15-213

Structured Data I: Homogenous Data
Feb. 10, 2000

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

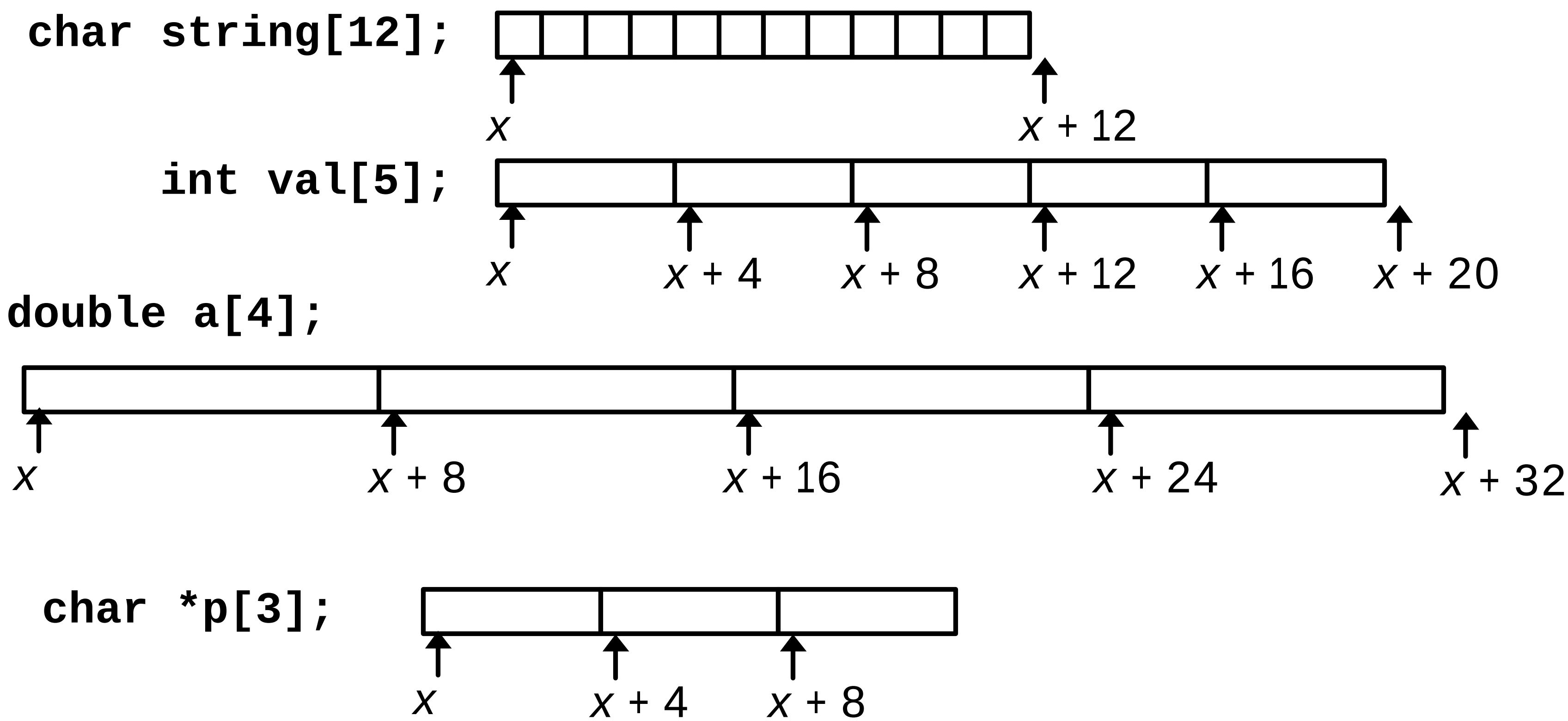
Intel	GAS	Bytes	C
Single	s	4	float
Double	l	8	double
Extended		10	--

Array Allocation

Basic Principle

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

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



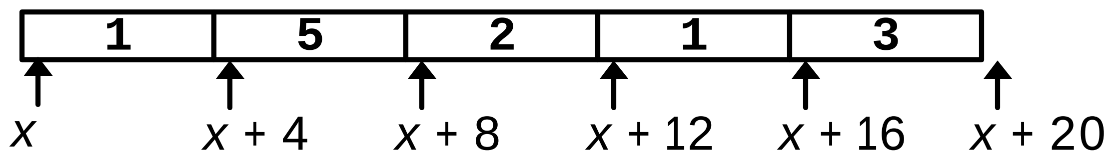
Array Access

Basic Principle

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

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

int val[5];

