Machine-Level Prog. IV - Structured Data

Today

- Arrays
- Structures
- Unions

Next time

- Buffer overflow, x86-64

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Basic data types

- Integral
  - Stored & operated on in general registers
  - Signed vs. unsigned depends on instructions used

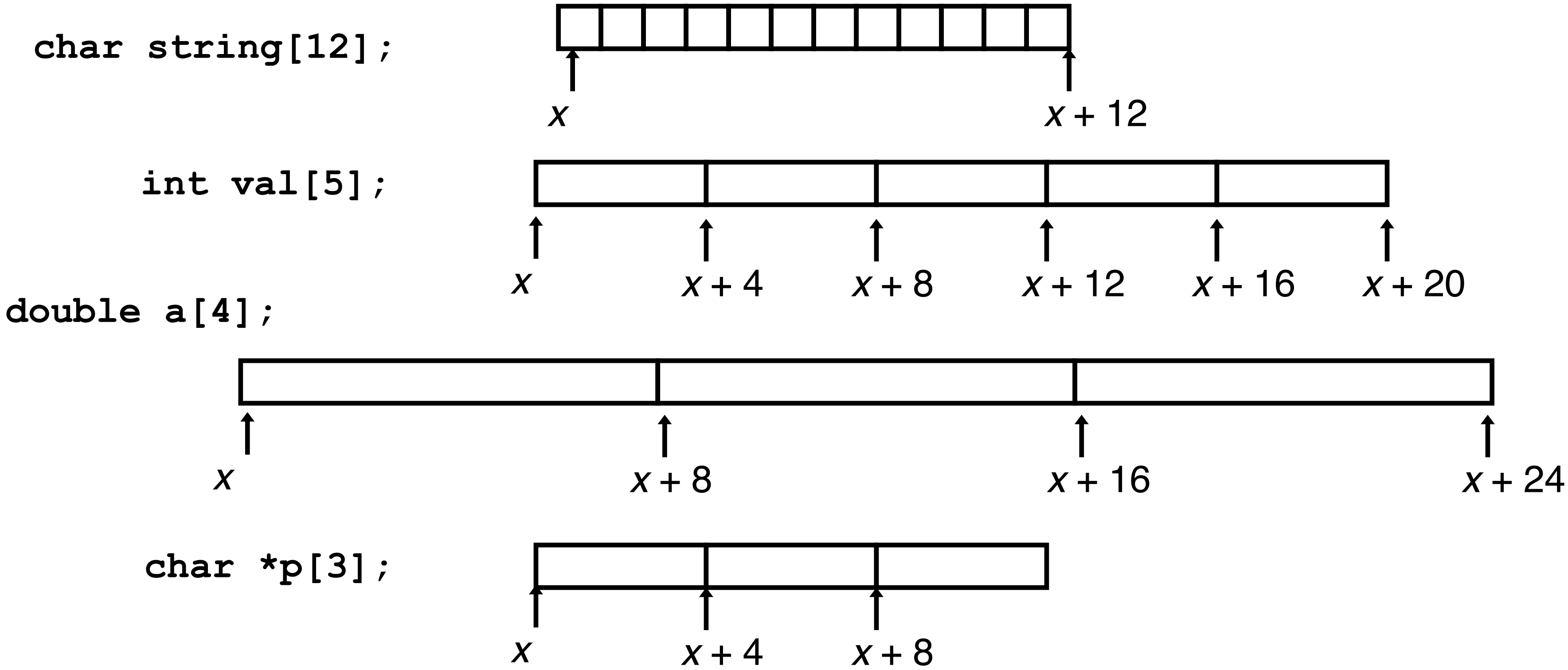
Intel	GAS	Bytes	C
byte	`b`	1	`[unsigned] char`
word	`w`	2	`[unsigned] short`
double word	`l`	4	`[unsigned] int`

