15-213

"The course that gives CMU its Zip!"

Machine-Level Programming IV: Structured Data
Sept. 19, 2002

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

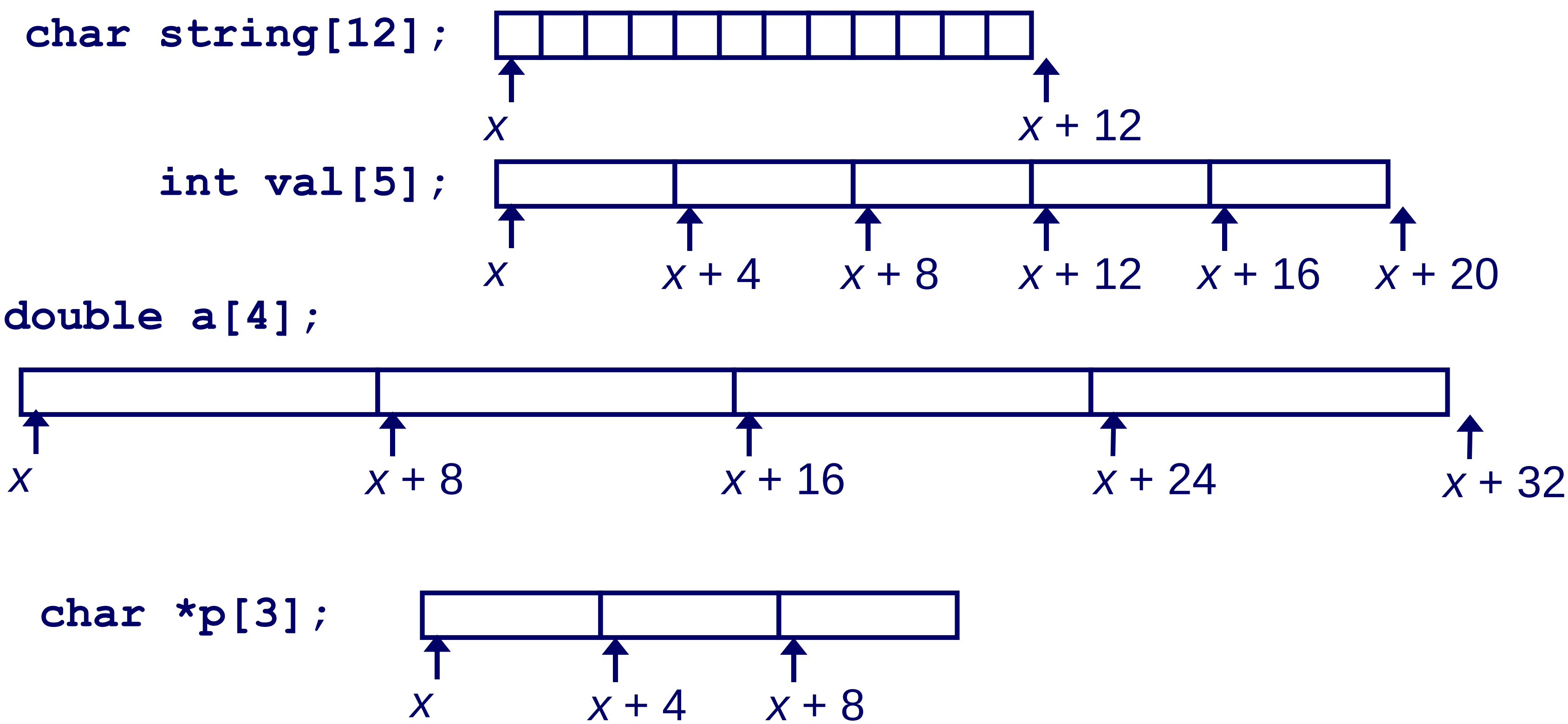
Intel	GAS	Bytes	C
Single	`s`	4	`float`
Double	`l`	8	`double`
Extended	`t`	10/12	`long double`

