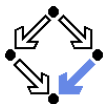


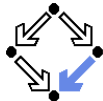
# Inheritance

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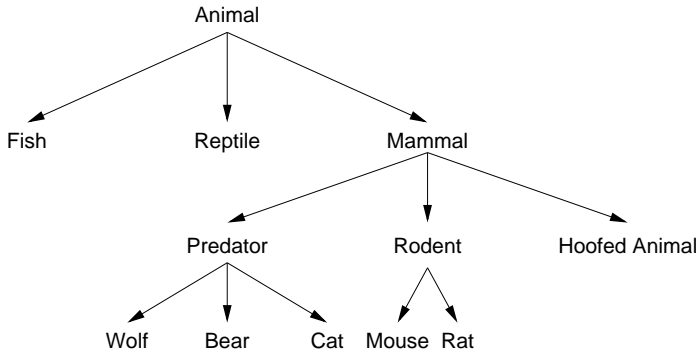


# Class Hierarchies



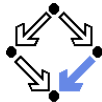
Classes represent collections of uniform objects.

- In reality, objects come in **variants**.
- Often the variants can be **hierarchically classified**.



**A bear is a predator, is a mammal, is an animal.**

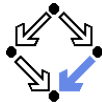
# Parent Classes and Child Classes



Two objects may share some features and differ in others.

- A wolf and a mouse are both mammals.
  - Both wolves and mice breastfeed their offspring.
- A wolf is a predator while a mouse is a rodent.
  - A wolf eats animals.
  - A mouse eats corn.
- “Mammal” is the parent of children “predator” and “rodent”.
  - Predators and rodents are both mammals, but of a different kind.

Object-oriented languages like C++ offer a similar organization of classes; their objects satisfy corresponding properties.



---

## 1. Deriving Classes from Base Classes

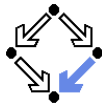
## 2. Generic Methods and Types

## 3. Virtual Functions and Overriding

## 4. Abstract Classes, Interfaces, Frameworks

# Example: An Internet Shop

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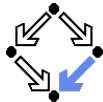


The shop offers as articles both books and CDs.

- Books:
  - Article number, title, price.
  - Author, publisher, ISBN number.
- CDs:
  - Article number, title, price.
  - Interpreter, list of songs.

A shopping cart shall list the number, title, and price of the selected articles; by clicking on an article the full information is displayed.

# Base Class

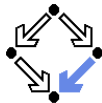


The common article functionality may be extracted to a base class.

```
class Article {
private:
    char* number;
    char* title;
    int price;
public:
    Article(...): ... { }
    char* getNumber() const { return number; }
    char* getTitle() const { return title; }
    int getPrice() const { return price; }
};
```

Books and CDs are special cases of articles.

# Derived Class

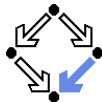


Special functionality may be added to the common functionality.

```
class Book : public Article { // Book is derived from Article
private:
    char* author;
    char* publisher;
    char* ISBN;
public:
    Book(...): ... { }
    char* getAuthor() const { return author; }
    char* getPublisher() const { return publisher; }
    char* getISBN() const { return ISBN; }
};
```

Class **Book** inherits all features of **Article**.

# Inheritance



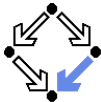
Derived classes inherit from their base classes.

```
class Derived : public Base, ... {  
    ...  
};
```

- Class *Derived* is **derived from** *Base*.
  - *Base* is the **(direct) base class** of *Derived*.
  - Derived classes are also called “subclasses” or “child” classes.
  - Base classes are also called “superclasses” or “parent” classes.
- Class *Derived* **inherits** from *Base*.
  - All data members and object functions of *Base*.
  - Can access them like its own **except those declared private**.
- Inheritance is **transitive**.
  - *Derived* inherits also from its **indirect base classes**, i.e. from the base class of *Base*, from the base class of the base class, and so on.

**A derived class inherits from all its ancestor classes.**





# Access Specifiers

Base classes may be provided with an access specifier.

```
class Derived : public Base, ... { ... }  
class Derived : protected Base, ... { ... }  
class Derived : private Base, ... { ... }  
class Derived : Base, ... { ... }
```

- Restricts access to members of *Base* for the **children of *Derived***:
  - **public**: all access specifiers in *Base* preserve their meaning.
  - **protected**: public members of *Base* become protected.
  - **private**: all members of *Base* become private.
- Default is private for class.
  - public for struct.