- 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

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



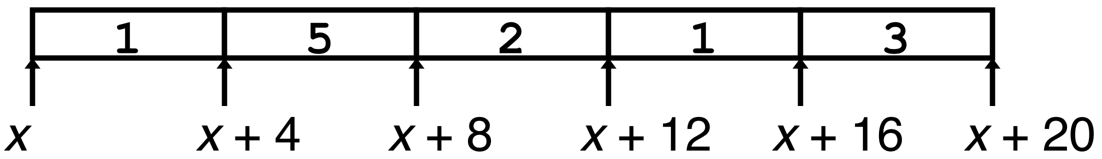
Array access

- Basic principle

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

  – Identifier `A` can be used as a pointer to array element 0

`int val[5];`



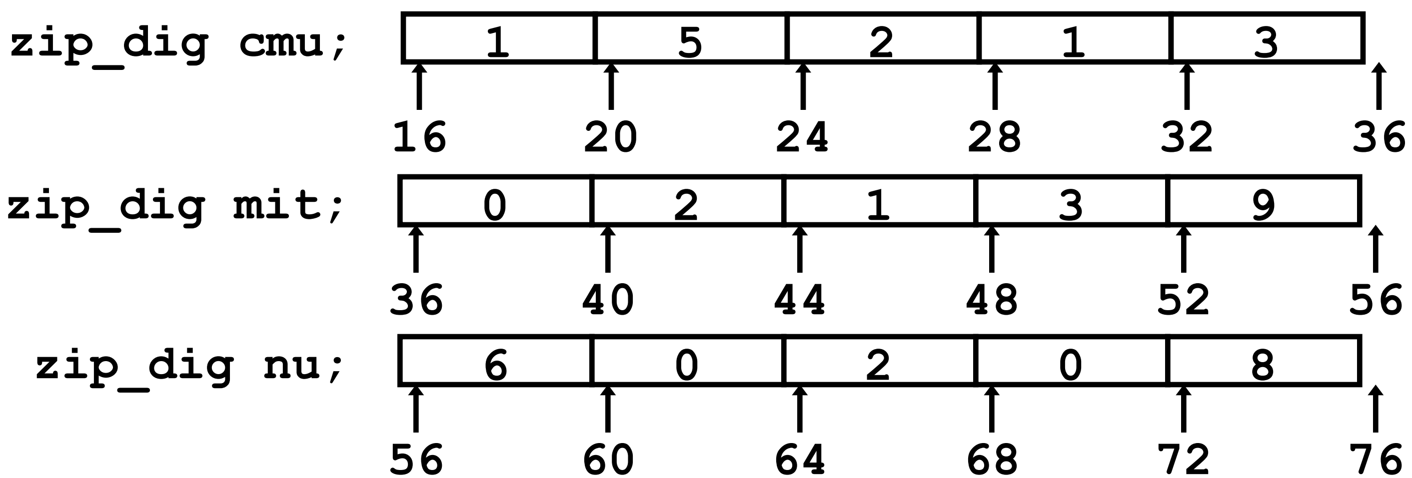
- Reference Type Value

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 nu = { 6, 0, 2, 0, 8 };
```



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

Array accessing example

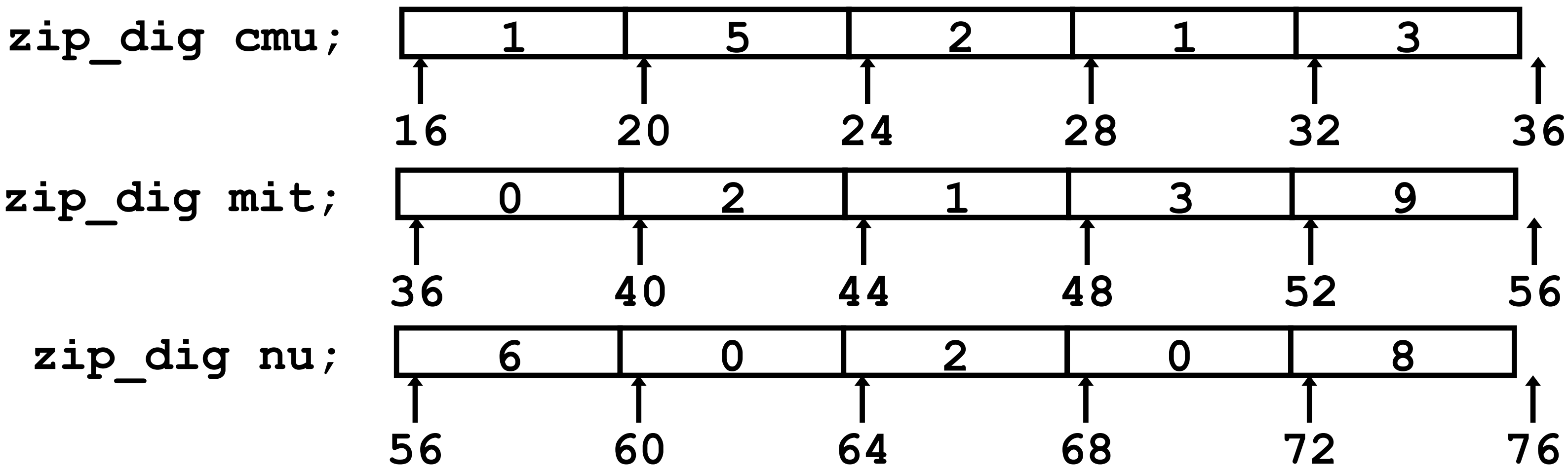
- Computation
  - Register `%edx` contains starting address of array
  - Register `%eax` contains array index
  - Desired digit at `%edx + %eax * 4`
  - Use memory reference `(%edx,%eax,4)`

