CS 240
Foundations of Computer Systems

WELLESLEY

Representing Data Structures

Multidimensional arrays
C structs

https://cs.wellesley.edu/~cs240/

Outline

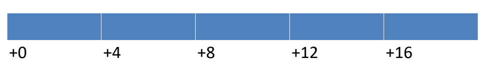
Goal: understand how we represented structured data in C and x86

- Arrays in x86
  - Array indexing
  - Arrays of pointers to arrays
  - 2-dimensional arrays
- 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

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

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

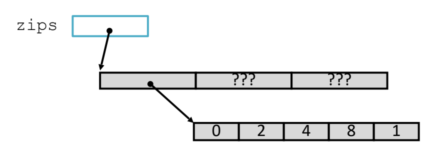
2. Assume:
   - Base address of val is `28(%rsp)`
   - i is in `%rcx`

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};
```

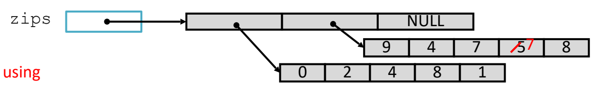
C: Arrays of pointers to arrays in x86

ex

%rdi %rsi %rdx

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

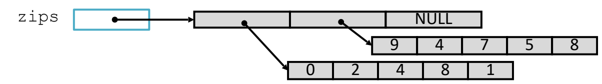
```
copyleft(zips, 1, 3)
```



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

C: Arrays of pointers to arrays: Pros/Cons



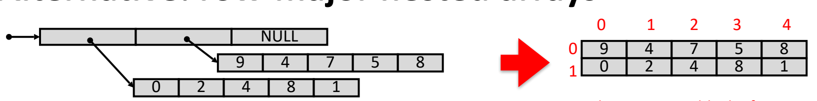
Pros:

- 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



Single contiguous block of memory

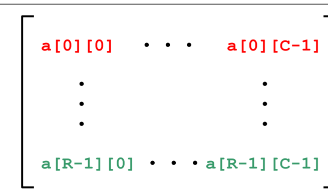
Pros:

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

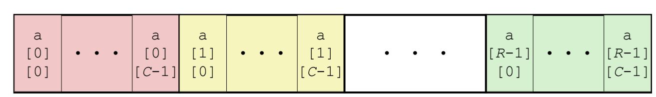
Cons:

- 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 *A + C×sizeof(int)×i + sizeof(int)×j*
(regular unscaled arithmetic)

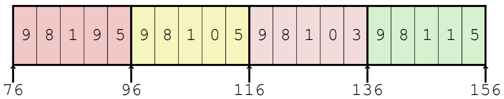
```
int* b = (int*)a;  // Treat as larger 1D array

&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-list, data.

Combines other, simpler types.

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

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


C structs

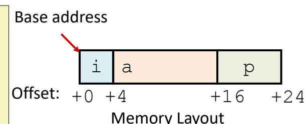
Like Java class/object without methods.

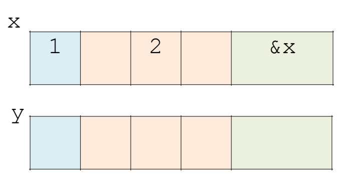
Compiler determines:

- 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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  int* p;
};

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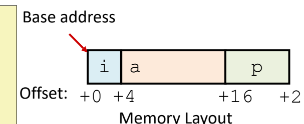
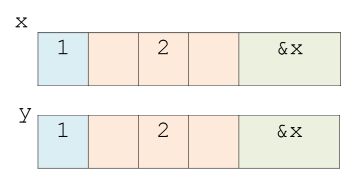
x.a[1] = 2;
x.p = &(x.i);

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





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x.a[1] = 2;
x.p = &(x.i);

// copy full struct
y = x;

