The Hardware/Software Interface

CSE351 Spring 2013

Data Structures I: Arrays

Data Structures in Assembly

- **Arrays**
  - One-dimensional
  - Multi-dimensional (nested)
  - Multi-level
- **Structs**
  - Alignment
- **Unions**

Array Allocation

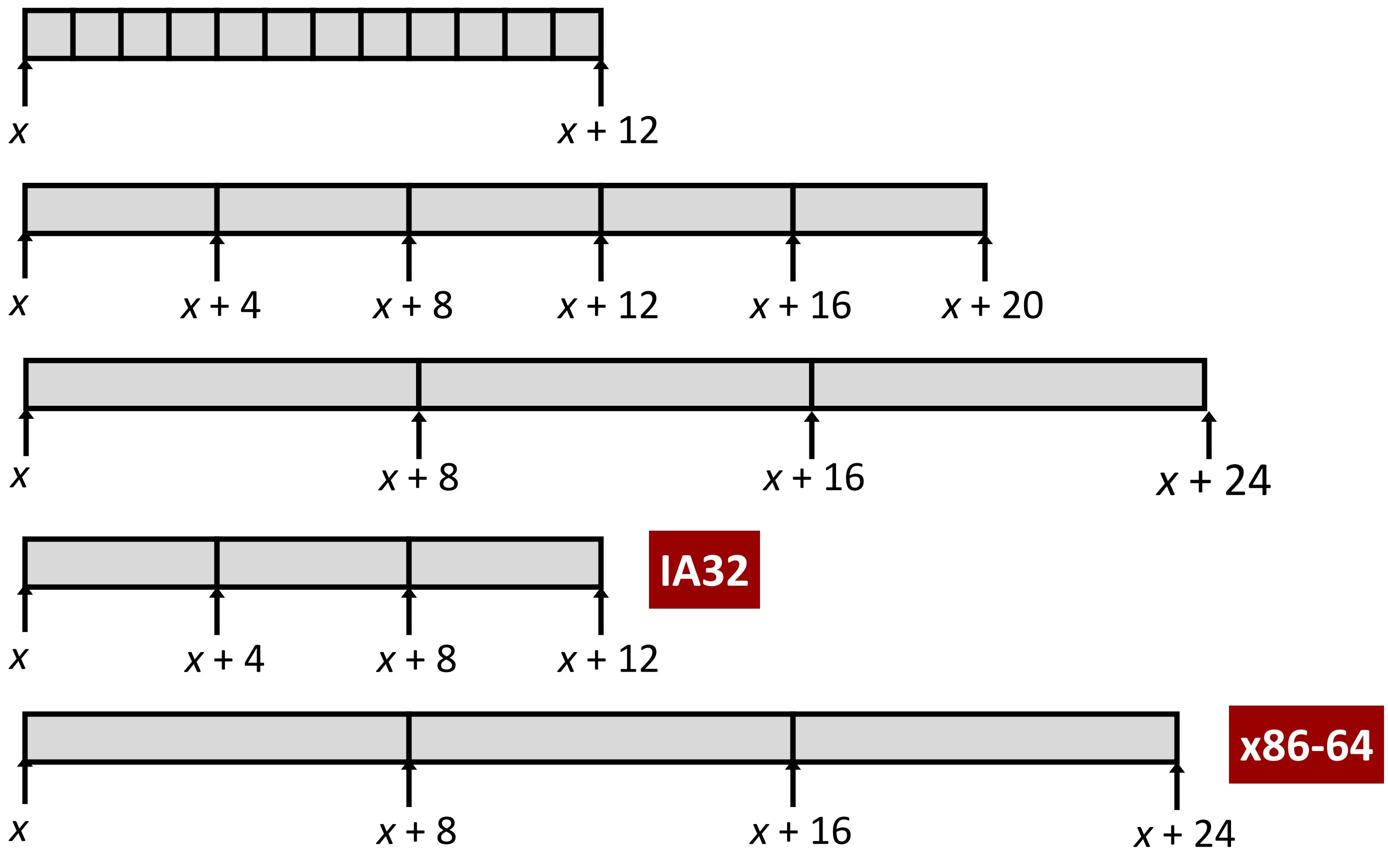
- **Basic Principle**
  - T A[N];
  - Array of data type T and length N
  - *Contiguously* allocated region of N * sizeof(T) bytes

`char string[12];`

`int val[5];`

`double a[3];`

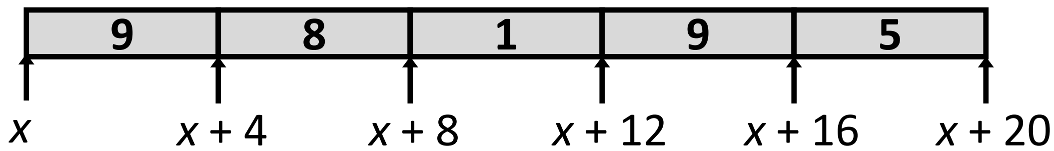
`char* p[3];`
(or `char *p[3];`)



Array Access

- **Basic Principle**
  - T A[N];
  - Array of data type T and length N
  - Identifier A can be used as a pointer to array element 0: Type T*

```
int val[5];
```

