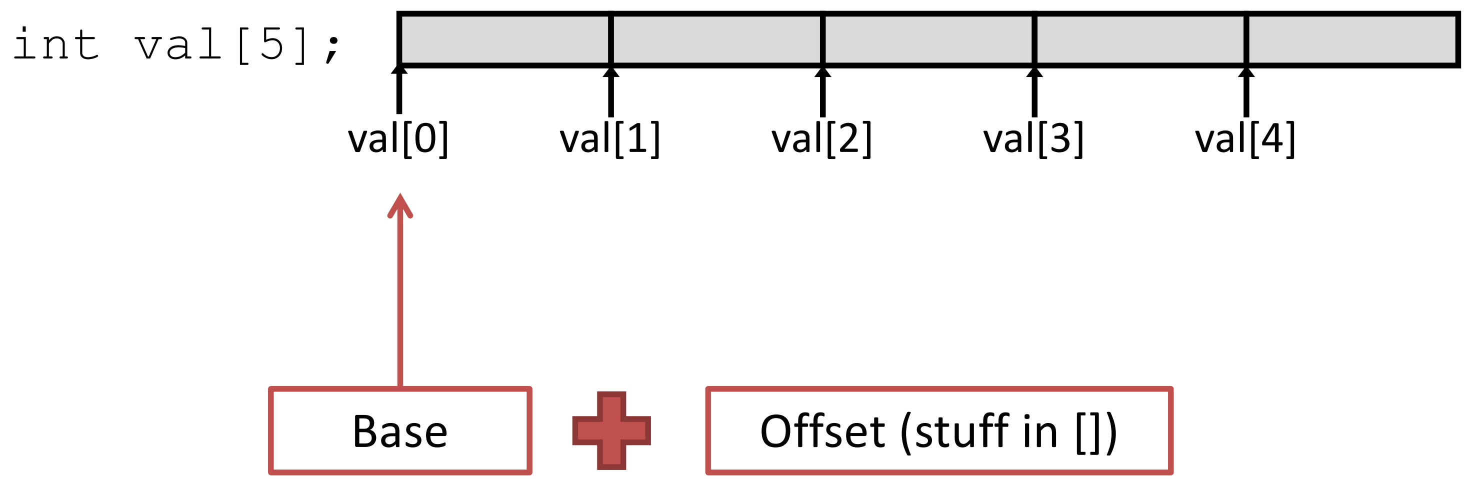


- ~~"We're goofy computer scientists who count starting from zero."~~

Base + Offset

- We know that arrays act as a pointer to the first element. For bucket [N], we just skip forward N.



This is why we start counting from zero!
Skipping forward with an offset of zero ([0]) gives us the first bucket…

Which expression would compute the address of iptr[3]?

A. 0x0824 + 3 * 4

B. 0x0824 + 4 * 4

C. 0x0824 + 0xC

D. More than one (which?)

E. None of these

Heap	
0x0824:	iptr[0]
0x0828:	iptr[1]
0x082C:	iptr[2]
0x0830:	iptr[3]

Which expression would compute the address of iptr[3]?

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Which expression would compute the address of iptr[3]?

What if this isn't known at compile time?

A. 0x0824 + 3 * 4 (requires an extra multiplication step)

B. 0x0824 + 4 * 4

C. 0x0824 + 0xC

D. More than one (which?)

E. None of these

Heap			
0x0824:	iptr[0]		
0x0828:	iptr[1]		
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Indexed Addressing Mode

- What we'd like in IA32 is to express accesses like iptr[N], where iptr doesn't change – it's a base.

- Displacement mode works, if we know which offset to use at *compile time*:
  - Variables on the stack: -4(%ebp)
  - Function arguments: 8(%ebp)
  - Accessing [5] of an integer array: 20(%base_register)

- If we only know at run time?
  - How do we express i(%ecx)?

Indexed Addressing Mode

- General form:

  displacement(%base, %index, scale)

- Translation: Access the memory at address…
  - base + (index * scale) + displacement

- Rules:
  - Displacement can be any 1, 2, or 4-byte value
  - Scale can be 1, 2, 4, or 8.

Example

ECX: Array base address

Suppose i is at %ebp - 8, and equals 2.

Registers:

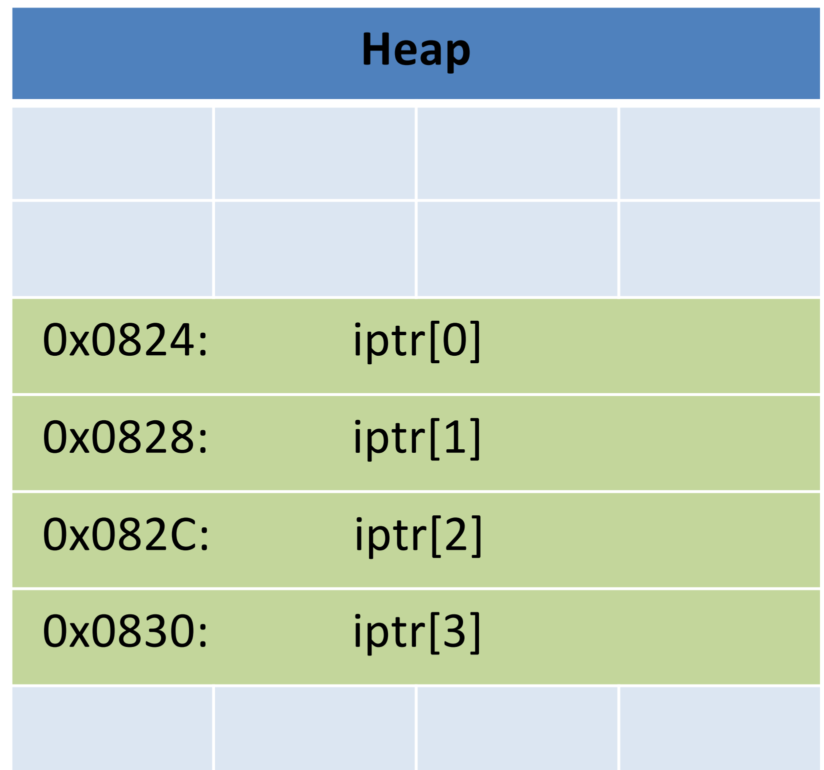
%ecx	0x0824
%edx	2

User says:

```
iptr[i] = 9;
```

Translates to:

```
movl -8(%ebp), %edx
```



Example

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iptr[i] = 9;
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Example

Suppose i is at %ebp - 8, and equals 2.

