Assembly IV: Complex Data Types

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Basic Data Types

- **Integer**
  - 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

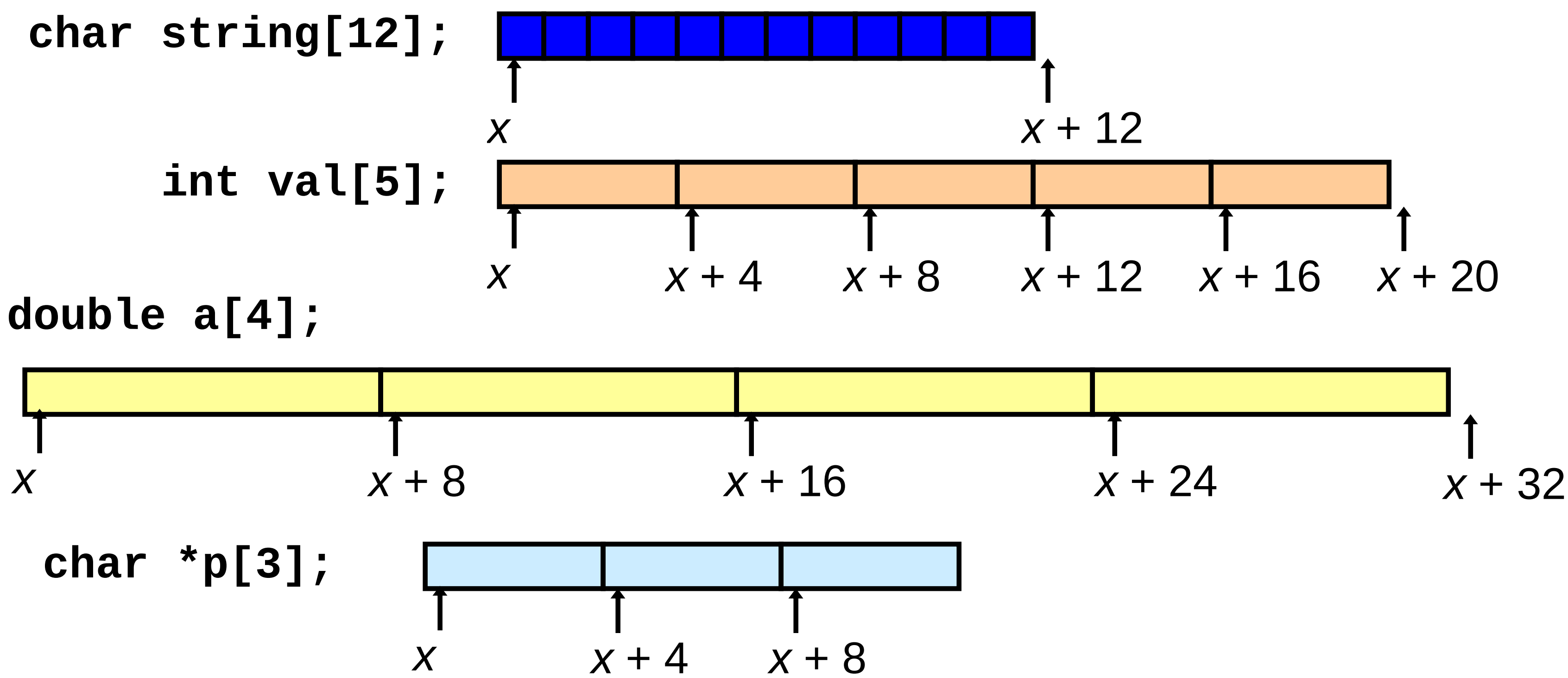
Intel	GAS	Bytes	C
Single	s	4	float
Double	l	8	double
Extended	t	10/12	long double

Complex Data Types

- **Complex data types in C**
  - Pointers
  - Arrays
  - Structures
  - Unions
  - …
- **Can be combined**
  - Pointer to pointer, pointer to array, …
  - Array of array, array of structure, array of pointer, …
  - Structure in structure, pointer in structure, array in structure, …

