# 15-213

## Structured Data II
## Heterogenous Data
## Feb. 15, 2000

**Topics**
- Structure Allocation
- Alignment
- Unions
- Byte Ordering
- Byte Operations
- IA32/Linux Memory Organization



# 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, char * |
| quad word | | 8 | |

## Floating Point
- Stored & operated on in floating point registers

| Intel | GAS | Bytes | C |
|---|---|---|---|
| Single | s | 4 | float |
| Double | l | 8 | double |
| Extended | | 10 | -- |

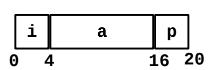


# Structures

## 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;
}
```

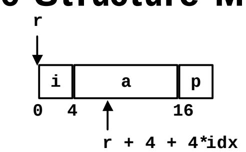
### Assembly

```
 # %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

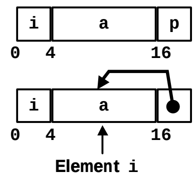
```
int *
find_a
 (struct rec *r, int idx)
{
  return &r->a[idx];
}
```

```
 # %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:

- **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



## Satisfying Alignment with Structures

### Offsets Within Structure

- Must satisfy element's alignment requirement

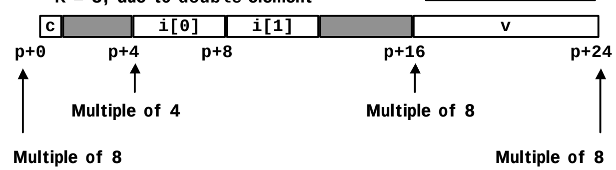
### Overall Structure Placement

- 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

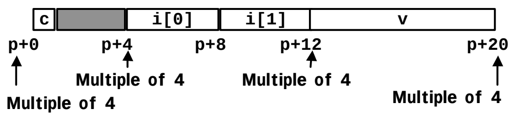
```
struct S1 {
  char c;
  int i[2];
  double v;
} *p;
```

**Windows (including Cygwin):**

- K = 8, due to double element


**Linux:**

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

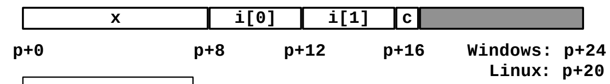





## Effect of Overall Alignment Requirement

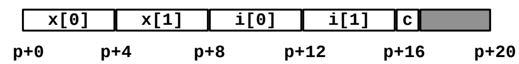
```
struct S2 {
  double x;
  int i[2];
  char c;
} *p;
```

**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)

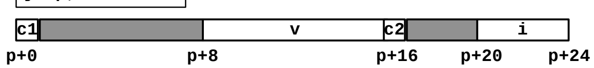





## Ordering Elements Within Structure

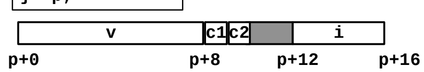
```
struct S4 {
  char c1;
  double v;
  char c2;
  int i;
} *p;
```

10 bytes wasted space in Windows




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

2 bytes wasted space



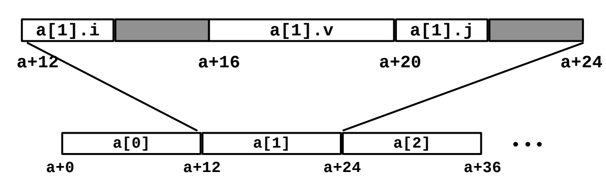



## Arrays of Structures

**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];
```