Registers:

%ecx	0x0824
%edx	2

User says:

```
iptr[i] = 9;
```

Translates to:

```
movl -8(%ebp), %edx
movl $9, (%ecx, %edx, 4)
```

Heap	
0x0824:	iptr[0]
0x0828:	iptr[1]
0x082C:	iptr[2]
0x0830:	iptr[3]

Example

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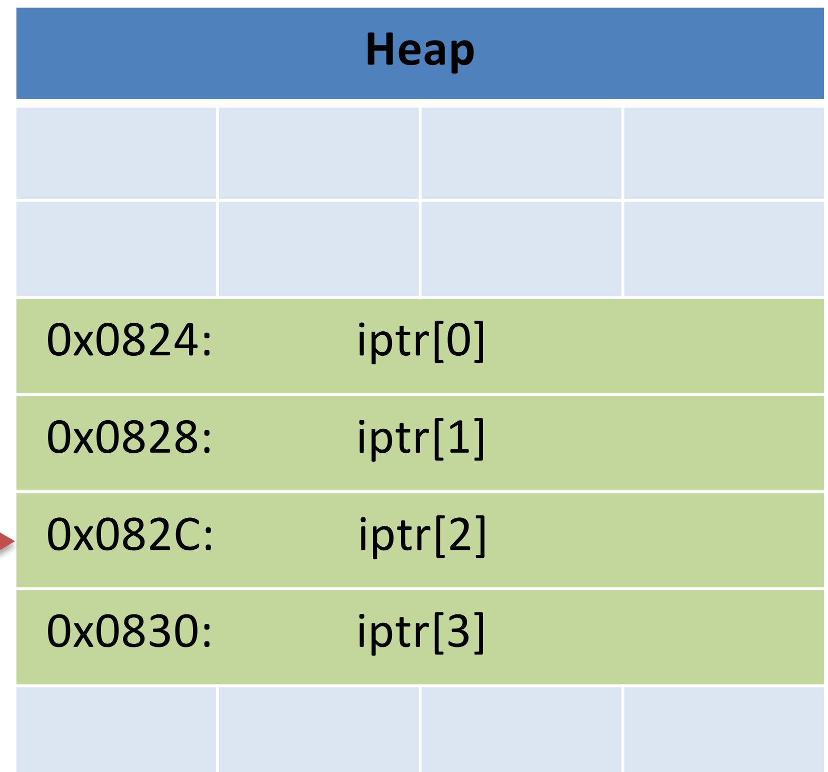
User says:

```
iptr[i] = 9;
```

Translates to:

```
movl -8(%ebp), %edx
movl $9, (%ecx, %edx, 4)
```

```
0x0824 + (2 * 4) + 0
0x0824 + 8 = 0x082C
```



Example:

Allowed us to preserve ecx, and compute an offset without changing the pointer to the base of our array

Suppose i is at %ebp - 8, and equals 2.

Registers:

%ecx	0x0824
%edx	2

User says:

```
iptr[i] = 9;
```

Translates to:

```
movl -8(%ebp), %edx
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```
0x0824 + (2 * 4) + 0
0x0824 + 8 = 0x082C
```

Heap	
0x0824:	iptr[0]
0x0828:	iptr[1]
0x082C:	iptr[2]
0x0830:	iptr[3]

What is the final state after this code?

```
addl $4, %eax
movl (%eax), %eax
sall $1, %eax
movl %edx, (%ecx, %eax, 2)
```

displacement(%base, %index, scale)
base + (index * scale) + displacement

(Initial state)
Registers:

%eax	0x2464
%ecx	0x246C
%edx	7

Memory:

Heap	
0x2464:	5
0x2468:	1
0x246C:	42
0x2470:	3
0x2474:	9

What is the final state after this code?

addl $4, %eax

movl (%eax), %eax

sall $1, %eax

movl %edx, (%ecx, %eax, 2)

(Initial state)
Registers:

%eax	0x2464
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Heap	
0x2464:	5
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0x2470:	3
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What is the final state after this code?

```
addl $4, %eax
movl (%eax), %eax
sall $1, %eax
movl %edx, (%ecx, %eax, 2)
```

Add 4 to eax = 0x2468

(Initial state)
Registers:

%eax	0x2464
%ecx	0x246C
%edx	7

Memory:

Heap	
0x2464:	5
0x2468:	1
0x246C:	42
0x2470:	3
0x2474:	9

What is the final state after this code?

addl $4, %eax

movl (%eax), %eax

sall $1, %eax

movl %edx, (%ecx, %eax, 2)

1. Add 4 to %eax = 0x2468

(Initial state)
Registers:

%eax	0x2468
%ecx	0x246C
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Memory:

Heap	
0x2464:	5
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What is the final state after this code?

```
addl $4, %eax
movl (%eax), %eax
sall $1, %eax
movl %edx, (%ecx, %eax, 2)
```

1. Add 4 to %eax = 0x2468
2. Overwriting the value of eax with 1

(Initial state)
Registers:

%eax	0x2468
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Memory:

Heap	
0x2464:	5
0x2468:	1
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0x2470:	3
0x2474:	9

What is the final state after this code?

addl $4, %eax

movl (%eax), %eax

sall $1, %eax

movl %edx, (%ecx, %eax, 2)

1. Add 4 to %eax = 0x2468
2. Overwriting the value of eax with 1

(Initial state)
Registers:

%eax	1
%ecx	0x246C
%edx	7

Memory:

Heap	
0x2464:	5
0x2468:	1
0x246C:	42
0x2470:	3
0x2474:	9

What is the final state after this code?

```
addl $4, %eax
movl (%eax), %eax
sall $1, %eax
movl %edx, (%ecx, %eax, 2)
```

(Initial state)
Registers:

%eax	1
%ecx	0x246C
%edx	7

Memory:

Heap	
0x2464:	5
0x2468:	1
0x246C:	42
0x2470:	3
0x2474:	9

1. Add 4 to %eax = 0x2468
2. Overwriting the value of eax with 1
3. shifting left by 1 = overwriting to 2

What is the final state after this code?

displacement(%base, %index, scale)
base + (index * scale) + displacement

```
addl $4, %eax
movl (%eax), %eax
sall $1, %eax
movl %edx, (%ecx, %eax, 2)
```

(Initial state)
Registers:

%eax	2
%ecx	0x246C
%edx	7

Memory:

Heap	
0x2464:	5
0x2468:	1
0x246C:	42
0x2470:	3
0x2474:	9

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(Initial state)
Registers:

%eax	2
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Heap	
0x2464:	5
0x2468:	1
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0x2470:	3
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1. Add 4 to %eax = 0x2468
2. Overwriting the value of %eax with 1
3. shifting left by 1 = overwriting to 2
4. 0x246C + 2*2 = 0x2470
   moving edx to the memory address

What is the final state after this code?

displacement(%base, %index, scale)

base + (index * scale) + displacement

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addl $4, %eax

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```

(Initial state)
Registers:

%eax	2
%ecx	0x246C
%edx	7

Memory:

Heap	
0x2464:	5
0x2468:	1
0x246C:	42
0x2470:	7
0x2474:	9

1. Add 4 to %eax = 0x2468
2. Overwriting the value of %eax with 1
3. shifting left by 1 = overwriting to 2
4. 0x246C + 2*2 = 0x2470
   moving edx to the memory address

Indexed Addressing Mode

- General form:
  displacement(%base, %index, scale)

- You have seen these probably in your maze.

Two-dimensional Arrays

- Why stop at an array of ints?
  How about an array of arrays of ints?