Array Allocation

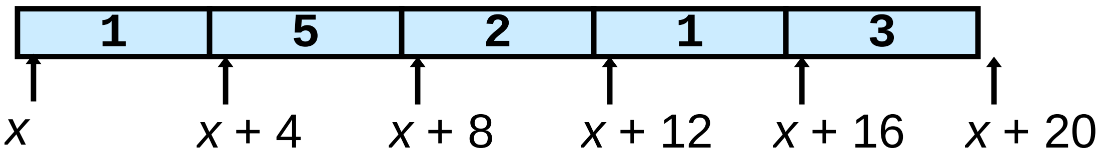
- **Basic principle: *T* A[*L*];**
  - Array of data type *T* and length *L*
  - Contiguously allocated region of *L* * **sizeof(*T*)** bytes



Array Access

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

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

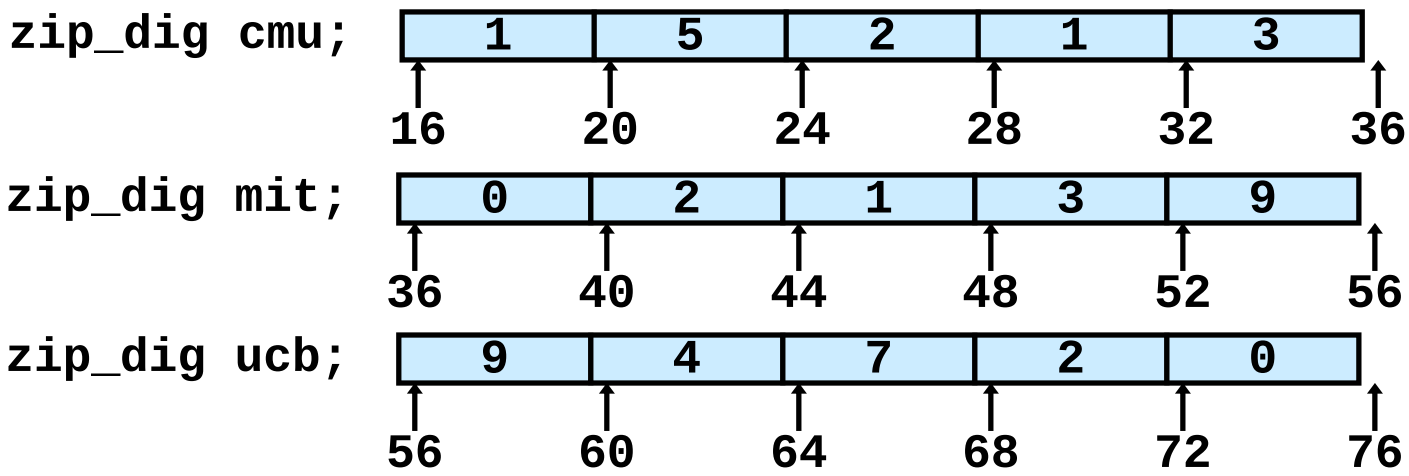


Reference	Type	Value
val[4]	int	3
val	int *	x
val + 1	int *	x + 4
&val[2]	int *	x + 8
val[5]	int	??
*(val+1)	int	5
val + i	int *	x + 4 * i

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**
  - Example arrays were allocated in successive 20 byte blocks
    - Not guaranteed to happen in general

Array Accessing Example (1)

