# 15-213

*"The course that gives CMU its Zip!"*

# Structured Data I: Homogenous Data

# February 8, 2001

## Topics

- **Arrays**
  - Single
  - Nested
- **Pointers**
  - Multilevel Arrays
- **Optimized Array Code**

# 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` |

## Pointer

- Stored & operated on in general registers

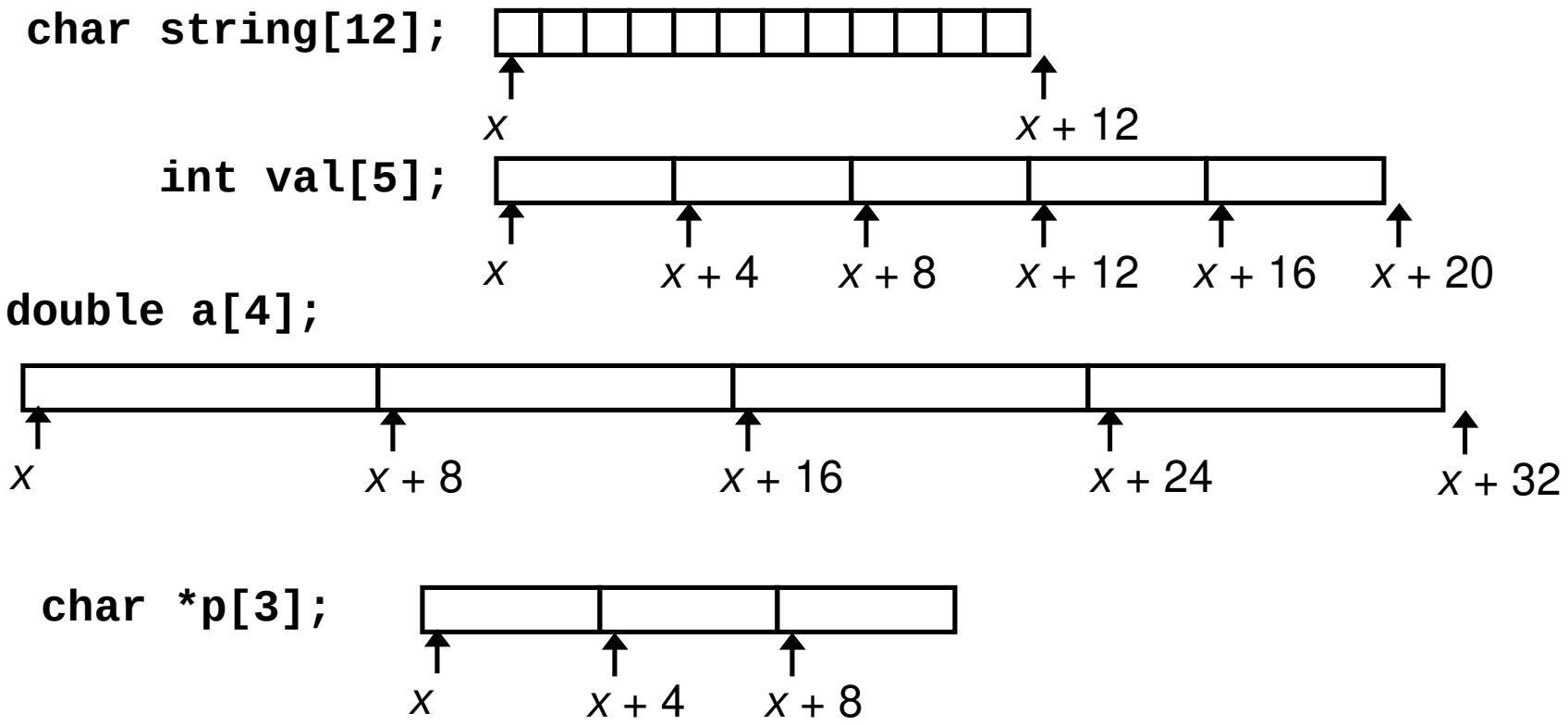
| Intel | GAS | Bytes | C |
|---|---|---|---|
| Double | `l` | 8 | `char *` |

# Array Allocation

## Basic Principle

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

- **Array named A of data type *T* with *L* elements**
- **Contiguously allocated region of *L* * sizeof(*T*) bytes**