Array Allocation

Basic Principle

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

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



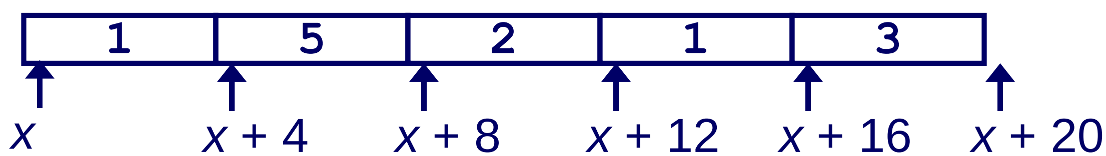
Array Access

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**

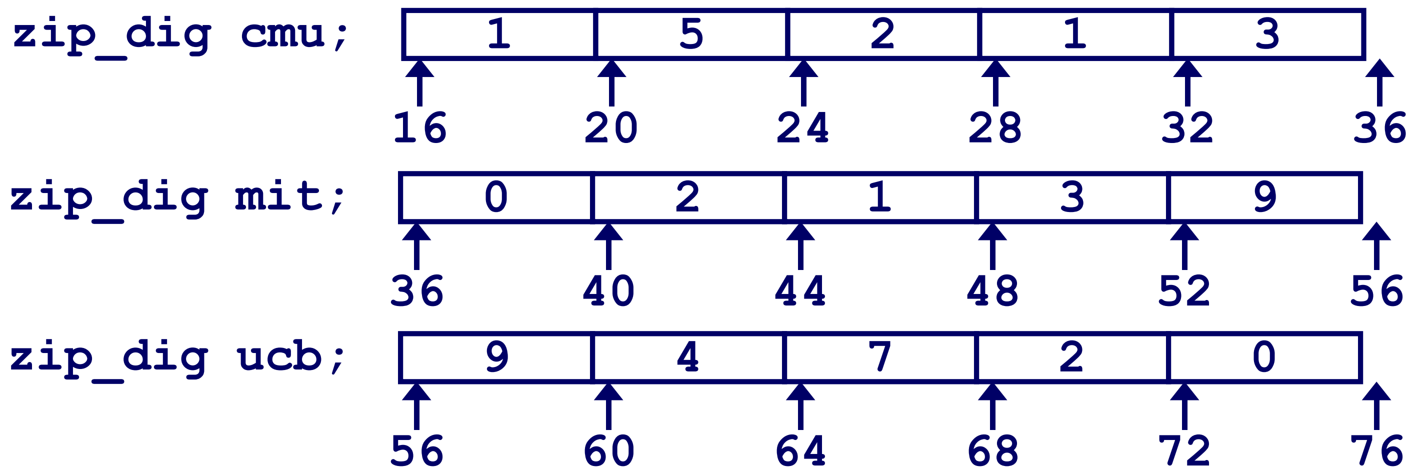
`int val[5];`



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

`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

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

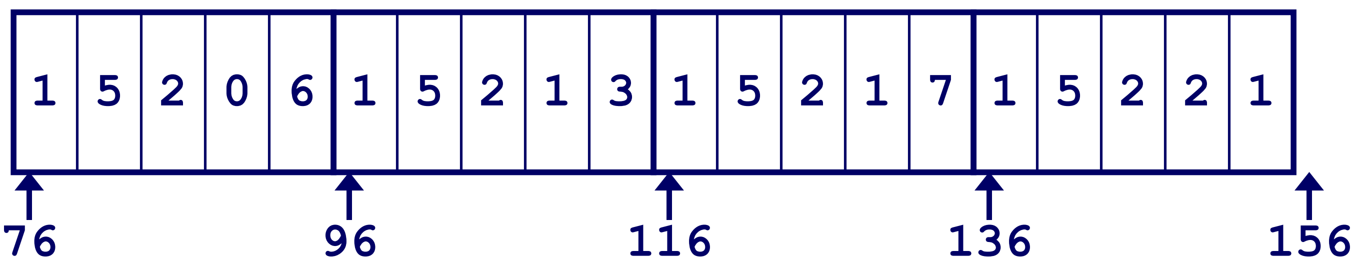
```
int zd2int(zip_dig z)
{
  int zi = 0;
  int *zend = z + 4;
  do {
    zi = 10 * zi + *z;
    z++;
  } while(z <= zend);
  return zi;
}
```

```
  # %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];`



- 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

$$\begin{bmatrix} \texttt{A[0][0]} & \cdots & \texttt{A[0][C-1]} \\ \vdots & & \vdots \\ \texttt{A[R-1][0]} & \cdots & \texttt{A[R-1][C-1]} \end{bmatrix}$$

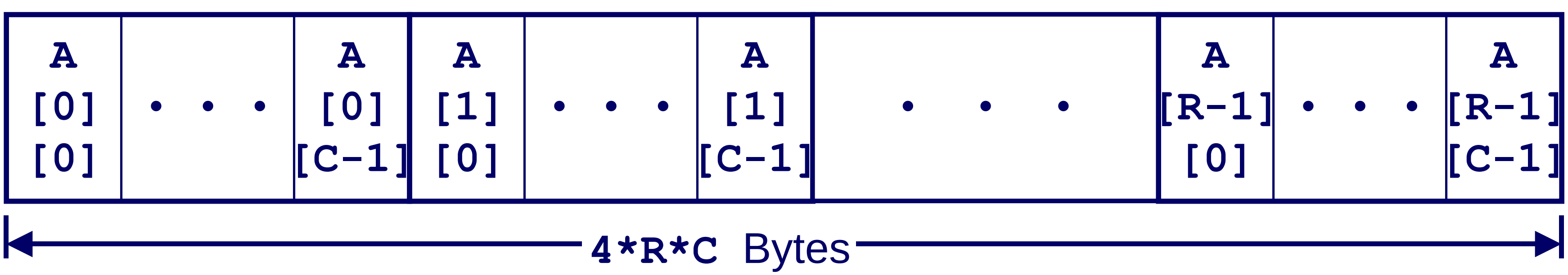
Array Size

- *R * C * K* bytes

Arrangement

- Row-Major Ordering

`int A[R][C];`

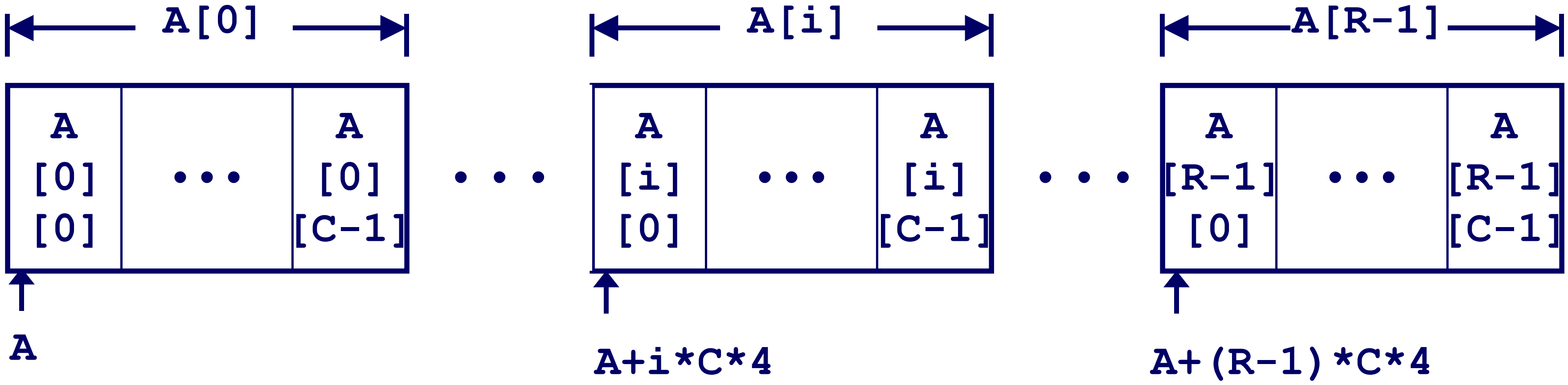


Nested Array Row Access

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

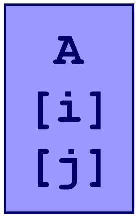
- Computes and returns address
- Compute as `pgh + 4*(index+4*index)`

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

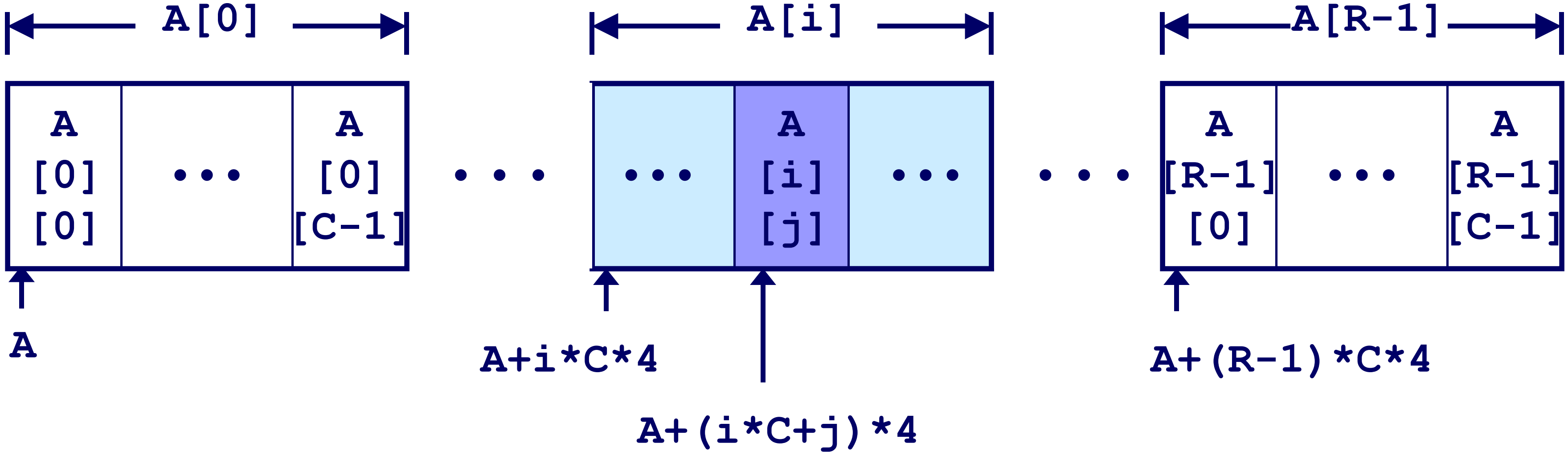
Nested Array Element Access

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

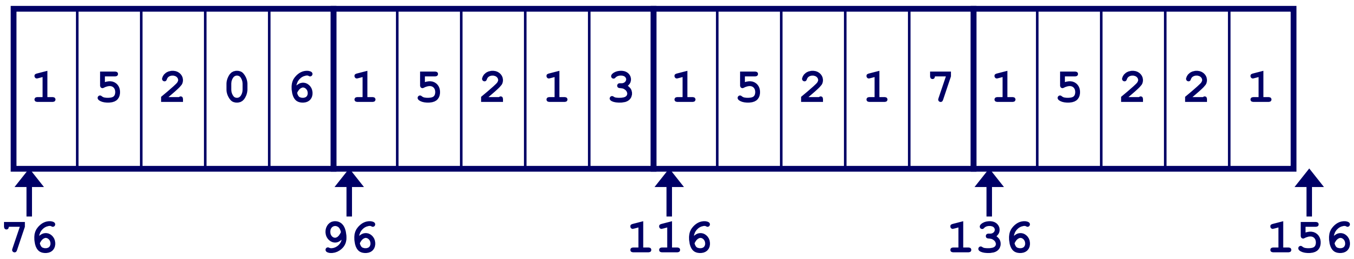
  `pgh + 4*dig + 4*(index+4*index)`

- `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