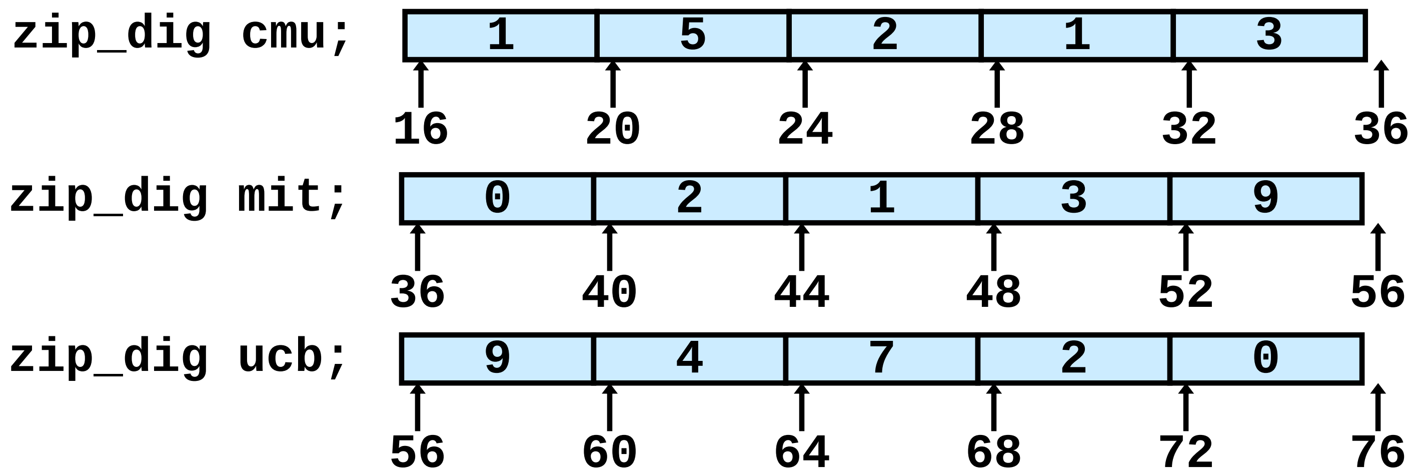
- **Computation**
  - Register **%edx** contains starting address of array
  - Register **%eax** contains array index
  - Desired digit at **4 * %eax + %edx**
  - Use memory reference: **(%edx,%eax,4)**

```
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]
```

Array Accessing Example (2)



- **Code does not do any bounds checking!**
  - Reference / Address / Value / Guaranteed?

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 (1)

- **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 Example (2)

- **Registers**

%ecx	z
%eax	zi
%ebx	zend

```
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
```

z++ increments by 4

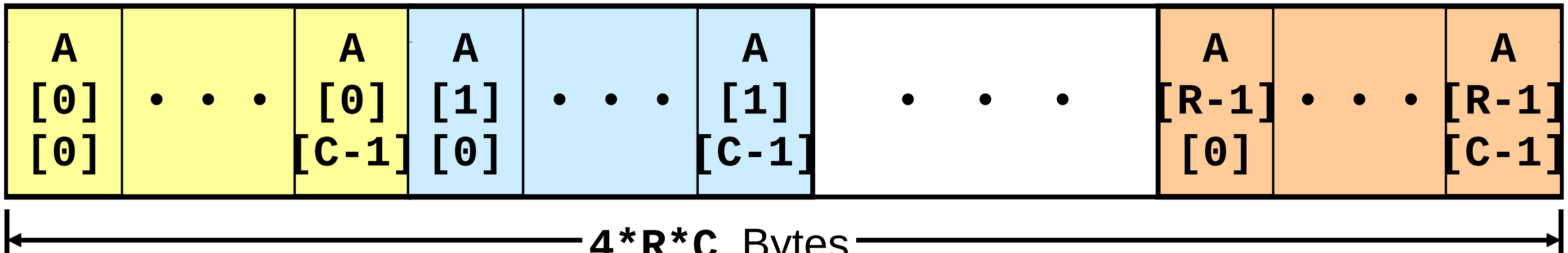
10 * zi + *z
= *z + 2*(zi+4*zi)

Nested Array (1)

- **Declaration: *T* A[*R*][C];**
  - 2D array of data type *T*
  - *R* rows, *C* columns
  - Array size = *R* * *C* * sizeof(*T*)

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

- **Arrangement**
  - Row-major ordering



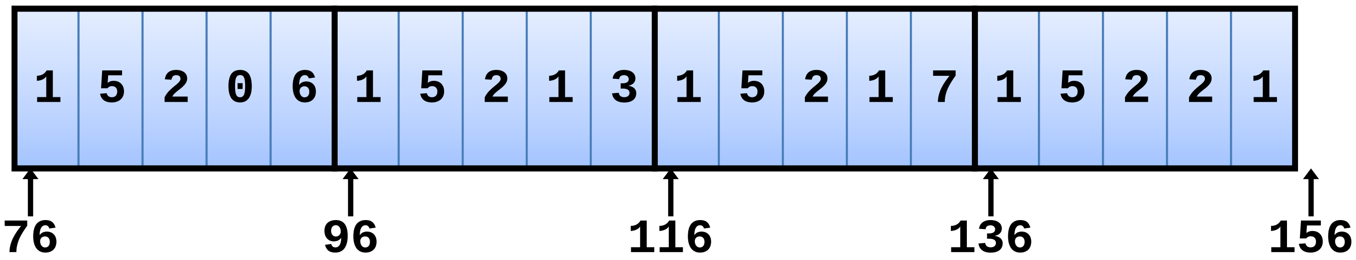
Nested Array (2)

