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Software Engineering Design & Construction

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Liskov Substitution Principle

***L**iskov **S**ubstitution **P**rinciple*

Subtypes must be behaviorally substitutable for their base types.

–Barbara Liskov, 1988 (ACM Turing Award Receiver)

External resource: The Liskov Substitution Principle: http://www.objectmentor.com/resources/articles/lsp.pdf

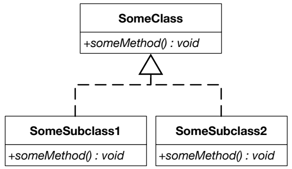
We identified class inheritance and subtype polymorphism as primary mechanisms for supporting the open-closed principle (OCP) in object-oriented designs.

The Liskov Substitution Principle

- … gives us a way to characterize good inheritance hierarchies.
- … increases our awareness about traps that will cause us to create hierarchies that do not conform to the open-closed principle.

Substitutability in object-oriented programms

```
void clientMethod(SomeClass sc)
{
    …
    sc.someMethod();
    …
}
```



In object-oriented programs, subclasses are substitutable for superclasses in client code: In `clientMethod`, `sc` may be an instance of `SomeClass` or any of its subclasses.
Hence, if `clientMethod` works with instances of `SomeClass`, it does so with instances of any subclass of `SomeClass`. They provide all methods of `SomeClass` and eventually more.

Liskov Substitution Principle by Example

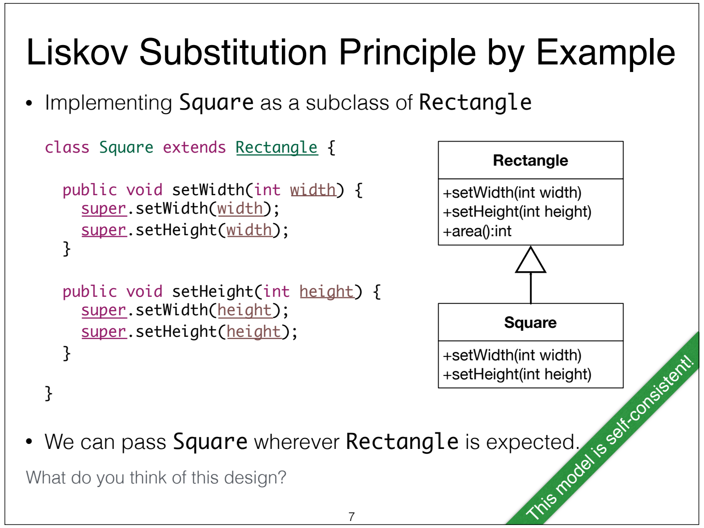
- Assume, we have implemented a class `Rectangle` in our system.

```
class Rectangle {
  public void setWidth(int width) { this.width = width; }
  public void setHeight(int height) { this.height = height;}
  public void area() { return height * width;}
}
```

- Let's now assume that we want to implement a class `Square` and want to maximize reuse.

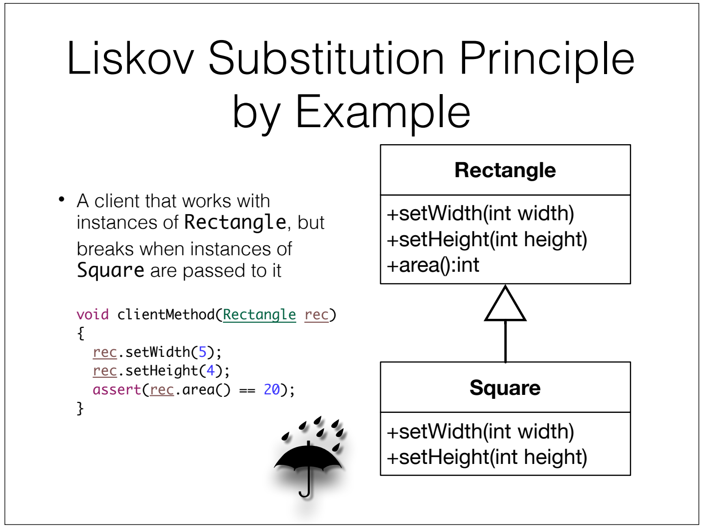
Since a square is a rectangle (mathematically speaking), we decided to implement Square as a subclass of Rectangle.