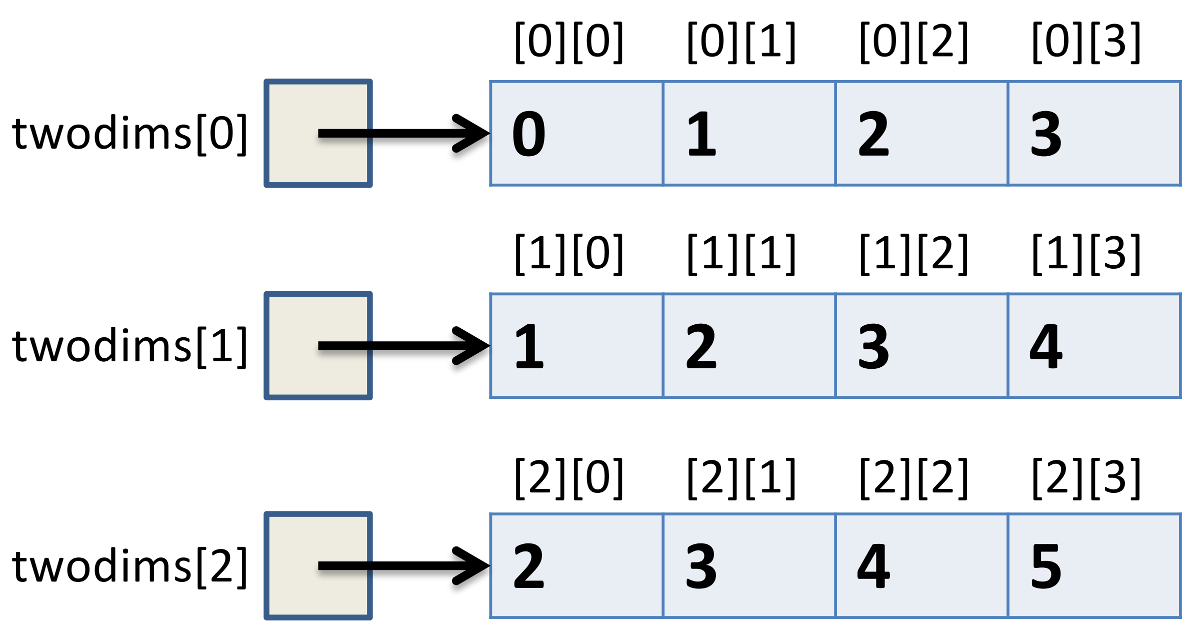
```
int twodims[3][4];
```

- “Give me three sets of four integers.”

- How should these be organized in memory?

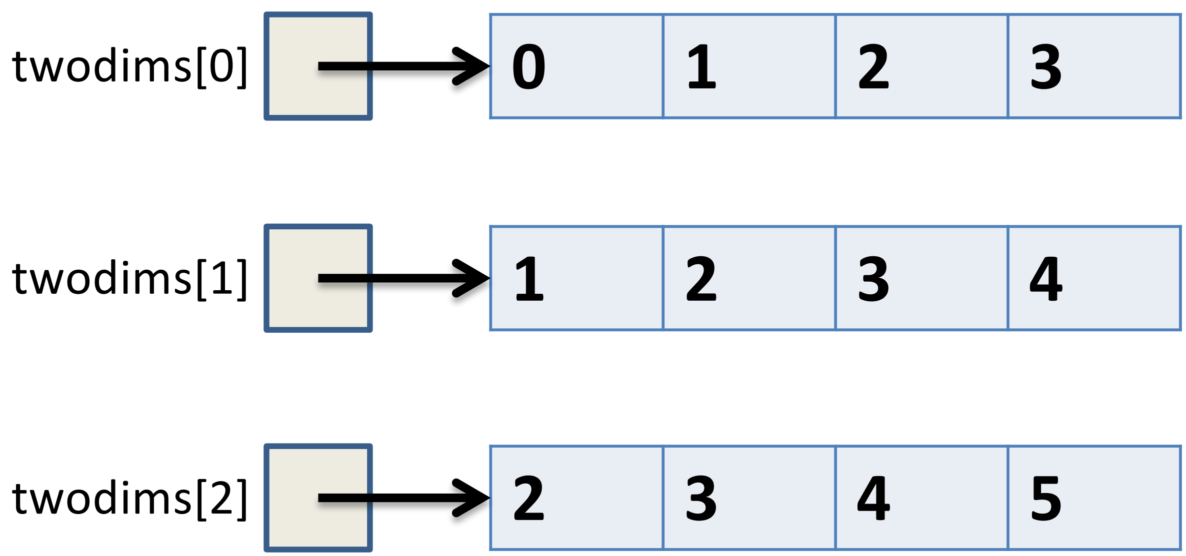
Two-dimensional Arrays

```
int twodims[3][4];
for(i=0; i<3; i++) {
   for(j=0; j<4; j++) {
      twodims[i][j] = i+j;
   }
}
```



Two-dimensional Arrays: Matrix

```
int twodims[3][4];
for(i=0; i<3; i++) {
  for(j=0; j<4; j++) {
     twodims[i][j] = i+j;
   }
}
```



Memory Layout

- Matrix: 3 rows, 4 columns

0	**1**	**2**	**3**
1	**2**	**3**	**4**
2	**3**	**4**	**5**

<u>Row Major Order</u>:
all Row 0 buckets,
followed by
all Row 1 buckets

`0xf260`	0	`twodim[0][0]`
`0xf264`	1	`twodim[0][1]`
`0xf268`	2	`twodim[0][2]`
`0xf26c`	3	`twodim[0][3]`
`0xf270`	1	`twodim[1][0]`
`0xf274`	2	`twodim[1][1]`
`0xf278`	3	`twodim[1][2]`
`0xf27c`	4	`twodim[1][3]`
`0xf280`	2	`twodim[2][0]`
`0xf284`	3	`twodim[2][1]`
`0xf288`	4	`twodim[2][2]`
`0xf28c`	5	`twodim[2][3]`

Memory Layout

- Matrix: 3 rows, 4 columns

0	**1**	**2**	**3**
1	**2**	**3**	**4**
2	**3**	**4**	**5**

`twodim[1][3]:`

base addr + row offset + col offset

`twodim + 1*ROWSIZE*4 + 3*4`

`0xf260 + 16 + 12 = 0xf27c`

0xf260	0	twodim[0][0]
0xf264	1	twodim[0][1]
0xf268	2	twodim[0][2]
0xf26c	3	twodim[0][3]
0xf270	1	twodim[1][0]
0xf274	2	twodim[1][1]
0xf278	3	twodim[1][2]
0xf27c	4	twodim[1][3]
0xf280	2	twodim[2][0]
0xf284	3	twodim[2][1]
0xf288	4	twodim[2][2]
0xf28c	5	twodim[2][3]

Memory Layout

- Matrix: 3 rows, 4 columns

0	**1**	**2**	**3**
1	**2**	**3**	**4**
2	**3**	**4**	**5**

`twodim[1][3]:`

base addr + row offset + col offset

`twodim +` **1*ROWSIZE*4** `+ 3*4`

`0xf260 + 16 + 12 = 0xf27c`

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0xf264	1	twodim[0][1]
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0xf26c	3	twodim[0][3]
0xf270	1	twodim[1][0]
0xf274	2	twodim[1][1]
0xf278	3	twodim[1][2]
0xf27c	4	twodim[1][3]
0xf280	2	twodim[2][0]
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0xf28c	5	twodim[2][3]

Memory Layout

- Matrix: 3 rows, 4 columns

0	**1**	**2**	**3**
1	**2**	**3**	**4**
2	**3**	**4**	**5**

`twodim[1][3]:`

base addr + row offset + col offset

`twodim +` **`1*ROWSIZE*4 + 3*4`**

`0xf260 + 16 + 12 = 0xf27c`

0xf260	0	twodim[0][0]
0xf264	1	twodim[0][1]
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0xf26c	3	twodim[0][3]
0xf270	1	twodim[1][0]
0xf274	2	twodim[1][1]
0xf278	3	twodim[1][2]
0xf27c	4	**twodim[1][3]**
0xf280	2	twodim[2][0]
0xf284	3	twodim[2][1]
0xf288	4	twodim[2][2]
0xf28c	5	twodim[2][3]

If we declared `int matrix[5][3];`, and the base of matrix is 0x3420, what is the address of `matrix[3][2]`?