- **C code**
  - Variable **pgh** denotes array of 4 elements
    - Allocated contiguously
  - Each element is an array of 5 **int**'s
    - Allocated contiguously

```
int pgh[4][5] =
  {{1, 5, 2, 0, 6},
   {1, 5, 2, 1, 3 },
   {1, 5, 2, 1, 7 },
   {1, 5, 2, 2, 1 }};
```

- **Row-major ordering of all elements guaranteed**

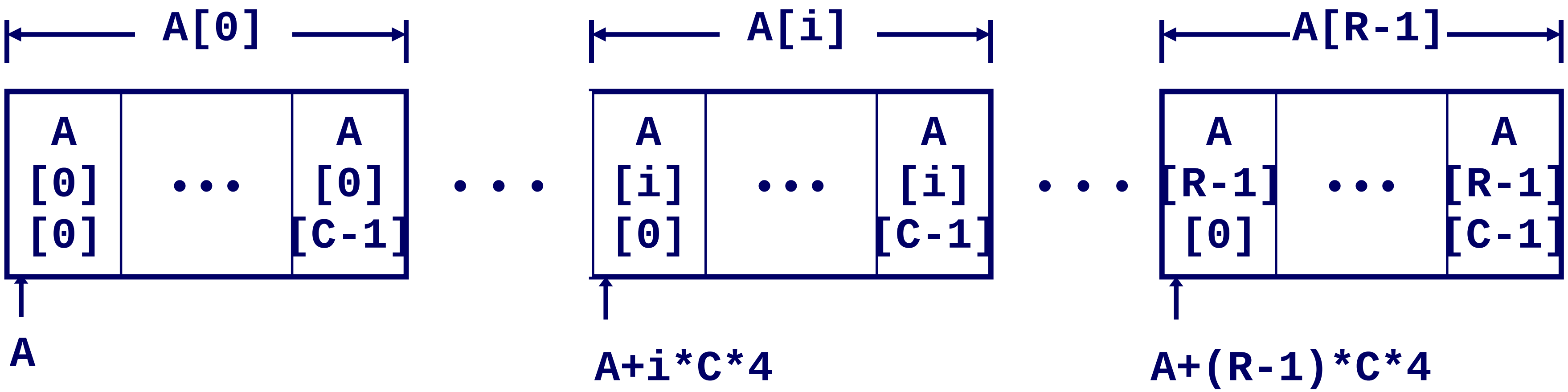
```
int
pgh[4][5];
```



Nested Array Access (1)

- **Row vectors**
  - **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 Access (2)

- Row vector
  - **pgh[index]** is array of 5 **int**'s
  - Starting address **pgh + 20 * index**

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

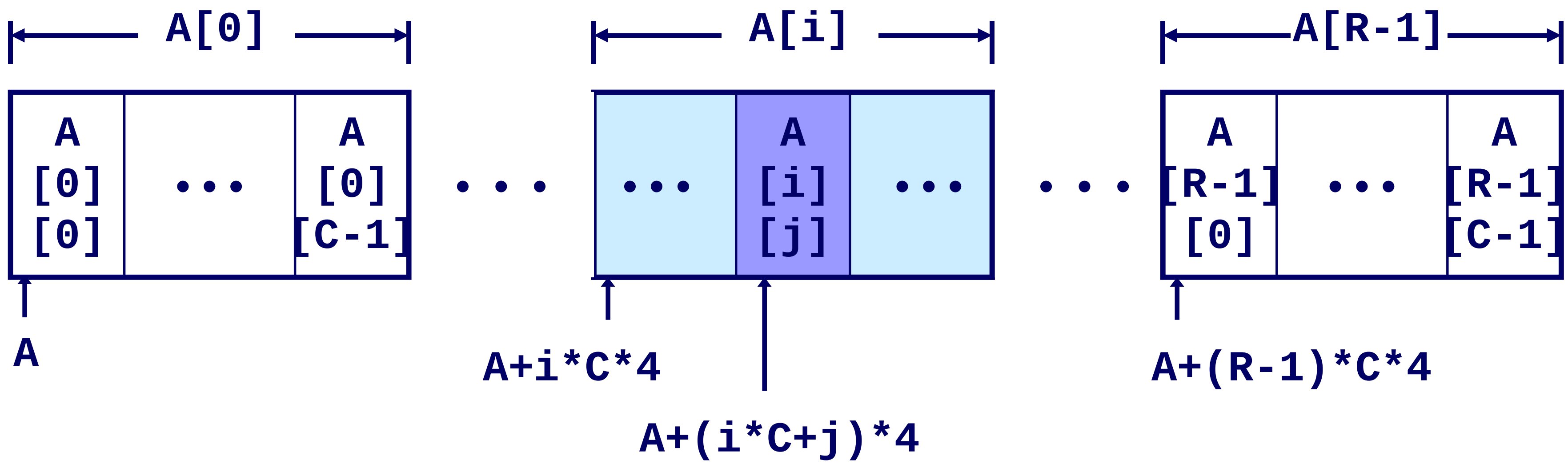
- Code
  - Computes and returns address
  - Compute as **pgh + 4 * (index + 4 * index)**

