OOP (C++): OO Modeling & Design

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Object Oriented Programming 2020/2021

Plan

A Kind of Definition

A model is an abstraction of the software system to be developed that makes the implementation (programming) of the system easier.

A model has three main characteristics (Herbert Stachowiak, 1973):

- *Mapping*: a model is always an image (mapping) of something.
- *Reduction*: a model does not capture all attributes of the original.
- *Pragmatism*: a model should be useful.

Quality of a Model

It is determined by the following characteristics (Bran Selic, 2003):

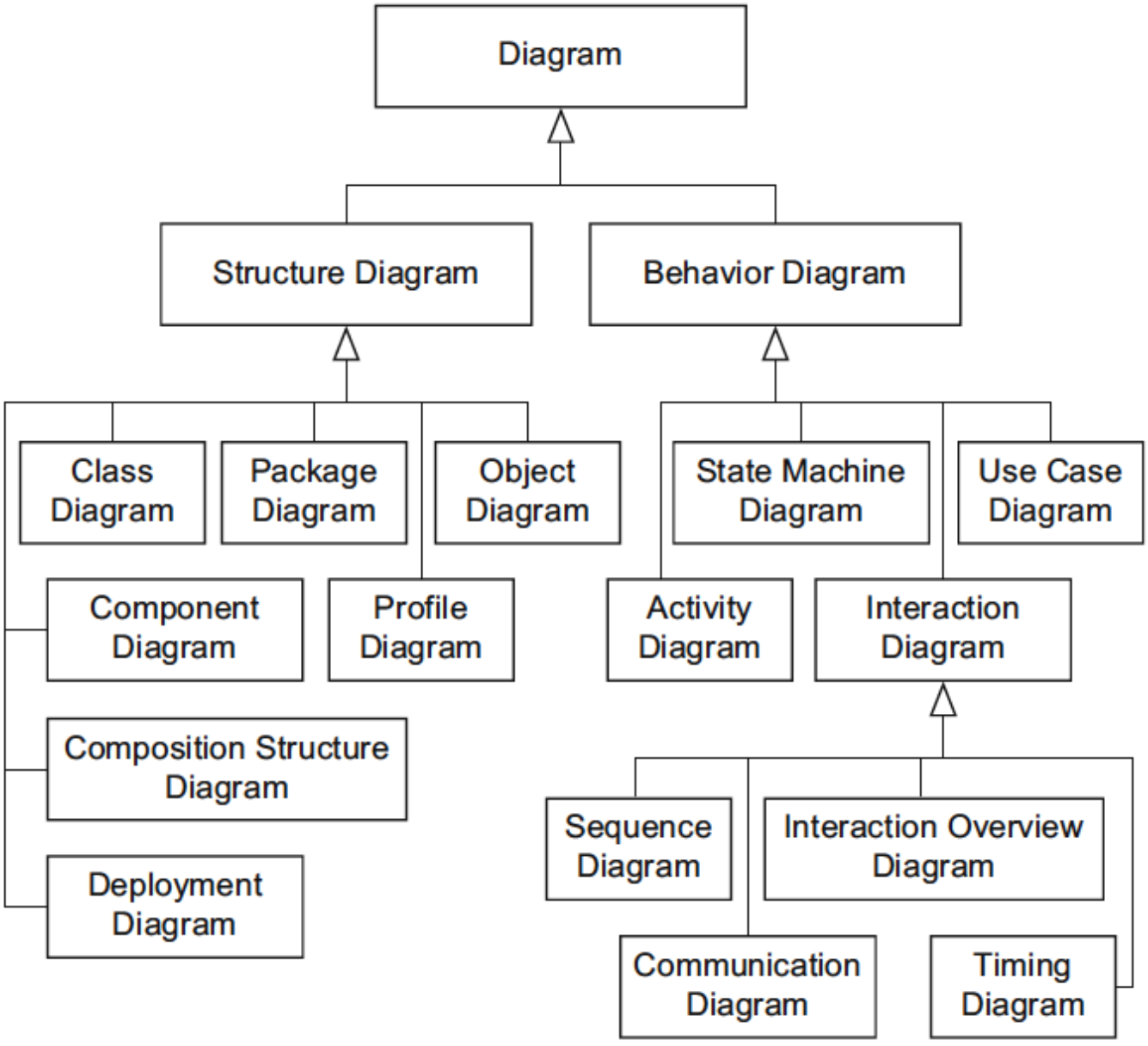
- Abstraction
- Understandability
- Accuracy
- Predictiveness
- Cost-effectiveness

UML

- To write a model, you need a modeling language.
- UML (Unified Modeling Language) is a language and modeling technique suitable for object-oriented programming UML is used to view, specify, build, and document object-oriented systems
- In this course we will use UML elements to explain the concepts and laws of OOP.
- Free soft tools: BOUML, Argouml (open source), Visual Paradigm UML (Online Express Edition),...

