18. Structs and Classes I

Rational Numbers, Struct Definition, Overlading Functions and Operators, Const-References, Encapsulation

Calculating with Rational Numbers

- Rational numbers ($\mathbb{Q}$) are of the form $\frac{n}{d}$ with n and d in $\mathbb{Z}$
- $\mathrm{C{+}{+}}$does not provide a built-in type for rational numbers

Goal

We build a $\mathrm{C{+}{+}}$-type for rational numbers ourselves! 🙂

Vision

How it could (will) look like

```
// input
std::cout << "Rational number r =? ";
rational r;
std::cin >> r;
std::cout << "Rational number s =? ";
rational s;
std::cin >> s;

// computation and output
std::cout << "Sum is " << r + s << ".\n";
```


A First Struct

```
struct rational {
  int n;
  int d; // INV: d != 0
};
```

Invariant: specifies valid value combinations (informal).

member variable (**n**umerator)

member variable (**d**enominator)

- `struct` defines a new *type*
- formal range of values: *cartesian product* of the value ranges of existing types
- real range of values: `rational` $\subsetneq$ `int` $\times$ `int`.

Accessing Member Variables

```
struct rational {
    int n;
    int d; // INV: d != 0
};

rational add (rational a, rational b)
{
    rational result;
    result.n = a.n * b.d + a.d * b.n;
    result.d = a.d * b.d;
    return result;
}
```

$$\frac{r_n}{r_d} := \frac{a_n}{a_d} + \frac{b_n}{b_d} = \frac{a_n \cdot b_d + a_d \cdot b_n}{a_d \cdot b_d}$$

A First Struct: Functionality

A `struct` defines a new *type*, not a *variable*!

```
// new type rational
struct rational {
   int n;
   int d; // INV: d != 0
};

// POST: return value is the sum of a and b
rational add (const rational a, const rational b)
{
  rational result;
  result.n =  a.n * b.d +  a.d * b.n;
  result.d = a.d * b.d;
  return result;
}
```

Meaning: every object of the new type is represented by two objects of type `int` the objects are called `n` and `d`.

member access to the `int` objects of `a`.

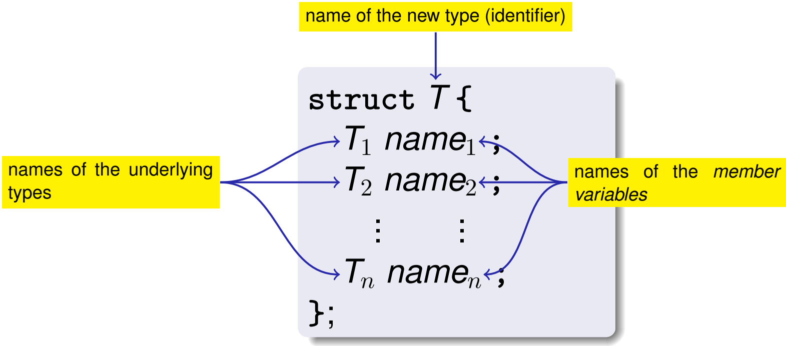
Input

```
// Input r
rational r;
std::cout << "Rational number r:\n";
std::cout << " numerator =? ";
std::cin >> r.n;
std::cout << " denominator =? ";
std::cin >> r.d;

// Input s the same way
rational s;
...
```


Vision comes within Reach ...

```
// computation
const rational t = add (r, s);

// output
std::cout << "Sum is " << t.n << "/" << t.d << ".\n";
```

Struct Definitions



Range of Values of T: $T_1 \times T_2 \times ... \times T_n$

Struct Defintions: Examples

```
struct rational_vector_3 {
  rational x;
  rational y;
  rational z;
};
```

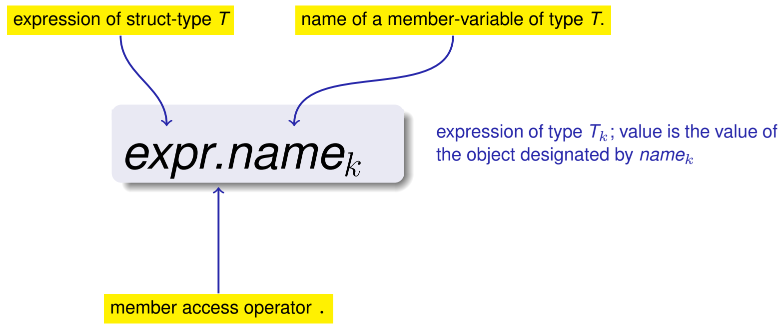
underlying types can be fundamental or user defined

Struct Definitions: Examples

```
struct extended_int {
  // represents value if is_positive==true
  // and -value otherwise
  unsigned int value;
  bool is_positive;
};
```

the underlying types can be different

Structs: Accessing Members



Structs: Initialization and Assignment

Default Initialization:

```
rational t;
```

- Member variables of `t` are default-initialized
- for member variables of fundamental types nothing happens (values remain undefined)

Structs: Initialization and Assignment

Initialization:

```
rational t = {5, 1};
```

- Member variables of `t` are initialized with the values of the list, according to the declaration order.

