15-213

"The course that gives CMU its Zip!"

Structured Data:
Sept. 20, 2001

Topics

- **Arrays**
- **Structs**
- **Unions**

Basic Data Types

Integral

- **Stored & operated on in general registers**
- **Signed vs. unsigned depends on instructions used**

Intel	GAS	Bytes	C
byte	`b`	1	`[unsigned] char`
word	`w`	2	`[unsigned] short`
double word	`l`	4	`[unsigned] int`

Floating Point

- **Stored & operated on in floating point registers**

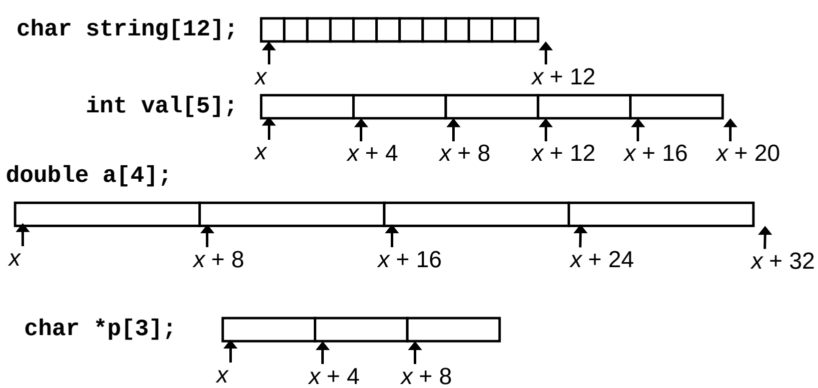
Intel	GAS	Bytes	C
Single	`s`	4	`float`
Double	`l`	8	`double`
Extended	`t`	10/12	`long double`

Array Allocation

Basic Principle

T **A[*L*];**

- **Array of data type *T* and length *L***
- **Contiguously allocated region of *L* * `sizeof(`*T*`)` bytes**

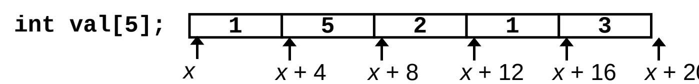


Array Access

Basic Principle

T **A[*L*];**

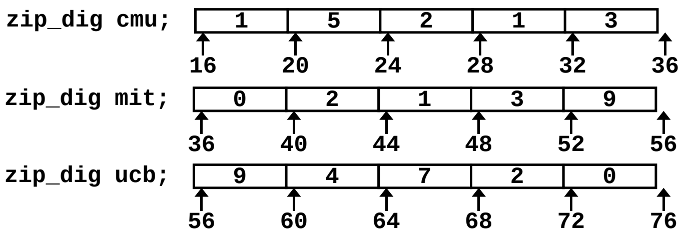
- **Array of data type *T* and length *L***
- **Identifier A can be used as a pointer to starting element of the array**



Reference	Type	Value
`val[4]`	`int`	3
`val`	`int *`	*x*
`val+1`	`int *`	*x* + 4
`&val[2]`	`int *`	*x* + 8
`val[5]`	`int`	??
`*(val+1)`	`int`	5
`val +` *i*	`int *`	*x* + 4 *i*

Array Example

```
typedef int zip_dig[5];

zip_dig cmu = { 1, 5, 2, 1, 3 };
zip_dig mit = { 0, 2, 1, 3, 9 };
zip_dig ucb = { 9, 4, 7, 2, 0 };
```



Notes

- **Declaration "`zip_dig cmu`" equivalent to "`int cmu[5]`"**
- **Example arrays were allocated in successive 20 byte blocks**
  - Not guaranteed to happen in general

