22. Subtyping, Inheritance and Polymorphism

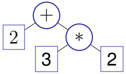
Expression Trees, Separation of Concerns and Modularisation, Type Hierarchies, Virtual Functions, Dynamic Binding, Code Reuse, Concepts of Object-Oriented Programming

Last Week: Expression Trees

- Goal: Represent arithmetic expressions, e.g.

  `2 + 3 * 2`

- Arithmetic expressions form a *tree structure*

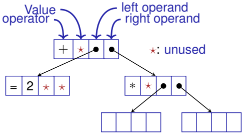


- Expression trees comprise *different* nodes: literals (e.g. 2), binary operators (e.g. $+$), unary operators (e.g. $\sqrt{\ }$), function applications (e.g. $\cos$), etc.

Disadvantages

Implemented via *a single* node type:

```
struct tnode {
  char op; // Operator ('=' for literals)
  double val; // Literal's value
  tnode* left; // Left child (or nullptr)
  tnode* right; // ...
  ...
};
```



Observation: **tnode** is the "sum" of all required nodes (constants, addition, . . .) ⇒ memory wastage, inelegant

Disadvantages

Observation: **tnode** is the "sum" of all required nodes – and every function must "dissect" this "sum", e.g.:

```
double eval(const tnode* n) {
  if (n->op == '=') return n->val; // n is a constant
  double l = 0;
  if (n->left) l = eval(n->left); // n is not a unary operator
  double r = eval(n->right);
  switch(n->op) {
    case '+': return l+r; // n is an addition node
    case '*': return l*r; // ...
    ...
```

⇒ Complex, and therefore error-prone

Disadvantages

```
struct tnode {
  char op;
  double val;
  tnode* left;
  tnode* right;
  ...
};
```

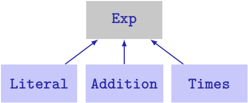
```
double eval(const tnode* n) {
  if (n->op == '=') return n->val;
  double l = 0;
  if (n->left) l = eval(n->left);
  double r = eval(n->right);
  switch(n->op) {
    case '+': return l+r;
    case '*': return l*r;
    ...
```

This code isn't *modular* – we'll change that today!

New Concepts Today

1. Subtyping

- Type hierarchy: `Exp` represents general expressions, `Literal` etc. are concrete expression
- Every `Literal` etc. also is an `Exp` (subtype relation)



- That's why a `Literal` etc. can be used everywhere, where an `Exp` is expected:

```
Exp* e = new Literal(132);
```


New Concepts Today

2. Polymorphism and Dynamic Dispatch

- A variable of *static* type `Exp` can "host" expressions of different *dynamic* types:

```
Exp* e = new Literal(2); // e is the literal 2
e = new Addition(e, e); // e is the addition 2 + 2
```

- Executed are the member functions of the *dynamic* type:

```
Exp* e = new Literal(2);
std::cout << e->eval(); // 2

e = new Addition(e, e);
std::cout << e->eval(); // 4
```

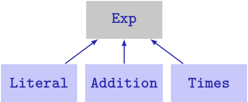

New Concepts Today

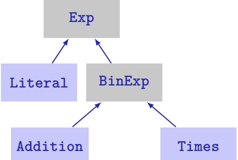
3. Inheritance

- Certain functionality is shared among type hierarchy members
- E.g. computing the size (nesting depth) of binary expressions (`Addition`, `Times`):

  $1 + size(left\ operand) + size(right\ operand)$

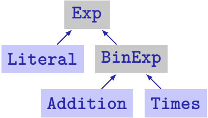
⇒ Implement functionality once, and let subtypes *inherit* it





Advantages

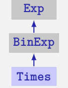
- Subtyping, inheritance and dynamic binding enable *modularisation through spezialisation*
- Inheritance enables sharing common code across modules
  $\Rightarrow$ *avoid code duplication*




```
Exp* e = new Literal(2);
std::cout << e->eval();

e = new Addition(e, e);
std::cout << e->eval();
```