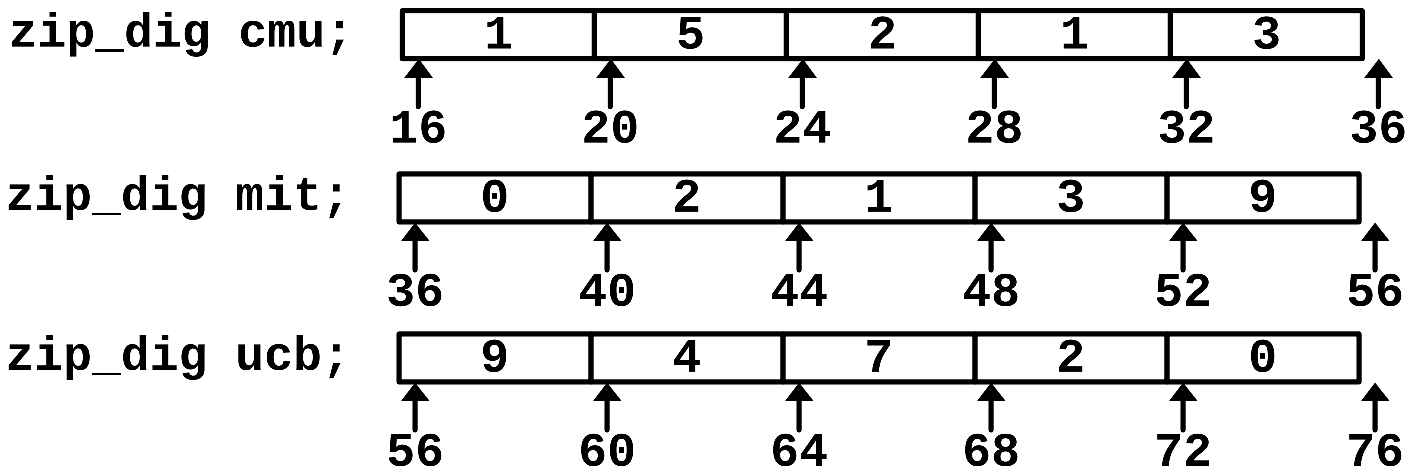


Reference	Type	Value
val[4]	int	3
val	int *	*x*
val+1	int *	*x* + 4
&val[2]	int *	*x* + 8
val[5]	int	??
*(val+1)	int	5
val + *i*	int *	*x* + 4 *i*

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

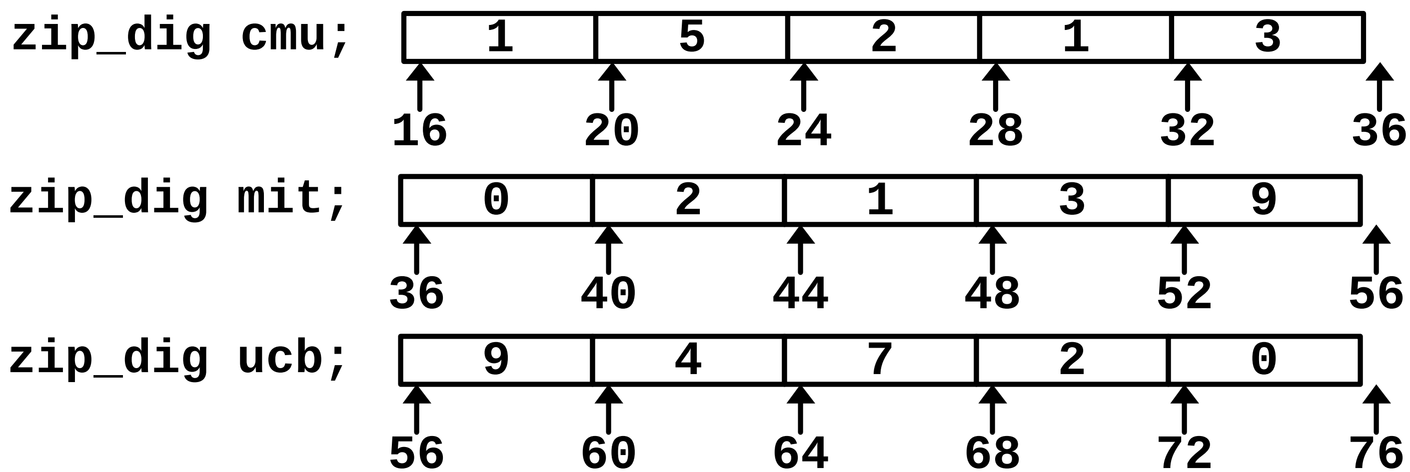
- Register `%edx` contains starting address of array
- Register `%eax` contains array index
- Desired digit at `4*%eax + %edx`
- Use memory reference `(%edx,%eax,4)`

```
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



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 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

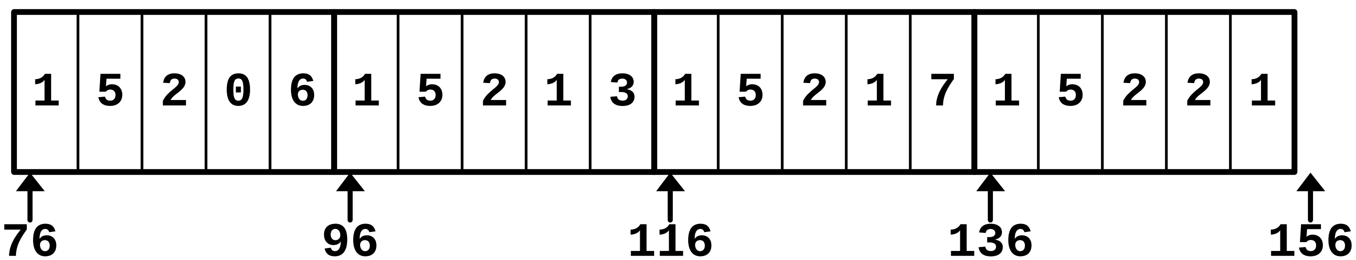
```
int zd2int(zip_dig z)
{
  int zi = 0;
  int *zend = z + 4;
  do {
    zi = 10 * zi + *z;
    z++;
  } while(z <= zend);
  return zi;
}
```