A. 0x3438
B. 0x3440
C. 0x3444
D. 0x344C
E. None of these

base addr + row offset + col offset

If we declared `int matrix[5][3];`, and the base of matrix is 0x3420, what is the address of `matrix[3][2]`?

A. 0x3438

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C. 0x3444

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E. None of these

base addr + row offset + col offset

0x3420 + 3 * ROWSIZE * 4 (int data type) + 2 (2 ints forward) * 4 (int data type)

If we declared `int matrix[5][3];`, and the base of matrix is 0x3420, what is the address of `matrix[3][2]`?

A. 0x3438
B. 0x3440
C. 0x3444
D. 0x344C
E. None of these

base addr + row offset + col offset

0x3420 + 3 * ROWSIZE * 4 (int data type) + 2 (2 ints forward) * 4 (int data type)
0x3420 + [36 + 8 = (44) = 0x2C] = 0x344C

Composite Data Types

- Combination of one or more existing types into a new type. (e.g., an array of *multiple* ints, or a struct)

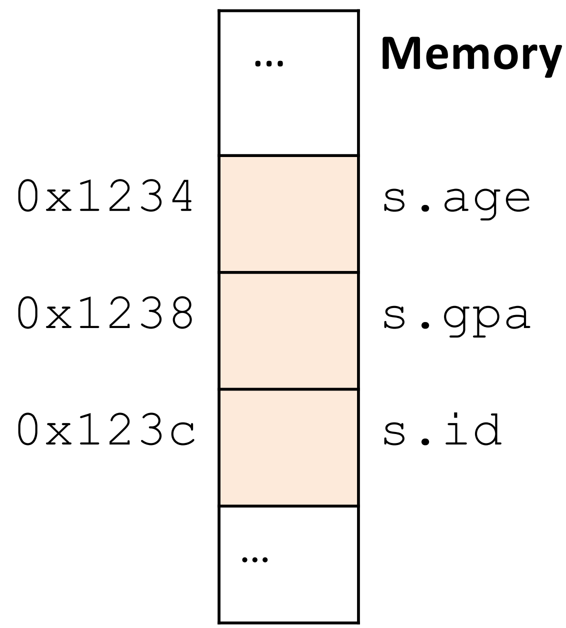
- Example: a queue
  - Might need a value (int) plus a link to the next item (pointer)

```
struct queue_node{
  int value;
  struct queue_node *next;
}
```

Structs

- Laid out contiguously by field
  - In order of field declaration.

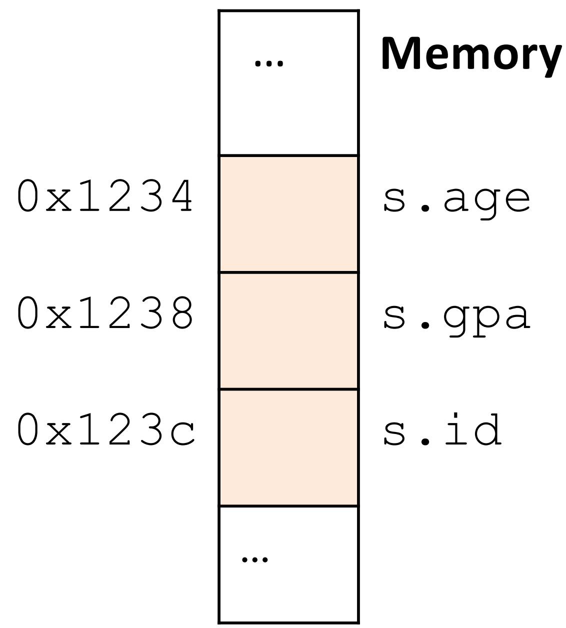
```
struct student{
  int age;
  float gpa;
  int id;
};

struct student s;
```



Structs

- Struct fields accessible as a base + displacement
  - Compiler knows (constant) displacement of each field

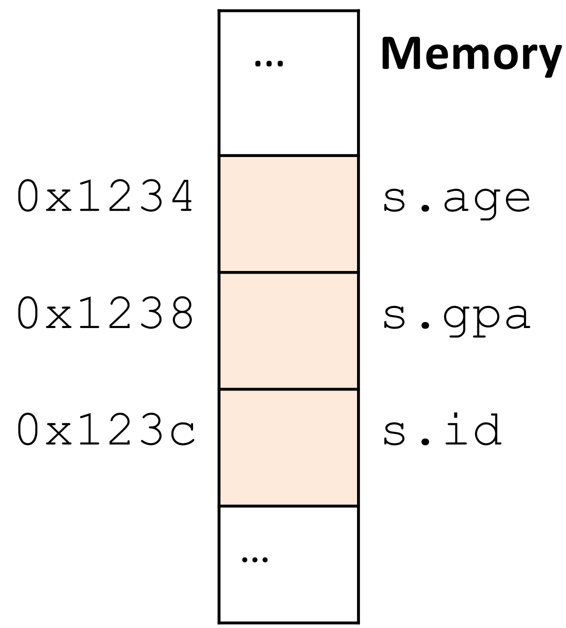
```
struct student{
   int age;
   float gpa;
   int id;
};

struct student s;
```



Structs

- Laid out contiguously by field
  - In order of field declaration.
  - May require some padding, for alignment.

```
struct student{
   int age;
   float gpa;
   int id;
};

struct student s;
```



Data Alignment:

- Where (which address) can a field be located?

- char (1 byte): can be allocated at any address:

  0x1230, 0x1231, 0x1232, 0x1233, 0x1234, …

- short (2 bytes): must be aligned on 2-byte addresses:

  0x123**0**, 0x123**2**, 0x123**4**, 0x123**6**, 0x123**8**, …

- int (4 bytes): must be aligned on 4-byte addresses:

  0x123**0**, 0x123**4**, 0x123**8**, 0x123**c**, 0x124**0**, …

Why do we want to align data on multiples of the data size?

A. It makes the hardware faster.

B. It makes the hardware simpler.

C. It makes more efficient use of memory space.

D. It makes implementing the OS easier.

E. Some other reason.

Why do we want to align data on multiples of the data size?

A. It makes the hardware faster.

B. It makes the hardware simpler.

C. It makes more efficient use of memory space.

D. It makes implementing the OS easier.

E. Some other reason.

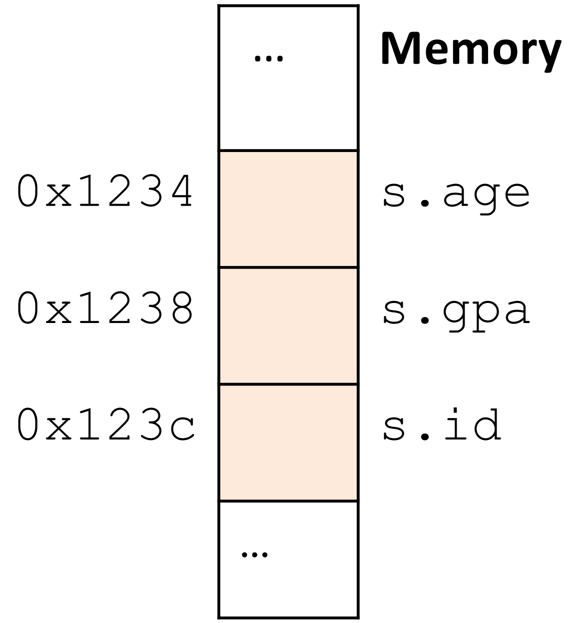
Data Alignment: Why?

