Systems I

Machine-Level Programming VII: Structured Data

Topics

- Arrays
- Structs
- Unions

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

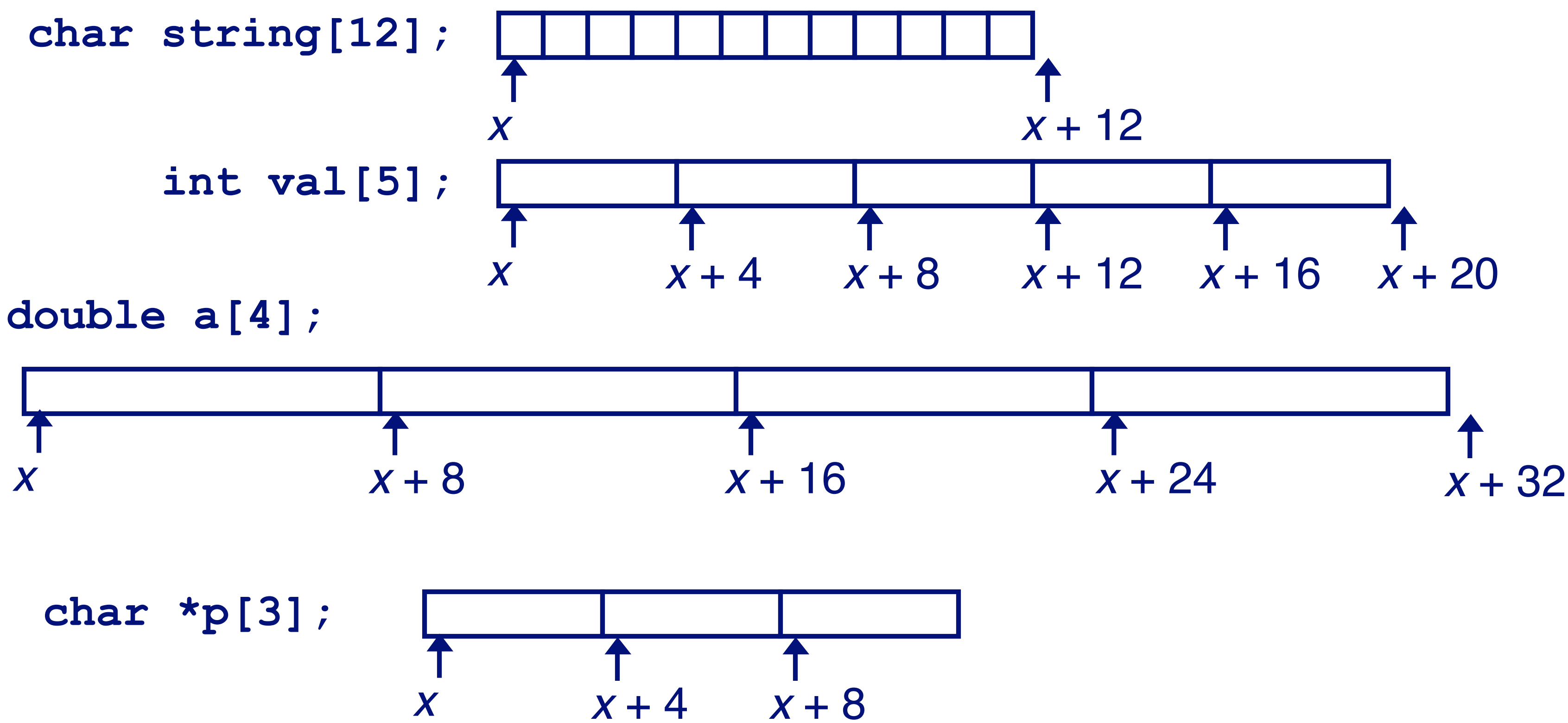
Intel	GAS	Bytes	C
Single	`s`	4	`float`
Double	`l`	8	`double`
Extended	`t`	10/12	`long double`

