Assembly IV: Complex Data Types

$\Rightarrow$ arr, structure

Jo, Heeseung

Basic Data Types

GAS = GNU

Integer

- 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

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

GAS: GNU Assembler Syntax

Complex Data Types

Complex data types in C

- Pointers
- Arrays
- Structures
- Unions
- ...

Can be combined

- Pointer to pointer, pointer to array, …
- Array of array, array of structure, array of pointer, …
- Structure in structure, pointer in structure, array in structure, …

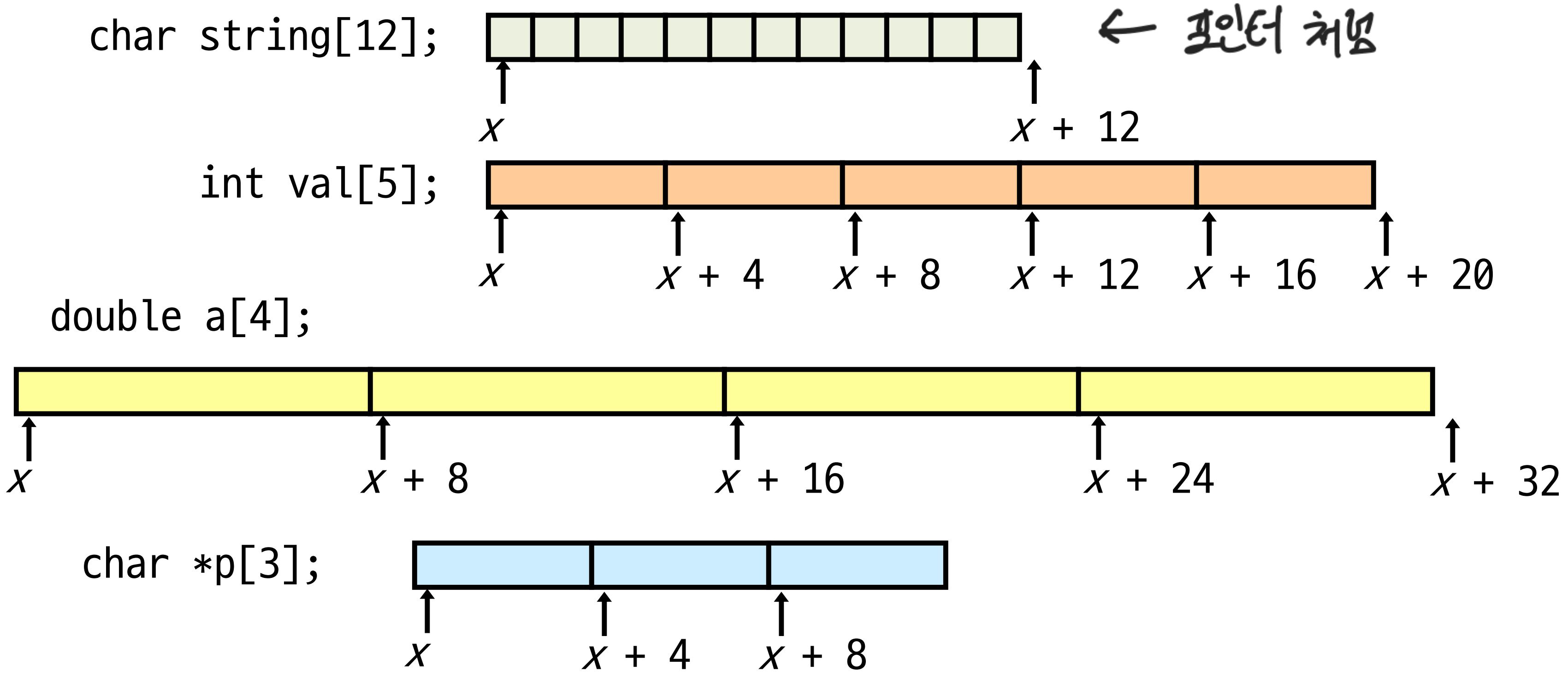
Array Allocation

메모리에 n byte 씩 연속적으로 할당

Basic principle: **T A[L];**

- Array of data type T and length L
- Contiguously allocated region of L * sizeof(T) bytes

4byte (32bit)
8byte (64bit)

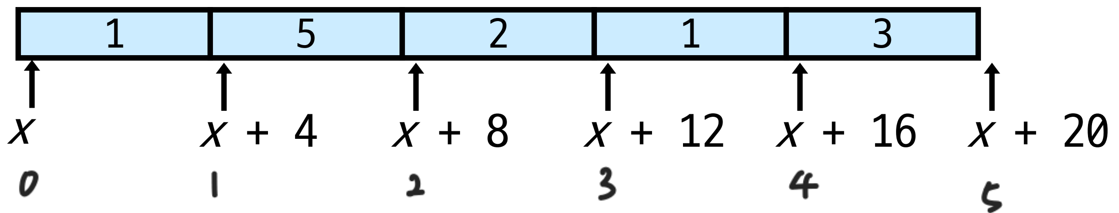


Array Access

Basic principle: **T A[L];**

- Array of data type T and length L
- Identifier A can be used as a pointer to element 0

int val[5];



Reference	Type	Value
val[4]	int	3
val	pointer	x
val + 1	pointer	x+4
&val[2]	pointer	x+8
val[5]	int	???
*(val+1)	int	5
val + i	pointer	val + i * 4