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

Nested Array Access (3)

- **Array elements**
  - **A[i][j]** is element of type *T*
  - Address $A + i * (C * K) + j * K = A + (i * C + j) * K$

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



Nested Array Access (4)

- **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];
}
```

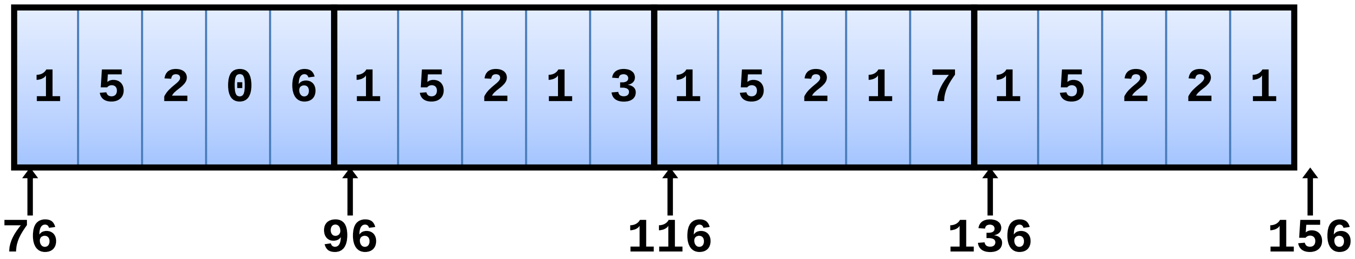
- **Code**
  - Computes address **pgh + 4*dig + 4*(index+4*index)**
  - **movl** performs memory reference

```
# %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)
```

Nested Array Access (5)

- **Strange referencing examples**
  - Code does not do any bounds checking
  - Ordering of elements within array guaranteed

```
int
pgh[4][5];
```



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

Summary

- **Arrays in C**
  - Contiguous allocation of memory
  - Pointer to first element
  - No bounds checking

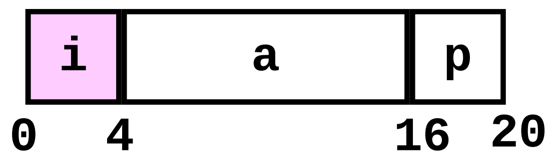
- **Compiler optimizations**
  - Compiler often turns array code into pointer code
  - Uses addressing modes to scale array indices
  - Lots of tricks to improve array indexing in loops

Structures

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

```
struct rec {
  int i;
  int a[3];
  int *p;
};
```

Memory Layout




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

Assembly

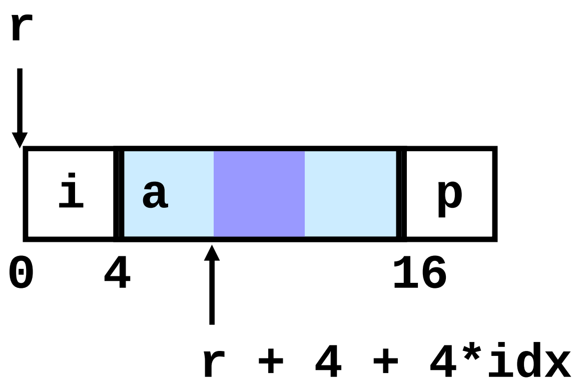
```
# %eax = val
# %edx = r
movl %eax,(%edx)    # Mem[r] = val
```

Structure Referencing (1)

- **Generating pointer to structure member**
  - Offset of each member determined at compile time

