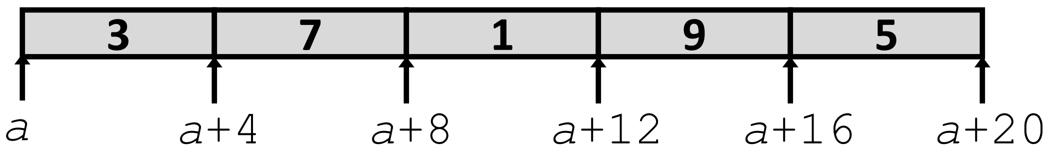
Data Structures in Assembly

- **Arrays**
  - One-dimensional
  - Multi-dimensional (nested)
  - **Multi-level**
- Structs
  - Alignment

Array Access

- Basic Principle
  - **T** A[N]; → array of data type **T** and length N
  - Identifier A returns address of array (type **T***)

int x[5];

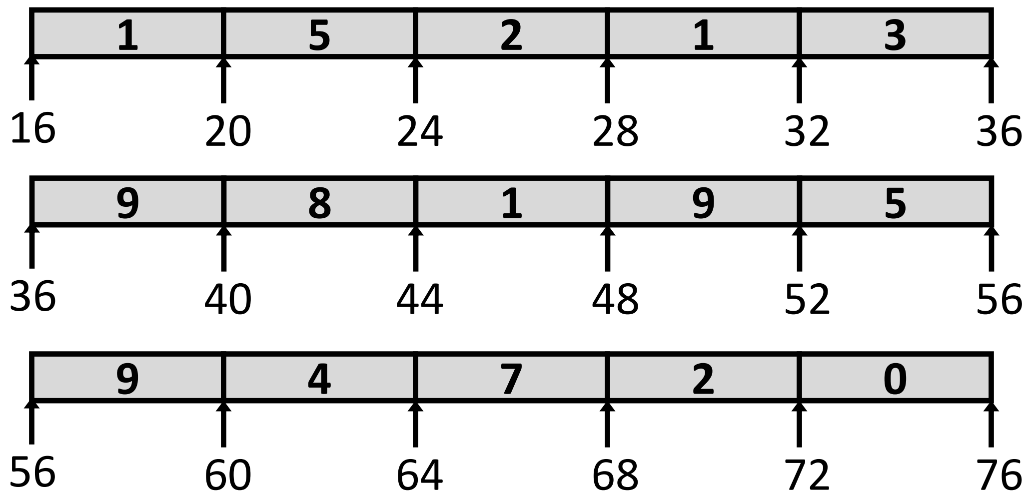


Reference	Type	Value
x[4]	**int**	5
x	**int***	a
x+1	**int***	a + 4
&x[2]	**int***	a + 8
x[5]	**int**	?? (whatever's in memory at addr x+20)
*(x+1)	**int**	7
x+i	**int***	a + 4*i

```
typedef int zip_dig[5];
```

Referencing Examples

```
zip_dig cmu;
zip_dig sfu;
zip_dig ucb;
```



Reference	Address	Value	Guaranteed?
`sfu[3]`	`36 + 4* 3 = 48`	`9`	Yes
`sfu[6]`	`36 + 4* 6 = 60`	`4`	No
`sfu[-1]`	`36 + 4*-1 = 32`	`3`	No
`cmu[15]`	`16 + 4*15 = 76`	`??`	No

- No bounds checking
- Example arrays happened to be allocated in successive 20 byte blocks
  - Not guaranteed to happen in general

```
typedef int zip_dig[5];
```

Nested Array Example

```
zip_dig sea[4] =
  {{ 9, 8, 1, 9, 5 },
   { 9, 8, 1, 0, 5 },
   { 9, 8, 1, 0, 3 },
   { 9, 8, 1, 1, 5 }};
```

Remember, `T A[N]` is an array with elements of type `T`, with length `N`

same as:

```
int sea[4][5];
```

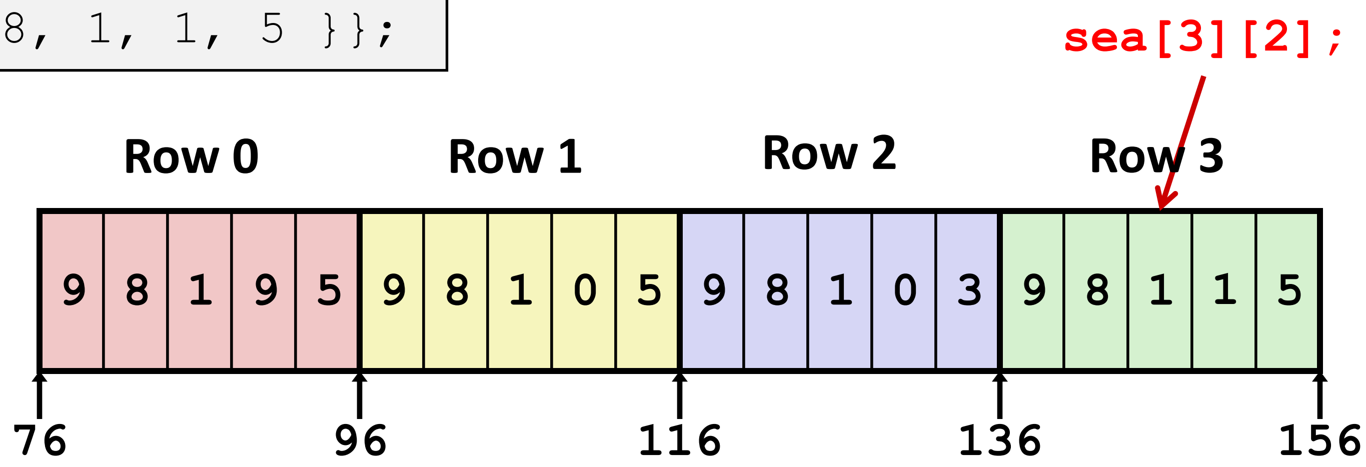
What is the layout in memory?

```
typedef int zip_dig[5];
```

