CS 240
Foundations of Computer Systems

WELLESLEY

Representing Data Structures

Multidimensional arrays

C structs

Outline

Goal: understand how we represented structured data in C and x86

- Arrays in x86
  - Array indexing
  - Arrays of pointers to arrays
  - 2-dimensional arrays (defer details to video)
- C structs (simpler version of objects)
  - Overview and accessing fields
  - Alignment
  - LinkedList example

C: Array layout and indexing

ex

`int val[5];`

Recall:

- Array layout will be contiguous block of memory
- The base address will be aligned based on the element type: here, a multiple of 4

For: `T a[N]`
Address of `a[i]` is:
`a + i * sizeof(T)`

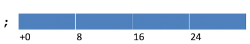
Write x86 code to load `val[i]` into `%eax`.

1. Assume:
   - Base address of val is in `%rdi`
   - i is in `%rsi`

2. Assume:
   - Base address of val is `28(%rsp)`
   - i is in `%rcx`

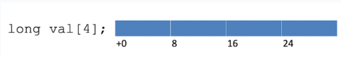
Which expression correctly loads val[i] into %rax? Assyme val is in %rdi and i is in %rsi.

`long val[4];`



- movq (%rsi,%rdi,4), %rax
- movq (%rdi,%rsi,4), %rax
- movq (%rdi,%rsi,8), %rax
- movq (%rsi,%rdi,8), %rax
- None of the above

Which expression correctly loads val[i] into %rax? Assyme val is in %rdi and i is in %rsi.



- movq (%rsi,%rdi,4), %rax — 0%
- movq (%rdi,%rsi,4), %rax — 0%
- movq (%rdi,%rsi,8), %rax — 0%
- movq (%rsi,%rdi,8), %rax — 0%
- None of the above — 0%

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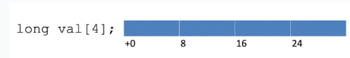

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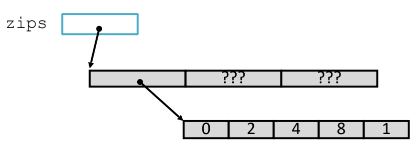
C: Arrays of pointers to arrays of …

reminder

C
```
int** zips = (int**)malloc(sizeof(int*)*3);
...
zips[0] = (int*)malloc(sizeof(int)*5);
...
int* zip0 = zips[0];
zip0[0] = 0;
zips[0][1] = 2;
zips[0][2] = 4;
zips[0][3] = 8;
zips[0][4] = 1;
```



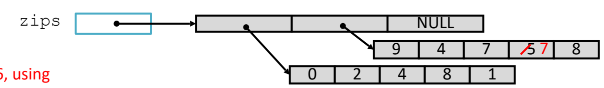
Java
```
int[][] zips = new int[3][];
zips[0] = new int[5] {0, 2, 4, 8, 1};
```


C: Arrays of pointers to arrays in x86

ex

%rdi %rsi %rdx
```
void copyfromleft(int** zips, long i, long j) {
  zipCodes[i][j] = zipCodes[i][j - 1];
}
```

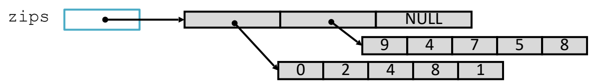
```
copyleft(zips, 1, 3)
```



Goal: translate to x86, using two scratch registers
`%rax`, `%ecx` (why 32 bits?)

1. Put `zips[i]` in a reg
2. Access element `[j-1]`
3. Set element `[j]`
4. Return (nothing)

C: Arrays of pointers to arrays: Pros/Cons



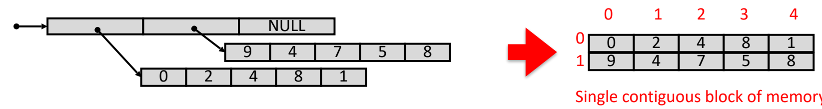
Pros:

- Flexible array lengths
  - Different elements can be different lengths
  - Lengths can change as the program runs
- Representation of empty elements saves space

Cons:

