15-213

“The course that gives CMU its Zip!”

Structured Data II
Heterogenous Data
February 13, 2001

Topics

- Structure Allocation
- Alignment
- Unions
- Byte Ordering
- Byte Operations
- IA32/Linux Memory Organization
- Understanding C declarations

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`, `long`, `char *`
quad word		8	[unsigned] `long long (in gcc)`

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`

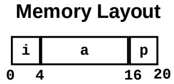
Structures

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

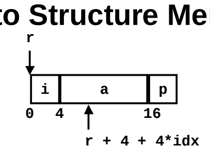
```
void
set_i(struct rec *r,
      int val)
{
  r->i = val;
}
```

Assembly

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


Generating Pointer to Structure Member

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



Generating Pointer to Array Element

- Offset of each structure member determined at compile time

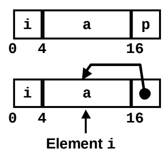
```
int *
find_a
 (struct rec *r, int idx)
{
  return &r->a[idx];
}
```

```
# %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**
- **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:

- **<u>1 byte</u> (e.g., `char`)**
  - no restrictions on address
- **<u>2 bytes</u> (e.g., `short`)**
  - lowest 1 bit of address must be 0_2
- **<u>4 bytes</u> (e.g., `int`, `float`, `char *`, etc.)**
  - lowest 2 bits of address must be 00_2
- **<u>8 bytes</u> (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
- **<u>12 bytes</u> (`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**

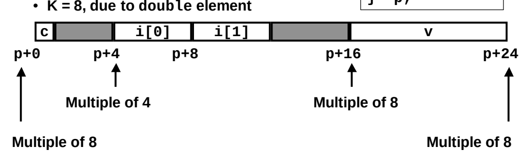
Overall Structure Placement

- **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**

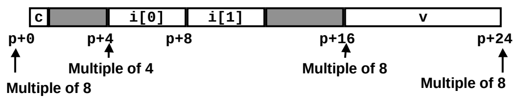


Linux vs. Windows

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

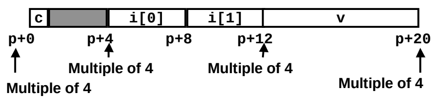
Windows (including Cygwin):

- K = 8, due to `double` element



Linux:

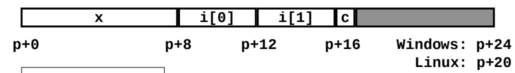
- K = 4; `double` treated like a 4-byte data type



Effect of Overall Alignment Requirement

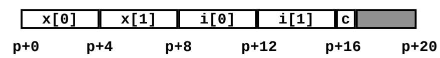
```
struct S2 {
  double x;
  int i[2];
  char c;
} *p;
```

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




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

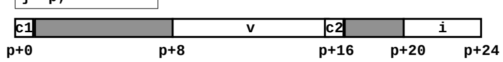
p must be multiple of 4 (in either OS)



Ordering Elements Within Structure

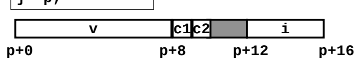
```
struct S4 {
  char c1;
  double v;
  char c2;
  int i;
} *p;
```

10 bytes wasted space in Windows




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

2 bytes wasted space

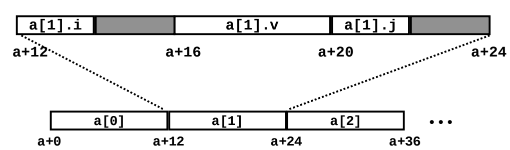


Arrays of Structures

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];
```



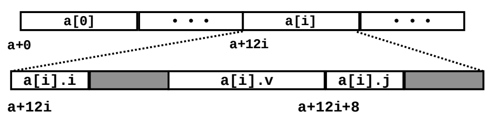
Accessing Element within Array

- Compute offset to start of structure
  - Compute 12*i as 4*(i+2i)
- 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
```

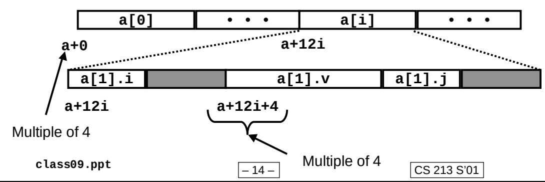


Satisfying Alignment within Structure

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 of 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];
```

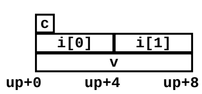


Union Allocation

Principles

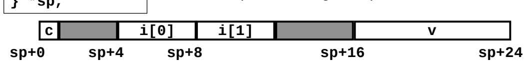
- Overlay union elements
- Allocate according to largest element
- Can only use one field at a time

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




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

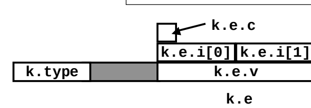
(Windows alignment)