```
  # %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

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

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

A [0] [0]	• • •	A [0] [C-1]	A [1] [0]	• • •	A [1] [C-1]	• • •	A [R-1] [0]	• • •	A [R-1] [C-1]

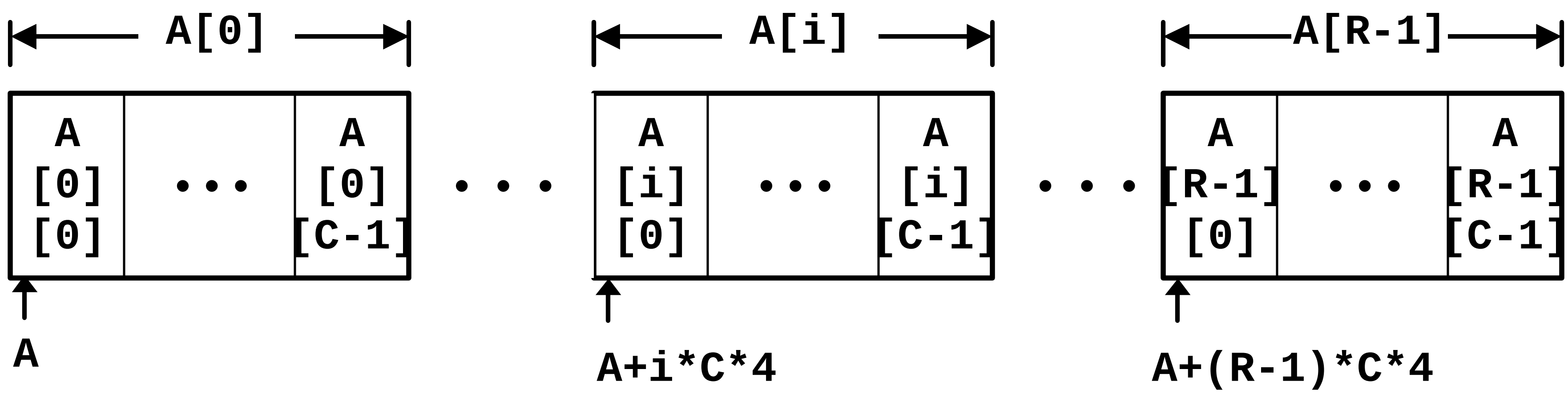
4*R*C Bytes

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

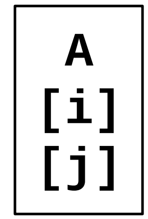
- Computes and returns address
- Compute as `pgh + 4*(index+4*index)`

