Lecture 6A
Machine-Level Programming IV: 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

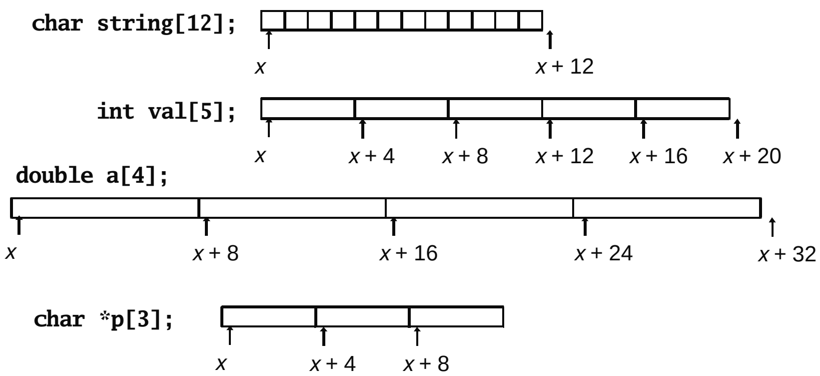
Intel	GAS	Bytes	C
Single	`s`	4	`float`
Double	`l`	8	`double`
Extended	`t`	10/12	`long double`

Array Allocation

Basic Principle

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

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

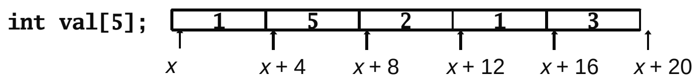


Array Access

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

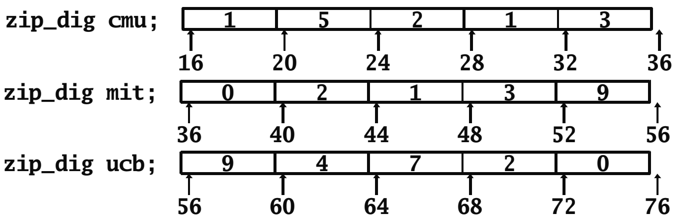


Reference	Type	Value
`val[4]`	`int`	3
`val`	`int *`	*x*
`val+1`	`int *`	*x* + 4
`&val[2]`	`int *`	*x* + 8
`val[5]`	`int`	??
`*(val+1)`	`int`	5
`val + `*i*	`int *`	*x* + 4 *i*

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

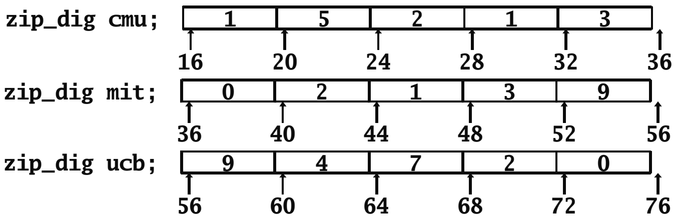
- Register %edx contains starting address of array
- Register %eax contains array index
- Desired digit at `4*%eax + %edx`
- Use memory reference `(%edx, eax,4)`

```
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

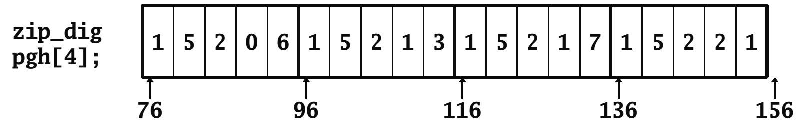
- `10*zi + *z` implemented as `*z + 2*(zi+4*zi)`
- z++ increments by 4