```
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`	`6`	**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

  Computes the integer represented by an array of 5 decimal digits.

```
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` and uses pointer arithmetic
  - Computes address of final element and uses that for test
  - 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

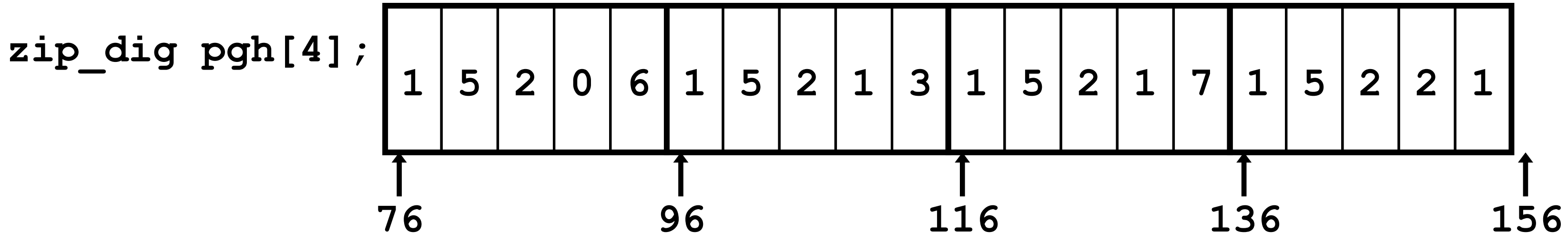
- Registers
  `%ecx  z`
  `%eax  zi`
  `%ebx  zend`
- Computations
  - `10*zi + *z` implemented as `*z + 2*(zi+4*zi)`
  - `z++` increments by 4

```
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

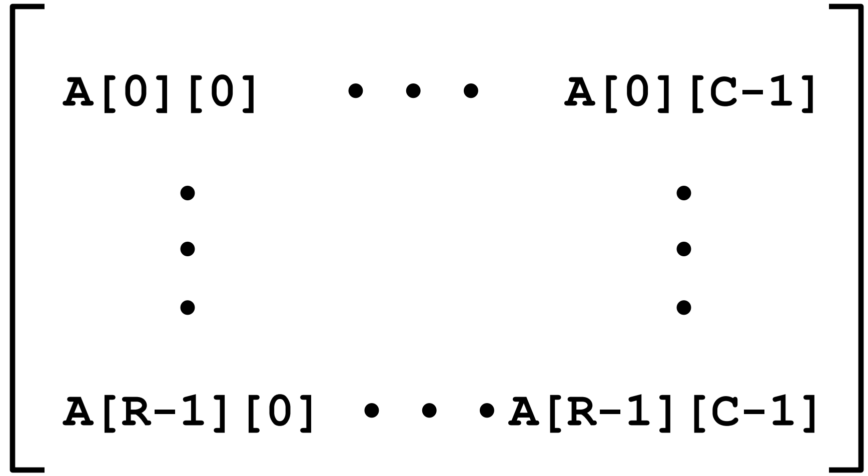
```
#define PCOUNT 4
zip_dig pgh[PCOUNT] =
  {{1, 5, 2, 0, 6},
   {1, 5, 2, 1, 3 },
   {1, 5, 2, 1, 7 },
   {1, 5, 2, 2, 1 }};
```



