15-213

"The course that gives CMU its Zip!"

Machine-Level Programming IV: Structured Data
Feb 5, 2004

- Topics
  - Arrays
  - Structs
  - Unions

class08.ppt

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

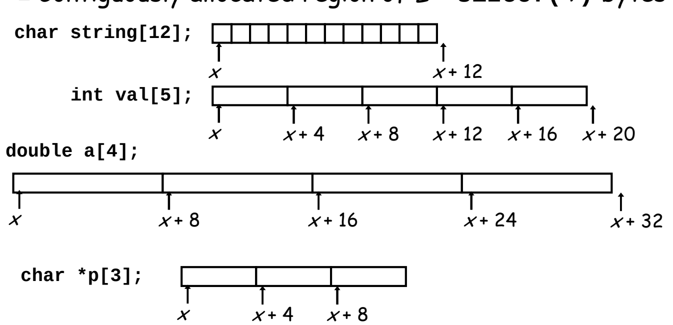
Intel	*GAS*	*Bytes*	*C*
Single	**s**	4	**float**
Double	**l**	8	**double**
Extended	**t**	10/12	**long double**

Array Allocation

Basic Principle

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

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

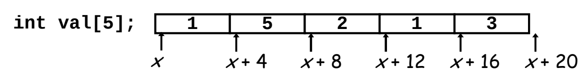


Array Access

Basic Principle

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

- Array of data type *T* and length *L*
- Identifier **A** can be used as a pointer to array element 0



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 };
```

```
zip_dig cmu;  | 1 | 5 | 2 | 1 | 3 |
             16  20  24  28  32  36
zip_dig mit;  | 0 | 2 | 1 | 3 | 9 |
             36  40  44  48  52  56
zip_dig ucb;  | 9 | 4 | 7 | 2 | 0 |
             56  60  64  68  72  76
```

Notes

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

Array Accessing Example

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

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)`**

Memory Reference Code

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


Referencing Examples

```
zip_dig cmu;  | 1 | 5 | 2 | 1 | 3 |
             16  20  24  28  32  36
zip_dig mit;  | 0 | 2 | 1 | 3 | 9 |
             36  40  44  48  52  56
zip_dig ucb;  | 9 | 4 | 7 | 2 | 0 |
             56  60  64  68  72  76
```

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

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

Original Source

- How do we implement this?
- Can we improve it?

First step, convert to do-while

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

Next?

Array Loop Example – convert to ptr

`z[i] → *(z+i)`

Can we further improve this?
(hint: what does `i` do?)

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

i	0	1	2	3	4	5
(z+i)	z	z+1	z+2	z+3	z+4	z+5

Do we need `z+i`?

Array Loop Example – optimize

```
zend = z+5;
if (z < zend) {
```

```
while (z < zend);
```

```
int zd2int(zip_dig z)
{
  int i;
  int zi = 0;
  i = 0;
  if (i < 5) {
    do {
      zi = 10 * zi + *(z++);
      i++;
    } while (i < 5);
  }
  return zi;
}
```

i	0	1	2	3	4	5
(z+i)	z	z+1	z+2	z+3	z+4	z+5
z++	z	z+1	z+2	z+3	z+4	z+5

Do we need `i`?

Array Loop Example – optimize

Can I do anything else?

```
int zd2int(zip_dig z)
{
  int* zend;
  int zi = 0;
  zend = z+5;
  if (z < zend) {
    do {
      zi = 10 * zi + *(z++);

    } while (z < zend);
  }
  return zi;
}
```


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