Array Accessing Example

Computation

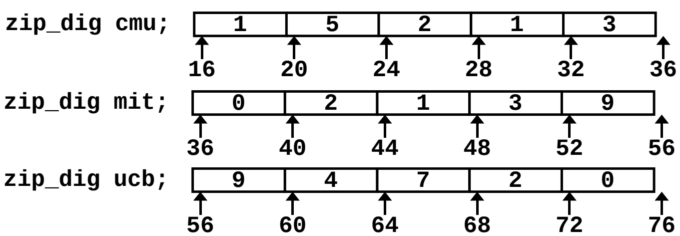
- **Register `%edx` contains starting address of array**
- **Register `%eax` contains array index**
- **Desired digit at `4*%eax + %edx`**
- **Use memory reference `(%edx,%eax,4)`**

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

Memory Reference Code

```
  # %edx = z
  # %eax = dig
   movl (%edx,%eax,4),%eax # z[dig]
```


Referencing Examples



Code Does Not Do Any Bounds Checking!

Reference	Address	Value	Guaranteed?
`mit[3]`	`36 + 4* 3 = 48`	3	Yes
`mit[5]`	`36 + 4* 5 = 56`	9	No
`mit[-1]`	`36 + 4*-1 = 32`	3	No
`cmu[15]`	`16 + 4*15 = 76`	??	No

- **Out of range behavior implementation-dependent**
  - No guaranteed relative allocation of different arrays

Array Loop Example

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;
}
```

Transformed Version

- **As generated by GCC**
- **Eliminate loop variable `i`**
- **Convert array code to pointer code**
- **Express in do-while form**
  - No need to test at entrance

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

Array Loop Implementation

Registers

```
%ecx  z
%eax  zi
%ebx  zend
```

Computations

- `10*zi + *z` implemented as `*z + 2*(zi+4*zi)`
- `z++` increments by 4

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

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


Nested Array Example

```
#define PCOUNT 4
zip_dig pgh[PCOUNT] =
  {{1, 5, 2, 0, 6},
   {1, 5, 2, 1, 3 },
   {1, 5, 2, 1, 7 },
   {1, 5, 2, 2, 1 }};
```

`zip_dig pgh[4];`

1	5	2	0	6	1	5	2	1	3	1	5	2	1	7	1	5	2	2	1

76 96 116 136 156

- **Declaration "`zip_dig pgh[4]`" equivalent to "`int pgh[4][5]`"**
  - Variable **pgh** denotes array of 4 elements
    - » Allocated contiguously
  - Each element is an array of 5 **`int`**'s
    - » Allocated contiguously
- **"Row-Major" ordering of all elements guaranteed**

Nested Array Allocation

Declaration

T **`A`**[*R*][*C*];

- **Array of data type** *T*
- *R* **rows**
- *C* **columns**
- **Type** *T* **element requires** *K* **bytes**

Array Size

- *R* * *C* * *K* **bytes**

Arrangement

- Row-Major Ordering

a[0][0]	• • •	a[0][C-1]
• • •		• • •
a[R-1][0]	• • •	a[R-1][C-1]

`int A[R][C];`

A [0] [0]	• • •	A [0] [C-1]	A [1] [0]	• • •	A [1] [C-1]	• • •	A [R-1] [0]	• • •	A [R-1] [C-1]

4*R*C Bytes

Nested Array Row Access

Row Vectors

- **`A[i]` is array of** *C* **elements**
- **Each element of type** *T*
- **Starting address `A` +** *i* * *C* * *K*

`int A[R][C];`

A[0]				A[i]				A[R-1]		
A [0] [0]	• • •	A [0] [C-1]	• • •	A [i] [0]	• • •	A [i] [C-1]	• • •	A [R-1] [0]	• • •	A [R-1] [C-1]

A A+i*C*4 A+(R-1)*C*4

Nested Array Row Access Code

```
int *get_pgh_zip(int index)
{
  return pgh[index];
}
```

Row Vector

- `pgh[index]` is array of 5 `int`'s
- Starting address `pgh+20*index`

Code

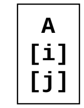
- Computes and returns address
- Compute as `pgh + 4*(index+4*index)`