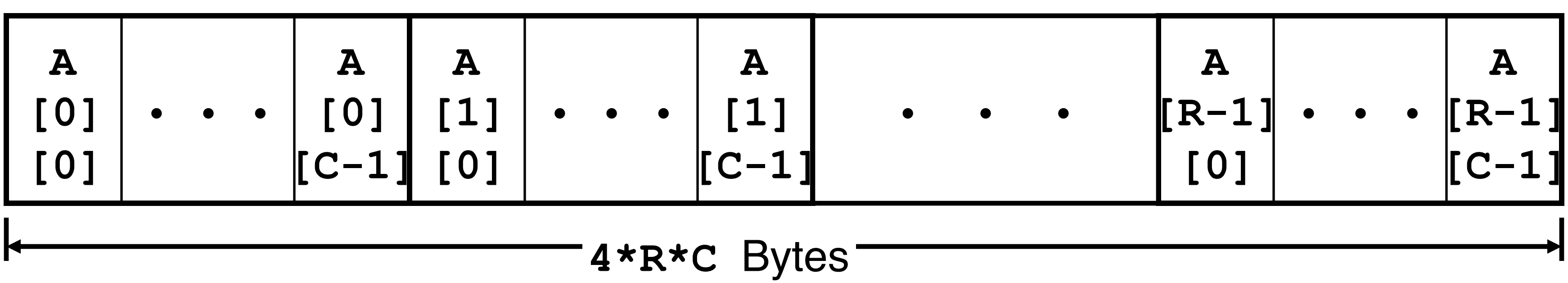
- Declaration "`zip_dig pgh[4]`" equivalent to "`int pgh[4][5]`"
  - Variable `pgh` denotes array of 4 elements
    - Allocated contiguously
  - Each element is an array of 5 `int`'s
    - Allocated contiguously
  - "Row-Major" ordering of all elements guaranteed

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



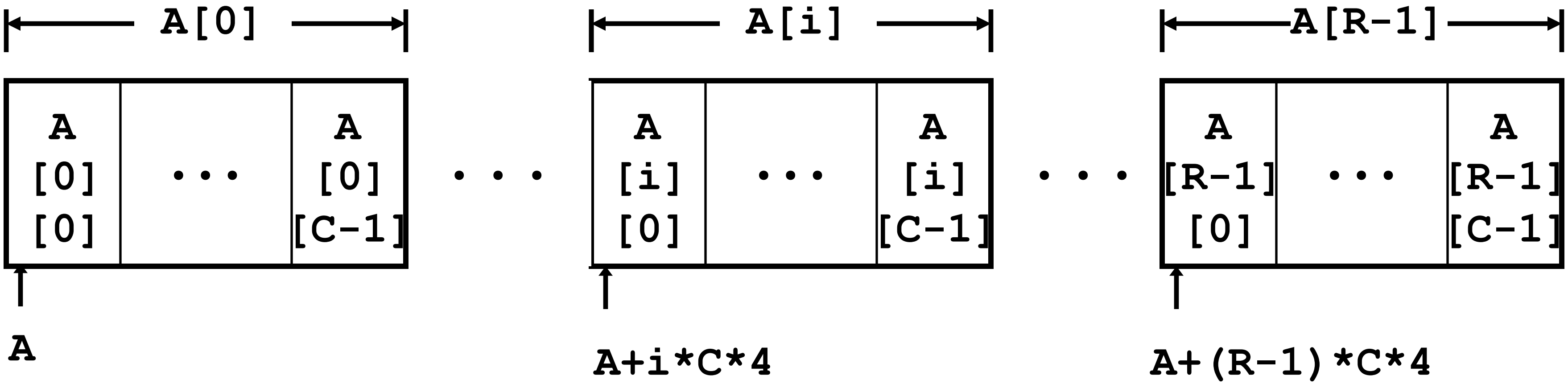
`int A[R][C];`



Nested array row access

- Row vectors
  - `A[i]` is array of *C* elements
  - Each element of type *T*
  - Starting address `A +` *i * C * K* *(sizeof(T) = K)*

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



Nested array row access code

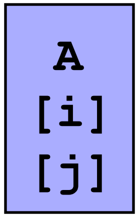
```
int *get_pgh_zip(int index)
{
  return pgh[index];
}
```