```
zip_dig
pgh[4];
```



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

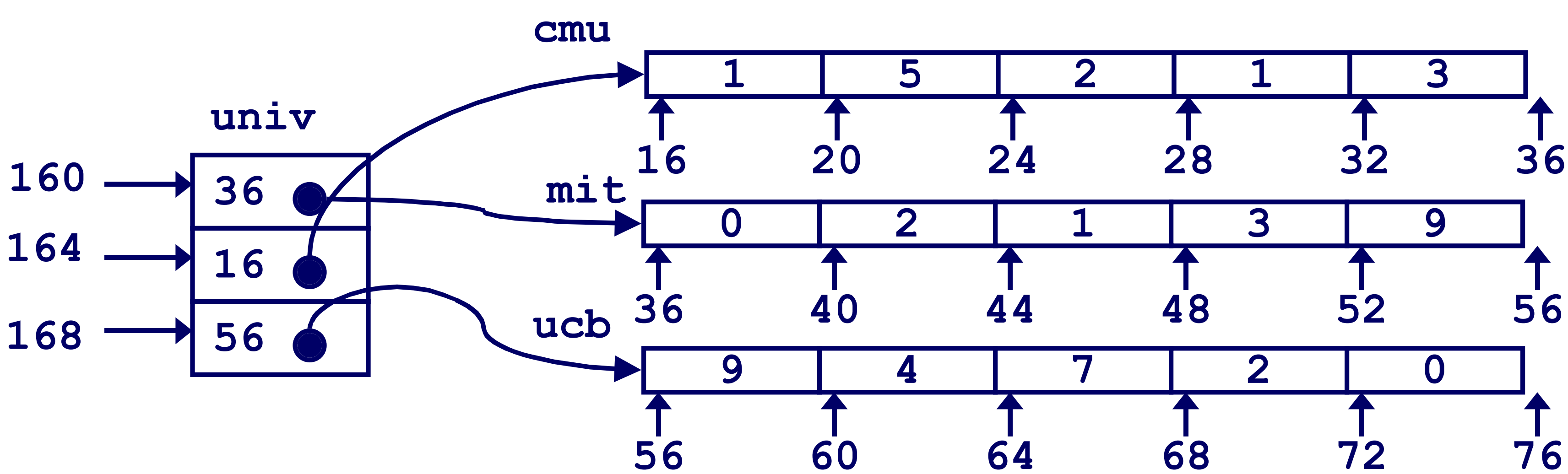
- Code does not do any bounds checking
- Ordering of elements within array guaranteed

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};
```