We override setWidth and setHeight and can reuse the implementation of area.



With this overriding of setHeight and setWidth – to set both dimensions to the same value – instances of Square remain mathematically valid squares. A square does comply to the mathematical properties of a rectangle: A square has four edges and only right angles and is therefore a rectangle.

We can indeed pass Square wherever Rectangle is expected, as far as the Java type system is concerned.
But, by doing so we may break assumptions that clients of Rectangle make about the “behavior” of a Rectangle.



The clientMethod method makes an assumption that is true for Rectangle: setting the width respectively height has no effect on the other attribute. This assumption does not hold for Square.

The Rectangle/Square hierarchy violates the Liskov Substitution Principle (LSP)! Square is behaviorally not a correct substitution for Rectangle.

A Square does not comply with the behavior of a rectangle: Changing the height/width of a square behaves differently from changing the height/width of a rectangle. Actually, it doesn't make sense to distinguish between the width and the height of a square.

Spot the LSP Violation in the following case:

```
class Person(val name : String) {
   override def equals(a : Any) : Boolean = {
     a match {case p : Person => p.name == this.name }
 } }
```

Hint: consider the contract defined by `java.lang.Object` related to `equals`.

Software Is All About Behavior

Programmers do not define entities that are something, but entities that behave somehow.

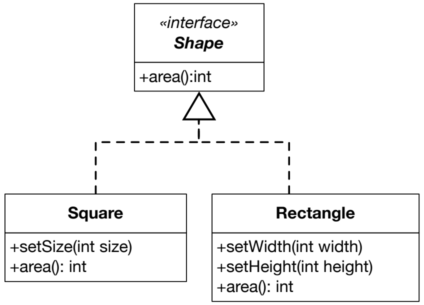
Validity is not Intrinsic!

Inspecting the `Square`/`Rectangle` hierarchy in isolation did not show any problems. In fact it even seemed like a self-consistent design.
We had to inspect the clients to identify problems.

- A model viewed in isolation can not be meaningfully validated!
  The validity of a model depends on the clients that use it.
- Hence, the validity of a model must be judged against the possible uses of the model.
  We need to anticipate the assumptions that clients will make about our classes.

Liskov Substitution Principle by Example

Rectangles and Square - LSP Compliant Solution



To get a LSP compliant solution, we make Rectangle and Square siblings.
We introduce the interface Shape to bundle common methods.

- Clients of Shape cannot make any assumptions about the behavior of setter methods.
- When clients want to change properties of the shapes, they have to work with the concrete classes.
- When clients work with the concrete classes, they can make true assumptions about the computation of the area.

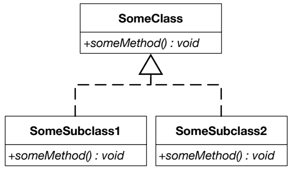
So what does the Liskov Substitution Principle add to the common object-oriented subtyping rules?

The Liskov Substitution Principle additionally requires behavioral substitutability

(Behavioral substitutability is generally not checked by compilers/static analysis tools!)

Behavioral Substitutability

- It's not enough that instances of `SomeSubclass1` and `SomeSubclass2` provide all methods declared in `SomeClass`.
  These methods should also behave like their heirs!
- A client method should not be able to distinguish the behavior of objects of `SomeSubclass1` and `SomeSubclass2` from that of objects of `SomeClass`.



Behavioral Subtyping

S is a behavioral subtype of T, if objects of type T in a program P may be replaced by objects of type S without altering any of the properties of P.

The Relation between LSP and OCP

- Consider a function `f` parameterized over type `T`
  - `S` is a derivate of `T`.
  - when passed to `f` in the guise of objects of type `T`, objects of type `S` cause `f` to misbehave.
  - `S` violates the Liskov Substitution Principle.

`f` is fragile in the presence of `S`

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I.e., `f` is not closed against derivations of `T` anymore.

When a developer encounters such code in a real project, the developer of `f` will most probably put a test to ensure that instances of `S` are treated properly.

Can you think of straightforward examples of violations of the *Liskov Substitution Principle*?

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Straightforward examples of violations of the Liskov Substitution Principle.

