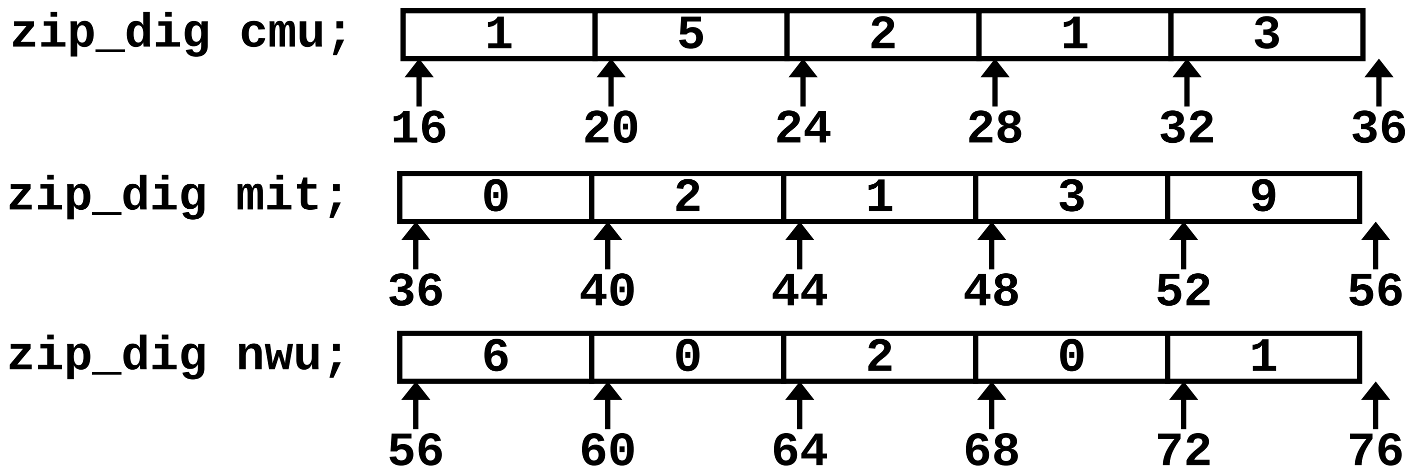
Referencing Examples



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`	`6`	No
`mit[-1]`	`36 + 4*-1 = 32`	`3`	No
`cmu[15]`	`16 + 4*15 = 76`	`??`	No

- **Out of range behavior implementation-dependent**
  - No guranteed 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

- **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

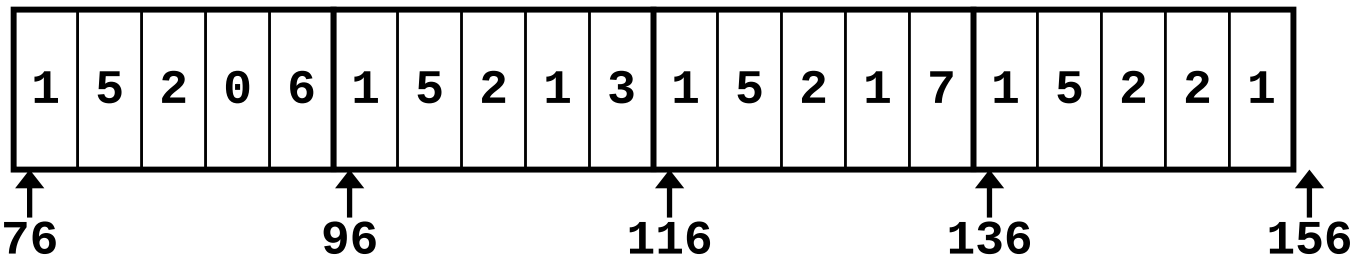
```
int zd2int(zip_dig z)
{
  int zi = 0;
  int *zend = z + 4;
  do {
    zi = 10 * zi + *z;
    z++;
  } while(z <= zend);
  return zi;
}
```

```
  # %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***];**

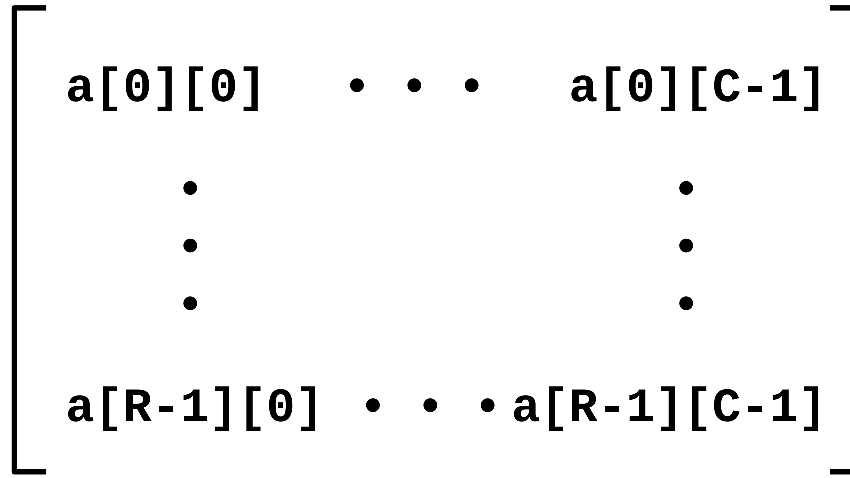
- **Array of data type** *T*
- *R* **rows**
- *C* **columns**
- **Type** *T* **element requires** *K* **bytes**

Array Size

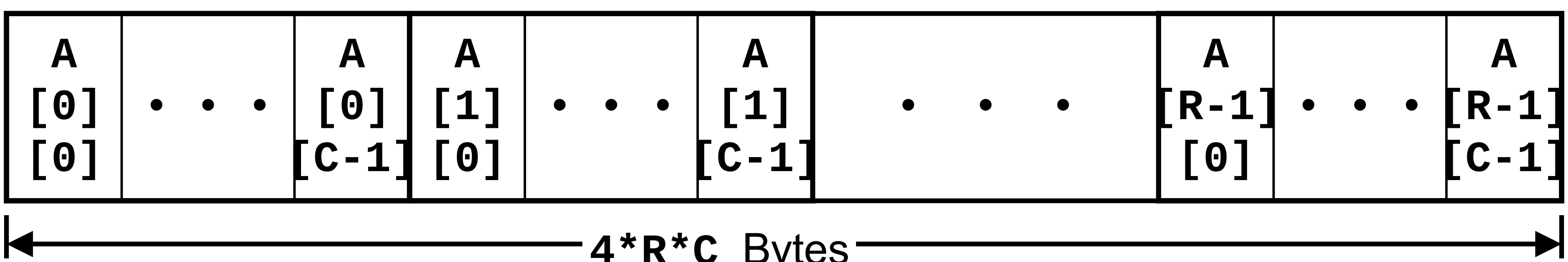
- *R* * *C* * *K* **bytes**

Arrangement

- Row-Major Ordering