```
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

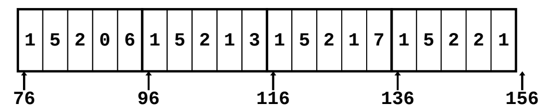
```
int zd2int(zip_dig z)
{
  int zi = 0;
  int *zend = z + 4;
  do {
    zi = 10 * zi + *z;
    z++;
  } while(z <= zend);
  return zi;
}
```

```
  # %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];`



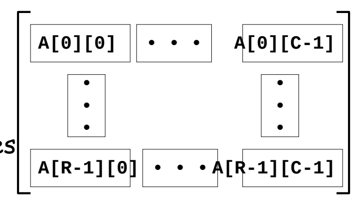
- Declaration "`zip_dig pgh[4]`" ⇔ "`int pgh[4][5]`"
  - Variable `pgh` denotes array of 4 elements
    - » Allocated contiguously
  - Each element is an array of 5 `int`'s
    - » Allocated contiguously
- "Row-Major" ordering of all elements guaranteed

Nested Array Allocation

Declaration

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

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



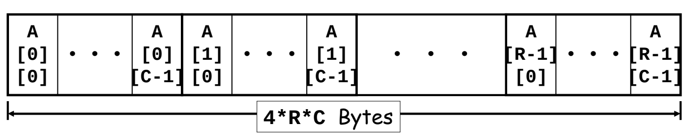
Array Size

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

Arrangement

- Row-Major Ordering

`int A[R][C];`

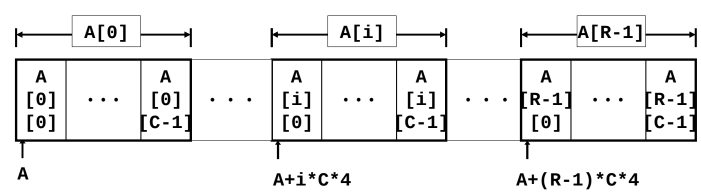


Nested Array Row Access

Row Vectors

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

`int A[R][C];`



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

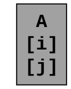
- Computes and returns address
- Compute as **pgh + 4*(index+4*index)**

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

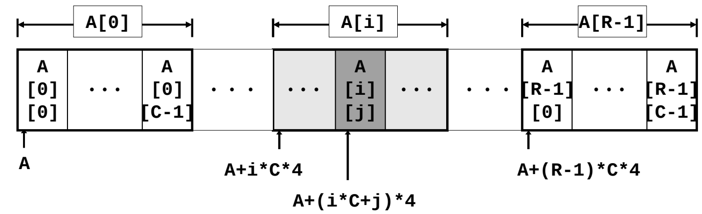

Nested Array Element Access

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

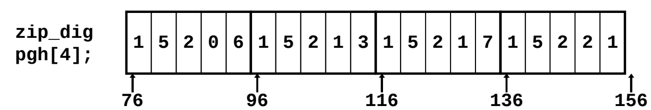
```
int get_pgh_digit
  (int index, int dig)
{
  return pgh[index][dig];
}
```

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

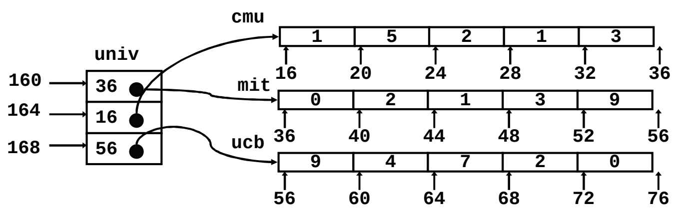
- Code does not do any bounds checking
- Ordering of elements within array is guaranteed

Multi-Level Array Example

- Variable **univ** denotes array of 3 elements
- Each elem is a pointer
  - 4 bytes
- Each pointer points to an 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};
```



Element Access in Multi-Level Array

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

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

```
                              # %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]
```

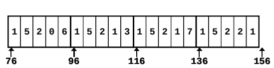

Array Element Accesses

Syntax is the same, computation is different!

Nested Array

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

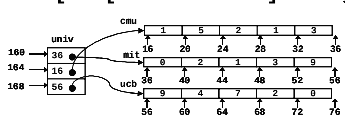
- Element at
  Mem[pgh+20*index+4*dig]



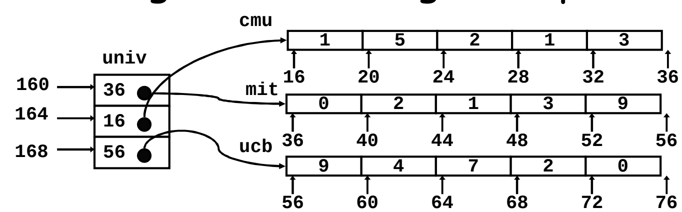
Multi-Level Array

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

- Element at
  Mem[Mem[univ+4*index]+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