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

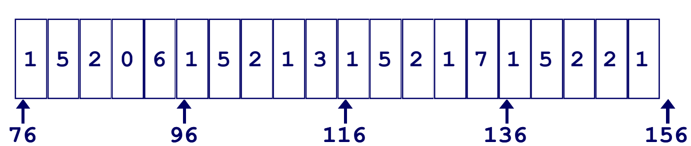
- Similar C references

Nested Array

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

- Element at

`Mem[pgh+20*index+4*dig]`



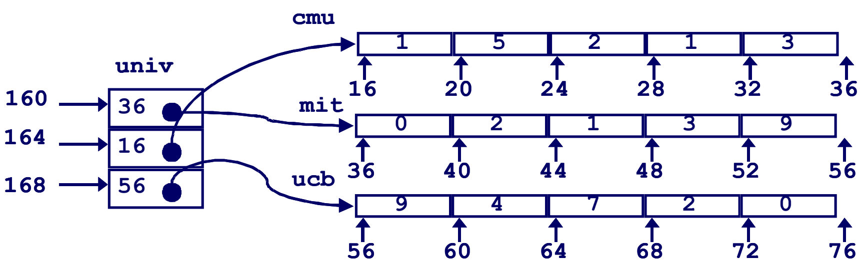
- Different address computation

Multi-Level Array

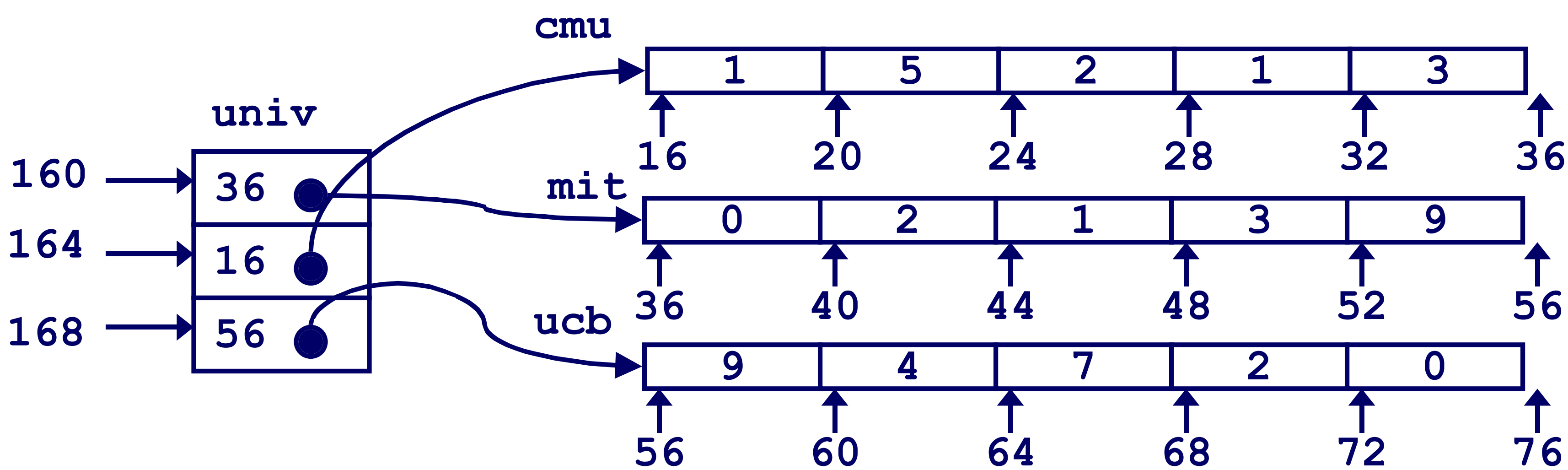
```
int get_univ_digit
  (int index, int dig)
{
  return univ[index][dig];
}
```

- 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

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

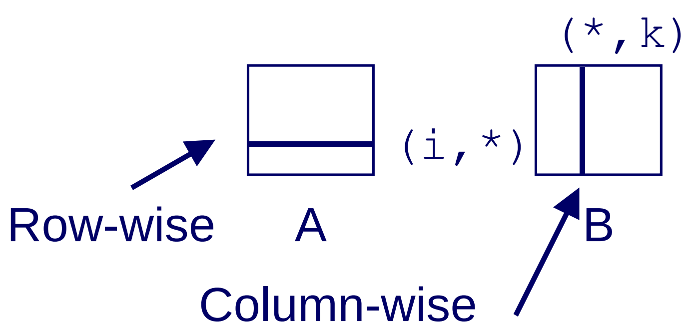
```
/* Compute element i,k of
   fixed matrix product */
int fix_prod_ele
(fix_matrix a, fix_matrix b,
 int i, int k)
{
  int j;
  int result = 0;
  for (j = 0; j < N; j++)
    result += a[i][j]*b[j][k];
  return result;
}
```

Strengths

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

Limitation

- Only works if have fixed array size



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];
}
```

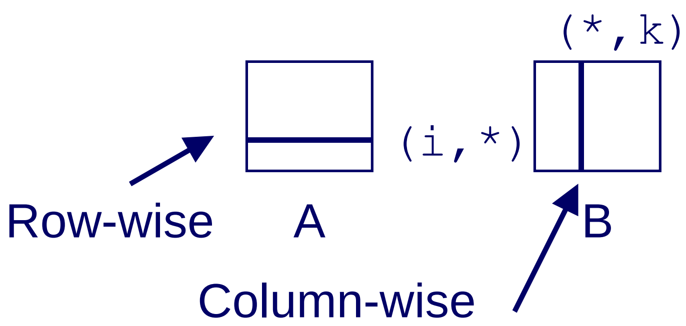
```
movl 12(%ebp),%eax          # i
movl 8(%ebp),%edx           # a
imull 20(%ebp),%eax         # n*i
addl 16(%ebp),%eax          # n*i+j
movl (%edx,%eax,4),%eax     # Mem[a+4*(i*n+j)]
```

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;
}
```