Array Allocation

Basic Principle

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

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



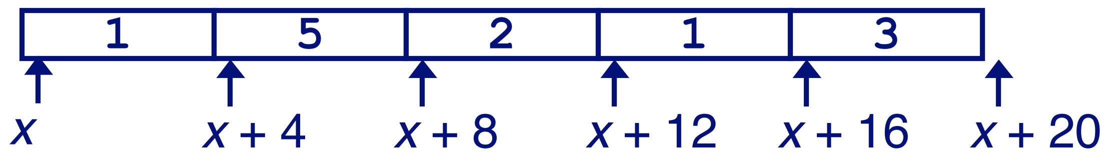
Array Access

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];`

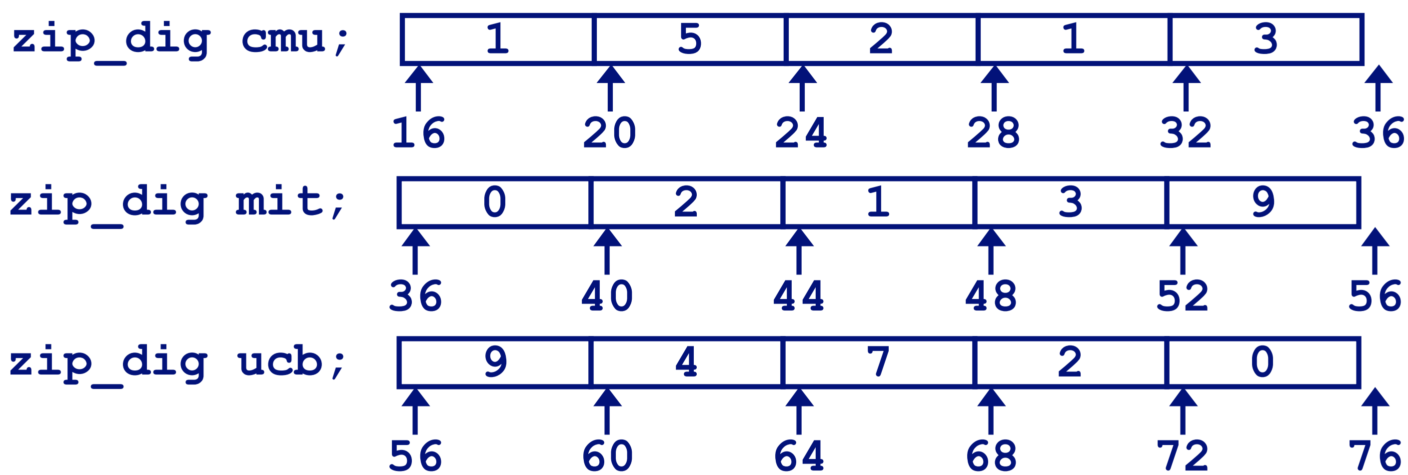


Reference	Type	Value
`val[4]`	`int`	3
`val`	`int *`	*x*
`val+1`	`int *`	*x* + 4
`&val[2]`	`int *`	*x* + 8
`val[5]`	`int`	??
`*(val+1)`	`int`	5
`val + i`	`int *`	*x* + 4 *i*