- Derivates that document that certain methods inherited from the superclass should not be called by clients.
  (Such situations arise due to insufficient means to specify access rights.)
- Derivates that throw additional (unchecked) exceptions.
- Derivates that behave differently in special cases (e.g., return “null” values)…

Properties extends Hashtable

LSP Violation in the JDK

Because `Properties` inherits from `Hashtable`, the `put` and `putAll` methods can be applied to a `Properties` object. Their use is strongly discouraged as they allow the caller to insert entries whose keys or values are not `Strings`. The `setProperty` method should be used instead. If the store or save method is called on a "compromised" Properties object that contains a non-String key or value, the call will fail.

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The “correct” solution would have been to use Object composition instead of inheritance.

What mechanisms can we use to support LSP?

Recall:
A model viewed in isolation cannot be meaningfully validated with respect to LSP.
Validity must be judged from the perspective of possible usages of the model.

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Hence, we need to anticipate assumptions that clients make about our models – which is de facto impossible. Most of the times we will only be able to view our model in isolation; we do not know how it will be used and how it will be extended by means of inheritance.

Trying to anticipate them all might yield needles complexity.

Design by Contract

- Solution to the validation problem: A technique for **explicitly stating what may be assumed**.
- Two main aspects of design-by-contract:
  - We can specify **contracts** using Pre-, Post-Conditions and Invariants.
    They must be respected by subclasses and clients can rely on them.
  - **Contract enforcement** (behavioral subtyping).
    Tools to check the implementation of subclasses against contracts of superclasses.

The programmer of a class defines a contract that abstractly specifies the behavior on which clients can rely.

Pre- and Post-conditions

- Declared for every method of the class (w.r.t. the potentially affected state).
- Preconditions must be true for the method to execute.
- Post-conditions must be true after the execution of the method.

Invariants

- Properties that are always true for instances of the class.
- May be broken temporarily during a method execution, but otherwise hold.

Contract for `Rectangle.setWidth(int)`

Design by Contract

```
public class Rectangle implements Shape {
  private int width;
  private int height;

  public void setWidth(int w) {
    this.width = w;
  }
}
```


Precondition for setWidth(int w):	w > 0
Postcondition for setWidth(int w):	width = w; height unchanged

Contract Enforcement

Subclasses must conform to the contract of their base class!

- This is called behavioral subtyping.
- It ensures that clients won't break when instances of subclasses are used in the guise of instances of their heirs!

What would the subtyping rules look like?
What does it mean for a subclass to conform to the contract of the base class?

Behavioral Subtyping

- Rule for Preconditions:
  - Preconditions of a class imply preconditions of its subclasses.
  - Preconditions may be replaced by (equal or) weaker ones.
- Rule for Postconditions:
  - Postconditions of a class are implied by those of its subclasses.
  - Postconditions may be replaced by equal or stronger ones.

Rationale for the rule for preconditions:

- A derived class must not impose more obligations on clients.
- Conditions that clients obey to before executing a method on an object of the base class should suffice to call the same method on instances of subclasses.

Rationale for the rule for postconditions:

- Properties assumed by clients after executing a method on an object of the base class still hold when the same method is executed on instances of subclasses.
- The guarantees that a method gives to clients can only become stronger.

"Standard" Subtyping

"Standard" subtyping relies on contra-variance of the argument types and covariance of the return type for enforcing "pre- and post-conditions on signatures".

- f: T1 → T2
  `// f is function taking values of type T1 and returning values of type T2`
- f': T1' → T2'
- f' <: f ⇔ T1 <: T1' and T2' <: T2 (f' is a subtype of f)

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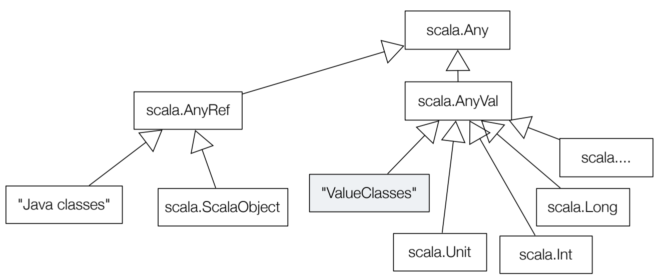
In Java, a method f that has the same name, the same return type and the same number of arguments as a method f defined in a superclass doesn't override the superclass's method if one or more argument types are contra-variant.