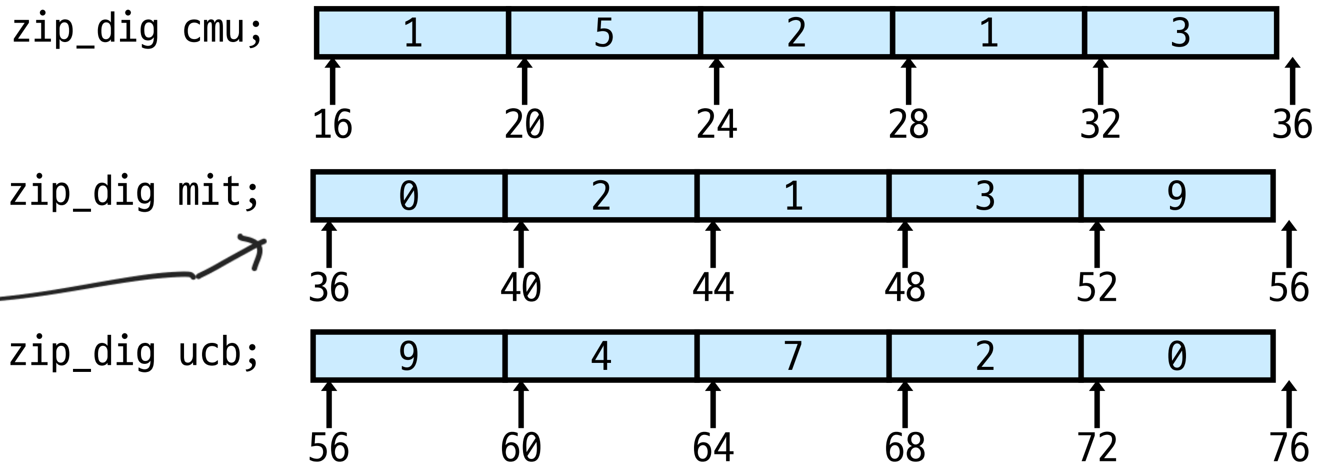
val+3 = x + 12

Array Example

```c
typedef int zip_dig[5];

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

20byte 보장

연속으로 선언했다고
꼭 연속으로 할당
되지는 않음



Notes

- Example arrays were allocated in successive 20 byte blocks
  - Not guaranteed to happen in general

Array Accessing Example (1)

Computation

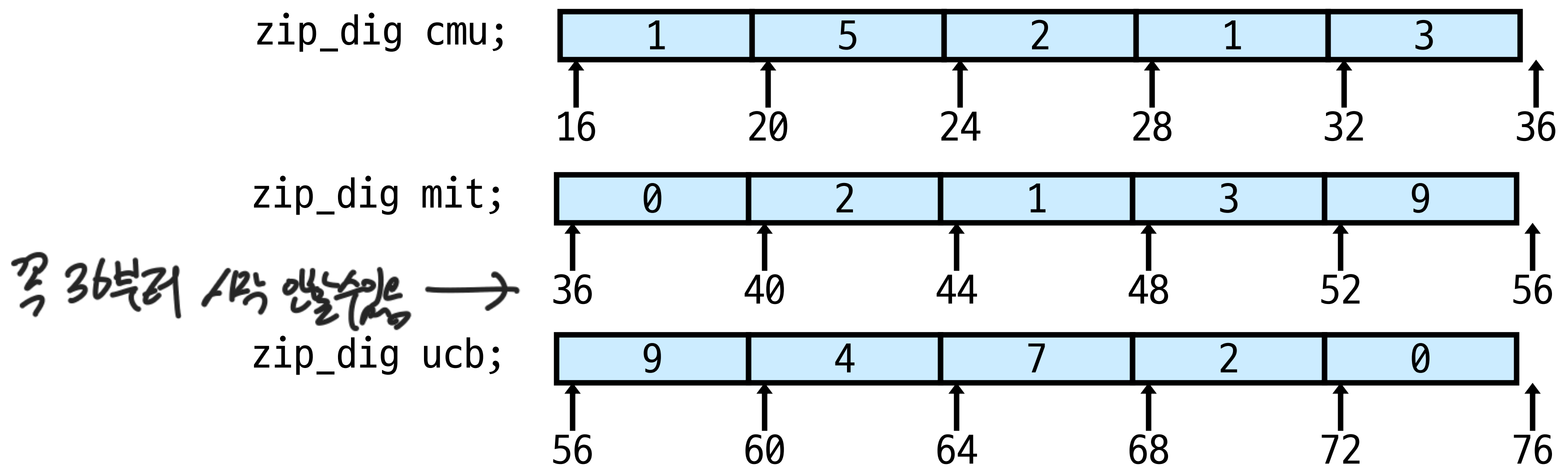
- Register %edx contains starting address of array
- Register %eax contains array index
- Desired digit at 4 * %eax + %edx
- Use memory reference: (%edx, %eax, 4)

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

Memory Reference Code

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

Array Accessing Example (2)



Code does not do any bounds checking!

Reference	Address	Value	Guaranteed?
mit[3]	48	3	O
mit[5]	56	9	X
mit[-1]	32	3	X
cmu[15]	76	?	X

- Out of range behavior implementation-dependent
- No guaranteed relative allocation of different arrays

Array Loop Example (1)

Original source

```
int zd2int(zip_dig z){
  int i;
  int zi = 0;
  for (i = 0; i < 5; i++)
    zi = 10 * zi + z[i];
  return zi;
}
```

Transformed version

- As generated by GCC
- Eliminate loop variable i
- Convert array code to pointer code
- Express in do-while form
  - No need to test at entrance

```
int zd2int(zip_dig z){
  int zi = 0;
  int *zend = z + 4;
  do {
    zi = 10 * zi + *z;     z + 16
    z++;
  } while(z <= zend);
  return zi;
}
```

Array Loop Example (2)

Registers

- %ecx z
- %eax zi
- %ebx zend

```
int zd2int(zip_dig z){
  int zi = 0;
  int *zend = z + 4;
  do {
    zi = 10 * zi + *z;
    z++;
  } while(z <= zend);
  return zi;
}
```

z++ increments by 4

10 * zi + *z
= *z + 2*(zi+4*zi)

```
                                   # %ecx = z
    xorl %eax, %eax                # zi = 0
    leal 16(%ecx), %ebx            # zend = z + 4
.L59:
    leal (%eax, %eax, 4), %edx     # 5*zi
    movl (%ecx), %eax              # *z
    addl $4, %ecx                  # z++
    leal (%eax, %edx, 2), %eax     # zi = *z + 2*(5*zi)
    cmpl %ebx, %ecx                # z : zend
    jle .L59                       # if <= goto loop
```

Question

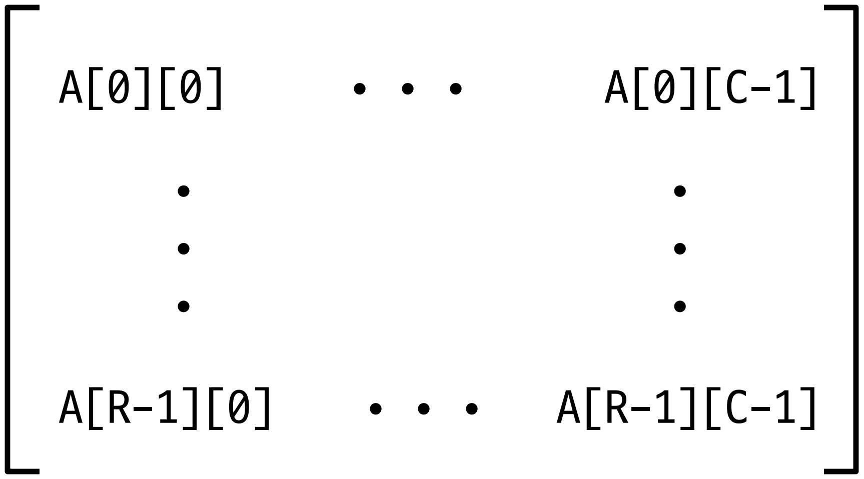
```
#define tri(x...) { \
          printf("[%d:%s:%d] %s = ", getpid(), \
          __func__, __LINE__, #x); \
          printf("%d\n", x); }

int main()
{
        int array[5]={2,4,8,10,12};
        int num=100;
        int *p=&num;

        tri(&num);       2686748
        tri(&num+1);    2686752
        tri(*(&num+1));   2