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

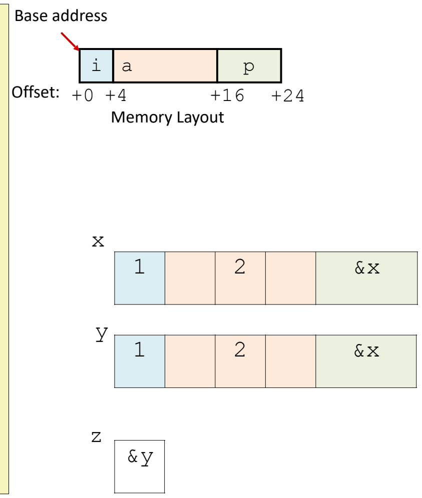

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- Total size
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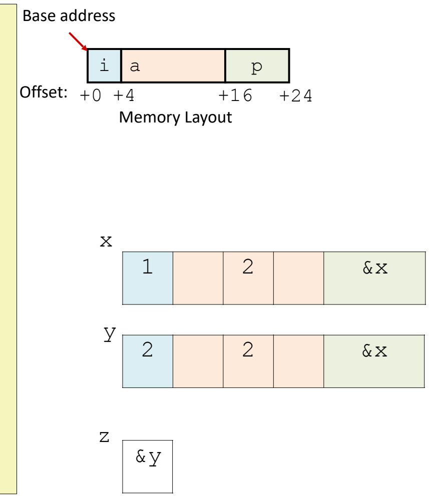
  int i;
  int a[3];
  int* p;
};

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

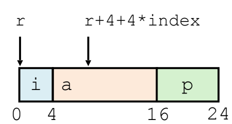
// copy full struct
y = x;

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



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: 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) {

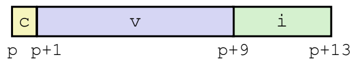



}
```

C: Struct field alignment

Alignment is especially important for structs

Unaligned Data (not what C does)




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

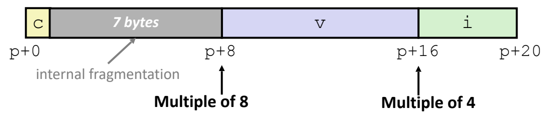
Defines new struct type and declares variable p of type struct S1*

Aligned Data (what C does)

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

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

C: align every struct field accordingly.



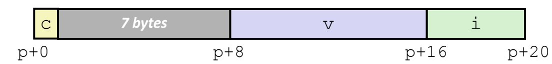
C: Struct packing

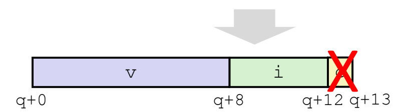
Put large data types first:

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

programmer

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





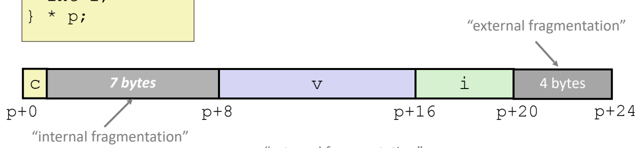
but actually...

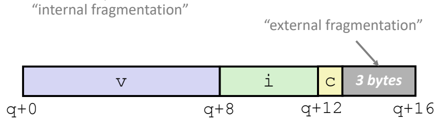
C: Struct alignment (full)

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;
```

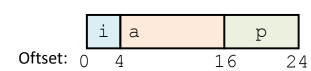





```
struct S2 {
  double v;
  int i;
  char c;
} * q;
```

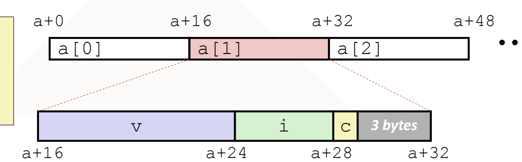

Array in struct

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



Struct in array

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



C: typedef

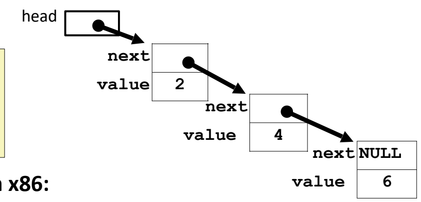
```
// give type T another name: U
typedef T U;
```

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

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


Linked Lists

ex



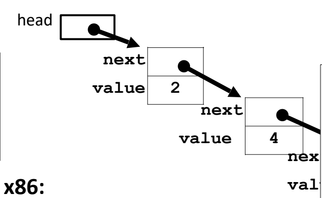

```
typedef
struct Node {
  struct Node* next;
  int value;
} Node;
```

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;
}
```


Linked Lists

ex




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

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  Node* n = (Node*)malloc(sizeof(Node));
  // 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
```