```
  # %eax = index
  leal (%eax,%eax,4),%eax  # 5 * index
  leal pgh(,%eax,4),%eax   # pgh + (20 * index)
```

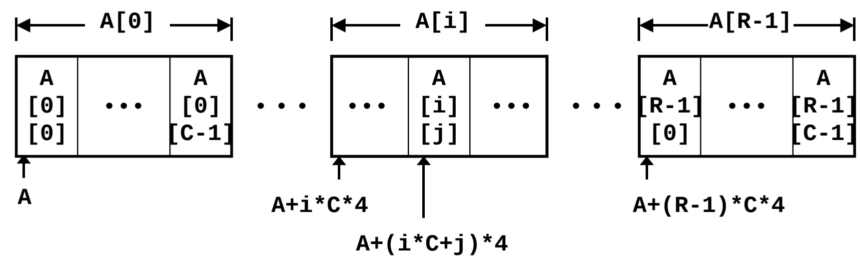

Nested Array Element Access

Array Elements

- `A[i][j]` is element of type *T*
- Address `A +` (*i* * *C* + *j*) * *K*



`int A[R][C];`



Nested Array Element Access Code

Array Elements

- `pgh[index][dig]` is `int`
- Address:
  `pgh + 20*index + 4*dig`

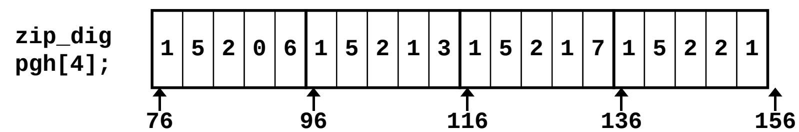
```
int get_pgh_digit
  (int index, int dig)
{
  return pgh[index][dig];
}
```

Code

- Computes address
  `pgh + 4*dig + 4*(index+4*index)`
- `movl` performs memory reference

```
 # %ecx = dig
 # %eax = index
 leal 0(,%ecx,4),%edx        # 4*dig
 leal (%eax,%eax,4),%eax     # 5*index
 movl pgh(%edx,%eax,4),%eax  # *(pgh + 4*dig + 20*index)
```


Strange Referencing Examples



Reference	Address	Value	Guaranteed?
pgh[3][3]	76+20*3+4*3 = 148	2	Yes
pgh[2][5]	76+20*2+4*5 = 136	1	Yes
pgh[2][-1]	76+20*2+4*-1 = 112	3	Yes
pgh[4][-1]	76+20*4+4*-1 = 152	1	Yes
pgh[0][19]	76+20*0+4*19 = 152	1	Yes
pgh[0][-1]	76+20*0+4*-1 = 72	??	No

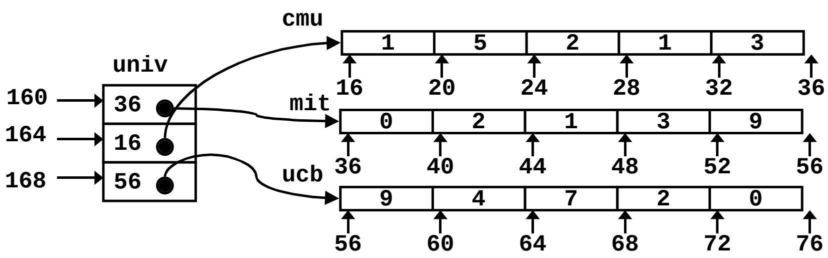
- Code does not do any bounds checking
- Ordering of elements within array guaranteed

Multi-Level Array Example

- **Variable `univ` denotes array of 3 elements**
- **Each element is a pointer**
  - 4 bytes
- **Each pointer points to array of `int`'s**

```
zip_dig cmu = { 1, 5, 2, 1, 3 };
zip_dig mit = { 0, 2, 1, 3, 9 };
zip_dig ucb = { 9, 4, 7, 2, 0 };
```