        tri(&p);        2686744
        tri(p);          2686748

        tri(&array);     2686752
        tri(array);      2686752

        tri(*array);      2
        tri(*array+1);    3          ) +1 보다 * 먼저
        tri(*(array+1));  4
}
```

2686768	12	
2686764	10	
2686760	8	
2686756	4	
2686752	2	array
2686748	100	num
2686744	2686748	p

Nested Array (1)

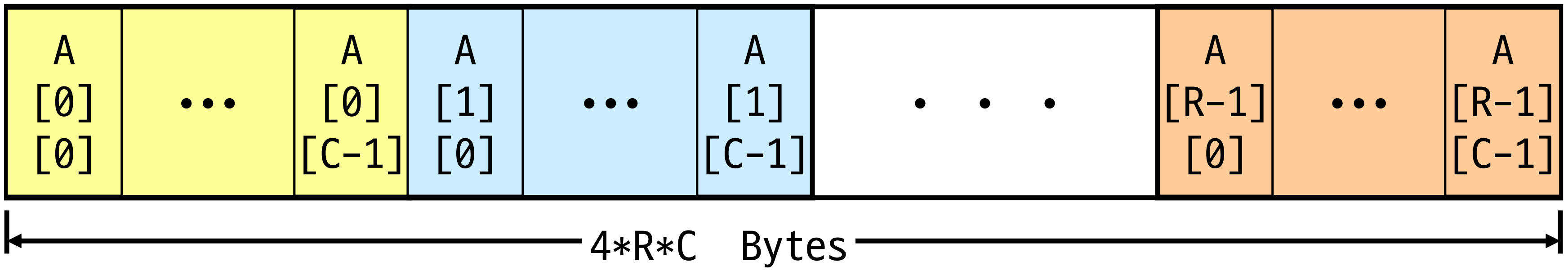
Declaration: **T A[R][C];**

- 2D array of data type T
- R rows, C columns
- Array size = R * C * sizeof(T)



Arrangement

- Row-major ordering



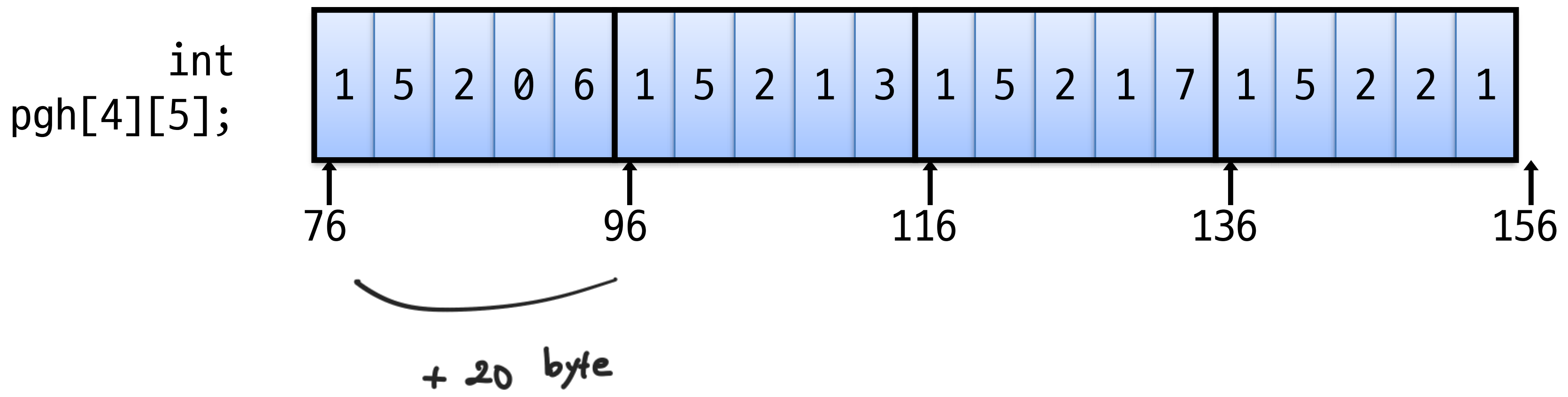
Nested Array (2)

C code

- Variable **pgh** denotes array of 4 elements ☆
  - Allocated contiguously
- Each element is an array of 5 int's
  - Allocated contiguously

```
int pgh[4][5] =
  {{1, 5, 2, 0, 6},
   {1, 5, 2, 1, 3 },
   {1, 5, 2, 1, 7 },
   {1, 5, 2, 2, 1 }};
```

Row-major ordering of all elements guaranteed



Nested Array Access (1)

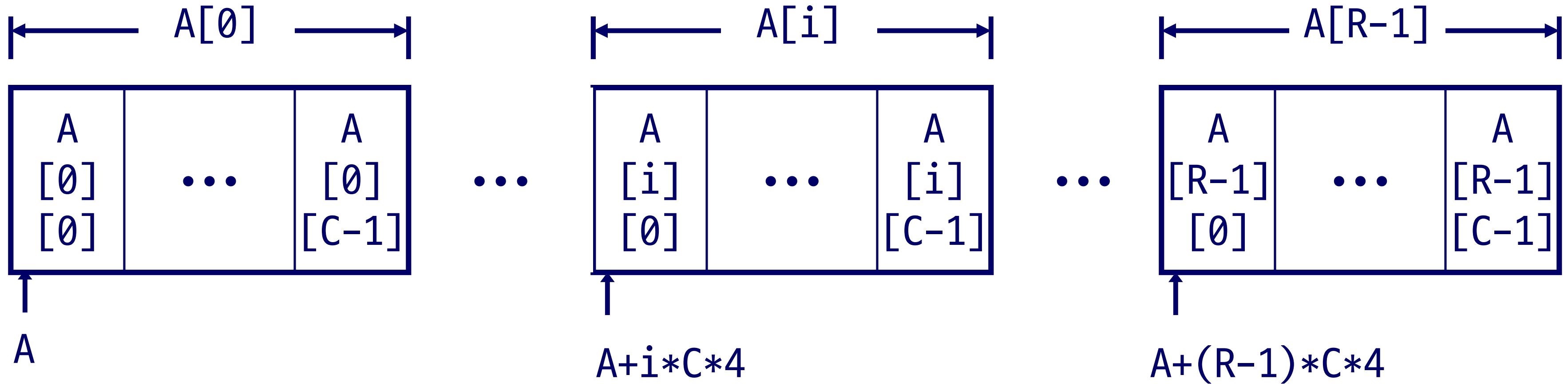
Row vectors

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