Nested Array Example

```
zip_dig sea[4] =
  {{ 9, 8, 1, 9, 5 },
   { 9, 8, 1, 0, 5 },
   { 9, 8, 1, 0, 3 },
   { 9, 8, 1, 1, 5 }};
```

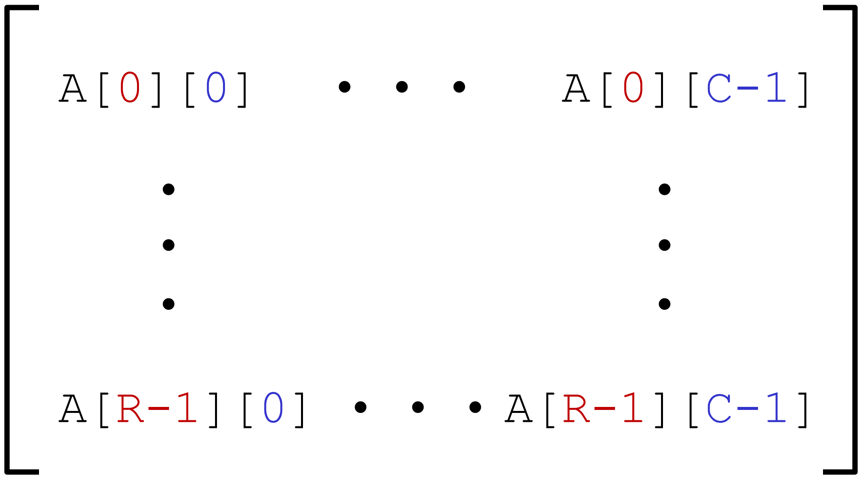
Remember, `T A[N]` is an array with elements of type `T`, with length `N`



- "Row-major" ordering of all elements
- Elements in the same row are contiguous
- Guaranteed (in C)

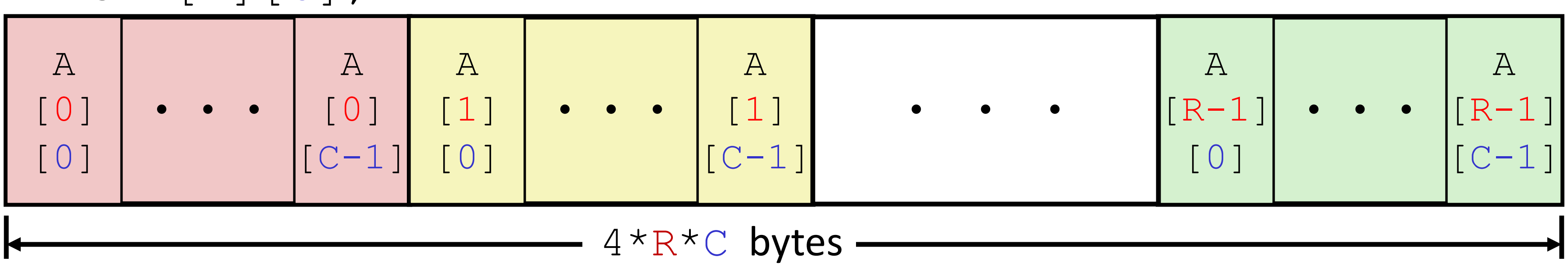
Two-Dimensional (Nested) Arrays

- Declaration: **T** A[R][C];
  - 2D array of data type T
  - R rows, C columns
  - Each element requires **sizeof**(**T**) bytes



- Array size:
  - R*C***sizeof**(**T**) bytes
- Arrangement: **row-major** ordering

```
int A[R][C];
```



Multi-Level Array Example

Multi-Level Array Declaration(s):

```
int cmu[5] = { 1, 5, 2, 1, 3 };
int  sfu[5] = { 9, 8, 1, 9, 5 };
int ucb[5] = { 9, 4, 7, 2, 0 };
```

```
int* univ[3] = {sfu, cmu, ucb};
```

Is a multi-level array the same thing as a 2D array?