- 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)`

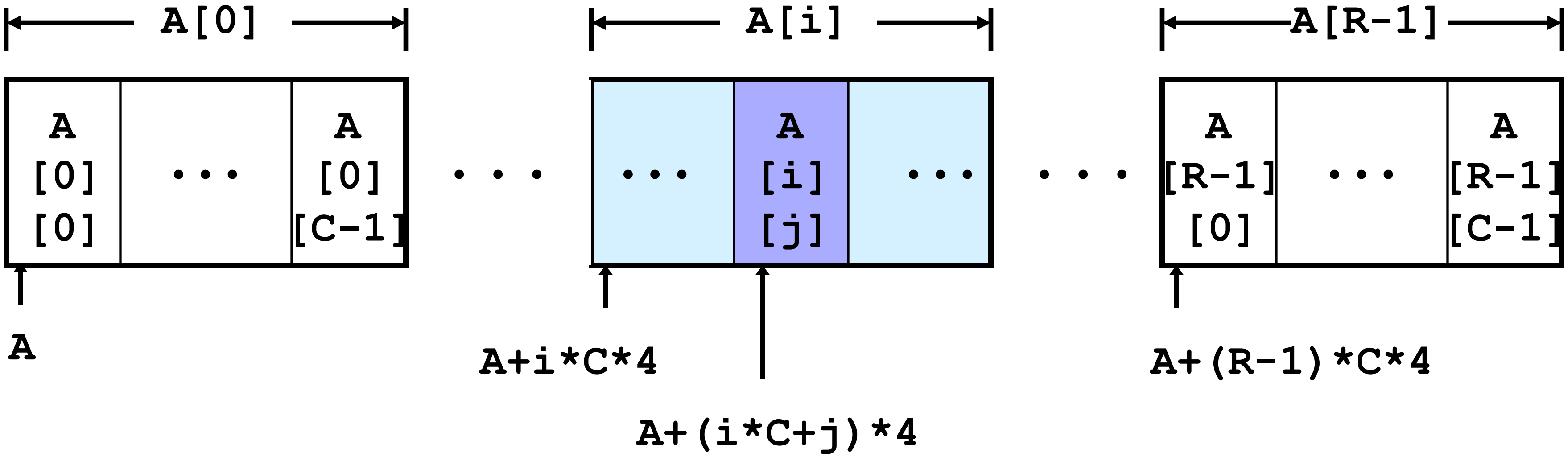
```
   # %eax = index
   leal (%eax,%eax,4),%eax     # 5 * index
   leal pgh(,%eax,4),%eax      # pgh + (20 * index)
```