Scala's Type Hierarchy



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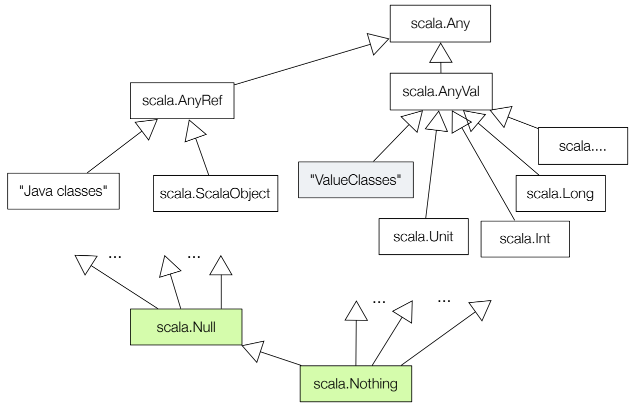
Value classes are supported since Scala 2.10.

Scala's Type Hierarchy



When compared to languages such as Java, Scala also has a well-defined least Type, i.e., a type that is the subtype of all other types.

"Standard" Subtyping in Scala

```
val f: (Seq[_]) ⇒ Boolean = (s) ⇒ { s eq null }

val af1: (Object) ⇒ Boolean // = f ?

val af2: (List[_]) ⇒ Boolean // = f ?

val af3: (Seq[_]) ⇒ Any // = f ?

val af4: (Seq[_]) ⇒ Nothing // = f ?
```

Is it possible to assign a value of type `f` to the variable: `af1`, `af2`, `af3` or `af4`?

`(Seq[_]) => Boolean` is the type of the function that takes a `Seq`uence of some type and returns a Boolean value. It is the same as the `Function1[Seq[_],Boolean]`.

Another example: val f : (List[Any]) => Set[Any] = (c : Traversable[Any]) => HashSet.empty[Any]

The answers are:

- 1: no
- 2: yes
- 3: yes
- 4: no (A client that can cope with "Nothing" will certainly not be able to cope with Booleans.)

Using Least Types

```scala
trait Store[+A] {
  def +[B >: A](b: B): Store[B]
  def contains(a: Any): Boolean
}
object EmptyStore extends Store[Nothing] {
  def +[B](b: B): Store[B] = new LinkedListStore(b, this)
  def contains(b: Any) = false
}
class LinkedListStore[+A](
  val v: A, val rest: Store[A]
) extends Store[A] {
  def +[B >: A](b: B): LinkedListStore[B] =
    new LinkedListStore(b, this)
  def contains(a: Any): Boolean =
    this.v == a || (rest contains a)
}
object Main extends App {
  val a: Store[Int] = EmptyStore + 1 + 2
  val b: Store[Any] = a
  println(b contains 1); println(b contains 3)
}
```


Scala has “definition-site variance”; Java has “use-site variance”.

*(Here, we state that **Stores are covariant**; the type A has to be used only in covariant positions. (by means of +A).)*

In this case we can use a single instance of an EmptyStore and assign it to every type of store.

Behavioral and Standard Subtyping in OO

Behavioral subtyping is a stronger notion than subtyping of functions defined in type theory.

- LSP imposes some standard requirements on signatures that have been adopted in OO languages:
  - contra-variance/covariance of method argument/return types.
  - no new (checked) exceptions should be thrown by methods of the subtype, except for those exceptions that are subtypes of exceptions thrown by the methods of the super-type.
- In addition, there are a number of conditions that behavioral subtypes must meet concerning values (rather than types) of input and output.
- Behavioral subtyping is undecidable in general.

If q is the property "method foo always terminates“ and holds for objects of type T, it's generally impossible for a program (compiler) to verify that it holds true for some subtype S.

LSP is useful, however, in reasoning about the design of class hierarchies.

Languages and Tools for Design-by-Contract

- Contracts as comments in code or in documentation.
- Unit-tests as contracts.
- Formalisms and tools for specifying contracts in a declarative way and enforcing them.