Plan

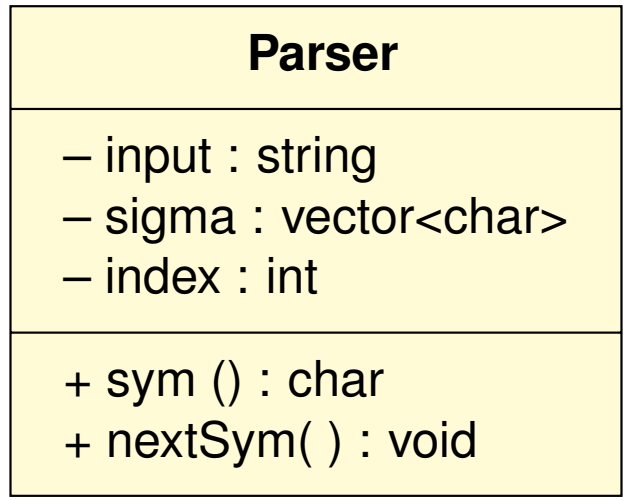
UML Diagrams



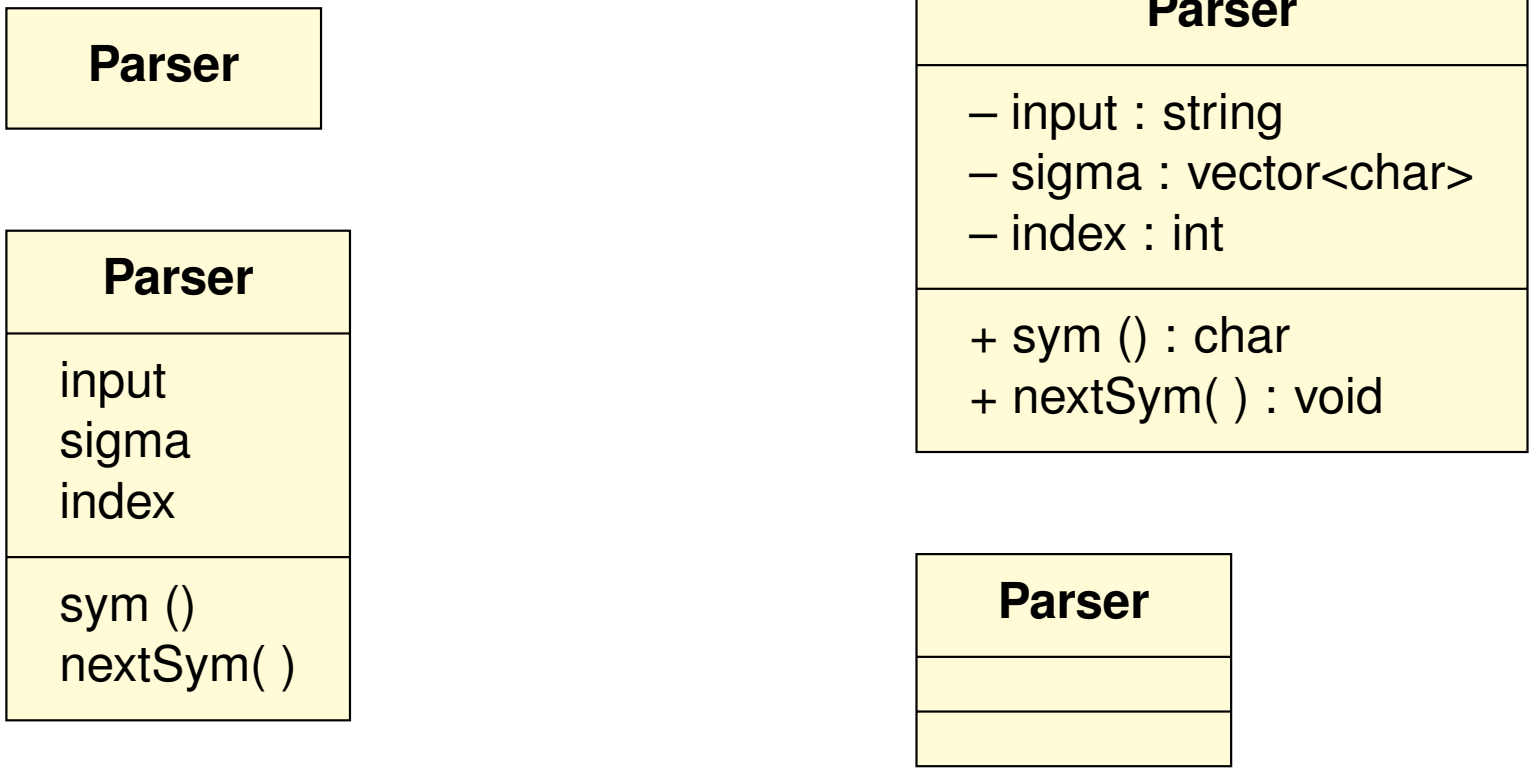
Plan

Specification of a Class in UML

```
class Parser {
 private:
   string input;
   vector<char> sigma;
   int index;
 public:
   char sym();
   void nextSym();
   ...
};
```

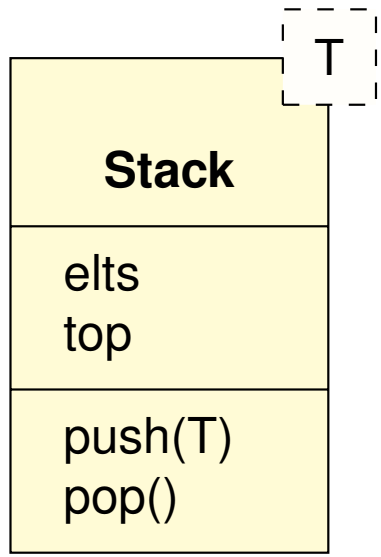


Notation


Parser
Parser
input
sigma
index
sym ()
nextSym( )
Parser
– input : string
– sigma : vector<char>
– index : int
+ sym () : char
+ nextSym( ) : void
Parser

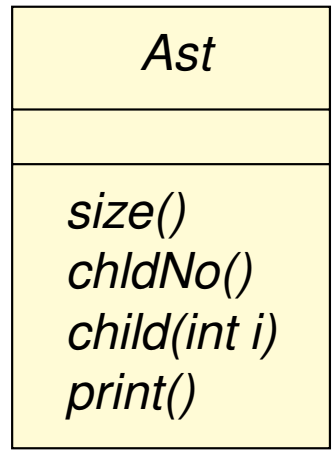
Parametrized Class

```
template<class T>
class Stack {
 private:
  T* elts;
  int top;
 public:
  void push(T);
  void pop();
  ...
};
```



Abstract Class

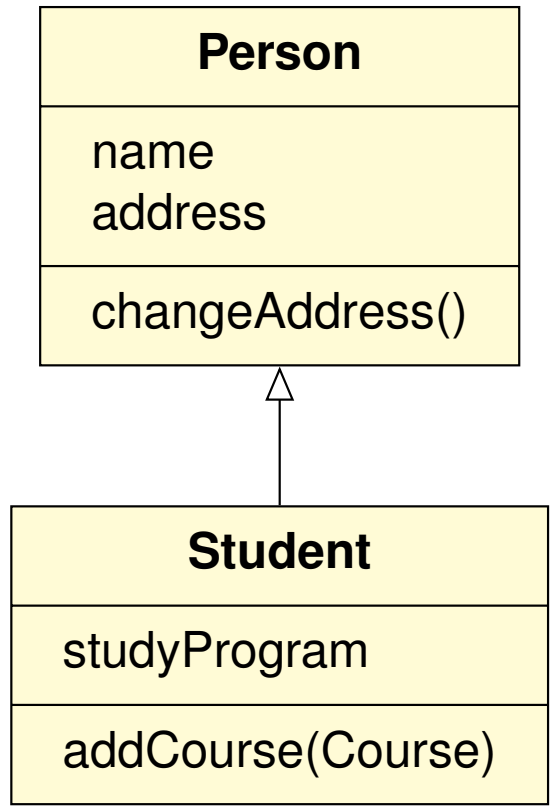
```
class Ast {
 public:
  virtual int size() = 0;
  virtual int chldNo() = 0;
  virtual Ast* child(int i) = 0;
  virtual void print() = 0;
};
```



Note the use of the italic font.

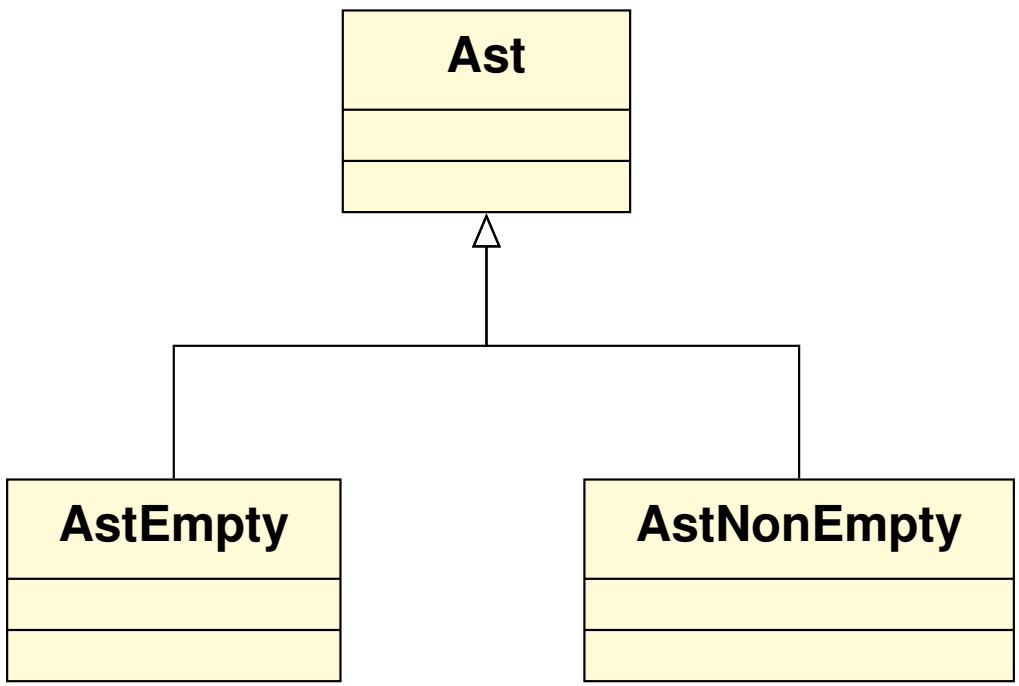
Generalization: Inheritance

```
class Person {
  string name;
  string address;
 public:
  void changeAddress();
};
class Student : public Person {
  list<Course> studyProgram;
 public:
  void addCourse(Course);
};
```



