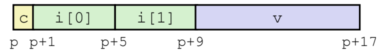
Lecture 17

Data Alignment

CPSC 275
Introduction to Computer Systems

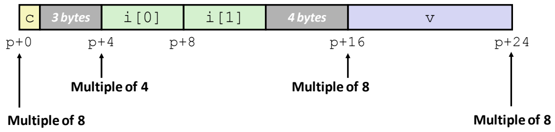
Structures & Alignment

- Unaligned Data



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

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



Alignment Principles

- Aligned Data
  - Primitive data type requires ***K*** bytes
  - Address must be multiple of ***K***
  - Required on some machines; advised on IA32
    - Treated differently by IA32 Linux, x86-64 Linux, and Windows!
- Motivation for Aligning Data
  - Memory accessed by (aligned) chunks of 4 or 8 bytes (system dependent)
    - Inefficient to load or store datum that spans quad word boundaries
    - Virtual memory very tricky when datum spans 2 *pages* (TBD later)
- Compiler
  - Inserts gaps in structure to ensure correct alignment of fields, e.g., `.align` directive

Specific Cases of Alignment (IA32)

- 1 byte: **`char`**, …
  - no restrictions on address
- 2 bytes: **`short`**, …
  - lowest 1 bit of address must be 0_2
- 4 bytes: **`int`**, **`float`**, **`char *`**, …
  - lowest 2 bits of address must be 00_2
- 8 bytes: **`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

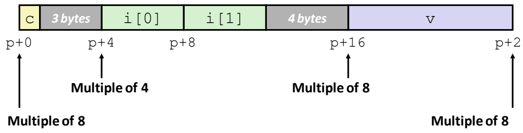
Specific Cases of Alignment (x86-64)

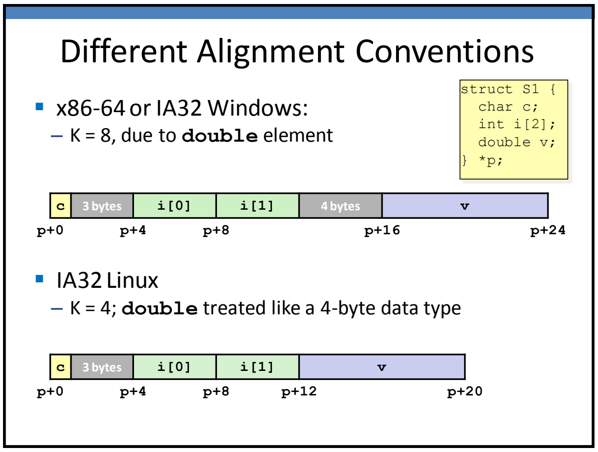
- 1 byte: **`char`**, …
  - no restrictions on address
- 2 bytes: **`short`**, …
  - lowest 1 bit of address must be 0_2
- 4 bytes: **`int`**, **`float`**, …
  - lowest 2 bits of address must be 00_2
- 8 bytes: **`double`**, **`char *`**, …
  - Windows & Linux:
    - lowest 3 bits of address must be 000_2
- 16 bytes: **`long double`**
  - Linux:
    - lowest 3 bits of address must be 000_2
    - i.e., treated the same as a 8-byte primitive data type

Satisfying Alignment with Structures

- Within structure:
  - Must satisfy each element's alignment requirement
- Overall structure placement
  - Each structure has alignment requirement **K**
    - **K** = Largest alignment of any element
  - Initial address & structure length must be multiples of **K**
- Example (under Windows or x86-64):
  - K = 8, due to **`double`** element