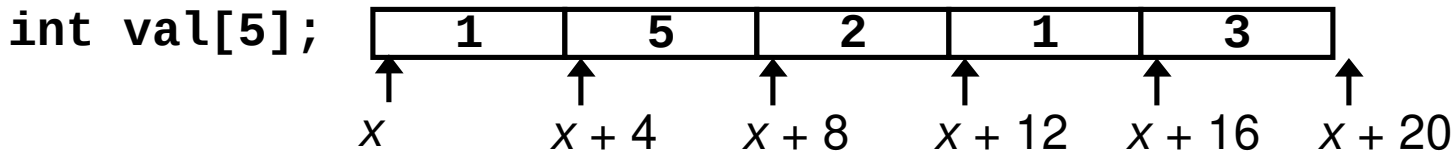


# Array Access

## Basic Principle

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

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

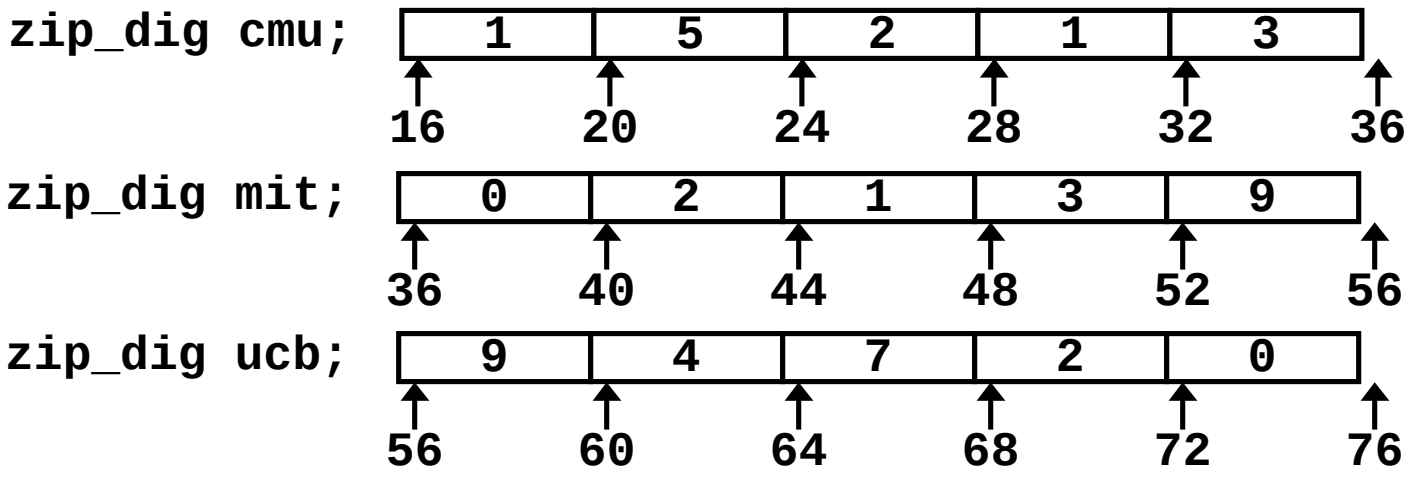



| Reference | Type | Value |
|---|---|---|
| `val[4]` | `int` | **3** |
| `val` | `int *` | *x* |
| `val+1` | `int *` | *x* **+ 4** |
| `&val[2]` | `int *` | *x* **+ 8** |
| `val[5]` | `int` | **??** |
| `*(val+1)` | `int` | **5** |
| `val +` *i* | `int *` | *x* **+ 4** *i* |

