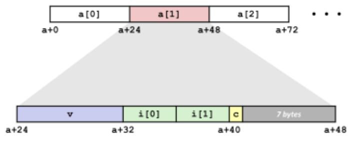
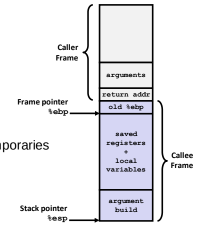
The HW/SW Interface

The x86 ISA: Data Structures



Recap: Procedures



- Procedure Call and Return
  `call <label>/*<dest> … ret`
- Stack Frame
  - old frame pointer, saved registers, local variables, temporaries
  - during call: arguments, return address
  - constructed/destructed by callee in prologue/epilogue
- Calling Convention
  - IA32:
    - registers: caller saved: eax, ecx, edx; callee saved: ebx, esi, edi, esp, ebp
    - arguments: on stack above return address, at %ebp + 4*i for the i^{th} argument
    - return value: eax
  - x86-64:
    - registers: caller saved: rax, r10, r11; callee saved: rbx, r12, r13, r14, r15, rsp, rbp
    - arguments: first 6: rdi, rsi, rdx, rcx, r8, r9, then on stack
    - return value: rax

Data Structures

- **Arrays**
  - **One-dimensional**
  - Multi-dimensional (nested)
  - Multi-level
- Structures
  - Allocation
  - Access
  - Alignment
- Unions

Acknowledgement: slides based on the cs:app2e material

Basic Data Types

- Integral
  - Stored & operated on in general (integer) registers
  - Signed vs. unsigned depends on instructions used

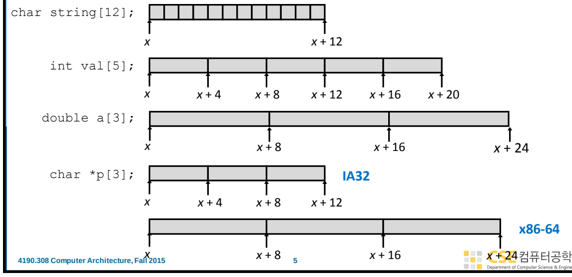
Intel	**ASM**	**Bytes**	**C**
byte	b	1	[unsigned] char
word	w	2	[unsigned] short
double word	l	4	[unsigned] int
quad word	q	8	[unsigned] long int (x86-64)

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

Intel	**ASM**	**Bytes**	**C**
Single	s	4	float
Double	l	8	double
Extended	t	10/12/16	long double

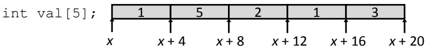
Array Allocation

- 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: Type T*

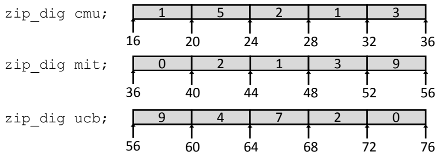


Reference	Type	Value
val[4]		
val		
val+1		
&val[2]		
val[5]		
*(val+1)		
&val[i] – val		

Array Example

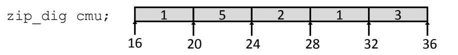
```
#define ZLEN 5
typedef int zip_dig[ZLEN];

zip_dig cmu = { 1, 5, 2, 1, 3 };
zip_dig mit = { 0, 2, 1, 3, 9 };
zip_dig ucb = { 9, 4, 7, 2, 0 };
```



- 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




```
int get_digit
  (zip_dig z, int dig)
{
  return z[dig];
}
```

IA32

```
  # %edx = z
  # %eax = dig
  movl (%edx,%eax,4),%eax  # z[dig]
```

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

Array Loop Example (IA32)

```
void zincr(zip_dig z) {
  int i;
  for (i = 0; i < ZLEN; i++)
    z[i]++;
}
```

```
  # edx = z
  movl  $0, %eax             #   %eax = i
.L4:                         # loop:
  addl  $1, (%edx,%eax,4)    #   z[i]++
  addl  $1, %eax             #   i++
  cmpl  $5, %eax             #   i:5
  jne   .L4                  #   if !=, goto loop
```


Pointer Loop Example (IA32)

```
void zincr_p(zip_dig z) {
  int *zend = z+ZLEN;
  do {
    (*z)++;
    z++;
  } while (z != zend);
}
```

```
void zincr_v(zip_dig z) {
  void *vz = z;
  int i = 0;
  do {
    (*((int *) (vz+i)))++;
    i += ISIZE;
  } while (i != ISIZE*ZLEN);
}
```