```
int A[R][C];
```

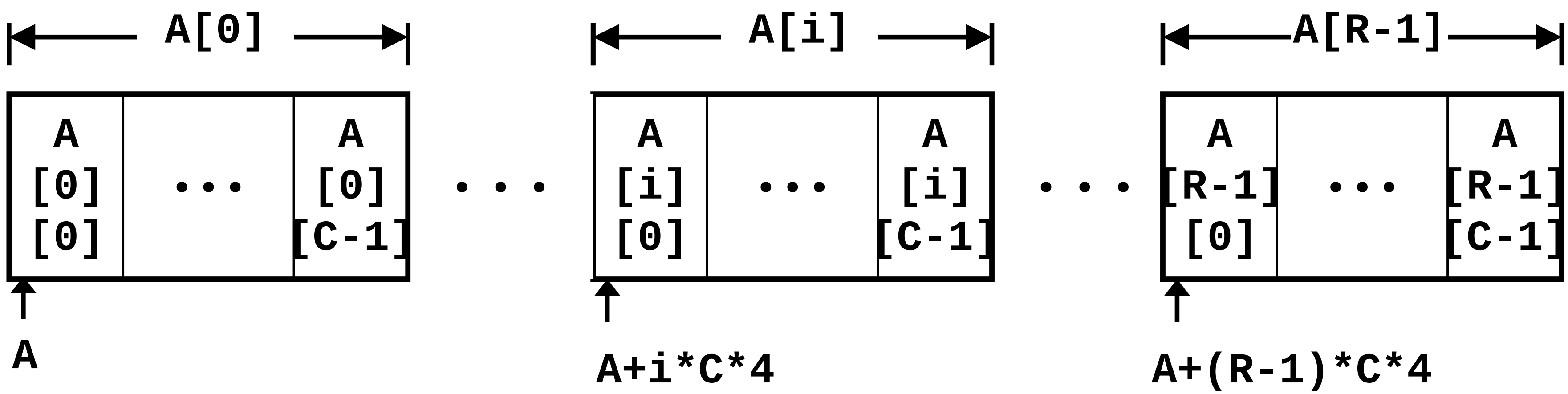


Nested Array Row Access

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

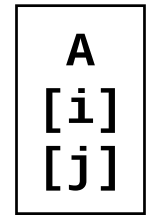
- Computes and returns address
- Compute as pgh `+ 4*(index+4*index)`

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

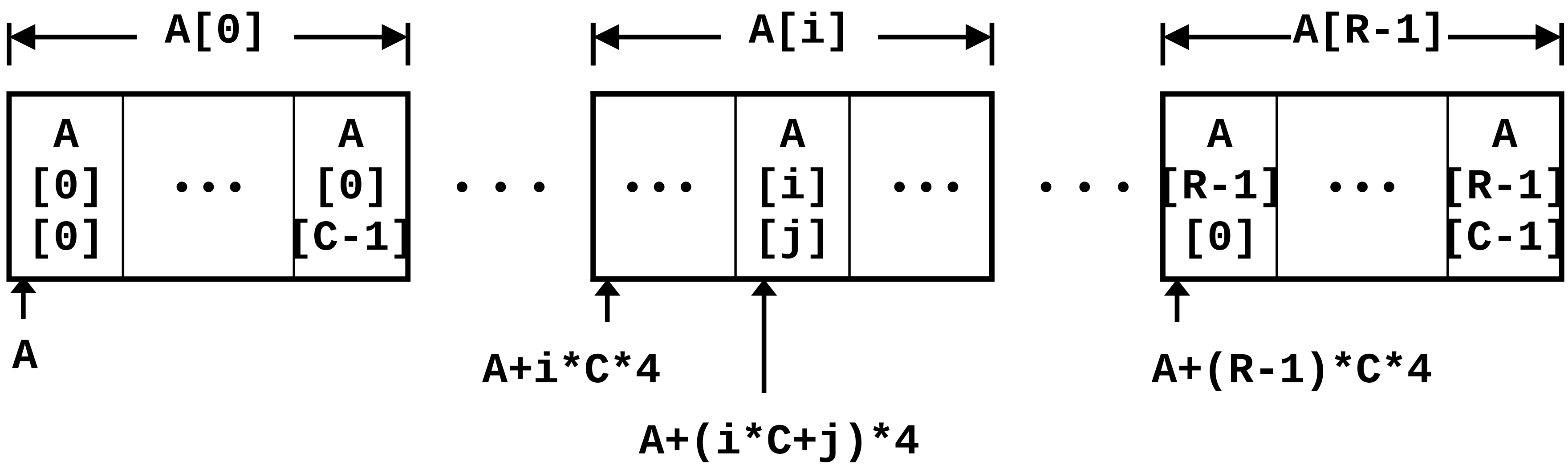
Nested Array Element Access

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

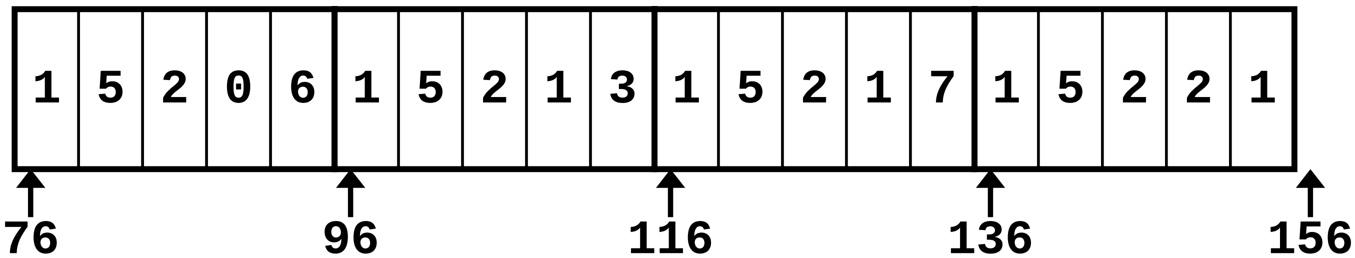
  `pgh + 4*dig + 4*(index+4*index)`
- `movl` performs memory reference