```
#define UCOUNT 3
int *univ[UCOUNT] = {mit, cmu, ucb};
```



Accessing Element in Multi-Level Array

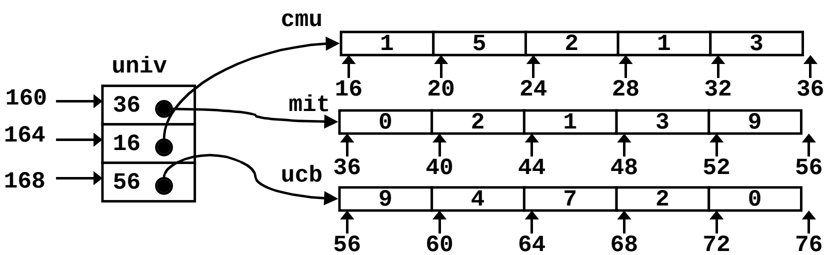
Computation

- **Element access `Mem[Mem[univ+4*index]+4*dig]`**
- **Must do two memory reads**
  - First get pointer to row array
  - Then access element within array

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

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


Strange Referencing Examples



Reference	Address	Value	Guaranteed?
`univ[2][3]`	`56+4*3 = 68`	2	Yes
`univ[1][5]`	`16+4*5 = 36`	0	No
`univ[2][-1]`	`56+4*-1 = 52`	9	No
`univ[3][-1]`	??	??	No
`univ[1][12]`	`16+4*12 = 64`	7	No

- **Code does not do any bounds checking**
- **Ordering of elements in different arrays not guaranteed**

Using Nested Arrays

Strengths

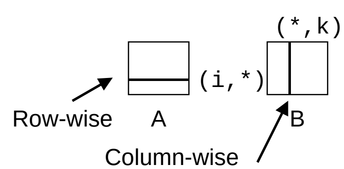
- **C compiler handles doubly subscripted arrays**
- **Generates very efficient code**
  - Avoids multiply in index computation

Limitation

- **Only works if have fixed array size**

```
#define N 16
typedef int fix_matrix[N][N];
```

```
/* Compute element i,k of
   fixed matrix product */
int fix_prod_ele
(fix_matrix a, fix_matrix b,
 int i, int k)
{
  int j;
  int result = 0;
  for (j = 0; j < N; j++)
    result += a[i][j]*b[j][k];
  return result;
}
```



Dynamic Nested Arrays

Strength

- Can create matrix of arbitrary size

Programming

- Must do index computation explicitly

Performance

- Accessing single element costly
- Must do multiplication

```
int * new_var_matrix(int n)
{
  return (int *)
    calloc(sizeof(int), n*n);
}
```

```
int var_ele
  (int *a, int i,
   int j, int n)
{
  return a[i*n+j];
}
```

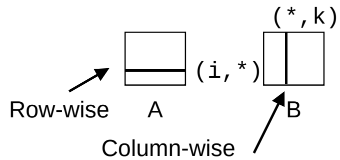
```
movl 12(%ebp),%eax       # i
movl 8(%ebp),%edx        # a
imull 20(%ebp),%eax      # n*i
addl 16(%ebp),%eax       # n*i+j
movl (%edx,%eax,4),%eax  # Mem[a+4*(i*n+j)]
```


Dynamic Array Multiplication

Without Optimizations

- Multiplies
  - 2 for subscripts
  - 1 for data
- Adds
  - 4 for array indexing
  - 1 for loop index
  - 1 for data

```
/* Compute element i,k of
   variable matrix product */
int var_prod_ele
  (int *a, int *b,
   int i, int k, int n)
{
  int j;
  int result = 0;
  for (j = 0; j < n; j++)
    result +=
      a[i*n+j] * b[j*n+k];
  return result;
}
```



Optimizing Dynamic Array Multiplication

Optimizations

- Performed when set optimization level to `-O2`

Code Motion

- Expression `i*n` can be computed outside loop

Strength Reduction

- Incrementing `j` has effect of incrementing `j*n+k` by `n`

Performance

- Compiler can optimize regular access patterns

```
{
  int j;
  int result = 0;
  for (j = 0; j < n; j++)
    result +=
      a[i*n+j] * b[j*n+k];
  return result;
}
```

