

15-213

“The course that gives CMU its Zip!”

Machine-Level Programming IV: Structured Data Sept. 23, 2004

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

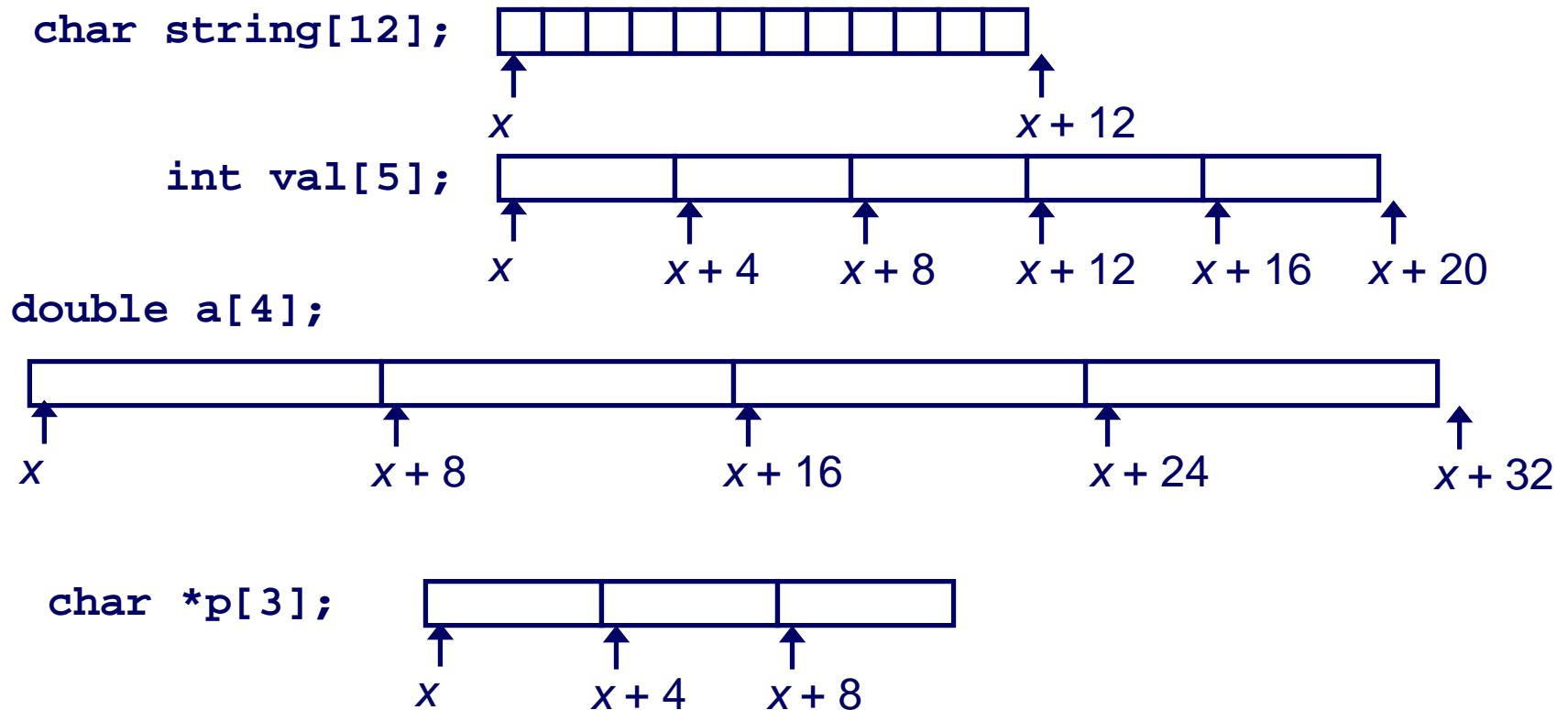
Intel	GAS	Bytes	C
Single	s	4	float
Double	l	8	double
Extended	t	10/12	long double

Array Allocation

Basic Principle

`T A[L];`

- Array of data type T and length L
- Contiguously allocated region of $L * \text{sizeof}(T)$ bytes

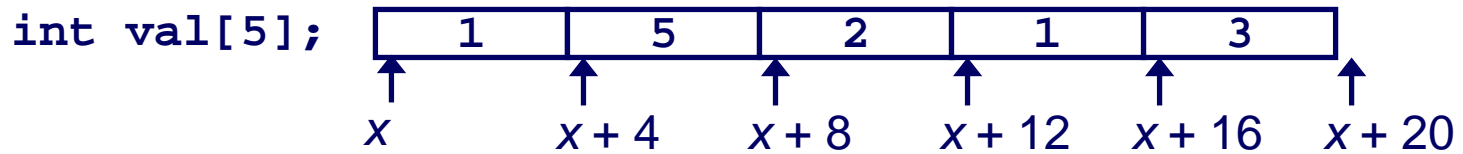


Array Access

Basic Principle

T $A[L]$;

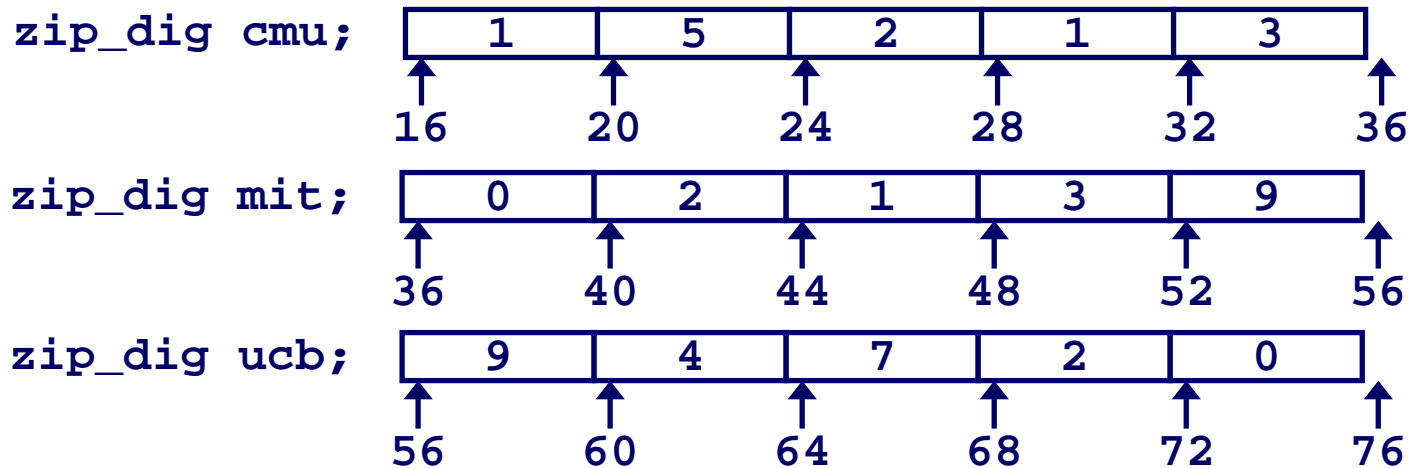
- Array of data type T and length L
- Identifier A can be used as a pointer to array element 0