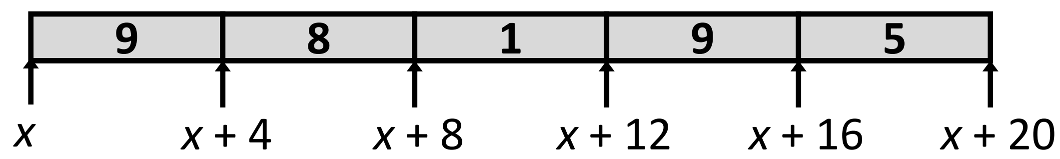


Reference	Type	Value
val[4]	int	
val	int *	
val+1	int *	
&val[2]	int *	
val[5]	int	
*(val+1)	int	
val + i	int *	

Array Access

- **Basic Principle**
  - T A[N];
  - Array of data type T and length N
  - Identifier A can be used as a pointer to array element 0: Type T*

```
int val[5];
```



- **Reference Type Value**

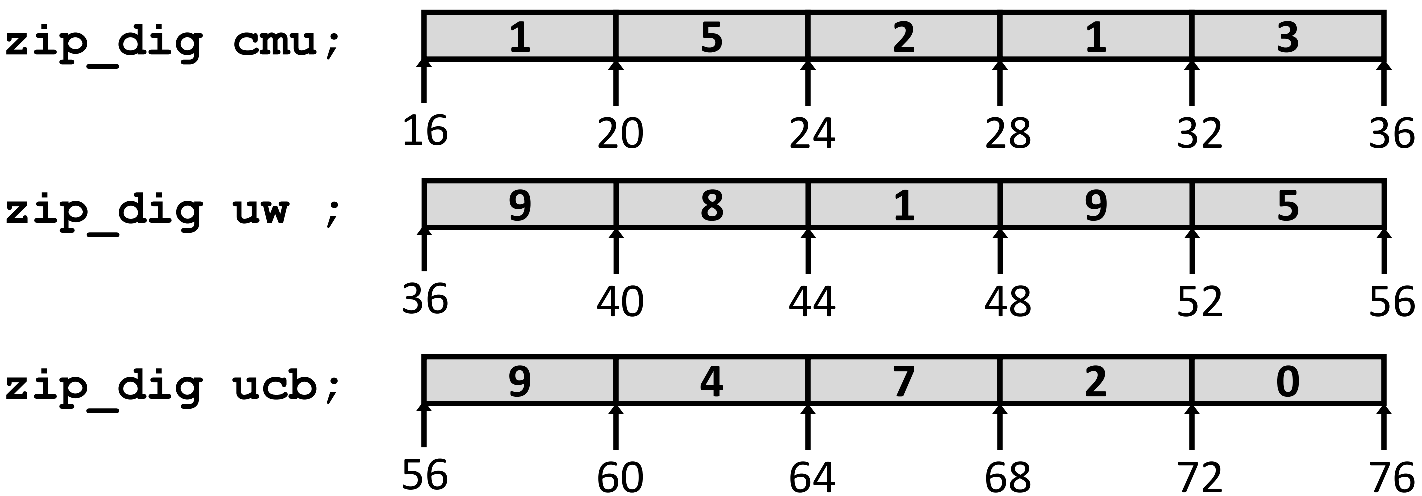
Reference	Type	Value
val[4]	int	5
val	int *	*x*
val+1	int *	*x* + 4
&val[2]	int *	*x* + 8
val[5]	int	?? (whatever is in memory at address *x* + 20)
*(val+1)	int	8
val + i	int *	*x* + 4*i

Array Example

```
typedef int zip_dig[5];

zip_dig cmu = { 1, 5, 2, 1, 3 };
zip_dig uw  = { 9, 8, 1, 9, 5 };
zip_dig ucb = { 9, 4, 7, 2, 0 };
```

Array Example

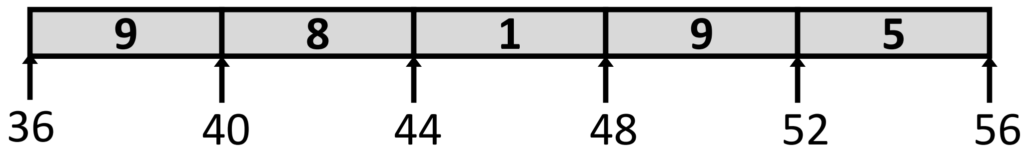
```
typedef int zip_dig[5];

zip_dig cmu = { 1, 5, 2, 1, 3 };
zip_dig uw  = { 9, 8, 1, 9, 5 };
zip_dig ucb = { 9, 4, 7, 2, 0 };
```