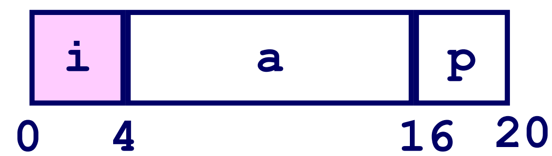
Structures

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

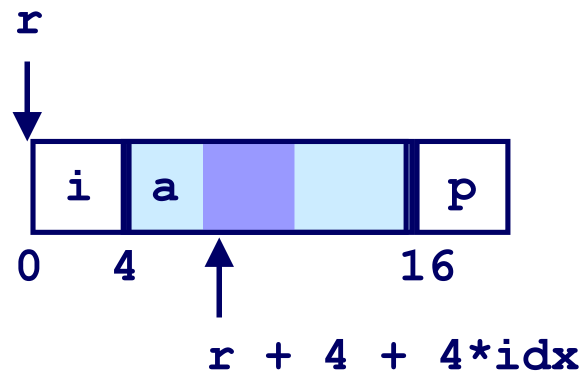
```
void
set_i(struct rec *r,
      int val)
{
  r->i = val;
}
```

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

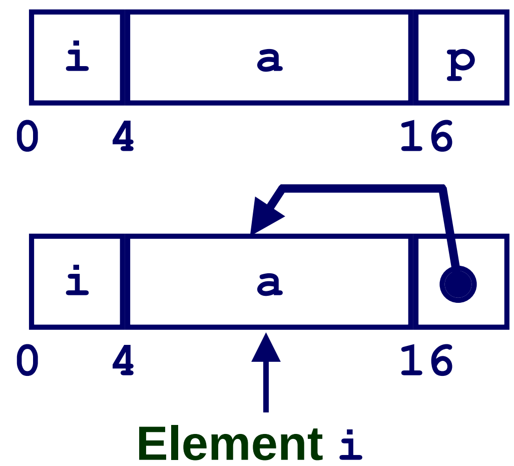
```
int *
find_a
 (struct rec *r, int idx)
{
  return &r->a[idx];
}
```

```
# %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

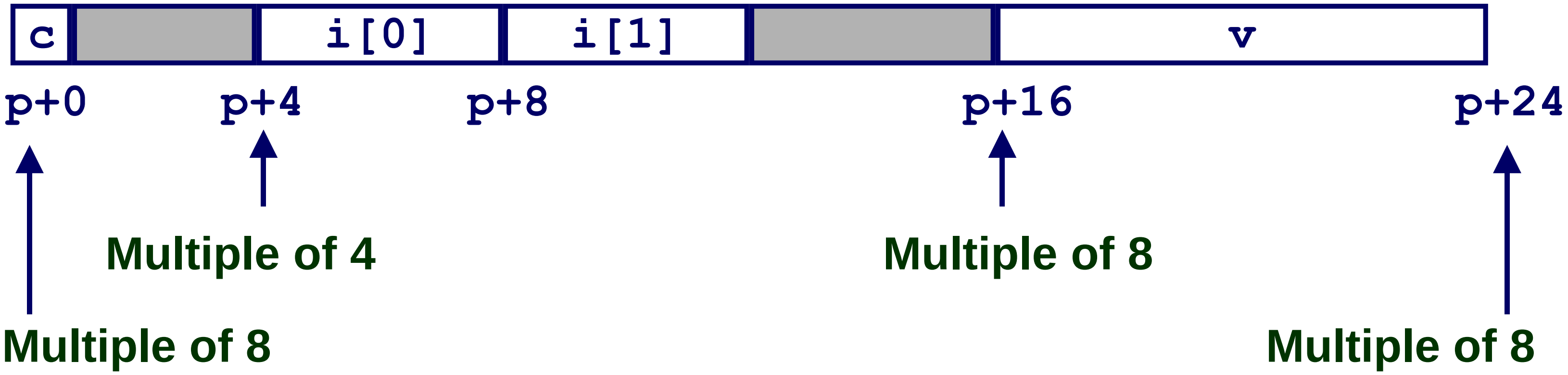
```
struct S1 {
  char c;
  int i[2];
  double v;
} *p;
```

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

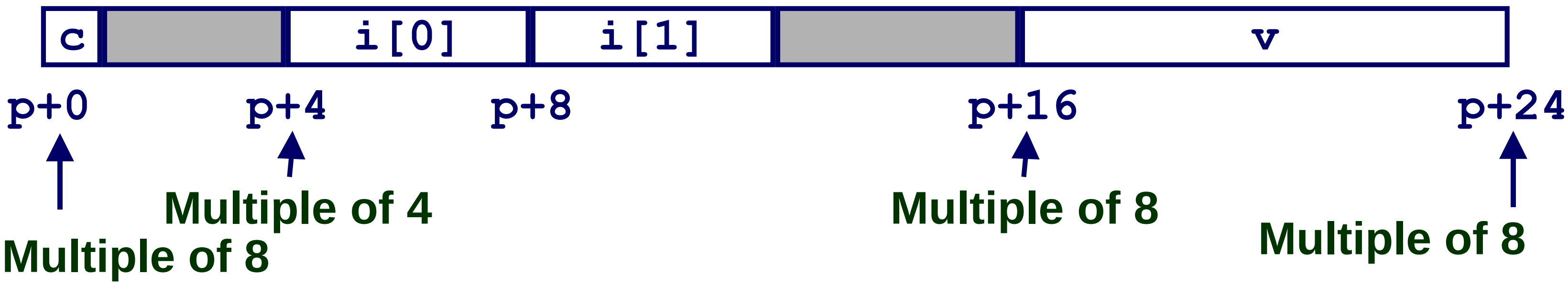


Linux vs. Windows

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

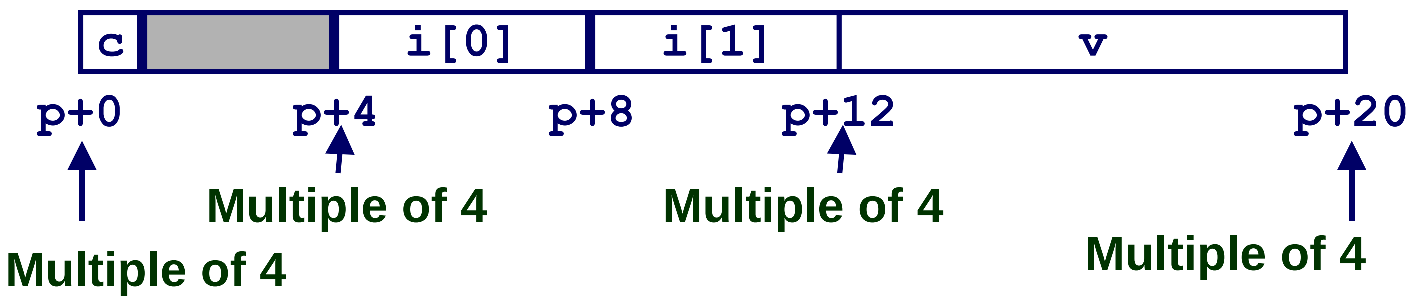
Windows (including Cygwin):

- K = 8, due to `double` element



