HARVARD
School of Engineering
and Applied Sciences

Assembly Programming: Structured Data

CS61, Lecture 5

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September 16, 2010

Announcements

- Lab 1 due Tuesday 21 Sept, 11:59pm.
  - Don't forget to request late days **before** the deadline
- Extra office hours on Monday and Tuesday
  - See website for details

Topics for today

- Structured data
  - Arrays
  - Multidimensional arrays
  - Multi-level arrays
  - Structs
  - Memory alignment
  - Arrays of structs

Basic data types

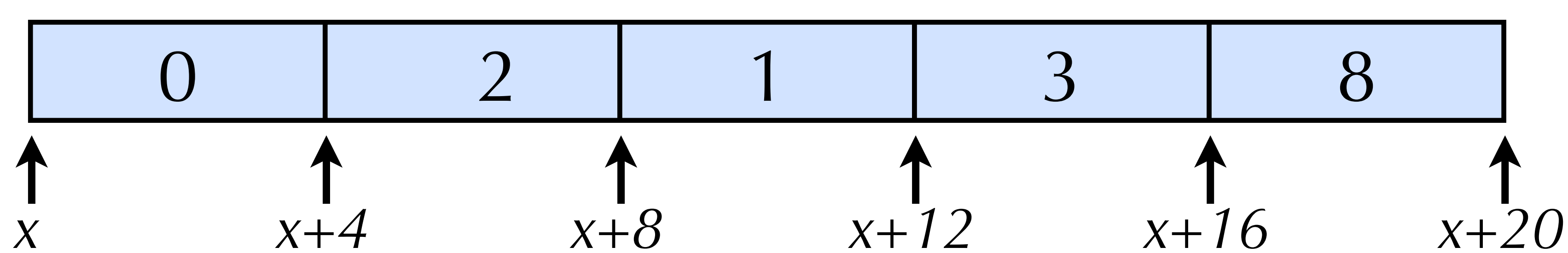
- Integer data types
  - Stored & operated on in general (integer) registers
  - Signed vs. unsigned depends on instructions used
- Floating Point
  - Stored & operated on in floating point registers

C declaration	Intel data type	Assembly code suffix	32-bit	64-bit
`char`	Byte	`b`	1	1
`short int`	Word	`w`	2	2
`int`	Double word	`l`	4	4
`long int`	Quad word	`q`	4	8
`float`	Single precision	`s`	4	4
`double`	Double precision	`d`	8	8
`long double`	Extended precision	`t`	10/16	10/12

Array allocation

- *T* `A[`*L*`];`
  - Declares array of data type *T* and length *L*
  - e.g., `int foo[5]`
- Represented as contiguously allocated region of $L \times$ `sizeof(`*T*`)` bytes

```
int foo[5];
foo[0] = 0;
foo[1] = 2;
foo[2] = 1;
foo[3] = 3;
foo[4] = 8;
```

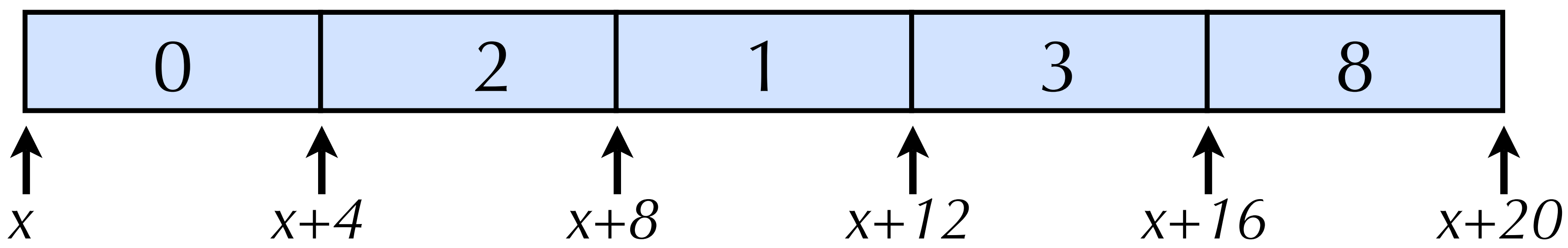


Array access

- Given T `A[`L`];`
  - `A[`i`]` accesses the ith element of the array
  - Identifier `A` can be used as a pointer to array element 0
    - Type of `A` is T `*`
    - E.g., `int foo[5];`
      `*foo = 4;` is equivalent to `foo[0] = 4;`

Array notation

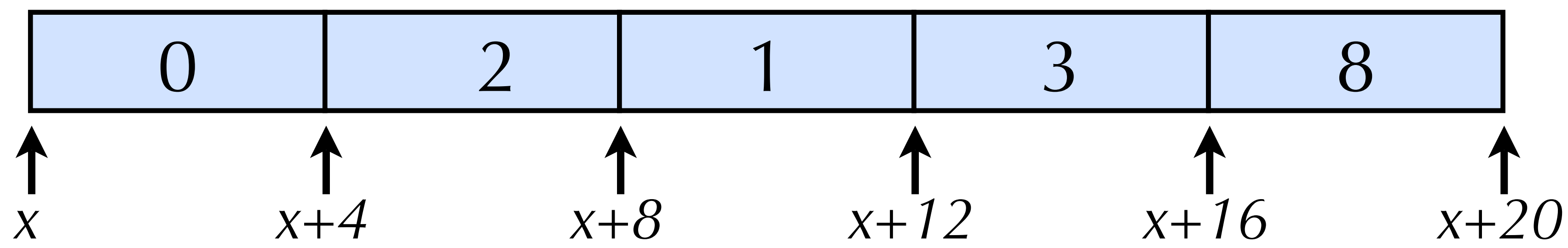
`int foo[5];`



Expression	Type	Value
`foo[2]`		
`foo`		
`foo+1`		
`&foo[2]`		
`foo[5]`		
`*(foo+1)`		
`foo + 3`		

