Machine Level Programming: Arrays, Structures and More

Computer Systems Organization (Spring 2016)
CSCI-UA 201, Section 2

Instructor: Joanna Klukowska

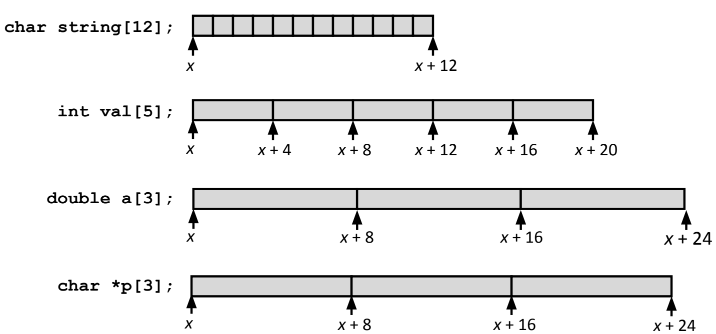
Slides adapted from
Randal E. Bryant and David R. O'Hallaron (CMU)
Mohamed Zahran (NYU)

1D Arrays

Array Allocation

- **Basic Principle**

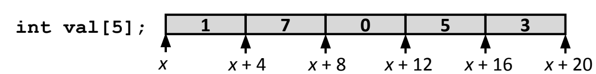
  T **A[*L*];**
  - Array of data type *T* and length *L*
  - Contiguously allocated region of *L* * **sizeof**(*T*) bytes in memory



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**

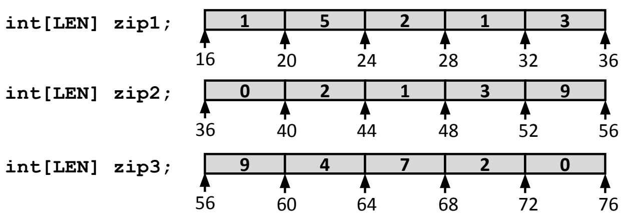


Reference	Type	Value
`val[4]`	`int`	3
`val`	`int *`	*x*
`val+1`	`int *`	*x* + 4
`&val[2]`	`int *`	*x* + 8
`val[5]`	`int`	??
`*(val+1)`	`int`	7
`val + i`	`int *`	*x* + 4 *i*

Array Example

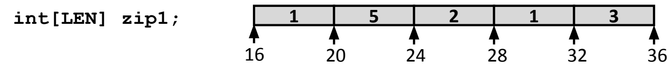
```
#define LEN 5

int zip1[LEN] = { 1, 5, 2, 1, 3 };
int zip2[LEN] = { 0, 2, 1, 3, 9 };
int zip3[LEN] = { 9, 4, 7, 2, 0 };
```



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

Array Accessing Example




```
int get_zip_digit ( int zip [LEN], int digit ) {
       return zip[digit];
}
```

```
# %rdi = z   <- it's an int pointer
# %esi = digit

movslq %esi, %rsi
movl   (%rdi,%rsi,4), %eax
ret
```

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

Array Loop Example

```
void incr( int zip [] ) {
    int i;
    for (i = 0; i < LEN; i++)
        zip[i]++;
}
```

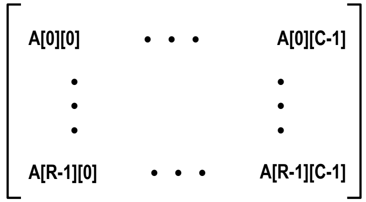
```
   #%rdi is zip
   movl   $0, %eax               # i = 0
   jmp .L3                       # goto L3
.L4:
   movslq %eax, %rdx             # extend to %rdx
   addl   $1, (%rdi,%rdx,4)      # z[i] ++
   addl   $1, %eax               # i++
.L3:
   cmpl   $4, %eax               # compare i to 4
   jle .L4                       # if <=, goto L4
   rep ret
```

See p. 208 (Aside) for explanation of the rep instruction.

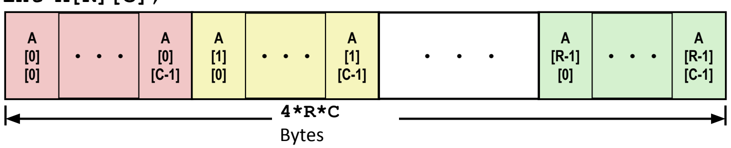
2D Arrays

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



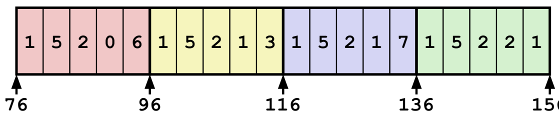
`int A[R][C];`



Nested Array Example

```
#define COUNT 4
int zips[LEN][COUNT] =
  {{1, 5, 2, 0, 6},
   {1, 5, 2, 1, 3 },
   {1, 5, 2, 1, 7 },
   {1, 5, 2, 2, 1 }};
```