```
# %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)
```

`Note: One Memory Fetch`

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

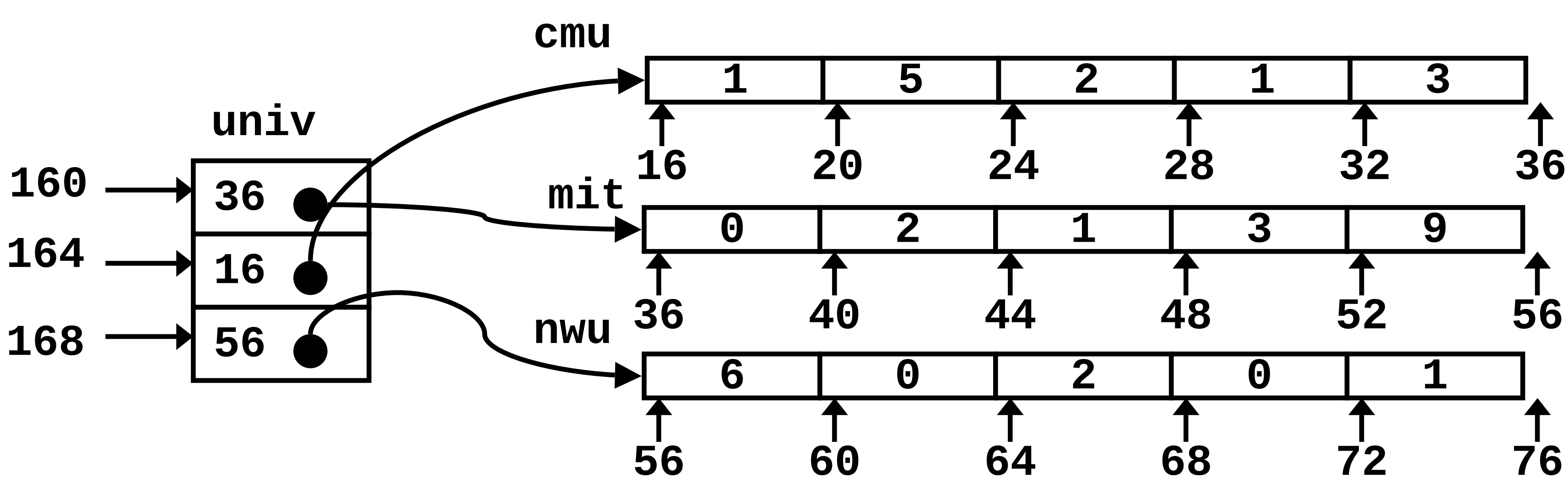
- Code does not do any bounds checking
- Ordering of elements within array guaranteed

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 nwu = { 6, 0, 2, 0, 1 };
```

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



Referencing “Row” in Multi-Level Array

Row Vector

- **univ[index]** is pointer to array of **int**’s
- Starting address **Mem[univ+4*index]**

```
int* get_univ_zip(int index)
{
  return univ[index];
}
```

Code

- Computes address within **univ**
- Reads pointer from memory and returns it

```
# %edx = index
leal 0(,%edx,4),%eax   # 4*index
movl univ(%eax),%eax   # *(univ+4*index)
```