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

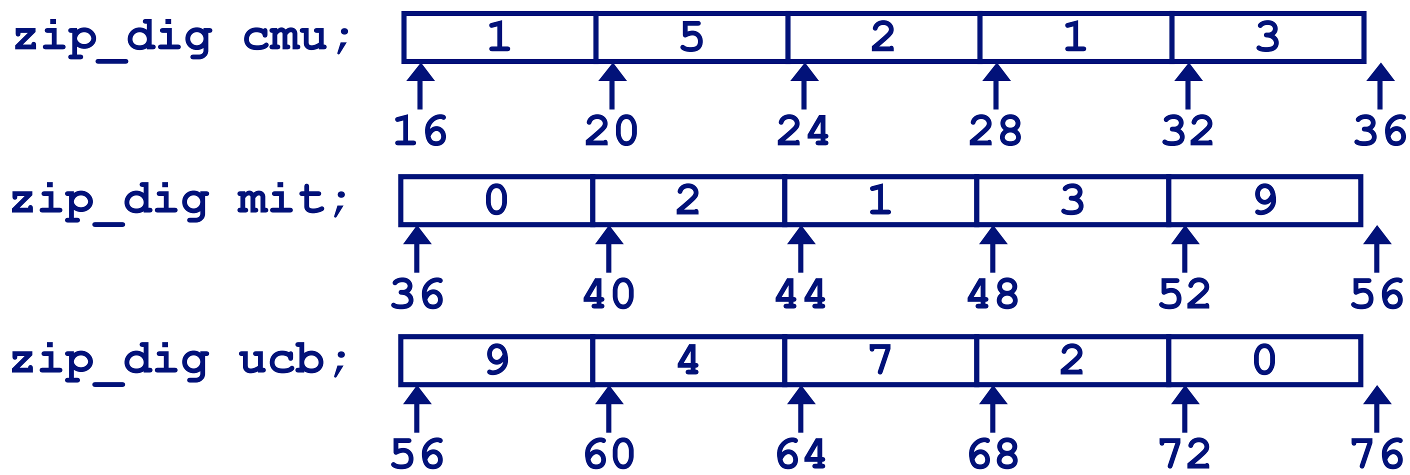
- Register `%edx` contains starting address of array
- Register `%eax` contains array index
- Desired digit at `4*%eax + %edx`
- Use memory reference `(%edx,%eax,4)`

```
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



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

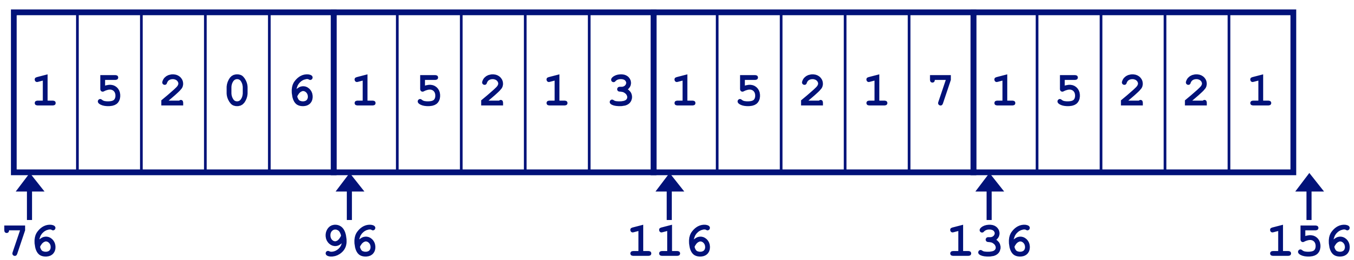
```
int zd2int(zip_dig z)
{
  int zi = 0;
  int *zend = z + 4;
  do {
    zi = 10 * zi + *z;
    z++;
  } while(z <= zend);
  return zi;
}
```

```
  # %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];`



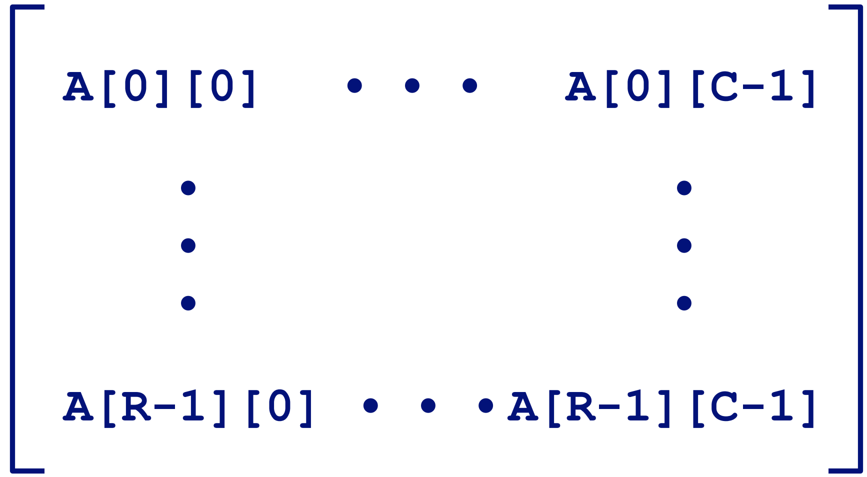
- Declaration "`zip_dig pgh[4]`" equivalent to "`int pgh[4][5]`"
  - Variable `pgh` denotes array of 4 elements
    - » Allocated contiguously
  - Each element is an array of 5 `int`'s
    - » Allocated contiguously
- "Row-Major" ordering of all elements guaranteed