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

Array Accessing Example

```
zip_dig uw;
```




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

IA32

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

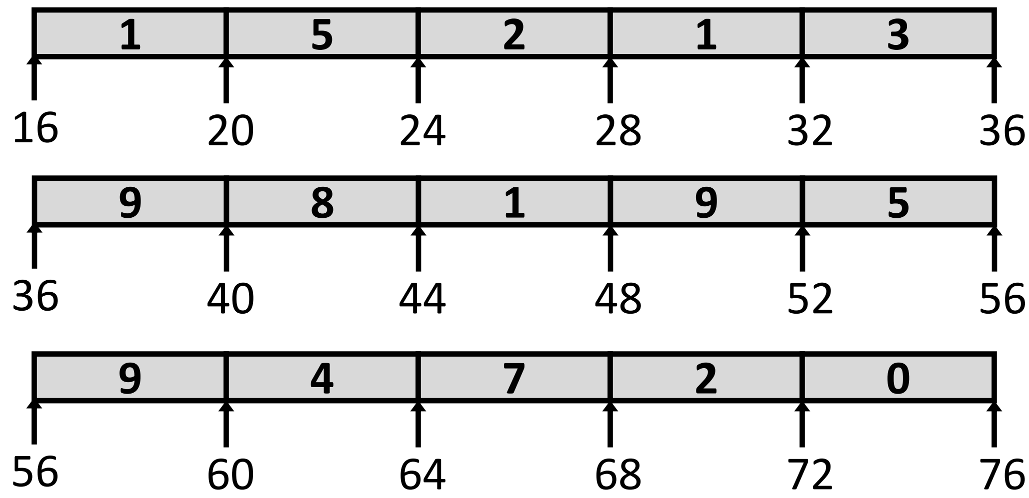
- Register `%edx` contains starting address of array
- Register `%eax` contains array index
- Desired digit at `4*%eax + %edx`
- Use memory reference `(%edx,%eax,4)`

Referencing Examples

`zip_dig cmu;`

`zip_dig  uw;`

`zip_dig ucb;`



Reference	Address	Value	Guaranteed?
`uw[3]`	`36 + 4* 3 = 48`	`9`	
`uw[6]`	`36 + 4* 6 = 60`	`4`	
`uw[-1]`	`36 + 4*-1 = 32`	`3`	
`cmu[15]`	`16 + 4*15 = 76`	`??`	

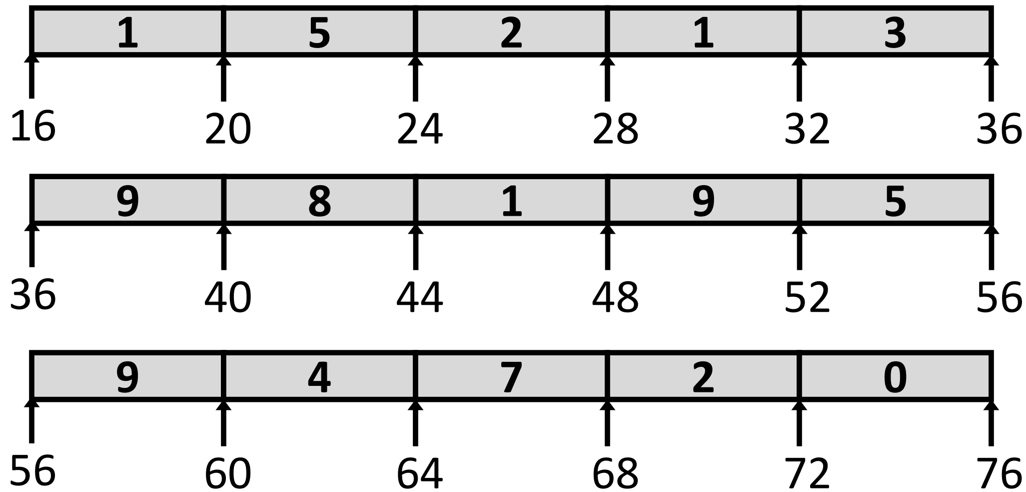
- No bounds checking
- Location of each separate array in memory is not guaranteed

Referencing Examples

`zip_dig cmu;`

`zip_dig  uw;`

`zip_dig ucb;`



Reference	Address	Value	Guaranteed?
`uw[3]`	`36 + 4* 3 = 48`	`9`	Yes
`uw[6]`	`36 + 4* 6 = 60`	`4`	No
`uw[-1]`	`36 + 4*-1 = 32`	`3`	No
`cmu[15]`	`16 + 4*15 = 76`	`??`	No

- No bounds checking
- Location of each separate array in memory is not guaranteed

Array Loop Example

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

Array Loop Example

- **Original**

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

- **Transformed**
  - Eliminate loop variable **`i`**, use pointer **`zend`** instead
  - Convert array code to pointer code
    - Pointer arithmetic on **`z`**
  - Express in do-while form (no 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 (IA32)