- Simplify hardware
  - e.g., only read ints from multiples of 4
  - Don’t need to build wiring to access 4-byte chunks at any arbitrary location in hardware
- Inefficient to load/store single value across alignment boundary (1 vs. 2 loads)
- Simplify OS:
  - Prevents data from spanning virtual pages
  - Atomicity issues with load/store across boundary

Structs

- Laid out contiguously by field
  - In order of field declaration.
  - May require some padding, for alignment.

```
struct student{
   int age;
   float gpa;
   int id;
};

struct student s;
```



Structs

```
struct student{
  char name[11];
  short age;
  int id;
};
```

How much space do we need to store one of these structures?

```
struct student{
  char name[11];
  short age;
  int id;
};
```

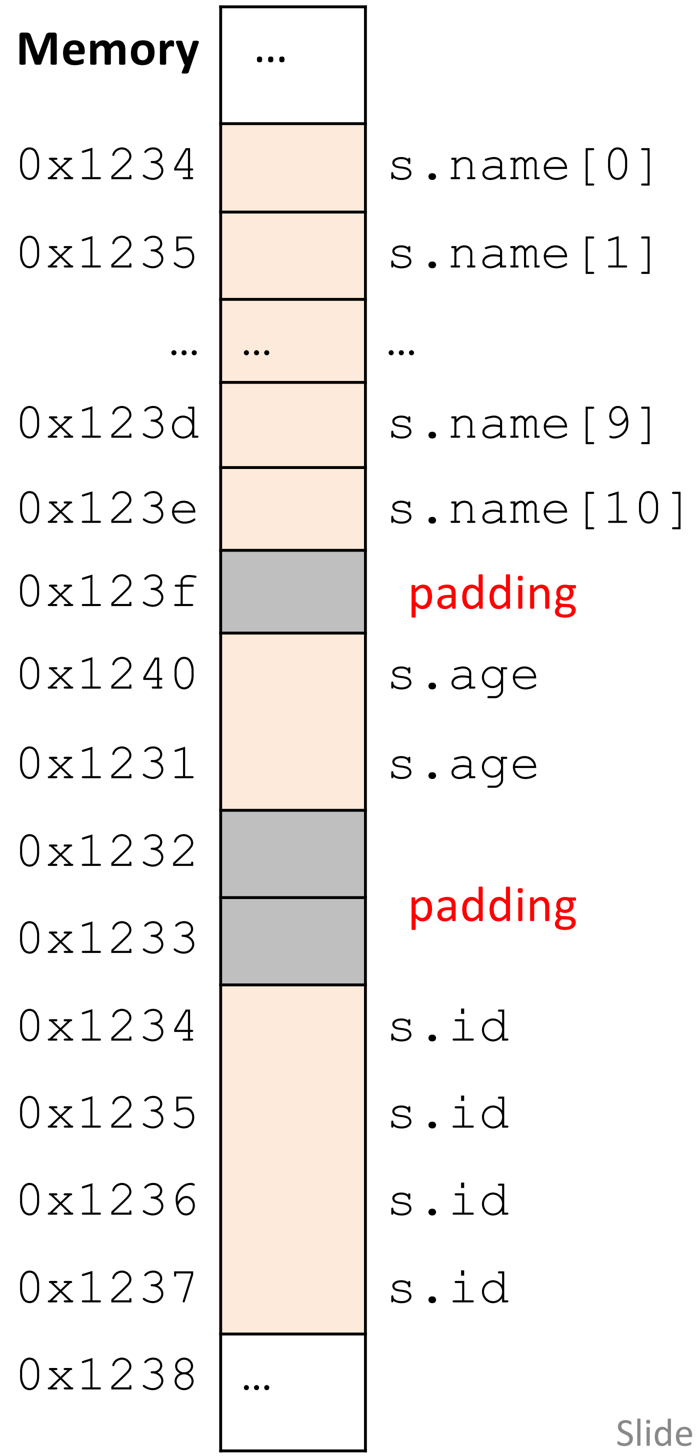
A. 17 bytes
B. 18 bytes
C. 20 bytes
D. 22 bytes
E. 24 bytes

Structs

```
struct student{
  char name[11];
  short age;
  int id;
};
```

- Size of data: 17 bytes
- Size of struct: 20 bytes

<u>Use sizeof() when allocating structs with malloc()!</u>



Alternative Layout

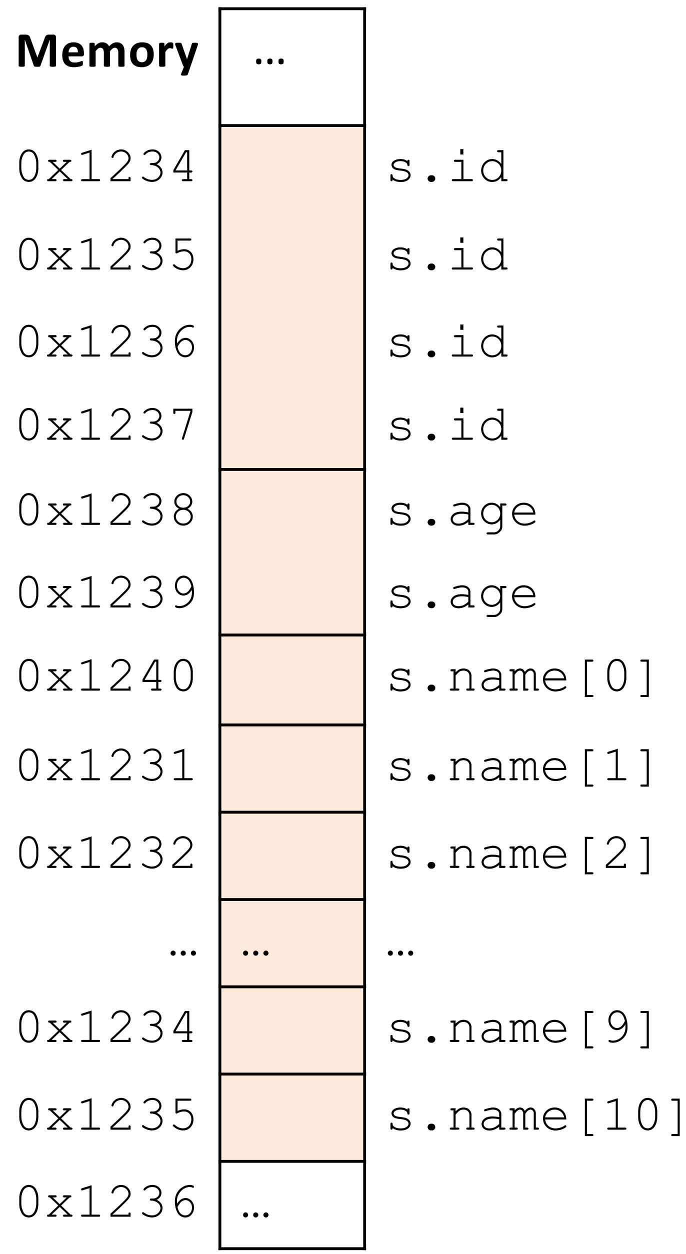
```
struct student{
    int id;
    short age;
    char name[11];
};
```

Same fields, declared in a different order.

