Programming Paradigms

Composite Types (Part 1)

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Quiz

Which (if any) of the following lines lead to a compile-time error in Java?

```
int a[], b;
int[] c, d;

a = new int[2];
b = new int[3];
c = new char[4];
d = new int[5];
```

Please vote via Ilias.

Quiz

Which (if any) of the following lines lead to a compile-time error in Java?

```
int a[], b;
int[] c, d;
```

`a` is an int array,

`b` is just an int variable.

```
a = new int[2];
b = new int[3];
c = new char[4];
d = new int[5];
```

Please vote via Ilias.

Quiz

Which (if any) of the following lines lead to a compile-time error in Java?

```
int a[], b;
int[] c, d;
```

Both `c` and `d` are int arrays.

```
a = new int[2];
b = new int[3];
c = new char[4];
d = new int[5];
```

Please vote via Ilias.

Quiz

Which (if any) of the following lines lead to a compile-time error in Java?

```
int a[], b;
int[] c, d;

a = new int[2];
b = new int[3];
c = new char[4];
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```

Error 1: Can't assign int array to int variable.

Please vote via Ilias.

Quiz

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int a[], b;
int[] c, d;

a = new int[2];
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```

Error 2: char array is incompatible with int array.

Please vote via Ilias.

Composite Types

- **New types formed by joining together simpler types using a type constructor**
- **Common type constructors**
  - Records
  - Arrays
  - Strings
  - Sets
  - Pointers
  - Lists

Overview

- Records 
- Arrays
- Pointers and Recursive Types

Records

- **A.k.a. structures**
- **Store and manipulate related data of heterogeneous types together**
  - Each data component is a field
- **Originate from**
  - Cobol: Introduced concept
  - Algol 68: Introducted `struct` keyword

Example

A struct in C:

```
struct element {          // defines a record
  char name[2];           // with four fields
  int atomic_number;
  double atomic_weight;
  _Bool metallic;
};
```

Example

A struct in C:

```
struct element {          // defines a record
  char name[2];           // with four fields
  int atomic_number;
  double atomic_weight;
  _Bool metallic;
};