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



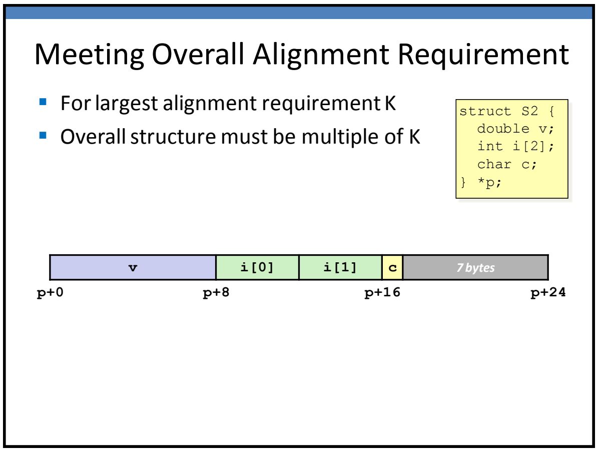


Different Alignment Conventions

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

- x86-64 or IA32 Windows:
  - K = 8, due to **`double`** element

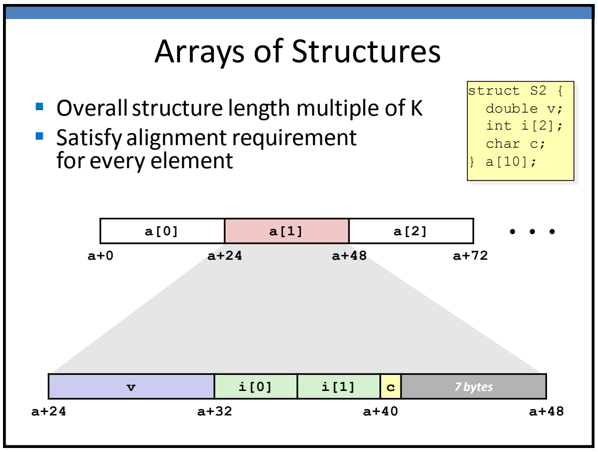
- IA32 Linux
  - K = 4; **`double`** treated like a 4-byte data type



Meeting Overall Alignment Requirement

- For largest alignment requirement K
- Overall structure must be multiple of K

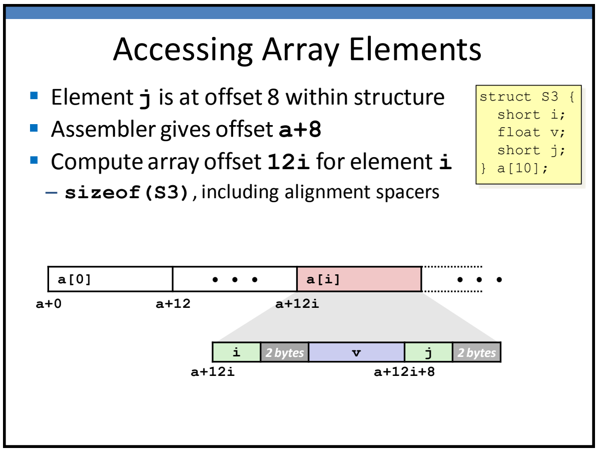
```
struct S2 {
  double v;
  int i[2];
  char c;
} *p;
```



Arrays of Structures

- Overall structure length multiple of K
- Satisfy alignment requirement for every element

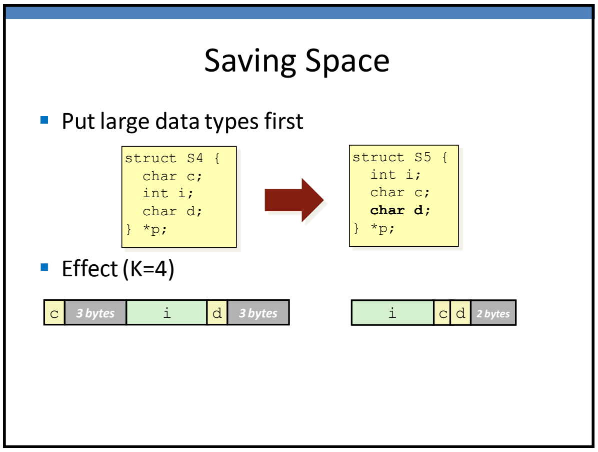
```
struct S2 {
  double v;
  int i[2];
  char c;
} a[10];
```



Accessing Array Elements

- Element **`j`** is at offset 8 within structure
- Assembler gives offset **`a+8`**
- Compute array offset **`12i`** for element **`i`**
  - **`sizeof(S3)`**, including alignment spacers

```
struct S3 {
  short i;
  float v;
  short j;
} a[10];
```