Accessing Element in Multi-Level Array

Computation

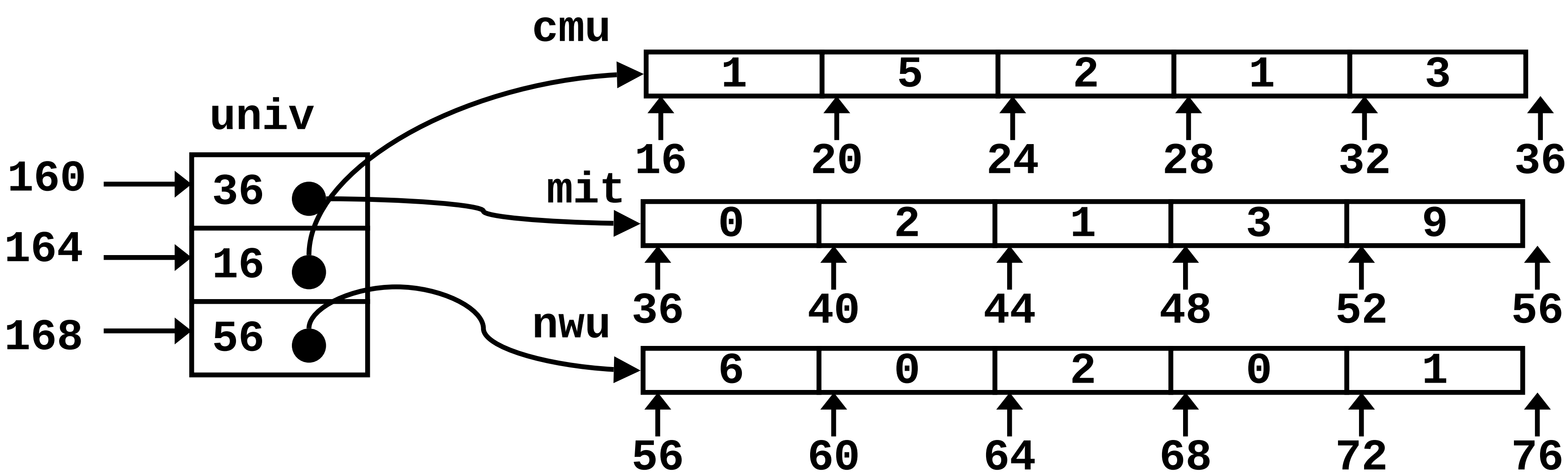
- **Element access** **`Mem[Mem[univ+4*index]+4*dig]`**
- **Must do two memory reads**
  - First get pointer to row array
  - Then access element within array

```
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]
```

`Note: Two Memory Fetches`

Strange Referencing Examples



Reference	Address	Value	Guaranteed?
`univ[2][3]`	`56+4*3 = 68`	`0`	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`	`2`	No

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

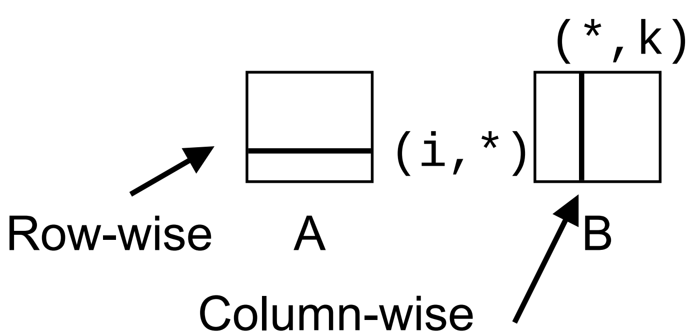
Using Nested Arrays

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)]
```

Structures

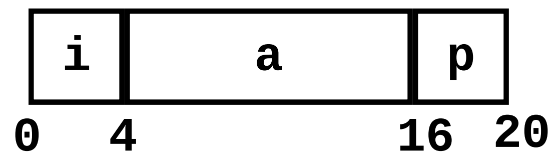
Hidden C++ fields
vtable pointer
typeinfo field

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

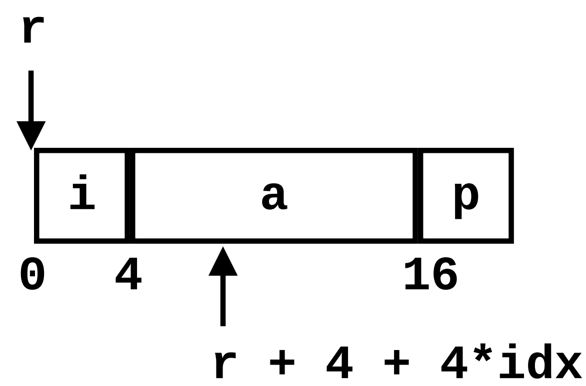
```
void
set_i(struct rec *r,
      int val)
{
  r->i = val;
}
```

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

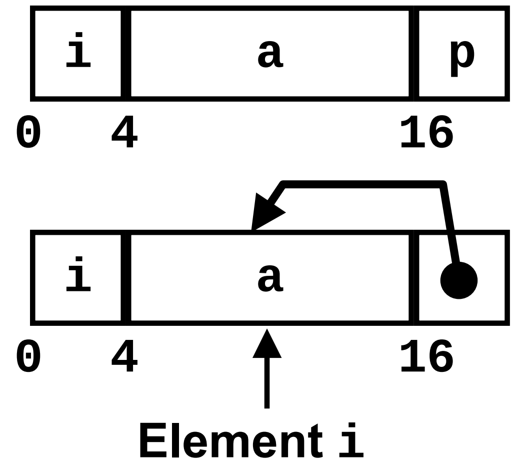
```
int *
find_a
 (struct rec *r, int idx)
{
  return &r->a[idx];
}
```

```
# %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:

- **<u>1 byte</u> (e.g., `char`)**
  - no restrictions on address
- **<u>2 bytes</u> (e.g., `short`)**
  - lowest 1 bit of address must be 0_2
- **<u>4 bytes</u> (e.g., `int`, `float`, `char *`, etc.)**
  - lowest 2 bits of address must be 00_2
- **<u>8 bytes</u> (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
- **<u>12 bytes</u> (`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**