Reference	Type	Value
<code>val[4]</code>	<code>int</code>	3
<code>val</code>	<code>int *</code>	x
<code>val+1</code>	<code>int *</code>	$x+4$
<code>&val[2]</code>	<code>int *</code>	$x+8$
<code>val[5]</code>	<code>int</code>	??
<code>*(val+1)</code>	<code>int</code>	5
<code>val + i</code>	<code>int *</code>	$x+4i$

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

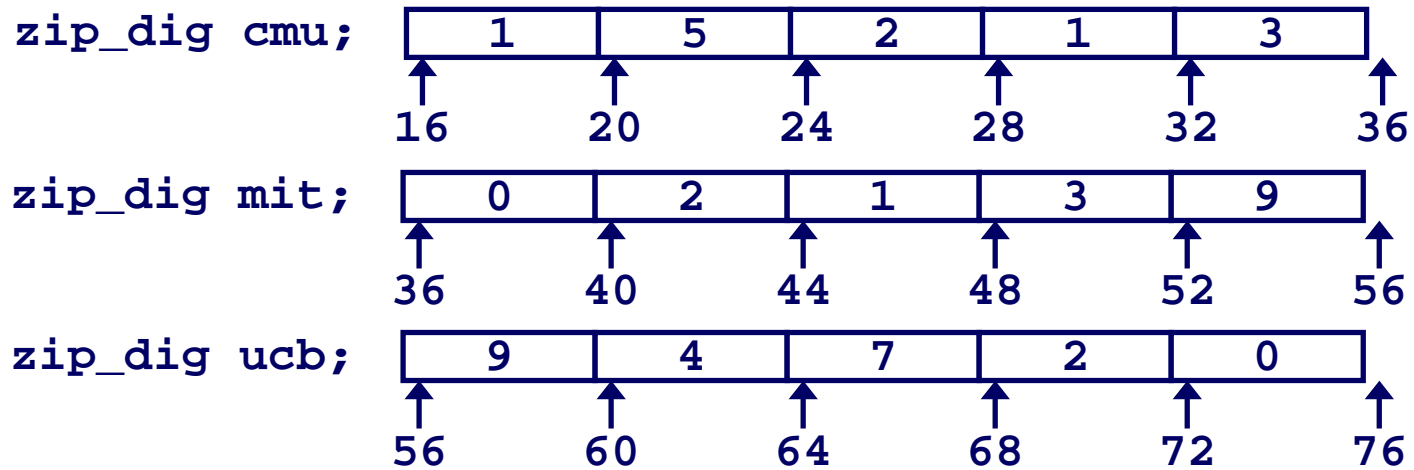
- Register `%edx` contains starting address of array
- Register `%eax` contains array index
- Desired digit at $4 * \%eax + \%edx$
- Use memory reference
(`%edx, %eax, 4`)

```
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?
<code>mit[3]</code>	$36 + 4 * 3 = 48$	3	Yes
<code>mit[5]</code>	$36 + 4 * 5 = 56$	9	No
<code>mit[-1]</code>	$36 + 4 * -1 = 32$	3	No
<code>cmu[15]</code>	$16 + 4 * 15 = 76$??	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

- $10 * z_i + *z$ implemented as $*z + 2 * (z_i + 4 * z_i)$
- $z++$ increments by 4

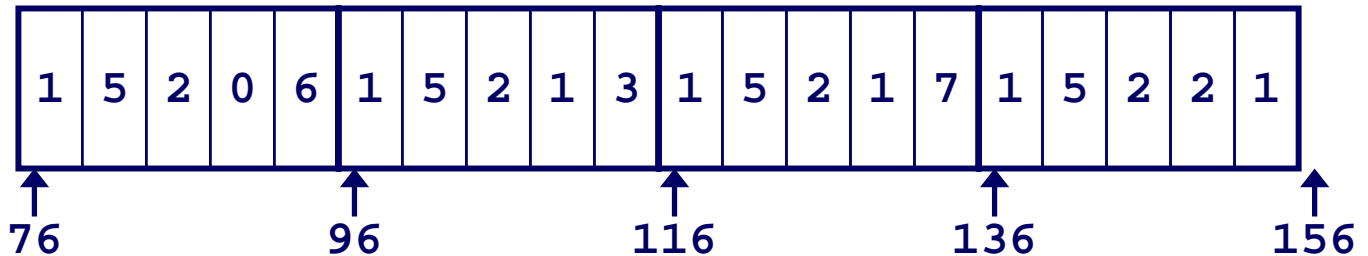
```
int zd2int(zip_dig z)
{
    int zi = 0;
    int *zend = z + 4;
    do {
        zi = 10 * zi + *z;
        z++;
    } while(z <= zend);
    return zi;
}
```

```
# %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];



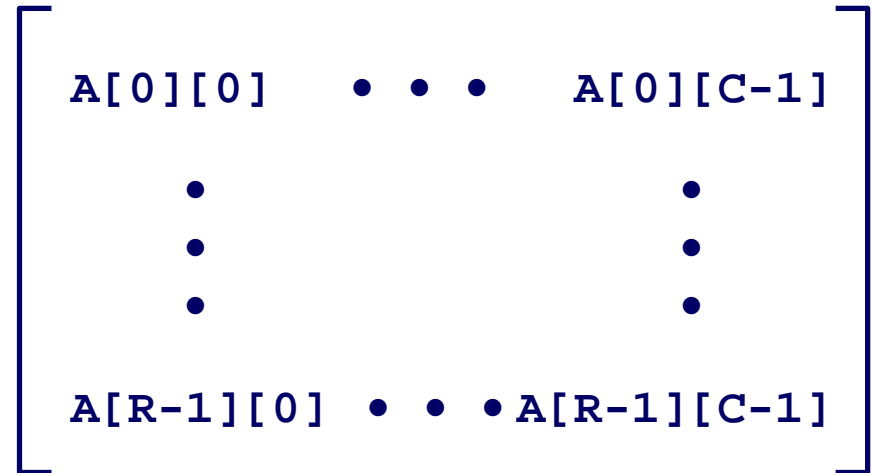
- Declaration “zip_dig pgh[4]” equivalent to “int pgh[4][5]”
 - Variable pgh denotes array of 4 elements
 - » Allocated contiguously
 - Each element is an array of 5 int’s
 - » Allocated contiguously
- “Row-Major” ordering of all elements guaranteed