Array notation

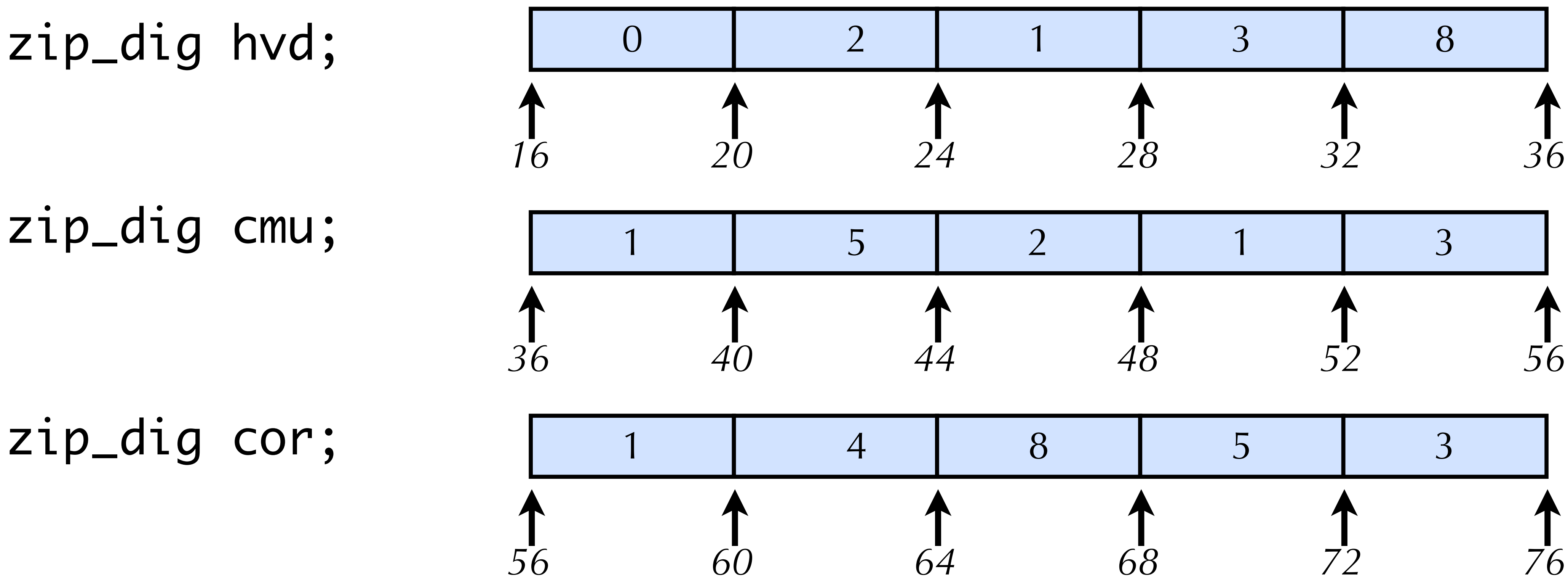
`int foo[5];`



Expression	Type	Value
`foo[2]`	`int`	1
`foo`	`int *`	*x*
`foo+1`	`int *`	*x*+4
`&foo[2]`	`int *`	*x*+8
`foo[5]`	`int`	???
`*(foo+1)`	`int`	2
`foo + 3`	`int *`	*x* + 4×3

Array example

```c
typedef int zip_dig[5];

zip_dig hvd = { 0, 2, 1, 3, 8 };
zip_dig cmu = { 1, 5, 2, 1, 3 };
zip_dig cor = { 1, 4, 8, 5, 3 };
```



- Note: declaration `zip_dig hvd` equivalent to `int hvd[5]`
- Example arrays were allocated in successive 20 byte blocks
  - Not guaranteed to be true!

Accessing arrays

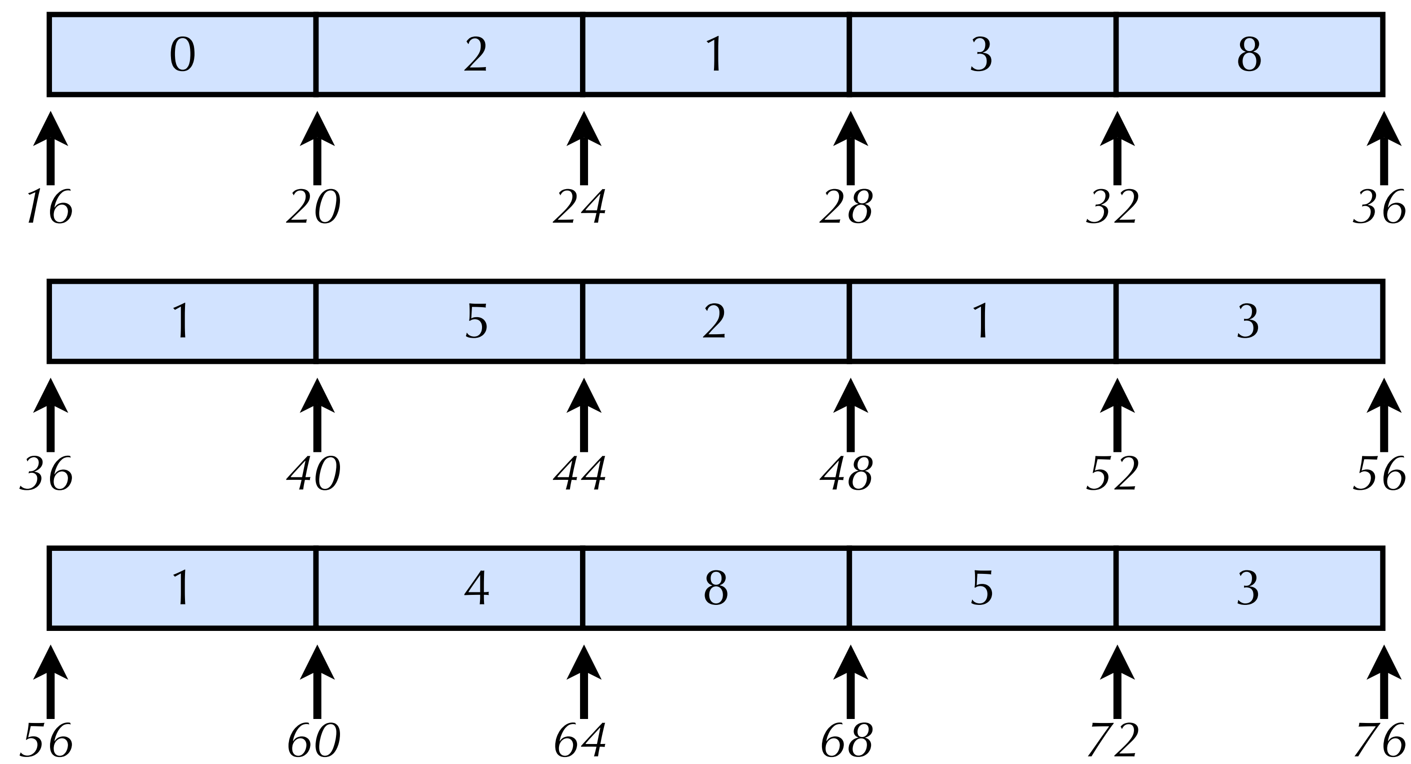
```
typedef int zip_dig[5];

int get_digit(zip_dig z, int dig) {
  return z[dig];
}
```

```
push    %ebp
mov     %esp,%ebp

mov     0xc(%ebp),%eax      # %eax = dig
mov     0x8(%ebp),%edx      # %edx = z
mov     (%edx,%eax,4),%eax # %eax = z[dig]

pop     %ebp
ret
```