Alternative Layout

```
struct student{
   int id;
   short age;
   char name[11];
};
```

- Size of data: 17 bytes
- Size of struct: 17 bytes!



In general, this isn't a big deal on a day-to-day basis. Don't go out and rearrange all your struct declarations.

Cool, so we can get rid of this padding by being smart about declarations?

A. Yes (why?)

B. No (why not?)

Cool, so we can get rid of this padding by being smart about declarations?

A. Yes (why?)

B. No (why not?)

Cool, so we can get rid of this padding by being smart about declarations?

- Answer: Maybe.
- Rearranging helps, but often padding after the struct can't be eliminated.

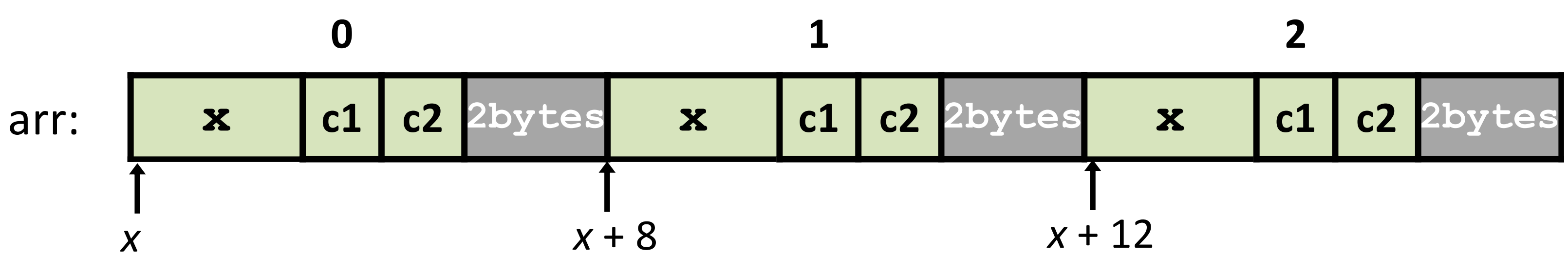
```
struct T1 {              struct T2 {
     char c1;                    int x;
     char c2;                       char c1;
     int  x;                           char c2;
};                  };
```

"External" Padding

- Array of Structs

  Field values in each bucket must be properly aligned:

```
struct T2 arr[3];
```



Buckets must be on a 4-byte aligned address

A note on struct syntax…

```
struct student {
  int id;
  short age;
  char name[11];
};
struct student s;

s.id = 406432;
s.age = 20;
strcpy(s.name, “Alice”);
```

A note on struct syntax…

```
struct student {
  int id;
  short age;
  char name[11];
};
struct student *s = malloc(sizeof(struct student));
```

Not a struct, but a pointer to a struct!

```
(*s).id = 406432;
(*s).age = 20;
strcpy((*s).name, "Alice");
```

This works, but is very ugly.

```
s->id = 406432;
s->age = 20;
strcpy(s->name, "Alice");
```

Access the struct field from a pointer with ->
Does a dereference and gets the field.

Stack Padding

- Memory alignment applies elsewhere too.

```
int x;              vs.     double y;
char ch[5];                 int x;
short s;                    short s;
double y;                   char ch[5];
```

Unions

- Declared like a struct, but only contains one field, rather than all of them.

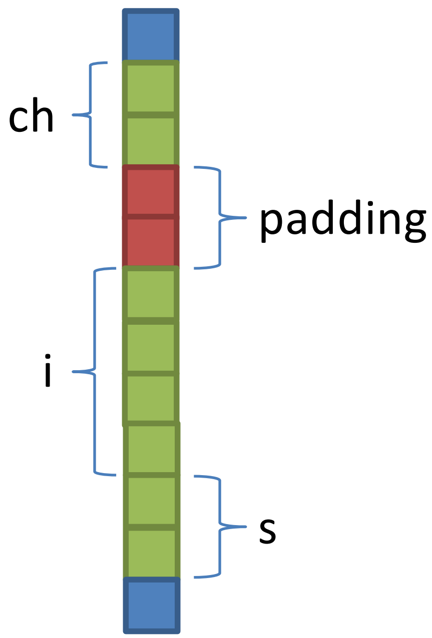
- Struct: field 1 <u>and</u> field 2 <u>and</u> field 3 …
- Union: field 1 <u>or</u> field 2 <u>or</u> field 3 …

- Intuition: you know you only need to store one of N things, don't waste space.

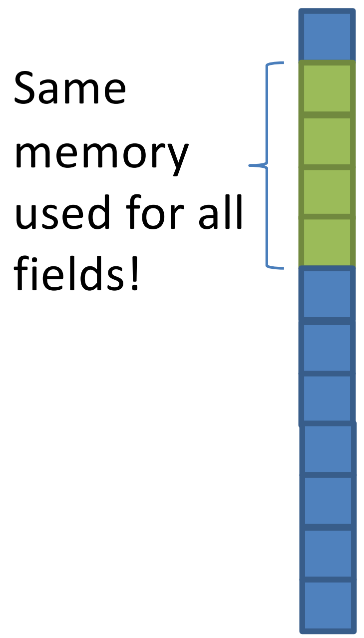
Unions

```
struct my_struct {
    char ch[2];
    int i;
    short s;
}
```

```
union my_union {
    char ch[2];
    int i;
    short s;
}
```



my_struct in memory

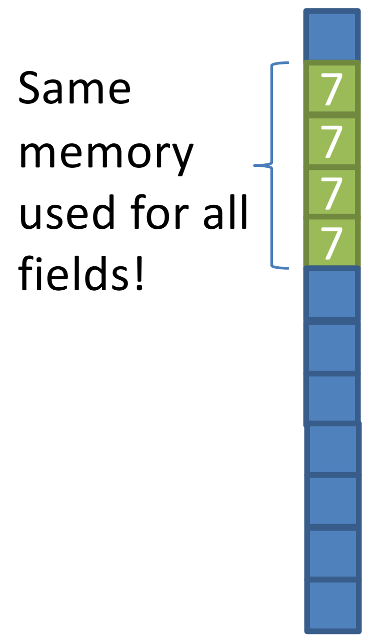


my_union in memory

Unions

```
my_union u;

u.i = 7;
```

```
union my_union {
    char ch[2];
    int i;
    short s;
}
```

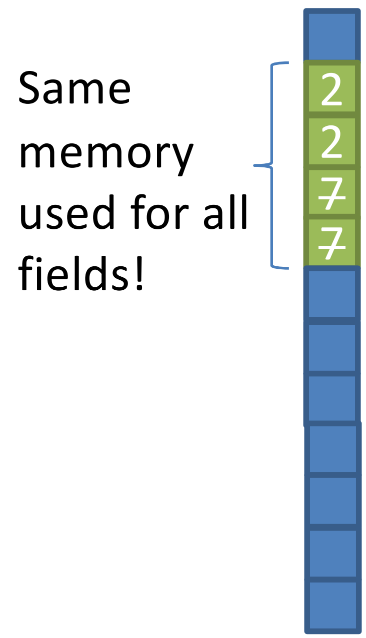


my_union in memory

Unions

```
my_union u;

u.i = 7;

u.s = 2;
```

```
union my_union {
    char ch[2];
    int i;
    short s;
}
```