`int zips[4];`

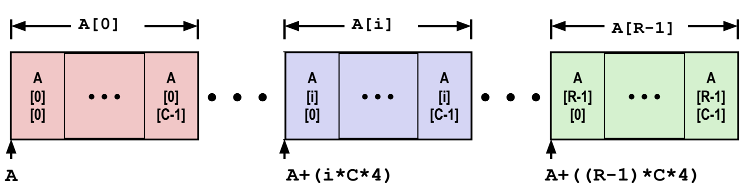


- Variable **`zips`**: array of 4 elements, allocated contiguously
- Each element is an array of 5 **`int`**'s, allocated contiguously
- **"Row-Major" ordering of all elements in memory**

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

```
#define ROWS 4
#define COLS 5
int* get_zip ( int zips [][COLS], int ind ) {
    return zips[ind];
}
```

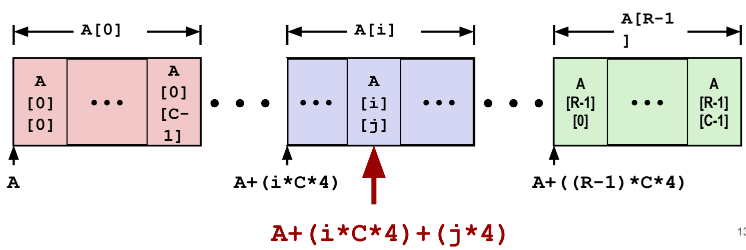
```
# %rdi = zips   %esi = ind
movslq %esi, %rsi
leaq   (%rsi,%rsi,4), %rax
salq   $2, %rax
addq   %rdi, %rax
ret
```

- **Row Vector**
  - **`zips[ind]`** is array of 5 **`int`**'s
  - Starting address **`zips+20*ind`**

Nested Array Element 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

```
#define ROWS 4
#define COLS 5
int get_zips_digit ( int zips [][COLS], int ind, int dig ) {
    return zips[ind][dig];
}
```

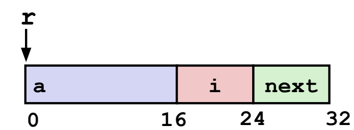
```
movslq %esi, %rsi
leaq   (%rsi,%rsi,4), %rax
salq   $2, %rax
addq   %rdi, %rax
movslq %edx, %rdx
movl   (%rax,%rdx,4), %eax
```

- **Array Elements**
  - `zips[ind][dig]` is `int`
  - Address: `zips + 20*ind + 4*dig`
    `= zips + 4*(5*ind + dig)`

Structures

Structure Representation

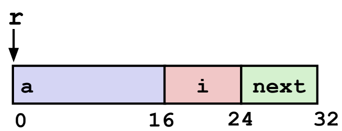
```
struct rec {
    int a[4];
    size_t i;
    struct rec *next;
};
```



- **Structure represented as block of memory**
  - **Big enough to hold all of the fields**
- **Fields ordered according to declaration**
  - **Even if another ordering could yield a more compact representation**
- **Compiler determines overall size + positions of fields**
  - **Machine-level program has no understanding of the structures in the source code**

Access to Structure Members

```
struct rec {
    int a[4];
    size_t i;
    struct rec *next;
};
```

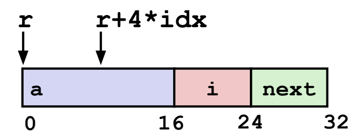



```
int * get_a (struct rec *r) {
    return r->a;
}
```

```
# r in %rdi
movq   %rdi, %rax
ret
```


Access to Structure Members

```
struct rec {
    int a[4];
    size_t i;
    struct rec *next;
};
```

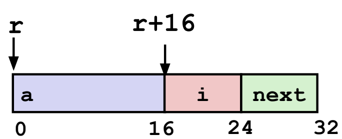



```
int * get_a_element (struct rec *r, int idx ) {
    return r->a[idx];
}
```

```
# r in %rdi
movslq %esi, %rsi
movl   (%rdi,%rsi,4), %eax
ret
```


Access to Structure Members

```
struct rec {
    int a[4];
    size_t i;
    struct rec *next;
};
```

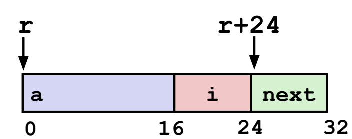



```
int get_i (struct rec *r ) {
    return  r->i;
}
```

```
# r in %rdi
movl   16(%rdi), %eax
ret
```


Access to Structure Members

```
struct rec {
    int a[4];
    size_t i;
    struct rec *next;
};
```

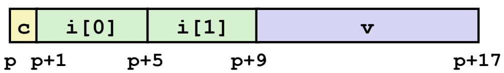



```
struct rec * get_next (struct rec *r ) {
    return  r->next;
}
```

```
# r in %rdi
movq   24(%rdi), %rax
ret
```