- `%edx` contains starting address of array
- `%eax` contains the array index
- Desired value at `%edx` + (`%eax` * 4)

Referencing examples

```
zip_dig hvd;
zip_dig cmu;
zip_dig cor;
```



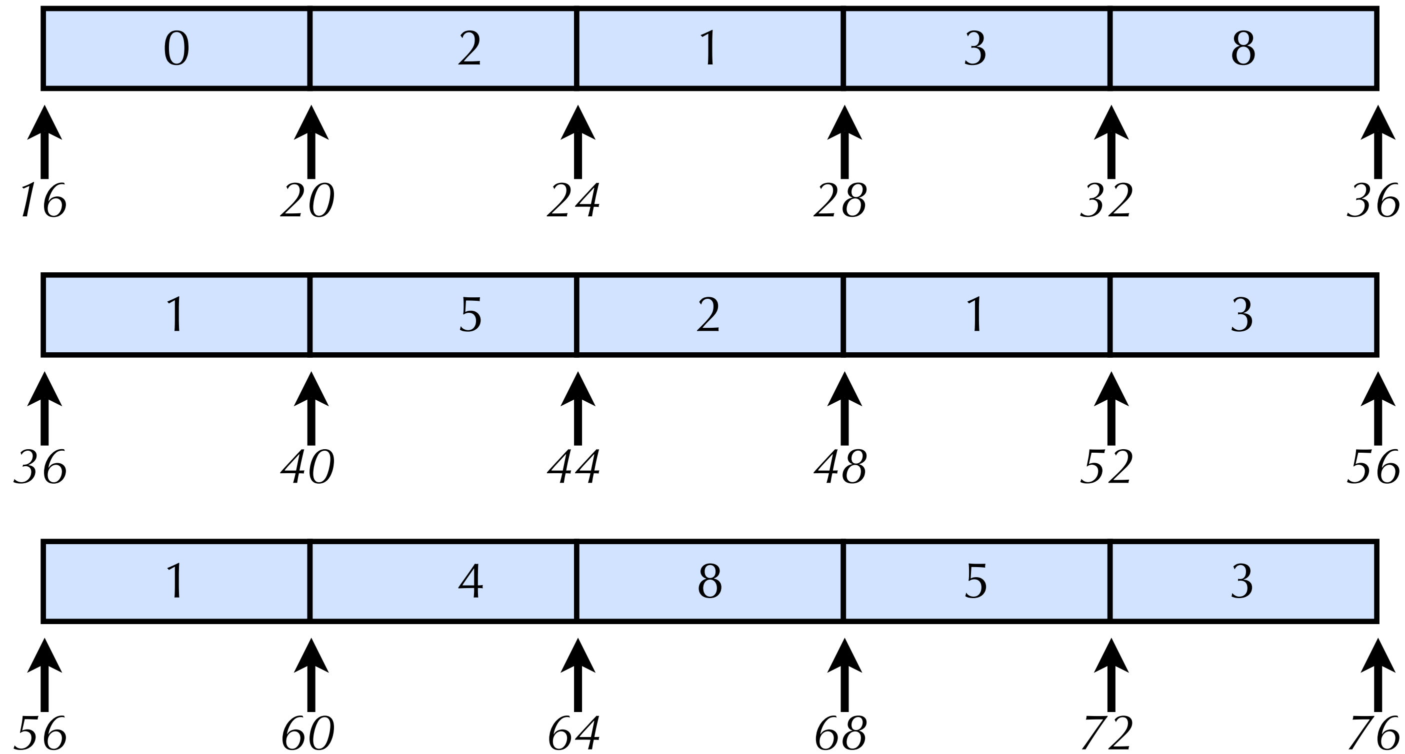
Expression	Address	Value	Guaranteed to work?
`cmu[3]`			
`cmu[5]`			
`cmu[-1]`			
`hvd[15]`			

Referencing examples

```
zip_dig hvd;
```

```
zip_dig cmu;
```

```
zip_dig cor;
```



Expression	Address	Value	Guaranteed to work?
`cmu[3]`	`36 + 4*3 = 48`	1	Yes
`cmu[5]`	`36 + 4*5 = 56`	1	No
`cmu[-1]`	`36 + 4*-1 = 32`	8	No
`hvd[15]`	`16+4*15 = 76`	??	No

Looping over an array

- Original source

```
int zd2int(zip_dig z) {
  int i;
  int zi = 0;
  for (i = 0; i < 5; i++) {
    zi = 10 * zi + z[i];
  }
  return zi;
}
```

- What gcc produces
  - (pseudocode)
  - Eliminate loop variable `i`
  - Convert array code to pointer code
  - Rewrite as do-while loop

```
int zd2int(zip_dig z) {
  int zi = 0;
  int *zend = z + 4;
  do {
    zi = 10 * zi + *z;
    z++;
  } while (z <= zend);
  return zi;
}
```

Looping over array in machine code

```
int zd2int(zip_dig z) {
  int zi = 0;
  int *zend = z + 4;
  do {
    zi = 10 * zi + *z;
    z++;
  } while (z <= zend);
  return zi;
}
```

- Notes:
  - `xorl %eax,%eax` sets `%eax` to zero
  - `leal` used for arithmetic
  - 4 added to `%ecx` each iteration

```
    ...                             # %ecx = z
    xorl %eax,%eax                  # zi = 0
    leal 16(%ecx),%ebx              # zend  = z+4
.L59:
    leal (%eax,%eax,4),%edx         # edx = zi + 4*zi = 5*zi
    movl (%ecx),%eax                # zi = *z
    addl $4,%ecx                    # z++
    leal (%eax,%edx,2),%eax         # zi = *z + 2*(5*zi)
    cmpl %ebx,%ecx                  # compare
    jle .L59                        # if z <= zend, loop
```

Strings

- x86 doesn't have an internal notion of a string datatype.
- In C, a string is represented as an array of char, terminated by a 0 byte
  - Each character is one ASCII encoded byte
  - E.g., "this is a string"

0x74	0x68	0x69	0x73	0x20	0x69	0x73	0x20	0x61	0x20	0x73	0x74	0x72	0x69	0x6e	0x67	0x00

0x74 is ASCII encoding of 't'

0x0 terminates string

- Different languages use different string representations
  - E.g., Java stores strings in Unicode format (1-4 bytes per character)