struct element copper; // variable of record type
copper.name[0] = 'C';
// ...
if (copper.metallic) { // access fields with
    // ...             // dot notation
}
```

Variants Available in Most PLs

Most PLs offer some record-like type constructor

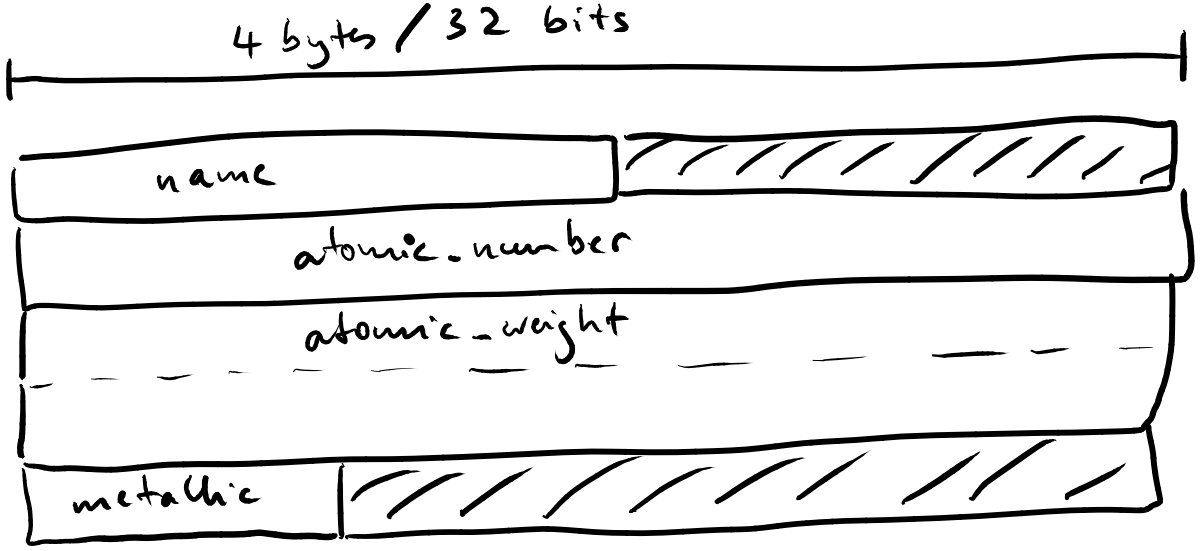
- C: structs
- C++: special form of class
- Fortran 90: simple called “types”
- C#, Swift: struct types (as opposed to class types)
- OCaml: tuples (where order of fields is irrelevant)
- Java: (no records/structs provided)

Memory Layout

How are records stored in memory?

- Usually, fields stored in adjacent locations
- Field access: Address + offset
- Alignment constraints may create “holes”
  - Alignment constraints depend on architecure
  - E.g., 4-byte ints on x86 must start at address divisble by 4

Example · Memory Layout



Packing and Recording

How to optimize for space?

- Option 1: Packing
  - Avoid holes and break alignment
  - Will need additional instructions to operate on fields

    (e.g., to reassemble value into register)
- Option 2: Reordering fields
  - Minimize holes but respect alignment

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Can instruct compiler to pack a record (e.g., via pragmas in gcc)

Packing and Recording

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    (e.g., to reassemble value into register)
- Option 2: Reordering fields
  - Minimize holes but respect alignment

System-level programmer may rely on memory layout: C/C++ don't reorder fields

Quiz: Memory Layout of Records

How many bytes does an array of five of the following structs need (without packing)?

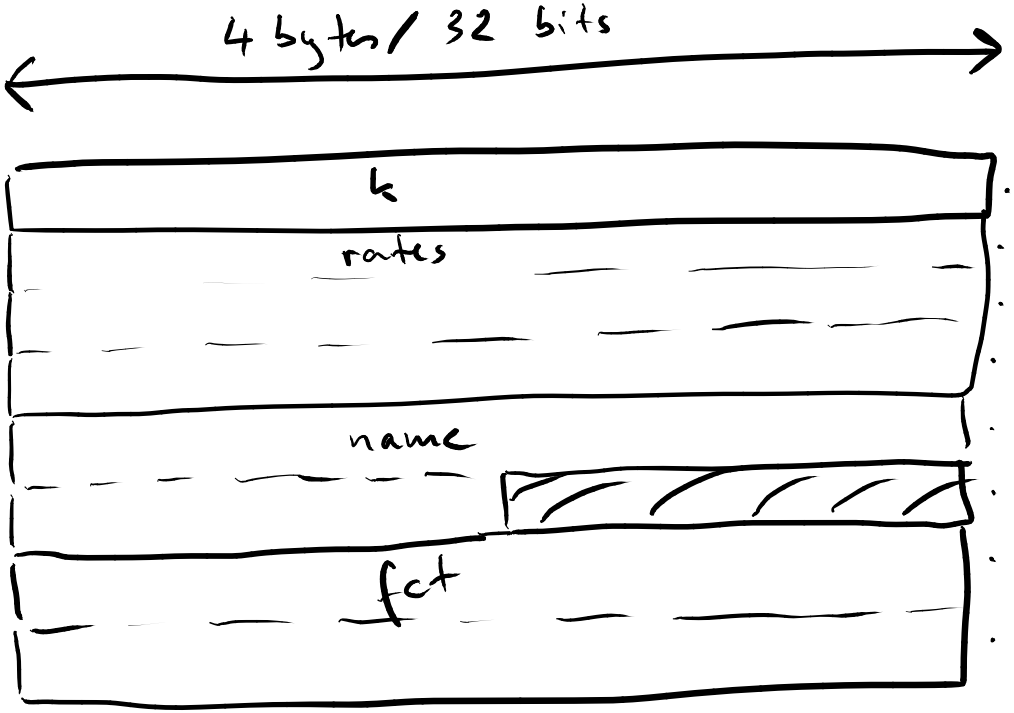
```
struct quiz {
    int k;
    float rates[3];
    char name[6];
    void *fct;
};
```

Assumptions:

- Size of char: 1 byte
- Size of int: 4 bytes
- Size of float: 4 bytes
- Size of pointer: 8 bytes
- Pointers must be aligned (divisible by 4)

Please vote via Ilias.

Quiz:



$8 \times 4 = 32$ bytes

$32 \cdot 5 = 160$ bytes

Quiz: Memory Layout of Records

How many bytes does an array of five of the following structs need (without packing)?