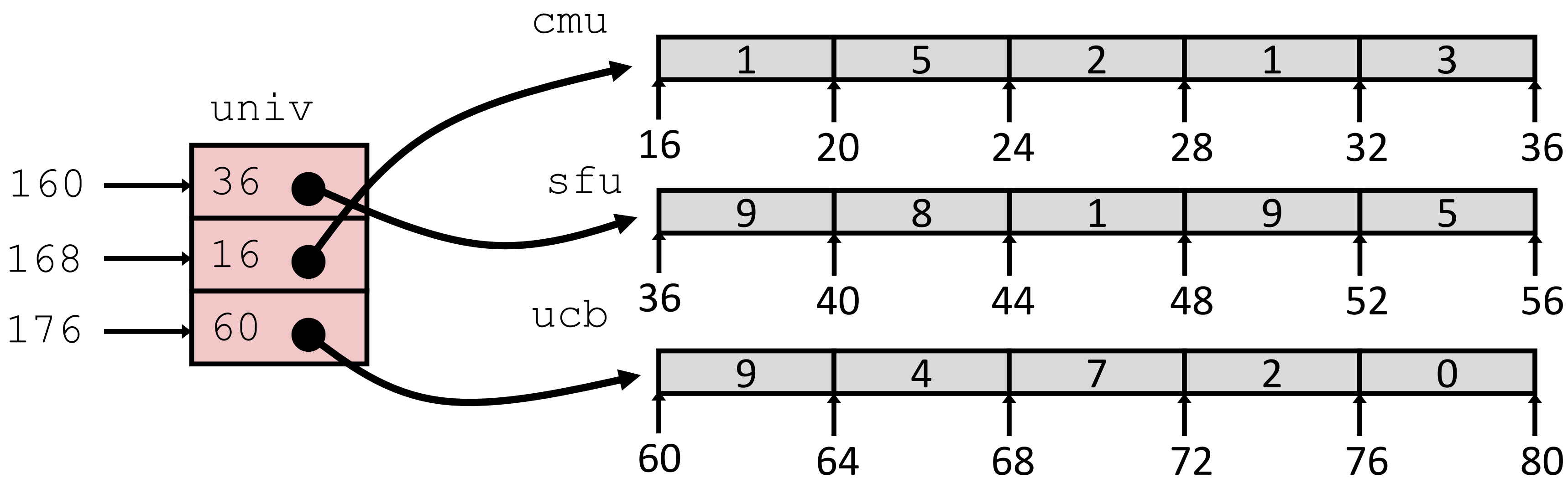
NO

2D Array Declaration:

```
zip_dig univ2D[3] = {
  { 9, 8, 1, 9, 5 },
  { 1, 5, 2, 1, 3 },
  { 9, 4, 7, 2, 0 }
};
```

One array declaration = one contiguous block of memory

Multi-Level Referencing Examples



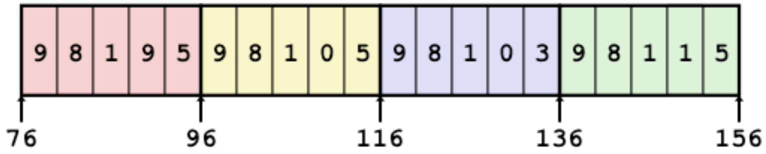
Reference	Address	Value	Guaranteed?
`univ[2][3]`			
`univ[1][5]`			
`univ[2][-2]`			
`univ[3][-1]`			
`univ[1][12]`			

- C code does not do any bounds checking
- Location of each lower-level array in memory is *not* guaranteed

Array Element Accesses

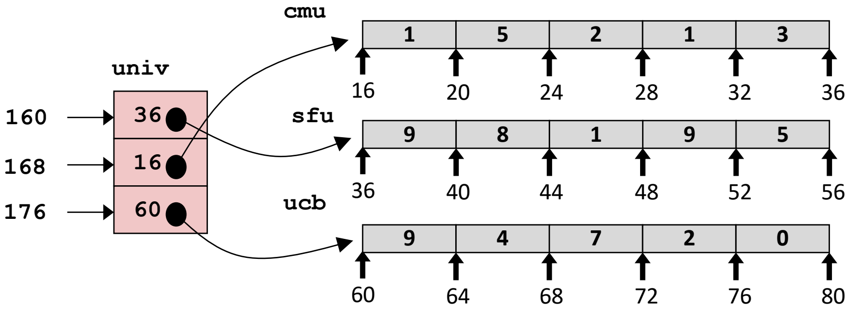
Nested array

```
int get_sea_digit
   (int index, int digit)
{
   return sea[index][digit];
}
```



Multi-level array

```
int get_univ_digit
   (int index, int digit)
{
   return univ[index][digit];
}
```



Access *looks* the same, but it isn't:

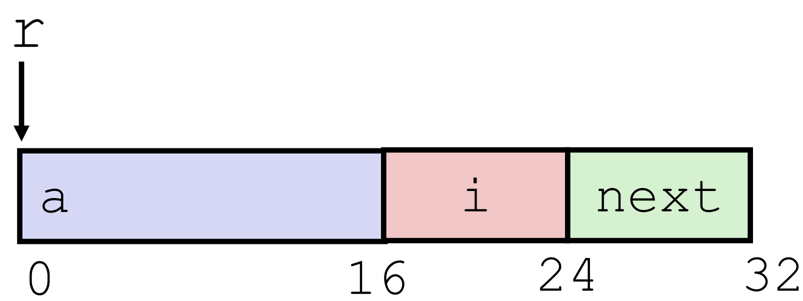
Mem[sea+20*index+4*digit]

Mem[Mem[univ+8*index]+4*digit]

C Structure Representation

```
struct rec {
    int a[4];
    long i;
    struct rec *next;
};

struct rec *r;
```

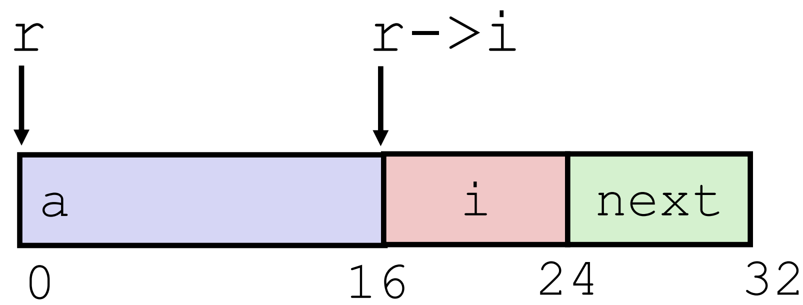


- Structure represented as block of memory
  - Big enough to hold all of the fields
- Fields ordered according to declaration order
  - Even if another ordering would be more compact
- Compiler determines overall size + positions of fields
  - Machine-level program has no understanding of the structures in the source code