```
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 }};
```



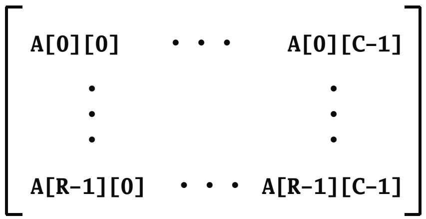
- Declaration "`zip_dig pgh[4]`" equivalent to "`int pgh[4][5]`"
  - Variable pgh denotes array of 4 elements
    - » Allocated contiguously
  - Each element is an array of 5 `int`'s
    - » Allocated contiguously
- "Row-Major" ordering of all elements guaranteed

Nested Array Allocation

Declaration

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

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



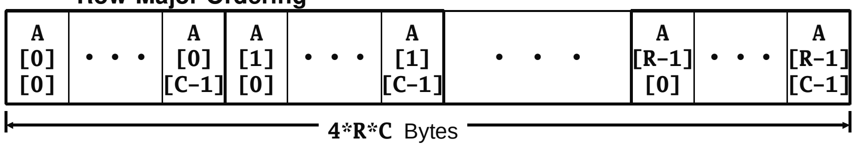
Array Size

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

Arrangement

- Row-Major Ordering

`int A[R][C];`

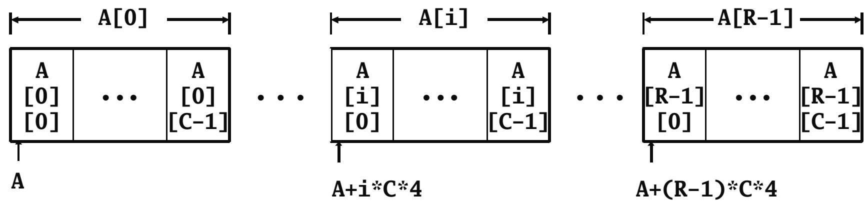


Nested Array Row Access

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

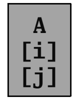
- Computes and returns address
- Compute as `pgh + 4*(index+4*index)`

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

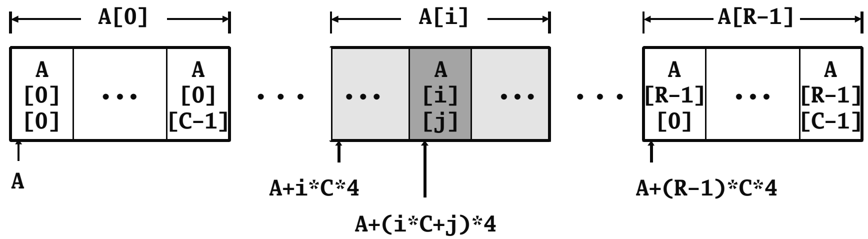

Nested Array Element Access

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`

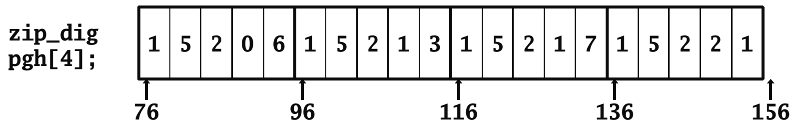
```
int get_pgh_digit
  (int index, int dig)
{
  return pgh[index][dig];
}
```

Code

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

```
# %ecx = dig
# %eax = index
leal (,%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



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

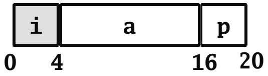
Structures

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

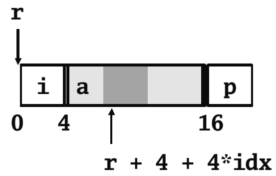
```
void
set_i(struct rec *r,
      int val)
{
  r->i = val;
}
```

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


Alignment

Aligned Data

- Primitive data type requires K bytes
- Address must be multiple of K
- 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

Specific Cases of Alignment

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`)
  - Linux:
    - » lowest 2 bits of address must be 00_2
    - » i.e., treated the same as a 4-byte primitive data type

Satisfying Alignment with Structures

Offsets Within Structure

- Must satisfy element's alignment requirement

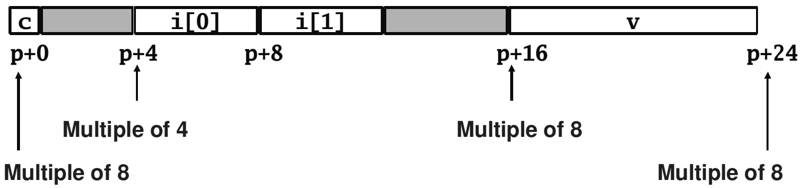
Overall Structure Placement

- Each structure has alignment requirement K
  - Largest alignment of any element
- Initial address & structure length must be multiples of K

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

Example (under Windows):

- K = 8, due to double element

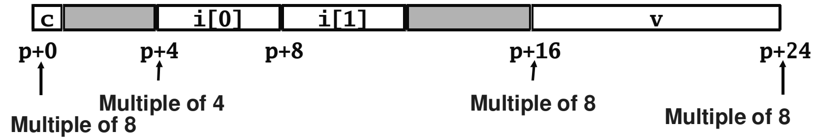


Linux vs. Windows

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

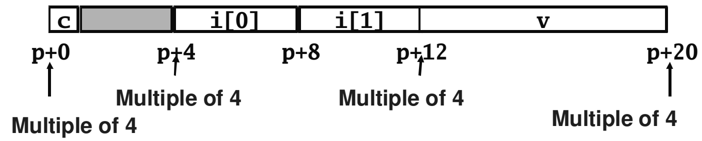
Windows (including Cygwin):

- K = 8, due to double element



Linux:

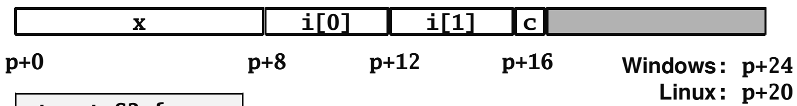
- K = 4; double treated like a 4-byte data type



Overall Alignment Requirement

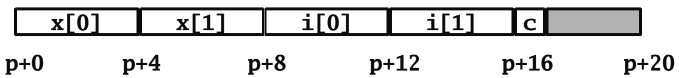
```
struct S2 {
  double x;
  int i[2];
  char c;
} *p;
```

