CS429: Computer Organization and Architecture

Instruction Set Architecture VI

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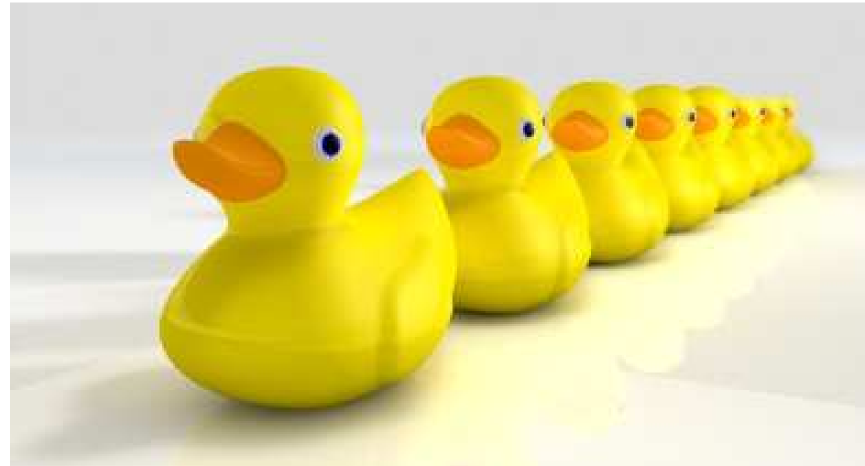
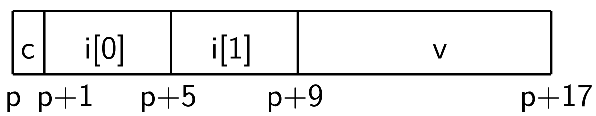
Alignment



Structures and Alignment

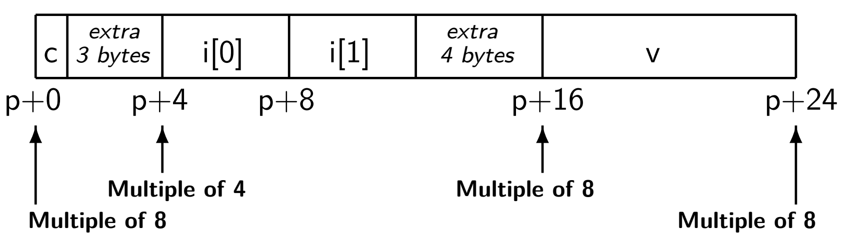
```
struct S1 {
  char c;
  int  i[2];
  double v;
} *p;
```

Unaligned Data



Aligned Data

- Primitive data type requires K bytes
- Starting/ending address must be a multiple of K



Alignment Principles

Aligned Data

- Primitive data type requires K bytes
- Address must be a multiple of K
- Required on some machines; advised on x86-64

Motivation for Aligning Data

- Memory accessed by (aligned) chunks of 4, 8 or more bytes (system dependent)
- It's inefficient to load or store datum that spans quad word boundaries
- Virtual memory is trickier when datum spans 2 pages

Compiler

- Inserts gaps in structure to ensure correct alignment of fields

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, long, char *, ...

- lowest 3 bits of address must be 000_2

16 bytes: long double (GCC on Linux)

- lowest 4 bits of address must be 0000_2

Satisfying Alignment with Structures

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

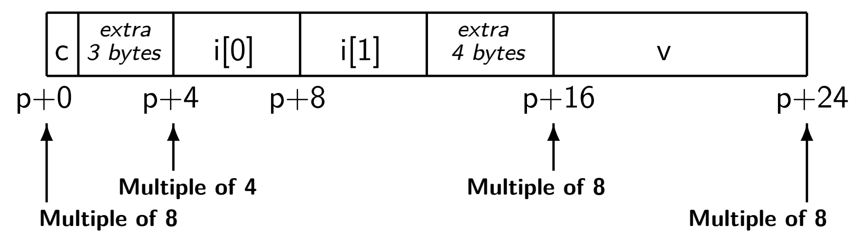
Within structure:

- Must satisfy each element's alignment requirement

Overall structure placement

- Each structure has alignment requirement K, where K is the *largest alignment of any element*
- Initial address and structure length must be multiples of K

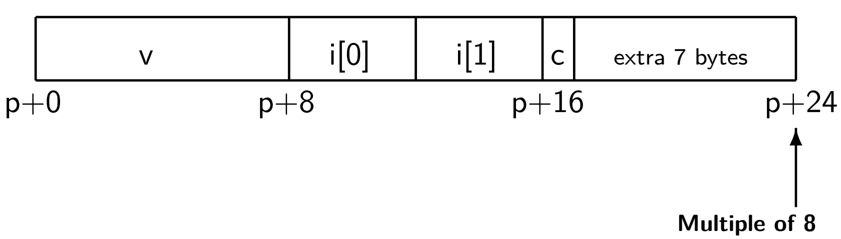
Example: K = 8, due to `double` element



Meeting Overall Alignment Requirement

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

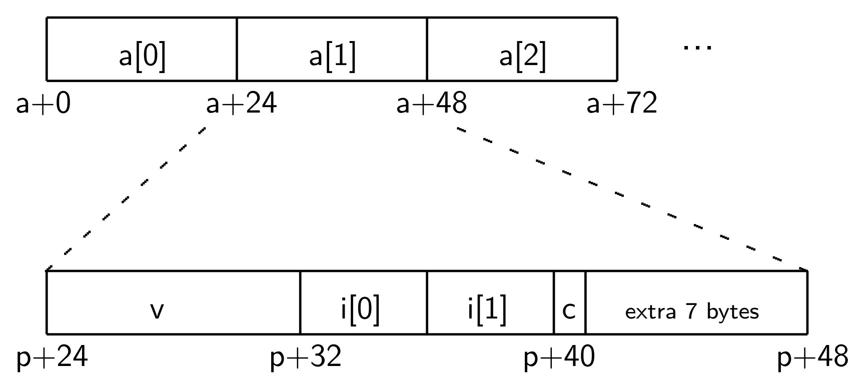
```
struct S2 {
   double v;
   int i[2];
   char c;
}
```



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

Compute array offset 12*idx

- `sizeof(S3)`, including alignment spacers

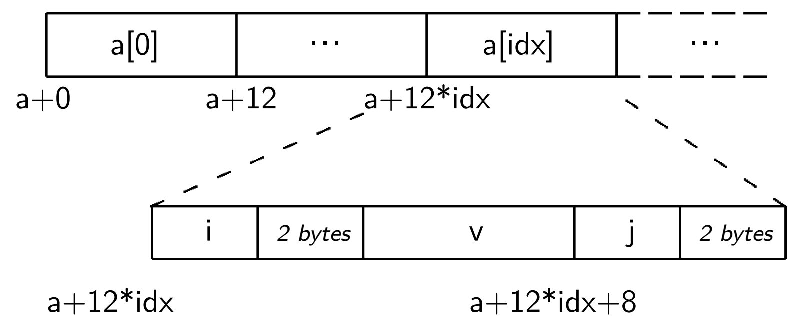
Element j is at offset 8 within structure

Assembler gives offset `a+8`

- Resolved during linking

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


Accessing Array Elements




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

```
# %rdi holds idx
leaq   (%rdi,%rdi,2),%rax   # 3*
    idx
movzwl a+8(,%rax,4), %eax
```


Saving Space

Put large data types first! Is this guaranteed to be the optimal use of space?

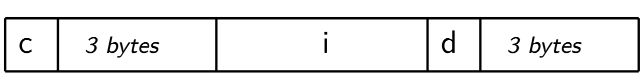
Instead of:

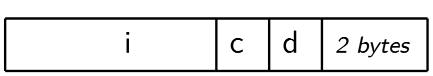
```
struct S4 {
   char c;
   int i;
   char d;
} *p;
```

do this:

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

Effect (K = 4)





Aside: The Knapsack Problem

The Knapsack Problem is a famous NP-hard computational problem. Given a bin of fixed size and a number of items, each characterised by a volume and a value, maximise the value of items that can fit in the bin.