Nested Array Allocation

Declaration

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

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



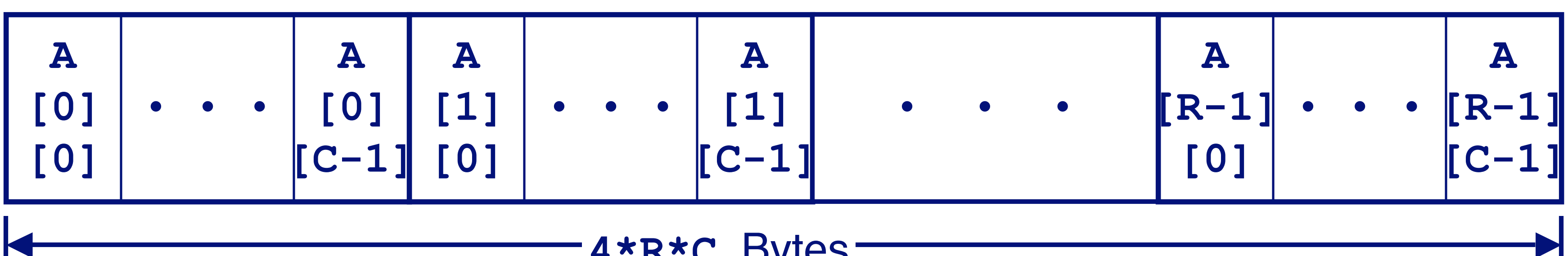
Array Size

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

Arrangement

- Row-Major Ordering

`int A[R][C];`

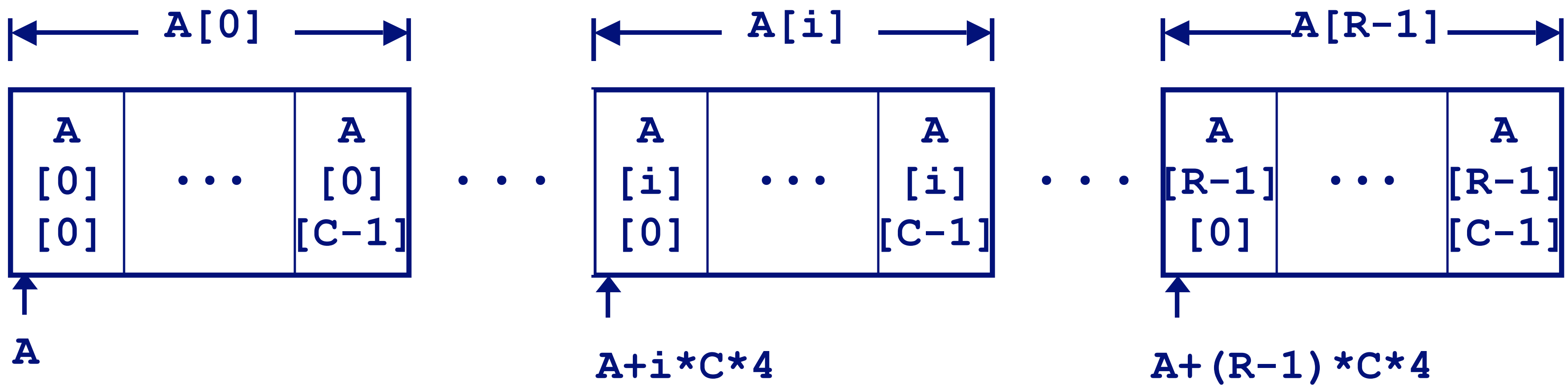


Nested Array Row Access

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`

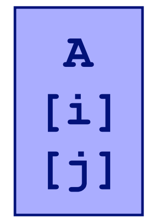
Code

- 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)