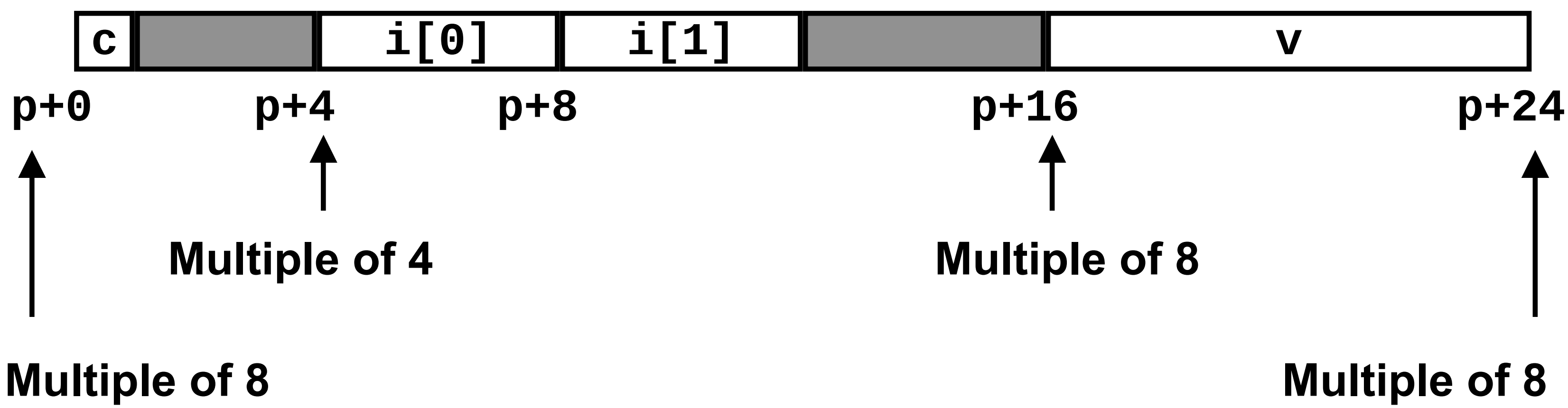
Overall Structure Placement

- **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**

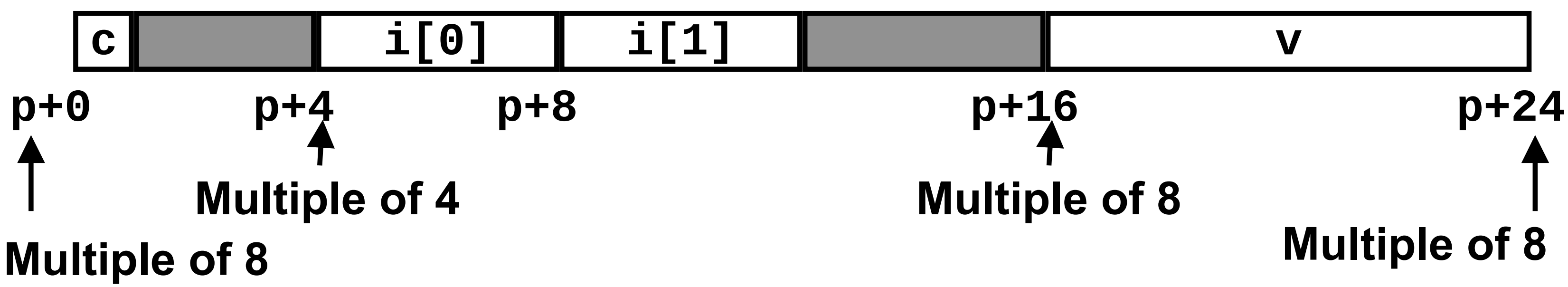


Linux vs. Windows

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

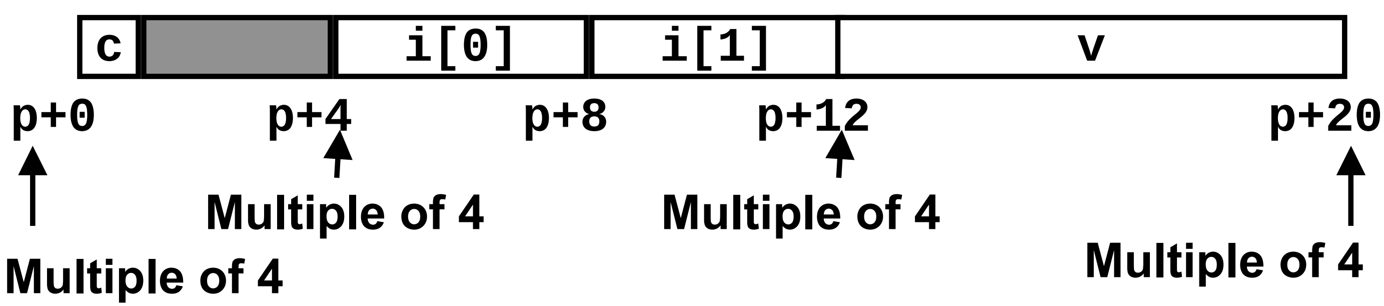
Windows (including Cygwin):

- K = 8, due to `double` element



Linux:

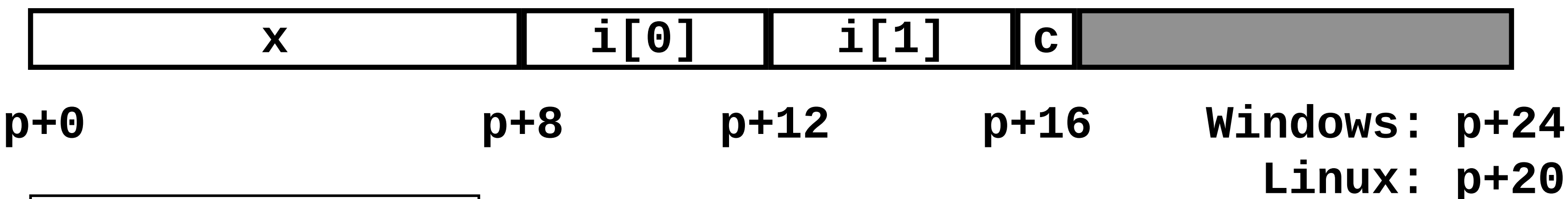
- K = 4; `double` treated like a 4-byte data type



Effect of Overall Alignment Requirement

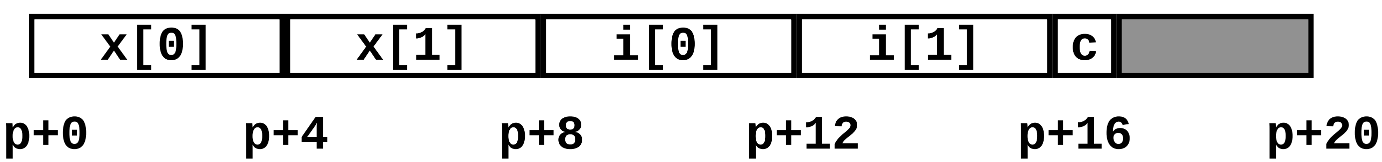
```
struct S2 {
  double x;
  int i[2];
  char c;
} *p;
```

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




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

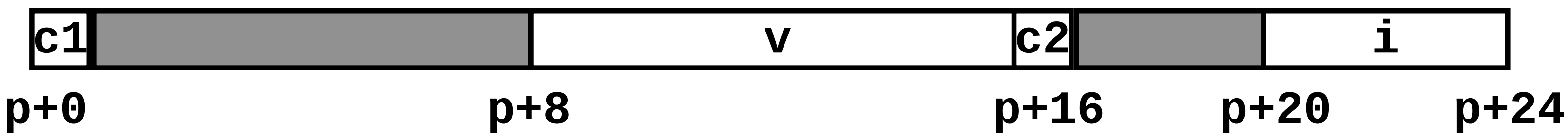
p must be multiple of 4 (in either OS)



Ordering Elements Within Structure

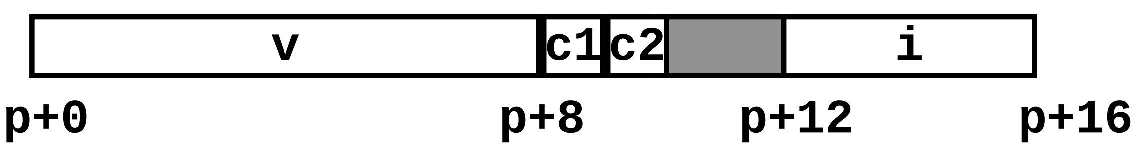
```
struct S4 {
  char c1;
  double v;
  char c2;
  int i;
} *p;
```