- **Registers**

```
%ecx  z
%eax  zi
%ebx  zend
```

- **Computations**
  - `10*zi + *z` implemented as `*z + 2*(5*zi)`
  - `z++` increments by 4

```c
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 # zi + 4*zi = 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

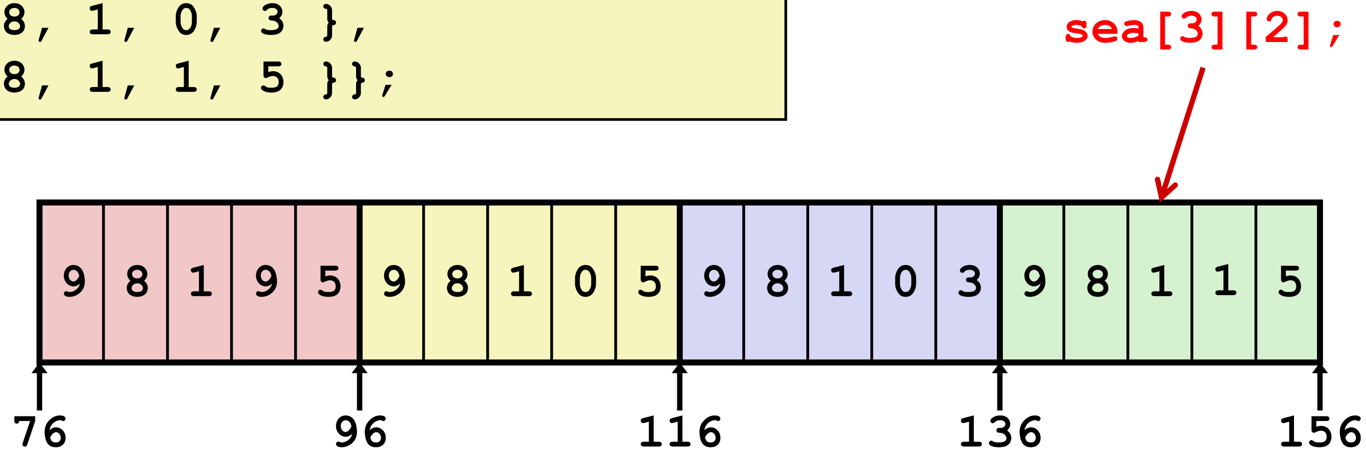
```
#define PCOUNT 4
zip_dig sea[PCOUNT] =
  {{ 9, 8, 1, 9, 5 },
   { 9, 8, 1, 0, 5 },
   { 9, 8, 1, 0, 3 },
   { 9, 8, 1, 1, 5 }};
```

Remember, **`T A[N]`** is an array with elements of type **`T`**, with length **`N`**

Nested Array Example

```
#define PCOUNT 4
zip_dig sea[PCOUNT] =
  {{ 9, 8, 1, 9, 5 },
   { 9, 8, 1, 0, 5 },
   { 9, 8, 1, 0, 3 },
   { 9, 8, 1, 1, 5 }};
```

Remember, **`T A[N]`** is an array with elements of type **`T`**, with length **`N`**



- **"Row-major" ordering of all elements**
- **Guaranteed?**

Multidimensional (Nested) Arrays

- **Declaration**
  - T A[R][C];
  - 2D array of data type T
  - R rows, C columns
  - Type T element requires K bytes
- **Array size?**

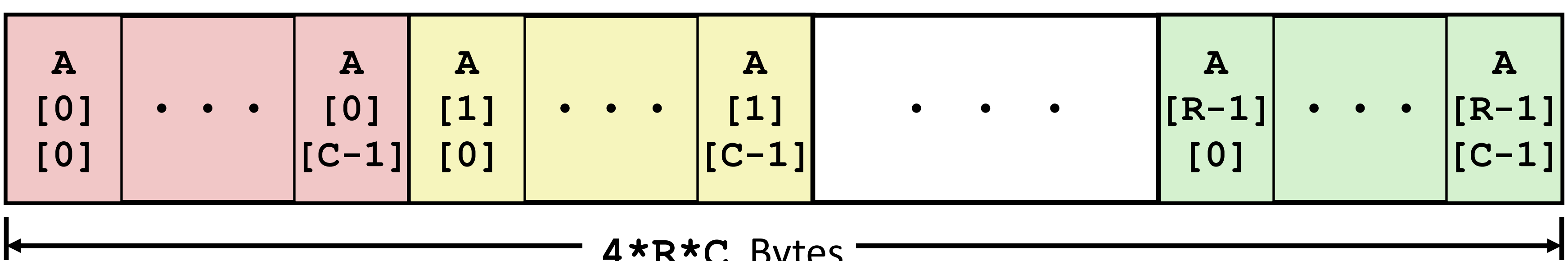
$$\begin{bmatrix} \texttt{A[0][0]} & \cdots & \texttt{A[0][C-1]} \\ \vdots & & \vdots \\ \texttt{A[R-1][0]} & \cdots & \texttt{A[R-1][C-1]} \end{bmatrix}$$

Multidimensional (Nested) Arrays

- **Declaration**
  - T A[R][C];
  - 2D 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

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

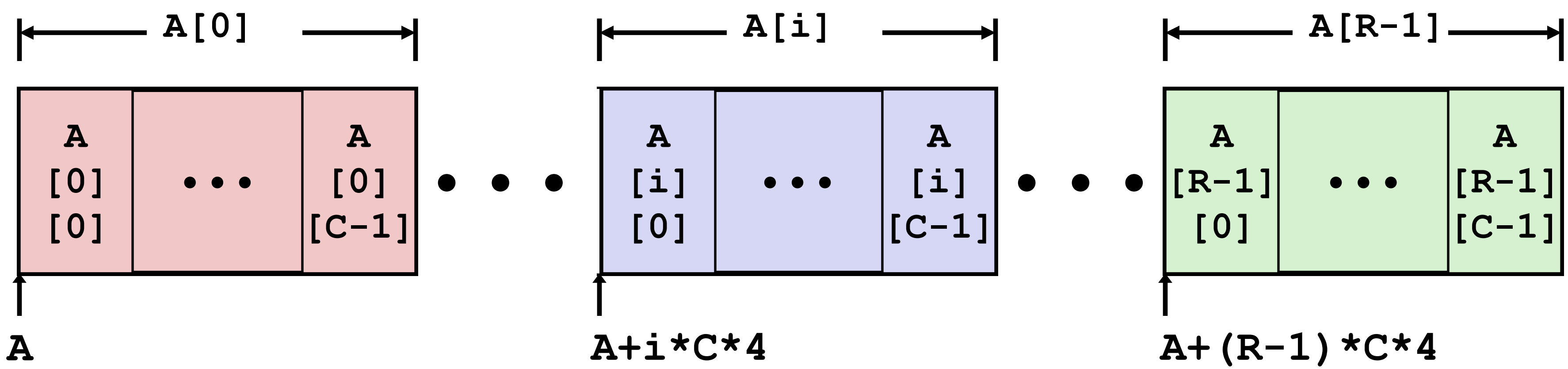
```
int A[R][C];
```



Nested Array Row Access

- **Row vectors**
  - T   A[R][C]: A[i] is array of C elements
  - Each element of type T requires K bytes
  - Starting address A + i * (C * K)

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



Nested Array Row Access Code