```
{
  int j;
  int result = 0;
  int iTn = i*n;
  int jTnPk = k;
  for (j = 0; j < n; j++) {
    result +=
      a[iTn+j] * b[jTnPk];
    jTnPk += n;
  }
  return result;
}
```

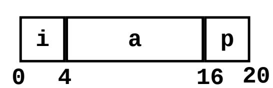

Structures

Concept

- Contiguously-allocated region of memory
- Refer to members within structure by names
- Members may be of different types

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

Memory Layout



Accessing Structure Member

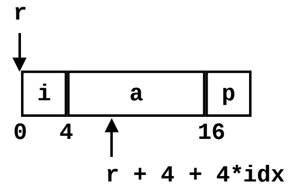
```
void
set_i(struct rec *r,
      int val)
{
  r->i = val;
}
```

Assembly

```
# %eax = val
# %edx = r
movl %eax,(%edx)    # Mem[r] = val
```

Generating Pointer to Structure Member

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



Generating Pointer to Array Element

- **Offset of each structure member determined at compile time**

```
int *
find_a
 (struct rec *r, int idx)
{
  return &r->a[idx];
}
```

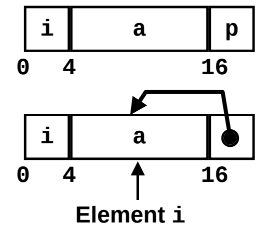
```
# %ecx = idx
# %edx = r
leal 0(,%ecx,4),%eax   # 4*idx
leal 4(%eax,%edx),%eax # r+4*idx+4
```


Structure Referencing (Cont.)

C Code

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

```
void
set_p(struct rec *r)
{
  r->p =
   &r->a[r->i];
}
```




```
# %edx = r
movl (%edx),%ecx       # r->i
leal 0(,%ecx,4),%eax   # 4*(r->i)
leal 4(%edx,%eax),%eax # r+4+4*(r->i)
movl %eax,16(%edx)     # Update r->p
```


Alignment

Aligned Data

- **Primitive data type requires K bytes**
- **Address must be multiple of K**
- **Required on some machines; advised on IA32**
  - treated differently by Linux and Windows!

Motivation for Aligning Data

- **Memory accessed by (aligned) double or quad-words**
  - Inefficient to load or store datum that spans quad word boundaries
  - Virtual memory very tricky when datum spans 2 pages

Compiler

- **Inserts gaps in structure to ensure correct alignment of fields**

Specific Cases of Alignment

Size of Primitive Data Type:

- **1 byte (e.g., `char`)**
  - no restrictions on address
- **2 bytes (e.g., `short`)**
  - lowest 1 bit of address must be 0_2
- **4 bytes (e.g., `int`, `float`, `char *`, etc.)**
  - lowest 2 bits of address must be 00_2
- **8 bytes (e.g., `double`)**
  - Windows (and most other OS's & instruction sets):
    - » lowest 3 bits of address must be 000_2
  - Linux:
    - » lowest 2 bits of address must be 00_2
    - » i.e., treated the same as a 4-byte primitive data type
- **12 bytes (`long double`)**
  - Linux:
    - » lowest 2 bits of address must be 00_2
    - » i.e., treated the same as a 4-byte primitive data type

Satisfying Alignment with Structures

Offsets Within Structure

- Must satisfy element's alignment requirement

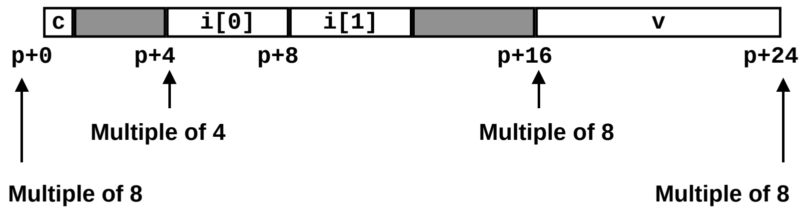
Overall Structure Placement

- Each structure has alignment requirement K
  - Largest alignment of any element
- Initial address & structure length must be multiples of K

Example (under Windows):

- K = 8, due to `double` element

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

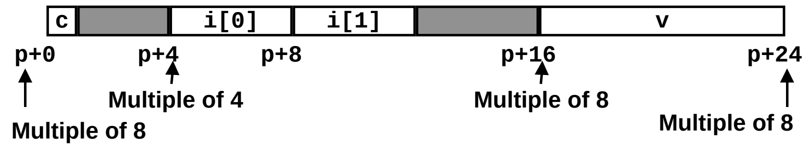


Linux vs. Windows

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

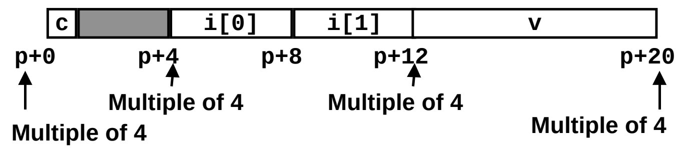
Windows (including Cygwin):

- K = 8, due to `double` element



Linux:

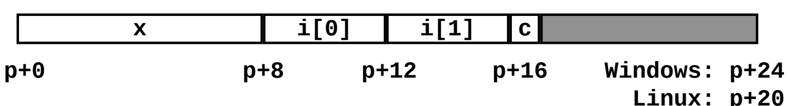
- K = 4; `double` treated like a 4-byte data type



Effect of Overall Alignment Requirement

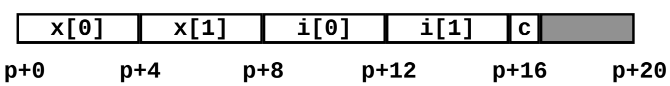
```
struct S2 {
  double x;
  int i[2];
  char c;
} *p;
```

p must be multiple of:
8 for Windows
4 for Linux