Topics for today

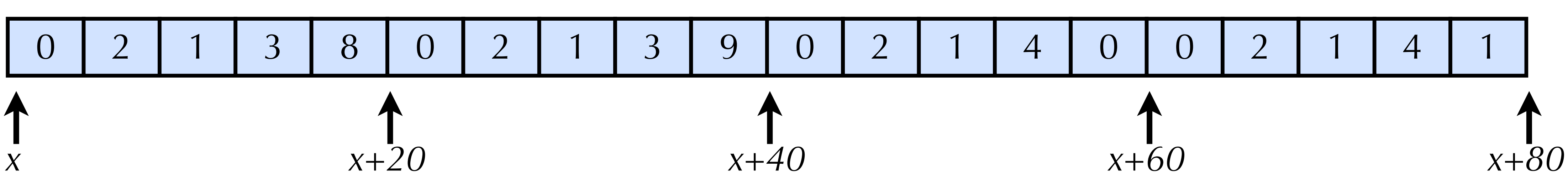
- Structured data
  - Arrays
  - Multidimensional arrays
  - Multi-level arrays
  - Structs
  - Memory alignment
  - Arrays of structs

Multidimensional arrays

- *T* `A[`*R*`][`*C*`];`
  - Two dimensional array of datatype *T*
  - *R* rows and *C* columns
- Represented as contiguously allocated region of

  R × *C* × `sizeof(`*T*`)` bytes
  - Row major ordering: rows stored one after the other

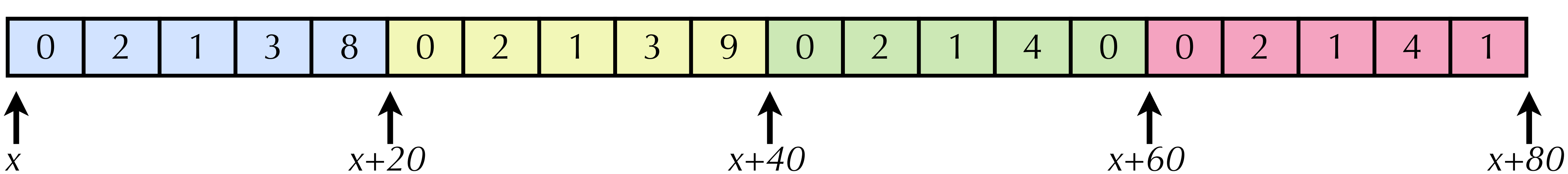
```
int cambridge_zips[4][5] =
  {{0, 2, 1, 3, 8},
   {0, 2, 1, 3, 9 },
   {0, 2, 1, 4, 0 },
   {0, 2, 1, 4, 1 }};
```



Multidimensional arrays

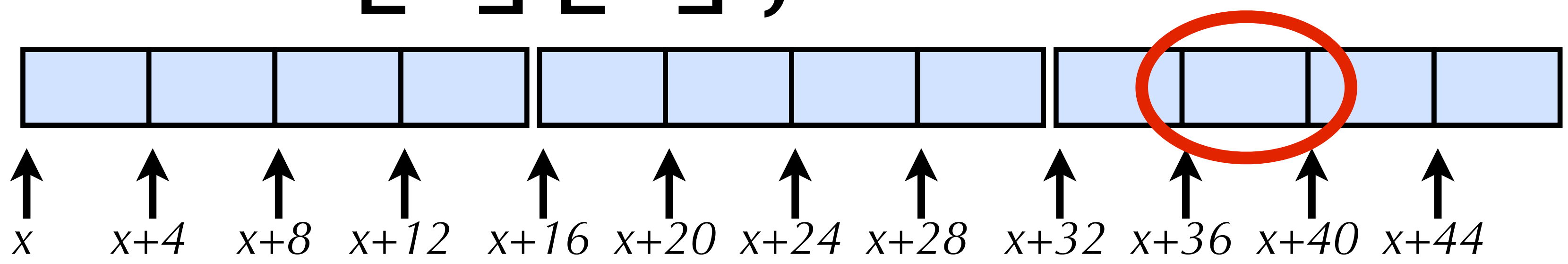
- `typedef int zip_dig[5];`
- `zip_dig cambridge_zips[4]`
  is equivalent to
  `int cambridge_zips[4][5]`
- `zip_dig cambridge_zips[4]`: array of 4 elements, allocated continuously
- Each element is an array of 5 ints, allocated continuously

```
int cambridge_zips[4][5] =
  {{0, 2, 1, 3, 8},
   {0, 2, 1, 3, 9 },
   {0, 2, 1, 4, 0 },
   {0, 2, 1, 4, 1 }};
```



Accessing a single array element

- *T* `A[`*R*`][`*C*`];`
  - `A[`*i*`][`*j*`]` is a single element of type *T*
  - Address is `A` + *i* * *C* * `sizeof(`*T*`)` + *j**`sizeof(`*T*`)`
- E.g., `int foo[3][4];`



- `&foo[2][1]` evaluates to

  $x + 2 * 4 *$ `sizeof(int)` $+ 1 *$ `sizeof(int)`

  $= x + 32 + 4 \quad = \quad x + 36$

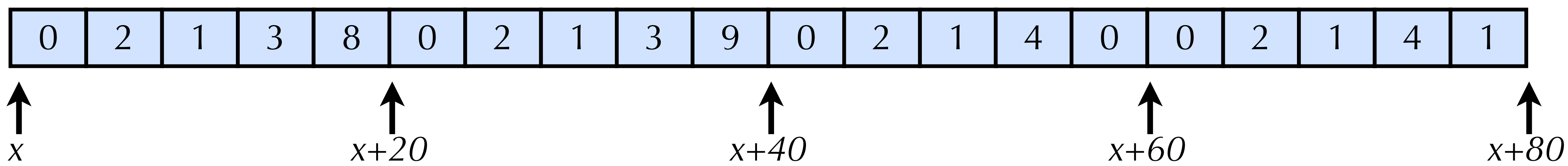
Machine code for array access

```
int cambridge_zips[4][5] = { ... };

int get_zip_digit(int index, int digit) {
  return cambridge_zips[index][digit];
}
```

```
...
# %ecx = digit
# %eax = index
leal 0(,%ecx,4),%edx                   # %edx = 4*digit
leal (%eax,%eax,4),%eax                # %eax = 5*index
movl cambridge_zips(%edx,%eax,4),%eax  # return contents of
                                       # cambridge_zips + 4*digit
                                       #    + 4*5*index
...
```

Strange referencing examples

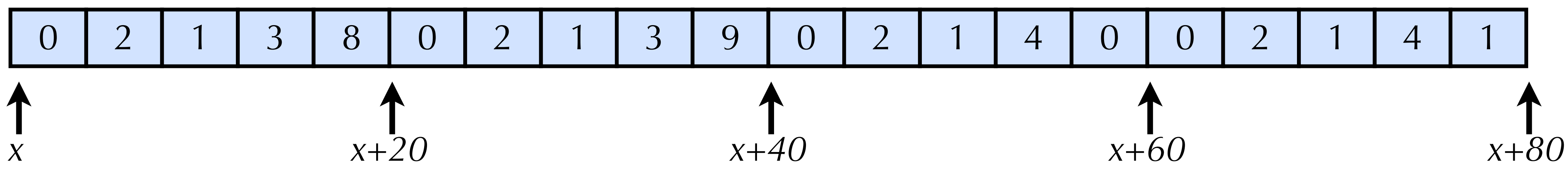
```
int zips[4][5];
```



Expression	Address	Value	Guaranteed to work?
`zips[3][3]`			
`zips[2][5]`			
`zips[2][-1]`			
`zips[4][-1]`			
`zips[0][19]`			
`zips[0][-1]`			