Structs: Initialization and Assignment

Assignment:

```
rational s;
...
rational t = s;
```

- The values of the member variables of `s` are assigned to the member variables of `t`.

Structs: Initialization and Assignment

```
t.n                .n
t.d = add (r, s)   .d   ;
```

Initialization:

```
rational t = add (r, s);
```

- `t` is initialized with the values of `add(r, s)`

Structs: Initialization and Assignment

Assignment:

```
rational t;
t = add (r, s);
```

- `t` is default-initialized
- The value of `add (r, s)` is assigned to `t`

Structs: Initialization and Assignment

`rational s;` ⟵ member variables are uninitialized

`rational t = {1,5};` ⟵ *member-wise* initialization: `t.n = 1, t.d = 5`

`rational u = t;` ⟵ member-wise copy

`t = u;` ⟵ member-wise copy

`rational v = add (u,t);` ⟵ member-wise copy

Comparing Structs?

For each fundamental type (`int, double,...`) there are comparison operators `==` and `!=` , not so for structs! Why?

- member-wise comparison does not make sense in general...
- ...otherwise we had, for example, $\frac{2}{3} \neq \frac{4}{6}$

Structs as Function Arguments

```
void increment(rational dest, const rational src)
{
    dest = add (dest, src); // modifies local copy only
}
```

Call by Value !

```
rational a;
rational b;
a.d = 1; a.n = 2;
b = a;
increment (b, a); // no effect!
std::cout << b.n << "/" << b.d; // 1 / 2
```

Structs as Function Arguments

```
void increment(rational & dest, const rational src)
{
    dest = add (dest, src );
}
```

Call by Reference

```
rational a;
rational b;
a.d = 1; a.n = 2;
b = a;
increment (b, a);
std :: cout << b.n << "/" << b.d; // 2 / 2
```


User Defined Operators

Instead of

```
rational t = add(r, s);
```

we would rather like to write

```
rational t = r + s;
```

This can be done with *Operator Overloading*.

Overloading Functions

- Functions can be addressed by name in a scope
- It is even possible to declare and to defined several functions with the same name
- the "correct" version is chosen according to the *signature* of the function.

Function Overloading

- A function is defined by name, types, number and order of arguments

```
double sq (double x) { ... }          // f1
int sq (int x) { ... }                // f2
int pow (int b, int e) { ... }        // f3
int pow (int e) { return pow (2,e); } // f4
```

- the compiler automatically chooses the function that fits "best" for a function call (we do not go into details)

```
std::cout << sq (3);     // compiler chooses f2
std::cout << sq (1.414); // compiler chooses f1
std::cout << pow (2);    // compiler chooses f4
std::cout << pow (3,3);  // compiler chooses f3
```

Operator Overloading

- Operators are special functions and can be overloaded
- Name of the operator *op*:

```
operatorop
```

- we already know that, for example, `operator+` exists for different types

Adding `rational` Numbers – Before

```
// POST: return value is the sum of a and b
rational add (rational a, rational b)
{
    rational result;
    result.n = a.n * b.d + a.d * b.n;
    result.d = a.d * b.d;
    return result;
}
...
const rational t = add (r, s);
```


Adding `rational` Numbers – After

```
// POST: return value is the sum of a and b
rational operator+ (rational a, rational b)
{
    rational result;
    result.n = a.n * b.d + a.d * b.n;
    result.d = a.d * b.d;
    return result;
}
...
const rational t = r + s;
```

↑ infix notation

Other Binary Operators for Rational Numbers

```
// POST: return value is difference of a and b
rational operator− (rational a, rational b);

// POST: return value is the product of a and b
rational operator* (rational a, rational b);

// POST: return value is the quotient of a and b
// PRE: b != 0
rational operator/ (rational a, rational b);
```

Unary Minus

has the same symbol as the binary minus but only one argument:

```
// POST: return value is -a
rational operator- (rational a)
{
    a.n = -a.n;
    return a;
}
```


Comparison Operators

are not built in for structs, but can be defined

```
// POST: returns true iff a == b
bool operator== (rational a, rational b)
{
    return a.n * b.d == a.d * b.n;
}
```

$$\frac{2}{3} = \frac{4}{6} \quad \checkmark$$

Arithmetic Assignment

We want to write

```
rational r;
r.n = 1; r.d = 2;                  // 1/2

rational s;
s.n = 1; s.d = 3;                  // 1/3

r += s;
std::cout << r.n << "/" << r.d;    // 5/6
```


Operator+= First Trial

```
rational operator+= (rational a, rational b)
{
    a.n = a.n * b.d + a.d * b.n;
    a.d *= b.d;
    return a;
}
```

does not work. Why?

- The expression `r += s` has the desired value, but because the arguments are R-values (call by value!) it does not have the desired effect of modifying `r`.
- The result of `r += s` is, against the convention of C++ no L-value.