Nested Array Allocation

Declaration

`T A[R][C];`

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



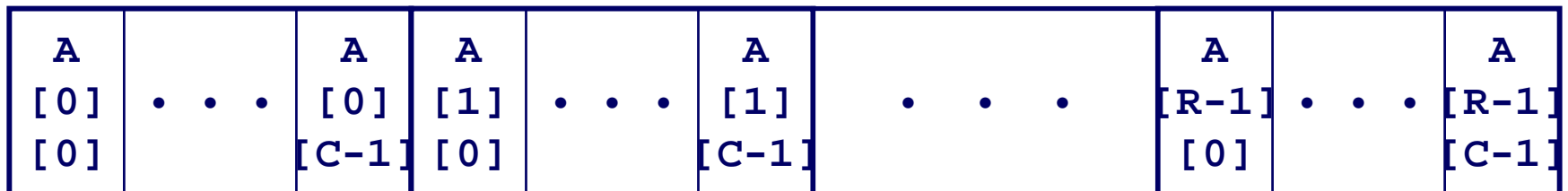
Array Size

- $R * C * K$ bytes

Arrangement

- Row-Major Ordering

`int A[R][C];`



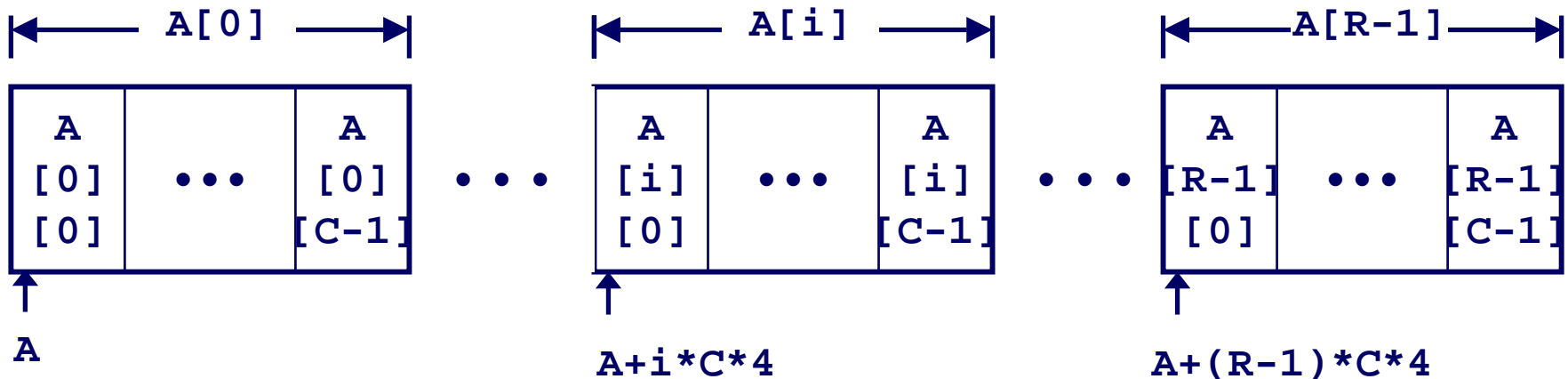
$4 * R * C$ Bytes

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];
```



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

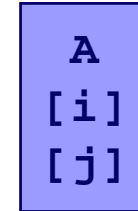
- Computes and returns address
- Compute as `pgh + 4*(index+4*index)`

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

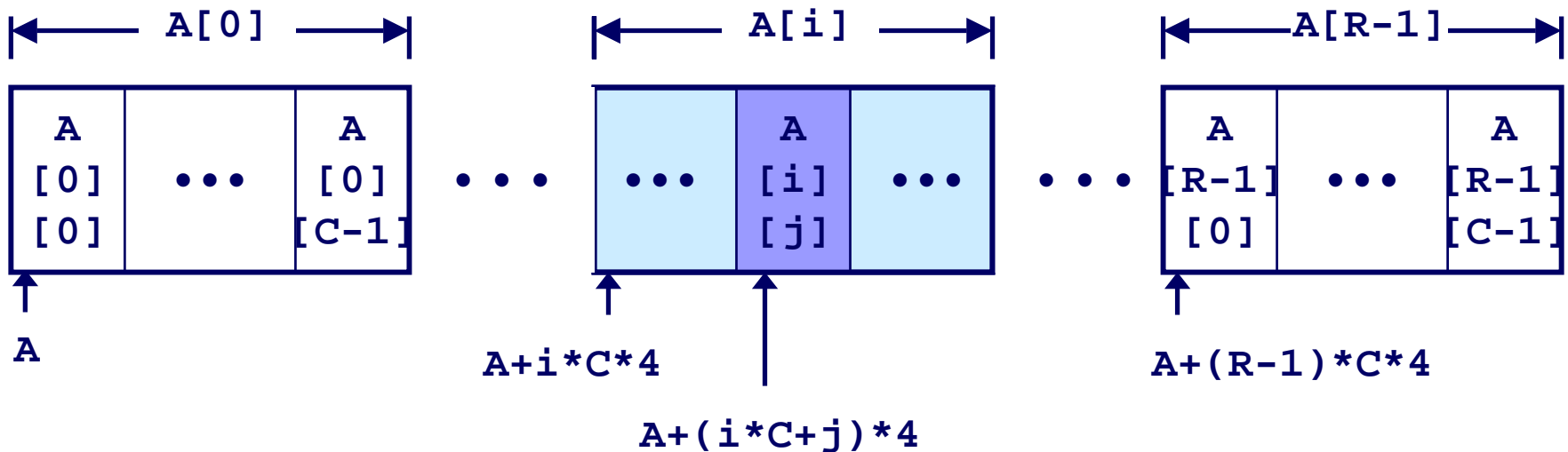
Nested Array Element Access

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`

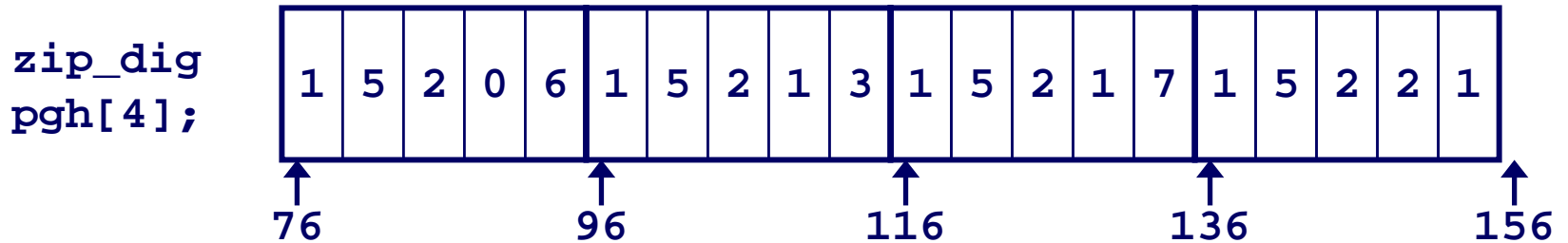
Code

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

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