Linux:

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



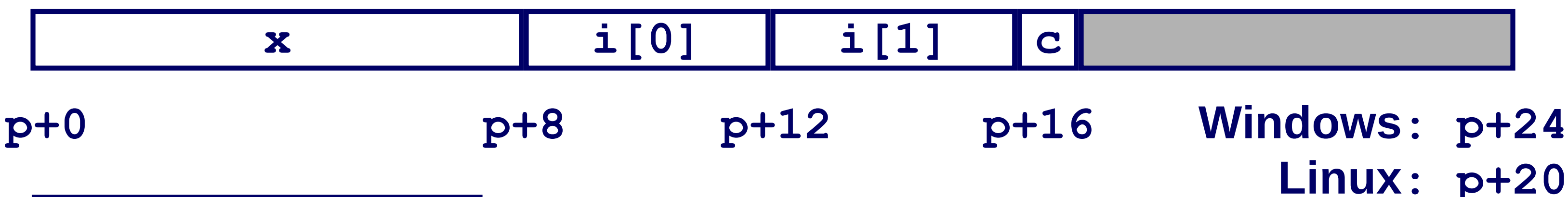
Overall Alignment Requirement

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

`p` must be multiple of:

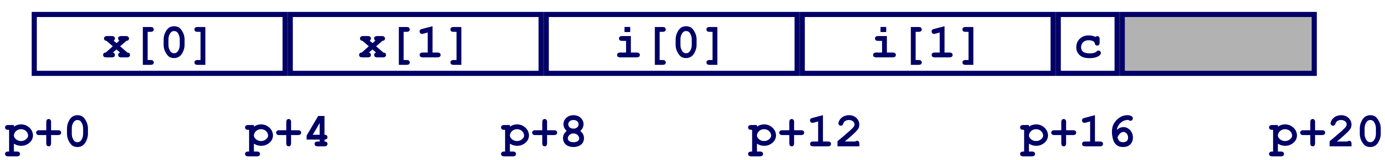
8 for Windows

4 for Linux




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

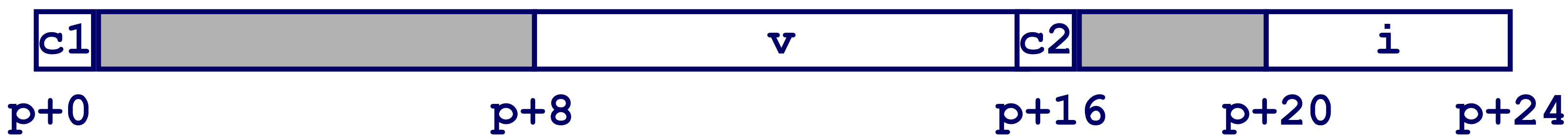
`p` must be multiple of 4 (in either OS)



Ordering Elements Within Structure

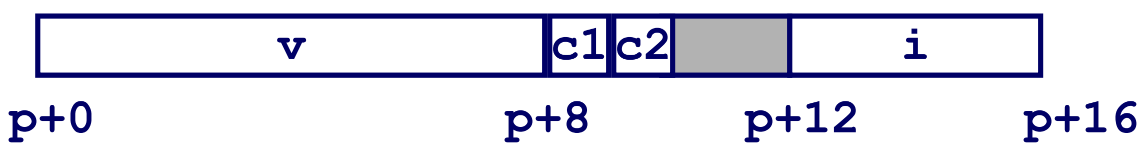
```
struct S4 {
  char c1;
  double v;
  char c2;
  int i;
} *p;
```

10 bytes wasted space in Windows




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

2 bytes wasted space

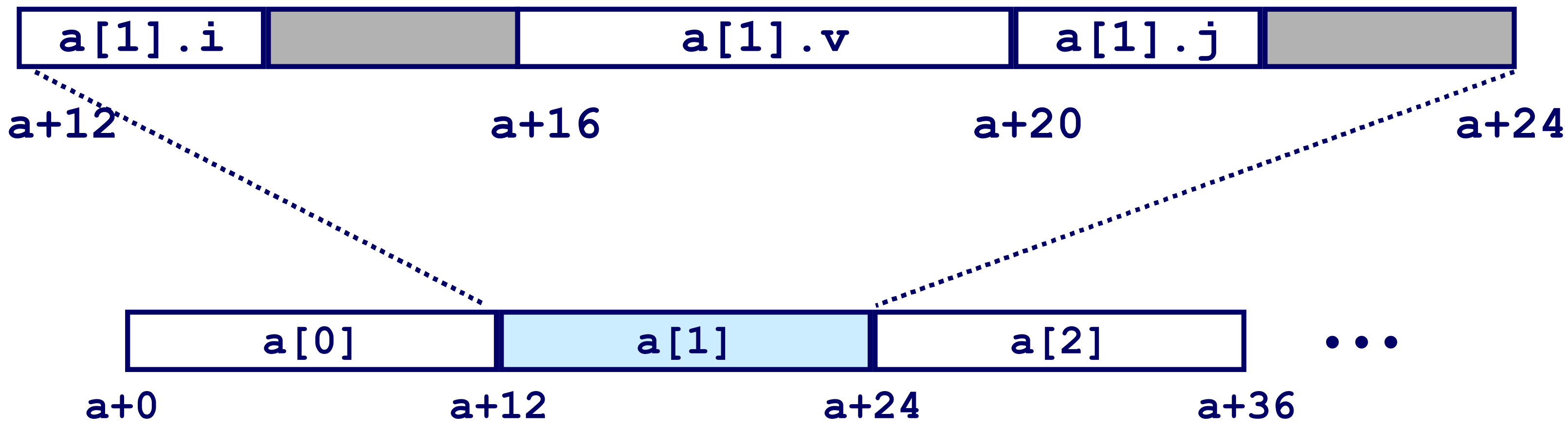


Arrays of Structures

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];
```