Typically, simply **public inheritance is applied.**

# Derived Classes

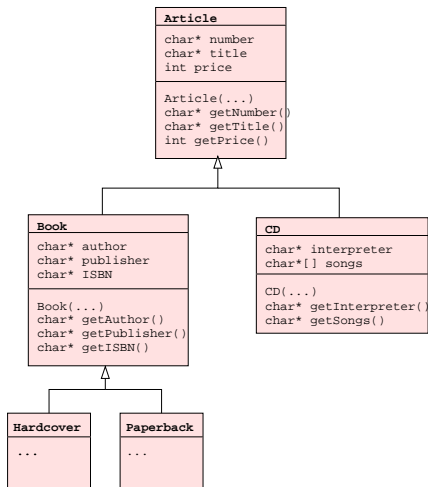
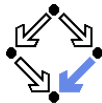


A class may have multiple children.

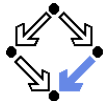
```
class CD : public Article { // CD is derived from Article
private:
    char*   interpreter;
    char*[] songs;
public:
    CD(...): ... { }
    char*   getInterpreter() const { return interpreter; }
    char*[] getSongs() const { return songs; }
};
```

Also CD inherits all features of Article.

# Inheritance Hierarchy



# Multiple Inheritance



In C++, a class may also have multiple parents.

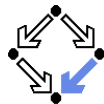
```
class Derived: public Base1, public Base2, ... {  
    ...  
};
```

- *Derived* inherits from *Base1*, and *Base2*, and ....
  - Object contains separate “subobjects” for each base class.
- Name clashes have to be resolved by qualification with base class.
  - Assume both *Base1* and *Base2* declare a data member *x*.
  - *Derived* can refer to *Base1::x* and *Base2::x* but not just to *x*.
- Thus a directed acyclic **inheritance graph** can be constructed.
  - If both *Base1* and *Base2* have a common ancestor class *A*, two separate subobjects of type *A* are created.
- Specifier **virtual** lets corresponding subobjects be shared.

```
class Base1: public virtual A, ... { ... }  
class Base2: public virtual A, ... { ... }
```

**Multiple inheritance may lead to complex class designs; use with care.**

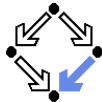
# Constructors



```
class Article {
private:
    char* number;
    char* title;
    int price;
public:
    Article(char* n, char* t, int p):
        number(n), title(t), price(p)
    { }
};
```

The constructors of a base class are not inherited.

# Constructors in Derived Classes



```
class Book : public Article { // Book is derived from Article
private:
    char* author;
    char* publisher;
    char* ISBN;
public:
    Book(char *n, char* t, int p, char *a, char *u, char *i):
        Article(n, t, p), author(a), publisher(u), ISBN(i)
    { }
};
```

- A derived class must define its own constructor.
  - May call (in its initialization list) first a constructor of the base class.
  - Otherwise, default constructor of base class is called first.

Derived class is responsible for initializing data members of base class.

# Inheritance for Code Sharing



Inheritance reduces the amount of code to be written.

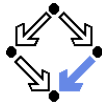
- Imperative programming:

Whenever there are two or more functions that share common functionality, this functionality should be put in a separate function; this function is then called by the other functions.

- Object-oriented programming:

Whenever there are two or more classes that share common functionality, this functionality should be put in a separate base class; from this base class, the other classes are then derived.

**Avoid code duplication among classes by inheritance.**



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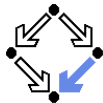
1. Deriving Classes from Base Classes

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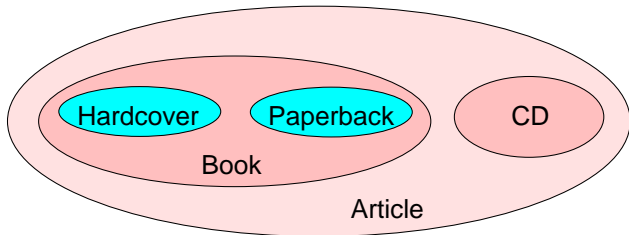




# Is-Relationship

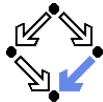
Inheritance constructs a **subset relationship**.