```

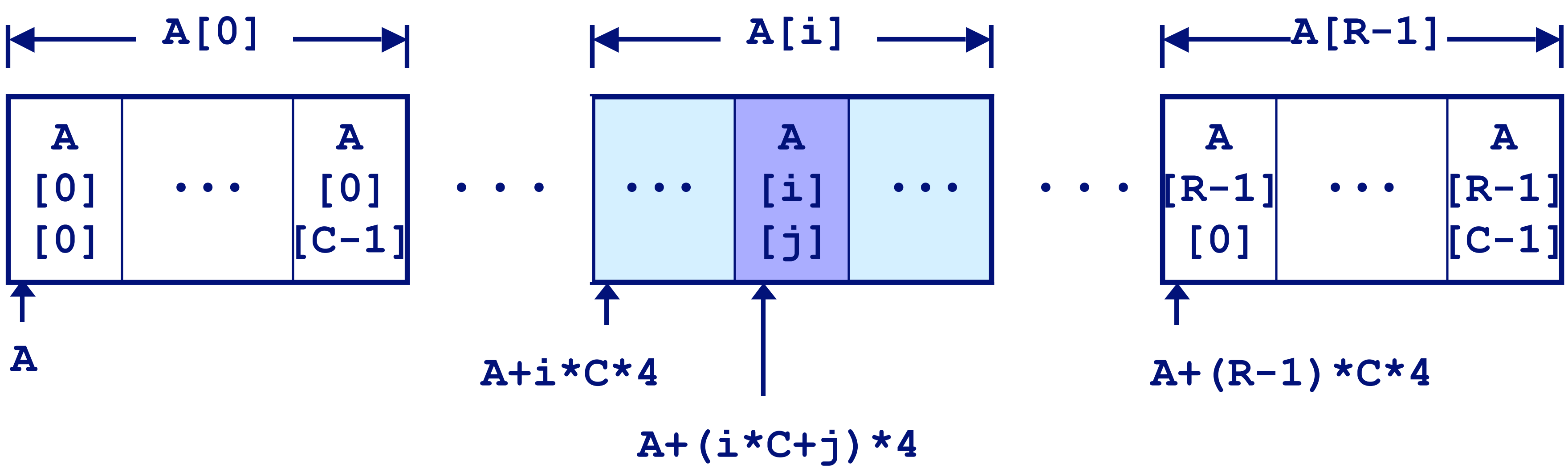
Nested Array Element Access

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

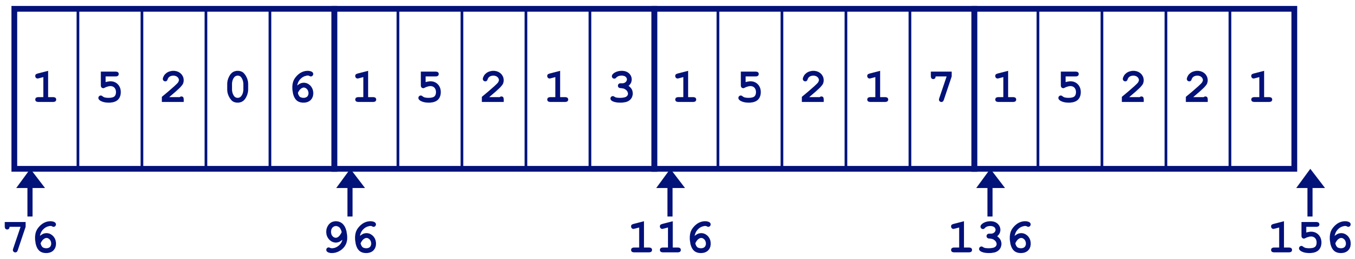
  `pgh + 4*dig + 4*(index+4*index)`

- `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

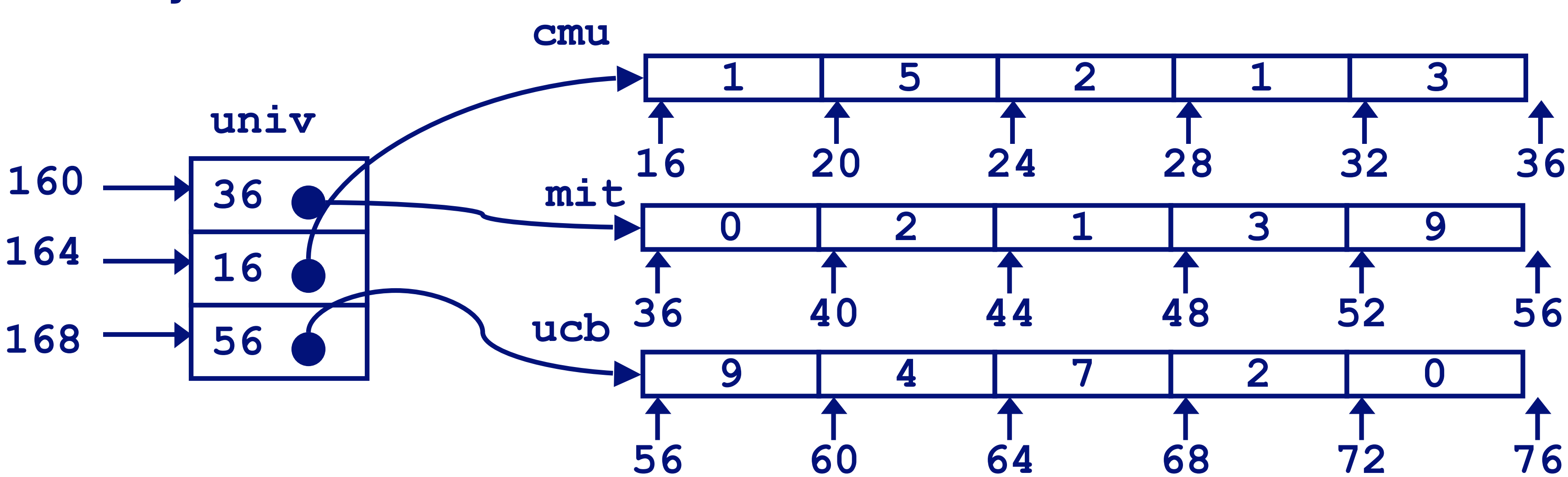
- Code does not do any bounds checking
- Ordering of elements within array guaranteed

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

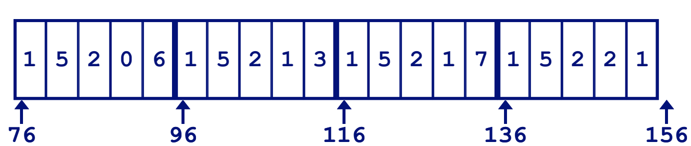
- Similar C references