Accessing a Structure Member

```
struct rec {
    int a[4];
    long i;
    struct rec *next;
};

struct rec *r;
```




```
long get_i(struct rec *r)
{
  return r->i;
}
```

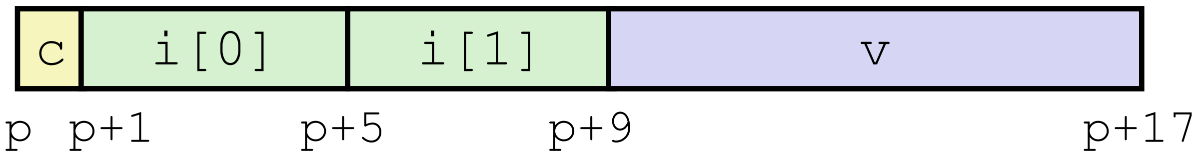
- Compiler knows the *offset* of each member within a struct
  - Compute as `*(r+offset)`
    - Referring to absolute offset, so no pointer arithmetic

```
add  a0, a1, 16 # Coming up in Week 3
  ret
```

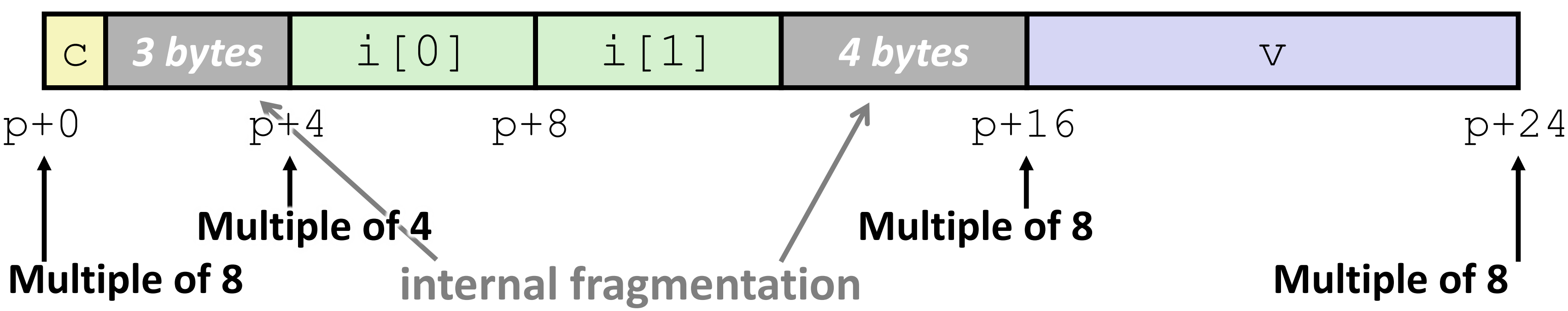
Structures & Alignment

```
struct S1 {
  char c;
  int i[2];
  double v;
} *p;
```

- Unaligned Data



- Aligned Data
  - Primitive data type requires K bytes
  - Address must be multiple of K

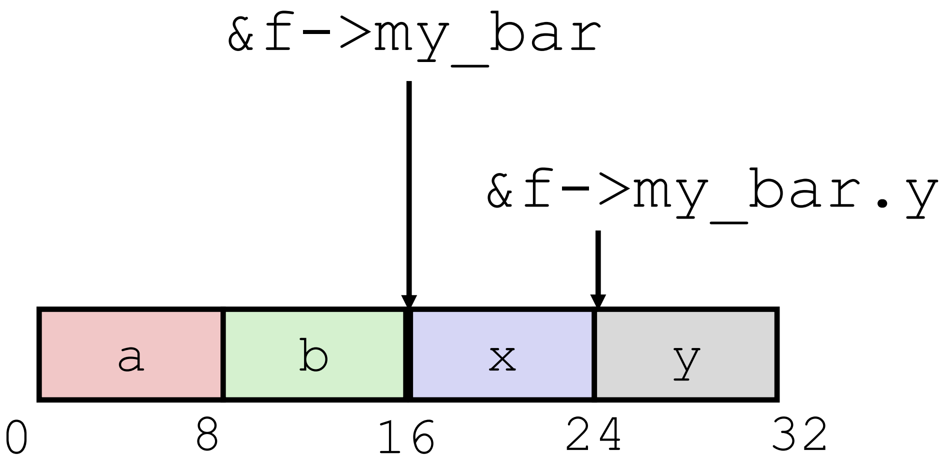


Nested Struct

```
struct foo {
    long a;
    long b;
    struct bar my_bar;
};

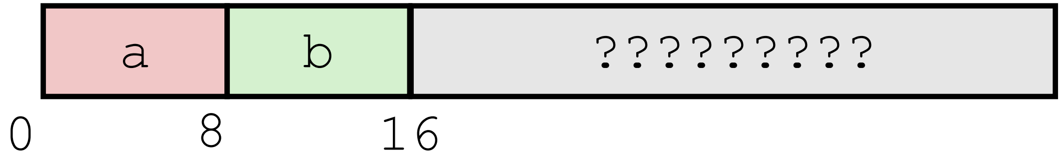
struct bar {
    long x;
    long y;
};

struct foo *f;
```