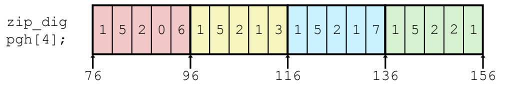
```
  # edx = z = vz
  movl  $0, %eax           #   i = 0
.L8:                       # loop:
  addl  $1, (%edx,%eax)    #   Increment vz+i
  addl  $4, %eax           #   i += 4
  cmpl  $20, %eax          #   Compare i:20
  jne   .L8                #   if !=, goto loop
```


Data Structures

- **Arrays**
  - One-dimensional
  - **Multi-dimensional (nested)**
  - Multi-level
- Structures
  - Allocation
  - Access
  - Alignment
- Unions

Nested Array Example

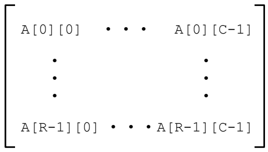
```
#define PCOUNT 4
zip_dig pgh[PCOUNT] =
  {{1, 5, 2, 0, 6},
   {1, 5, 2, 1, 3 },
   {1, 5, 2, 1, 7 },
   {1, 5, 2, 2, 1 }};
```



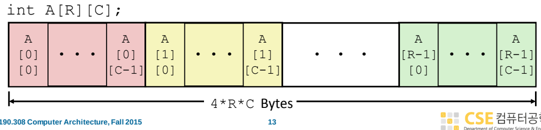
- "zip_dig pgh[4]" equivalent to "int pgh[4][5]"
  - Variable pgh: array of 4 elements, allocated contiguously
  - Each element is an array of 5 int's, allocated contiguously
- "Row-Major" ordering of all elements guaranteed

Multidimensional (Nested) Arrays

- Declaration
  - T A[R][C];
  - 2D 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



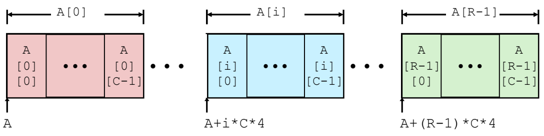
`int A[R][C];`



Nested Array Row Access

- Row Vectors
  - A[i] is array of C elements
  - Each element of type T requires K bytes
  - Starting address A + i * (C * K)

`int A[R][C];`



Nested Array Row Access Code

```
int *get_pgh_zip(int index)
{
  return pgh[index];
}
```

```
#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 }};
```

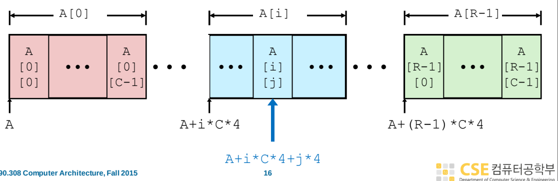
```
  # %eax = index
  leal (%eax,%eax,4),%eax  # 5 * index
  leal pgh(,%eax,4),%eax   # pgh + (20 * index)
```

- Row Vector
  - pgh[index] is array of 5 int's
  - Starting address pgh+20*index
- IA32 Code
  - Computes and returns address
  - Compute as pgh + 4*(index+4*index)

Nested Array Row Access

- Array Elements
  - A[i][j] is element of type T, which requires K bytes
  - Address A + i * (C * K) + j * K = A + (i * C + j)* K

`int A[R][C];`



Nested Array Element Access Code

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

```
movl  8(%ebp), %eax         # index
leal  (%eax,%eax,4), %eax   # 5*index
addl  12(%ebp), %eax        # 5*index+dig
movl  pgh(,%eax,4), %eax    # offset 4*(5*index+dig)
```

- Array Elements
  - pgh[index][dig] is int
  - Address: pgh + 20*index + 4*dig
    - = pgh + 4*(5*index + dig)
- IA32 Code
  - Computes address pgh + 4*((index+4*index)+dig)

Data Structures

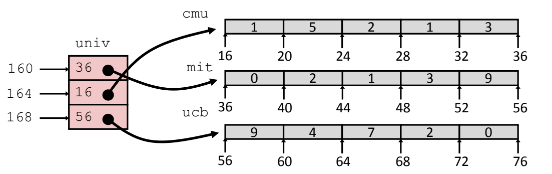
- **Arrays**
  - One-dimensional
  - Multi-dimensional (nested)
  - **Multi-level**
- Structures
  - Allocation
  - Access
  - Alignment
- Unions