# Array Example

```
typedef int zip_dig[5];

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




## Notes

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

# Array Accessing Example

## Computation

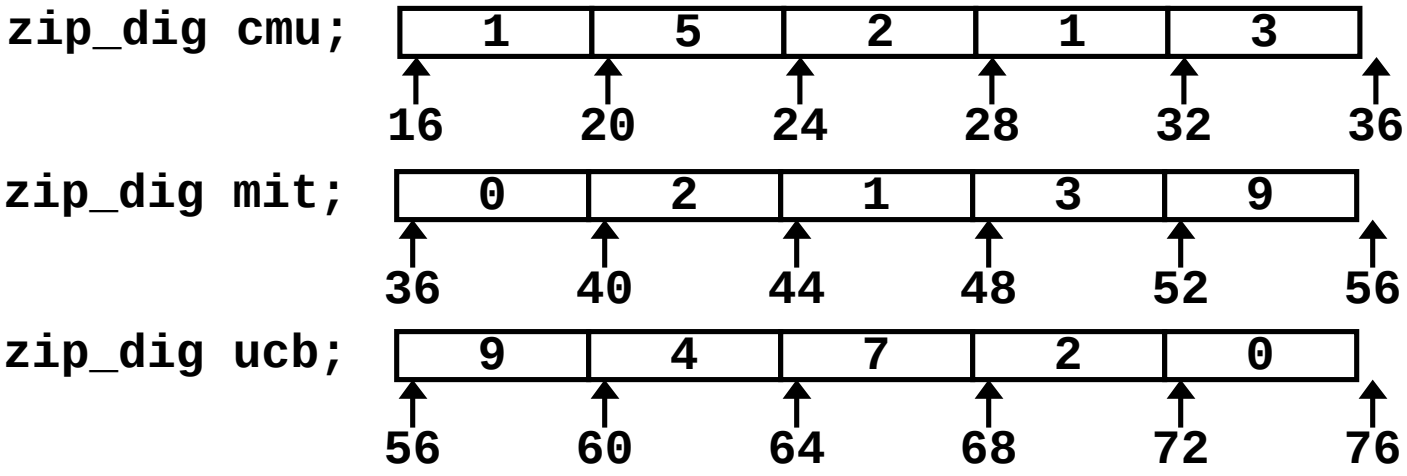
- Register %edx contains starting address of array
- Register %eax contains array index
- Desired digit at 4*%eax + %edx
- Use memory reference (%edx,%eax,4)

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

## Memory Reference Code

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

# Referencing Examples




**Code Does Not Do Any Bounds Checking!**

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

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

# Array Loop Example

## Original Source

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

## Transformed Version

- **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

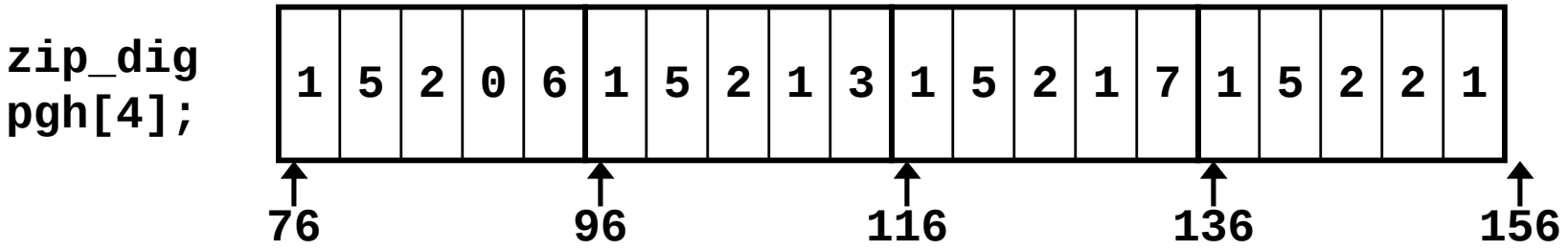
- `10*zi + *z` implemented as `*z + 2*(zi+4*zi)`
- `z++` increments by 4