Strange referencing examples

`int zips[4][5];`



Expression	Address	Value	Guaranteed to work?
`zips[3][3]`	`x + 20*3 + 4*3 = x+72`	4	Yes
`zips[2][5]`	`x + 20*2 + 4*5 = x+60`	0	Yes
`zips[2][-1]`	`x + 20*2 + 4*-1 = x+36`	9	Yes
`zips[4][-1]`	`x + 20*4 + 4*-1 = x+76`	1	Yes
`zips[0][19]`	`x + 20*0 + 4*19 = x+76`	1	Yes
`zips[0][-1]`	`x + 0*2 + 4*-1 = x-4`	???	No

Topics for today

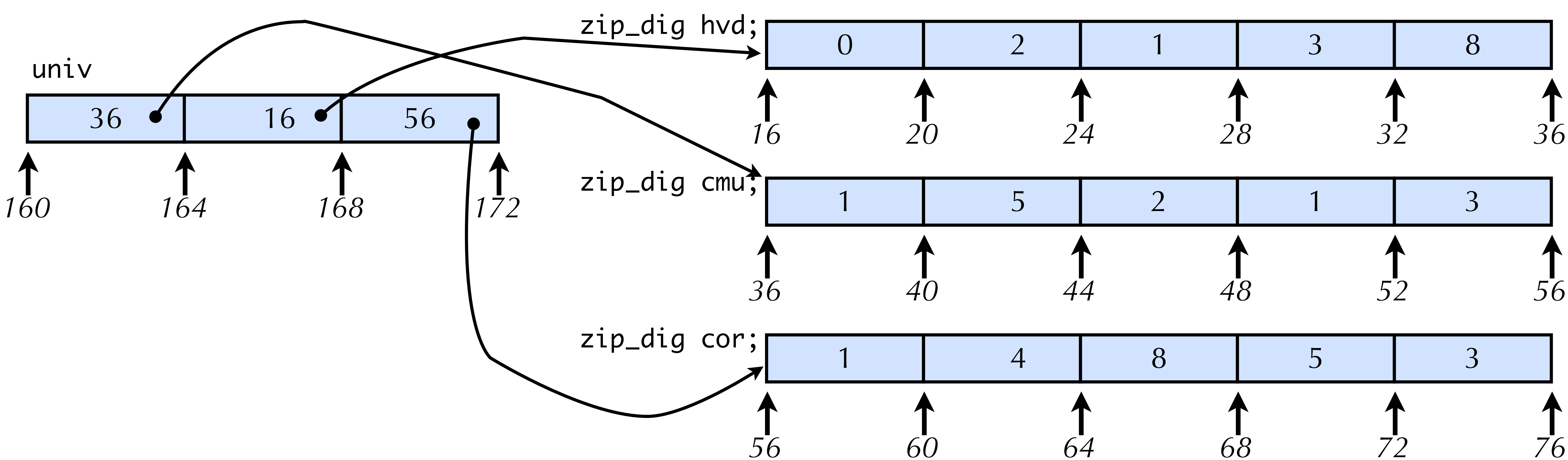
- Structured data
  - Arrays
  - Multidimensional arrays
  - Multi-level arrays
  - Structs
  - Memory alignment
  - Arrays of structs

Multi-level array

```
typedef int zip_dig[5];

zip_dig hvd = { 0, 2, 1, 3, 8 };
zip_dig cmu = { 1, 5, 2, 1, 3 };
zip_dig cor = { 1, 4, 8, 5, 3 };
```

```
int *univ[3] = {cmu, hvd, cor};
```

- `univ` is array of 3 elements
- Each element is a pointer (4 bytes)
- Each pointer points to an array of `int`s

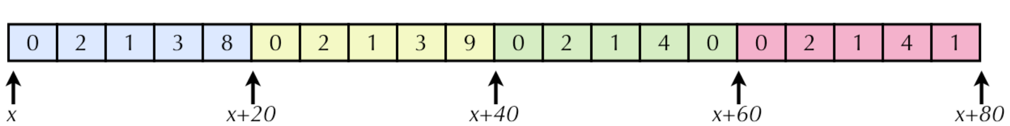


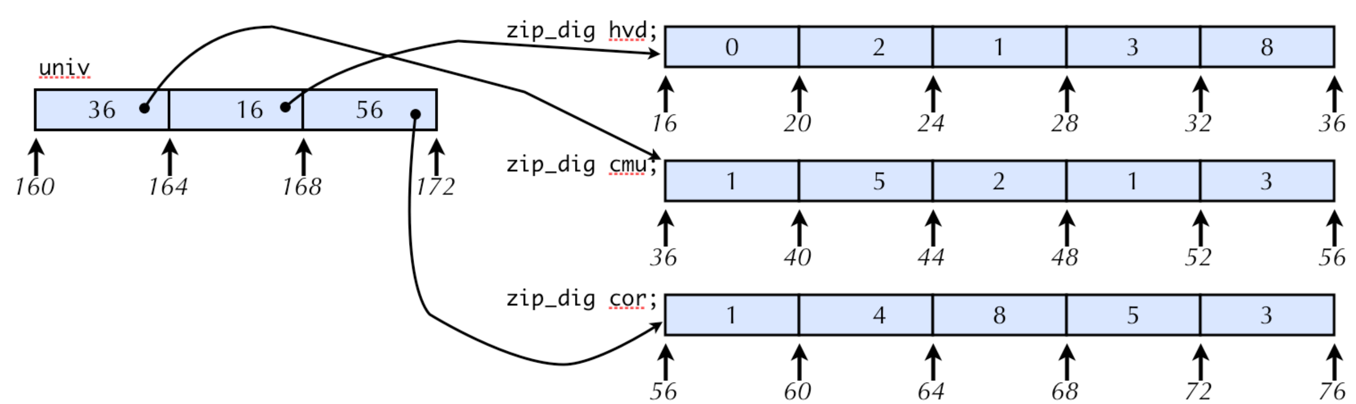
Multilevel array element access

```
int cambridge_zips[4][5] = { ... };

int get_digit(int index, int digit) {
  return cambridge_zips[index][digit];
}
```

```
int *univ[3] = {cmu, hvd, cor};

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

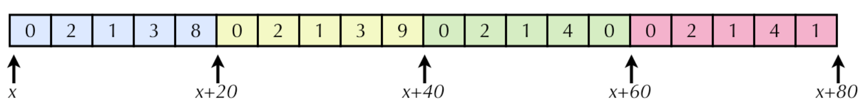
- Access looks similar, but evaluation is quite different!





Multilevel array element access

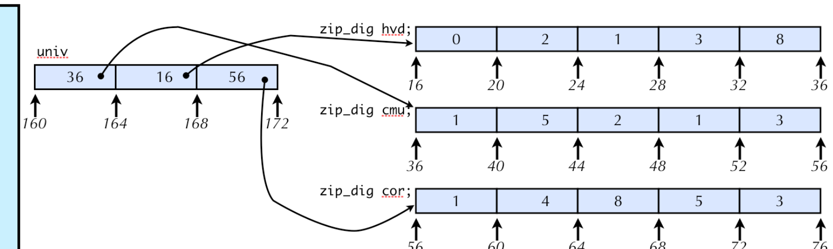
```
int cambridge_zips[4][5] = { ... };