Multi-Level Array Example

```
zip_dig cmu = { 1, 5, 2, 1, 3 };
zip_dig mit = { 0, 2, 1, 3, 9 };
zip_dig ucb = { 9, 4, 7, 2, 0 };
```

```
#define UCOUNT 3
int *univ[UCOUNT] = {mit, cmu, ucb};
```

- Variable univ denotes array of 3 elements
- Each element is a pointer
  - 4 bytes
- Each pointer points to array of int's



Element Access in Multi-Level Array

```
int get_univ_digit
  (int index, int dig)
{
  return univ[index][dig];
}
```

```
  movl  8(%ebp), %eax           # index
  movl  univ(,%eax,4), %edx     # p = univ[index]
  movl  12(%ebp), %eax          # dig
  movl  (%edx,%eax,4), %eax     # p[dig]
```

- Computation (IA32)
  - Element access Mem[Mem[univ+4*index]+4*dig]
  - Must do two memory reads
    - First get pointer to row array
    - Then access element within array

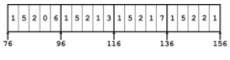
Array Element Accesses

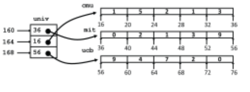
Nested array

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

Multi-level array

```
int get_univ_digit
  (int index, int dig)
{
  return univ[index][dig];
}
```





Accesses looks similar in C, but addresses very different:

`Mem[pgh+20*index+4*dig]`   `Mem[Mem[univ+4*index]+4*dig]`

N X N Matrix Code

- Fixed dimensions
  - Know value of N at compile time
  - 1st dimension can be left unspecified
- Variable dimensions, explicit indexing
  - Traditional way to implement dynamic arrays
- Variable dimensions, implicit indexing
  - defined in C99 standard

```
#define N 16
typedef int fix_matrix[N][N];
/* Get element a[i][j] */
int fix_ele
  (fix_matrix a, int i, int j)
{
  return a[i][j];
}
```

```
#define IDX(n, i, j) ((i)*(n)+(j))
/* Get element a[i][j] */
int vec_ele
 (int n, int *a, int i, int j)
{
  return a[IDX(n,i,j)];
}
```

```
/* Get element a[i][j] */
int var_ele
 (int n, int a[n][n], int i, int j)
{
  return a[i][j];
}
```


16 X 16 Matrix Access

- Array Elements
  - Address A + i * (C * K) + j * K
  - C = 16, K = 4

```
/* Get element a[i][j] */
int fix_ele(fix_matrix a, int i, int j) {
  return a[i][j];
}
```

```
  movl  12(%ebp), %edx     # i
  sall  $6, %edx           # i*64
  movl  16(%ebp), %eax     # j
  sall  $2, %eax           # j*4
  addl  8(%ebp), %eax      # a + j*4
  movl  (%eax,%edx), %eax  # *(a + j*4 + i*64)
```


n X n Matrix Access – Explicit Indexing

- Array Elements
  - Address A + i * (C * K) + j * K
  - C = n, K = 4

```
#define IDX(n, i, j) ((i)*(n)+(j))
/* Get element a[i][j] */
int vec_ele(int n, int *a, int i, int j) {
  return a[IDX(n,i,j)];
}
```

```
  movl  16(%ebp), %edx          # i
  imull 8(%ebp), %edx           # i*n
  addl  20(%ebp), %edx          # i*n + j
  movl  12(%ebp), %eax          # a
  movl  (%eax,%edx,4), %eax     # *(a + (i*n+j)*4)
```

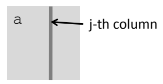
n X n Matrix Access – Implicit Indexing

- Array Elements
  - Address A + i * (C * K) + j * K
  - C = n, K = 4

```
/* Get element a[i][j] */
int var_ele(int n, int a[n][n], int i, int j) {
  return a[i][j];
}
```

```
  movl   8(%ebp), %eax      # n
  sall   $2, %eax           # n*4
  imull  16(%ebp), %eax     # i*n*4
  movl   20(%ebp), %edx     # j
  sall   $2, %edx           # j*4
  addl   12(%ebp), %edx     # a + j*4
  movl   (%edx,%eax), %eax  # *(a + j*4 + i*n*4)
```