Generalization: Classification

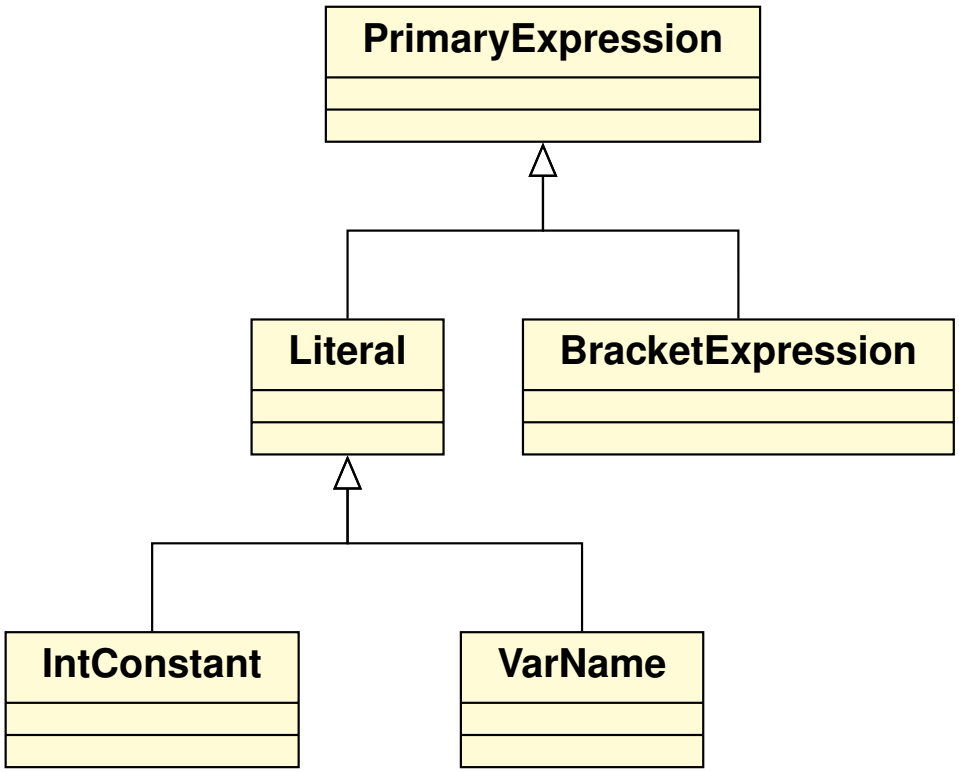
```
class AstEmpty : public Ast {
   ...
};
class AstNonEmpty : public Ast {
   ...
};
```



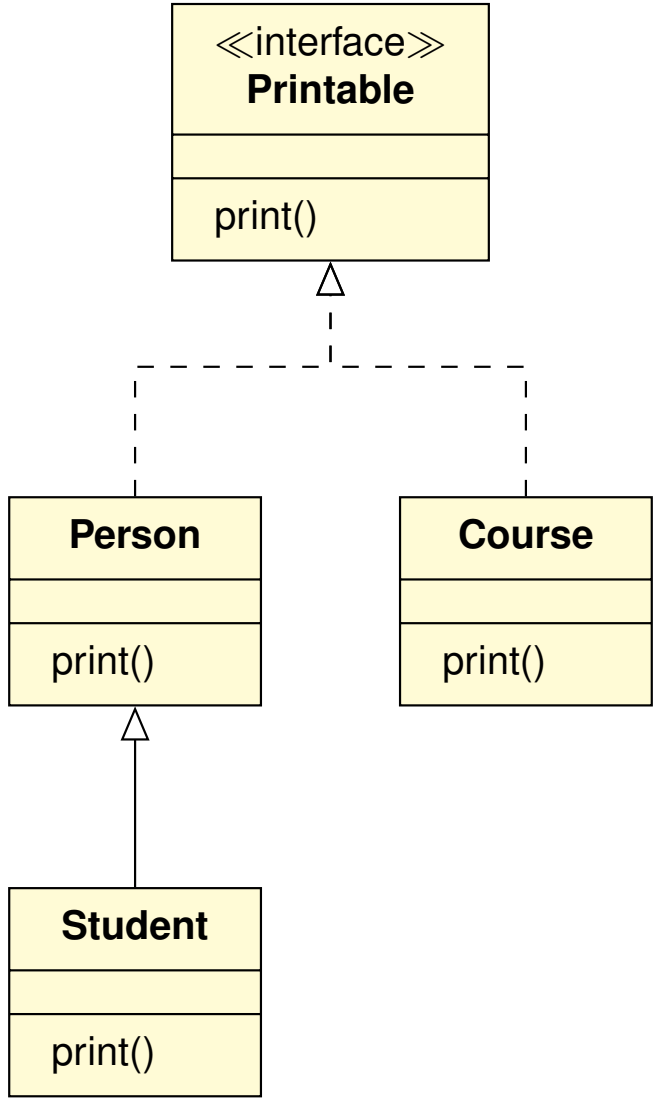
Classification: A Simple Case Study

Frm C++ Grammar (simplified)

```
literal:
        int-constant
        var-name

primary-expression:
        literal
        ( expression )
```



Interface


≪interface≫
Printable
print()
Person
print()
Course
print()
Student
print()

Interfaces in C++

Are described using abstract classes:

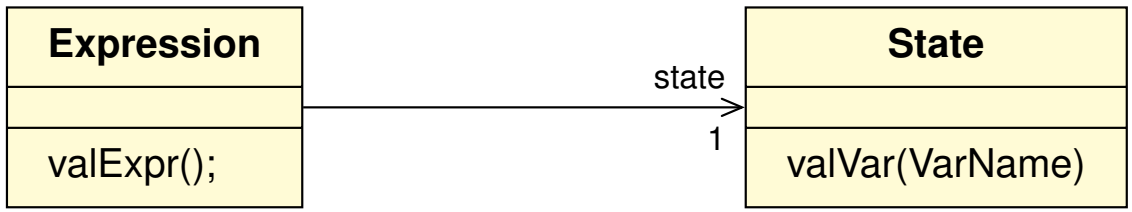
```
class Printable {
 public: virtual void print() = 0;
};

class Person : public Printable {
 public: virtual void print();
}
...
void Person::print() {
  ...
}
```

Bidirectional Binary Associations


```
class Professor {
 private: list<Course*> courses;
   ...
}
class Course {
  private: Profesor* lecturers[2];
   ..
}
```

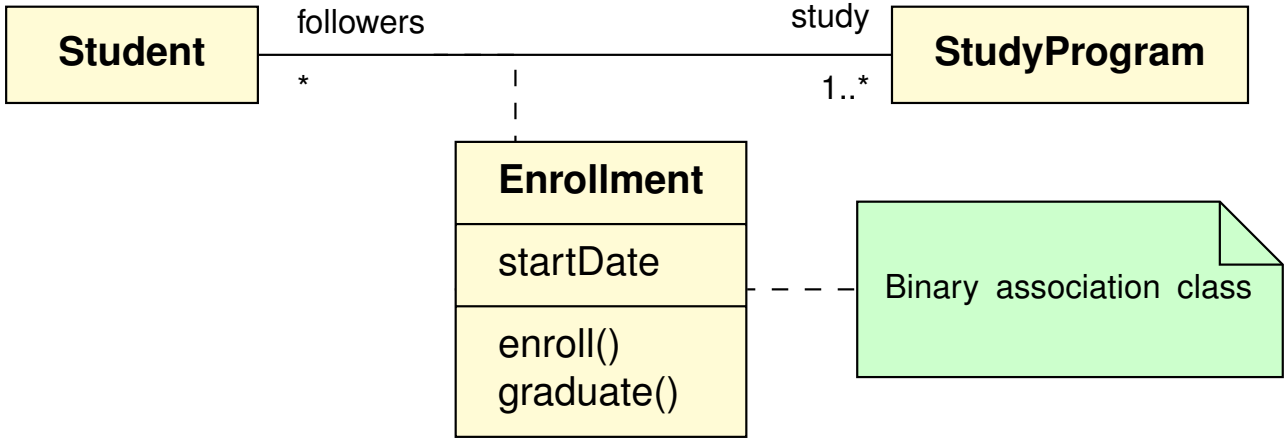
Unidirectional Binary Associations

– an expression is evaluated in a state (the expression knows the state it is evaluated)
– the state does not know for which expression it is used for evaluation



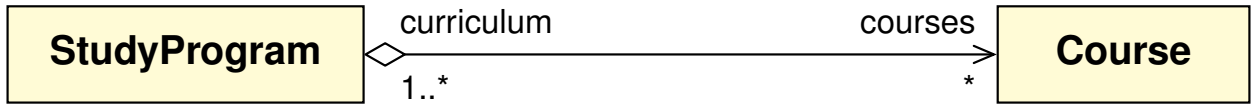

```
class Expression {
 private:  State* state;
 public: int valExpr(); // uses state->valVar()
   ...
}
class State {
  public : int valVar(VarName vn);
     // returns the value of the variable vn
   ...
}
```