Nested Struct

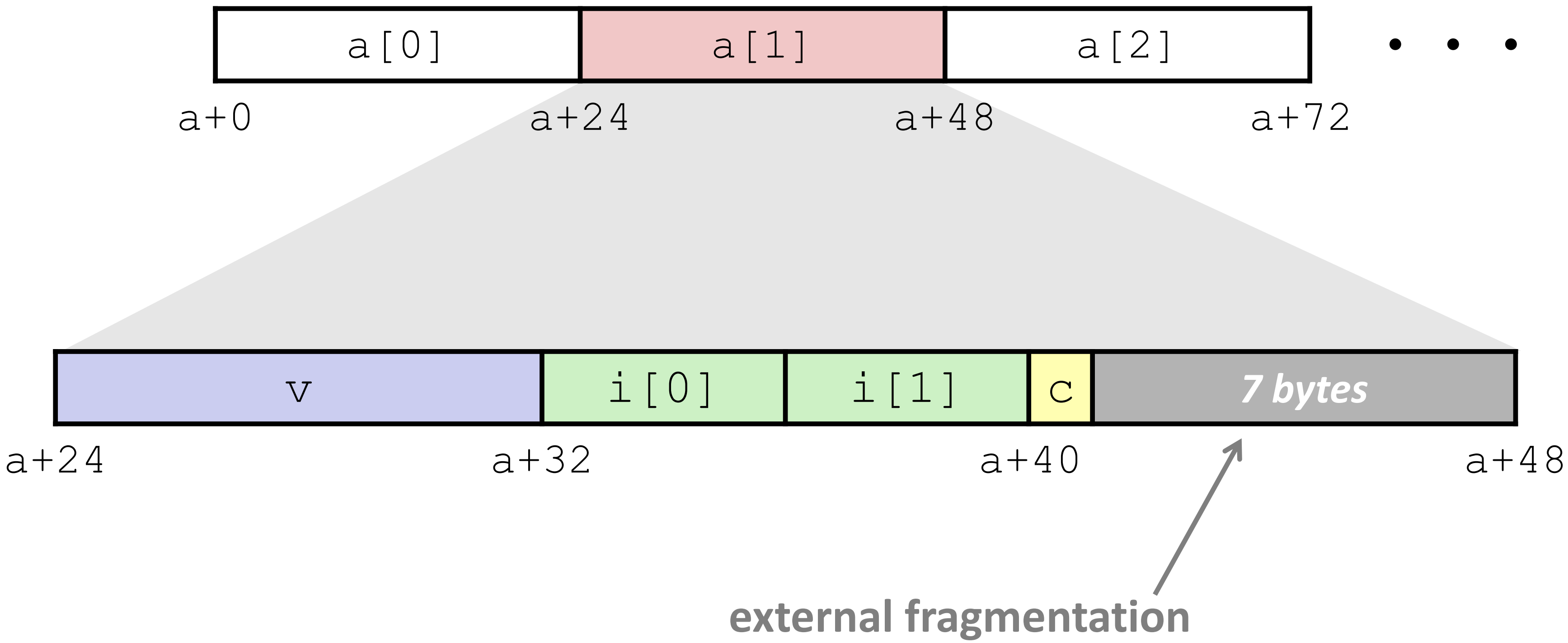
```
struct foo {
    long a;
    long b;
    struct foo my_foo;
};
```



Arrays of Structures

- Overall structure length multiple of K_{max}
- Satisfy alignment requirement for every element in array

```
struct S2 {
  double v;
  int i[2];
  char c;
} a[10];
```



Sparse Arrays (Array of Structs)

Arrays

Array of structures (non zeros)


```
struct coo { int row; int col; int val; } // each non-zero
int nnz                                   // number of non zeros
struct coo_array[nnz]                     // Array of non zeros
```

```
for i = 0 to nnz
   int* base = &coo[i]
   int r = *base
   int c = *(base+1)
   int val = *(base+2)
```

Sparse Arrays (Structs of Arrays)

- int row[nnz]

0	0	0	0	0	0

- int col[nnz]

0	2	4	5	7	8

- int val[nnz]

1	3	5	6	7	9

```
for i = 0 to nnz
  int r = row[i]
  int c = col[i]
  int val = val[i]
```

Multiple Ways to Store Program Data

Multiple Ways to Store Program Data

- Static global data
  - *Fixed size* at compile-time
  - Entire *lifetime of the program* (loaded from executable)
  - Portion is read-only (e.g. string literals)
- Stack-allocated data
  - Local/temporary variables
    - *Can* be dynamically sized (in some versions of C)
  - *Known lifetime* (deallocated on `return`)
- **Dynamic (heap) data**
  - Size known only at runtime (i.e. based on user-input)
  - Lifetime known only at runtime (long-lived data structures)

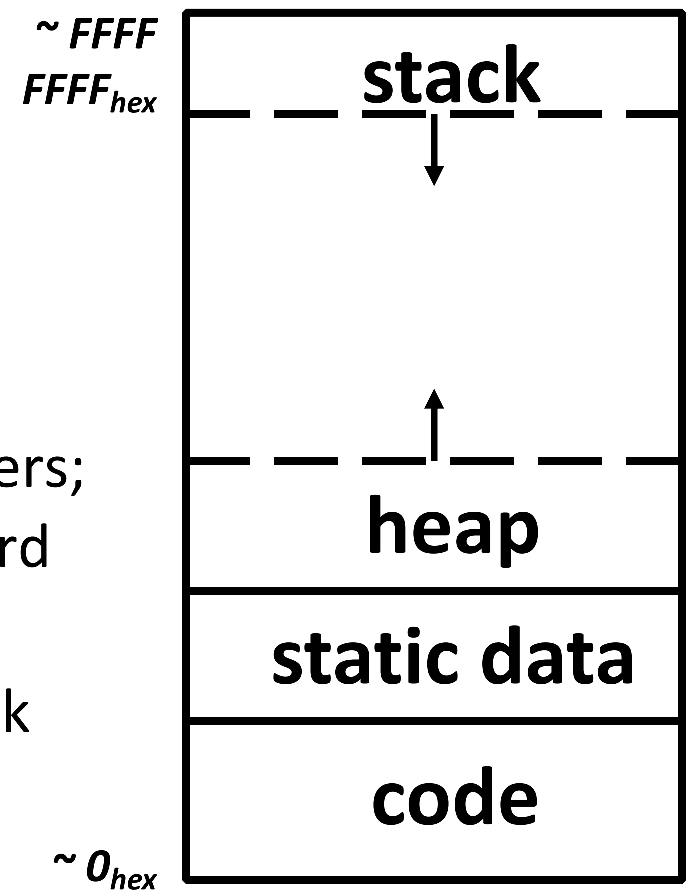
```
int array[1024];

void foo(int n) {
  int tmp;
  int local_array[n];

  int* dyn =
    (int*)malloc(n*sizeof(int));
}
```