- Different address computation

Nested Array

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

- Element at

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

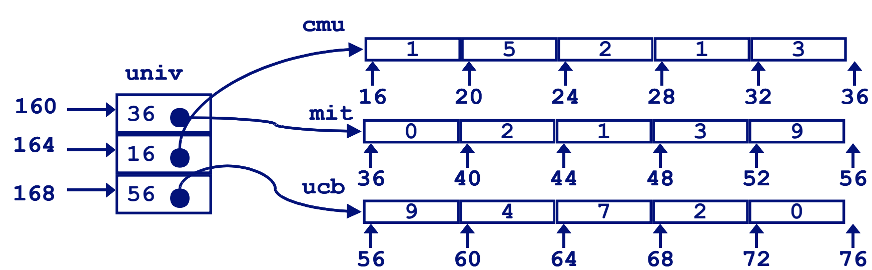


Multi-Level Array

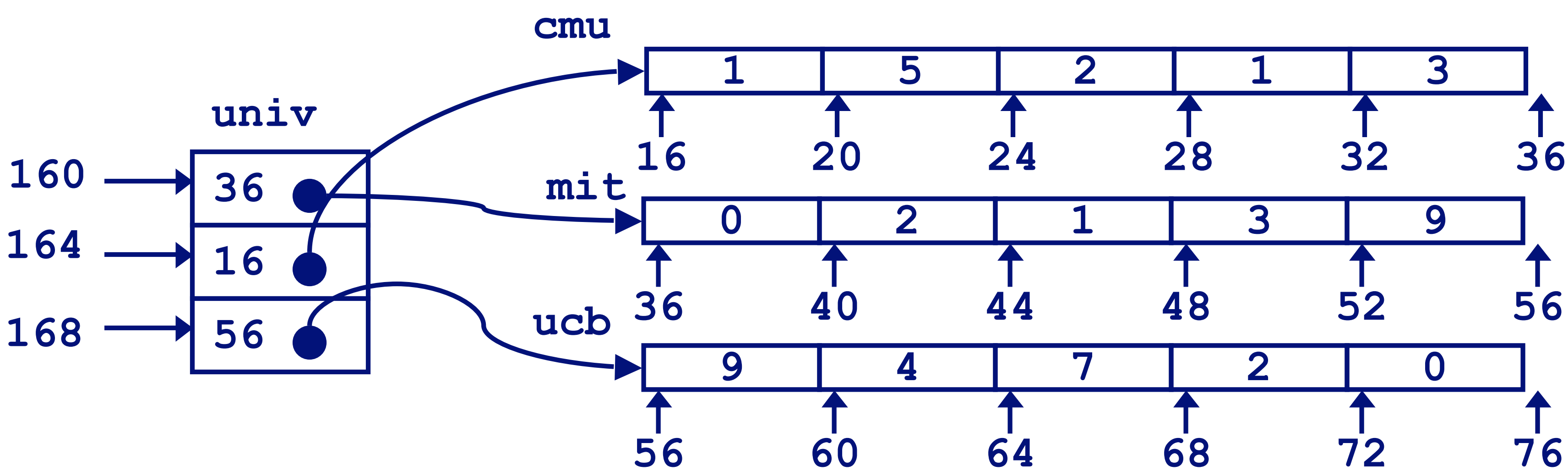
```
int get_univ_digit
  (int index, int dig)
{
  return univ[index][dig];
}
```

- 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

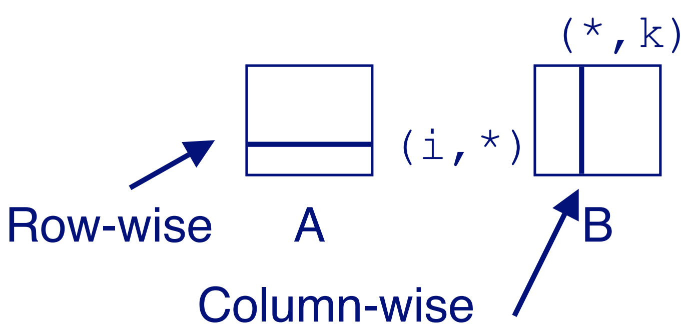
Using Nested Arrays

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;
}
```