```
struct rec {
  int i;
  int a[3];
  int *p;
};
```

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



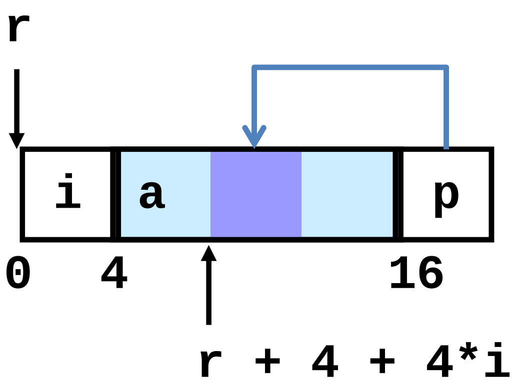

```
# %ecx = idx
# %edx = r
leal 0(,%ecx,4),%eax    # 4*idx
leal 4(%eax,%edx),%eax # r+4*idx+4
```

Structure Referencing (2)

- **Generating pointer to member (cont'd)**

```
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(%eax,%edx),%eax     # r+4+4*(r->i)
movl %eax,16(%edx)         # update r->p
```

Alignment (1)

- **Aligned data**
  - Primitive data type requires ***K*** bytes
  - Address must be multiple of ***K***
  - Required on some machines; advised on IA-32
    - 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 (or "pads") in structure to ensure correct alignment of fields

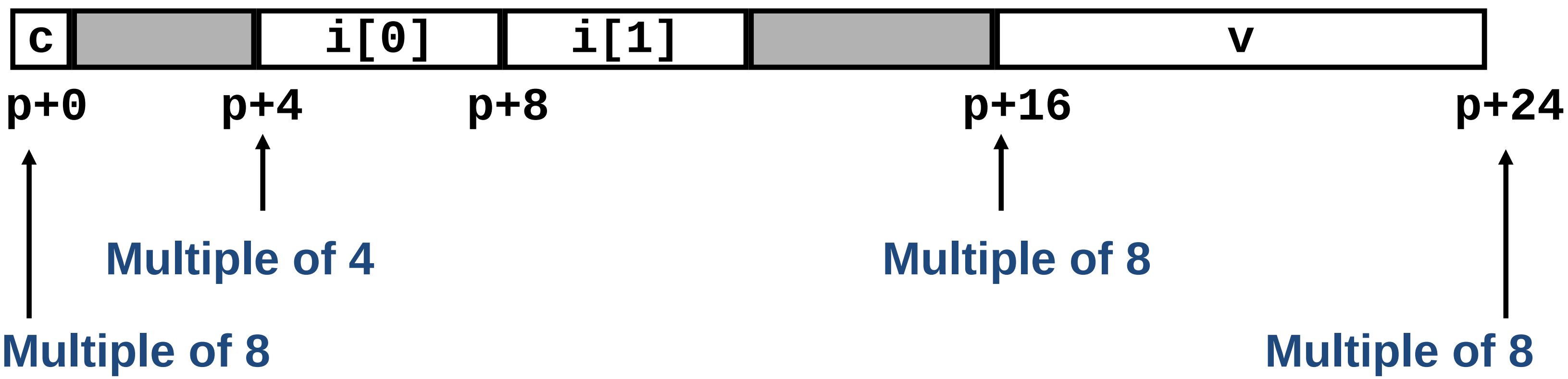
Alignment (2)

- **Size of primitive data type:**
  - 1 byte (e.g., char): No restrictions on address
  - 2 bytes (e.g., short)
    - lowest 1 bit of address must be 0_2
  - 4 bytes (e.g., int, float, char *, etc)
    - lowest 2 bits of address must be 00_2