Syntax and Terminology

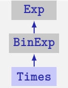
```
struct Exp {
  ...
}

struct BinExp : public Exp {
  ...
}

struct Times : public BinExp {
  ...
}
```



Note: Today, we focus on the new concepts (subtyping, ...) and ignore the orthogonal aspect of encapsulation (`class`, `private` vs. `public` member variables)

Syntax and Terminology

```
struct Exp {
  ...
}

struct BinExp : public Exp {
  ...
}

struct Times : public BinExp {
  ...
}
```



- `BinExp` is a *subclass*[1] of `Exp`
- `Exp` is the *superclass*[2] of `BinExp`
- `BinExp` *inherits* from `Exp`
- `BinExp` *publicly* inherits from `Exp` (`public`), that's why `BinExp` is a *subtype* of `Exp`
- Analogously: `Times` and `BinExp`
- Subtype relation is transitive: `Times` is also a subtype of `Exp`

[1] derived class, child class [2] base class, parent class

Abstract Class `Exp` and Concrete Class `Literal`

```
struct Exp {
  virtual int size() const = 0;
  virtual double eval() const = 0;
};
```

... that makes `Exp` an *abstract* class

Activates dynamic dispatch

Enforces implementation by derived classes ...

```
struct Literal : public Exp {
  double val;

  Literal(double v);
  int size() const;
  double eval() const;
};
```

`Literal` inherits from `Exp` ...

... but is otherwise just a regular class

`Literal`: Implementation

```
Literal::Literal(double v): val(v) {}
```

```
int Literal::size() const {
  return 1;
}
```

```
double Literal::eval() const {
  return this->val;
}
```


Subtyping: A Literal is an Expression . . .

A pointer to a subtype can be used everywhere, where a pointer to a supertype is required:

```
Literal* lit = new Literal(5);
Exp* e = lit; // OK: Literal is a subtype of Exp
```

But not vice versa:

```
Exp* e = ...
Literal* lit = e; // ERROR: Exp is not a subtype of Literal
```


Polymorphie: . . . a Literal Behaves Like a Literal

```
struct Exp {
  ...
  virtual double eval();
};

double Literal::eval() {
  return this->val;
}
```

```
Exp* e = new Literal(3);
std::cout << e->eval(); // 3
```

- *virtual* member function: the *dynamic* (here: `Literal`) type determines the member function to be executed
  ⇒ *dynamic binding*
- Without `Virtual` the *static type* (hier: `Exp`) determines which function is executed
- We won't go into further details

Further Expressions: `Addition` and `Times`

```
struct Addition : public Exp {
  Exp* left; // left operand
  Exp* right; // right operand
  ...
};
```

```
int Addition::size() const {
  return 1 + left->size()
           + right->size();
}
```

```
struct Times : public Exp {
  Exp* left; // left operand
  Exp* right; // right operand
  ...
};
```

```
int Times::size() const {
  return 1 + left->size()
           + right->size();
}
```

😃 Separation of concerns

🤬 Code duplication

Extracting Commonalities . . . : BinExp

```
struct BinExp : public Exp {
  Exp∗ left;
  Exp∗ right;

  BinExp(Exp∗ l, Exp∗ r);
  int size() const;
};
```

```
BinExp::BinExp(Exp∗ l, Exp∗ r): left(l), right(r) {}
```

```
int BinExp::size() const {
  return 1 + this−>left−>size() + this−>right−>size();
}
```

Note: `BinExp` does not implement `eval` and is therefore also an abstract class, just like `Exp`

. . . Inheriting Commonalities: Addition

```
struct Addition : public BinExp {
  Addition(Exp∗ l, Exp∗ r);
  double eval() const;
};
```

`Addition` inherits member variables (`left`, `right`) and functions (`size`) from `BinExp`

```
Addition::Addition(Exp∗ l, Exp∗ r): BinExp(l, r) {}
```

Calling the *super constructor* (constructor of `BinExp`) initialises the member variables `left` and `right`

```
double Addition::eval() const {
  return
    this−>left−>eval() +
    this−>right−>eval();
}
```


. . . Inheriting Commonalities: Times

```
struct Times : public BinExp {
  Times(Exp∗ l, Exp∗ r);
  double eval() const;
};
```

```
Times::Times(Exp∗ l, Exp∗ r): BinExp(l, r) {}
```

```
double Times::eval() const {
  return
    this−>left−>eval() ∗
    this−>right−>eval();
}
```

Observation: `Additon::eval()` and `Times::eval()` are very similar and could also be unified. However, this would require the concept of *functional programming*, which is outside the scope of this course.