```
# %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?
<code>pgh[3][3]</code>	$76+20*3+4*3 = 148$	2		Yes
<code>pgh[2][5]</code>	$76+20*2+4*5 = 136$	1		Yes
<code>pgh[2][-1]</code>	$76+20*2+4*-1 = 112$	3		Yes
<code>pgh[4][-1]</code>	$76+20*4+4*-1 = 152$	1		Yes
<code>pgh[0][19]</code>	$76+20*0+4*19 = 152$	1		Yes
<code>pgh[0][-1]</code>	$76+20*0+4*-1 = 72$??		No

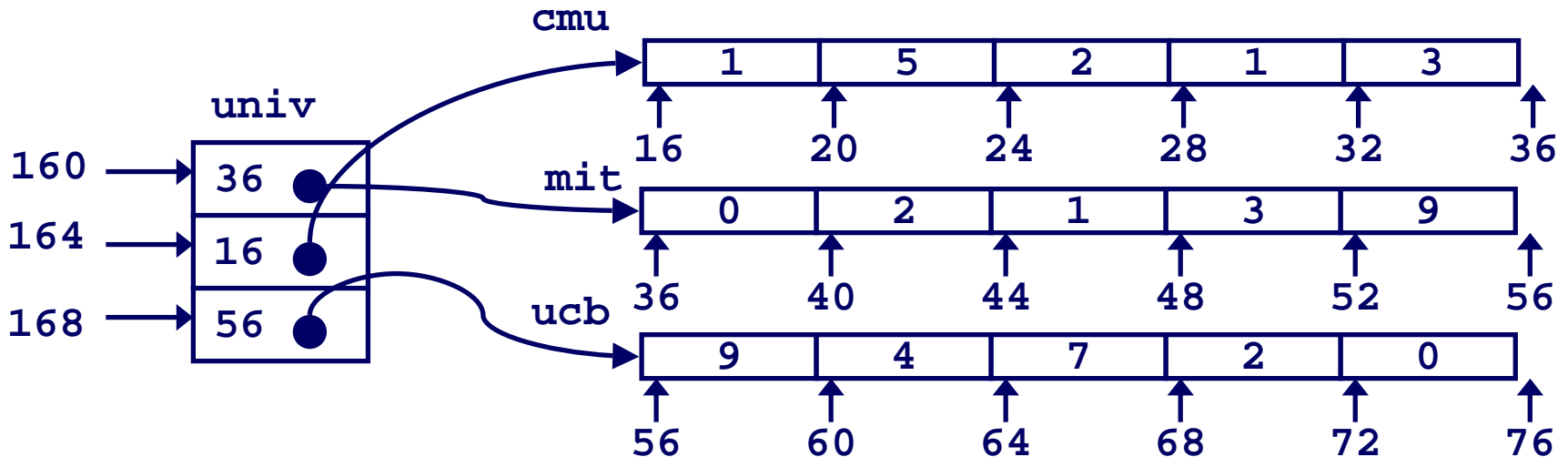
- Code does not do any bounds checking
- Ordering of elements within array guaranteed