```
int pgh[4][5] =
  {{1, 5, 2, 0, 6},
   {1, 5, 2, 1, 3 },
   {1, 5, 2, 1, 7 },
   {1, 5, 2, 2, 1 }};
```

ex) A + 3 × 5 × 4
= pgh + 60 = pgh[3]

int A[R][C];



** → * type casting 가능.

pgh = 전체

pgh[0] = { 1, 5, 2, 0, 6 }

*pgh = 〃 , *pgh[0] = 1

Nested Array Access (2)

Row vectors

- pgh[index] is array of 5 int's
- Starting address **pgh + 20 * index** ← A + i * (C * K)

★

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

Code

- Computes and returns address
- Compute as **pgh + 4 * (index + 4 * index)**

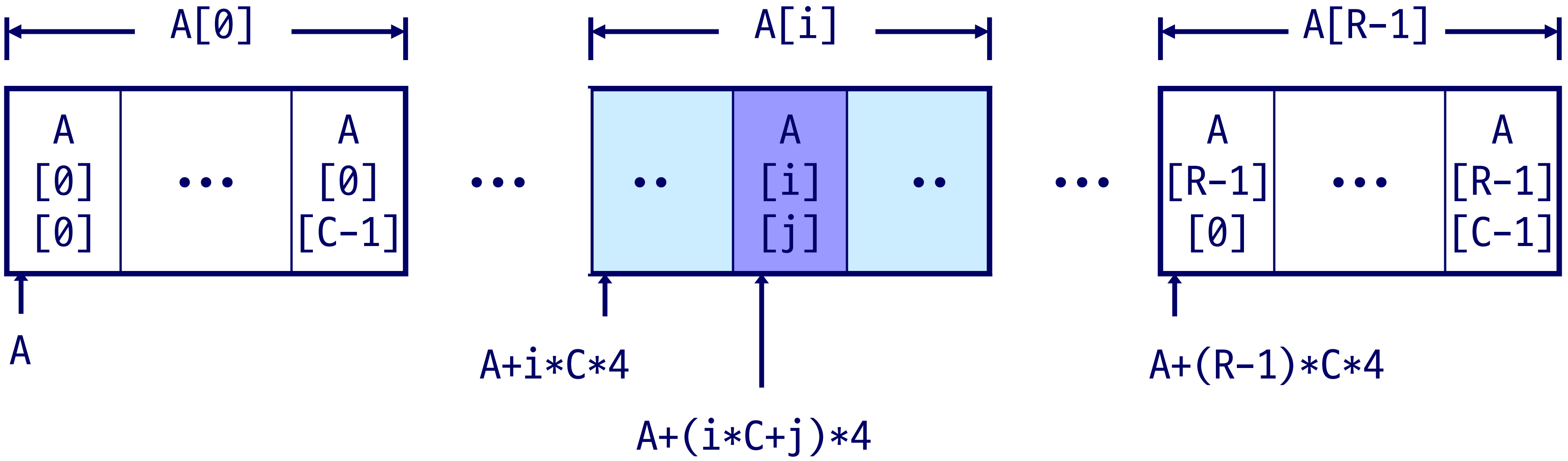
```
  # %eax = index
   leal (%eax,%eax,4),%eax       # 5 * index
   leal pgh(,%eax,4),%eax        # pgh + (20 * index)
```

Nested Array Access (3)

Array elements

- `A[i][j]` is element of type `T`
- Address **`A + i * (C * K) + j * K = A + (i * C + j) * K`**

```
int A[R][C];
```



Nested Array Access (4)

Array elements

- pgh[index][dig] is int
- Address:
  pgh + 20 * index + 4 * dig

☆

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

1차원 액세스 = int* return

2차원 액세스 = int return

Code

- Computes address **pgh + 4*dig + 4*(index + 4*index)**
- **movl** performs memory reference

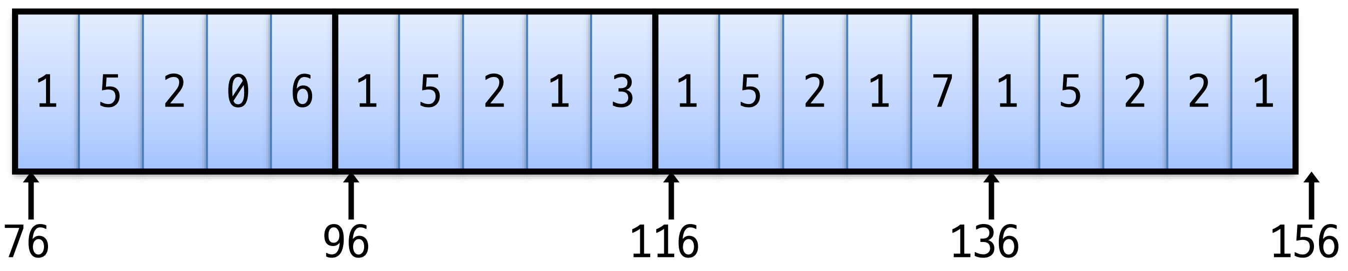
```
# %ecx = dig
# %eax = index
leal 0(,%ecx,4), %edx               # 4*dig
leal (%eax,%eax,4), %eax            # 5*index
movl pgh(%edx,%eax,4), %eax         # *(pgh + 4*dig + 20*index)
```

Nested Array Access (5)

Strange referencing examples

- Code does not do any bounds checking
- Ordering of elements within array guaranteed

```
int
pgh[4][5];
```



Reference	Address	Value	Guaranteed?
pgh[3][3]	76 + 20*3 + 4*3 = 148	2	Yes
pgh[2][5]	76 + 40 + 20 = 136	1	O
pgh[2][-1]	76 + 40 − 4 = 112	3	O
pgh[4][-1]	76 + 80 − 4 = 152	2	O
pgh[0][19]	76 + 0 + 76 = 152	2	O
pgh[0][-1]	76 + 0 − 4 = 72	?	X

Summary

Arrays in C

- Contiguous allocation of memory
- 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

Exercise

```
  0    -1    -2    -3    -4
-10   -11   -12   -13   -14
-20   -21   -22   -23   -24
-30   -31   -32   -33   -34
```

```
2686688
2686688

2686708 5
2687088 100

-10
-10

-9
-11

2687088
74          // garbage

-11
-20
0           // garbage

-20
-30
```

```
int pgh[4][5];                                              ☆
int *x=(int *)pgh;

printf("%d\n", pgh);  → 시작 주소값
printf("%d\n", pgh[0]);  → 0행 시작 〃
printf("\n");       -10 시작〃
                      ↑
printf("%d %d\n", pgh[1], pgh[1]-pgh[0] );
printf("%d %d\n", pgh[20], pgh[20]-pgh[0] );
printf("\n");       끝값〃          주소값 빼기

printf("%d\n", pgh[1][0]);  -10
printf("%d\n", *pgh[1]);  -10 주소가 가리키는 값
printf("\n");
                            -10+1
printf("%d\n", *pgh[1]+1 );
printf("%d\n", *(pgh[1]+1) );  -11
printf("\n");

printf("%d\n", pgh[20]);   주소값
printf("%d\n", *pgh[20]);  쓰레기 값
printf("\n");

printf("%d\n", *( *(pgh+1) +1 ) );  -11
printf("%d\n", *( *pgh+10) );   -20
printf("%d\n", **(pgh+10) );    0
printf("\n");

printf("%d\n", *(x+10) );  )  1차원 배열
printf("%d\n", *(x+15) );  )
```

Structures

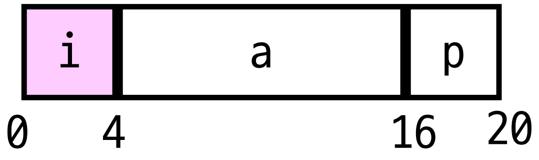
Concept

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

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

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

Memory Layout



Assembly

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

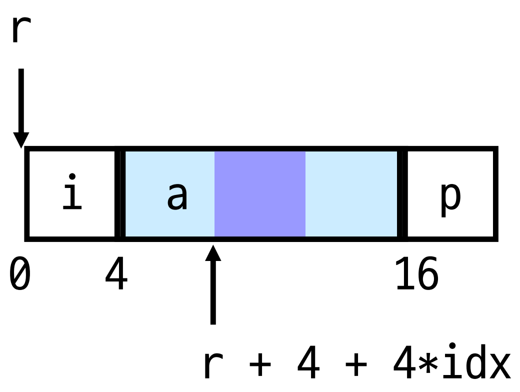
Structure Referencing (1)

Generating pointer to structure member

- Offset of each member determined at compile time

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