10 bytes wasted space in Windows




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

2 bytes wasted space

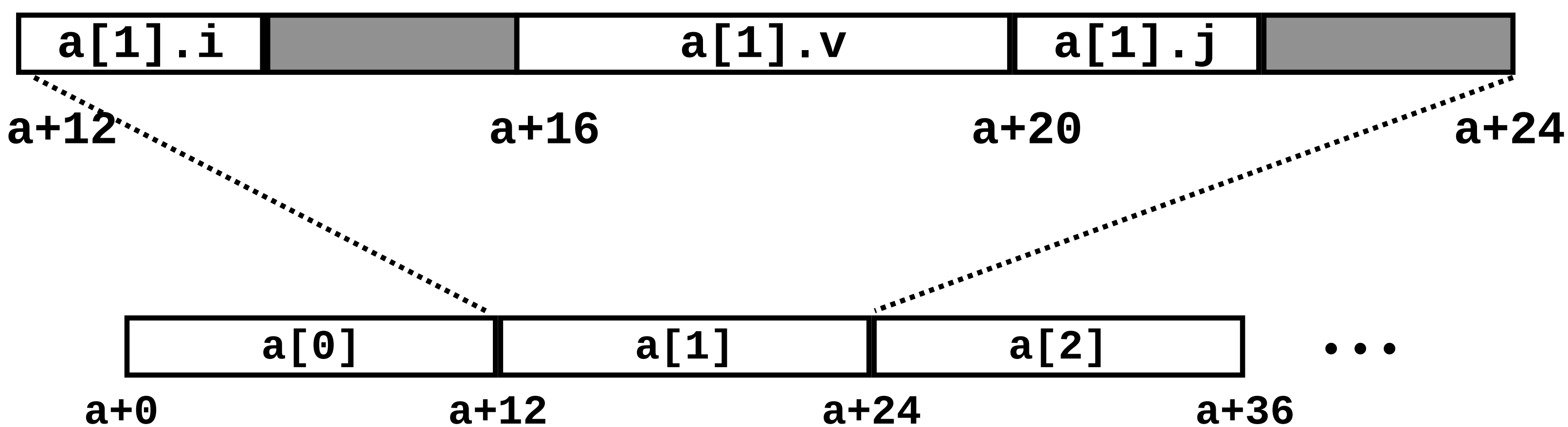


Arrays of Structures

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];
```



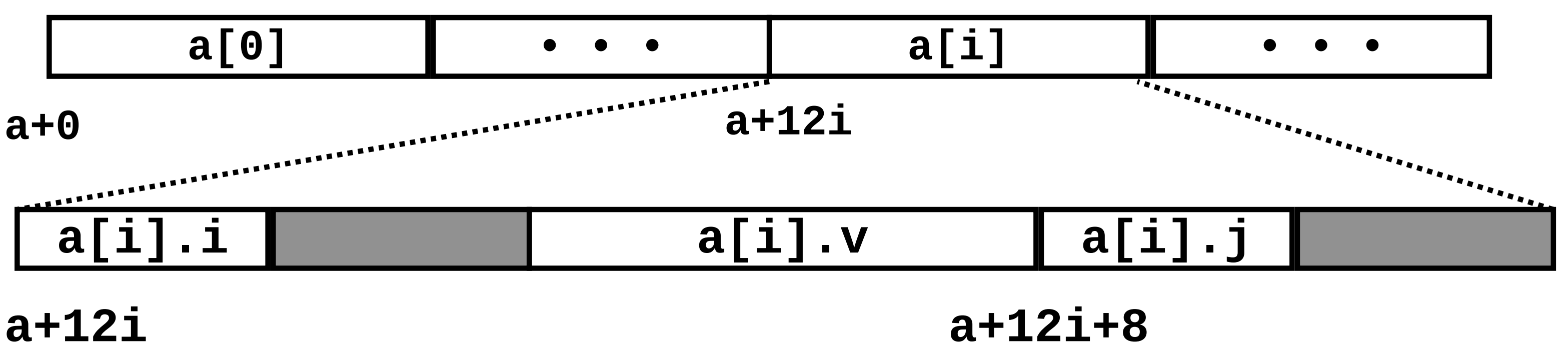
Accessing Element within Array

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

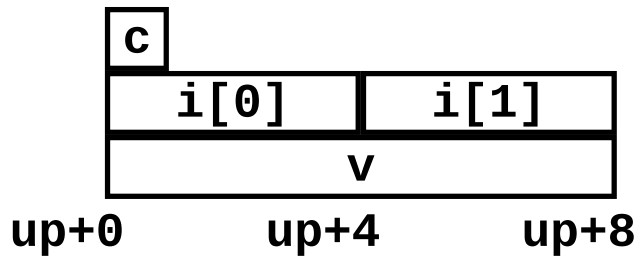


Union Allocation

Principles

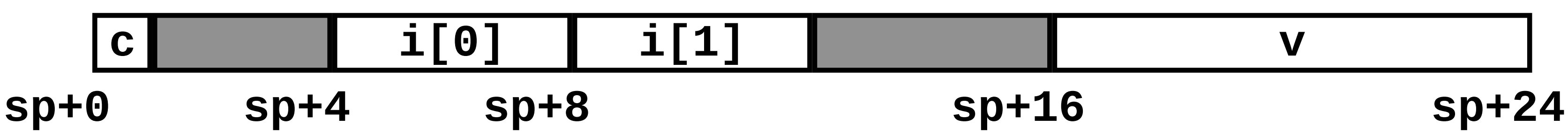
- Overlay union elements
- Allocate according to largest element
- Can only use one field at a time

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




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

(Windows alignment)



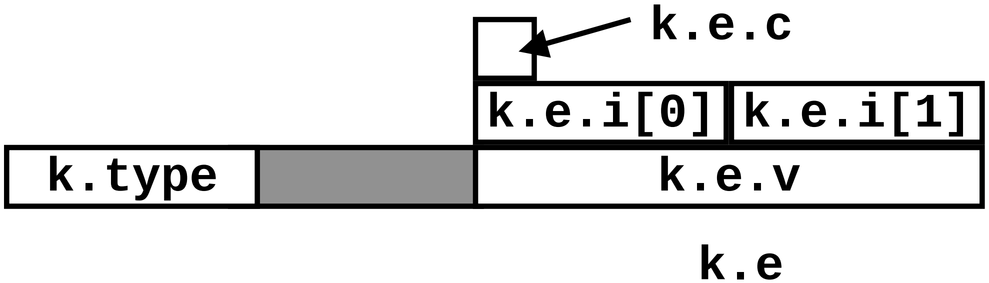
Implementing “Tagged” Union

- **Structure can hold 3 kinds of data**
- **Only one form at any given time**
- **Identify particular kind with flag `type`**

```
typedef enum { CHAR, INT, DBL }
  utype;

typedef struct {
  utype type;
  union {
    char c;
    int i[2];
    double v;
  } e;
} store_ele, *store_ptr;