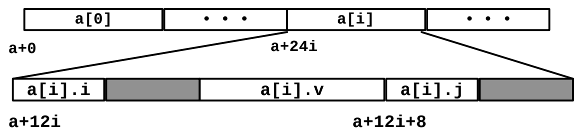
# Accessing Element within Array

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



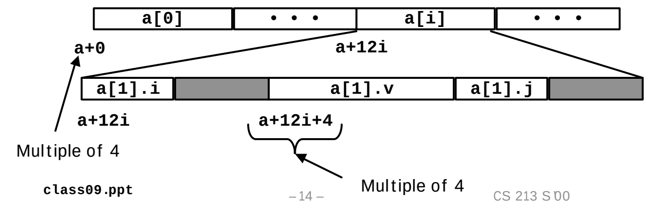



# Satisfying Alignment within Structure

## 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 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];
```



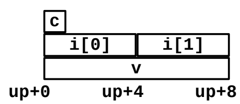



# Union Allocation

## Principles

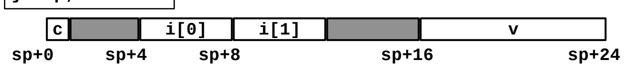
- **Overlay union elements**
- **Allocate according to largest element**
- **Can only use one field at a time**

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




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

*(Windows alignment)*

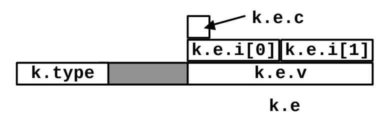





# Implementing "Tagged" Union

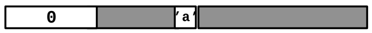
- **Structure can hold 3 kinds of data**
- **Only one form at any given time**
- **Identify particular kind with flag type**

```
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;
```

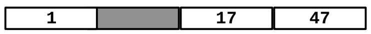


# Using “Tagged” Union

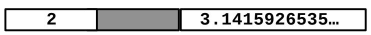
```
store_ele k1;
k1.type = CHAR;
k1.e.c = 'a';
```




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



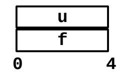

```
store_ele k3;
k3.type = DBL;
k1.e.v =
  3.14159265358979323846;
```






# 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**

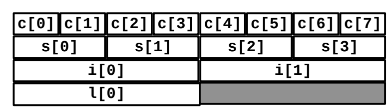
## Little Endian

- **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;
```



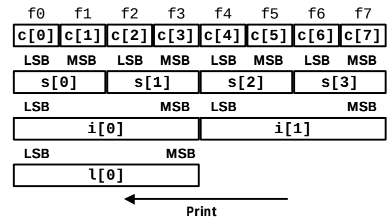
# Byte Ordering Example (Cont).

```
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



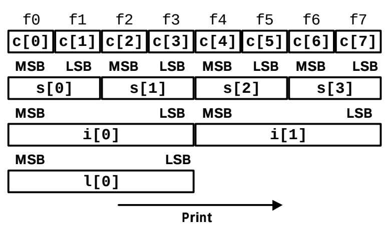

### Output on Pentium:

```
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



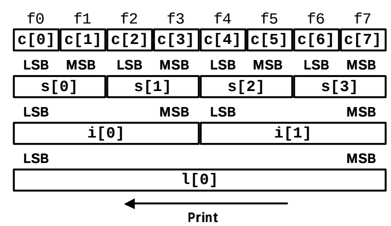

### Output on Sun:

```
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

**Compiler**

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

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



# Byte-Level Operation Example

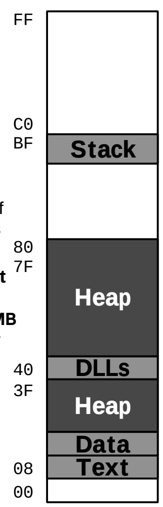
- Compute Xor of characters in string

```
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




Upper 2 hex digits of address

**Red Hat v. 5.2 ~1920MB memory**

**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**

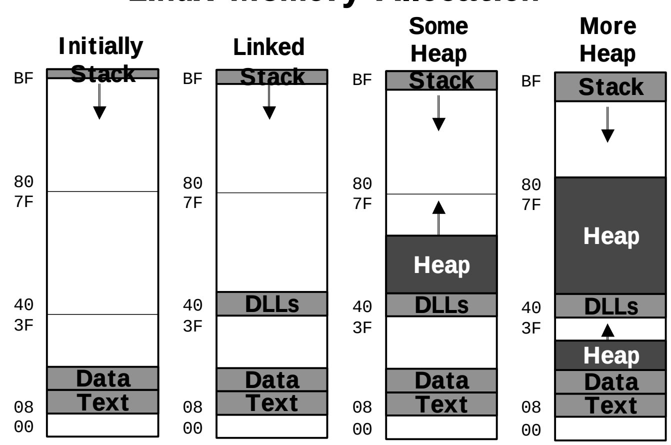
- Statically allocated data
- E.g., arrays & strings declared in code

**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 |