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 + 4*(5*index + dig)=`

    `pgh + 20*index + 4*dig`

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

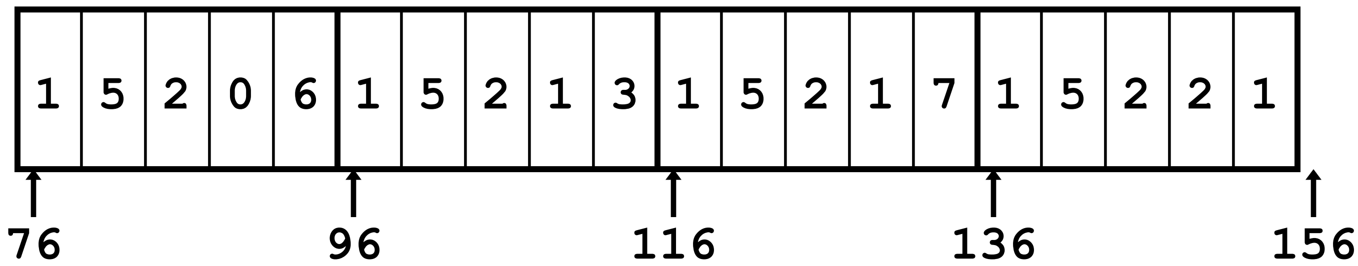
- Code
  - Computes address

    `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

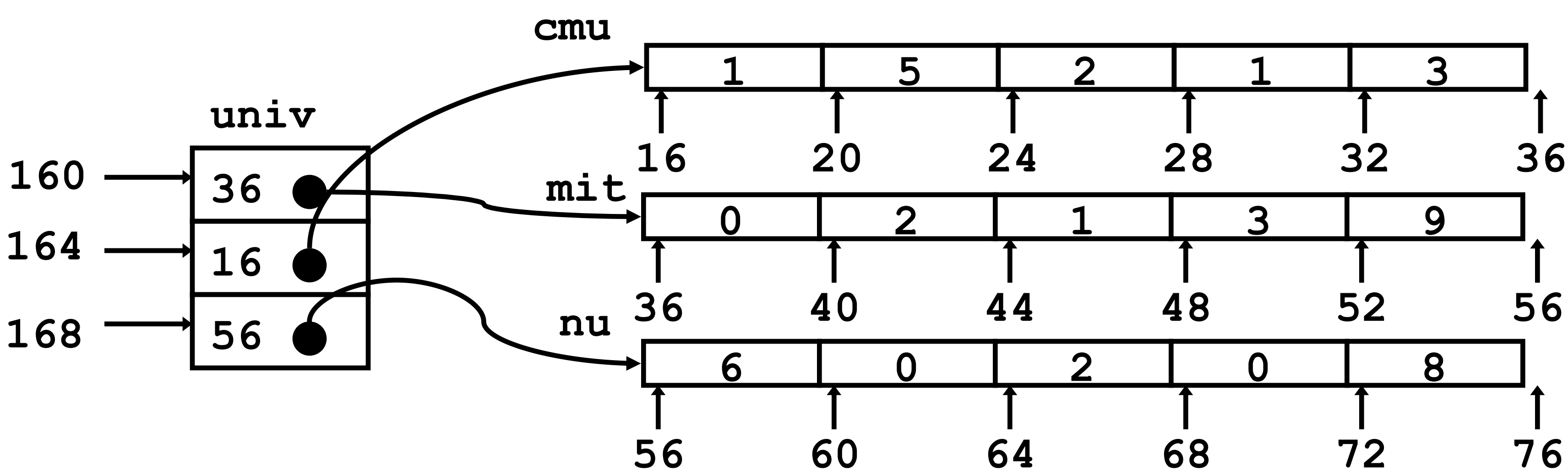
– Ordering of elements within array guaranteed

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 nu = { 6, 0, 2, 0, 8 };
```

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



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

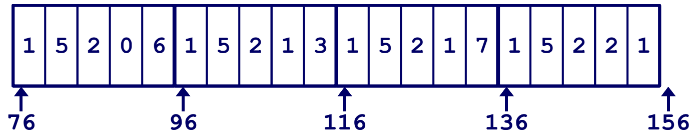
Different address computation

- Nested Array

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

- Element at

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

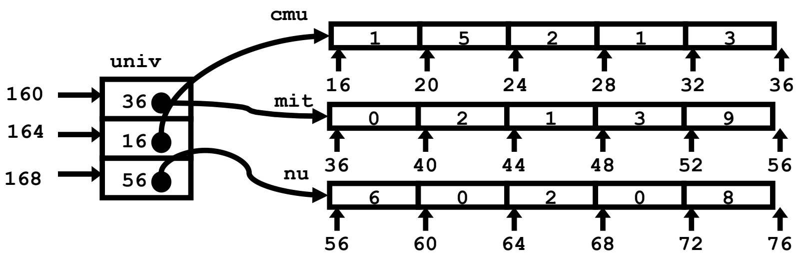


- Multi-Level Array

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

- Element at

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



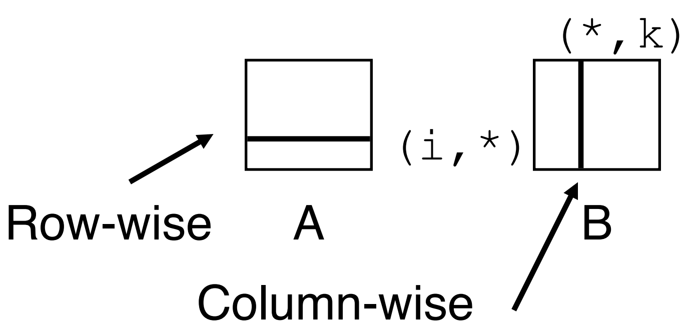
Using nested arrays

- 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];
}
```