Implementing "Tagged" Union

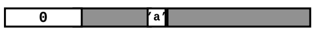
- Structure can hold 3 kinds of data
- Only one form at any given time
- Identify particular kind with flag **type**

```
typedef enum { CHAR, INT, DBL }
  utype;

typedef struct {
  utype type;
  union {
    char c;
    int i[2];
    double v;
  } e;
} store_ele, *store_ptr;

store_ele k;
```

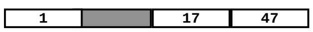


Using “Tagged” Union

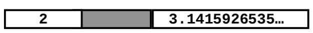
```
store_ele k1;
k1.type = CHAR;
k1.e.c = 'a';
```




```
store_ele k2;
k2.type = INT;
k2.e.i[0] = 17;
k2.e.i[1] = 47;
```

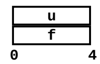



```
store_ele k3;
k3.type = DBL;
k1.e.v =
  3.14159265358979323846;
```



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;
}
```


Byte Ordering

Idea

- Long/quad words stored in memory as 4/8 consecutive bytes
- Which is most (least) significant?
- Can cause problems when exchanging binary data between machines

Big Endian

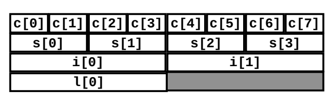
- Most significant byte has lowest address
- IBM 360/370, Motorola 68K, Sparc

Little Endian

- Least significant byte has lowest address
- Intel x86, Digital VAX

Byte Ordering Example

```
union {
  unsigned char c[8];
  unsigned short s[4];
  unsigned int i[2];
  unsigned long l[1];
} dw;
```

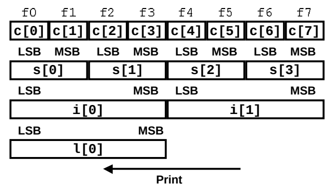


Byte Ordering Example (Cont).

```
int j;
for (j = 0; j < 8; j++)
dw.c[j] = 0xf0 + j;

printf("Characters 0-7 ==
[0x%x,0x%x,0x%x,0x%x,0x%x,0x%x,0x%x,0x%x]\n",
    dw.c[0], dw.c[1], dw.c[2], dw.c[3],
    dw.c[4], dw.c[5], dw.c[6], dw.c[7]);

printf("Shorts 0-3 ==
[0x%x,0x%x,0x%x,0x%x]\n",
    dw.s[0], dw.s[1], dw.s[2], dw.s[3]);

printf("Ints 0-1 == [0x%x,0x%x]\n",
    dw.i[0], dw.i[1]);

printf("Long 0 == [0x%lx]\n",
    dw.l[0]);
```


Byte Ordering on x86

Little Endian

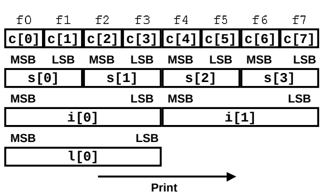


Output on Pentium:

```
Characters 0-7 == [0xf0,0xf1,0xf2,0xf3,0xf4,0xf5,0xf6,0xf7]
Shorts     0-3 == [0xf1f0,0xf3f2,0xf5f4,0xf7f6]
Ints       0-1 == [0xf3f2f1f0,0xf7f6f5f4]
Long       0   == [f3f2f1f0]
```


Byte Ordering on Sun

Big Endian

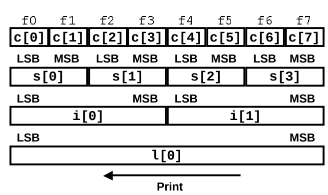


Output on Sun:

```
Characters 0-7 == [0xf0,0xf1,0xf2,0xf3,0xf4,0xf5,0xf6,0xf7]
Shorts     0-3 == [0xf0f1,0xf2f3,0xf4f5,0xf6f7]
Ints       0-1 == [0xf0f1f2f3,0xf4f5f6f7]
Long       0   == [0xf0f1f2f3]
```


Byte Ordering on Alpha

Little Endian



Output on Alpha:

```
Characters 0-7 == [0xf0,0xf1,0xf2,0xf3,0xf4,0xf5,0xf6,0xf7]
Shorts     0-3 == [0xf1f0,0xf3f2,0xf5f4,0xf7f6]
Ints       0-1 == [0xf3f2f1f0,0xf7f6f5f4]
Long       0   == [0xf7f6f5f4f3f2f1f0]
```

Byte-Level Operations

IA32 Support

- Arithmetic and data movement operations have byte-level version
  `movb`, `addb`, `testb`, etc.
- Some registers partially byte-addressable
- Can perform single byte memory references

`%eax`	`%ah`	`%al`
`%edx`	`%dh`	`%dl`
`%ecx`	`%ch`	`%cl`
`%ebx`	`%bh`	`%bl`

Compiler

- Parameters and return values of type `char` passed as `int`'s
- Use `movsbl` to sign-extend byte to `int`

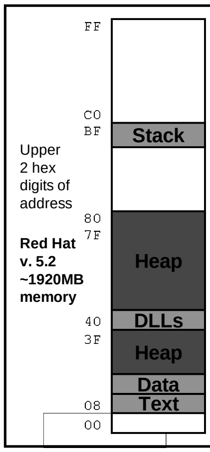
Byte-Level Operation Example

- Compute Xor of characters in string