Association Class




```
class Enrollment {
  // class invariant: study != empty
 private:
  list<Student*>  followers;
  list<StudyProgram*> study;
  Date statDate;
public:
  void enroll(Student, StudyProgram);
  void graduate(Student, StudyProgram);
  ...
};
```

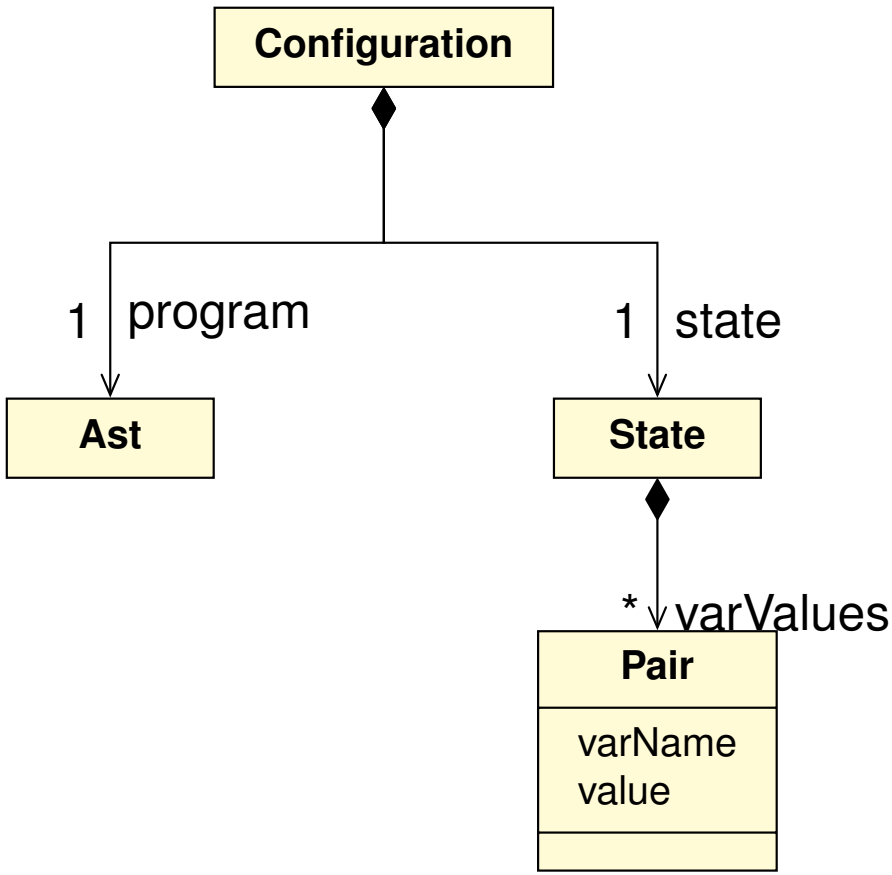
Shared Agregation




```
class StudyProgram {
 private: vector<Course*> courses;
  ...
};
class Course {
  // class invariant: includedIn != empty
 private: list<StudyProgram*> curriculum;
  ...
};
```

Strong Agregation (Composition)

configuration $= \langle$ program, state $\rangle$
state $=$ var1 $\mapsto$ *val*1, var2 $\mapsto$ *val*2, ...




```
class Configuration {
 private:
  Ast program;
  State state;
  ...
};
class State {
 private:
  map<VarName, Value> varValues;
 ...
};
```

Plan

Plan

Definition

Single-Responsibility Principle

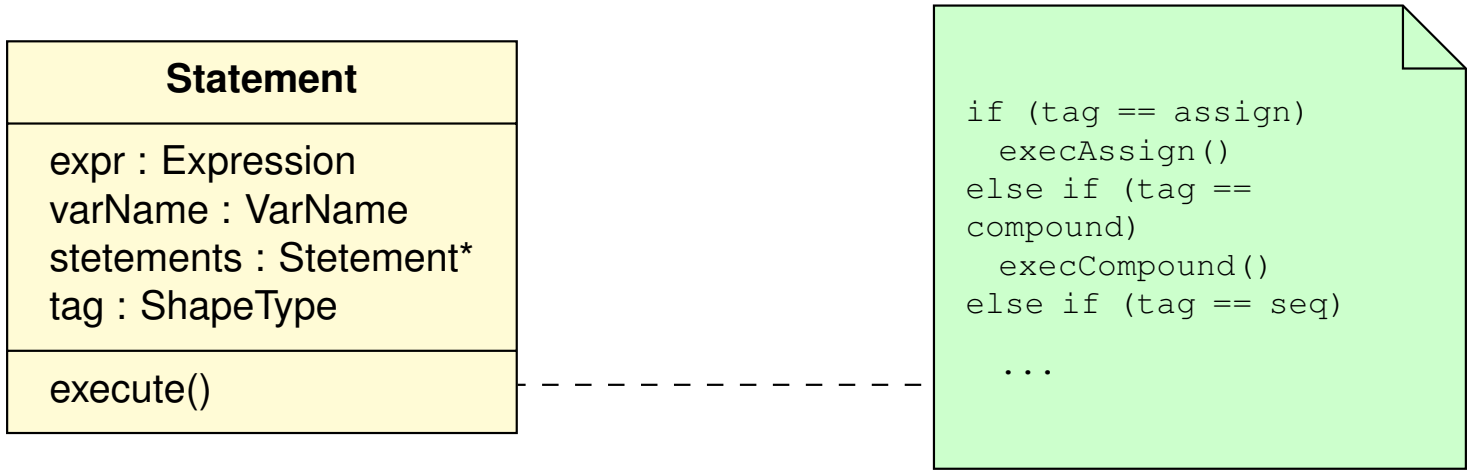
A class should have one and only one reason to change, meaning that a class should have only one job.

Robert C. Martin. Principles of Object Oriented Design.
`https://drive.google.com/file/d/0ByOwmqah_nuGNHEtcU5OekdDMkk/view`

From C++ grammar (modified)

```
statement:
        var-name = expression ;   //asignement
        { statement }             // compound statetement
        (statement)*              //sequential composition
        if ( expression ) statement    // if
        if ( expression ) statement else statement   //if
        ...
```

~~SRP~~ 2/2



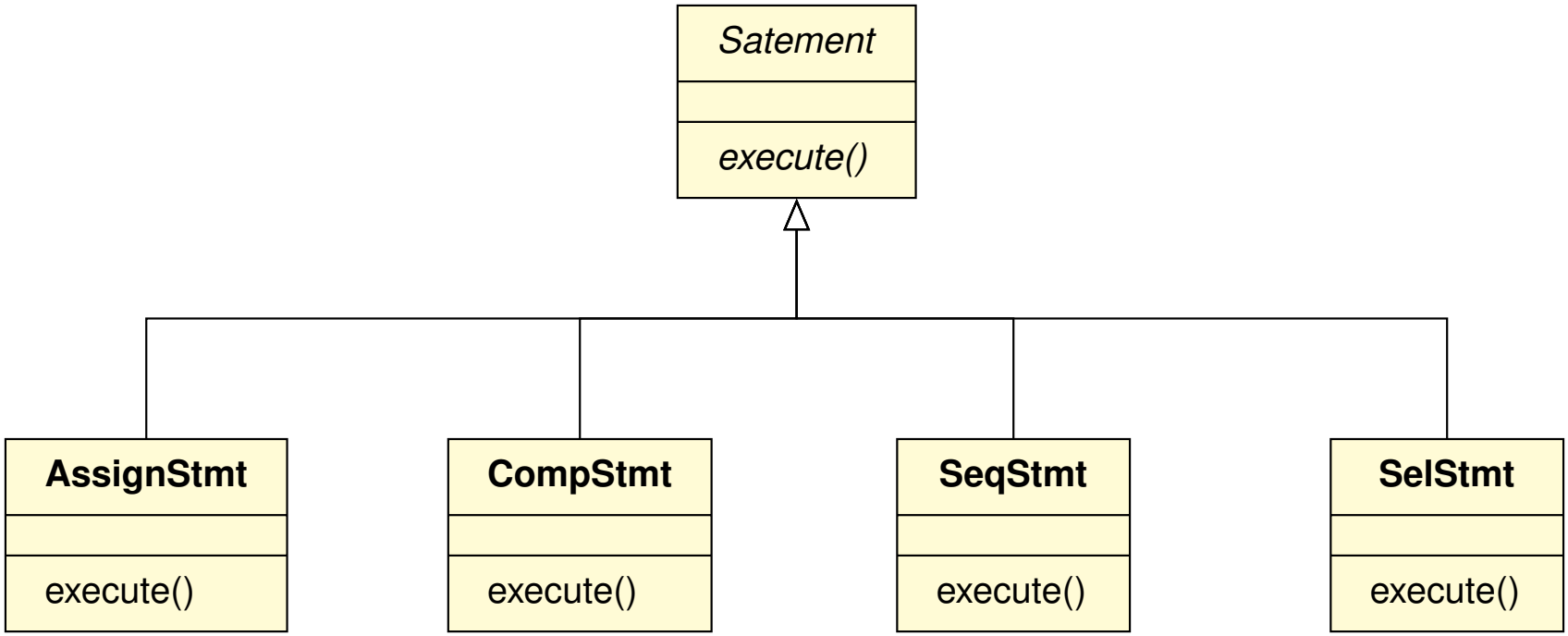
Too many responsibilities.