```
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
```

leal n(, ,) 비어있으면 생각하지 않는다.

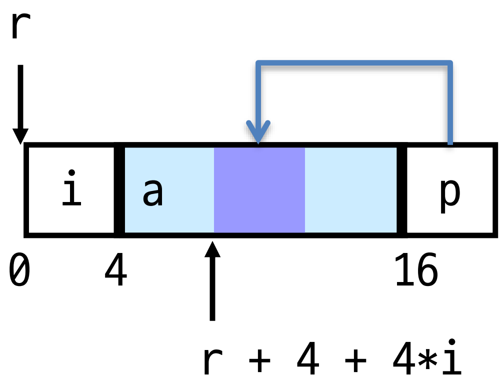
Structure Referencing (2)

☆

Generating pointer to member (cont'd)

```
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(%eax,%edx),%eax        # r+4+4*(r->i)
movl %eax,16(%edx)            # update r->p
```

Alignment 다 같이 변형되어 출제.

Alignment (1)

정렬X, 워드를 잘 맞춰 넣는 것

Aligned data

- Primitive data type requires **K** bytes
- Address must be multiple of **K**
- Required on some machines; advised on IA-32
  - 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

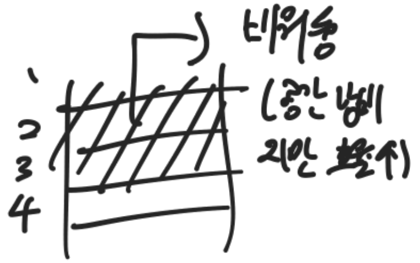
Compiler

- Inserts gaps (or "pads") in structure to ensure correct alignment of fields

ex) int data 자료에서 k = 4의 배수 주소에 할당 ⇒ very good

Alignment (2)

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 , 2배수
- 4 bytes (e.g., int, float, char *, etc)
  - lowest 2 bits of address must be 00_2 , 4배수
- 8 bytes (e.g., double)
  - Windows (and most other OS's & instruction sets): lowest 3 bits of address must be 000_2 , 8배수
  - Linux: lowest 2 bits of address must be 00_2 (i.e, treated the same as a 4-byte primitive data type) , 4배수
- 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) , 4배수

Alignment (3)

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

Offsets within structure

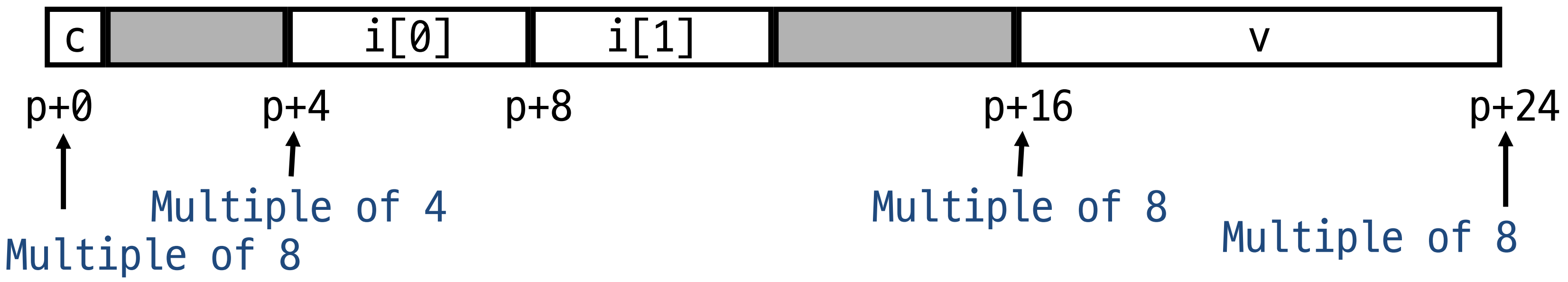
- Must satisfy element's alignment requirement

Overall structure placement

- Each structure has alignment requirement K
  - Largest alignment of any element
- Initial address & structure length must be multiples of K

Example (under Windows):

- K = 8, due to double element

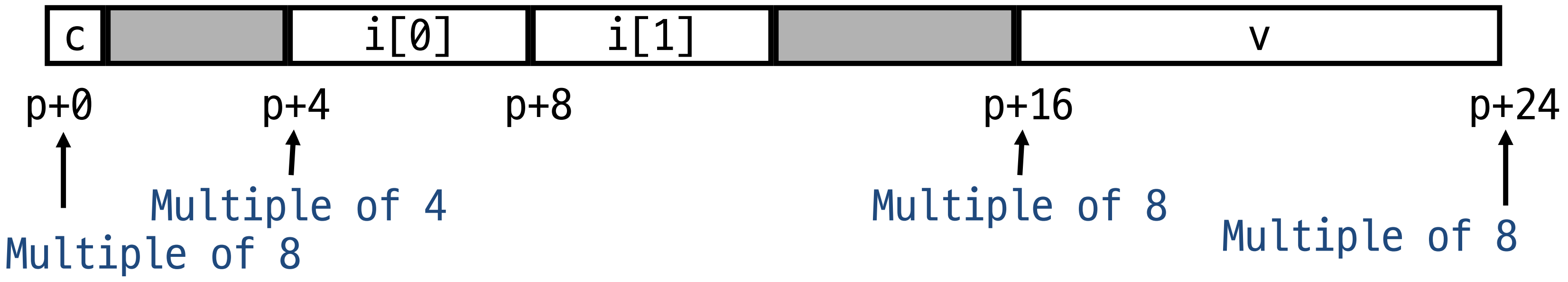


Alignment (4)

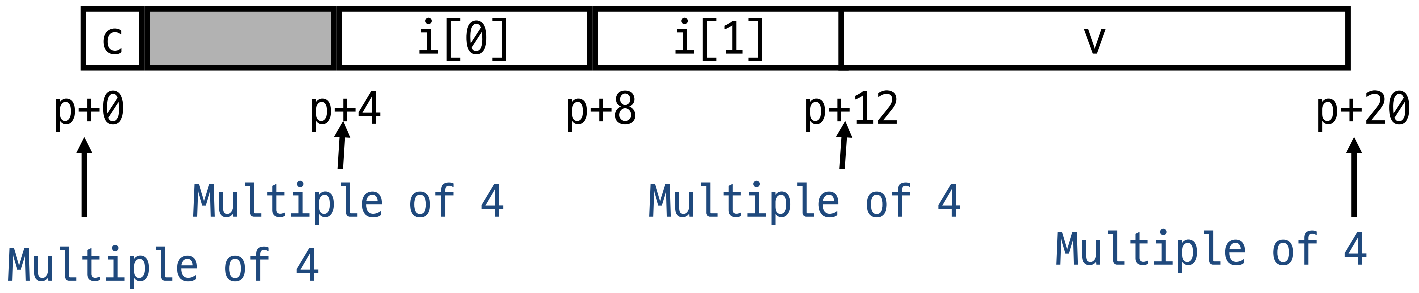
```
struct S1 {
  char c;
  int i[2];
  double v;
} *p;
```

Linux vs. Windows

- Windows (including Cygwin): K = 8



- Linux: K = 4

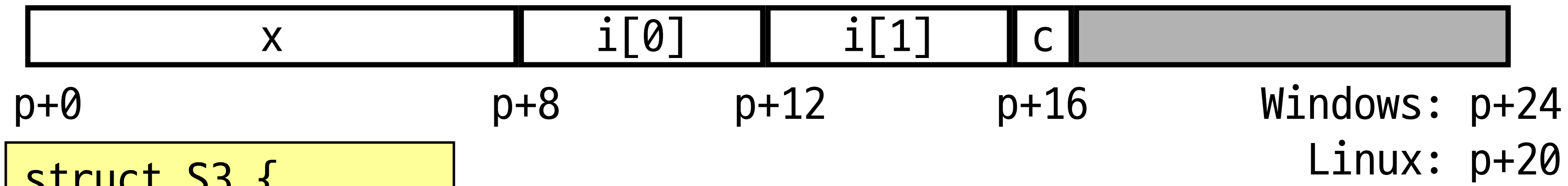


Alignment (5)

Overall alignment requirement

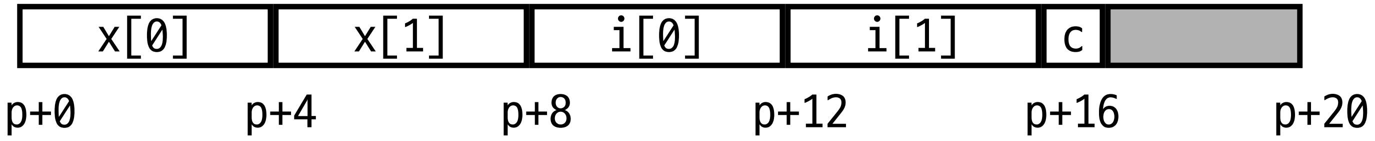
```
struct S2 {
  double x;
  int i[2];
  char c;
} *p;
```

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 (all cases)

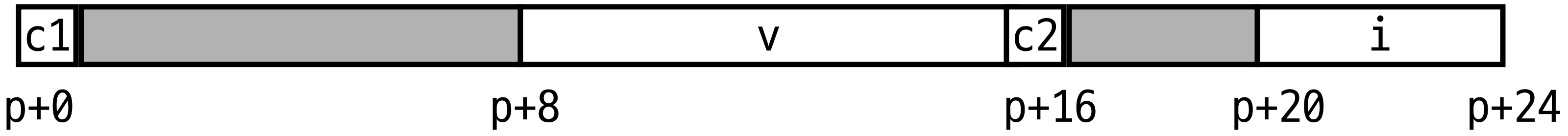


Alignment (6)

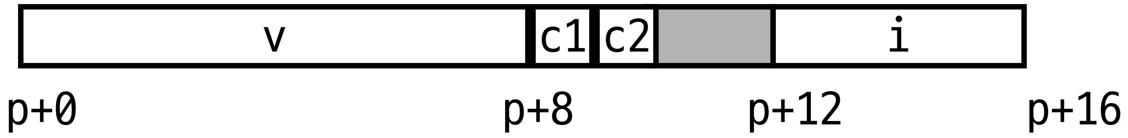
Ordering elements within structure