Operator +=

```
rational& operator+= (rational& a, rational b)
{
    a.n = a.n * b.d + a.d * b.n;
    a.d *= b.d;
    return a;
}
```

this works

- The L-value `a` is increased by the value of `b` and returned as L-value

`r += s;` now has the desired effect.

In/Output Operators

can also be overloaded.

- Before:

```
std::cout << "Sum is "
          << t.n << "/" << t.d << "\n";
```

- After (desired):

```
std::cout << "Sum is "
          << t << "\n";
```


In/Output Operators

can be overloaded as well:

```
// POST: r has been written to out
std::ostream& operator<< (std::ostream& out,
                          rational r)
{
    return out << r.n << "/" << r.d;
}
```

writes `r` to the output stream
and returns the stream as L-value.

Input

```
// PRE: in starts with a rational number
// of the form "n/d"
// POST: r has been read from in
std::istream& operator>> (std::istream& in,
                          rational& r)
{
    char c; // separating character '/'
    return in >> r.n >> c >> r.d;
}
```

reads `r` from the input stream
and returns the stream as L-value.

Goal Attained!

```
// input
std::cout << "Rational number r =? ";
rational r;
std::cin >> r;

std::cout << "Rational number s =? ";
rational s;
std::cin >> s;

// computation and output
std::cout << "Sum is " << r + s << ".\n";
```

operator >>

operator +

operator<<

Recall: Large Objects ...

```
struct SimulatedCPU {
    unsigned int pc;
    int stack[16];
    unsigned int stackPosition;
    unsigned int memory[65536];
};

void outputState (SimulatedCPU p) {
    std::cout << "pc=" << p.pc;
    std::cout << ", stack: ";
    for (unsigned int i = p.stackPosition; i != 0; --i)
        std::cout << p.stack[i-1];
}
```

call by value: more than 256k get copied!

... are Better Passed as Const-Reference

```
struct SimulatedCPU {
    unsigned int pc;
    int stack[16];
    unsigned int stackPosition;
    unsigned int memory[65536];
};

void outputState (const SimulatedCPU& p) {
    std::cout << "pc=" << p.pc;
    std::cout << ", stack: ";
    for (int i = p.stackPosition; i != 0; --i)
        std::cout << p.stack[i-1];
}
```

call by reference: only the address gets copied.

A new Type with Functionality. . .

```
struct rational {
    int n;
    int d; // INV: d != 0
};

// POST: return value is the sum of a and b
rational operator+ (rational a, rational b)
{
    rational result;
    result.n = a.n * b.d + a.d * b.n;
    result.d = a.d * b.d;
    return result;
}
...
```

…should be in a Library!

`rational.h:`

- Definition of a struct `rational`
- Function declarations

`rational.cpp:`

- arithmetic operators (`operator+`, `operator+=`, …)
- relational operators (`operator==`, `operator>`, …)
- in/output (`operator >>`, `operator <<`, …)

Thought Experiment

The three core missions of ETH:

- research
- education
- technology transfer

We found a startup: RAT PACK®!

- Selling the `rational` library to customers
- ongoing development according to customer's demands

The Customer is Happy

…and programs busily using `rational`.

- output as `double`-value $(\frac{3}{5} \rightarrow 0.6)$

```
// POST: double approximation of r
double to_double (rational r)
{
  double result = r.n;
  return result / r.d;
}
```


The Customer Wants More

"Can we have rational numbers with an extended value range?"

- Sure, no problem, e.g.:

```
struct rational {
  int n;
  int d;
};
```

$\Rightarrow$

```
struct rational {
  unsigned int n;
  unsigned int d;
  bool is_positive;
};
```

New Version of RAT PACK®

It sucks, nothing works any more!

- What is the problem?

$-\frac{3}{5}$ is sometimes 0.6, this cannot be true!

- That is your fault. Your conversion to `double` is the problem, our library is correct.

Up to now it worked, therefore the new version is to blame!

Liability Discussion

```
// POST: double approximation of r
double to_double (rational r){
  double result = r.n;
  return result / r.d;
}
```

`r.is_positive` and `result.is_positive` do not appear.

correct using...

```
struct rational {
  int n;
  int d;
};
```

... not correct using

```
struct rational {
  unsigned int n;
  unsigned int d;
  bool is_positive;
};
```


We are to Blame!!

- Customer sees and uses our representation of rational numbers (initially `r.n, r.d`)
- When we change it (`r.n, r.d, r.is_positive`), the customer's programs do not work anymore.
- No customer is willing to adapt the programs when the version of the library changes.

⇒ RAT PACK® is history...

Idea of Encapsulation (Information Hiding)

- A type is uniquely defined by its *value range* and its *functionality*
- The representation should not be visible.
- ⇒ The customer is not provided with representation but with functionality!

↑

`str.length(),`
`v.push_back(1),...`

Classes

- provide the concept for encapsulation in C++
- are a variant of structs
- are provided in many object oriented programming languages

Encapsulation: `public` / `private`

```
class rational {
  int n;
  int d; // INV: d != 0
};
```

is used instead of `struct` if anything at all shall be “hidden”

only difference

- `struct`: by default *nothing* is hidden
- `class` : by default *everything* is hidden