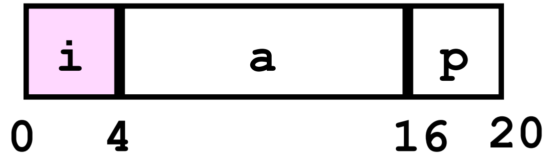
```
movl 12(%ebp),%eax          # i
movl 8(%ebp),%edx           # a
imull 20(%ebp),%eax         # n*i
addl 16(%ebp),%eax          # n*i+j
movl (%edx,%eax,4),%eax     # Mem[a+4*(i*n+j)]
```

Structures

- Concept
  - Members may be of different types
  - Contiguously-allocated region of memory
  - Refer to members within structure by names

```
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; /* Same as (*r).i */
}
```

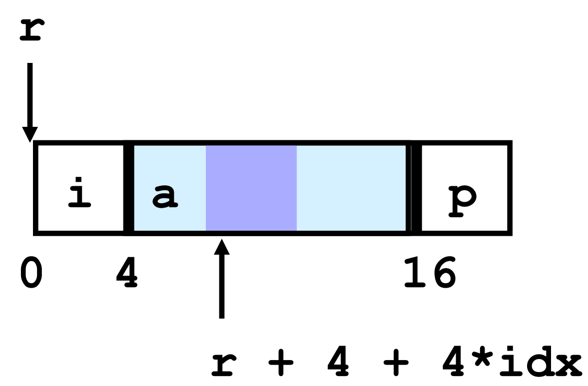
Assembly

Since the offset of i is 0, the address of r->i is r

```
# %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

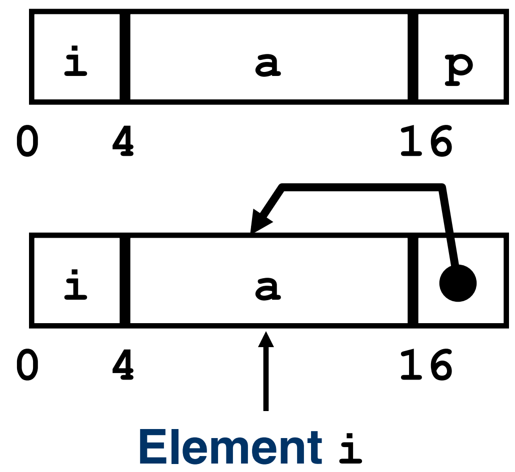
```
int *
find_a
 (struct rec *r, int idx)
{
  return &r->a[idx];
}
```

```
# %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
```

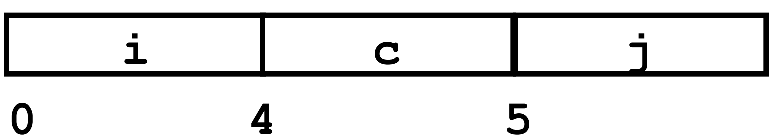
Alignment

- Aligned data
  - Primitive data type requires K bytes
  - Address must be multiple of K (typically 2,4 or 8)
  - 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

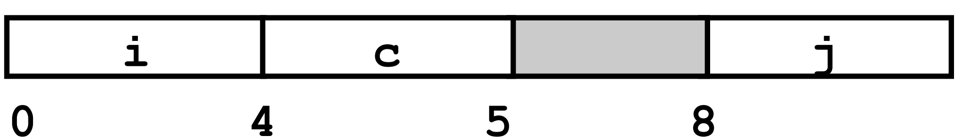
Satisfying alignment with structures

- 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
- Example