SRP 1/2

From C++ grammar (simplified)

```
statement:
        assign-statement
        compound-statement
        statement-seq
        selection-statement

assign-statement:
        var-name = expression ;

compound-statement:
        { statement }
statement-seq:
        statement
        statement-seq statement

selection-statement:
        if ( condition ) statement
        if ( condition ) statement else statement
```

SRP 2/2


Satement
execute()
AssignStmt
execute()
CompStmt
execute()
SeqStmt
execute()
SelStmt
execute()

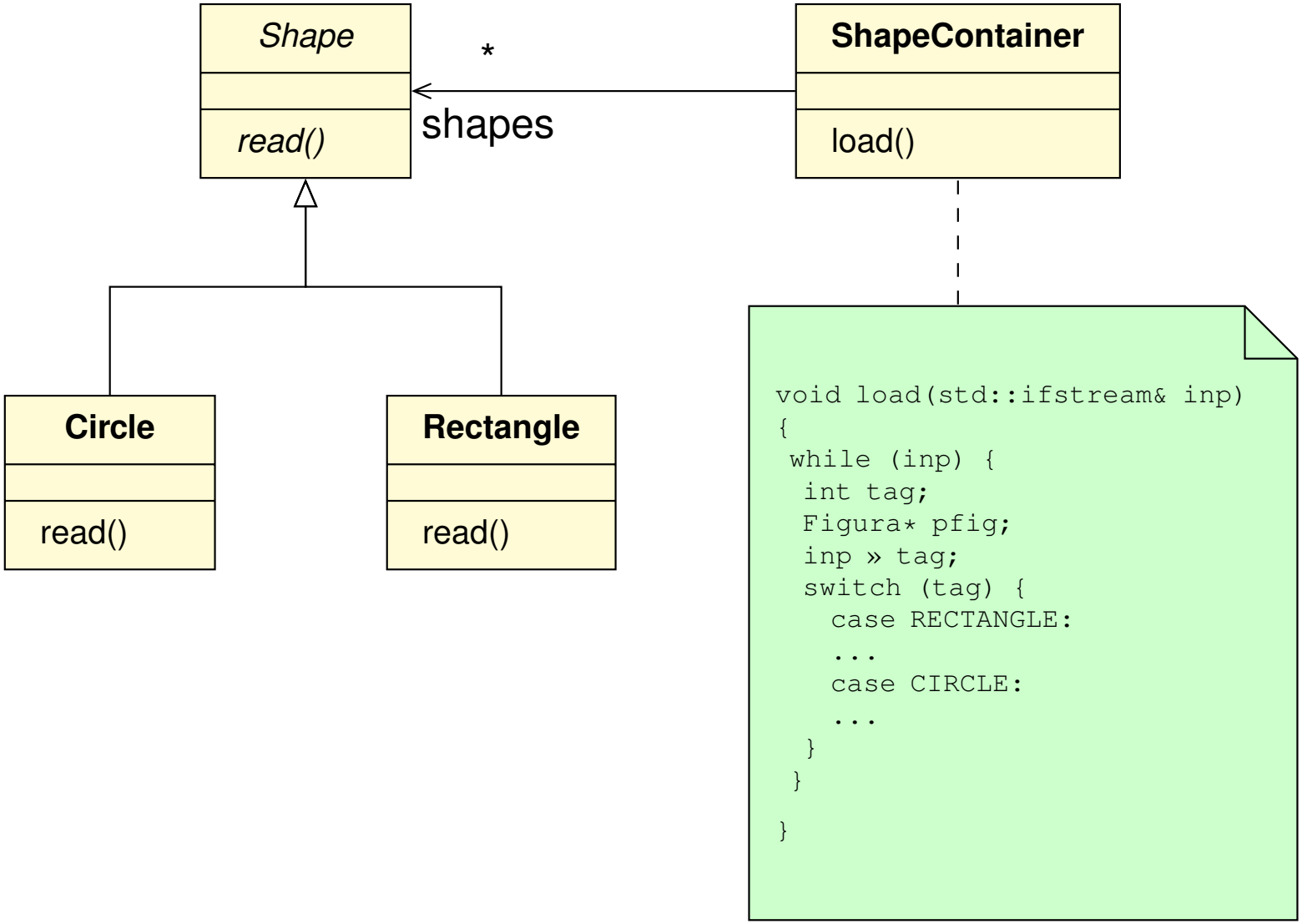
Plan

Definition

Open-Closed Principle

Software entities (classes, modules, functions, etc.) should be open for extension, but closed for modification.

Robert C. Martin. Principles of Object Oriented Design.
https://drive.google.com/file/d/
0BwhCYaYDn8EgN2M5MTkwM2EtNWFkZC00ZTI3LWFjZTUtNTFhZGZiYmUzODc1/view



If we add more shapes, we have to modify `ShapeContainer::load()`.

OCP

The previous example can be fixed to respect OCP using Object Factory Pattern (next lecture).

Plan

Definition

Liskov[1] Substitution Principle

Let $P(x)$ be a property provable about objects x of type T. Then $P(y)$ should be true for objects y of type S, where S is a subtype of T.

In other words, S is a subtype of T if anywhere you can use a T, you could also use an S (a T can be substituted by an S).

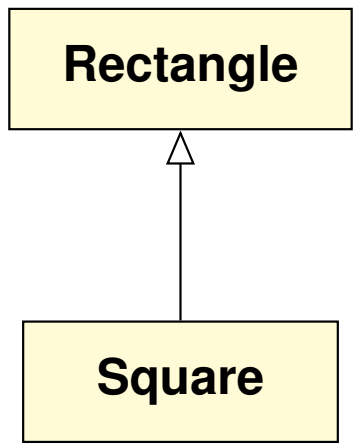
NB Here the notion of "subtype" should be meant as "behavioural subtype" (we will explain later the difference).

Barbara Liskov, Jeannette M. Wing: A Behavioral Notion of Subtyping. ACM Trans. Program. Lang. Syst. 16(6): 1811-1841 (1994)

[1] Turing Award, 2008, for contributions to programming languages development, especially OO languages.