```
int *get_sea_zip(int index)
{
  return sea[index];
}
```

```
#define PCOUNT 4
zip_dig sea[PCOUNT] =
  {{ 9, 8, 1, 9, 5 },
   { 9, 8, 1, 0, 5 },
   { 9, 8, 1, 0, 3 },
   { 9, 8, 1, 1, 5 }};
```

Nested Array Row Access Code

```
int *get_sea_zip(int index)
{
  return sea[index];
}
```

```
#define PCOUNT 4
zip_dig sea[PCOUNT] =
  {{ 9, 8, 1, 9, 5 },
   { 9, 8, 1, 0, 5 },
   { 9, 8, 1, 0, 3 },
   { 9, 8, 1, 1, 5 }};
```

- What data type is `sea[index]`?
- What is its starting address?

```
  # %eax = index
   leal (%eax,%eax,4),%eax
   leal sea(,%eax,4),%eax
```

Translation?

Nested Array Row Access Code

```
int *get_sea_zip(int index)
{
  return sea[index];
}
```

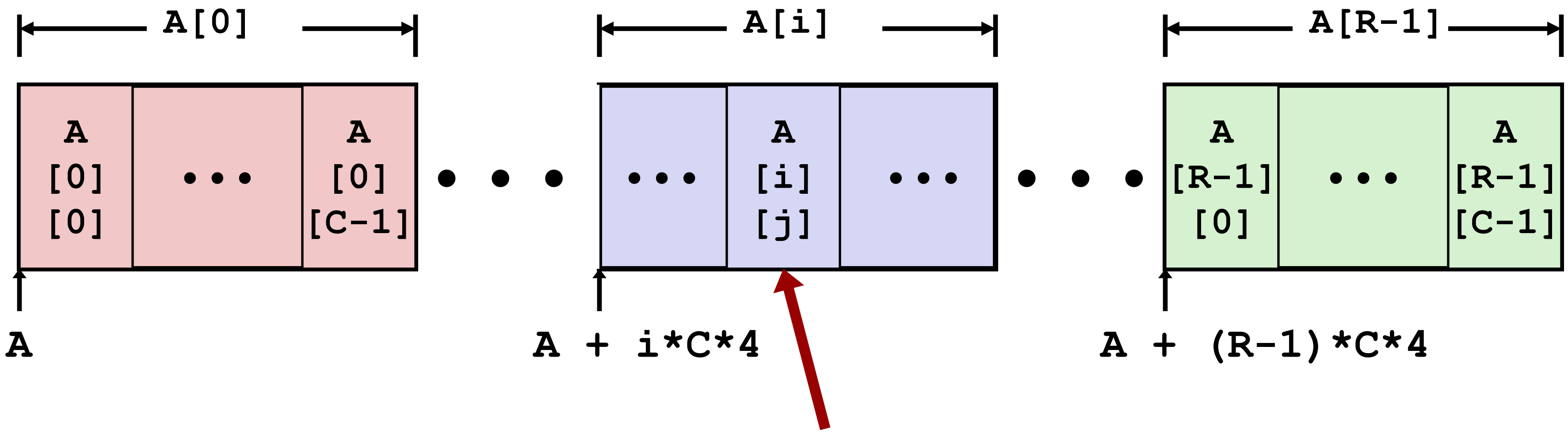
```
#define PCOUNT 4
zip_dig sea[PCOUNT] =
  {{ 9, 8, 1, 9, 5 },
   { 9, 8, 1, 0, 5 },
   { 9, 8, 1, 0, 3 },
   { 9, 8, 1, 1, 5 }};
```

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

- **Row Vector**
  - **`sea[index]`** is array of 5 **`int`**s
  - Starting address **`sea+20*index`**
- **IA32 Code**