```
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 }};
```



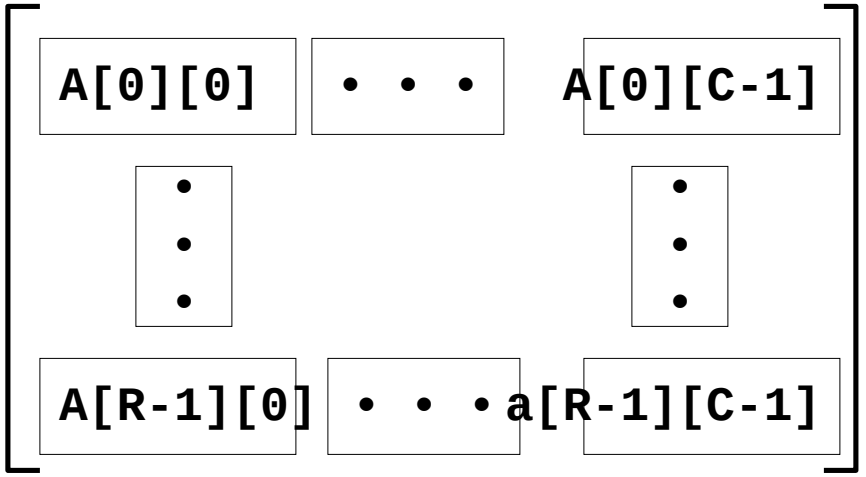

- **Declaration "`zip_dig pgh[4]`" equivalent to "`int pgh[4][5]`"**
  - Variable **pgh** denotes array of 4 elements
    - » Allocated contiguously
  - Each element is an array of 5 **`int`**'s
    - » Allocated contiguously
- **"Row-Major" ordering of all elements guaranteed**

# Nested Array Allocation

## Declaration

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

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



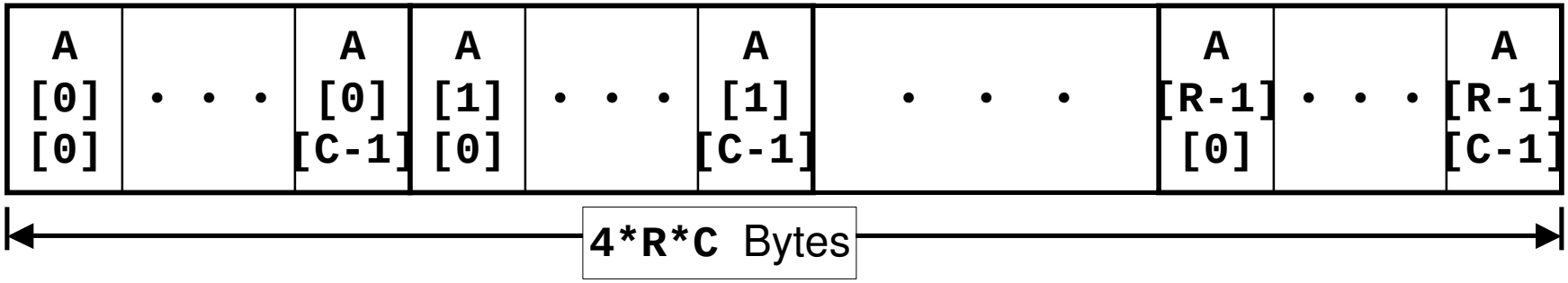

## Array Size

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