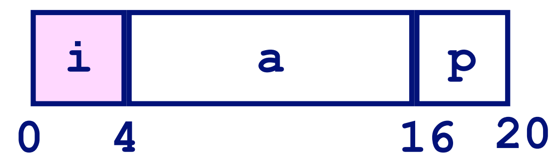
Structures

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

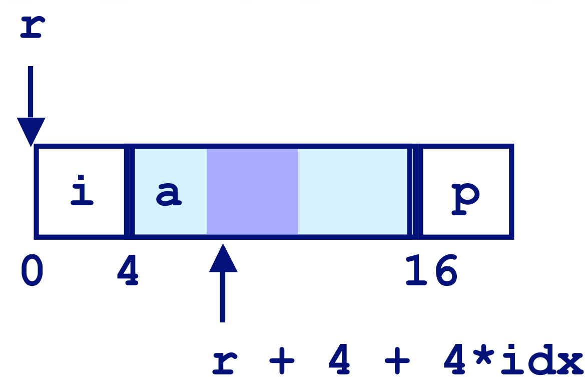
```
void
set_i(struct rec *r,
      int val)
{
  r->i = val;
}
```

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];
}
```

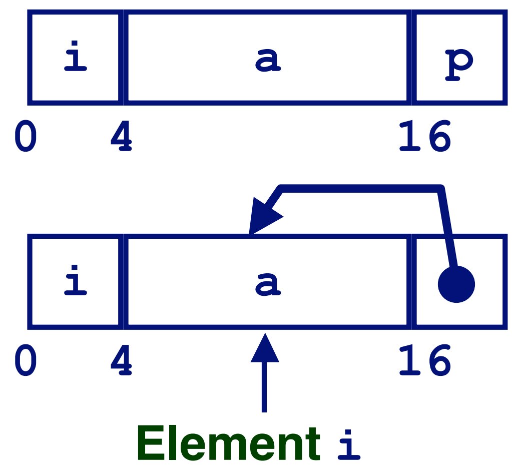
```
# %ecx = idx
# %edx = r
leal 0(,%ecx,4),%eax    # 4*idx
leal 4(%eax,%edx),%eax # r+4*idx+4
```

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
```

Summary

Today

- Primitive and Compound Data Types
- Arrays and array layout
- Multidimensional arrays

Next Time

- Alignment
- Bounds checking and buffer overflow