C Memory Layout

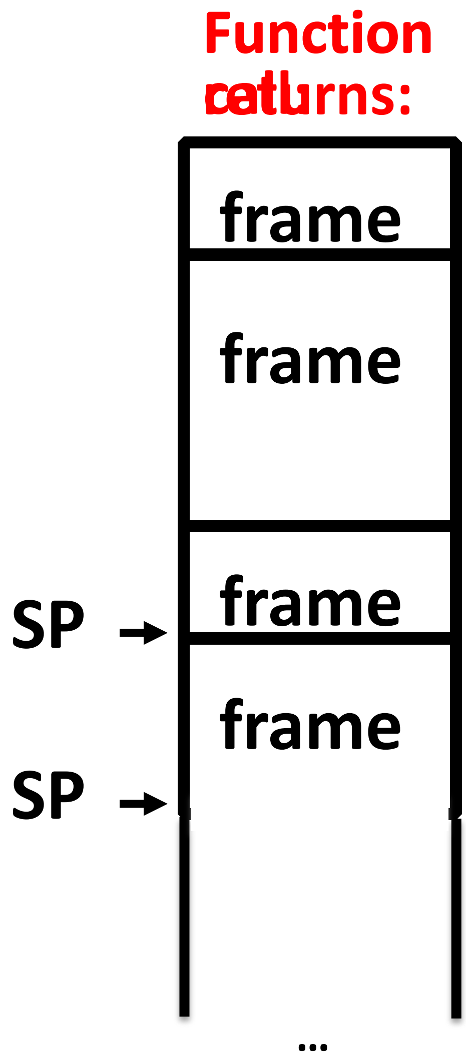
- Program's *address space* contains 4 regions:
  - Stack: local variables, grows downward
  - Heap: space requested via `malloc()` and used with pointers; resizes dynamically, grows upward
  - Static Data: global and static variables, does not grow or shrink
  - Code: loaded when program starts, does not change



OS prevents accesses between stack and heap (via virtual memory)

The Stack

- Each stack frame is a contiguous block of memory holding the local variables of a single procedure
- A stack frame includes:
  - Location of caller function
  - Function arguments
  - Space for local variables
- Stack pointer (SP) tells where lowest (current) stack frame is
- When procedure ends, stack pointer is moved back (but data remains (garbage!)); frees memory for future stack frames;