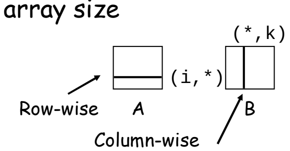
Using Nested Arrays

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];
}
```

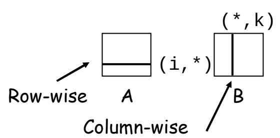
```
movl 12(%ebp),%eax      # i
movl 8(%ebp),%edx       # a
imull 20(%ebp),%eax     # n*i
addl 16(%ebp),%eax      # n*i+j
movl (%edx,%eax,4),%eax # Mem[a+4*(i*n+j)]
```


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;
}
```



Can we optimize this?

Optimizing Dynamic Array Mult

```
/* 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;
}
```

iter	0	1	2	3
a index	i*n	i*n+4	i*n+8	i*n+12
b index	k	n+k	2*n+k	3*n+k

Optimizing Dynamic Array Mult

```
/* 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;
}
```

iter	0	1	2	3
a index	i*n	i*n+4	i*n+8	i*n+12
b index	k	n+k	2*n+k	3*n+k

Invariant Code Motion

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

iter	0	1	2	3
a index	i*n	i*n+4	i*n+8	i*n+12
b index	k	n+k	2*n+k	3*n+k

Invariant Code Motion

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

Anything else?

iter	0	1	2	3
a index	i*n	i*n+4	i*n+8	i*n+12
b index	k	n+k	2*n+k	3*n+k

Induction Var + Strength Reduciton

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

iter	0	1	2	3
a index	i*n	i*n+4	i*n+8	i*n+12
b index	k	n+k	2*n+k	3*n+k

Optimizing Dynamic Array Mult.

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;
}
```

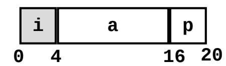

Structures

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

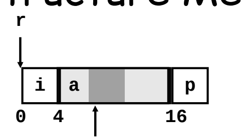
```
void
set_i(struct rec *r,
      int val)
{
  r->i = val;
}
```

Assembly

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


Generating Ptr 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];
}
```

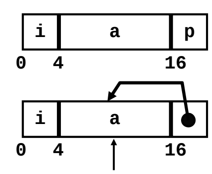
```
# %ecx = idx
# %edx = r
leal 0(,%ecx,4),%eax    # 4*idx
leal 4(%eax,%edx),%eax  # r+4*idx+4
```


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 in Structures

Offsets Within Structure

- Must satisfy element's alignment requirement

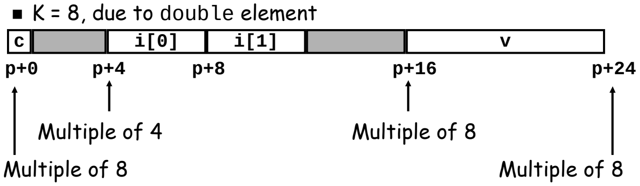
Overall Structure Placement

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

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

Example (under Windows):

- K = 8, due to double element

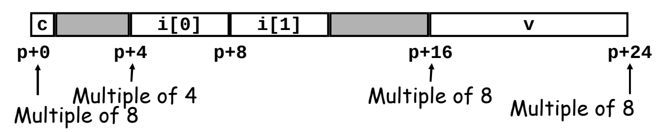


Linux vs. Windows

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

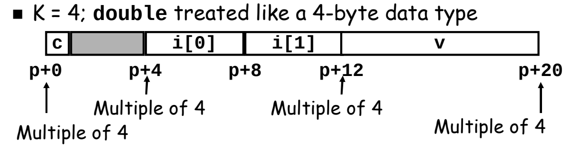
Windows (including Cygwin):

- K = 8, due to **double** element



Linux:

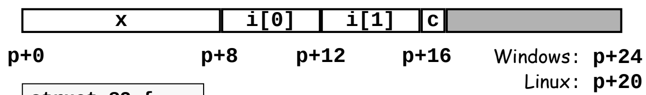
- K = 4; **double** treated like a 4-byte data type



Overall Alignment Requirement

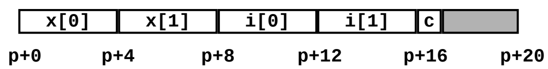
```
struct S2 {
  double x;
  int i[2];
  char c;
} *p;
```