```
struct S1 {
  int i;
  char c;
  int j;
} *p;
```



Impossible to satisfy 4-byte alignment requirement for both I and j

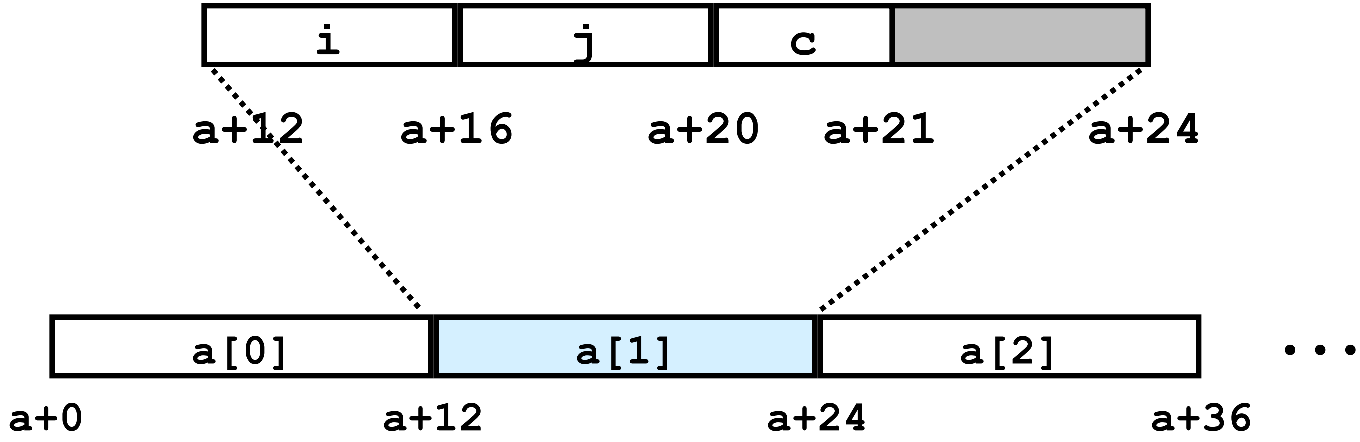


Compiler inserts a 3-byte gap to solve this

Arrays of structures

- Principle
  - Allocated by repeating allocation for array type
  - In general, may nest arrays & structures to arbitrary depth
  - Compiler may need to add padding to ensure each element satisfies its alignment requirements

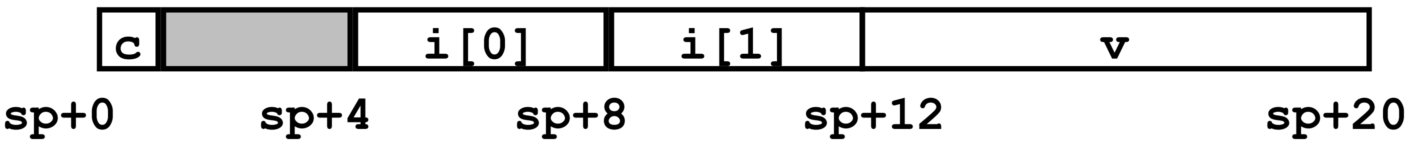
```
struct S2 {
   int i;
   int j;
   char c;
} a[4];
```



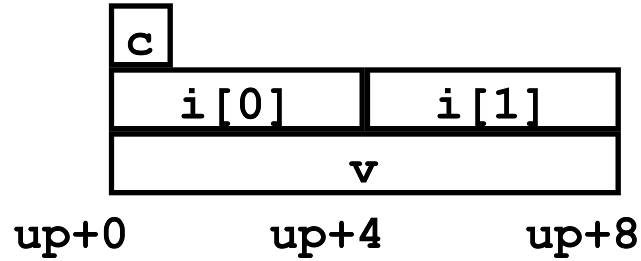
Union allocation

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

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

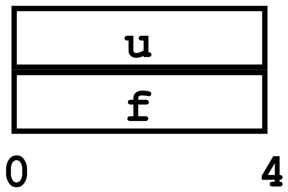



```
union U1 {
  char c;
  int i[2];
  double v;
} *up;
```



Using union to access bit patterns

```
unsigned copy (unsigned u) {
   return u;
}
```




```
unsigned float2bit(float f) {
  union {
    float f;
    unsigned u;
 } temp;
 temp.f = f;
 return temp.u;
}
```

- Store it using one type & access it with another one
- Get direct access to bit representation of float
- `float2bit` generates bit pattern from float
  - Same code as the one generated for `copy`
  - NOT the same as `(unsigned) f`

There's no type info in assembly code!

```
pushl   %ebp
movl    %esp, %ebp
movl    8(%ebp), %eax
popl    %ebp
ret
```

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
  - Uses addressing modes to scale array indices
  - Lots of tricks to improve array indexing in loops
- Structures
  - Allocate bytes in order declared
  - Pad in middle and at end to satisfy alignment
- Unions
  - Overlay declarations
  - Way to circumvent type system