Computer Architecture (Practical Class)
Heterogeneous Data Structures

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Heterogenous data structures in C

In C, we have two ways of combining variables of different types:

- *structures*, declared using the keyword `struct`, aggregate multiple variables under the same name;
- *unions*, declared using the keyword `union`, allow a single variable to use several data types.

Today, we will discuss *structures in C and Assembly*.

- A *structure* is:
  - A continuous memory region (similarly to arrays), composed of different *members*
  - Members are accessed by their name and can have different types
- We can have structures in C by:
  - defining a single structure in a variable;
  - declaring a structure type;
  - declaring a new data type.

Defining structures in C (1/3)

In the example below, we define a *single structure* in a variable called “c1”.

Structure in C - Defining a structure held by a variable

```
#include <stdio.h>

/* define a structure in a global variable c1 */
struct  {
  int   n_wheels;
  int   n_passengers;
  float fuel_consumption;
} c1;

int main(){
  /* init and access the data in c1 */
  c1.n_wheels=4;
  c1.n_passengers=2;
  c1.fuel_consumption=12.5;
  printf("The car has %d wheels, %d passengers.Consumption is %f l/100 km.\n",
         c1.n_wheels,c1.n_passengers,c1.fuel_consumption);
  return 0;
}
```

- The structure has only one instantiation (in c1); no other instantiations of the structure exist.

Defining structures in C (2/3)

In the example below, we declare a *structure type* called "`s_car`".

Structure in C - Declaring a structure type

```
#include <stdio.h>

/* declare a structure type called s_car */
struct s_car {
  int   n_wheels;
  int   n_passengers;
  float fuel_consumption;
} ;

int main(){
  /* define two structures of type s_car */
  struct s_car c1, c2;

  /* init and acess the data in c1 and c2 */
  c1.n_wheels=4; c1.n_passengers=2; c1.fuel_consumption=12.5;
  c2.n_wheels=5; c2.n_passengers=4; c2.fuel_consumption=20.0;
  printf("Car 2 has %d wheels, %d passengers. Consumption is %f l/100 km.\n",
         c2.n_wheels,c2.n_passengers,c2.fuel_consumption);
  return 0;
}
```

- To instantiate the *s_car structure*, we define new variables using the name of the structure after the keyword `struct`.

In the example below, we declare a new *data type* called "t_car" using the keyword "typedef".

Structure in C - Declaring a data type for a structure

```c
#include <stdio.h>

/* declare a data type called t_car */
typedef struct { /* we could write 'typedef struct s_car' */
  int   n_wheels;
  int   n_passengers;
  float fuel_consumption;
} t_car; /* this is the name of the structure data type */

int main(){
  /* define two cars */
  t_car c1, c2;

  /* init and access the data in c1 and c2 */
  c1.n_wheels=4; c1.n_passengers=2; c1.fuel_consumption=12.5;
  c2.n_wheels=5; c2.n_passengers=4; c2.fuel_consumption=20.0;
  printf("Car 2 has %d wheels, %d passengers. Consumption is %f l/100 km.\n",
         c2.n_wheels,c2.n_passengers,c2.fuel_consumption);
  return 0;
}
```

- To instantiate the *t_car data type*, we define new variables using the name of the data type.

Pointers to structures in C (1/2)

- We can define pointers to structures

```
struct s_car *ptr;    /* pointer to structure type */
t_car *ptr;           /* pointer to a structure data type */
```

- To access the fields of a structure referenced by a pointer, use ->

```
ptr->n_wheels
ptr->n_passengers
ptr->fuel_consumption
```

instead of:

```
(*ptr).n_wheels
(*ptr).n_passengers
(*ptr).fuel_consumption
```

Notes:

- To obtain the address of a structure, use the & operator
- Structures are very similar to arrays (continuous block of memory), ***except*** **in this aspect** (must use & to get address)