  - Computes and returns address
  - Compute as **`sea+4*(index+4*index)=sea+20*index`**

Nested Array Row Access

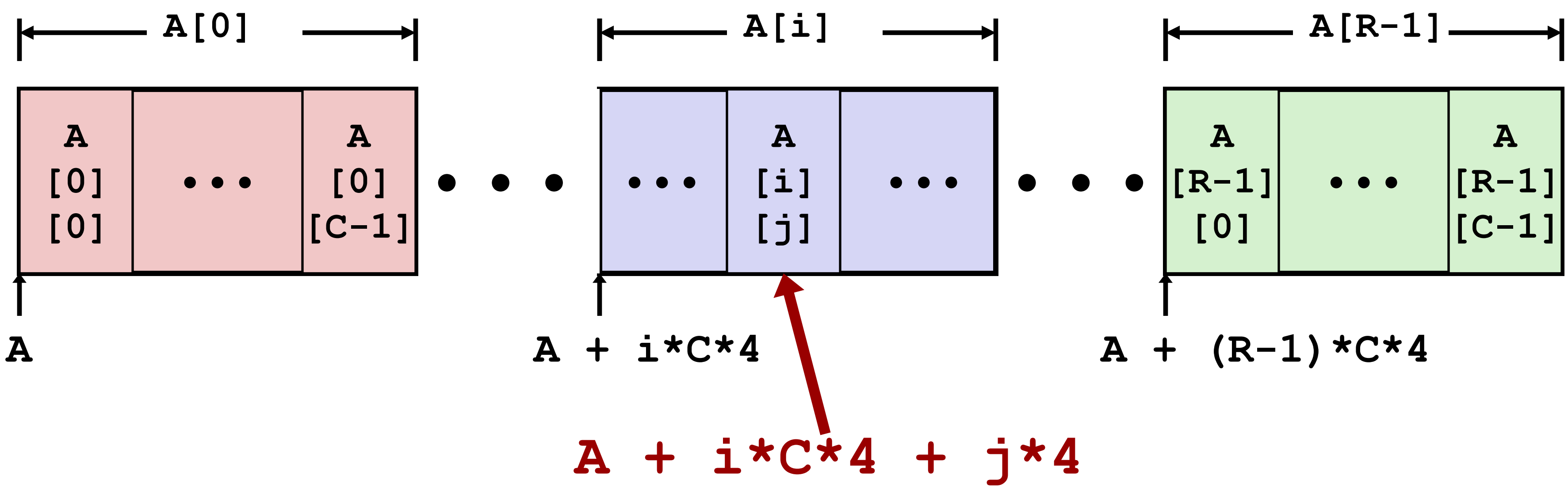
```
int A[R][C];
```



Nested Array Row Access

- **Array Elements**
  - A[i][j] is element of type T, which requires K bytes
  - Address A + i * (C * K) + j * K = A + (i * C + j)* K

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



Nested Array Element Access Code

```
int get_sea_digit
  (int index, int dig)
{
  return sea[index][dig];
}
```

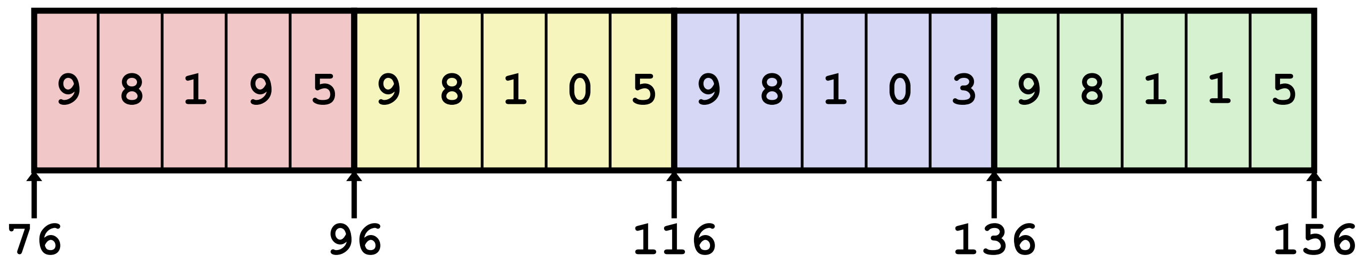
```
zip_dig sea[PCOUNT] =
  {{ 9, 8, 1, 9, 5 },
   { 9, 8, 1, 0, 5 },
   { 9, 8, 1, 0, 3 },
   { 9, 8, 1, 1, 5 }};
```

```
# %ecx = dig
# %eax = index
leal 0(,%ecx,4),%edx          # 4*dig
leal (%eax,%eax,4),%eax       # 5*index
movl sea(%edx,%eax,4),%eax    # *(sea + 4*dig + 20*index)
```

- **Array Elements**
  - sea[index][dig] is int
  - Address: sea + 20*index + 4*dig
- **IA32 Code**
  - Computes address sea + 4*dig + 4*(index+4*index)
  - movl performs memory reference

Strange Referencing Examples