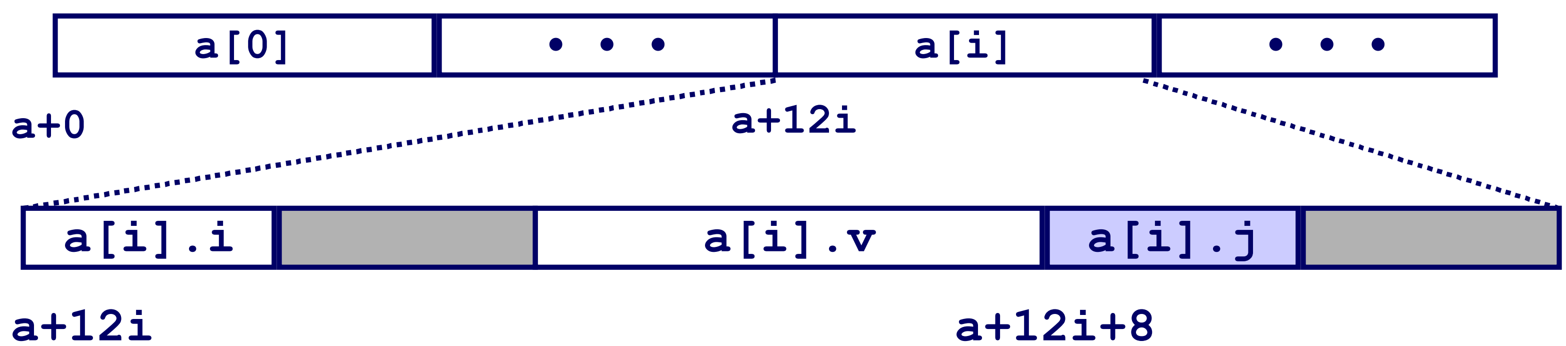
Accessing Element within Array

- 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
```

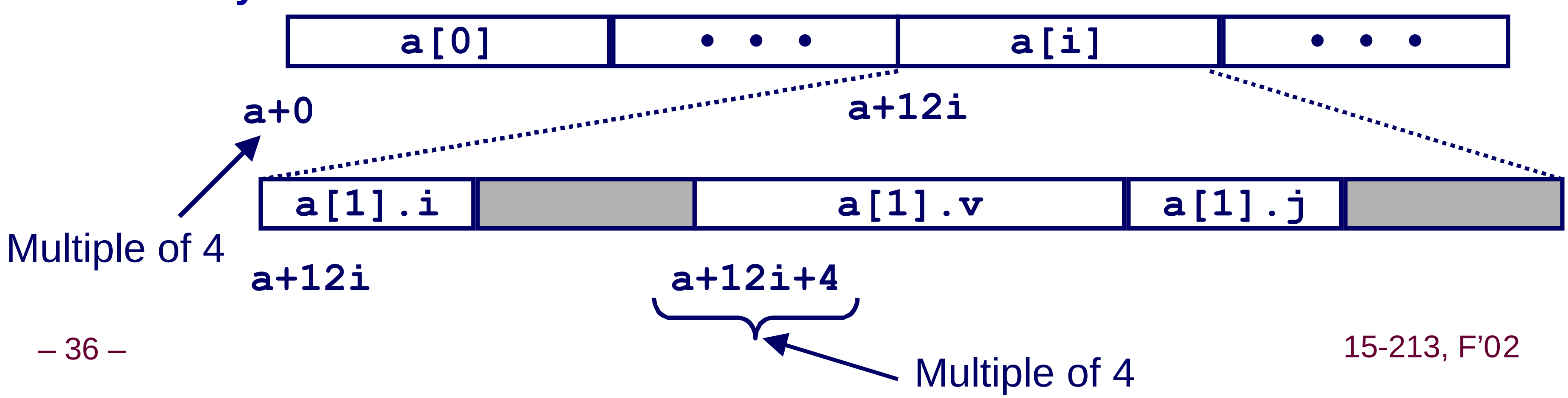


Satisfying Alignment within Structure

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];
```

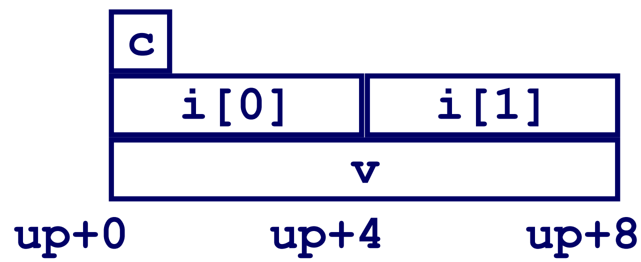


Union Allocation

Principles

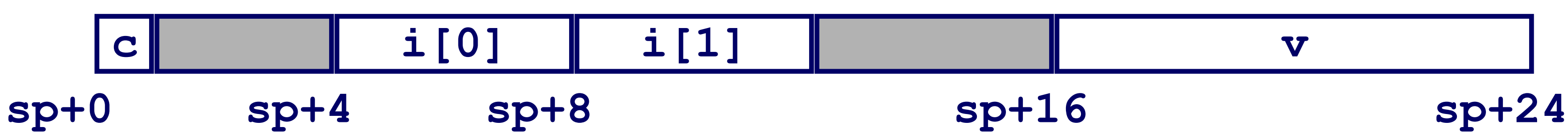
- Overlay union elements
- Allocate according to largest element
- Can only use one field at a time

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



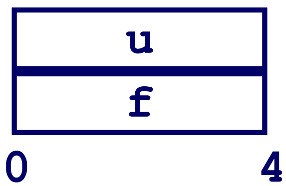

```
struct S1 {
  char c;
  int i[2];
  double v;
} *sp;
```

(Windows alignment)



Using Union to Access Bit Patterns

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



- 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`

```
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;
}
```