- Contracts as comments are easy and always possible, but not machine checkable.
- Unit test are machine checkable, but not declarative, possibly cumbersome and need to maintained/updated whenever a new subclass is added.
- The Eifel (http://eiffel.com) language has built-in support for design-by-contracts (the term was coined by B. Meyer).
- The Java Modeling Language (JML)](http://www.eecs.ucf.edu/~leavens/JML/index.shtml) uses annotations to specify pre-/post-conditions for Java.
- Recent languages, e.g., IBMs X10, integrate DbC into the type system by means of dependent types (values in type expressions).

Java Modeling Language

- A behavioral interface specification language that can be used to specify the behavior of Java modules.

```
public class Rectangle implements Shape {

  private int width;
  private int height;

  /*@
    @ requires w > 0;
    @ ensures height = \old(height) && width = w;
    @*/
  public void setWidth(double w) {
    this.width = w;
  }
}
```


In JML, specifications are written as Java annotation comments to the Java program, which hence can be compiled with any Java compiler.

To process JML specifications several tools exist:

- an assertion-checking compiler (jmlc) which performs runtime verification of assertions,
- a unit testing tool (jmlunit),
- an enhanced version of javadoc (jmldoc) that understands JML specifications and
- an extended static checker ([ESC/Java](http://en.wikipedia.org/wiki/ESC/Java)) a static verification tool that uses JML as its front-end.

Contracts in Documentation

One should document any restrictions on how a method may be overridden in subclasses.

The Contract of `Object.equals(...)`

`public boolean equals(Object obj)`

Indicates whether some other object is "equal to" this one.

The equals method implements an equivalence relation on non-null object references:

- *It is reflexive: for any non-null reference value x, x.equals(x) should return true.*
- *It is symmetric: for any non-null reference values x and y, x.equals(y) should return true if and only if y.equals(x) returns true.*
- *It is transitive: for any non-null reference values x, y, and z, if x.equals(y) returns true and y.equals(z) returns true, then x.equals(z) should return true.*
- *It is consistent: for any non-null reference values x and y, multiple invocations of x.equals(y) consistently return true or consistently return false, provided no information used in equals comparisons on the objects is modified.*
- *For any non-null reference value x, x.equals(null) should return false.*

The equals method for class Object implements the most discriminating possible equivalence relation on objects...

The documentation consists almost entirely of restrictions on how it may be overridden.

The method equals in Object implements identity-based equality to mean: Each instance of a class is equal only to itself. Java classes may override it to implement logical equality. This method is a real “hot spot” and it is overridden frequently. Violations of the restrictions may have dire consequences and it can be very difficult to pin down the source of the failure. Many classes, including nearly all collection classes, depend on the objects passed to them obeying the equals contract.

Object.equals(Object o)

Example Implementation

```
/**
 * Case-insensitive string. Case of the original string is preserved
 * by toString, but ignored in comparisons.
 */
public final class CaseInsensitiveString {
  private String s;
  public CaseInsensitiveString(String s) {
    if (s == null) throw new NullPointerException();
    this.s = s;
  }
  public boolean equals(Object o) {
    if (o instanceof CaseInsensitiveString)
      return s.equalsIgnoreCase(((CaseInsensitiveString) o).s);
    if (o instanceof String)
      return s.equalsIgnoreCase((String) o);
    return false;
  }
  // Remainder omitted
}
```


This implementation violates the defined contract. The requirement that the implementation has to be symmetric is violated:

```
s1 = new CaseInsensitiveString("Hello");
s2 = "hello";
s1.equals(s2) == true;
s2.equals(s1) == false;
```

Example Usage of CaseInsensitiveString

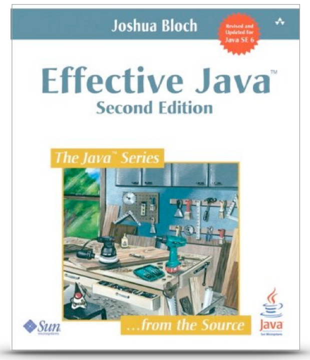
```
Object cis = new CaseInsensitiveString("Polish");
List list = new ArrayList();
list.add(cis);

return list.contains("polish"); // true or false ?
```


Nobody knows what `list.contains(s)` would return. The result may vary from one Java implementation to another. The result changes when we check the equality of the parameter against the element or vice versa!

Once you have violated `equals`'s contract, you simply don't know how other objects will behave when confronted with your object.