```
struct S3 {
  float x[2];
  int i[2];
  char c;
} *p;
```

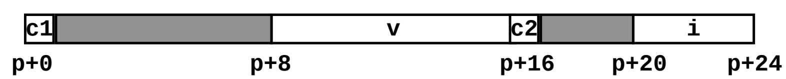
p must be multiple of 4 (in either OS)



Ordering Elements Within Structure

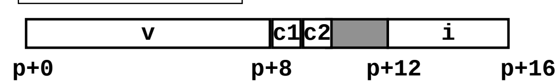
```
struct S4 {
  char c1;
  double v;
  char c2;
  int i;
} *p;
```

10 bytes wasted space in Windows




```
struct S5 {
  double v;
  char c1;
  char c2;
  int i;
} *p;
```

2 bytes wasted space

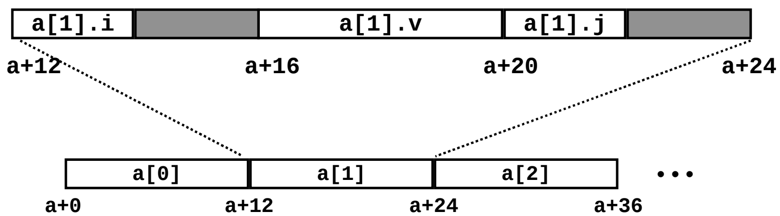


Arrays of Structures

Principle

- **Allocated by repeating allocation for array type**
- **In general, may nest arrays & structures to arbitrary depth**

```
struct S6 {
  short i;
  float v;
  short j;
} a[10];
```



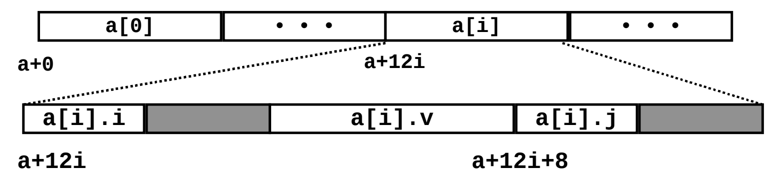
Accessing Element within Array

- **Compute offset to start of structure**
  - Compute 12**i* as 4*(*i*+2*i*)
- **Access element according to its offset within structure**
  - Offset by 8
  - Assembler gives displacement as a + 8
    - » Linker must set actual value