- Accessing a nested element requires multiple memory operations

Alternative: row-major nested arrays



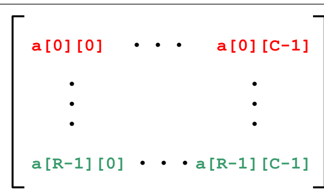
Pros:

- Accessing nested elements now a single memory operation!
- Calculations can be done ahead of time, via arithmetic

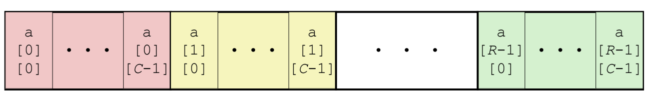
Cons:

- Less space efficient depending on the shape of the data
- Need to be careful with our order of indexing!

C: Row-major nested arrays




```
int a[R][C];
```



Suppose a's base address is *A*.

`&a[i][j]` is $\underline{A + C \times sizeof(int) \times i + sizeof(int) \times j}$
(regular unscaled arithmetic)

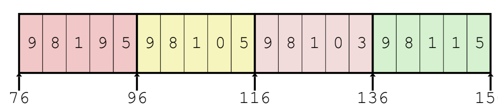
```
int* b = (int*)a;   // Treat as larger 1D array

&a[i][j] == &b[ C*i + j ]
```


C: Strange array indexing examples

ex

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



Reference	Address	Value
sea[3][3]		
sea[2][5]		
sea[2][-1]		
sea[4][-1]		
sea[0][19]		
sea[0][-1]		

C does not do any bounds checking.
Row-major array layout is guaranteed.

C structs

Like Java class/object, without methods.

Models structured, but not necessarily list-like, data.

Combines other, simpler types.

```
struct point {
  int xcoordinate;
  int ycoordinate;
};
```

```
struct student {
  int classyear;
  int id;
  char* name;
};
```


C structs

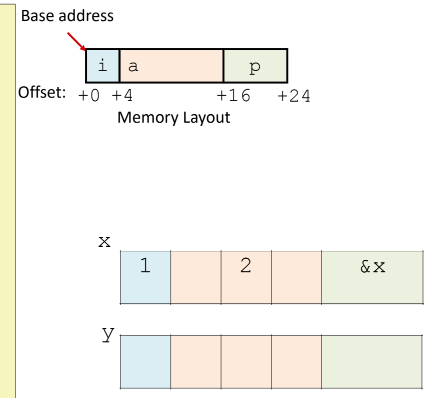
Like Java class/object without methods.

Compiler determines:

- Total size
- Offset of each field

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

struct rec x;
struct rec y;
x.i = 1;
x.a[1] = 2;
x.p = &(x.i);
```



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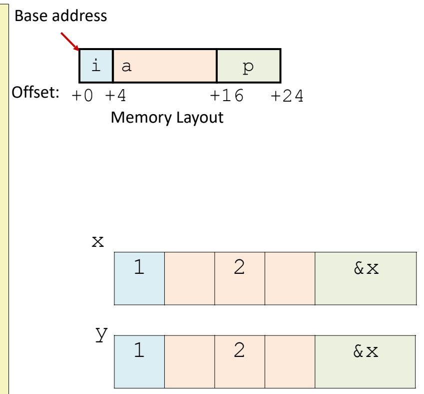
// copy full struct
y = x;
```