```
zip_dig
sea[4];
```



Reference	Address	Value	Guaranteed?
`sea[3][3]`	`76+20*3+4*3 = 148`	`1`	Yes
`sea[2][5]`	`76+20*2+4*5 = 136`	`9`	Yes
`sea[2][-1]`	`76+20*2+4*-1 = 112`	`5`	Yes
`sea[4][-1]`	`76+20*4+4*-1 = 152`	`5`	Yes
`sea[0][19]`	`76+20*0+4*19 = 152`	`5`	Yes
`sea[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

```
zip_dig cmu = { 1, 5, 2, 1, 3 };
zip_dig uw  = { 9, 8, 1, 9, 5 };
zip_dig ucb = { 9, 4, 7, 2, 0 };
```

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

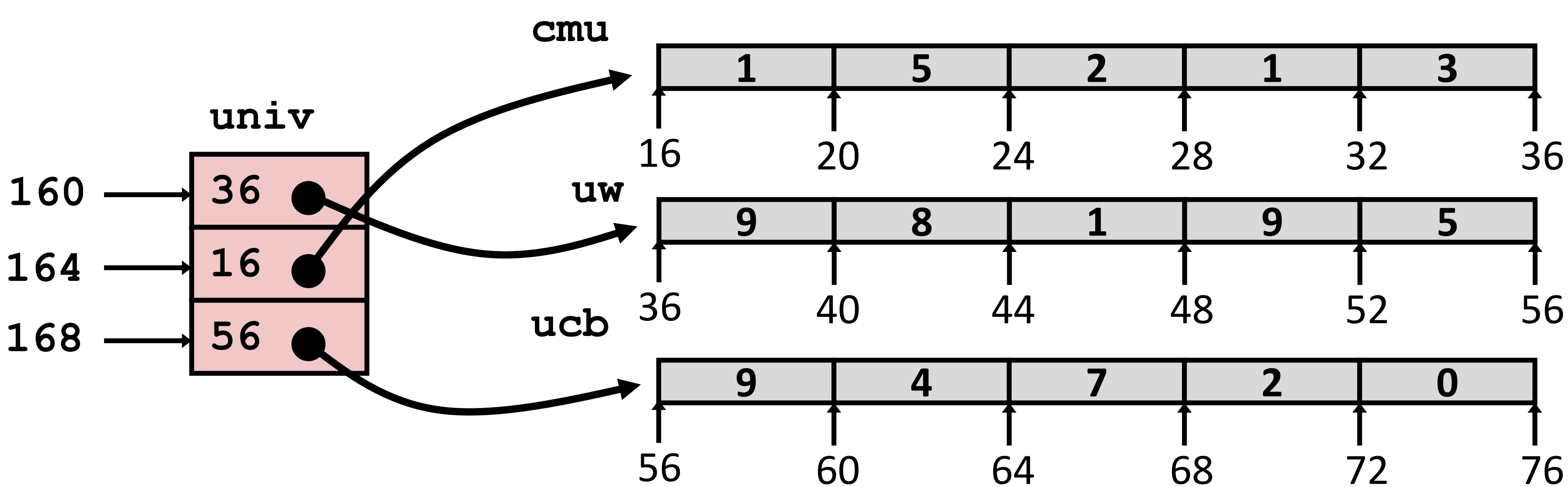
Same thing as a 2D array?

Multi-Level Array Example

```
zip_dig cmu = { 1, 5, 2, 1, 3 };
zip_dig uw  = { 9, 8, 1, 9, 5 };
zip_dig ucb = { 9, 4, 7, 2, 0 };
```

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

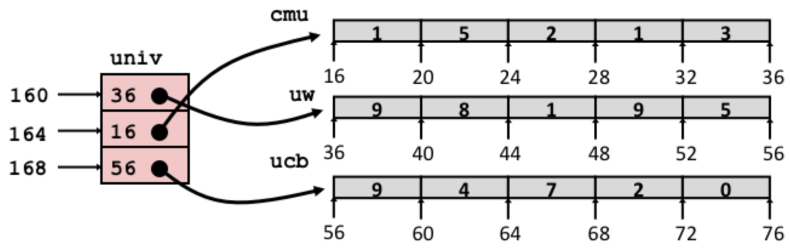
- Variable `univ` denotes array of 3 elements
- Each element is a pointer
  - 4 bytes
- Each pointer points to array of `int`s



Note: this is how Java represents multi-dimensional arrays.

Element Access in Multi-Level Array

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



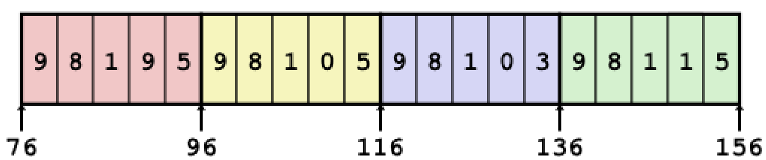