int get_zip_digit(int index, int digit) {
  return cambridge_zips[index][
}
```




```
...
# %ecx = digit
# %eax = index
leal 0(,%ecx,4),%edx          # %edx = 4*digit
leal (%eax,%eax,4),%eax       # %eax = 5*index
movl cambridge_zips(%edx,%eax,4),%eax
  # return Mem[cambridge_zips + 20*index + 4*dig]
...
```

One memory read

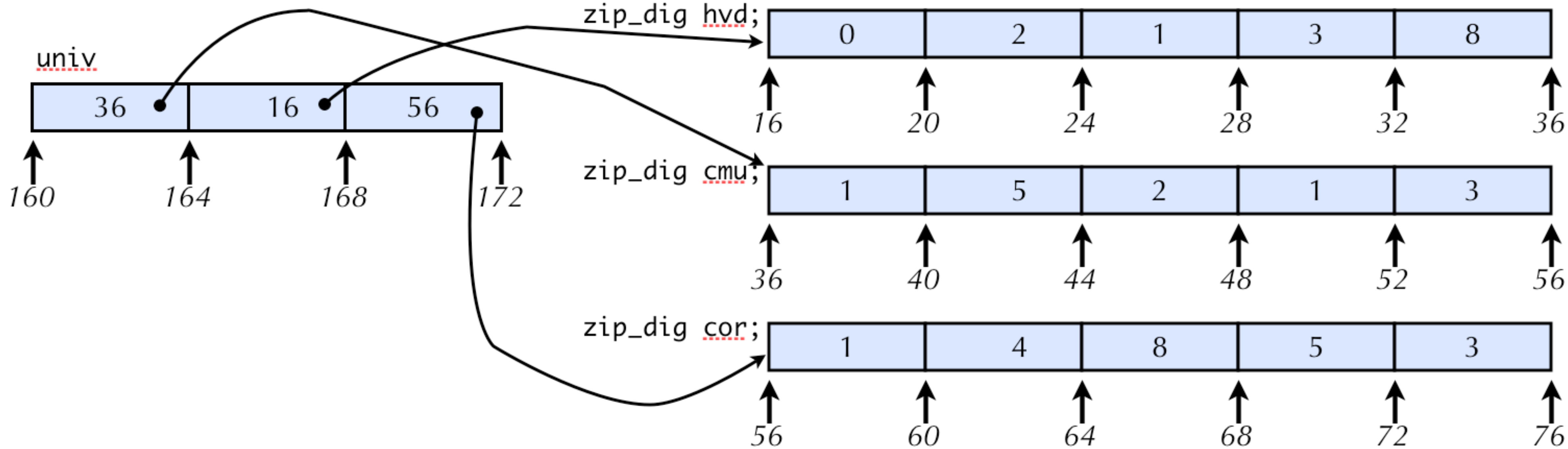
```
int *univ[3] = {cmu, hvd, cor};

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




```
...
# %ecx = index
# %eax = dig
leal 0(,%ecx,4),%edx    # %edx = 4*index
movl univ(%edx),%edx    # %edx = Mem[univ + 4*index]
movl (%edx,%eax,4),%eax # Mem[%edx + 4*dig]
...
```

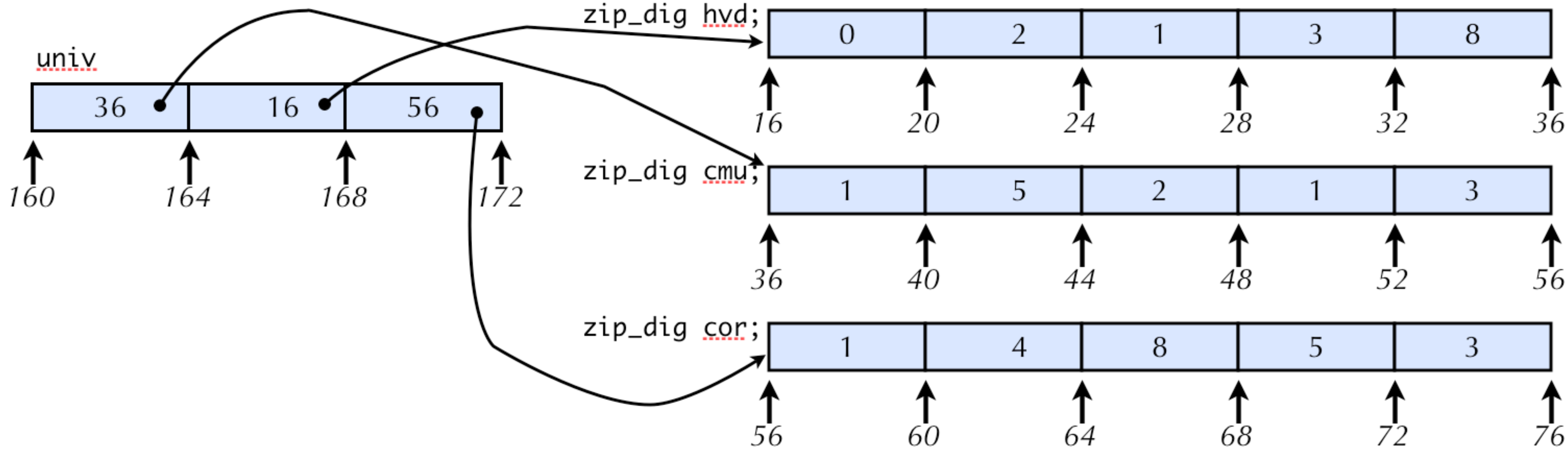
Two memory reads
- First get pointer to array
- Then access array

Strange referencing examples



Expression	Address	Value	Guaranteed to work?
`univ[2][3]`			
`univ[1][5]`			
`univ[2][-1]`			
`univ[3][-1]`			
`univ[1][12]`			