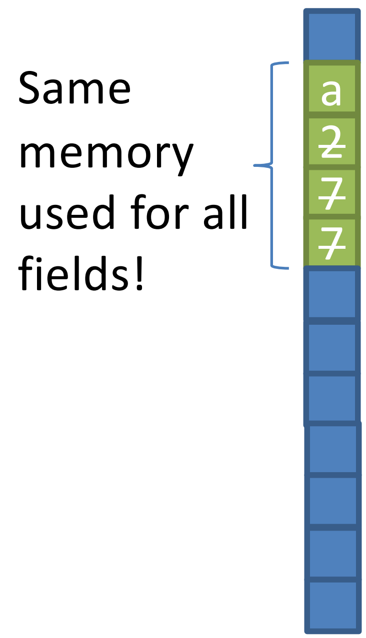
my_union in memory

Unions

```
my_union u;

u.i = 7;

u.s = 2;

u.ch[0] = 'a';
```

Reading i or s here would be bad!

```
union my_union {
      char ch[2];
      int i;
      short s;
}
```



my_union in memory

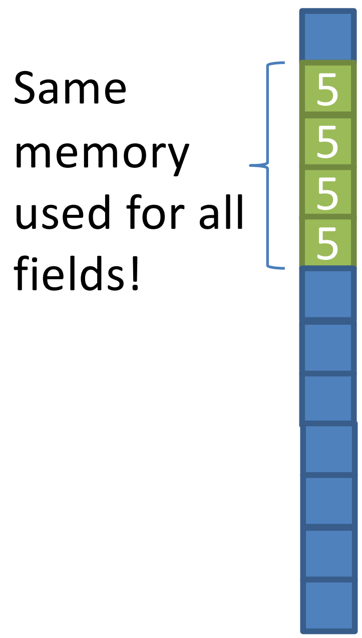
Unions

```
my_union u;

u.i = 7;

u.s = 2;

u.ch[0] = 'a';
```

Reading i or s here would be bad!

```
u.i = 5;
```

```
union my_union {
    char ch[2];
    int i;
    short s;
}
```

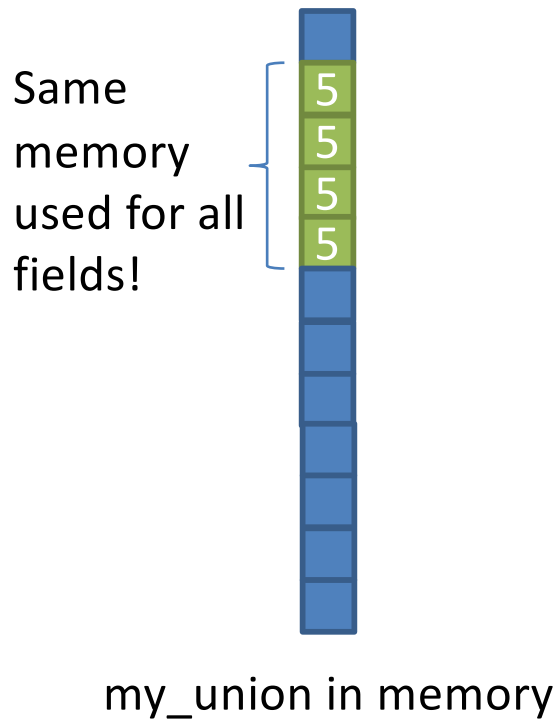


my_union in memory

Unions

- You probably won't use these often.
- Use when you need mutually exclusive types.
- Can save memory.

```
union my_union {
    char ch[2];
    int i;
    short s;
}
```



Recall: Characters and Strings

- A character (type `char`) is numerical value that holds one letter.

    char my_letter = ‘w’;   // Note: single quotes

- What is the numerical value?
    - printf(“%d   %c”, my_letter, my_letter);
    - Would print: 119   w
- Why is ‘w’ equal to 119?
    - ASCII Standard says so.

Dec	Hex	Char	Dec	Hex	Char	Dec	Hex	Char	Dec	Hex	Char
0	00	Null	32	20	Space	64	40	@	96	60	`
1	01	Start of heading	33	21	!	65	41	A	97	61	a
2	02	Start of text	34	22	"	66	42	B	98	62	b
3	03	End of text	35	23	#	67	43	C	99	63	c
4	04	End of transmit	36	24	$	68	44	D	100	64	d
5	05	Enquiry	37	25	%	69	45	E	101	65	e
6	06	Acknowledge	38	26	&	70	46	F	102	66	f
7	07	Audible bell	39	27	'	71	47	G	103	67	g
8	08	Backspace	40	28	(	72	48	H	104	68	h
9	09	Horizontal tab	41	29	)	73	49	I	105	69	i
10	0A	Line feed	42	2A	*	74	4A	J	106	6A	j
11	0B	Vertical tab	43	2B	+	75	4B	K	107	6B	k
12	0C	Form feed	44	2C	,	76	4C	L	108	6C	l
13	0D	Carriage return	45	2D	-	77	4D	M	109	6D	m
14	0E	Shift out	46	2E	.	78	4E	N	110	6E	n
15	0F	Shift in	47	2F	/	79	4F	O	111	6F	o
16	10	Data link escape	48	30	0	80	50	P	112	70	p
17	11	Device control 1	49	31	1	81	51	Q	113	71	q
18	12	Device control 2	50	32	2	82	52	R	114	72	r
19	13	Device control 3	51	33	3	83	53	S	115	73	s
20	14	Device control 4	52	34	4	84	54	T	116	74	t
21	15	Neg. acknowledge	53	35	5	85	55	U	117	75	u
22	16	Synchronous idle	54	36	6	86	56	V	118	76	v
23	17	End trans. block	55	37	7	87	57	W	119	77	w
24	18	Cancel	56	38	8	88	58	X	120	78	x
25	19	End of medium	57	39	9	89	59	Y	121	79	y
26	1A	Substitution	58	3A	:	90	5A	Z	122	7A	z
27	1B	Escape	59	3B	;	91	5B	[	123	7B	{
28	1C	File separator	60	3C	<	92	5C	\	124	7C	|
29	1D	Group separator	61	3D	=	93	5D	]	125	7D	}
30	1E	Record separator	62	3E	>	94	5E	^	126	7E	~
31	1F	Unit separator	63	3F	?	95	5F	_	127	7F	□

Characters and Strings

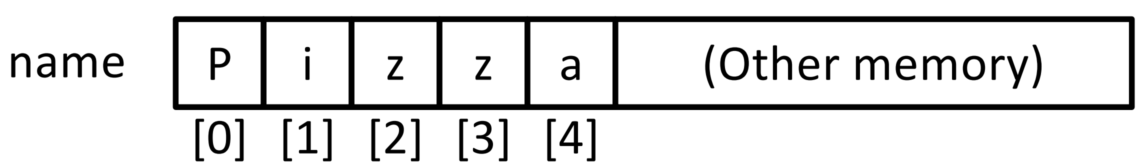
Recall: Characters and Strings

- A character (type `char`) is numerical value that holds one letter.
- A string is a memory block containing characters, one after another…
- Examples:

  char name[6] = “Pizza”;

Hmm, suppose we used printf and %s to print name.