```
  # %ecx = index
  # %eax = dig
  leal 0(,%ecx,4),%edx     # 4*index
  movl univ(%edx),%edx     # Mem[univ+4*index]
  movl (%edx,%eax,4),%eax # Mem[...+4*dig]
```

- **Computation (IA32)**
  - 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

Array Element Accesses

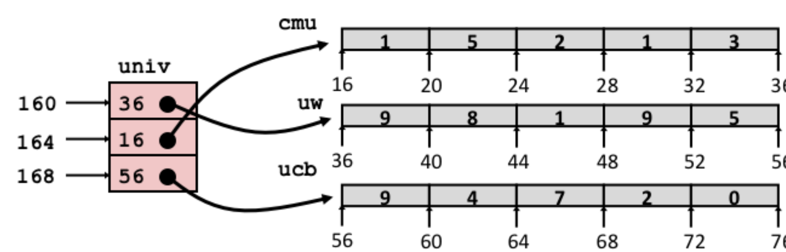
Nested array

```
int get_sea_digit
  (int index, int dig)
{
  return sea[index][dig];
}
```



Multi-level array

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

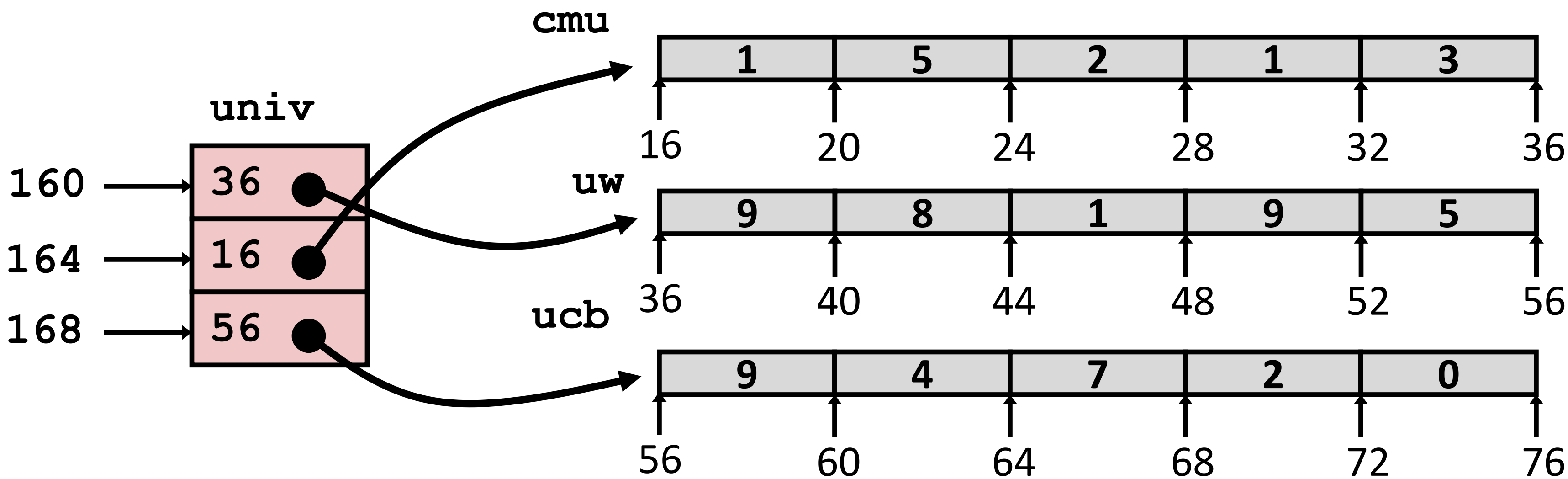


Access looks similar, but it isn't:

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

`Mem[Mem[univ+4*index]+4*dig]`

Strange Referencing Examples



- **Reference / Address / Value / Guaranteed?**

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

  - Code does not do any bounds checking
  - Location of each lower-level array in memory is not guaranteed

Using Nested Arrays

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

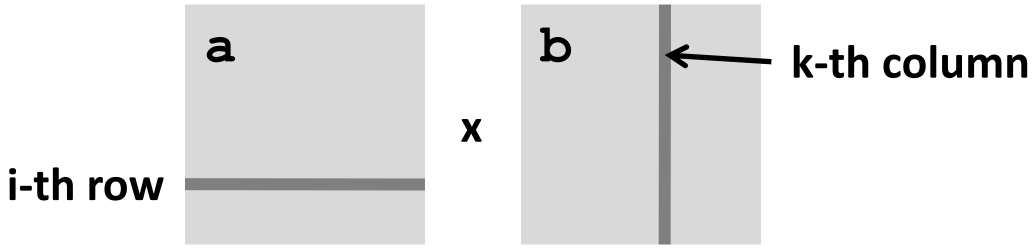
```
/* Compute element i,k of
   fixed matrix product */
int fix_prod_ele
(fix_matrix a, fix_matrix b,
 int i, int k)
{
  int j;
  int result = 0;
  for (j = 0; j < N; j++)
    result += a[i][j]*b[j][k];
  return result;
}
```

Using Nested Arrays

- **Strengths**
  - Generates very efficient assembly code
  - Avoids multiply in index computation
- **Limitation**
  - Only works for 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 any 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)]
```

Arrays in C

- Contiguous allocations of memory
- No bounds checking
- Can usually be treated like a pointer to first element