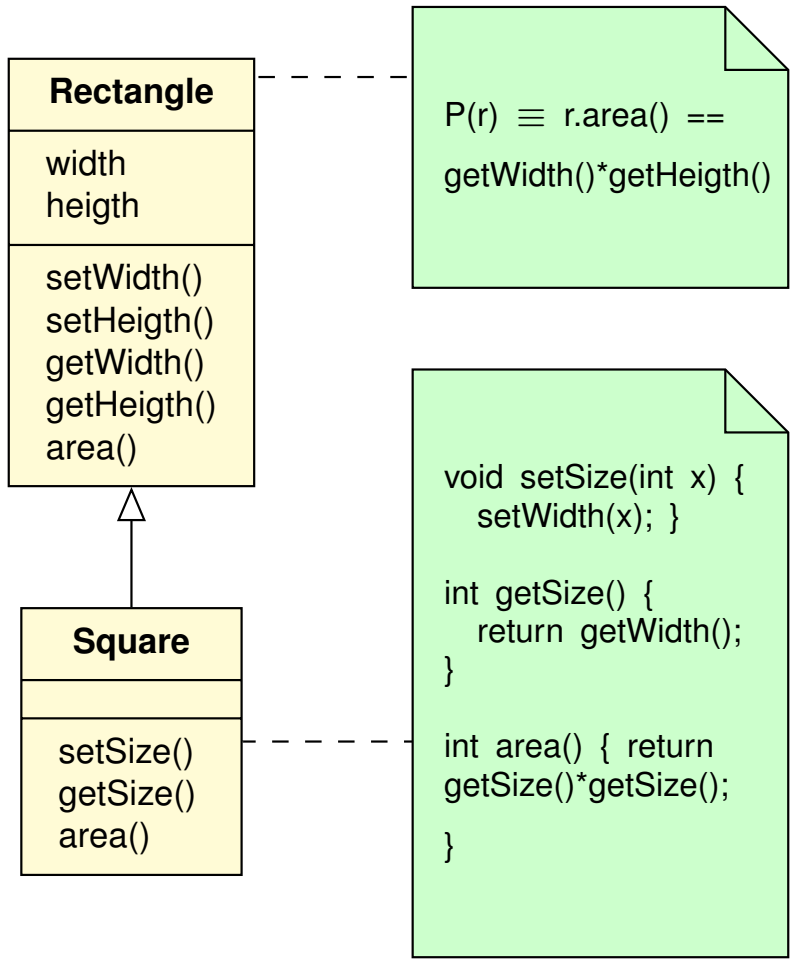
A Counter-Example 1/4

A rushed modeling of the relation "Any square is a rectangle" (this is an instance of the "is a" relation):



A Counter-Example 2/4

Let's refine it:



A Counter-Example 3/4

Consider the code:

```
Square s;
s.setWidth(5);        // inherited
s.setHeight(10);      // inherited
```

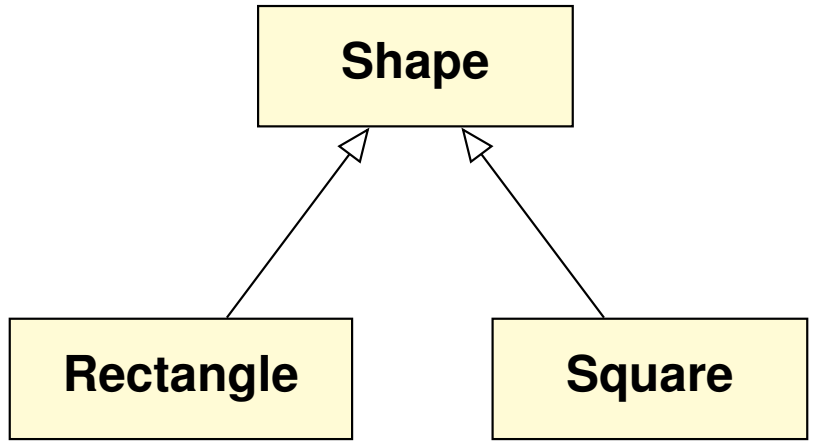
Assume that `s` plays the role of a `Rectangle`.
Does it satisfy the property P(`s`)? No.

Question

What is the right relationship between "subclass" and "subtype"?

A Counter-Example 4/4

A correct hierarchy:



Question

It seems that the subclass relation, given by

(child-class, partent-class)

is not the same with that of subtype.

So,
What is the right relationship between "subclass" and "subtype"?

Types, Types, Types, . . . 1/3

From (online) manuals[2] (partial):
Objects, references, functions including function template specializations, and expressions have a property called type, which both restricts the operations that are permitted for those entities and provides semantic meaning to the otherwise generic sequences of bits.

Type classification
The C++ type system consists of the following types:

- fundamental types
  - void
  - signed integer types int, long int, . . .
  - floating-point types float, double,. . .
  - . . .
- compound type
  - reference type
  - pointer type
  - array types
  - function types
  - class types
  - . . .

[2] https://en.cppreference.com/w/cpp/language/type

Types, Types, Types, . . . 2/3

So, a class is a type?

No, not completely true.

A class includes two orthogonal things:

- static/behavioral type
- implementation

Types, Types, Types, . . . 3/3

Static types (abstract view):

Declaration of X	Type associated to X	Remark
`int X;`	`int`	

`struct X {`
`  int a;`
`  double b;`
`}`
	`int` × `double`	product type

`int X(double a);`	`double` → `int`	function type

`class X {`
`  int size;`
`public:`
`  int getSize();`
`  void setSize(int a);`
`}`
	`void` → `X`
	`X` → `int`
	`X` × `int` → `X`
		constructor `X()`
		`getSize`
		`setSize`

For classes, only the types of the public members (interface) are considered.

Static Subtype 1/2

A type T consists of:

- a set of possible values which a variable/expression can possess during program execution
- a set of operations/functions that can apply values

S is a subtype of T, $S <: T$ if:

- S values "are" T values
- the operations/functions applied to T can also be applied to S preserving semantics

Static Subtype 2/2

Examples: `int` <: `long int`

We do not have `int` <: `float` because _/_ on `int` has a different semantics from that of `float`.

For classes definition becomes more complex.

On Contravariance/Covariance/Invariance

Within a type system, the variance refers how the subtype relation is promoted to compound types.

- a rule is covariant if preserves the ordering of types $<:$
- a rule is contravariant if it reverses this ordering $<:$
- a rule is invariant if it is not neither covariant nor cotravariant

E.g., the rule for function types is contravariant on arguments and covariant on result:

$$\frac{A' <: A \quad B <: B'}{(A \to B) <: (A' \to B')}$$

Contravariance/Covariance/Invariance in C++

C++ for overridden functions is invariant on parameters type and covariant on result type.

From the manual:

The return type of an overriding function shall be either identical to the return type of the overridden function or covariant with the classes of the functions. If a function D::f overrides a function B::f, the return types of the functions are covariant if they satisfy the following criteria:

(8.1) — both are pointers to classes, both are lvalue references to classes, or both are rvalue references to classes

(8.2) — the class in the return type of B::f is the same class as the class in the return type of D::f, or is an unambiguous and accessible direct or indirect base class of the class in the return type of D::f

(8.3) — both pointers or references have the same cv-qualification and the class type in the return type of D::f has the same cv-qualification as or less cv-qualification than the class type in the return type of B::f.

C++: Return Covariant Example 1

Not really:

```
class Base
{
public:
    Base() = default;
    virtual Base* clone() const { return new Base; }
    virtual ~Base(){ std::cout << "~Base()\n"; }
};

class Derived : public Base
{
public:
    Derived () = default;
    Derived* clone() const override { return new Derived; }
    ~Derived() override { std::cout << "~Derived()\n"; }
};
```

C++: Return Covariant Example 2

```
class Animal {
public:
    virtual void makeNoise() = 0;
    virtual ~Animal() =  default;
};

class Dog : public Animal {
public:
    void makeNoise() override { std::cout << "ham!\n"; }
};

class AnimalBreeder {
public:
    virtual Animal* produce() = 0;
};

class DogBreeder : public AnimalBreeder {
public:
     Dog* produce() override { return new Dog(); }
};
```

C++: Argument Contravariant (Contra)Example

```
class Animal {
public:
    virtual void makeNoise() = 0;
    virtual ~Animal() =  default;
};

class Dog : public Animal {
public:
    void makeNoise() override { std::cout << "ham!\n"; }
};

class DogDoctor  {
public:
    virtual void treat(Dog *dog) { std::cout << "Dog treated!\n"; }
};

class AnimalDoctor : public DogDoctor {
public:
    void treat(Animal * animal) override { std::cout << "Animal treated!\n"; }  // error
};
```

Remember that C++ is invariant on arguments.