```
char string_xor(char *s)
{
  char result = 0;
  char c;
  do {
    c = *s++;
    result ^= c;
  } while (c);
  return result;
}
```

```
  # %edx = s, %cl = result
  movb $0,%cl      # result = 0
L2:                # loop:
  movb (%edx),%al  # *s
  incl %edx        # s++
  xorb %al,%cl     # result ^= c
  testb %al,%al    # al
  jne L2           # If != 0, goto loop
  movsbl %cl,%eax  # Sign extend to int
```


Linux Memory Layout



Stack

- Runtime stack (8MB limit)

Heap

- Dynamically allocated storage
- When call `malloc`, `calloc`, `new`

DLLs

- Dynamically Linked Libraries
- Library routines (e.g., `printf`, `malloc`)
- Linked into object code when first executed

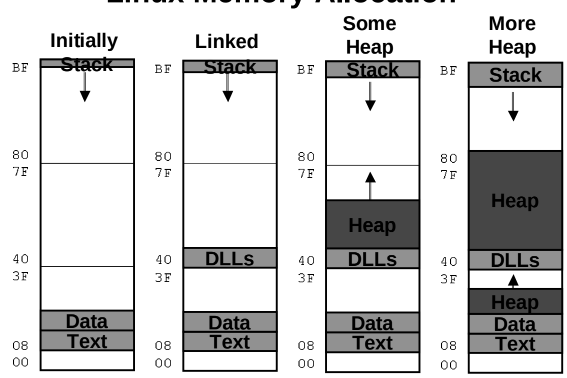
Data

- Statically allocated data
- E.g., arrays & strings declared in code

Text

- Executable machine instructions
- Read-only

Linux Memory Allocation



Memory Allocation Example

```
char big_array[1<<24];  /*  16 MB */
char huge_array[1<<28]; /* 256 MB */
int beyond;
char *p1, *p2, *p3, *p4;
int useless() {  return 0; }

int main()
{
 p1 = malloc(1 <<28);  /* 256 MB */
 p2 = malloc(1 << 8);  /* 256 B  */
 p3 = malloc(1 <<28);  /* 256 MB */
 p4 = malloc(1 << 8);  /* 256 B  */
 /* Some print statements ... */
}
```


Dynamic Linking Example

```
(gdb) print malloc
  $1 = {<text variable, no debug info>}
    0x8048454 <malloc>
(gdb) run
  Program exited normally.
(gdb) print malloc
  $2 = {void *(unsigned int)}
    0x40006240 <malloc>
```

Initially

- Code in text segment that invokes dynamic linker
- Address `0x8048454` should be read `0x08048454`

Final

- Code in DLL region

Breakpointing Example

```
(gdb) break main
(gdb) run
  Breakpoint 1, 0x804856f in main ()
(gdb) print $esp
  $3 = (void *) 0xbffffc78
```

Main

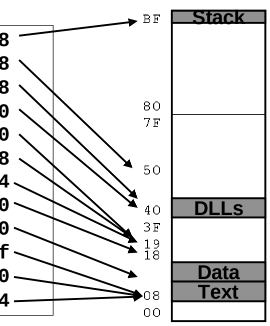
- Address `0x804856f` should be read `0x0804856f`

Stack

- Address `0xbffffc78`

Example Addresses

$esp	0xbffffc78
p3	0x500b5008
p1	0x400b4008
Final `malloc`	0x40006240
p4	0x1904a640
p2	0x1904a538
beyond	0x1904a524
big_array	0x1804a520
huge_array	0x0804a510
main()	0x0804856f
useless()	0x08048560
Initial `malloc`	0x08048454



C operators

Operators	Associativity
`() [] -> .`	left to right
`! ~ ++ -- + - * & (type) sizeof`	right to left
`* / %`	left to right
`+ -`	left to right
`<< >>`	left to right
`< <= > >=`	left to right
`== !=`	left to right
`&`	left to right
`^`	left to right
`|`	left to right
`&&`	left to right
`||`	left to right
`?:`	right to left
`= += -= *= /= %= &= ^= != <<= >>=`	right to left
`,`	left to right

Note: Unary +, -, and * have higher precedence than binary forms

C pointer declarations

`int *p`	p is a pointer to int
`int *p[13]`	p is an array[13] of pointer to int
`int *(p[13])`	p is an array[13] of pointer to int
`int **p`	p is a pointer to a pointer to an int
`int (*p)[13]`	p is a pointer to an array[13] of int
`int *f()`	f is a function returning a pointer to int
`int (*f)()`	f is a pointer to a function returning int
`int (*(*f())[13])()`	f is a function returning ptr to an array[13] of pointers to functions returning int
`int (*(*x[3])())[5]`	x is an array[3] of pointers to functions returning pointers to array[5] of ints