Multi-Level Array Example

- Variable `univ` denotes array of 3 elements
 - 4 bytes
- Each element is a pointer 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};
```



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

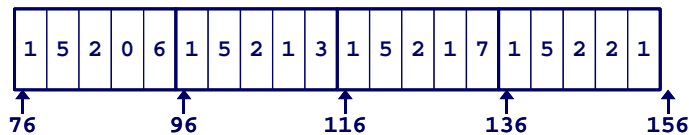
- Similar C references

Nested Array

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

- Element at

$\text{Mem}[\text{pgh} + 20 * \text{index} + 4 * \text{dig}]$



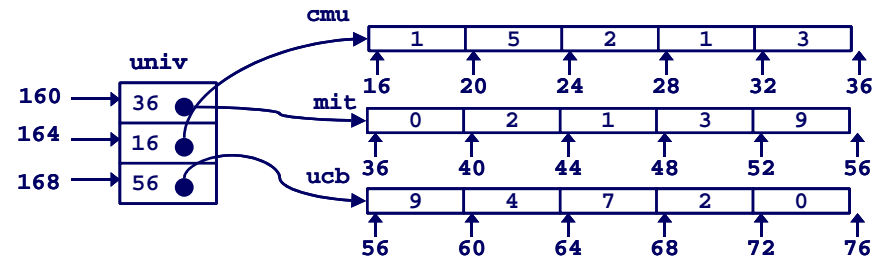
- Different address computation

Multi-Level Array

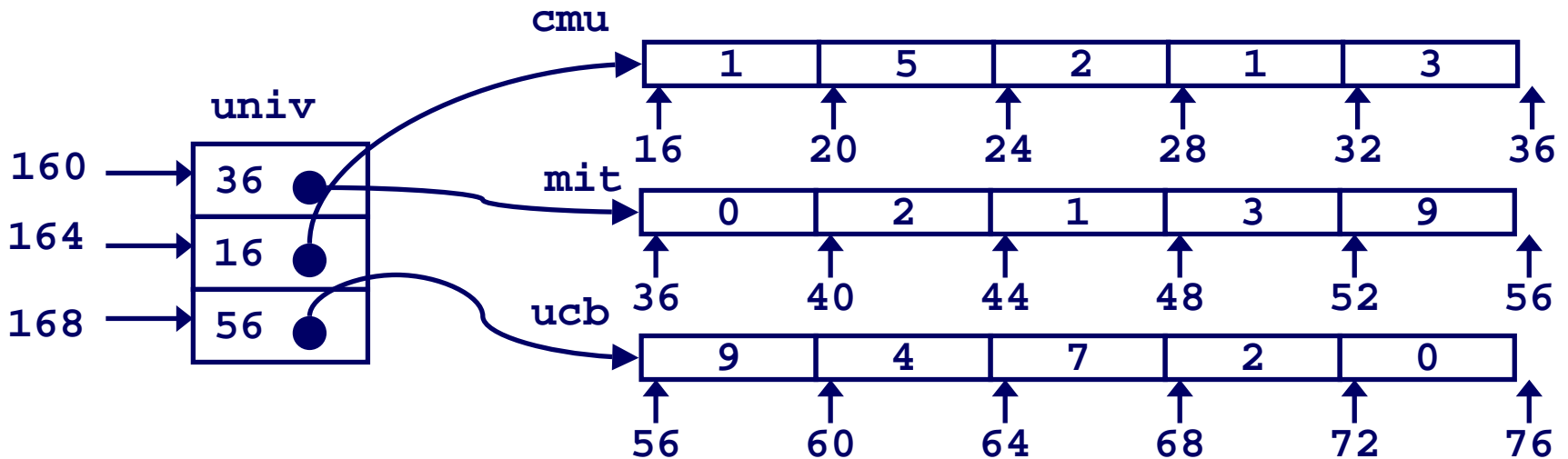
```
int get_univ_digit
(int index, int dig)
{
    return univ[index][dig];
}
```

- Element at

$\text{Mem}[\text{Mem}[\text{univ} + 4 * \text{index}] + 4 * \text{dig}]$



Strange Referencing Examples



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

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

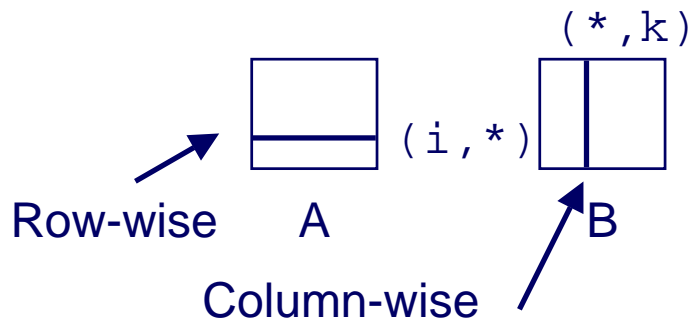
Using Nested Arrays

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

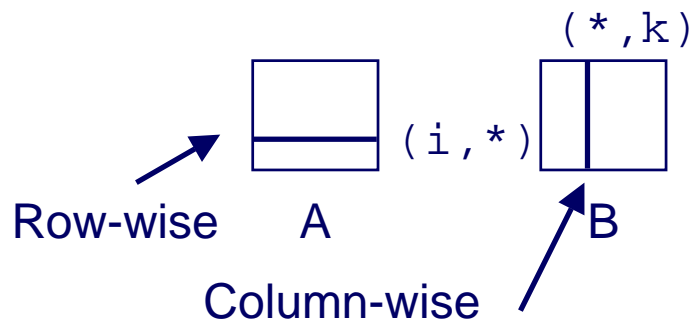
Without Optimizations

■ 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 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;  
}
```

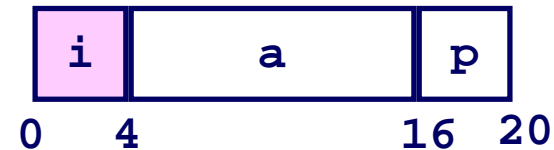

Structures

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

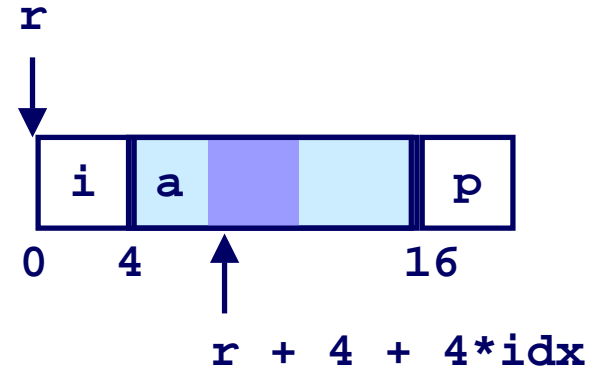
```
void  
set_i(struct rec *r,  
      int val)  
{  
    r->i = val;  
}
```

Assembly

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

Generating Pointer to Struct. 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];  
}
```

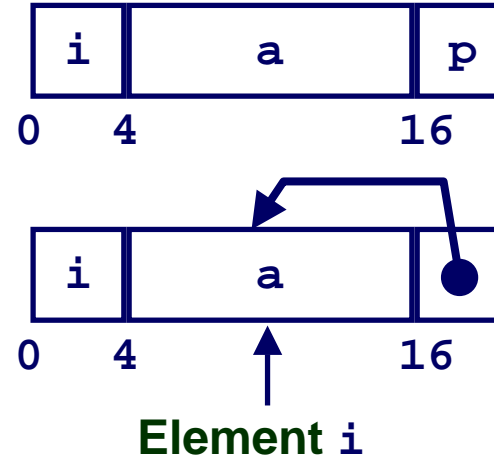
```
# %ecx = idx  
# %edx = r  
leal 0(,%ecx,4),%eax # 4*idx  
leal 4(%eax,%edx),%eax # r+4*idx+4
```

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

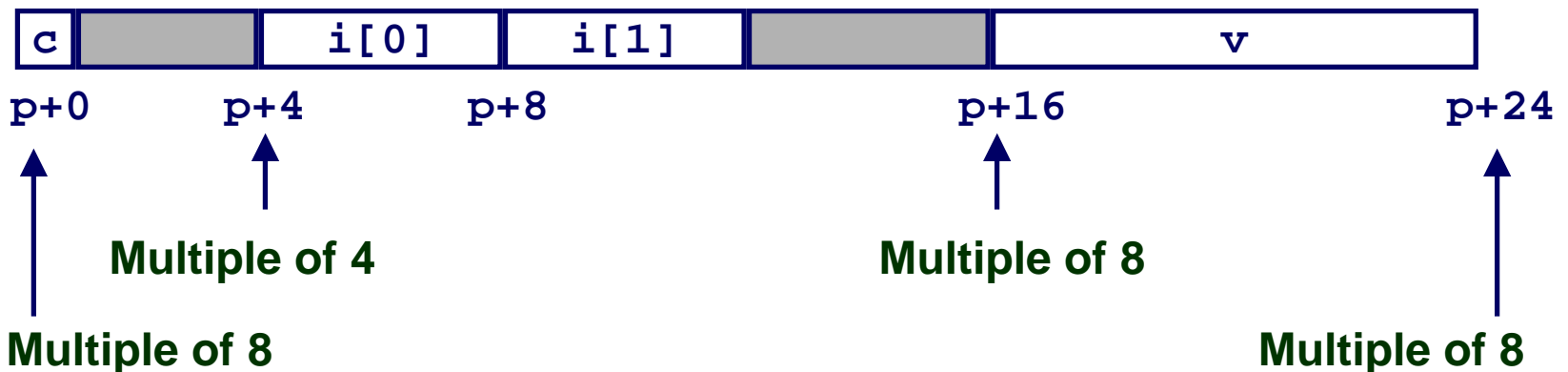
Overall Structure Placement

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