## Arrangement

- Row-Major Ordering

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

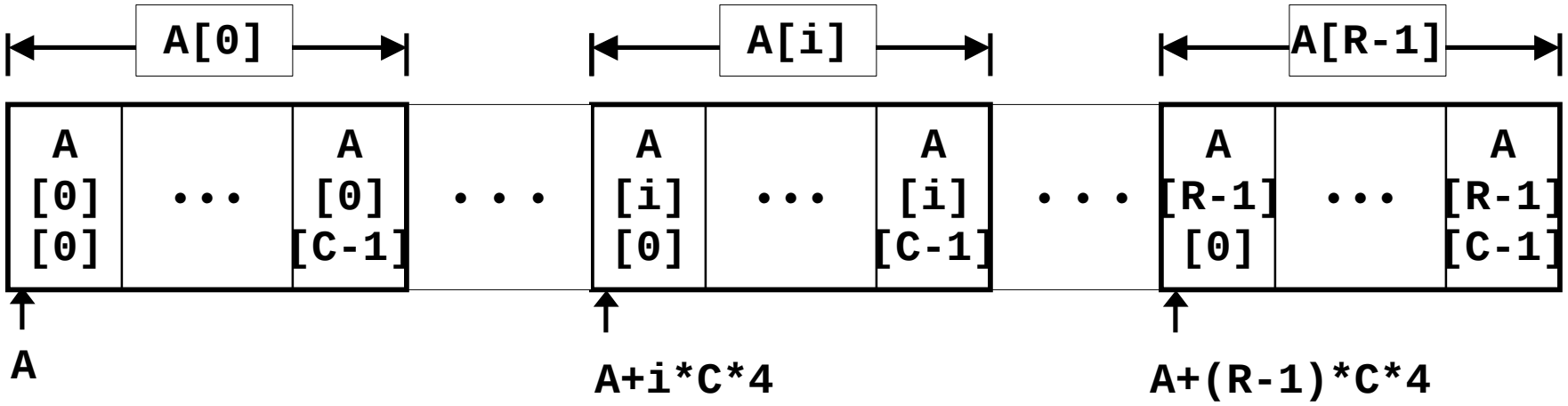


# Nested Array Row Access

## 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

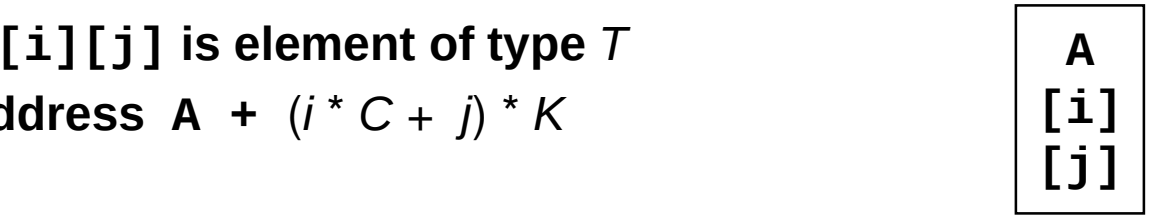
- Computes and returns address
- Compute as `pgh + 4*(index+4*index)`

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

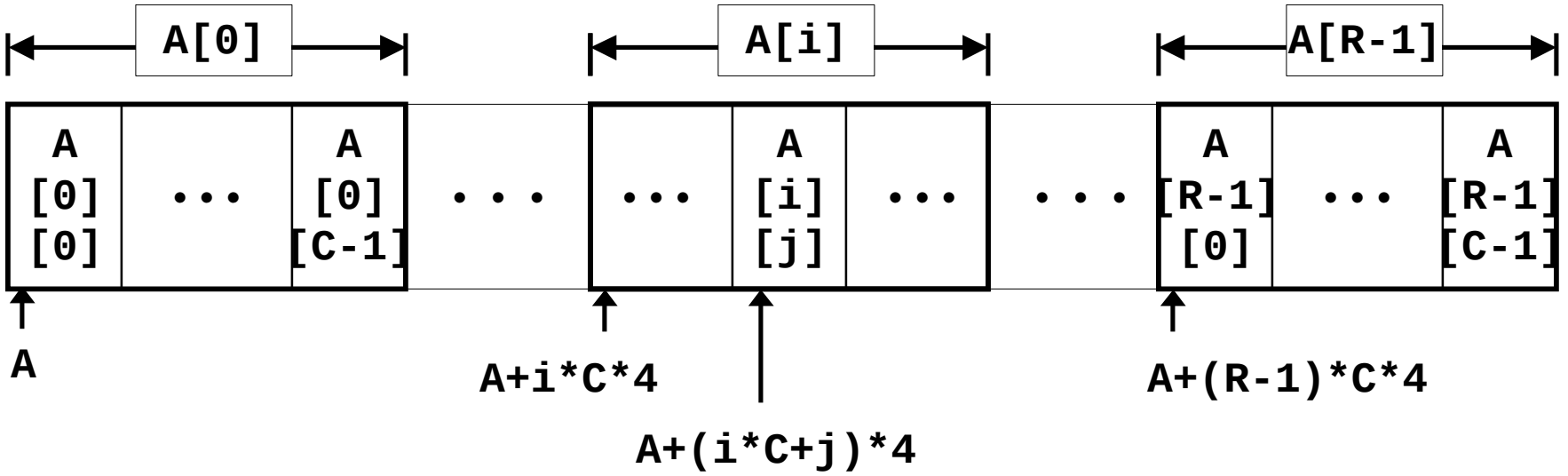
# Nested Array Element Access

## 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

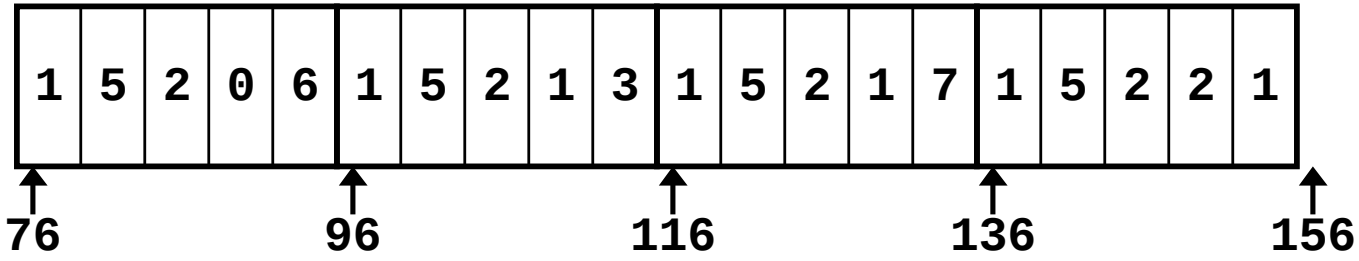
  `pgh + 4*dig + 4*(index+4*index)`

- `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)
```