```
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

sizeof(p) 하면 alignment 때문에 값이
생각과 다르게 나올 수 있음

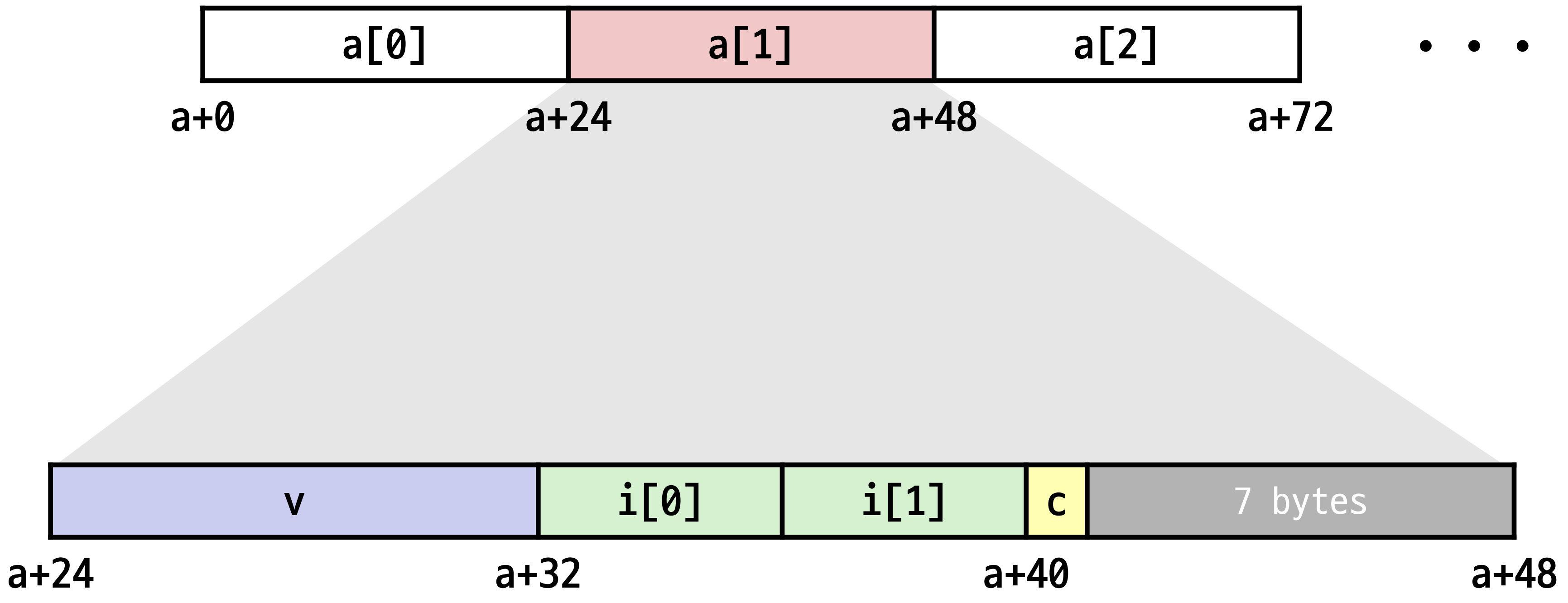
Arrays of Structures

Overall structure length multiple of K

Satisfy alignment requirement
for every element

유심히 볼 필요 없음.