store_ele k;
```



IA32 Floating Point

History

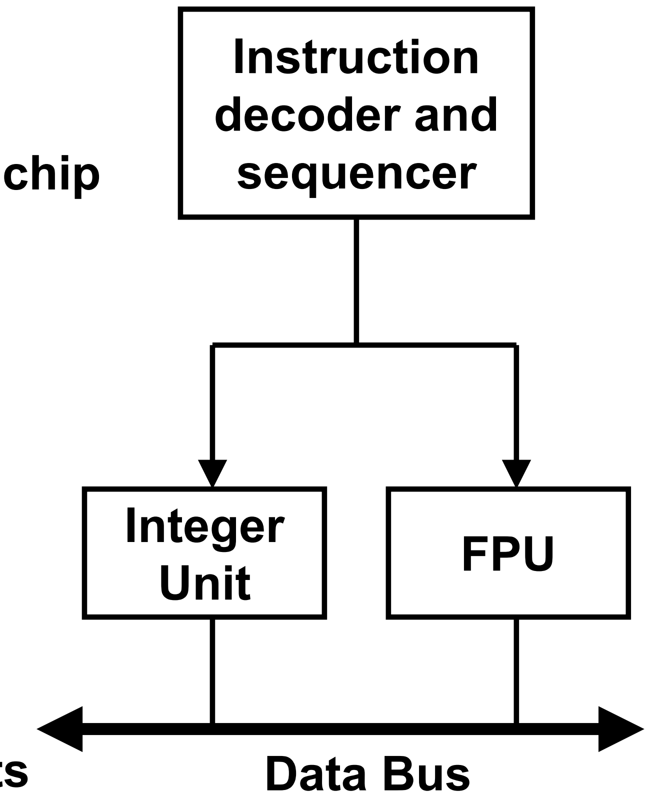
- **8086: first computer to implement IEEE FP**
  - separate 8087 FPU (floating point unit)
- **486: merged FPU and Integer Unit onto one chip**

Summary

- **Hardware to add, multiply, and divide**
- **Floating point data registers**
- **Various control & status registers**

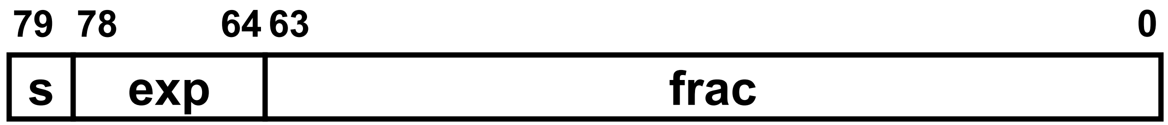
Floating Point Formats

- **single precision (C `float`): 32 bits**
- **double precision (C `double`): 64 bits**
- **extended precision (C `long double`): 80 bits**



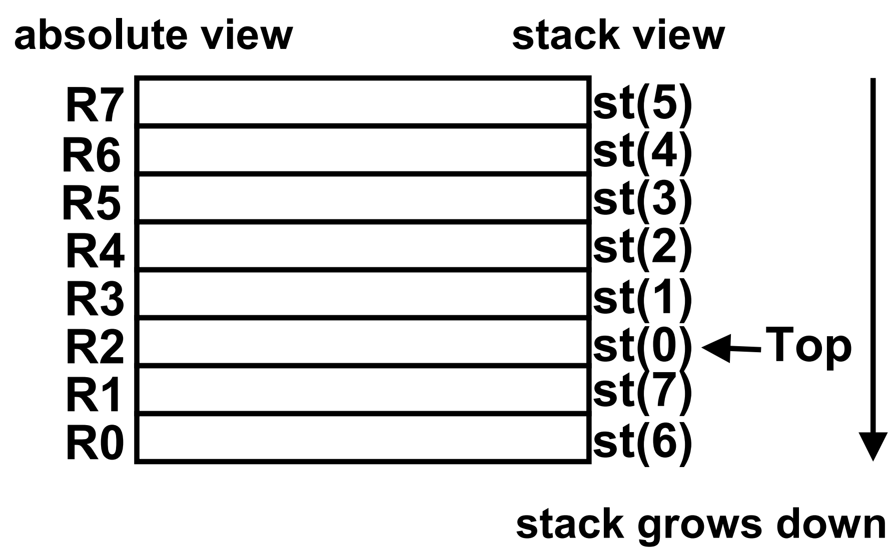
FPU Data Register Stack

FPU register format (extended precision)



FPU register “stack”

- **stack grows down**
  - wraps around from R0 -> R7
- **FPU registers are typically referenced relative to top of stack**
  - st(0) is top of stack (Top)
  - followed by st(1), st(2),…
- **push: increment Top, load**
- **pop: store, decrement Top**
- **Run out of stack? Overwrite!**



FPU instructions

Large number of floating point instructions and formats

- ~50 basic instruction types
- load, store, add, multiply
- sin, cos, tan, arctan, and log!

Sampling of instructions:

Instruction	Effect	Description
fldz	push 0.0	Load zero
flds S	push S	Load single precision real
fmuls S	st(0) <- st(0)*S	Multiply
faddp	st(1) <- st(0)+st(1); pop	Add and pop

Floating Point Code Example

Compute Inner Product of Two Vectors

- **Single precision arithmetic**
- **Scientific computing and signal processing workhorse**

```
float ipf (float x[],
           float y[],
           int n)
{
  int i;
  float result = 0.0;

  for (i = 0; i < n; i++) {
    result += x[i] * y[i];
  }
  return result;
}
```

```
   pushl %ebp                 # setup
   movl %esp,%ebp
   pushl %ebx

   movl 8(%ebp),%ebx          # %ebx=&x
   movl 12(%ebp),%ecx         # %ecx=&y
   movl 16(%ebp),%edx         # %edx=n
   fldz                       # push +0.0
   xorl %eax,%eax             # i=0
   cmpl %edx,%eax             # if i>=n done
   jge .L3
.L5:
   flds (%ebx,%eax,4)         # push x[i]
   fmuls (%ecx,%eax,4)        # st(0)*=y[i]
   faddp                      # st(1)+=st(0); pop
   incl %eax                  # i++
   cmpl %edx,%eax             # if i<n repeat
   jl .L5
.L3:
   movl -4(%ebp),%ebx         # finish
   leave
   ret                        # st(0) = result
```

Inner product stack trace