  - 8 bytes (e.g., double)
    - Windows (and most other OS's & instruction sets): lowest 3 bits of address must be 000_2
    - Linux: lowest 2 bits of address must be 00_2 (i.e, treated the same as a 4-byte primitive data type)
  - 12 bytes (long double)
    - Windows, Linux: lowest 2 bits of address must be 00_2 (i.e., treated the same as a 4-byte primitive data type)

Alignment (3)

- **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 (under Windows):**
  - K = 8, due to **double** element

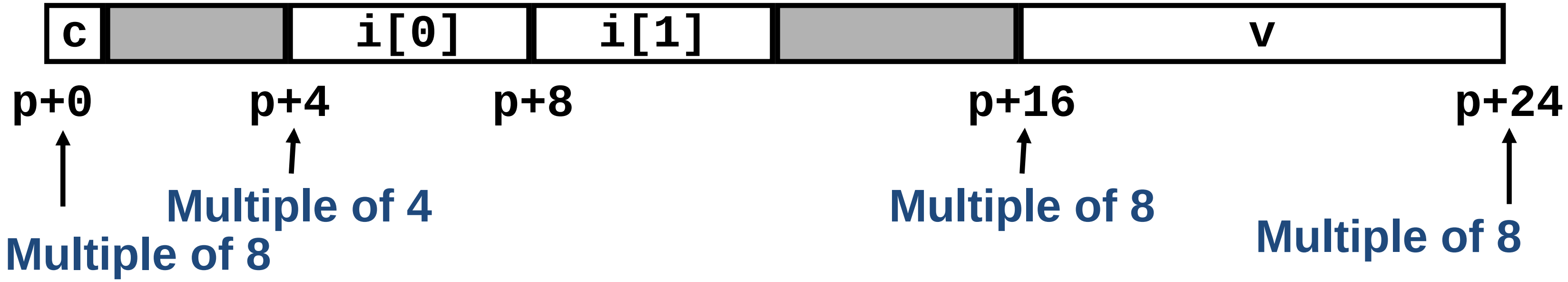
```
struct S1 {
  char c;
  int i[2];
  double v;
} *p;
```



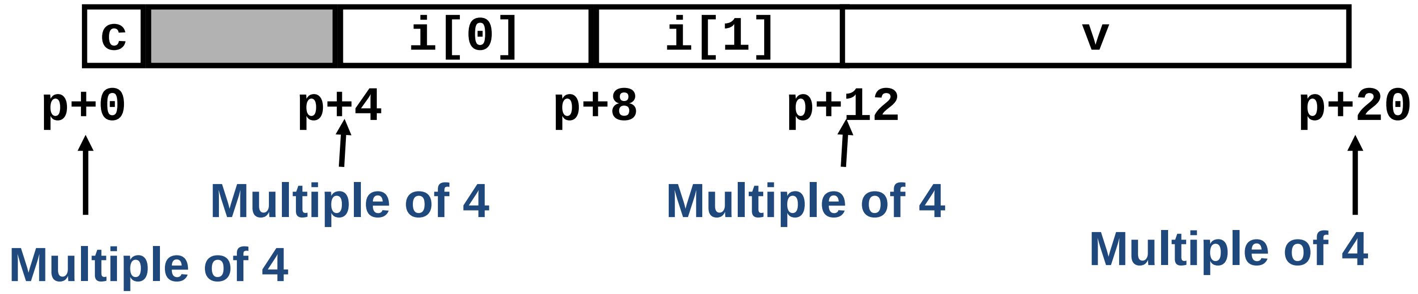
Alignment (4)

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

- **Linux vs. Windows**
  - Windows (including Cygwin): ***K*** = 8



  - Linux: ***K*** = 4

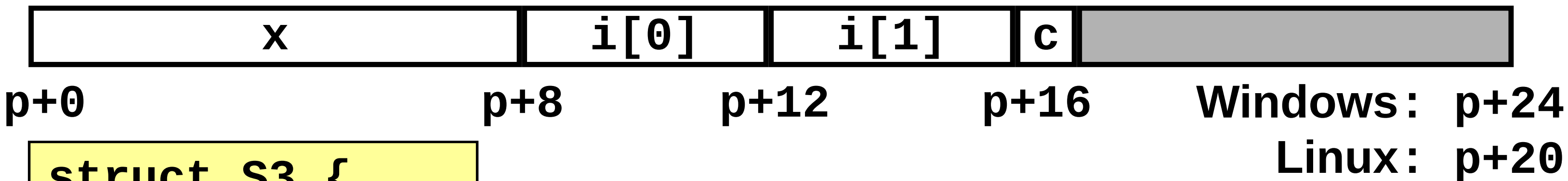


Alignment (5)

- **Overall alignment requirement**

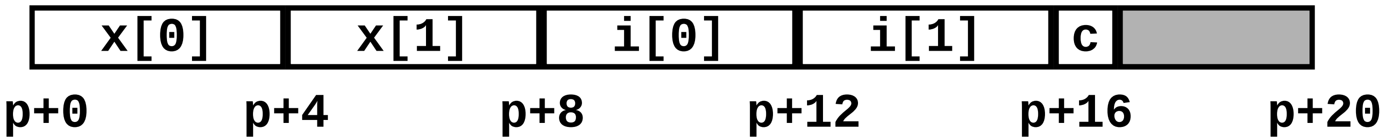
```
struct S2 {
  double x;
  int i[2];
  char c;
} *p;
```

p must be multiple of:
8 for Windows
4 for Linux