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



Accessing Array Elements

Compute array offset 12*i

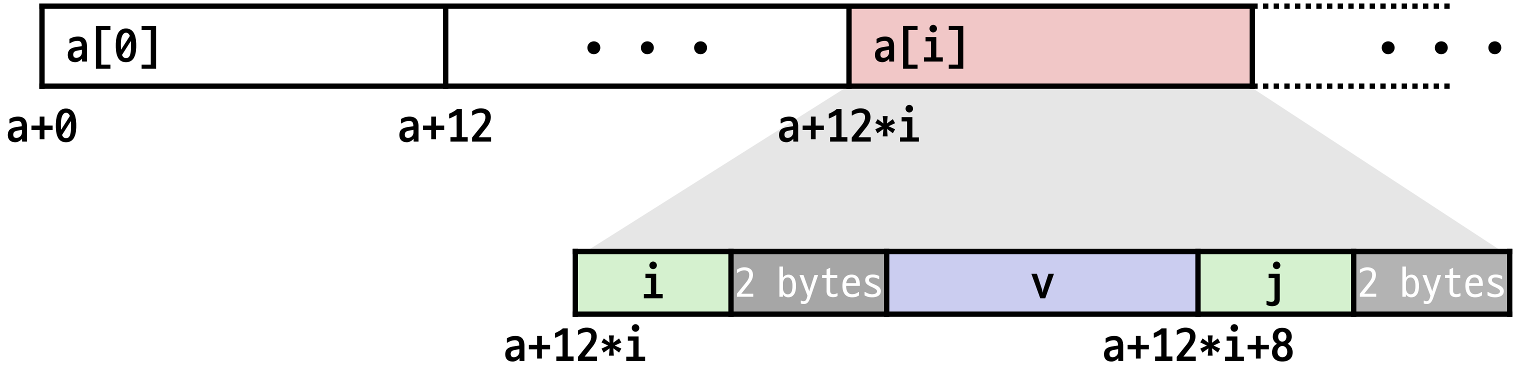
- sizeof(S3), including alignment spacers

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];
```



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

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

Saving Space

Put large data types first

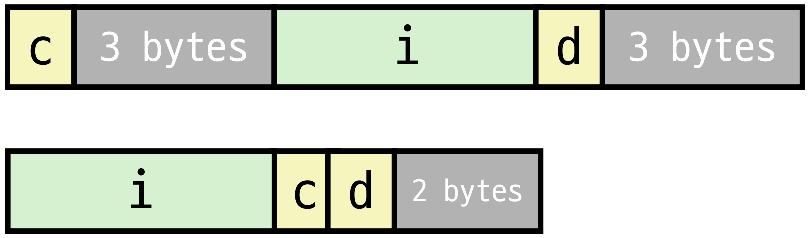
```
struct S4 {
  char c;
  int i;
  char d;
} *p;
```

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

data size 내림차순으로 선언.

→ 가능 메모리 낭비 ↓

Effect (K=4)

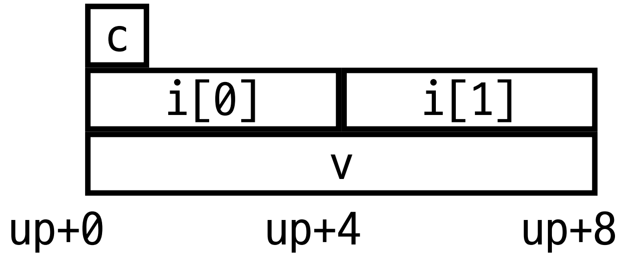


Union Allocation

Principles

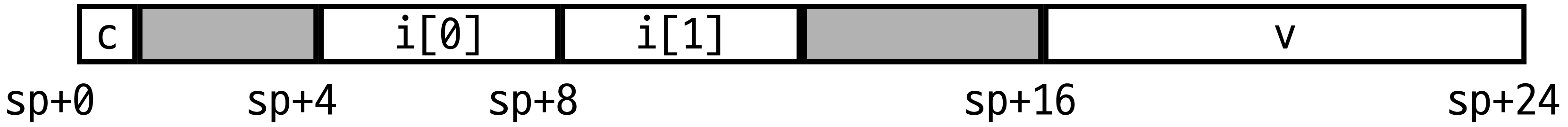
- Overlay union elements
- Allocate according to largest element
- Can only use one field at a time

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



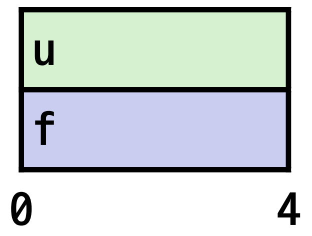
```
struct S1 {
  char c;
  int i[2];
  double v;
} *sp;
```

(Windows alignment)



Using Union to Access Bit Patterns

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



1000 0000 ....

```
float bit2float(unsigned u) {
  bit_float_t arg;          4 1
  arg.u = u;
  return arg.f; →
}
```

```
unsigned float2bit(float f) {
  bit_float_t arg;      4 - 0
  arg.f = f;
  return arg.u; →   2^31
}
```

Same as (float) u ?

X

Same as (unsigned) f ?

X

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

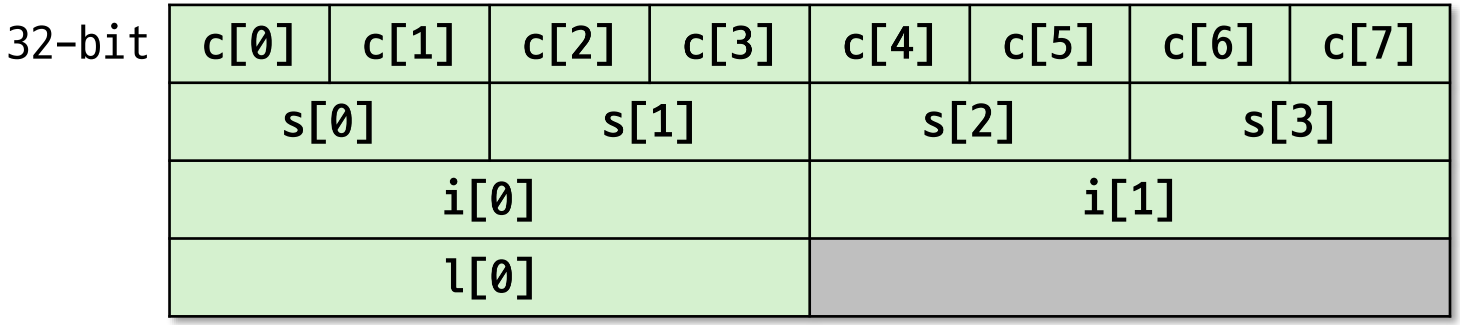
- Most significant byte has lowest address
- Sparc

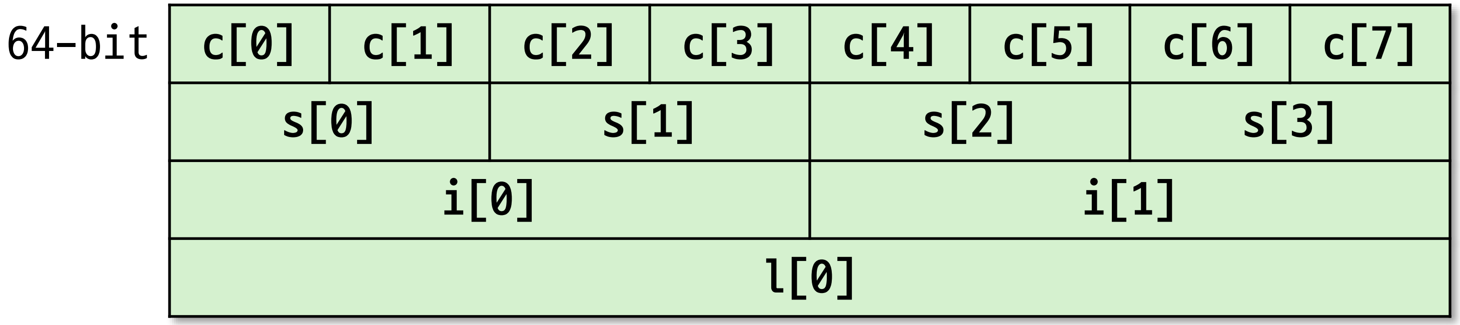
Little Endian

- 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;
```