Structure in C - Obtaining a pointer to a structure

```
#include <stdio.h>

typedef struct {
   int   n_wheels;
   int   n_passengers;
   float fuel_consumption;
} t_car;

int main(){
   /* define a car */
   t_car c1;
   /* define a pointer to a car */
   t_car *car_ptr = &c1;

   /* init and access the data in c1 using the pointer */
   car_ptr->n_wheels=4;
   car_ptr->n_passengers=2;
   car_ptr->fuel_consumption=12.5;
   printf("The car has %d wheels, %d passengers. Consum. is %f l/100 km.\n",
           car_ptr->n_wheels,car_ptr->n_passengers,car_ptr->fuel_consumption);

   return 0;
}
```

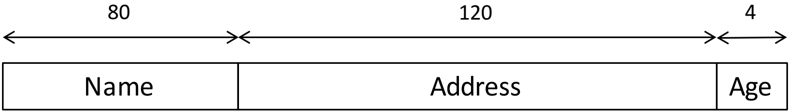
Storing structures in memory

- Consider the following structure in C

Example structure in C to store personal data

```
struct s_person_data{ /* we could also have used typedef ... */
   char name[80];       /* 80 bytes  */
   char address[120];   /* 120 bytes */
   int  age;            /* 4 bytes  */
} ;
```

- To store this structure, we need 204 bytes (80+120+4)



Important note

We will see some subtleties of structure sizes in a moment

Structures in Assembly (1/5)

- In Assembly, we refer to members within a structure by their *offset*
- The offset of each member of the structure refers to the displacement, in bytes, from the start of the structure
- To simplify this access, we can define constants for the offset of each member using the `.equ` directive

```
.equ DATA_SIZE, 204       # total size
.equ NAME_OFFSET, 0       # name is at the beginning of the structure
.equ ADDRESS_OFFSET, 80   # the address starts at byte 80
.equ AGE_OFFSET,200       # age starts at byte 200
```

Structures in Assembly (2/5)

Function set_age in C

```c
void set_age(struct
  s_person_data *pdata){
  /* age = 30 */
  pdata->age = 30;
}
```

Function set_age in Assembly

```
set_age:
  # *pdata on %rdi
  # age = 30
  movl $30, AGE_OFFSET(%rdi)
  ret
```

Example: Access to a structure member

Structure Declaration

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

Access in C

```
void set_x(struct rec *r,
           int val){
  /* access by name */
  r->x=val;
}
```

Access in Assembly

```
# *r in %rdi
# val in %esi

# access by offset
movl %esi,(%rdi)
```

Memory layout for the structure `rec`

x			a			p		
0	...	3	4	...	15	16	...	23

- Note that the address of *x* (the first member of the structure) is equal to the address of *r* (the struture)

Example: Obtaining the address of a structure member

Structure Declaration

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

Access in C

```
int* find_a(struct rec *r,
            unsigned int i){
  /* address of a[i] */
  return &(r->a[i]);
}
```

Access in Assembly

```
# *r in %rdi
# i in %esi

# %rax = r + 4 + (4 * i)
leaq 4(%rdi,%rsi,4),%rax
```

Memory layout for the structure `rec`

x			a			p		
0	...	3	4	...	15	16	...	23

- To access field *a*, we need to add the the appropriate offset to the address of the structure (in this case 4 bytes). Then, we need to access the element *i* within *a*, by adding offset $i * 4$

Example: Obtaining a pointer and changing a structure member

Structure Declaration

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

Access in C

```
void set_p(struct rec *r){
  /* address of a[i],
  where i is the value
  of member x */
  r->p = &(r->a[r->x]);
}
```

Access in Assembly

```
# *r in %rdi
# %rcx = r->x
movslq (%rdi),%rcx
# %rax = r + 4 + 4*(r->x)
leaq 4(%rdi,%rcx,4),%rax
# r->p = %rax
movq %rax,16(%rdi)
```

Memory layout for the structure `rec`

x			a			p		
0	...	3	4	...	15	16	...	23

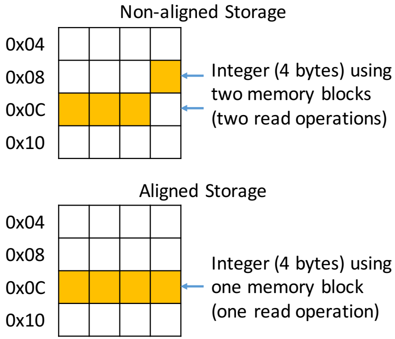
- Based on the size of each member (according to its data type), and the start address of the structure, we must compute the addresses