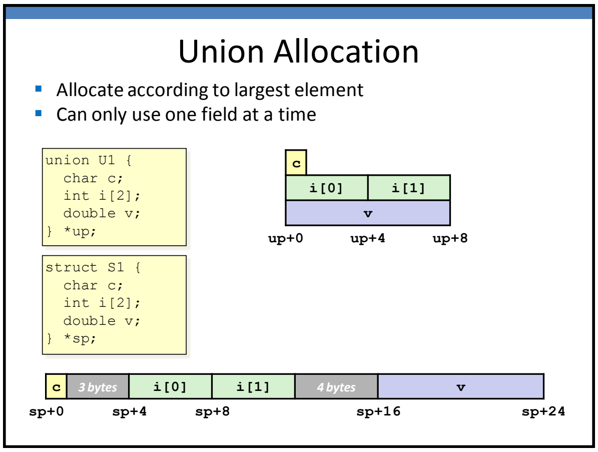
Saving Space

- Put large data types first

```
struct S4 {
  char c;
  int i;
  char d;
} *p;
```

```
struct S5 {
  int i;
  char c;
  char d;
} *p;
```

- Effect (K=4)



Union Allocation

- 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;
```

Byte Ordering, Revisited

- Idea
  - Short/long/quad words stored in memory as 2/4/8 consecutive bytes
  - Which is most (least) significant?
  - Can cause problems when exchanging binary data between machines
- Big Endian
  - Most significant byte has lowest address
  - Sun Sparc
- Little Endian
  - Least significant byte has lowest address
  - Intel x86

Byte Ordering Example

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

<table>
<tr><td>32-bit</td><td>c[0]</td><td>c[1]</td><td>c[2]</td><td>c[3]</td><td>c[4]</td><td>c[5]</td><td>c[6]</td><td>c[7]</td></tr>
<tr><td></td><td colspan="2">s[0]</td><td colspan="2">s[1]</td><td colspan="2">s[2]</td><td colspan="2">s[3]</td></tr>
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</table>

<table>
<tr><td>64-bit</td><td>c[0]</td><td>c[1]</td><td>c[2]</td><td>c[3]</td><td>c[4]</td><td>c[5]</td><td>c[6]</td><td>c[7]</td></tr>
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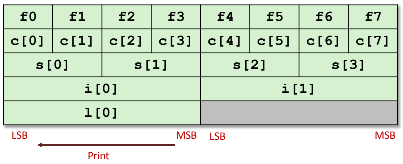
</table>

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 IA32

Little Endian



<table>
<tr><td>f0</td><td>f1</td><td>f2</td><td>f3</td><td>f4</td><td>f5</td><td>f6</td><td>f7</td></tr>
<tr><td>c[0]</td><td>c[1]</td><td>c[2]</td><td>c[3]</td><td>c[4]</td><td>c[5]</td><td>c[6]</td><td>c[7]</td></tr>
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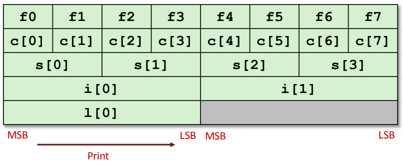
</table>

Output:

```
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   == [0xf3f2f1f0]
```

Byte Ordering on Sun

Big Endian



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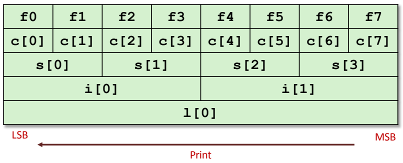
Output on Sun:

```
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 x86-64

Little Endian



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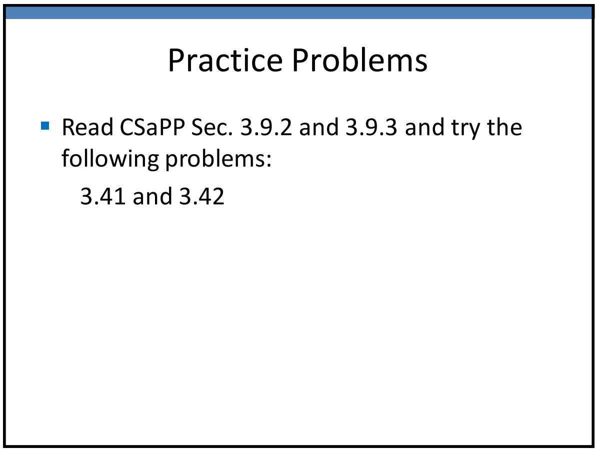
</table>

Output on x86-64:

```
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]
```



Practice Problems

- Read CSaPP Sec. 3.9.2 and 3.9.3 and try the following problems:

  3.41 and 3.42