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;
```

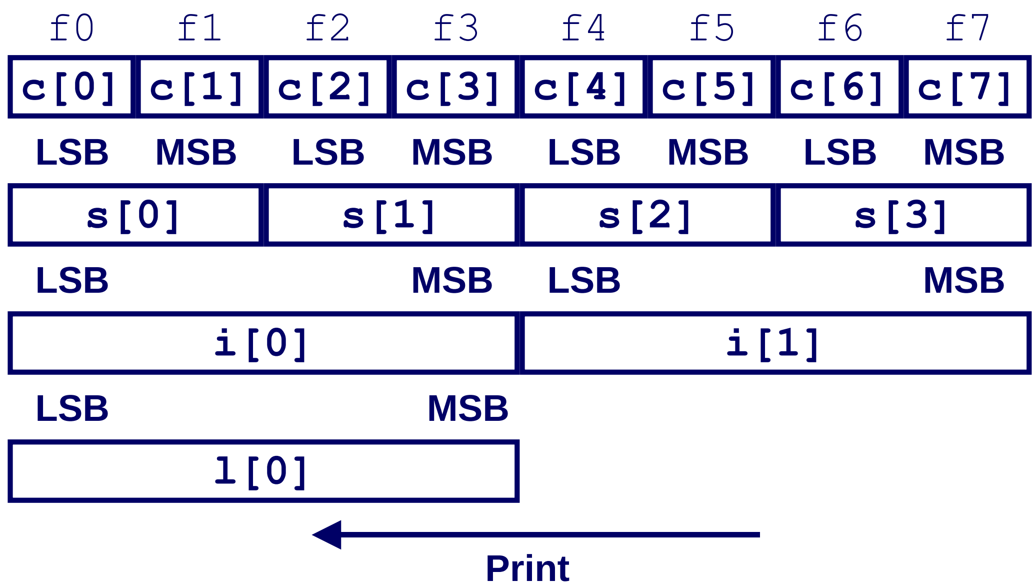
<table>
<tr><td>c[0]</td><td>c[1]</td><td>c[2]</td><td>c[3]</td><td>c[4]</td><td>c[5]</td><td>c[6]</td><td>c[7]</td></tr>
<tr><td colspan="2">s[0]</td><td colspan="2">s[1]</td><td colspan="2">s[2]</td><td colspan="2">s[3]</td></tr>
<tr><td colspan="4">i[0]</td><td colspan="4">i[1]</td></tr>
<tr><td colspan="4">l[0]</td><td colspan="4"></td></tr>
</table>

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

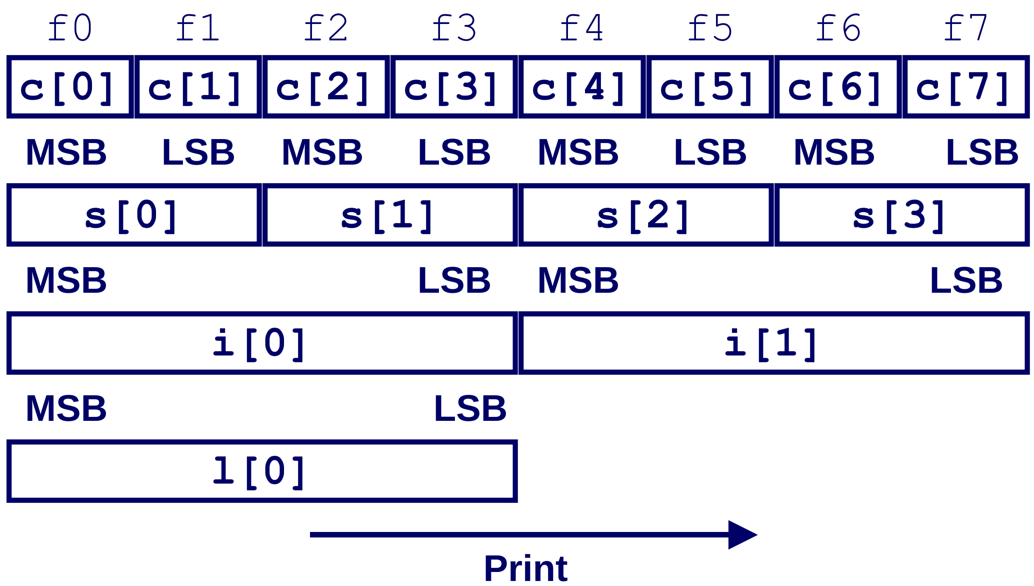


Output on Pentium:

```
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

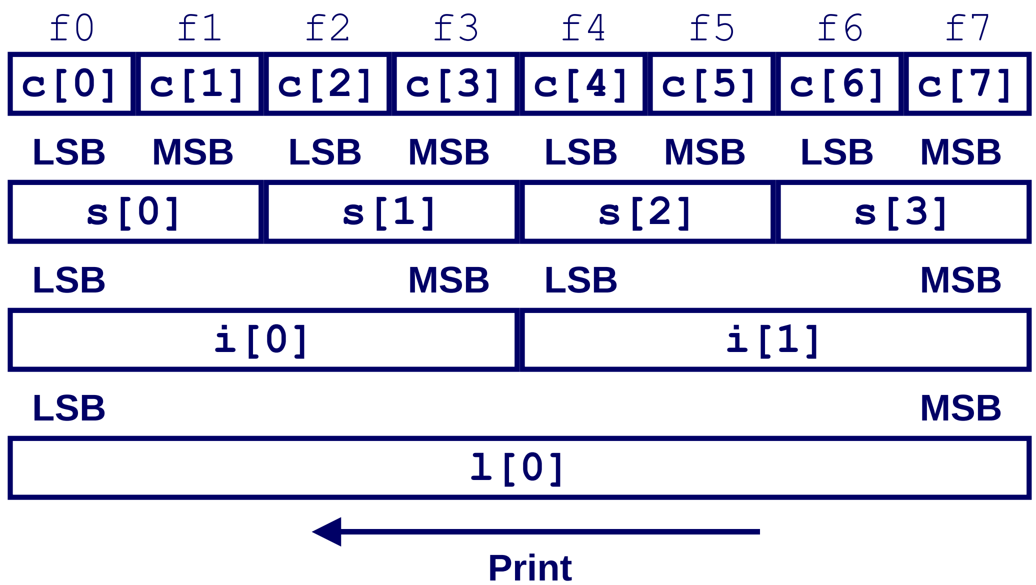


Output on Sun:

```
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