- A class denotes the set of objects belonging to the class.
- A derived class denotes a subset of the base class.
- An object of a derived class is also an object of the base class (and therefore of any ancestor class).



An object of type **Book** is also of type **Article** (but not vice versa).

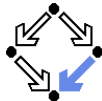
# Type Compatibility



- A derived class is compatible with the base class.
  - Has all data members and member functions of the base class.
- **General rule:**
  - Wherever an object of a class  $C$  is expected, also an object of a class may be used that is (directly or indirectly) derived from  $C$ .
- Example: internet shop.
  - Implement shopping cart that works with object of type `Article`.
  - Later derive classes `Book`, `CD`, ... from `Article`.
  - Shopping cart can hold objects of type `Book`, `CD`, ....

Inheritance may be used to implement programs that are “generic” i.e. operate on multiple data types.

# Object Assignment



Objects may be assigned to object variables.

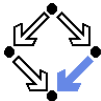
```
void printTitle(Article a) { cout << a.getTitle(); }
```

```
Book book("1234", "My Title", 2490,  
    "My Author", "My Publisher", "12345678");
```

```
Article a = book; // copy constructor  
a = book;        // copy assignment  
printTitle(book); // copy constructor
```

- An object of a derived class may be assigned to a variable of a base (in general: ancestor) class.
- By the assignment, the object is **sliced**.
  - The additional members of the derived class are removed.

By object slicing, all additional information is lost; while this is technically legal, it is costly and often denotes a programming error.



# Pointer Assignment

Object pointers may be assigned to pointer variables.

```
void printTitle(Article* a) { cout << a->getTitle(); }
```

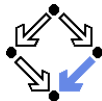
```
Book* book = new Book("1234", "My Title", 2490,  
    "My Author", "My Publisher", "12345678");
```

```
Article* a = book; // pointer assignment  
a = book;         // pointer assignment  
printTitle(book); // pointer assignment
```

- A pointer to an object of a derived class may be assigned to a variable whose type is a pointer to the base (ancestor) class.
- By the assignment, only the static (compile-time) type information is lost; the object itself preserves in memory its original identity.

This is the preferred way of writing generic code; objects are not sliced because only pointers are copied.

# Dynamic Casts



After a pointer assignment, the full type identity may be restored.

```
#define NULL (0)
Article *a = ...;

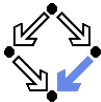
Book *book = dynamic_cast<Book*>(a);
if (book != NULL) { cout << book->getAuthor(); }

CD *cd = dynamic_cast<CD*>(a);
if (cd != NULL) { cout << cd->getInterpreter(); }
```

## ■ `dynamic_cast<C*>(p)`

- Checks whether  $p$  points to object of class  $C$  (or a subclass of  $C$ ).
- If yes, it returns a pointer of type  $C^*$  to the object.
- If not, a `NULL` pointer is returned.

Dynamic casts must be explicitly applied for assigning pointers of base classes to pointer variables of derived classes.



# Object/Pointer Assignments

---

A summary of the possible assignments.

```
class D : public C { ... };
```

```
D d(...);
```

```
C c = d;           // legal, object is sliced  
d = c;           // illegal, compiler reports error
```

```
D* d = new D(...);
```

```
C* c = d;         // legal, pointer is copied  
d = c;           // illegal, compiler reports error  
d = dynamic_cast<D*>(c); // legal, result is NULL, if cast fails
```

The general “is”-relationship only holds in one direction!



# Static versus Dynamic Types

---

An object (or object pointer) variable has two different types.

- **Static type:** the type appearing in the declaration.

...

```
Article* ap = ...;
```

- Determines which members can be accessed.
- **Dynamic type:** the type of the object stored at runtime.

```
Book* bp = new Book(...);
```

```
Article* ap = bp;
```

- May be (directly or indirectly) derived from the static type.
- Determines which virtual member functions are called (see later).

**While the static type is fixed at compile time, the dynamic type can change at runtime.**



# Generic Methods

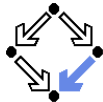
```
void printInfo(Article *a) {  
    cout << "Article" << a->getTitle();  
    cout << " (" << a->getNumber() << " ): ";  
    int price = a->getPrice();  
    cout << (price/100) << "." << (price%100) << "Euro\n";  
}
```

```
Book* book = new Book(...);  
CD* cd = new CD(...);  
printInfo(book);  
printInfo(cd);
```

Generic methods can operate on arguments of multiple dynamic types.