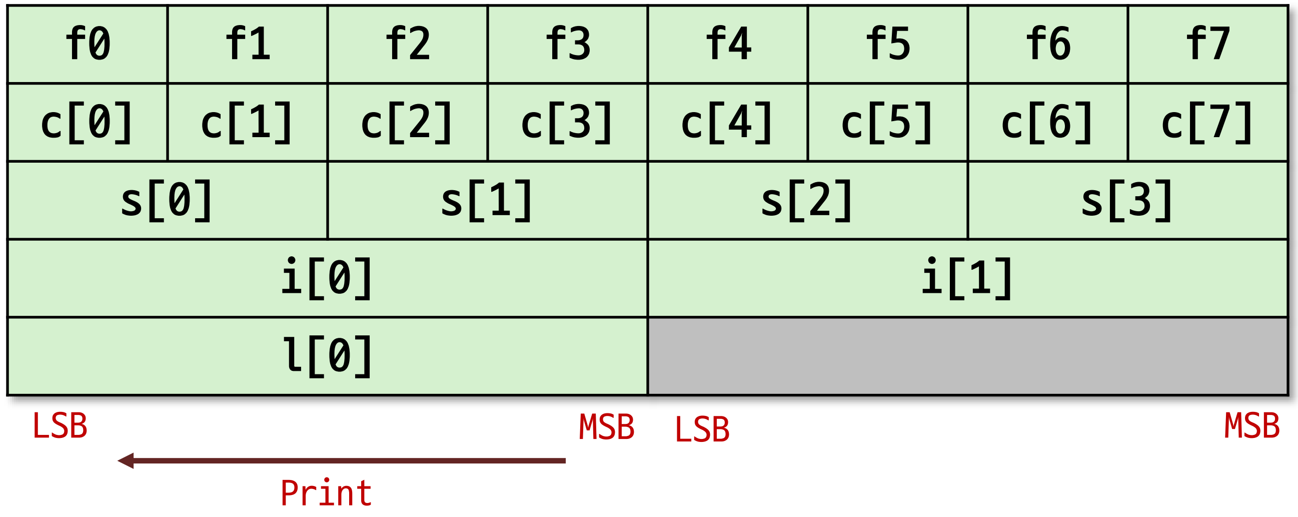
Byte Ordering Example (Cont).

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

```
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

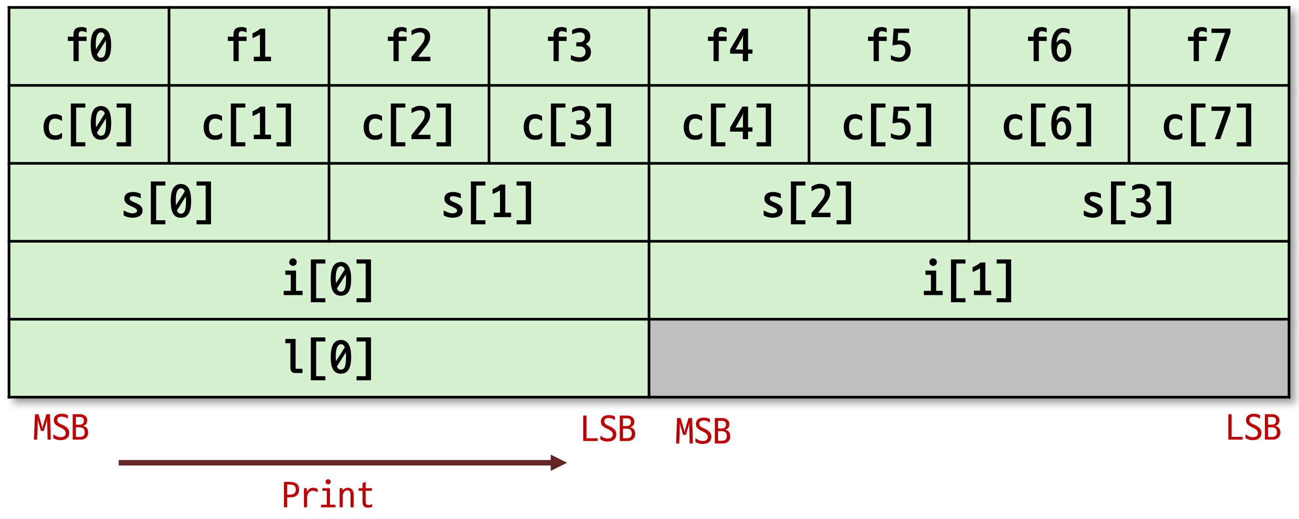


Output:

```
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

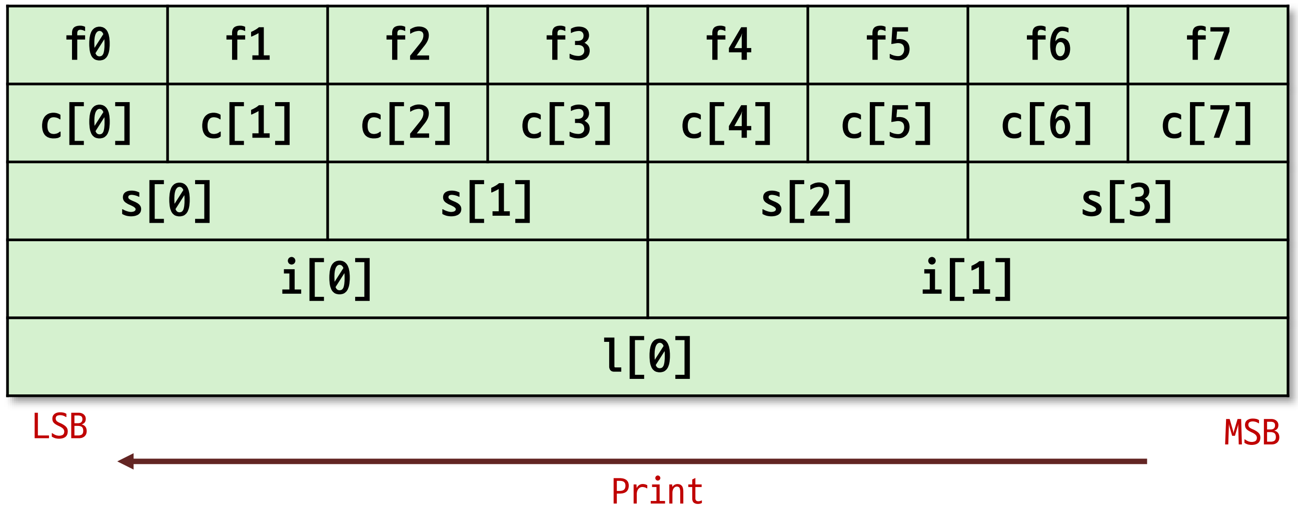


Output on Sun:

```
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



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

Structures

- Allocate bytes in order declared
- To reduce memory consumption, consider allocation order
- Pad in middle and at end to satisfy alignment

Unions

- Overlay declarations

가장 큰 data size 만큼 공간을 잡음