```
struct quiz {
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Assumptions:

- Size of char: 1 byte
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- Size of float: 4 bytes
- Size of pointer: 8 bytes
- Pointers must be aligned (divisible by 4)

Tip: Check it yourself with `sizeof(struct quiz)`

Nested Records

- Option 1: **Lexically nested**

```
struct outer_record {
  char some_field[10];
  struct { // no name for this inner record
    int some_other_field;
    double yet_another_field;
  } nested_field;
};
```

- Option 2: **Fields of record type**

```
struct outer_record {
  char some_field[10];
  struct inner_record nested_field;
};
```

Semantics of Nested Records

What's the meaning of referring to a nested record?

```
struct S s1;
struct S s2;
s1.n.j = 0;
s2 = s1;
s2.n.j = 7;
print("%d\n", s1.n.j);
```

Semantics of Nested Records

What's the meaning of referring to a nested record?

```
struct S s1;
struct S s2;
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s2 = s1;
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print("%d\n", s1.n.j);
```

Does it print 0 or 7?

Reference Model vs. Value Model

- **Occurrence of a variable may mean**
  - a reference to its memory location
  - the value stored in the variable
- **E.g., C:**
  - Reference model if variable is left-hand side of assignment
  - Value model otherwise
- **E.g., Java: Value model only for built-in types**

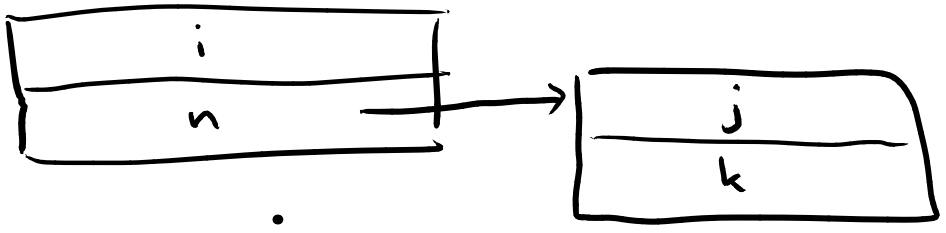
Example:

C:

```
struct T {
    int j;
    int k;
}
struct S {
    int i;
    struct T n;
{
```

Java:

```
class T {
    public int j;
    public int k;
}
class S {
    public i;
    public T n;
}
```



Semantics of Nested Records

What's the meaning of referring to a nested record?

```c
// C code
struct S s1;
struct S s2;
s1.n.j = 0;
s2 = s1;
s2.n.j = 7;
print("%d\n", s1.n.j);
```

```java
// Java code
S s1 = new S();
s1.n = new T();
s1.n.j = 0;
S s2 = s1;
s2.n.j = 7;
System.out.println(s1.n.j);
```

Semantics of Nested Records

What's the meaning of referring to a nested record?

```
// C code
struct S s1;
struct S s2;
s1.n.j = 0;
s2 = s1;
s2.n.j = 7;
print("%d\n", s1.n.j);
```

Prints 0

```
// Java code
S s1 = new S();
s1.n = new T();
s1.n.j = 0;
S s2 = s1;
s2.n.j = 7;
System.out.println(s1.n.j);
```

Prints 7

Variant Records (Unions)

- **Special kind of record**
- **Reuses same memory location for multiple variables**
  - Assumption: Variables never used at the same time
  - Size of record = size of largest member

Demo

Demo: union.c

Use Cases for Unions

- **Bytes interpreted differently at different times**
  - E.g., implementation of memory manager: Memory blocks contain bookkeeping information and user data
- **Represent single data type with alternative sets of fields**
  - E.g., record for employees: Properties depend on department of employee