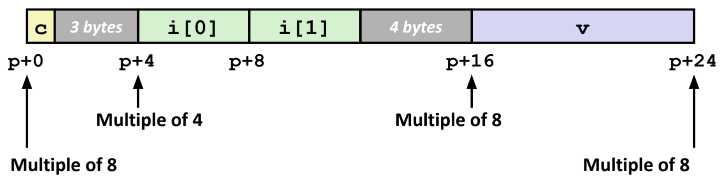
Structures & Alignment

- **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 and used on x86-64
- **Motivation for Aligning Data**
  - Memory accessed by (aligned) chunks of 4 or 8 bytes (system dependent)
    - Inefficient to load or store data that spans quad word boundaries
    - Virtual memory trickier when data spans 2 pages
- **Compiler**
  - Inserts gaps in structure to ensure correct alignment of fields

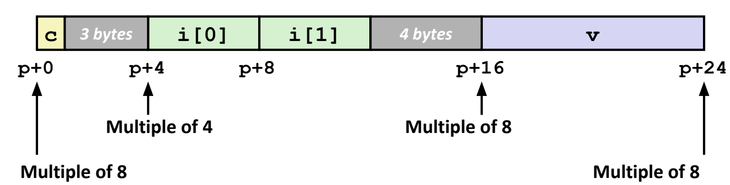
Specific Cases of Alignment (x86-64)

- **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

- **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:**
  - K = 8, due to **`double`** element

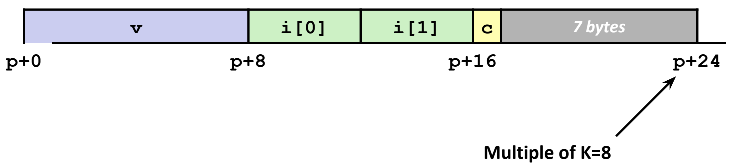
```
struct S1 {
  char c;
  int i[2];
  double v;
} *p;
```



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;
```



Saving Space

- Put large data types first

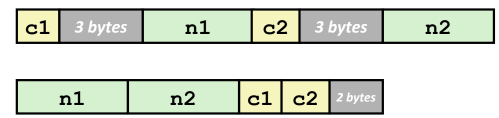
```
struct S1 {
    char c1;
    int n1;
    char c2;
    int n2;
};
```

```
struct S2 {
    int n1;
    int n2;
    char c1;
    char c2;
};
```

- Effect (K=4)

S1 uses 16 bytes

S2 uses 12 bytes

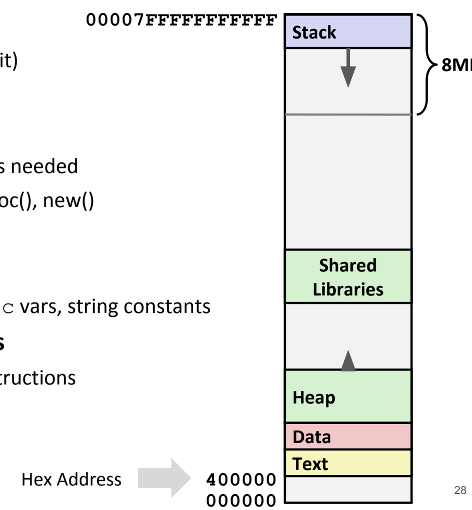


Memory Layout

x86-64 Linux Memory Layout

not drawn to scale

- **Stack**
  - Runtime stack (8MB limit)
  - E. g., local variables
- **Heap**
  - Dynamically allocated as needed
  - When call malloc(), calloc(), new()
- **Data**
  - Statically allocated data
  - E.g., global vars, `static` vars, string constants
- **Text / Shared Libraries**
  - Executable machine instructions
  - Read-only



Memory Allocation Example

not drawn to scale

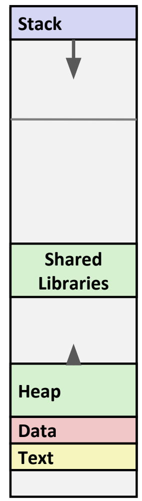
```
char big_array[1L<<24];  /* 16 MB */
char huge_array[1L<<31]; /*  2 GB */

int global = 0;

int useless() { return 0; }

int main ()
{
    void *p1, *p2, *p3, *p4;
    int local = 0;
    p1 = malloc(1L << 28); /* 256 MB */
    p2 = malloc(1L << 8);  /* 256  B */
    p3 = malloc(1L << 32); /*   4 GB */
    p4 = malloc(1L << 8);  /* 256  B */
 /* Some print statements ... */
}
```

Where does everything go?



x86-64 Example Addresses

not drawn to scale

address range ~2^{47}

`local`	`0x00007ffe4d3be87c`
`p1`	`0x00007f7262a1e010`
`p3`	`0x00007f7162a1d010`
`p4`	`0x000000008359d120`
`p2`	`0x000000008359d010`
`big_array`	`0x0000000080601060`
`huge_array`	`0x0000000000601060`
`main()`	`0x000000000040060c`
`useless()`	`0x0000000000400590`