Further Expressions and Operations

- Further expressions, as classes derived from `Exp`, are possible, e.g. $-$, $/$, $\sqrt{\,}$, $\cos$, $\log$
- A former bonus exercise (included in today's lecture examples on Code Expert) illustrates possibilities: variables, trigonometric functions, parsing, pretty-printing, numeric simplifications, symbolic derivations, . . .

Mission: Monolithic → Modular ✓

```
struct tnode {
  char op;
  double val;
  tnode* left;
  tnode* right;
  ...
}

double eval(const tnode* n) {
  if (n->op == '=') return n->val;
  double l = 0;
  if (n->left != 0) l = eval(n->left);
  double r = eval(n->right);
  switch(n->op) {
    case '+': return l + r;
    case '*': return l - r;
    case '-': return l - r;
    case '/': return l / r;
    default:
      // unknown operator
      assert (false);
  }
}

int size (const tnode* n) const { ... }

...
```

```
struct Literal : public Exp {
  double val;
  ...
  double eval() const {
    return val;
  }
};

struct Addition : public Exp {
  ...
  double eval() const {
    return left->eval() + right->eval();
  }
};

struct Times : public Exp {
  ...
  double eval() const {
    return left->eval() * right->eval();
  }
}
```

\+

```
struct Cos : public Exp {
  ...
  double eval() const {
    return std::cos(argument->eval());
  }
}
```


And there is so much more ...

Not shown/discussed:

- Private inheritance (`class B : ~~public~~ A`)
- Subtyping and polymorphism without pointers
- Non-virtuell member functions and static dispatch (`~~virtual~~ double eval()`)
- Overriding inherited member functions and invoking overridden implementations
- Multiple inheritance
- ...

Object-Oriented Programming

In the last 3rd of the course, several concepts of *object-oriented programming* were introduced, that are briefly summarised on the upcoming slides.

Encapsulation (weeks 10-13):

- Hide the implementation details of types (private section) from users
- Definition of an interface (public area) for accessing values and functionality in a controlled way
- Enables ensuring invariants, and the modification of implementations without affecting user code

Object-Oriented Programming

Subtyping (week 14):

- Type hierarchies, with super- and subtypes, can be created to model relationships between more abstract and more specialised entities
- A subtype supports at least the functionality that its supertype supports – typically more, though, i.e. a subtype extends the interface (public section) of its supertype
- That's why supertypes can be used anywhere, where subtypes are required ...
- ... and functions that can operate on more abstract type (supertypes) can also operate on more specialised types (subtypes)
- The streams introduced in week 7 form such a type hierarchy: `ostream` is the abstract supertyp, `ofstream` etc. are specialised subtypes

Polymorphism and *dynamic binding* (week 14):

- A pointer of static typ T_1 can, at runtime, point to objects of (dynamic) type T_2, if T_2 is a subtype of T_1
- When a virtual member function is invoked from such a pointer, the dynamic type determines which function is invoked
- I.e.: despite having the same static type, a different behaviour can be observed when accessing the common interface (member functions) of such pointers
- In combination with subtyping, this enables adding further concrete types (streams, expressions, . . .) to an existing system, without having to modify the latter

Inheritance (week 14):

- Derived classes inherit the functionality, i.e. the implementation of member functions, of their parent classes
- This enables sharing common code and thereby avoids code duplication
- An inherited implementation can be overridden, which allows derived classes to behave differently than their parent classes (not shown in this course)

— End of the Course —