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struct rec* z;
z = &y;
```

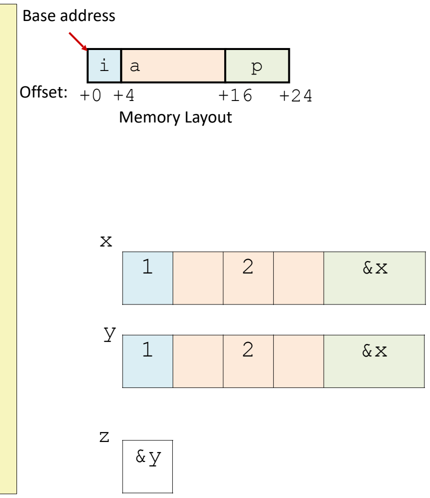

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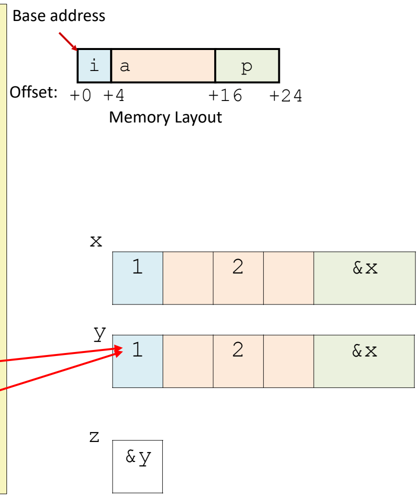
// copy full struct
y = x;

struct rec* z;
z = &y;
(*z).i++;
// same as:
// z->i++
```



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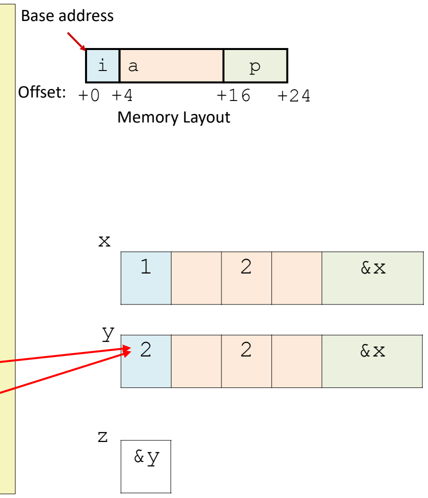

C: Accessing struct fields

ex

```
struct student {
  int classyear;
  int id;
  char* name;
};
```

Example: traversing a list of structs

```
// Given a null-terminated list of students,
// return the name of the student with a given ID, or null
// if there is no student with that ID.
char* getStudentNameWithId(struct student s[], int id) {







}
```


C: Accessing struct fields

ex

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};
```

Example: traversing a list of structs


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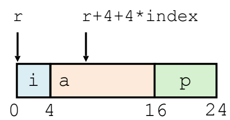
// Given a null-terminated list of students,
// return the name of the student with a given ID, or null
// if there is no student with that ID.
char* getStudentNameWithId(struct student s[], int id) {
    struct student *cursor = s;
    while (*cursor) {
        if (cursor->id == id)
            return cursor->name;
        cursor++;
    }
    return NULL;
}
```

C: Accessing struct field

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




```
int get_i_plus_elem(struct rec* r, int index) {
    return r->i + r->a[index];
}
```

```
movl  0(%rdi),%eax            # Mem[r+0]
addl  4(%rdi,%rsi,4),%eax.    # Mem[r+4*index+4]
retq
```

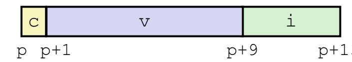

C: Struct field alignment

Alignment is especially important for structs

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

Defines new struct type and declares variable `p` of type `struct S1*`

Unaligned Data (not what C does)

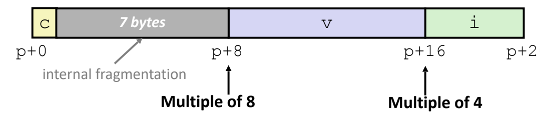


Aligned Data (what C does)

Primitive data type requires ***K*** bytes

Address must be multiple of ***K***

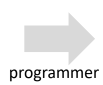
C: align every struct field accordingly.



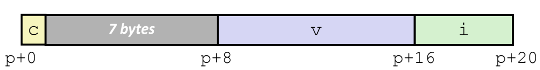
C: Struct packing

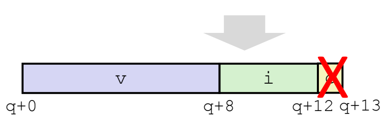
Put large data types first:

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




```
struct S2 {
  double v;
  int i;
  char c;
} * q;
```





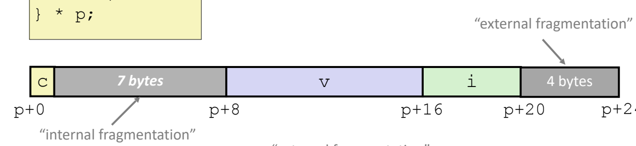
but actually…

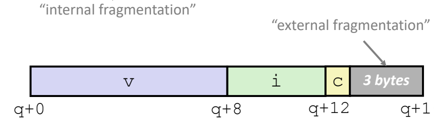
C: Struct alignment (full)

Base *and total size* must align largest internal primitive type.