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




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

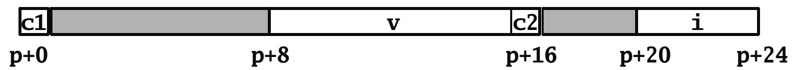
p must be multiple of 4 (in either OS)



Ordering Elements Within Structure

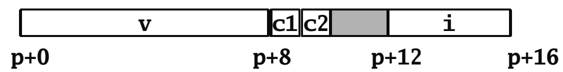
```
struct S4 {
  char c1;
  double v;
  char c2;
  int i;
} *p;
```

10 bytes wasted space in Windows




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

2 bytes wasted space

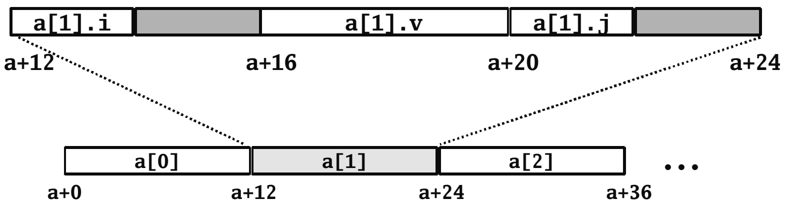


Arrays of Structures

Principle

- Allocated by repeating allocation for array type
- In general, may nest arrays & structures to arbitrary depth

```
struct S6 {
  short i;
  float v;
  short j;
} a[10];
```



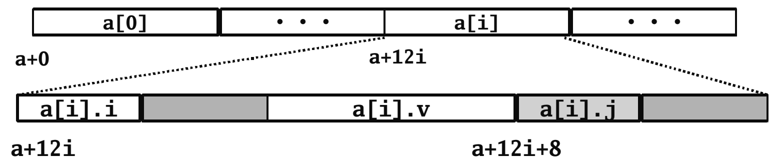
Accessing Element within Array

- Compute offset to start of structure
  - Compute 12**i* as 4*(*i*+2*i*)
- Access element according to its offset within structure
  - Offset by 8
  - Assembler gives displacement as a + 8
    - » Linker must set actual value

```
struct S6 {
  short i;
  float v;
  short j;
} a[10];
```

```
short get_j(int idx)
{
  return a[idx].j;
}
```

```
# %eax = idx
leal (%eax,%eax,2),%eax # 3*idx
movswl a+8(,%eax,4),%eax
```

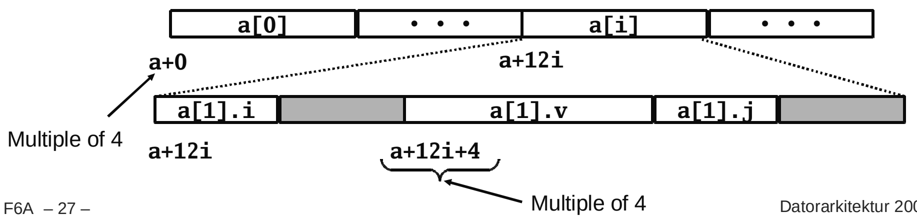


Satisfying Alignment within Structure

Achieving Alignment

- Starting address of structure array must be multiple of worst-case alignment for any element
  - a must be multiple of 4
- Offset of element within structure must be multiple element's alignment requirement
  - v's offset of 4 is a multiple of 4
- Overall size of structure must be multiple of worst-case alignment for any element
  - Structure padded with unused space to be 12 bytes

```
struct S6 {
  short i;
  float v;
  short j;
} a[10];
```

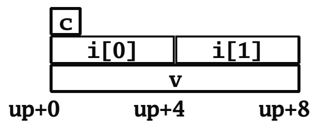


Union Allocation

Principles

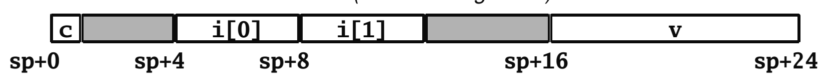
- Overlay union elements
- Allocate according to largest element
- Can only use one field at a time

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



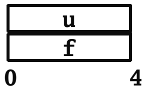

```
struct S1 {
  char c;
  int i[2];
  double v;
} *sp;
```

(Windows alignment)



Using Union to Access Bit Patterns

```
typedef union {
  float f;
  unsigned u;
} bit_float_t;
```



- Get direct access to bit representation of float
- `bit2float` generates float with given bit pattern
  - NOT the same as `(float) u`
- `float2bit` generates bit pattern from float
  - NOT the same as `(unsigned) f`

```
float bit2float(unsigned u) {
  bit_float_t arg;
  arg.u = u;
  return arg.f;
}
```

```
unsigned float2bit(float f) {
  bit_float_t arg;
  arg.f = f;
  return arg.u;
}
```


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

Structures

- Allocate bytes in order declared
- Pad in middle and at end to satisfy alignment

Unions

- Overlay declarations
- Way to circumvent type system