Bit-Level Operations in C

- & (AND), | (OR), ^ (XOR), ~ (NOT)
  - View arguments as bit vectors, apply operations bitwise
  - Apply to any "integral" data type
    - `long`, `int`, `short`, `char`, `unsigned`
- Examples with `char a, b, c;`
  - ```
    a = (char) 0x41;    // 0x41->0b 0100 0001
    b = ~a;             //       0b           ->0x
    ```
  - ```
    a = (char) 0x69;    // 0x69->0b 0110 1001
    b = (char) 0x55;    // 0x55->0b 0101 0101
    c = a & b;          //       0b           ->0x
    ```
  - ```
    a = (char) 0x41;    // 0x41->0b 0100 0001
    b = a;              //       0b 0100 0001
    c = a ^ b;          //       0b           ->0x
    ```
    ```

Intuition for logical operators

Operator	Input	Output
& 1 : Copy	1001 & 1111	1001
| 1 : Set	1001 | 1111	1111
& 0 : Reset	1001 |0000	0000
| 0 : Copy	1001 | 0000	1001
^ 1 : Flip	1001 ^ 1111	0110
^ 0 : Copy	1001 ^ 0000	1001

e.g., extract bits at position 3 and 2 from number

number & 1100 - Copy positions 3 and 2. Reset positions 1 and 0

1001 & 1100 = 1000

1000 → --10

Shift Operations (also watch Lab 3 video)

- Left shift (`x<<n`)
  - Fill with `0`s on right
- Right shift (`x>>n`)
  - Logical shift (for unsigned values)
    - Fill with 0s on left
  - Arithmetic shift (for signed values)
    - Replicate most significant bit on left

	x	0010 0010
	x<<3	0001 0000
logical:	x>>2	0000 1000
arithmetic:	x>>2	0000 1000

	x	1010 0010
	x<<3	0001 0000
logical:	x>>2	0010 1000
arithmetic:	x>>2	1110 1000

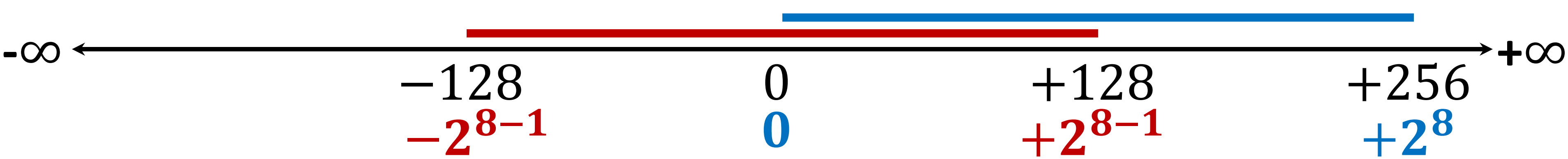
- Notes:
  - Shifts by `n<0` or `n≥w` (bit width of x) are *undefined*
  - **In C:** behavior of `>>` is determined by compiler
    - depends on data type of `x` (signed/unsigned)
  - **In Java:** logical shift is `>>>` and arithmetic shift is `>>`

Integers

- Sign and unsigned variables in C
  - Bit pattern remains the same, just *interpreted* differently
  - Strange things can happen with our arithmetic when we convert/cast between sign and unsigned numbers
    - Type of variables affects behavior of operators (shifting, comparison)