```
struct S6 {
  short i;
  float v;
  short j;
} a[10];
```

```
short get_j(int idx)
{
  return a[idx].j;
}
```

```
# %eax = idx
leal (%eax,%eax,2),%eax # 3*idx
movswl a+8(,%eax,4),%eax
```

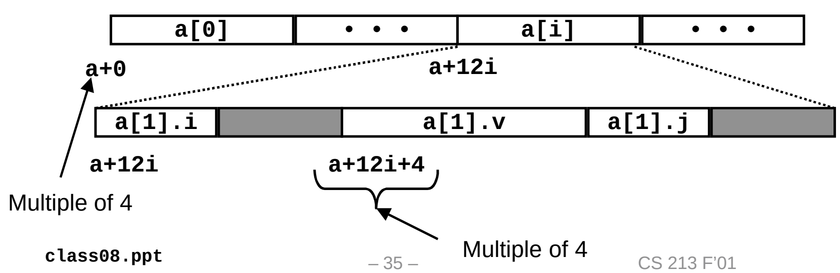


Satisfying Alignment within Structure

Achieving Alignment

- **Starting address of structure array must be multiple of worst-case alignment for any element**
  - **a** must be multiple of 4
- **Offset of element within structure must be multiple of element's alignment requirement**
  - **v**'s offset of 4 is a multiple of 4
- **Overall size of structure must be multiple of worst-case alignment for any element**
  - Structure padded with unused space to be 12 bytes

```
struct S6 {
  short i;
  float v;
  short j;
} a[10];
```

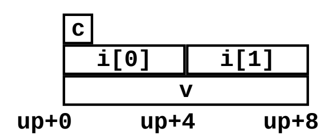


Union Allocation

Principles

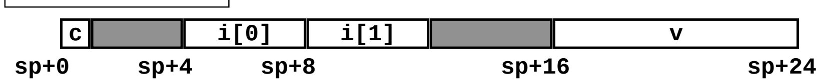
- **Overlay union elements**
- **Allocate according to largest element**
- **Can only use one field at a time**

```
union U1 {
  char c;
  int i[2];
  double v;
} *up;
```




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

(Windows alignment)



Using Union to Access Bit Patterns

```
typedef union {
  float f;
  unsigned u;
} bit_float_t;
```

u	
f	
0	4

```
float bit2float(unsigned u)
{
  bit_float_t arg;
  arg.u = u;
  return arg.f;
}
```

```
unsigned float2bit(float f)
{
  bit_float_t arg;
  arg.f = f;
  return arg.u;
}
```

- **Get direct access to bit representation of float**
- **`bit2float` generates float with given bit pattern**
  - NOT the same as **`(float) u`**
- **`float2bit` generates bit pattern from float**
  - NOT the same as **`(unsigned) f`**

Byte Ordering

Idea

- **Long/quad words stored in memory as 4/8 consecutive bytes**
- **Which is most (least) significant?**
- **Can cause problems when exchanging binary data between machines**

Big Endian

- **Most significant byte has lowest address**
- **IBM 360/370, Motorola 68K, Sparc**

Little Endian

- **Least significant byte has lowest address**
- **Intel x86, Digital VAX**

Byte Ordering Example

```
union {
  unsigned char c[8];
  unsigned short s[4];
  unsigned int i[2];
  unsigned long l[1];
} dw;
```

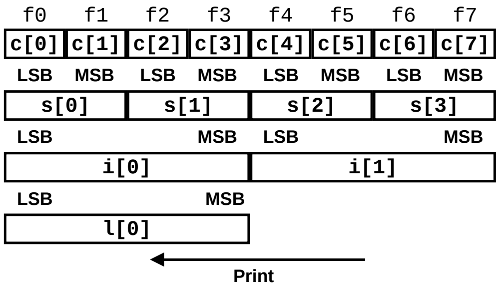
c[0]	c[1]	c[2]	c[3]	c[4]	c[5]	c[6]	c[7]
s[0]		s[1]		s[2]		s[3]	
i[0]				i[1]			
l[0]							

Byte Ordering Example (Cont).