Optimizing Fixed Array Access




```
#define N 16
typedef int fix_matrix[N][N];
```

```
/* Retrieve column j from array */
void fix_column
  (fix_matrix a, int j, int *dest)
{
  int i;
  for (i = 0; i < N; i++)
    dest[i] = a[i][j];
}
```

- Computation
  - Step through all elements in column j
- Optimization
  - Retrieving successive elements from single column

Optimizing Fixed Array Access

- Optimization
  - Compute ajp = &a[i][j]
    - Initially = a + 4*j
    - Increment by 4*N

Register	Value
%ecx	ajp
%ebx	dest
%edx	i

```
/* Retrieve column j from array */
void fix_column
  (fix_matrix a, int j, int *dest)
{
  int i;
  for (i = 0; i < N; i++)
    dest[i] = a[i][j];
}
```

```
.L8:                          # loop:
   movl  (%ecx), %eax         #   Read *ajp
   movl  %eax, (%ebx,%edx,4)  #   Save in dest[i]
   addl  $1, %edx             #   i++
   addl  $64, %ecx            #   ajp += 4*N
   cmpl  $16, %edx            #   i:N
   jne   .L8                  #   if !=, goto loop
```


Optimizing Variable Array Access

- Compute ajp = &a[i][j]
  - Initially = a + 4*j
  - Increment by 4*n

Register	Value
%ecx	ajp
%edi	dest
%edx	i
%ebx	4*n
%esi	n

```
/* Retrieve column j from array */
void var_column
  (int n, int a[n][n],
   int j, int *dest)
{
  int i;
  for (i = 0; i < n; i++)
    dest[i] = a[i][j];
}
```

```
.L18:                         # loop:
   movl  (%ecx), %eax         #   Read *ajp
   movl  %eax, (%edi,%edx,4)  #   Save in dest[i]
   addl  $1, %edx             #   i++
   addl  $ebx, %ecx           #   ajp += 4*n
   cmpl  $edx, %esi           #   n:i
   jg    .L18                 #   if >, goto loop
```

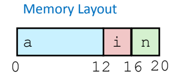

Data Structures

- Arrays
  - One-dimensional
  - Multi-dimensional (nested)
  - Multi-level
- **Structures**
  - **Allocation**
  - **Access**
  - Alignment
- Unions

Structure Allocation

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

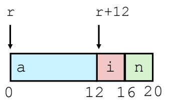
Memory Layout



- Concept
  - Contiguously-allocated region of memory
  - Refer to members within structure by names
  - Members may be of different types

Structure Access

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



- Accessing Structure Member
  - Pointer indicates first byte of structure
  - Access elements with offsets

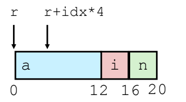
```
void
set_i(struct rec *r,
      int val)
{
  r->i = val;
}
```

IA32 Assembly

```
# %edx = val
# %eax = r
movl %edx, 12(%eax)  # Mem[r+12] = val
```


Generating Pointer to Structure Member

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



- Generating Pointer to Array Element
  - Offset of each structure member determined at compile time
  - Arguments
    - Mem[%ebp+8]: r
    - Mem[%ebp+12]: idx

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

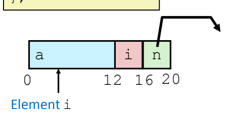
```
movl   12(%ebp), %eax    # Get idx
sall   $2, %eax          # idx*4
addl   8(%ebp), %eax     # r+idx*4
```


Following Linked List

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

- C Code

```
void set_val
  (struct rec *r, int val)
{
  while (r) {
    int i = r->i;
    r->a[i] = val;
    r = r->n;
  }
}
```



Register	Value
%edx	r
%ecx	val

```
.L17:                          # loop:
  movl   12(%edx), %eax        # r->i
  movl   %ecx, (%edx,%eax,4)   # r->a[i] = val
  movl   16(%edx), %edx        # r = r->n
  testl  %edx, %edx            # Test r
  jne    .L17                  # If != 0 goto loop
```


Data Structures

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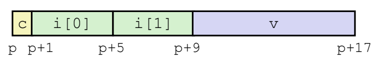
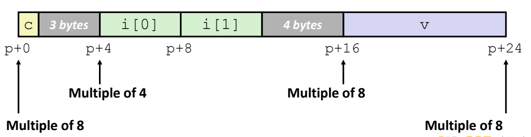
Structures & Alignment

- 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
- Compiler
  - Inserts gaps in structure to ensure correct alignment of fields