# Generic Types



```
class ShoppingCart {
    ...
    void add(Article* a);
    Article* getArticle(int index);
};

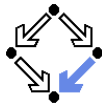
ShoppingCart cart(...);
Book* book = new Book(...);
CD* cd = new CD(...);

cart.add(book);
cart.add(cd);

Article* a = cart.getArticle(0); // may be book or CD
```

Generic containers can contain elements of multiple dynamic types.

# Generic Pointers



The type `void*` can refer to an object of any class.

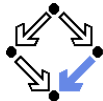
```
class Stack {
    int number;
    int size;
    void** stack;
    void resize();
public:
    Stack();
    int length();
    void push(void *e);
    void *pop();
    void *top();
};
```

```
Book *book = new Book(...);
Stack s();
s.push(book);
Book *book0 = reinterpret_cast<Book*>(s.pop());
```

- `reinterpret_cast<C*>(p)`
  - Similar to `dynamic_cast`.
  - Can be applied to safely convert between pointers of unrelated base types.

Generic containers can also hold arbitrary objects.

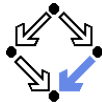
# Generic Pointers



```
Stack::Stack(): number(0), size(10), stack(new void*[size]) { }
int Stack::length() { return number; }
void* Stack::pop() { number = number-1; return stack[number]; }
void* Stack::top() { return stack[number-1]; }

void Stack::push(void *e) {
    if (number == size) resize();
    stack[number] = e;
    number = number+1;
}

void Stack::resize() {
    int size0 = 2*size;
    void **stack0 = new void*[size0];
    for (int i=0; i<size; i++) stack0[i] = stack[i];
    delete[] stack;
    size = size0; stack = stack0;
}
```



---

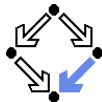
1. Deriving Classes from Base Classes

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# Declaring Methods in Base Classes

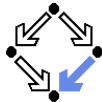


```
class Article {
private:
    char* number;
    char* title;
    int price;
public:
    ...
    void printInfo();
};

void Article::printInfo() {
    cout << "Article" << getTitle();
    cout << " (" << getNumber() << " ): ";
    int price = getPrice();
    cout << (price/100) << "." << (price%100) << "Euro\n";
}
```

Method `printInfo` is inherited by all classes derived from `Article`.

# Inheriting Methods from Base Classes



Classes Book and CD may use `printInfo`.

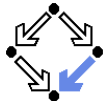
```
class Book: public Article { ... };  
class CD: public Article { ... };
```

```
Book* book = new Book(...); book->printInfo();  
CD* cd = new CD(...); cd->printInfo();  
Article* a1 = book; a1->printInfo();  
Article* a2 = cd; a2->printInfo();
```

- **Problem:** `printInfo()` is too general.
  - Only prints generic information on articles.
  - Does not print information specific to books or CDs.

How to customize `printInfo` for derived classes?

# Virtual Functions



```
class Base {
    virtual T func(...);
};
T Base::func(...) { ... }

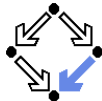
class Derived : public Base {
    virtual T func(...); // overrides Base::func()
};
T Derived::func(...) { ... }

Base *object = new Base(...); // dynamic type is Base
... object->func(...) ... // calls Base::func()

Base *object = new Derived(...); // dynamic type is Derived
... object->func(...) ... // calls Derived::func()
```

- A function declared as `virtual` can be **overridden**.
  - In a derived class, a function is declared with same name and same types for parameters and return value.
- When a virtual function is called on an object, the function definition for the **dynamic type** of the object is executed.
  - Form of genericity called **type polymorphism**.
- Base function may be still called (e.g. by the overriding function).
  - **object->Base::func(...)**

# Example



```
class Article {
    ...
    virtual void printInfo();
};
void Article::printInfo() { ... }

class Book: public Article {
    char *author;
    virtual void printInfo();
};

void Book::printInfo() {
    Article::printInfo();
    cout << author << "\n";
}

class CD: public Article {
    char *interpreter;
    virtual void printInfo();
};

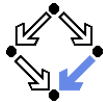
void CD::printInfo() {
    Article::printInfo();
    cout << interpreter << "\n";
}

Book* book = new Book(...); book->printInfo(); // Book::printInfo()
CD* cd = new CD(...); cd->printInfo(); // CD::printInfo()
Article* a1 = book; a1->printInfo(); // Book::printInfo()
Article* a2 = cd; a2->printInfo(); // CD::printInfo()
```

Overriding functions may use functionality of base function.