```
struct s1 {  
    char c;  
    int i[2];  
    double v;  
} *p;
```

Example (under Windows):

- $K = 8$, due to `double` element

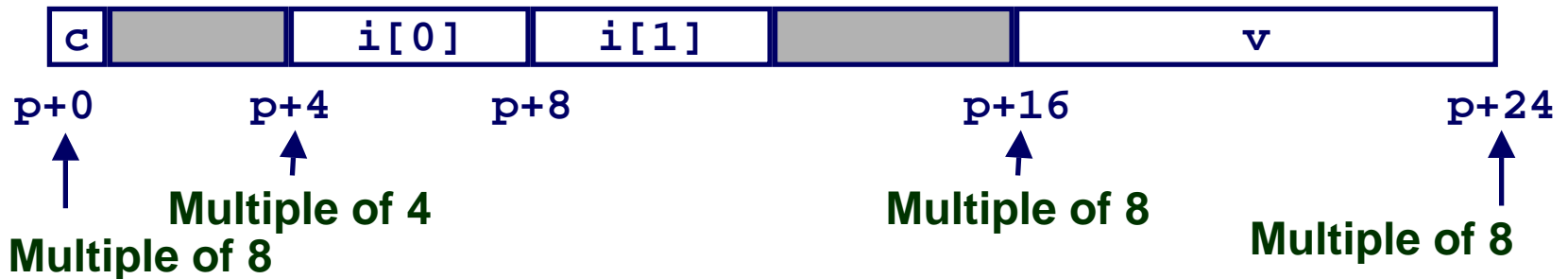


Linux vs. Windows

```
struct s1 {  
    char c;  
    int i[2];  
    double v;  
} *p;
```

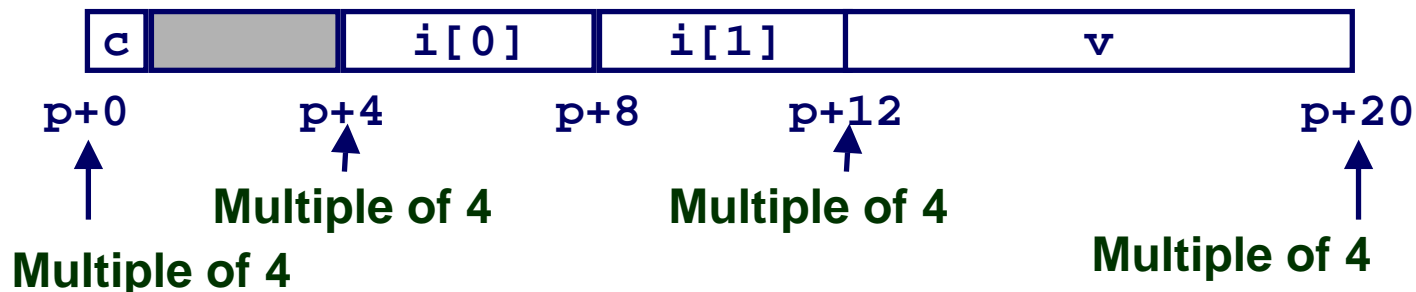
Windows (including Cygwin):

- `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**



p+0

p+8

p+12

p+16

Windows: p+24

Linux: p+20

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

p must be multiple of 4 (in either OS)



p+0

p+4

p+8

p+12

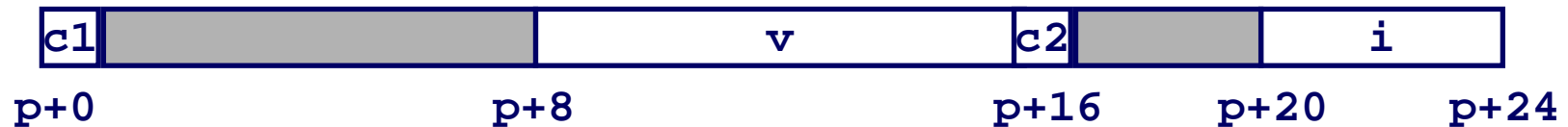
p+16

p+20

Ordering Elements Within Structure

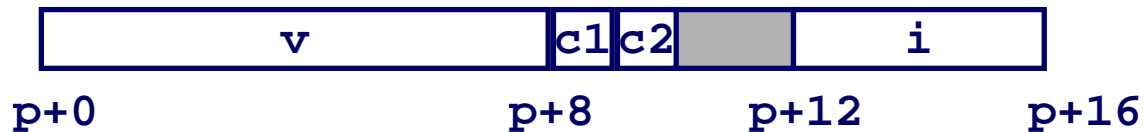
```
struct S4 {  
    char c1;  
    double v;  
    char c2;  
    int i;  
} *p;
```

10 bytes wasted space in Windows



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

2 bytes wasted space

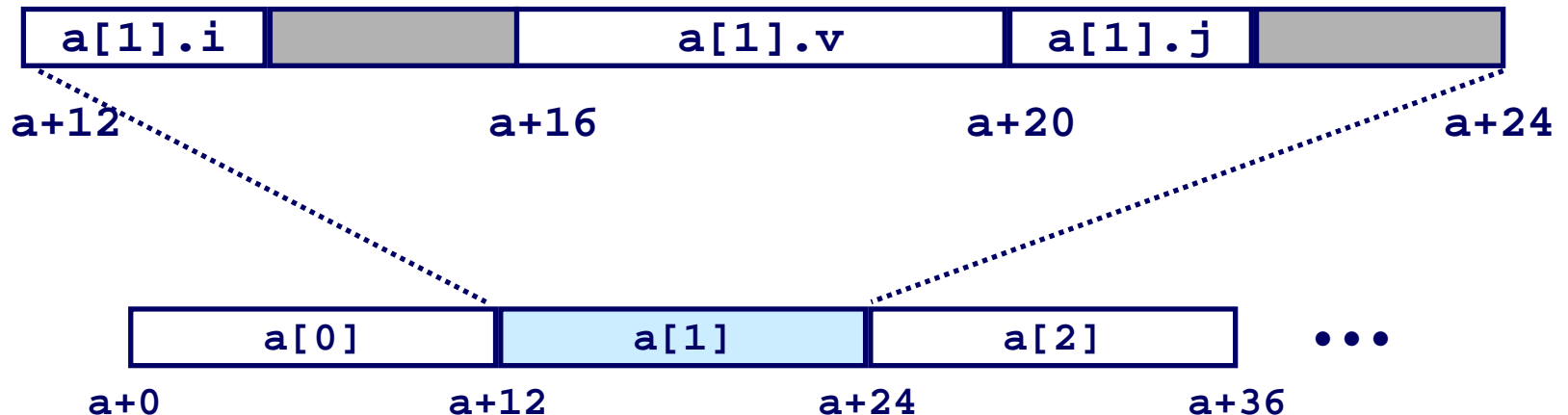


Arrays of Structures

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];
```