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

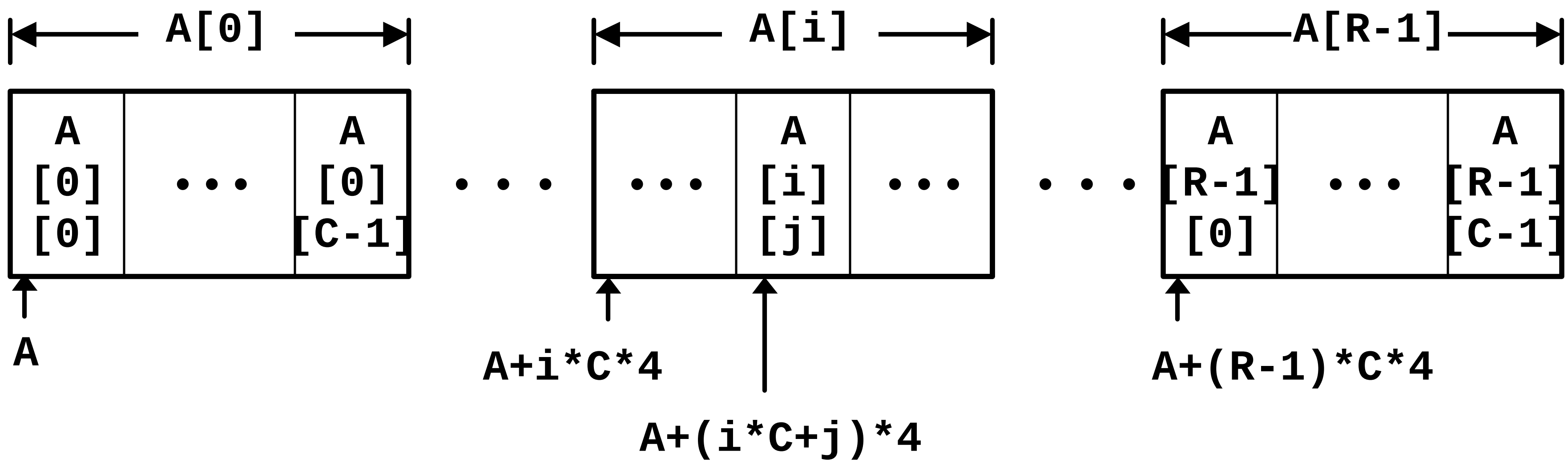
Nested Array Element Access

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`

```
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];
```

1	5	2	0	6	1	5	2	1	3	1	5	2	1	7	1	5	2	2	1

76 96 116 136 156

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

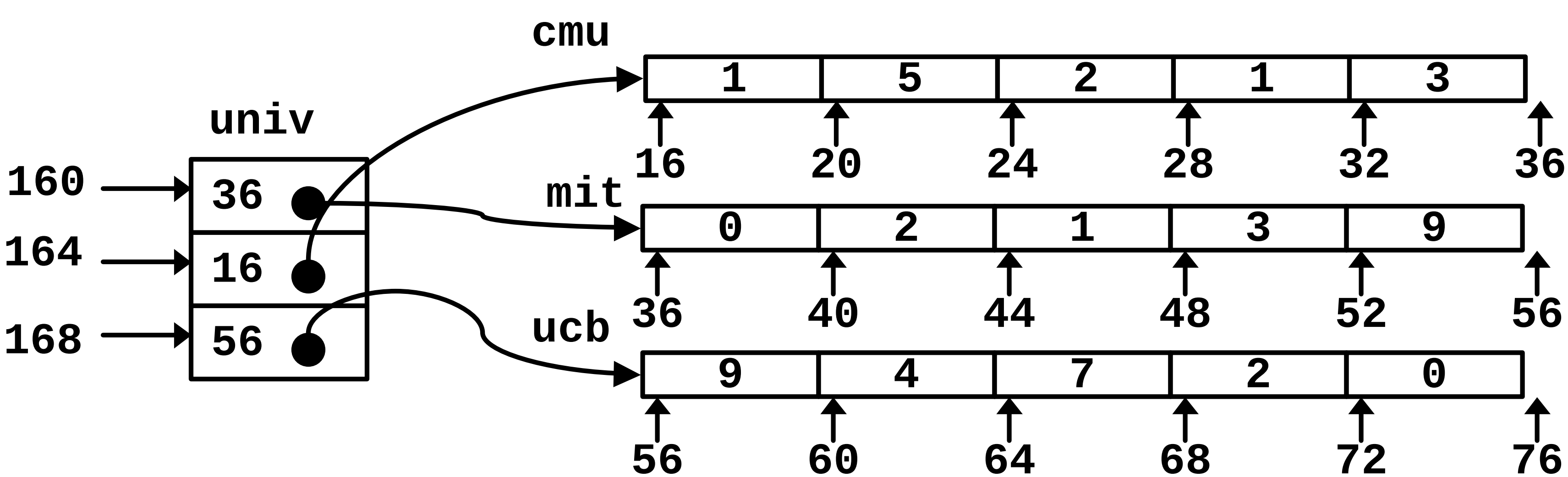
- Code does not do any bounds checking
- Ordering of elements within array guaranteed