```
int j;
for (j = 0; j < 8; j++)
dw.c[j] = 0xf0 + j;

printf("Characters 0-7 ==
[0x%x,0x%x,0x%x,0x%x,0x%x,0x%x,0x%x,0x%x]\n",
    dw.c[0], dw.c[1], dw.c[2], dw.c[3],
    dw.c[4], dw.c[5], dw.c[6], dw.c[7]);

printf("Shorts 0-3 ==
[0x%x,0x%x,0x%x,0x%x]\n",
    dw.s[0], dw.s[1], dw.s[2], dw.s[3]);

printf("Ints 0-1 == [0x%x,0x%x]\n",
    dw.i[0], dw.i[1]);

printf("Long 0 == [0x%lx]\n",
    dw.l[0]);
```

Byte Ordering on x86

Little Endian

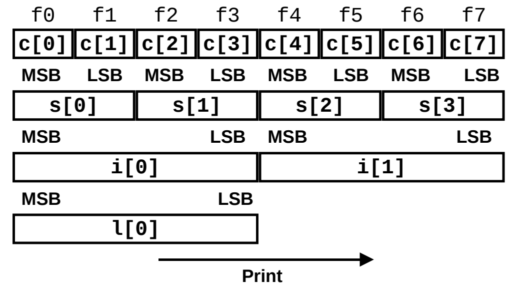


Output on Pentium:

```
Characters 0-7 == [0xf0,0xf1,0xf2,0xf3,0xf4,0xf5,0xf6,0xf7]
Shorts     0-3 == [0xf1f0,0xf3f2,0xf5f4,0xf7f6]
Ints       0-1 == [0xf3f2f1f0,0xf7f6f5f4]
Long       0   == [f3f2f1f0]
```


Byte Ordering on Sun

Big Endian

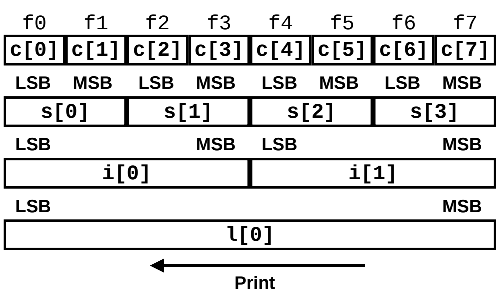


Output on Sun:

```
Characters 0-7 == [0xf0,0xf1,0xf2,0xf3,0xf4,0xf5,0xf6,0xf7]
Shorts     0-3 == [0xf0f1,0xf2f3,0xf4f5,0xf6f7]
Ints       0-1 == [0xf0f1f2f3,0xf4f5f6f7]
Long       0   == [0xf0f1f2f3]
```


Byte Ordering on Alpha

Little Endian



Output on Alpha:

```
Characters 0-7 == [0xf0,0xf1,0xf2,0xf3,0xf4,0xf5,0xf6,0xf7]
Shorts     0-3 == [0xf1f0,0xf3f2,0xf5f4,0xf7f6]
Ints       0-1 == [0xf3f2f1f0,0xf7f6f5f4]
Long       0   == [0xf7f6f5f4f3f2f1f0]
```


Summary

Arrays in C

- Contiguous allocation of memory
- Pointer to first element
- No bounds checking

Compiler Optimizations

- Compiler often turns array code into pointer code
  `zd2int`
- Uses addressing modes to scale array indices
- Lots of tricks to improve array indexing in loops

Structures

- Allocate bytes in order declared
- Pad in middle and at end to satisfy alignment

Unions

- Overlay declarations
- Way to circumvent type system