Strange referencing examples



Expression	Address	Value	Guaranteed to work?
`univ[2][3]`	`56 + 4*3 = 68`	5	Yes
`univ[1][5]`	`16 + 4*5 = 36`	1	No
`univ[2][-1]`	`56 + 4*-1 = 52`	3	No
`univ[3][-1]`	`???`	???	No
`univ[1][12]`	`16 + 4*12 = 64`	8	No

Topics for today

- Structured data
  - Arrays
  - Multidimensional arrays
  - Multi-level arrays
  - Structs
  - Memory alignment
  - Arrays of structs

Structs

- A struct groups objects into a single object
  - Each field accessed by name
  - Each field can have a different type

Declare a struct datatype

Use fields of a struct

Convenient way to initialize fields of struct

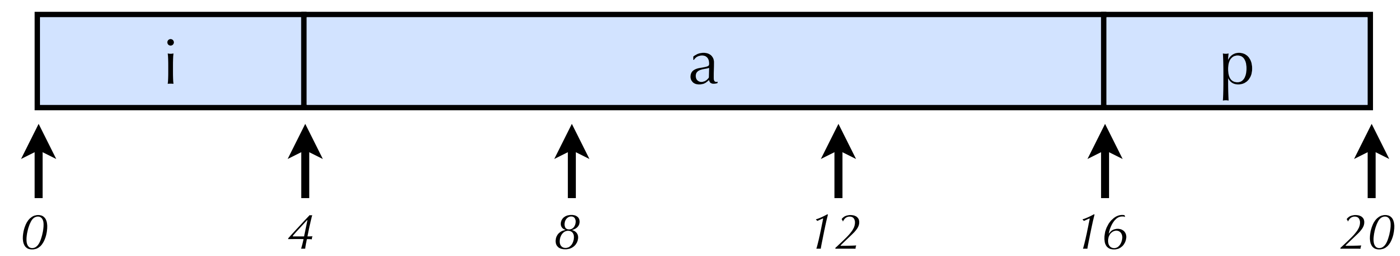
Equivalent

```c
struct rect {
    int llx;
    int lly;
    int width;
    int height;
    char *name;
};

struct rect r;
r.llx = r.lly = 0;
struct rect s =
   {0, 0, 10, 20, “Rodney”};

struct rect *rp = &s;
rp->height = rp->width;
(*rp).height = (*rp).width;
```

Implementing structs

- Struct represented as contiguous region of memory
  - E.g.,

```
struct rec {
  int i;
  int a[3];
  int *p;
};
```



- Compiler generates code using appropriate offsets

```
struct rec *myrec;
int someint;

void demo_struct() {
  myrec->i = 42;
  myrec->a[0] = 43;
  myrec->p = &someint;
}
```

```
demo_struct:
  pushl %ebp
  movl %esp, %ebp
  movl myrec, %eax
  movl $42, (%eax)
  movl $43, 4(%eax)
  movl $someint, 16(%eax)
  popl %ebp
  ret
```

Memory alignment

- Many systems require data to be aligned in memory
  - E.g., Linux/x86 requires integers to be stored at memory address that is multiple of 4 bytes
- Why?
  - 32-bit machines typically read and write 4 bytes of memory at a time from **word aligned** addresses
  - If not aligned, reading an int from memory may require two memory accesses!

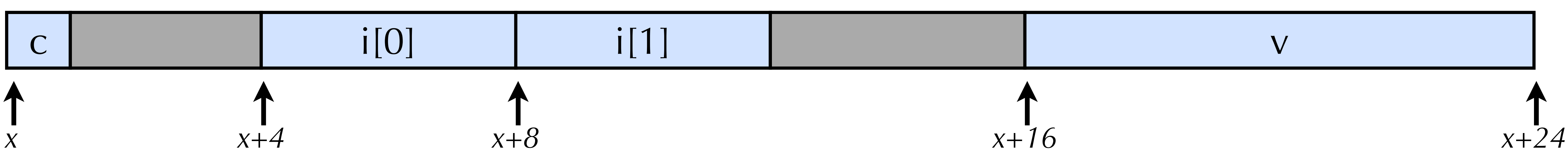
Memory alignment

- Some processors **require** aligned access
  - If you try to access an "int" not stored on an aligned address, would get an "alignment fault"
- Intel x86 does **not require** memory access to be aligned
  - However, Intel strongly recommends that compilers generate code that uses aligned access, to get the best performance.
- Different OS's and compilers have different rules
  - Linux: 2-byte types aligned to 2 byte boundaries, 4 byte and larger types aligned to 4 byte boundaries
  - Windows: primitive object of *K* bytes must have an address that is a multiple of *K*

Alignment within structs

- Each field in struct must be aligned correctly
  - Compiler may have to insert **padding** within struct
- E.g., using Windows alignment rules
  - Field `i` must be aligned on 4 byte address
  - Field `v` must be aligned on 8 byte address

```
struct S {
  char c;
  int i[2];
  double v;
};
```

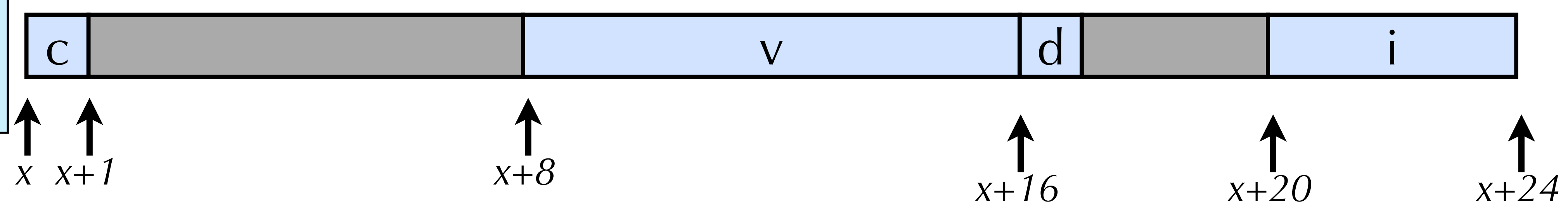


- `sizeof(struct S)` is 24, not 1+4+4+8 = 17

Save memory!