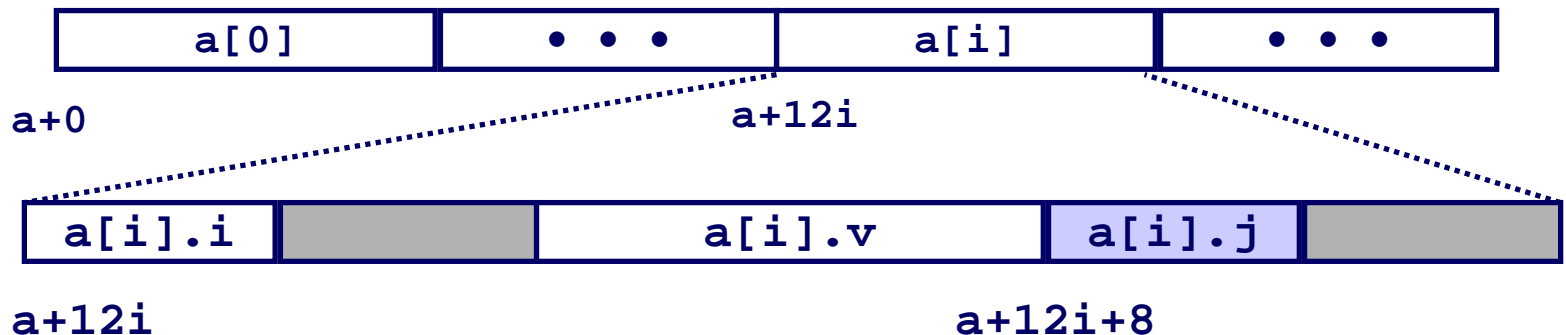
Accessing Element within Array

- Compute offset to start of structure
 - Compute $12*i$ as $4*(i+2i)$
- 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
```

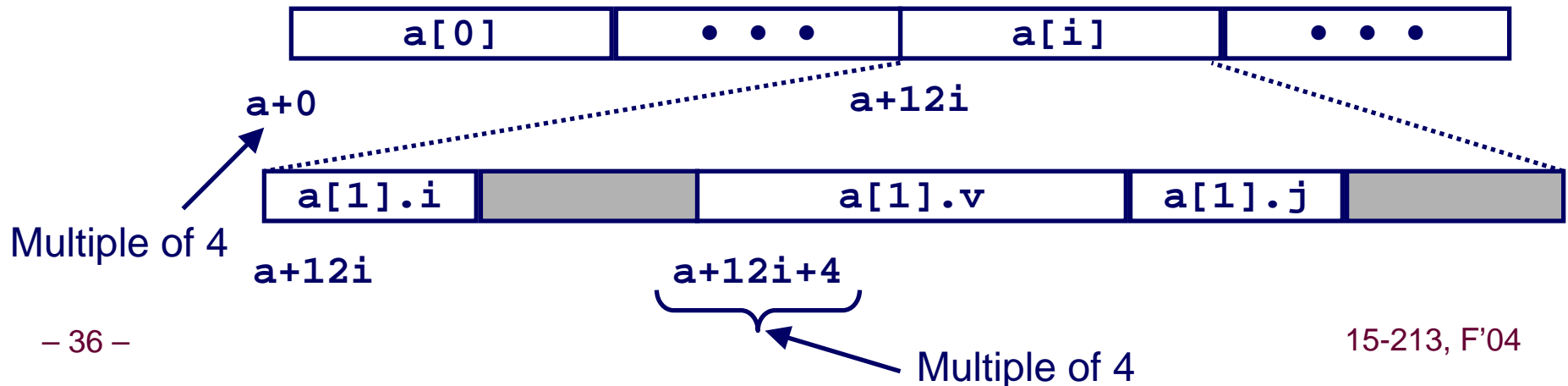


Satisfying Alignment within Structure

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];
```



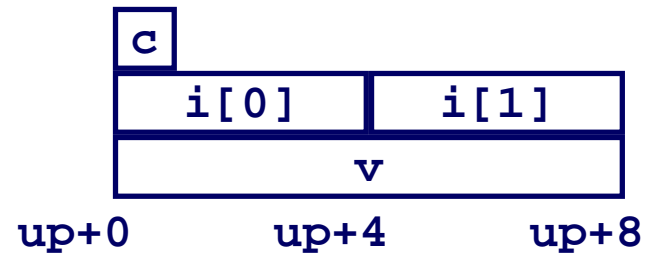
Union Allocation

Principles

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

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

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

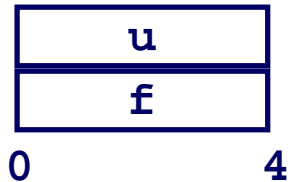


(Windows alignment)