Fields must align their type's largest alignment requirement.

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

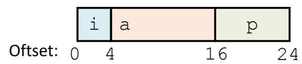





```
struct S2 {
  double v;
  int i;
  char c;
} * q;
```

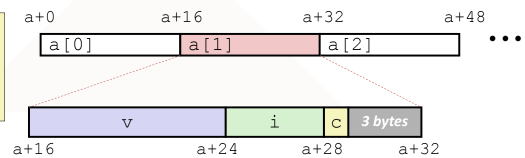
Array in struct

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



Struct in array

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



C: typedef

```
// give type T another name: U
typedef T U;
```

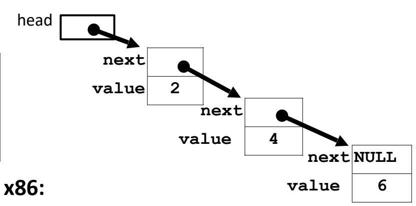
```
// struct types can be verbose
struct Node { ... };
...
struct Node* n = …;

// typedef can help
typedef struct Node {
   ...
} Node;
...
Node* n = ...;
```


Linked Lists

ex

```
typedef
struct Node {
  struct Node* next;
  int value;
} Node;
```



Implement append in x86:

```
void append(Node* head, int x) {
  // assume head != NULL
  Node* cursor = head;
  // find tail
  while (cursor->next != NULL) {
    cursor = cursor->next;
  }
  Node* n = (Node*)malloc(sizeof(Node));
  // error checking omitted
  // for x86 simplicity
  cursor->next = n;
  n->next = NULL;
  n->value = x;
}
```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ex

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typedef
struct Node {
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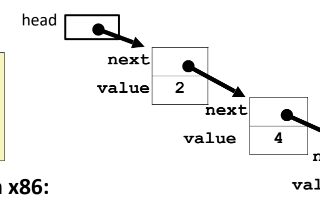

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  // error checking omitted
  // for x86 simplicity
  cursor->next = n;
  n->next = NULL;
  n->value = x;
}
```

Extra fun: try a recursive version too!

```
append:
  pushq %rbp
  movl  %esi, %ebp
  pushq %rbx
  movq  %rdi, %rbx
  subq  $8, %rsp
  jmp   .L3
.L6:
  movq  %rax, %rbx
.L3:
  movq  (%rbx), %rax
  testq %rax, %rax
  jne   .L6
  movl  $16, %edi
  call  malloc
  movq  %rax, (%rbx)
  movq  $0, (%rax)
  movl  %ebp, 8(%rax)
  addq  $8, %rsp
  popq  %rbx
  popq  %rbp
  ret
```

2-D array practice problem

ex

```
long array[2][3];
```

1. Draw a picture of how this array is laid out in memory, labeling the indices and byte offset of each element (starting with `array[0][0]` at offset `+0`);

Recall: `index = C*r + c`
scale by element size

```
long get_elem_1_2(long array[2][3]){
  return array[1][2];
}
```

2. Write x86 assembly code to implement this function.

Struct practice problem (similar to CSAPP 3.45)

ex

```
struct s {
  char *a;
  short b;
  int *c;
  char d;
  long e;
  char f;
};
```

1. Draw a picture of how this struct is laid out in memory, labeling the byte offset of each field (starting with `a` at offset `+0`);

2. Modify your picture to show how much space a single element of this struct would take if used as an element of an array (e.g., the total size).

Recall: a short is 2 bytes in C

3. Rearrange the fields of the struct to minimize wasted space. Draw the new offsets and the total size.