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

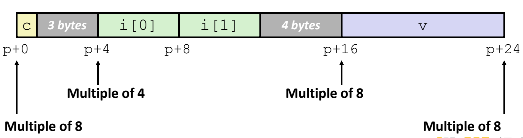
Specific Cases of Alignment (x86-64)

- 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

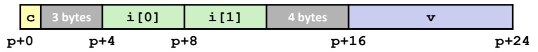
```
struct S1 {
  char c;
  int i[2];
  double v;
} *p;
```



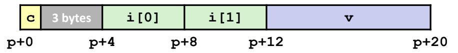
Different Alignment Conventions

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

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



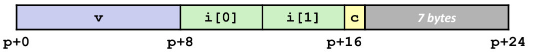
- IA32 Linux
  - K = 4; double treated like a 4-byte data type



Meeting Overall Alignment Requirement

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

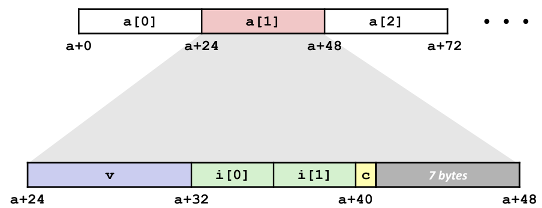
```
struct S2 {
  double v;
  int i[2];
  char c;
} *p;
```



Arrays of Structures

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

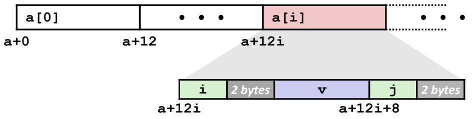
```
struct S2 {
  double v;
  int i[2];
  char c;
} a[10];
```



Accessing Array Elements

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

- Compute array offset 12i
  - sizeof(S3), including alignment spacers
- Element j is at offset 8 within structure
- Assembler gives offset a+8
  - Resolved during linking




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

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

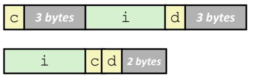

Saving Space

- 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)



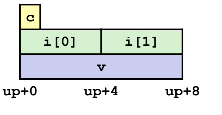
Data Structures

- Arrays
  - One-dimensional
  - Multi-dimensional (nested)
  - Multi-level
- Structures
  - Allocation
  - Access
  - Alignment
- **Unions**

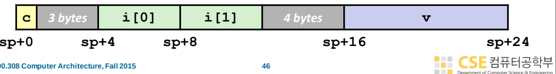
Union Allocation

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

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

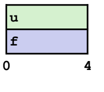



```
struct S1 {
  char c;
  int i[2];
  double v;
} *sp;
```



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;
}
```

Same as `(float) u` ?

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

Same as `(unsigned) f` ?

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
  - 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;
```

32-bit

c[0]	c[1]	c[2]	c[3]	c[4]	c[5]	c[6]	c[7]
s[0]		s[1]		s[2]		s[3]	
i[0]				i[1]			
l[0]							

64-bit

c[0]	c[1]	c[2]	c[3]	c[4]	c[5]	c[6]	c[7]
s[0]		s[1]		s[2]		s[3]	
i[0]				i[1]			
l[0]							

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

f0	f1	f2	f3	f4	f5	f6	f7
c[0]	c[1]	c[2]	c[3]	c[4]	c[5]	c[6]	c[7]
s[0]		s[1]		s[2]		s[3]	
i[0]				i[1]			
l[0]							

LSB MSB LSB MSB

Print

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

f0	f1	f2	f3	f4	f5	f6	f7
c[0]	c[1]	c[2]	c[3]	c[4]	c[5]	c[6]	c[7]
s[0]		s[1]		s[2]		s[3]	
i[0]				i[1]			
l[0]							

MSB LSB MSB LSB

Print

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

f0	f1	f2	f3	f4	f5	f6	f7
c[0]	c[1]	c[2]	c[3]	c[4]	c[5]	c[6]	c[7]
s[0]		s[1]		s[2]		s[3]	
i[0]				i[1]			
l[0]							

LSB MSB

Print

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]
```


Summary

- Arrays in C
  - Contiguous allocation of memory
  - Aligned to satisfy every element's alignment requirement
  - Pointer to first element
  - No bounds checking
- Structures
  - Allocate bytes in order declared
  - Pad in middle and at end to satisfy alignment
- Unions
  - Overlay declarations
  - Way to circumvent type system