# 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 |

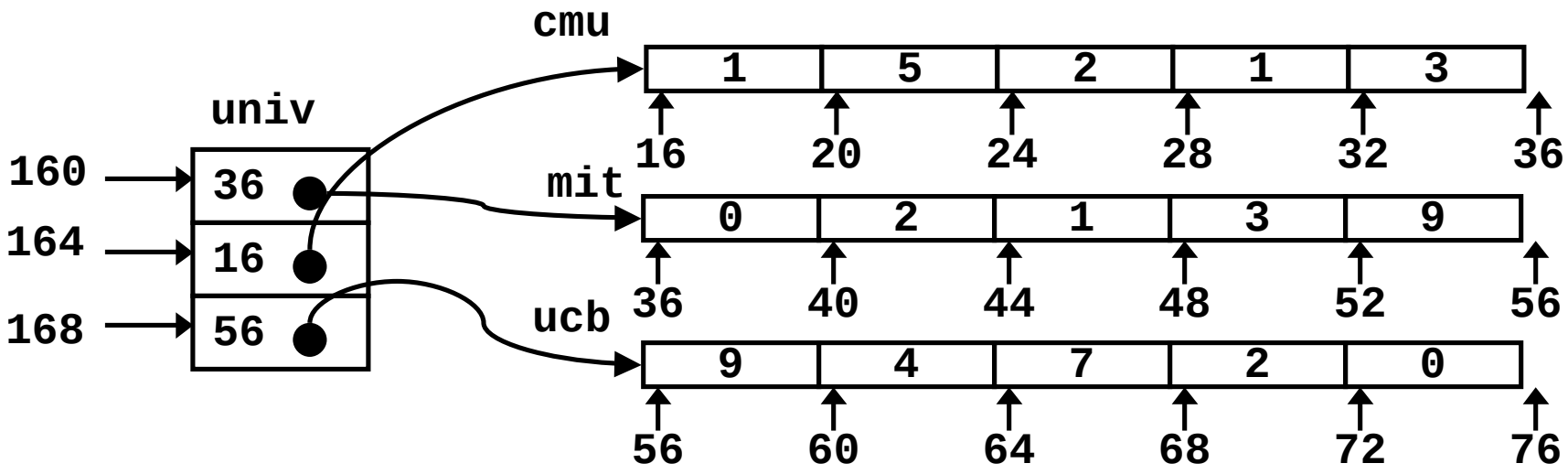
- Code does not do any bounds checking
- Ordering of elements within array guaranteed