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

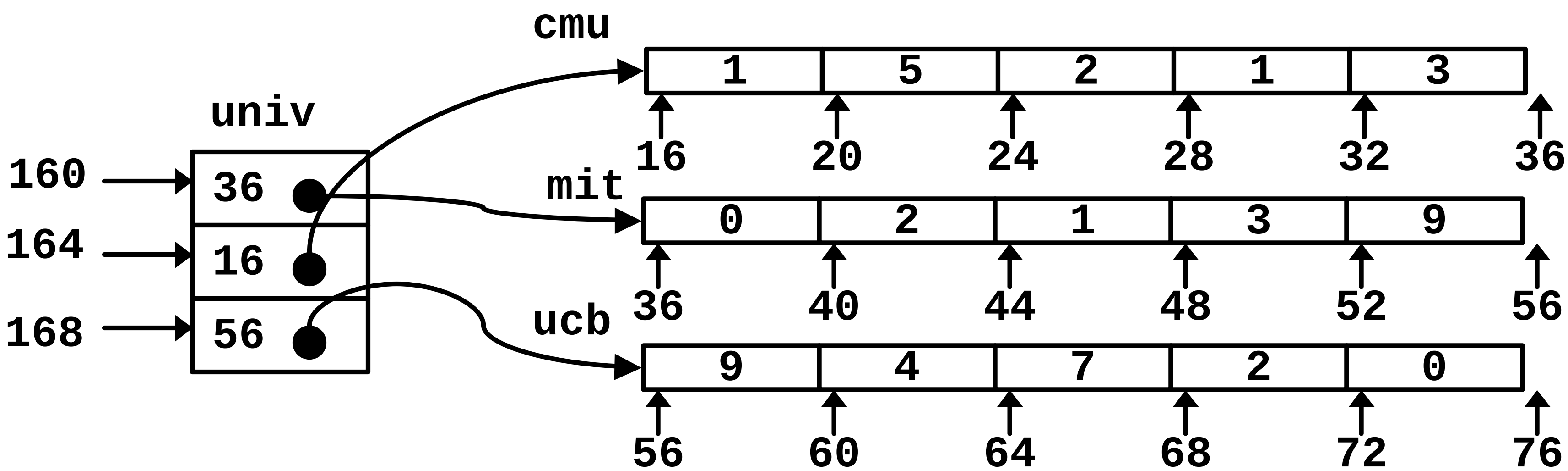
Computation

- **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[...+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

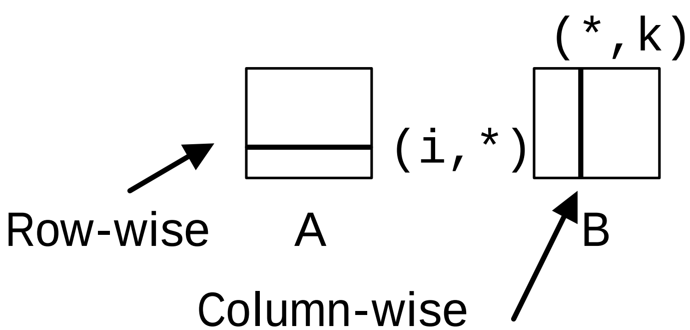
Using Nested Arrays

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];
}
```

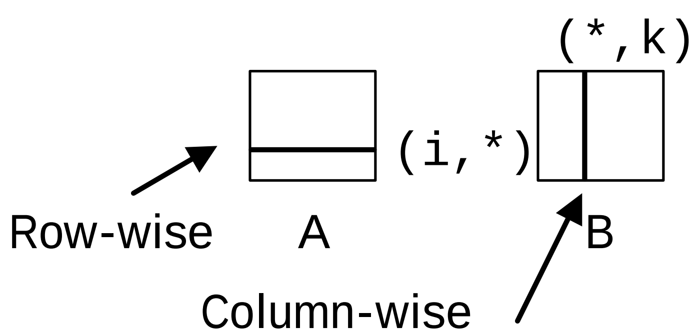
```
movl 12(%ebp),%eax      # i
movl 8(%ebp),%edx       # a
imull 20(%ebp),%eax     # n*i
addl 16(%ebp),%eax      # n*i+j
movl (%edx,%eax,4),%eax # Mem[a+4*(i*n+j)]
```

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[..]
  movl 12(%ebp),%edi           # b
  incl %edx                    # j++
  imull (%edi,%ebx,4),%eax     # b[..]*a[..]
  addl %eax,%ecx               # result += ..
  addl %esi,%ebx               # jTnPk += j
  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