Behavioral Type of a Class 1/3

Consider the following simple example:

```
class Square {
  int size;
 public:
  Square(int s = 0);
  int getSize();
  int area() throw(overflow_error);
  void halve();
}
```

Behavioral Type of a Class 2/3

Includes also the behavioral interface of the objects and consists of:

- a description of the value space
  - class invariants
    Example: `getSize()` ≥ 0
  - for each constructor *c*
    - its signature
      Example: `Square` : `int` $\rightarrow$ `Square`
    - precondition
      Example: `s` $\geq$ `0`
    - postcondition
      Example: `getSize()` ≥ 0
    - the exceptions it signals

Behavioral Type of a Class 3/3

- for each public method *m*:
  - its signature
    Example: `area` : `Square` $\rightarrow$ `int`
    `halve` : `Square` $\rightarrow$ `Square`
  - precondition
    Example: `even(getSize())` (for `halve`)
  - postcondition
    Example: `area()` $==$ `0.25` $*$ `old(area())` (for `halve`)
  - the exceptions it signals
- for each public attribute *a*:
  - its type

A Possible Specification for the Behavioral Type

```
type Square {
   invariant getSize() >= 0
   Square(int s = 0)
     requires s >= 0
     ensures true
     noexcept(true);
   int getSize()
     requires true
     ensures true
     noexcept(true);
  int area()
     requires true
     ensures result == getSize()*getSize()
     throw(overflow_error)
  void halve();
     requires even(getSize())
     ensures area() == 0.25*old(area())
     noexcept(true);
}
```

The Substitution Principle Explained using Behavioral Types 1/2

A child class (subclass) B is a behavioral subtype of the parent class (superclass) A, $B <: A$, if:

- the invariants of the superclass are preserved by the subclass (B values are A values): the conjunction of the B invariants implies conjunction of the A invariants, i.e.,

$$\bigwedge_{\phi \in Inv(B)} \phi \implies \bigwedge_{\phi \in Inv(A)} \phi$$

- for each overridden method m
  - $B::m()$ and $A::m()$ have the same number of arguments
  - contravariance of arguments: if the i-th argument of $B::m()$ is β_i and the i-th argument of $A::m()$ is α_i, then $\alpha_i <: \beta_i$
  - covariance of result: if the result type of $A::m()$ is α and the result type of $B::m()$ is β, then $\beta <: \alpha$

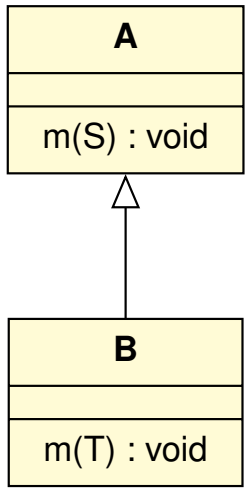
The Substitution Principle Explained using Behavioral Types 2/2

- exception rule: the set of exceptions signaled by $B::m()$ is included in the set of exceptions signaled by $A::m()$
- semantics is preserved:
  - the precondition of $A::m()$ implies the precondition of $B::m()$
  - the postcondition of $B::m()$ implies the postcondition of $A::m()$

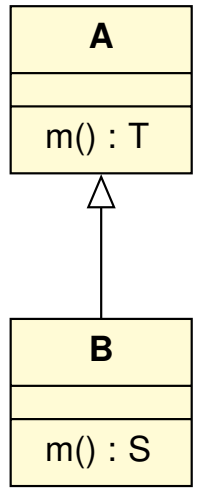
N.B. This is a simplified version of the original definition.
Exercise. Show that $T <: T$ ($<:$ is reflexive).

Contravariance/Covariance Rule with Diagrams

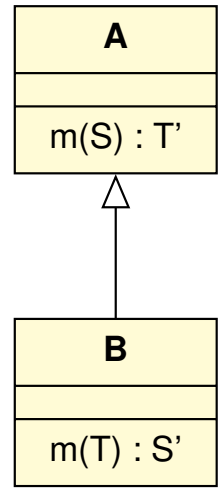
$S <: T$
$S' <: T'$



Contravariance of arguments

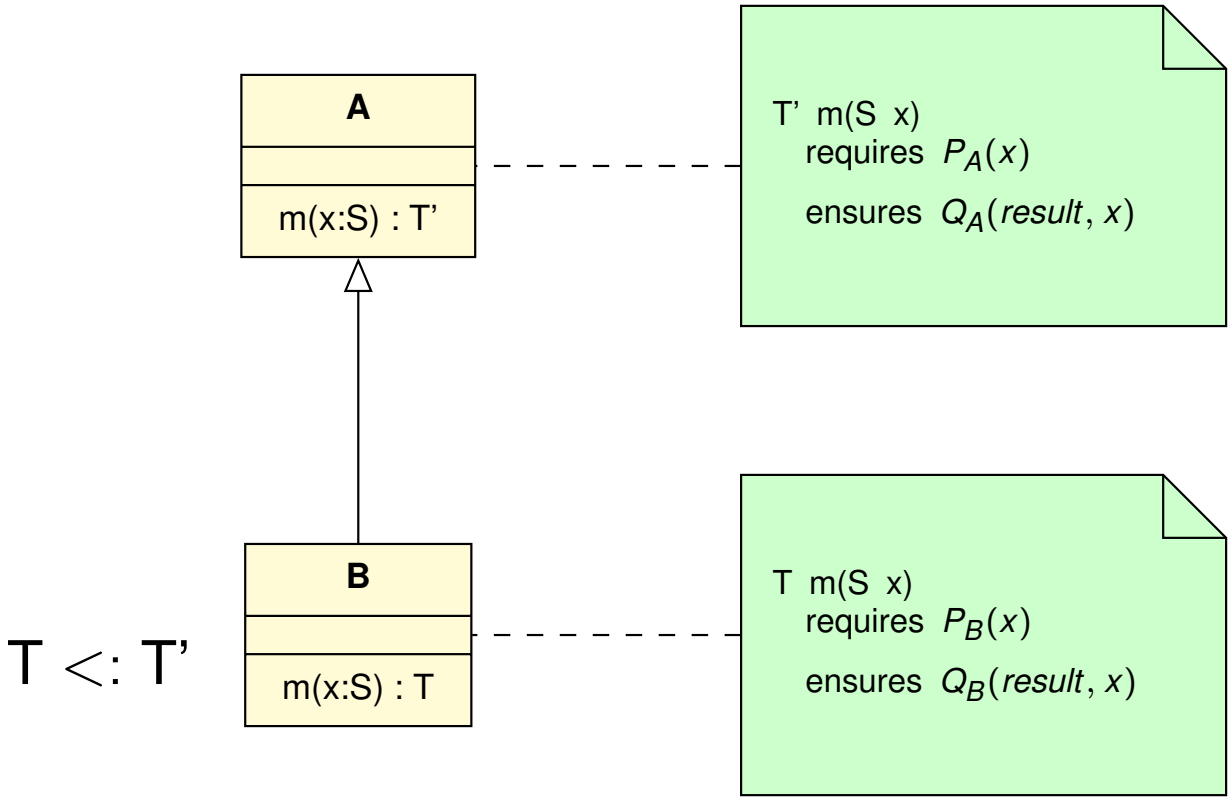


Covariance of result



Contravariance of arguments and Covariance of result

Semantics Rule with Diagrams



$$P_A \implies P_B$$
$$Q_B \implies Q_A$$

Contra-Example Revisited

The example "any square is a rectangle" violates several rules:

- the nethod `Square::setHeigth()` does not preserve the `Square` invariant `getWidth()` = `getHeigth()`
- the postcondition of `Square::area()` does not imply the postcondition of `Rectangle::area()`