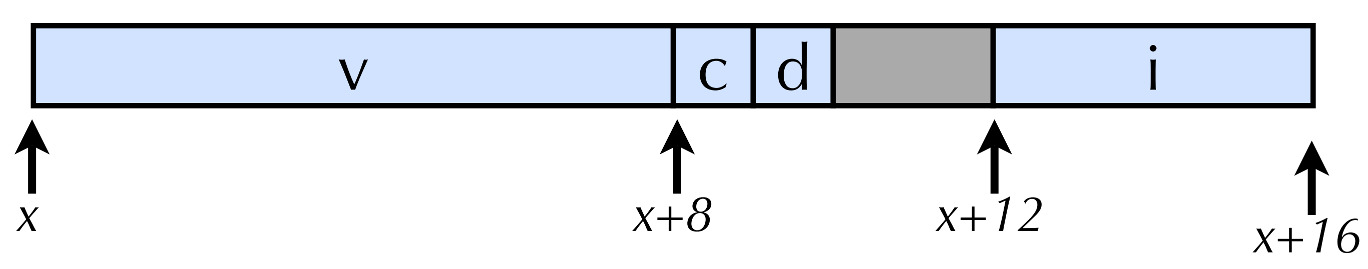
```
struct T1 {
  char c;
  double v;
  char d;
  int i;
};
```

10 bytes wasted space (Windows alignment)




```
struct T2 {
  double v;
  char c;
  char d;
  int i;
};
```

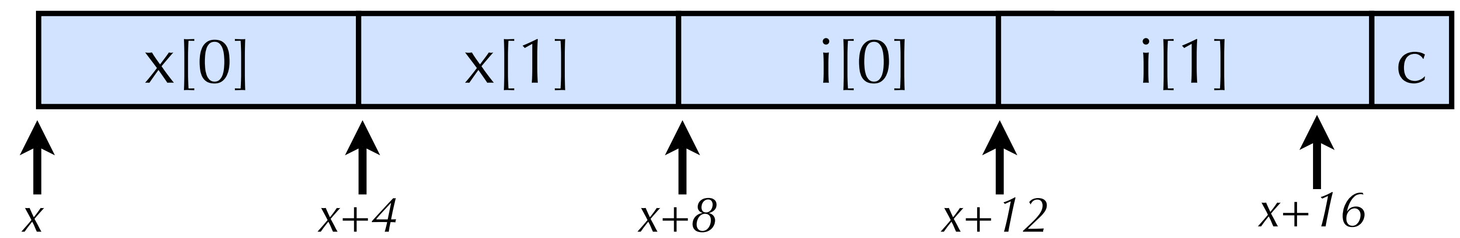
2 bytes wasted space (Windows alignment)



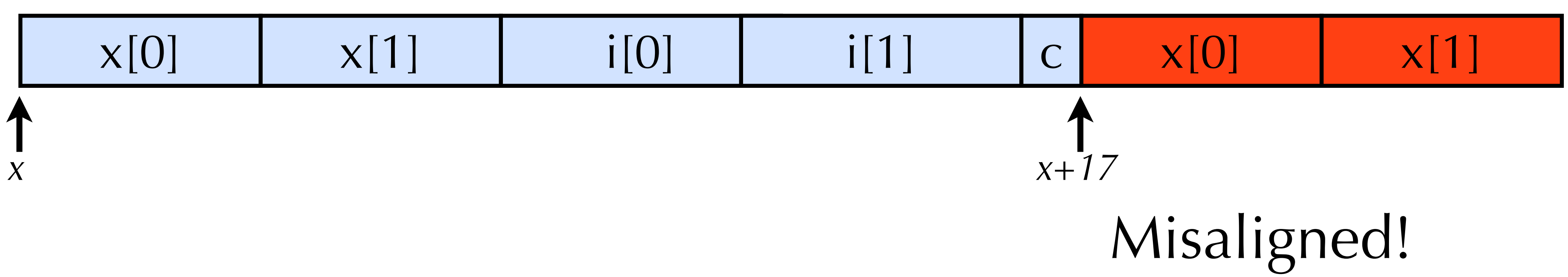
Alignment of whole structs

- E.g.,

```
struct U {
  float x[2];
  int i[2];
  char c;
};
```



- No padding needed within struct
- But what about `struct U foo[2]` ?

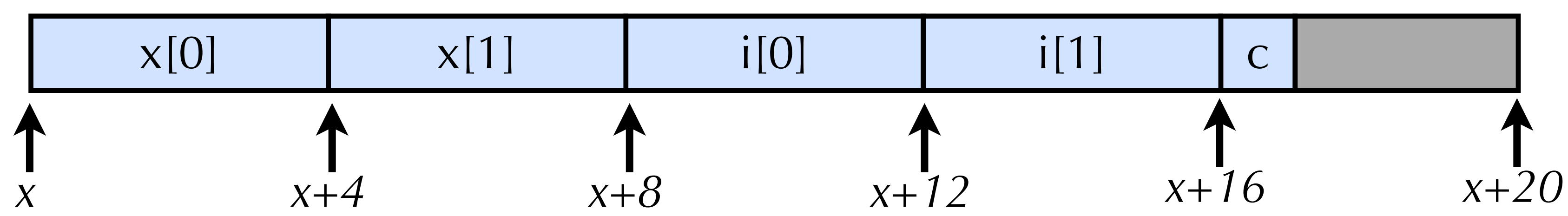


Padding at end of struct

- To ensure that arrays of structs are correctly aligned, may need to pad at end of struct
- E.g.,

```
struct U {
  float x[2];
  int i[2];
  char c;
};
```

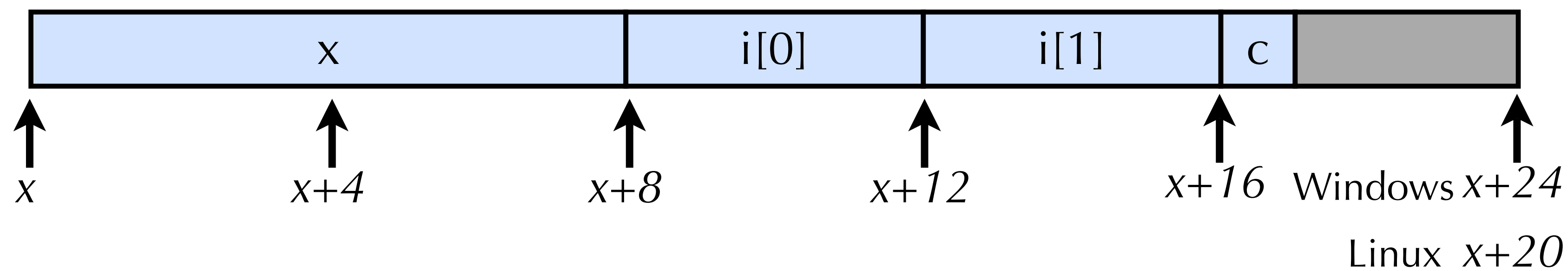
`sizeof(U)` must be multiple of 4 (Windows and Linux)



- E.g.,

```
struct V {
  double x;
  int i[2];
  char c;
};
```

`sizeof(V)` must be multiple of 8 for Windows, 4 for Linux



Next lecture

- Buffer overruns and stack exploits
  - B3 l33t H4x0r and pwnzorz the interwebz
  - (Use your powers wisely)