```
struct S3 {
  float x[2];
  int i[2];
  char c;
} *p;
```

p must be multiple of 4 (all cases)

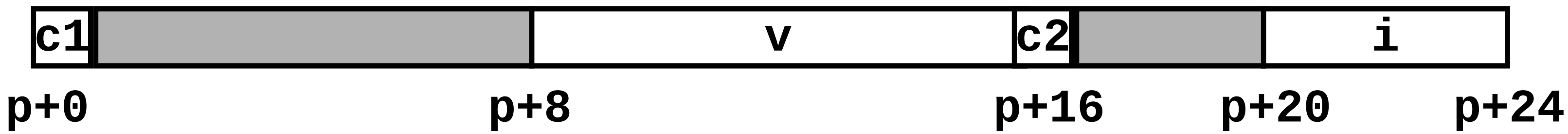


Alignment (6)

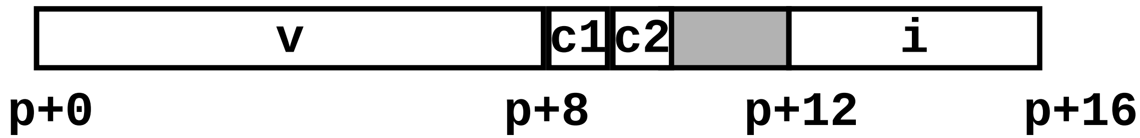
- **Ordering elements within structure**

```
struct S4 {
  char c1;
  double v;
  char c2;
  int i;
} *p;
```

10 bytes wasted space in Windows




```
struct S5 {
  double v;
  char c1;
  char c2;
  int i;
} *p;
```

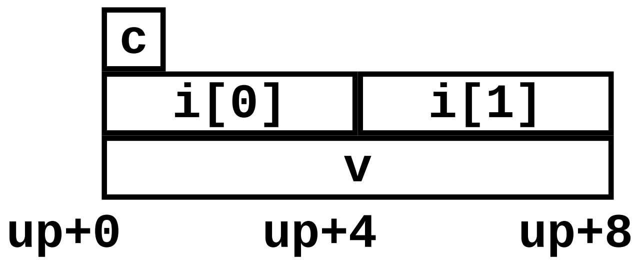


2 bytes wasted space

Union Allocation

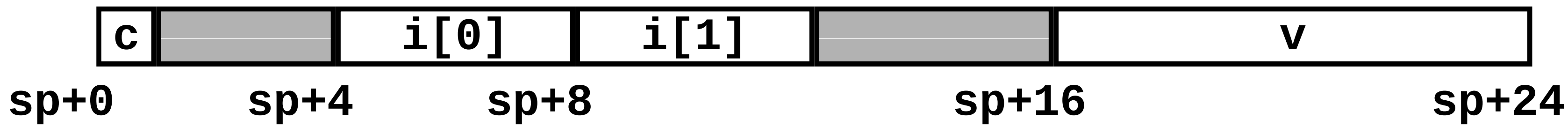
- **Principles**
  - Overlay union elements
  - Allocate according to largest element
  - Can only use one field at a time

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




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

(Windows alignment)



Summary

- **Structures**
  - Allocate bytes in order declared
  - Pad in middle and at end to satisfy alignment
- **Unions**
  - Overlay declarations
  - Way to circumvent type system