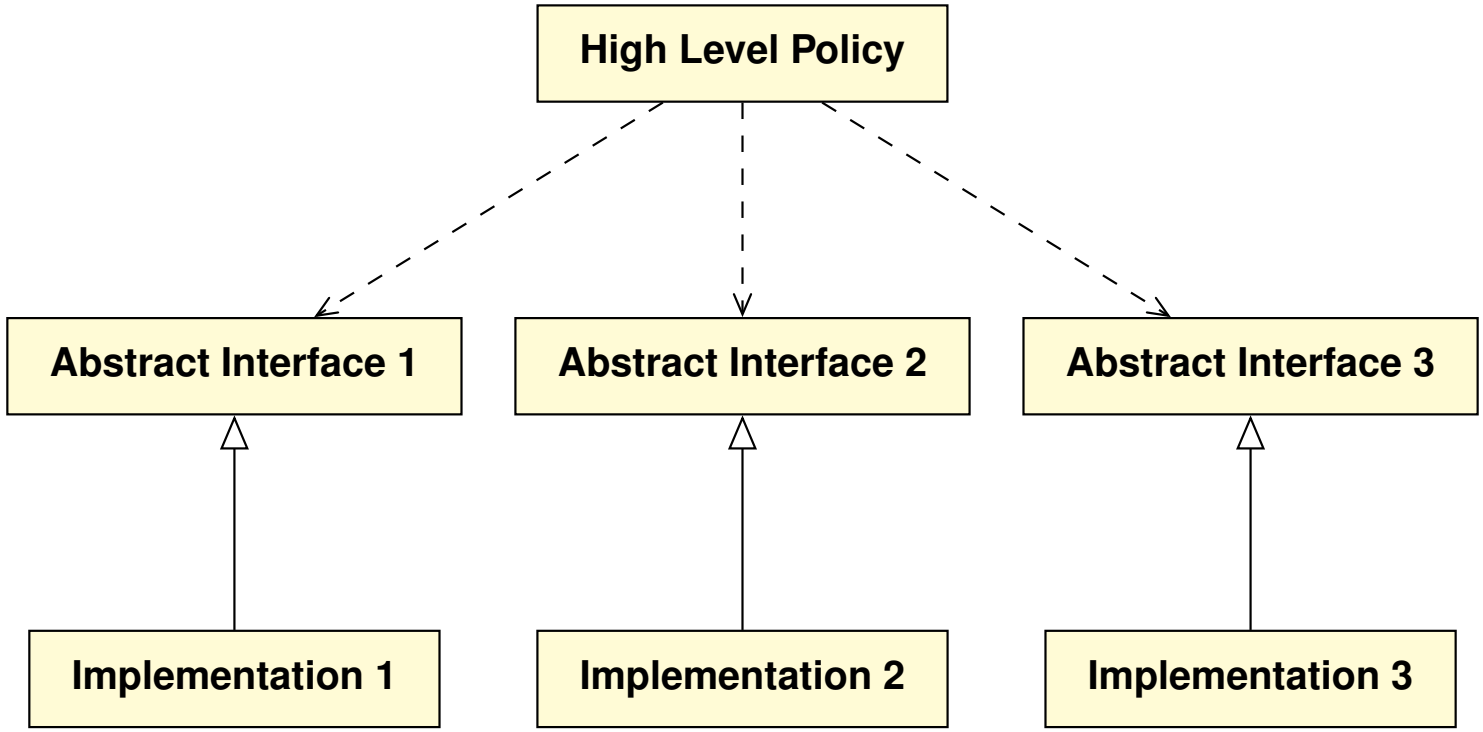
Plan

Definition

- High-level modules should not depend on low-level modules. Both should depend on abstractions.
- Abstractions should not depend on details. Details should depend on abstractions.

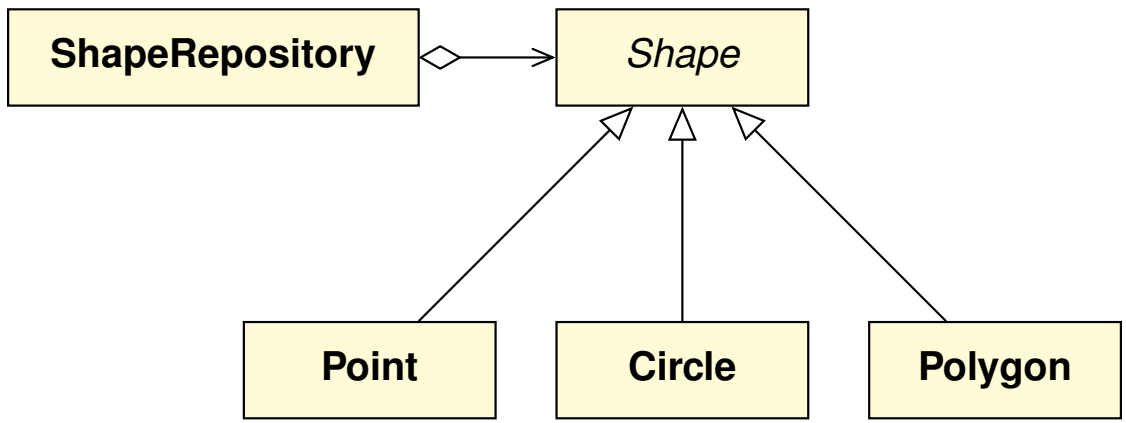
Robert C. Martin. Principles of Object Oriented Design.
https://fi.ort.edu.uy/innovaportal/file/2032/1/design_principles.pdf

Abstract View

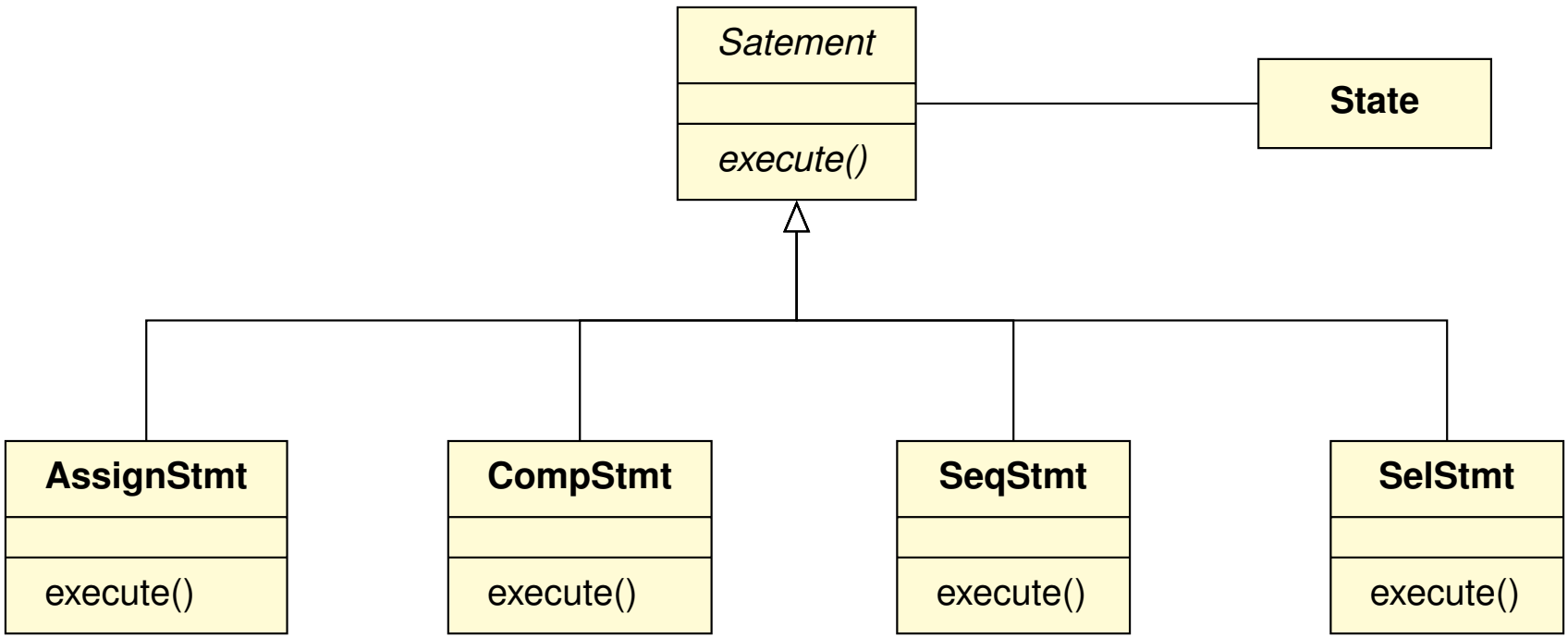


Note the notational difference between the dependence and inheritance relations. Inheritance also implies dependency.

Example



Example


Satement
execute()
State
AssignStmt
execute()
CompStmt
execute()
SeqStmt
execute()
SelStmt
execute()

Plan

Conclusion

- Models first.
- Apply the right OO Design Principle wherever such a principle is applicable
- Revise your applications from previous laboratories and design their models and identify the places where principles are applicable.