The Contract of `Object.equals(...)`



The Implementation of `java.net.URL.equals`

`public boolean equals(Object obj)`

- *Compares this URL for equality with another object.*
- *If the given object is not a URL then this method immediately returns false.*
- *Two URL objects are equal if they have the same protocol, reference equivalent hosts, have the same port number on the host, and the same file and fragment of the file.*
- *Two hosts are considered equivalent if both host names can be resolved into the same IP addresses; else if either host name can't be resolved, the host names must be equal without regard to case; or both host names equal to null.*
- *Since hosts comparison requires name resolution, this operation is a blocking operation.*

Assessment

- `java.net.URL`'s equals method violates the consistent part of equals contract.
- The implementation of that method relies on the IP addresses of the hosts in URLs being compared. Translating a host name to an IP address can require network access, and it isn't guaranteed to yield the same results over time.
- This can cause the URL equals method to violate the equals contract, and it has caused problems in practice.
- (Unfortunately, this behavior cannot be changed due to compatibility requirements.)

Later on the problems with the implementation were documented:
Note: The defined behavior for equals is known to be inconsistent with virtual hosting in HTTP.

Enforcing Documented Contracts

- Maybe hard when done manually …
- May require very powerful tooling (theorem proving) …
- Is un-decidable in general.

The Imperative of Documenting Contracts

It is necessary to carefully and precisely document methods that may be overridden because one cannot deduce the intended specification from the code.

```
package java.lang;

class Object {
  public boolean equals(Object ob ) {
    return this == ob;
  }
}
```


Recall the contract of equals. This contract cannot be guessed by studying the implementation of `Object.equals`!

The Imperative of Documenting Contracts

RFC (Request for Comments) 2119 defines keywords - may, should, must, etc. – which can be used to express so-called „subclassing directives“.

```
/**
 * Subclasses should override...
 * Subclasses may call super...
 * New implementation should call addPage...
 */
 public void addPages() {...}
```


Contracts can also be regarded as a way of recording details of method responsibilities.

Writing contracts...

- … helps to avoid constantly checking arguments.
  (E.g. consider the complexity of checking that a given array is sorted (precondition) vs. finding a value in a sorted array (functionality of a method)).
- … helps to determine who is responsible:

```
/*@ requires x >= 0.0;
 @ ensures JMLDouble.approximatelyEqualTo(x,
 @              \result * \result, eps); '
 @*/
public static double sqrt(doublex) {…}
```

Here, the client has the obligation to pass a non-negative number and can expect to get an approximation of the square root. The implementor has the obligation to compute and return square roots. It can assume that the argument is non-negative.

On the Quality of the Documentation

When documenting methods that may be overridden, one must be careful to document the method in a way that will **make sense for all potential overrides** of the function.

Investigations we have done with documentations of stable, intensively used frameworks in the context of the CodeRecommenders project show that often there is a discrepancy between documentation and the actual overriding. Two possible reasons:

- outdated documentation,
- framework designer cannot foresee all possible extension/usage scenarios.

Generating API Documentation with JAutoDoc

The complete documentation was auto-generated.

```
/**
 * The number of questions.
 */
private int numberOfQuestions;

/**
 * Sets the number of questions.
 *
 * @param numberOfQuestions the number of questions
 * @throws IllegalArgumentException the illegal argument exception
 */
public void setNumberOfQuestions(int numberOfQuestions)
      throws IllegalArgumentException {



}
```


What People Say About JAutoDoc

- User: Anonymous (2009-08-02 11:32:37)
  Rating: 9
  Wow exactly what I needed!
- User: Anonymous (2009-02-13 19:58:32)
  Rating: 9
  Thank you... this plugin rocks!
- User: Anonymous (2009-02-13 19:58:32)
  Rating: 9
  Works perfectly. Smarter than I expected!

Takeaway

Subtypes must be behaviorally substitutable for their base types.

Takeaway

- Behavioral subtyping extends “standard” OO subtyping.
  Additionally ensures that assumptions of clients about the behavior of a base class are not broken by subclasses.
- Behavioral subtyping helps with supporting OCP.
  Only behavioral subclassing (subtyping) truly supports open-closed designs.
- Design-by-Contract is a technique for supporting LSP.
  Makes the contract of a class to be assumed by the clients and respected by subclasses explicit (and checkable).