How does it know where the string ends and other memory begins?



Recall: How can we tell where a string ends?

A. Mark the end of the string with a special character.

B. Associate a length value with the string, and use that to store its current length.

C. A string is always the full length of the array it's contained within (e.g., `char name[20]` must be of length 20).

D. All of these could work (which is best?).

E. Some other mechanism (such as?).

Recall: How can we tell where a string ends?

A. Mark the end of the string with a special character (what C does).

B. Associate a length value with the string, and use that to store its current length.

C. A string is always the full length of the array it's contained within (e.g., `char name[20]` must be of length 20).

D. All of these could work (which is best?).

E. Some other mechanism (such as?).

Special stuff over here in the lower values.

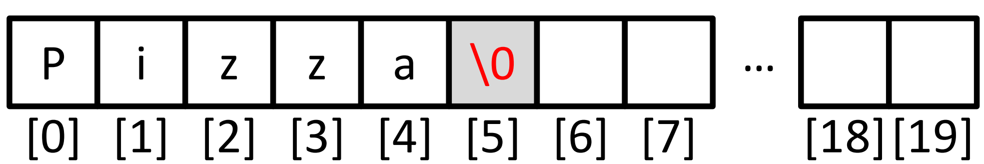
Dec	Hex	Char	Dec	Hex	Char	Dec	Hex	Char	Dec	Hex	Char
0	00	Null	32	20	Space	64	40	@	96	60	`
1	01	Start of heading	33	21	!	65	41	A	97	61	a
2	02	Start of text	34	22	"	66	42	B	98	62	b
3	03	End of text	35	23	#	67	43	C	99	63	c
4	04	End of transmit	36	24	$	68	44	D	100	64	d
5	05	Enquiry	37	25	%	69	45	E	101	65	e
6	06	Acknowledge	38	26	&	70	46	F	102	66	f
7	07	Audible bell	39	27	'	71	47	G	103	67	g
8	08	Backspace	40	28	(	72	48	H	104	68	h
9	09	Horizontal tab	41	29	)	73	49	I	105	69	i
10	0A	Line feed	42	2A	*	74	4A	J	106	6A	j
11	0B	Vertical tab	43	2B	+	75	4B	K	107	6B	k
12	0C	Form feed	44	2C	,	76	4C	L	108	6C	l
13	0D	Carriage return	45	2D	-	77	4D	M	109	6D	m
14	0E	Shift out	46	2E	.	78	4E	N	110	6E	n
15	0F	Shift in	47	2F	/	79	4F	O	111	6F	o
16	10	Data link escape	48	30	0	80	50	P	112	70	p
17	11	Device control 1	49	31	1	81	51	Q	113	71	q
18	12	Device control 2	50	32	2	82	52	R	114	72	r
19	13	Device control 3	51	33	3	83	53	S	115	73	s
20	14	Device control 4	52	34	4	84	54	T	116	74	t
21	15	Neg. acknowledge	53	35	5	85	55	U	117	75	u
22	16	Synchronous idle	54	36	6	86	56	V	118	76	v
23	17	End trans. block	55	37	7	87	57	W	119	77	w
24	18	Cancel	56	38	8	88	58	X	120	78	x
25	19	End of medium	57	39	9	89	59	Y	121	79	y
26	1A	Substitution	58	3A	:	90	5A	Z	122	7A	z
27	1B	Escape	59	3B	;	91	5B	[	123	7B	{
28	1C	File separator	60	3C	<	92	5C	\	124	7C	|
29	1D	Group separator	61	3D	=	93	5D	]	125	7D	}
30	1E	Record separator	62	3E	>	94	5E	^	126	7E	~
31	1F	Unit separator	63	3F	?	95	5F	_	127	7F	□

Characters and Strings

Recall: Characters and Strings

- A character (type `char`) is numerical value that holds one letter.
- A string is a memory block containing characters, one after another, with a null terminator (numerical 0) at the end.
- Examples:

  char name[20] = “Pizza”;



Recall: Strings in C

- C String library functions: `#include <string.h>`
  - Common functions (strlen, strcpy, etc.) make strings easier
  - Less friendly than Python strings

- More on strings later, in labs.

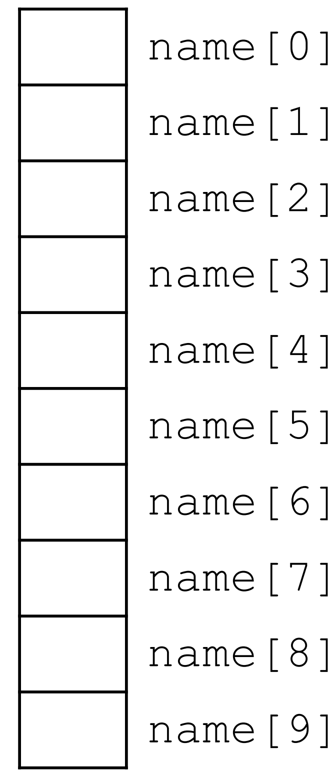
- For now, remember about strings:
  - Allocate enough space for null terminator!
  - If you're modifying a character array (string), don't forget to set the null terminator!
  - If you see crazy, unpredictable behavior with strings, check these two things!

Strings

- Strings are *character arrays*

- Layout is the same as:
  - char name[10];

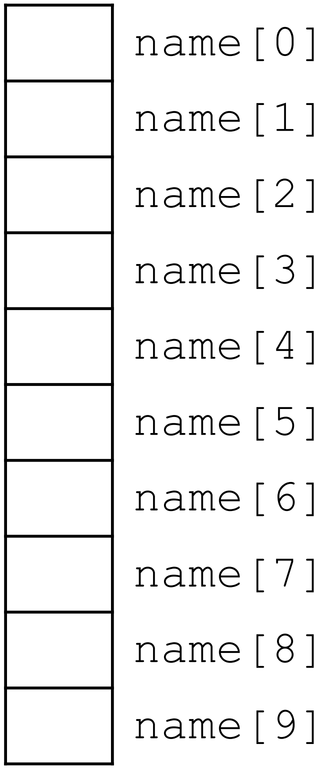
- Often accessed as (char *)



String Functions

- C library has many built-in functions that operate on char *'s:
  - strcpy, strdup, strlen, strcat, strcmp, strstr

```
char name[10];
strcpy(name, "CS 31");
```



String Functions

- C library has many built-in functions that operate on char *'s:
  - strcpy, strdup, strlen, strcat, strcmp, strstr

```
char name[10];
strcpy(name, "CS 31");
```

C	name[0]
S	name[1]
	name[2]
3	name[3]
1	name[4]
\0	name[5]
?	name[6]
?	name[7]
?	name[8]
?	name[9]

- Null terminator (\0) ends string.
  - We don't know/care what comes after

String Functions

- C library has many built-in functions that operate on char *’s:
  - strcpy, strdup, strlen, strcat, strcmp, strstr
- Seems simple on the surface.
  - That null terminator is tricky, strings error-prone.
  - Strings used everywhere!
- You will implement these functions in a future lab.