Data alignment

Why

- Memory is accessed in blocks of fixed size
  - Usually, 4 or 8 bytes, depending on the system
- Storing data at addresses multiple of the block size — *aligned to the block size* — will reduce the number of memory accesses

The following example depicts a system accessing memory in blocks of 4 bytes:



Data alignment is performed by the compiler

- **The compiler inserts “spaces” in the data stored in memory to ensure that the members are aligned**
- This improves the performance of the code
- This is required in some architectures; in x86-64 it is just recommended
  - in x86-64 data can be misaligned, at the cost of a performance penalty
- May be treated differently by different operating systems

Data alignment rules in x86-64

The alignment rules are based on the principle that any primitive object of K bytes must have an address that is a multiple of K

- **$\mathbb{K} = 1$ byte: char**
  - No restrictions
- **$\mathbb{K} = 2$ bytes: short**
  - The least significant bit must be 0 (that is, the address must be a multiple of 2)
- **$\mathbb{K} = 4$ bytes: int, float, ...**
  - The 2 least significant bits must be 0 (that is, the address must be a multiple of 4)
- **$\mathbb{K} = 8$ bytes: double, long, long long, char *, ...**
  - The 3 least significant bits must be 0 (that is, the address must be a multiple of 8)

Important notes

These restrictions hold for most x86-64 operating systems, except that on Windows, the *long* type has size and alignment 4 (The *long long* type has size and alignment 8 on all x86-64 operating systems)

Particularly important to know about data alignment when dealing with structures in C

- In order to be able to share structures between C and Assembly, we have to be aware of the data alignment made by the compiler

Inside the structure

- We must satisfy the alignment requirements for each member of the structure
- Each structure has an alignment requirement of $\mathbb{K}$, which may require implicit internal padding, depending on the previous member

Placement of the structure in memory

- Given $\mathbb{K}$, the largest aligment requirement inside the structure:
- The starting address of the structure must be a multiple of $\mathbb{K}$
- The total size of the structure must be a multiple of $\mathbb{K}$, which may require padding after the last member (external padding)

Data alignment in structures: Examples

Total size: 24 bytes

- $\mathbb{K}$=8, due to the member *c* of type `long`

```
struct S1{
  char a;
  int b[2];
  long c;
};
```

a	3 bytes	b	4 bytes	c
0	[gap]	4 … 11	[gap]	16 … 23

Total size: 24 bytes

- $\mathbb{K}$=8, due to the member *b* of type `long`

```
struct S2{
  int a;
  long b;
  short c;
};
```

a	4 bytes	b	c	6 bytes
0 … 3	[gap]	8 … 15	16 .. 17	[gap]

Important note

The starting address of both structures must be a multiple of $\mathbb{K} = 8$

Practice problem

Consider the following data type:

```
typedef struct{
  char age;
  short number;
  int grades[10];
  char name[80];
  char address[120];
}Student;
```

- Develop in Assembly the function `void save_grades(Student *s, int *new_grades, int size)` that copies all the elements of the array `new_grades` to the field `grades` of the structure pointed by `s`

Practice problem

Function save_grades in Assembly

```
# void save_grades(Student *s, int *new_grades, int size)
save_grades:
   # *s in %rdi, *new_grades in %rsi, size in %edx

   addq $4, %rdi                 # rdi = &(s->grades[0])
   movslq %edx, %rdx             # rdx = size
   cmpq $0, %rdx
   jle end

   movl $0, %rcx                 # index = 0

loop_grades:
   cmpq %rcx, %rdx
   je end

   movl (%rsi, %rcx, 4), %eax    # place grade to copy on %eax
   movl %eax, (%rdi, %rcx, 4)    # copy grade in %eax to new_grades

   incq %rcx                     # index++
   jmp loop_grades

end:
   ret
```