- We can only represent so many numbers in *w* bits
  - When we exceed the limits, *arithmetic overflow* occurs
  - *Sign extension* tries to preserve value when expanding
- Shifting is a useful bitwise operator
  - Right shifting can be arithmetic (sign) or logical (0)
  - Can be used in multiplication with constant or bit masking

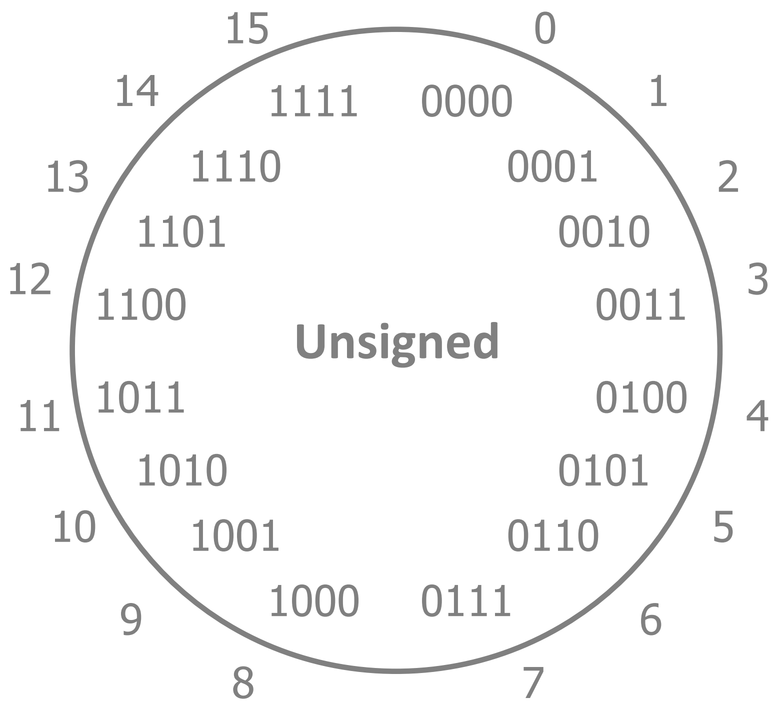
Encoding Integers

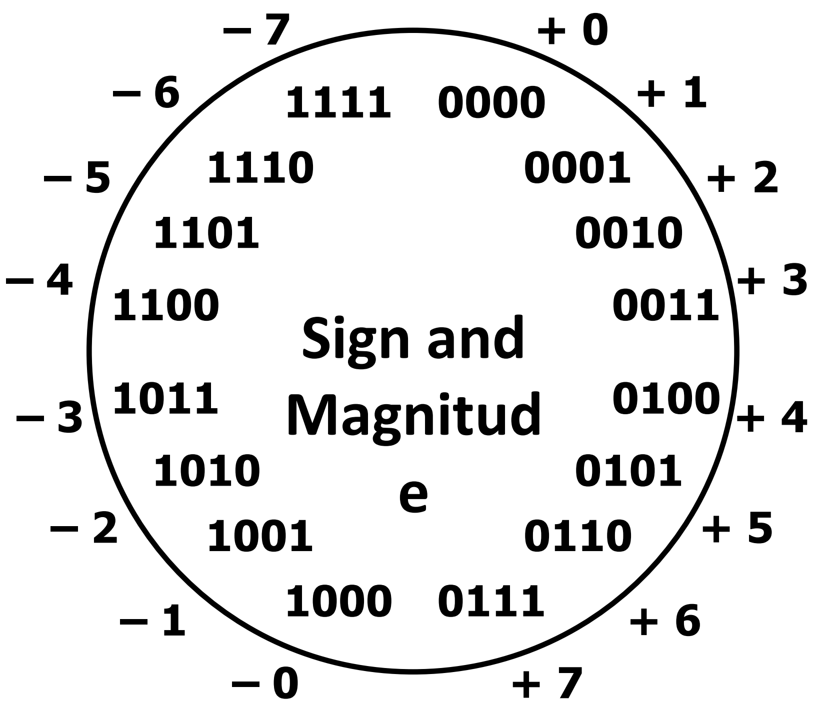
- The hardware (and C) supports two flavors of integers
  - *unsigned* – only the non-negatives
  - *signed* – both negatives and non-negatives
- Cannot represent all integers with w bits
  - Only 2^w distinct bit patterns
  - Unsigned values: $0 \ldots 2^w-1$
  - Signed values: $-2^{(w-1)} \ldots 0 \ldots 2^{(w-1)}-1$
- **Example:** 8-bit integers (*e.g.* `char`)



Sign and Magnitude

- MSB is the sign bit, rest of the bits are magnitude
- Drawbacks?





Sign and Magnitude

- MSB is the sign bit, rest of the bits are magnitude
- Drawbacks:
  - Two representations of 0 (bad for checking equality)
  - Arithmetic is cumbersome
    - Example: `4-3 != 4+(-3)`

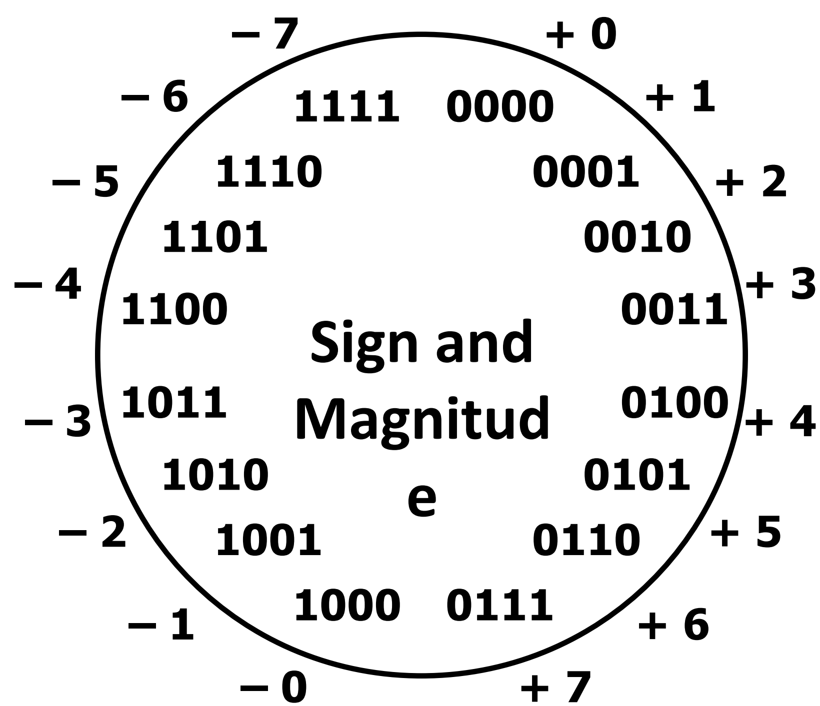
4	0100
− 3	− 0011
1	0001

✓

4	0100
+ −3	+ 1011
−7	1111

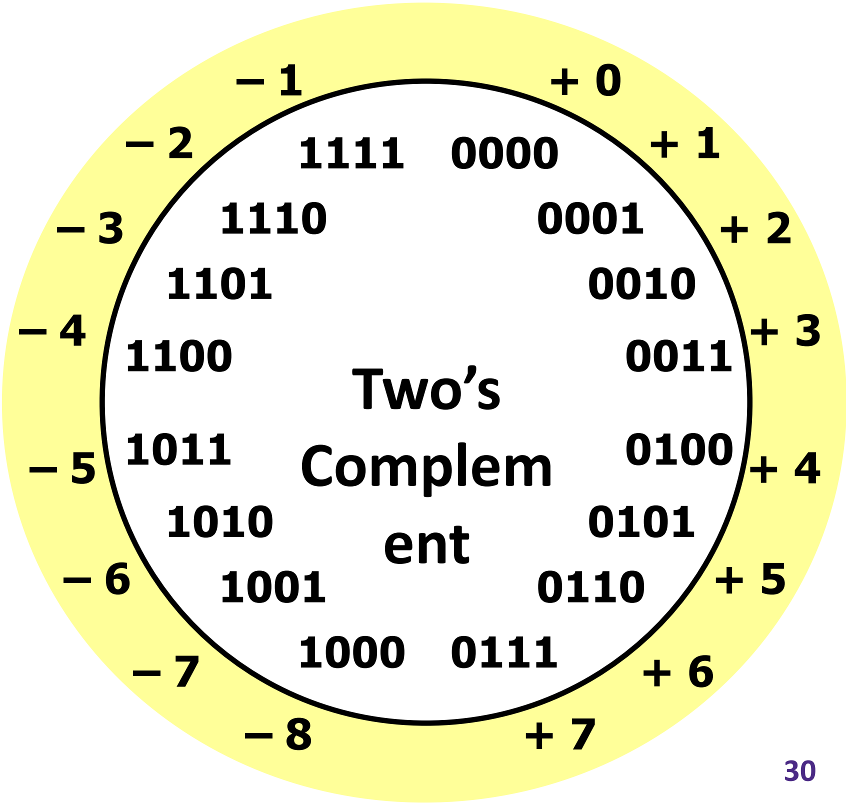
✗

    - Negatives "increment" in wrong direction!



Why Two's Complement is So Great

- Roughly same number of (+) and (–) numbers
- Positive number encodings match unsigned
- Simple arithmetic (x + -y = x – y)
- Single zero
- All zeros encoding = 0
- Simple negation procedure:
  - Get negative representation of any integer by taking bitwise complement and then adding one!
    `( ~x + 1 == -x )`



Sign Extension

- **Task:** Given a w-bit signed integer X, convert it to $w+k$-bit signed integer X' *with the same value*
- **Rule:** Add k copies of sign bit
  - Let x_i be the i-th digit of X in binary
  - $\mathrm{X}' = \underbrace{x_{w-1}, \ldots, x_{w-1}}_{k \text{ copies of MSB}}, \underbrace{x_{w-1}, x_{w-2}, \ldots, x_1, x_0}_{\text{original } \mathrm{X}}$