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;
```

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]);

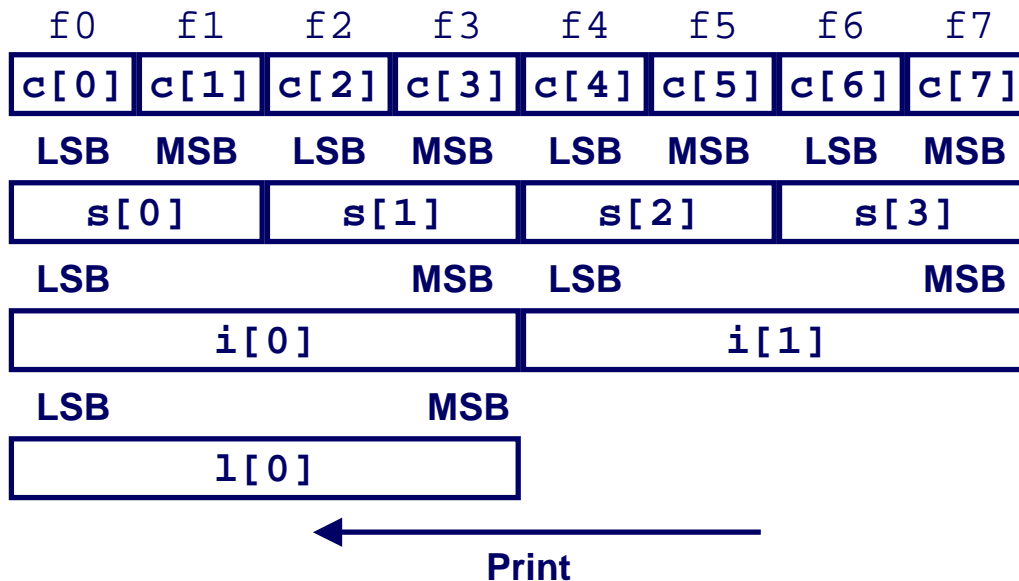
printf("Shorts 0-3 ==
[0x%x,0x%x,0x%x,0x%x]\n",
    dw.s[0], dw.s[1], dw.s[2], dw.s[3]);

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

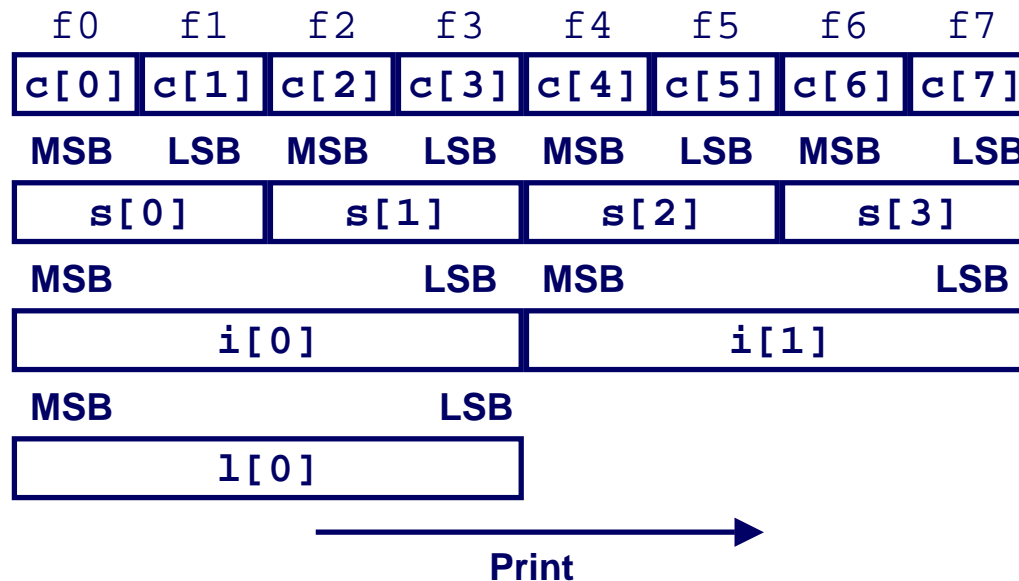


Output on Pentium:

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 == [0xf3f2f1f0]

Byte Ordering on Sun

Big Endian

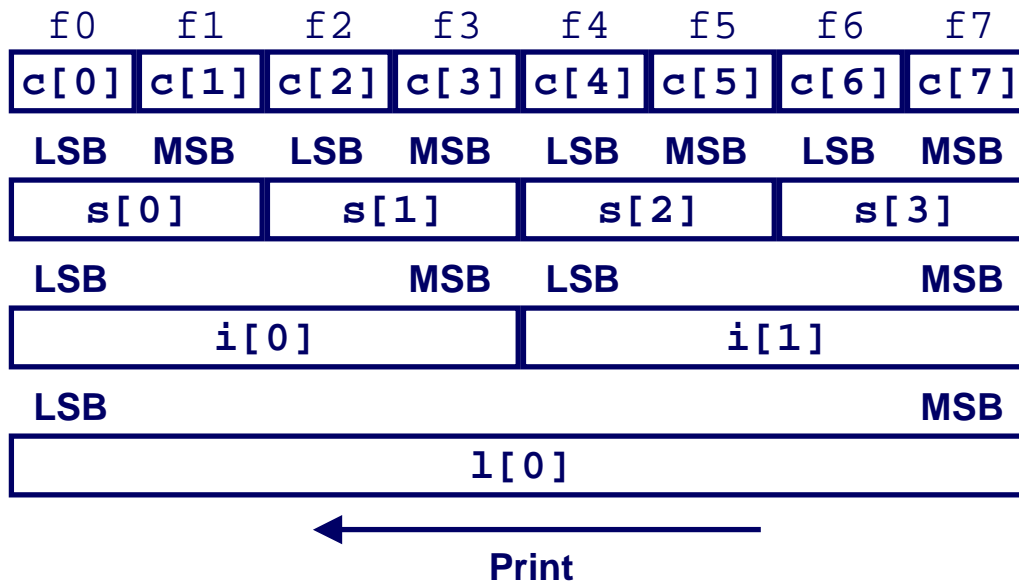


Output on Sun:

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