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




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

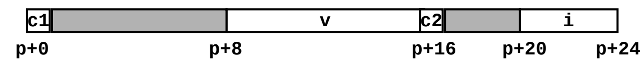
p must be multiple of 4 (in either OS)



Ordering Elements Within Structure

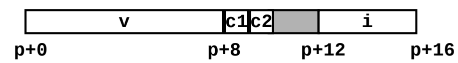
```
struct S4 {
  char c1;
  double v;
  char c2;
  int i;
} *p;
```

10 bytes wasted space in Windows




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

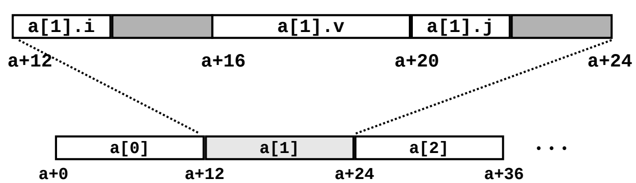
2 bytes wasted space



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];
```



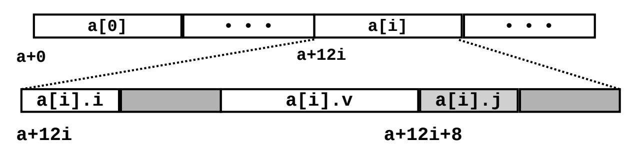
Accessing Element within Array

- 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
```

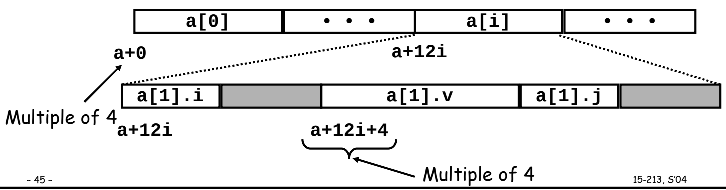


Satisfying Alignment within Structure

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];
```

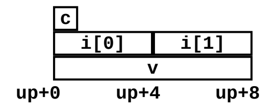


Union Allocation

Principles

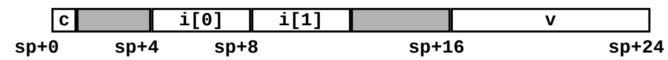
- Overlay union elements
- Allocate according to largest element
- Can only use one field at a time

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



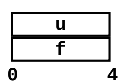

```
struct S1 {
  char c;
  int i[2];
  double v;
} *sp;
```

(Windows alignment)



Using Union to Access Bit Patterns

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




```
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 Revisited

Idea

- Short/long/quad words stored in memory as 2/4/8 consecutive bytes
- Which is most (least) significant?
- Can cause problems when exchanging binary data between machines

Big Endian

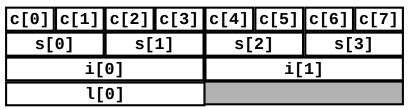
- Most significant byte has lowest address
- PowerPC, Sparc

Little Endian

- Least significant byte has lowest address
- Intel x86, Alpha

Byte Ordering Example

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

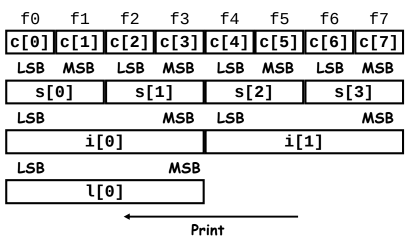


Byte Ordering Example (Cont).

```
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

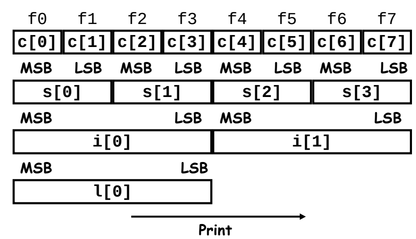


Output on Pentium:

```
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

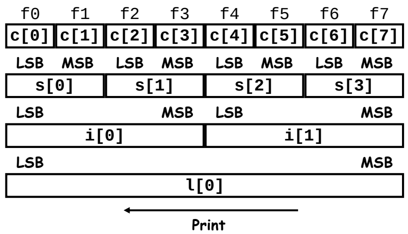


Output on Sun:

```
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