For example: suppose you have items of sizes $\{1, 4, 5, 7\}$ and a container of size 10.

Using a *greedy algorithm* heuristic, you'd put the largest items in first, resulting in putting in $\{7, 1\}$, for a total of 8 in the container, 9 left outside.

A better solution is to put in $\{4, 5, 1\}$, for a total of 10 in the container and 7 outside.

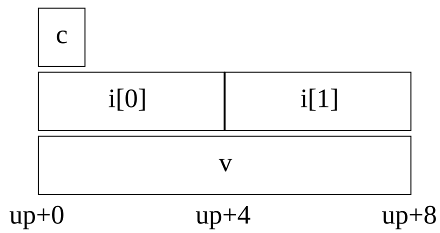
The knapsack problem is an instance of a class of problems called **bin packing problems.**

Union Allocation

Principles

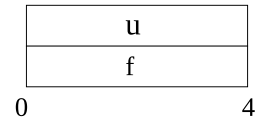
- Overlay union elements.
- Allocate according to the largest element.
- Can only use one field at a time.

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



Using Union to Access Bit Patterns

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




```
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;
}
```

- Get direct representation to bit representation of float.
- `bit2float` generates float with given bit pattern.
- Note: this is not the same as `(float) u`.
- `float2bit` generates bit pattern from float.
- Note: this is not the same as `(unsigned) f`.

Byte Order Revisited

Idea

- Short/long/quad words stored in memory as 2/4/8 consecutive bytes.
- Which is the most (least) significant?
- Can cause problems when exchanging binary data between machines.

Big Endian

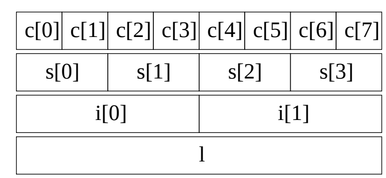
- Most significant byte has lowest address.
- PowerPC, Sparc

Little Endian

- Least significant byte has lowest address.
- Intel x86, Alpha

Byte Ordering Example

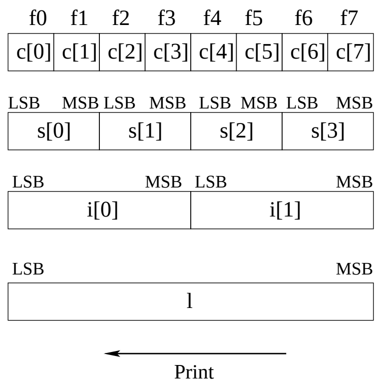
```
union {
    unsigned char c[8];
    unsigned short s[4];
    unsigned int i[2];
    unsigned long l;
} dw;
```




```
int j;
for (j = 0; j < 8; j++)
  dw.c[j] = 0xf0 + j;
printf("Chars 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 == [0x%lx]\n", dw.l);
```

Byte Ordering on the x86

Little Endian

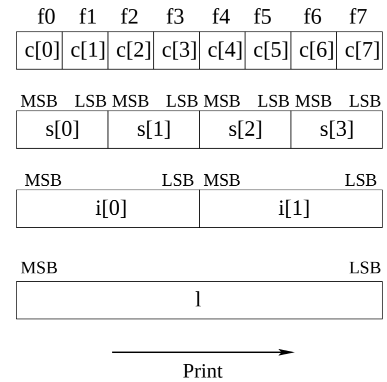


Output on Pentium:

```
Chars  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 Ordering on Sun

Big Endian



Output on Sun:

```
Chars  0-7 == [0xf0,0xf1,0xf2,0xf3,0xf4,0xf5,0xf6,0xf7]
Shorts 0-3 == [0xf0f1,0xf2f3,0xf4f5,0xf6f7]
Ints   0-1 == [0xf0f1f2f3,0xf4f5f6f7]
Long   0   == [0xf0f1f2f3f4f5f6f7]
```


Summary

Arrays in C

- Contiguous allocation of memory, row order.
- 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

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

Unions

- Overlay declarations.
- Way to circumvent type system.