# 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};
```



# 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

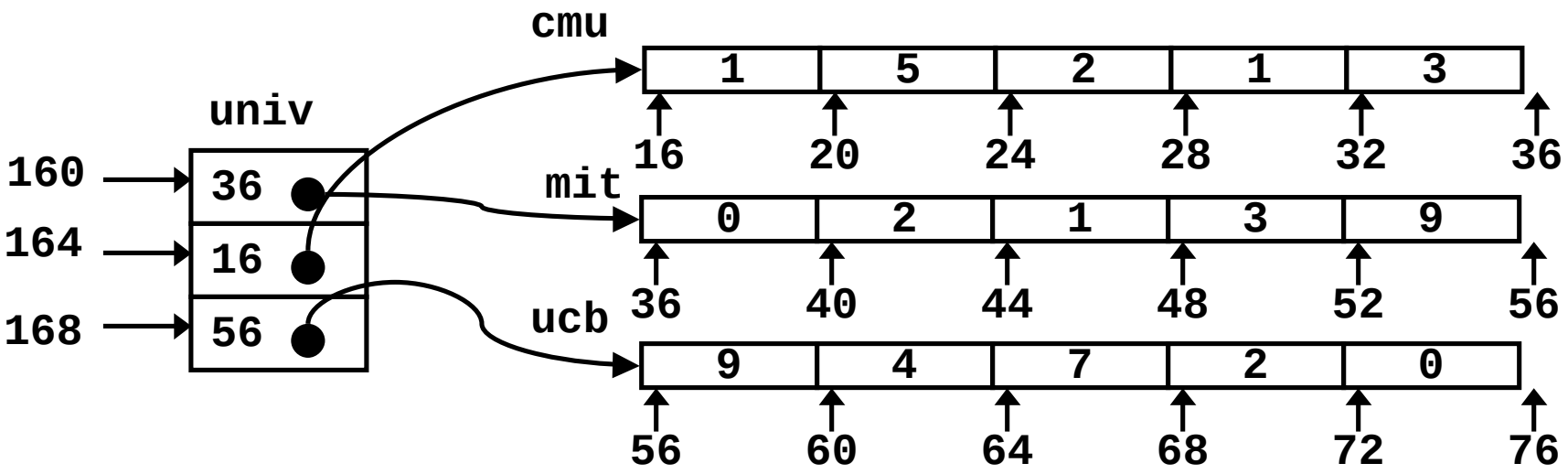
## Computation

- **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[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

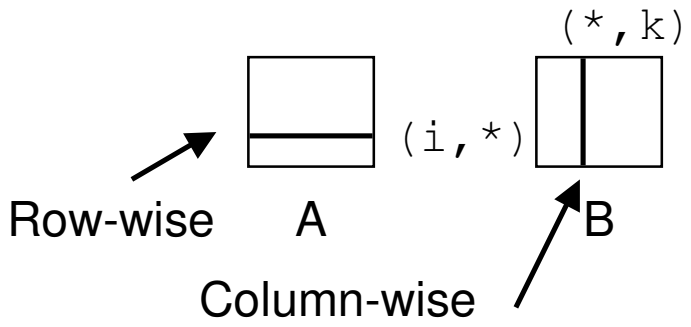
# Using Nested Arrays

## 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];
}
```

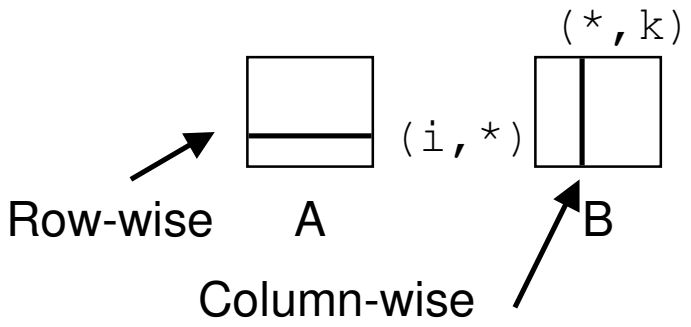
```
movl 12(%ebp),%eax      # i
movl 8(%ebp),%edx       # a
imull 20(%ebp),%eax     # n*i
addl 16(%ebp),%eax      # n*i+j
movl (%edx,%eax,4),%eax # Mem[a+4*(i*n+j)]
```

# 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;
}
```



# Optimizing Dynamic Array Multiplication

## Optimizations

- Performed when set optimization level to `-O2`

## Code Motion

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

## Strength Reduction

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

## Performance

- Compiler can optimize regular access patterns

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

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

# Dynamic Array Multiplication

```
{
  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;
}
```

| | |
|---|---|
| %ecx | result |
| %edx | j |
| %esi | n |
| %ebx | jTnPk |
| Mem[-4(%ebp)] | iTn |

```
.L44:                           # loop
  movl -4(%ebp),%eax            # iTn
  movl 8(%ebp),%edi             # a
  addl %edx,%eax                # iTn+j
  movl (%edi,%eax,4),%eax       # a[iTn+j]
  movl 12(%ebp),%edi            # b
  incl %edx                     # j++
  imull (%edi,%ebx,4),%eax      # b[jTnPk]*a[iTn+j]
  addl %eax,%ecx                # result += ..
  addl %esi,%ebx                # jTnPk += n
  cmpl %esi,%edx                # j : n
  jl .L44                       # if < goto loop
```

## Inner Loop

# 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**
  - code motion
  - reduction in strength