# Generic Types/Methods



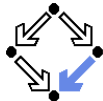
```
class ShoppingCart {
    int number;
    Article* articles[];
    ...
    void add(Article* a) { ...; articles[number] = a; ... }

    void printArticles() {
        for (int i=0; i<number; i++) {
            articles[i]->printInfo(); // Book::printInfo() or CD::printInfo()
        }
    }
};

ShoppingCart cart(...);
Book* book = new Book(...); cart.add(book);
CD* cd = new CD(...); cart.add(cd);
cart.printArticles();
```

Core of object-oriented programming: generic types/methods call the methods associated to the dynamic types of their elements/arguments.

# Covariant Return Types



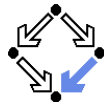
The return type of an overriding function may be actually more special than the return type of the base function.

```
class Number {  
    ...  
    virtual Number* add(Number* n);  
};  
  
class Fraction : public Number {  
    ...  
    virtual Fraction* add(Number* n);  
};
```

- Pointer/reference to some base type may be replaced by a pointer/reference to some derived type.
  - Need not be the type of the class itself.
  - Only for the return type, not for the argument types!

**The signature of the overriding function may be a bit more specific.**

# Constructors/Destructors



Inside a constructor/destructor, **also for virtual functions** the definitions of the **current class** are applied.

```
class Base {
    virtual void func();
    Base();
}
Base::func() { ... }
Base::Base() {
    func(); // Base::func();
}

class Derived: public Base {
    virtual void func();
    Derived();
}
Derived::func() { ... }
Derived::Derived() {
    func(); // Derived::func();
}
```

Derived object;

- When object is constructed, first constructor of base class is called:  
Executes `Base::func()`
- Afterwards, constructor of derived class is called:  
Executes `Derived::func()`

**Prevents access to still uninitialized part of the object.**



# Virtual Destructors

- By default, the **destructor of a class is not virtual**.
  - If an object is deleted, the destructor of its static type is called.

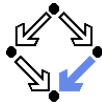
```
class Base { }; // implicit default destructor
Base* object = new Derived(...);
delete object; // Base::~~Base() is called
```
  - In most situations, this is not what is wanted/expected.

The compiler may produce a corresponding warning.
- A destructor can be **declared as virtual in the base class**.
  - Then the destructor of the dynamic type is called.

The destructors of derived classes automatically get virtual.

```
class Base { virtual ~Base() { ... } ; };
Base* object = new Derived(...);
delete object; // Base::~~Derived() is called
```
  - For a virtual constructor, an explicit definition must be given.

**A class with virtual functions should also have a virtual destructor.**



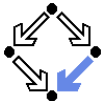
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1. Deriving Classes from Base Classes

2. Generic Methods and Types

3. Virtual Functions and Overriding

**4. Abstract Classes, Interfaces, Frameworks**



# Abstract Classes

A virtual function need not have a definition.

```
// abstract class                // concrete class
class Base {                      class Derived: public Base {
    virtual T func(...) = 0;      virtual T func(...);
};                                 };
                                  T Derived::func(...) { ... }
```

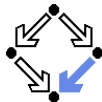
- A **pure virtual function** is declared with the **pure specifier** “=0”.
  - Such a function is also called an **abstract function**.
  - Need not (but may have) a definition in the current class.
- An **abstract class** has at least one pure virtual function.
  - Can be used in type declarations but not for object creations.

```
Base* o = ... ;           // legal
... = new Base();        // illegal
```
- A **concrete class** has no pure virtual functions.
  - All pure virtual functions of base class must receive definitions.

```
Base* o = new Derived(); // legal
```

**Abstract classes may serve as static types but not as dynamic ones.**

# Interfaces

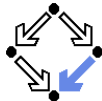


Abstract classes can represent interfaces.

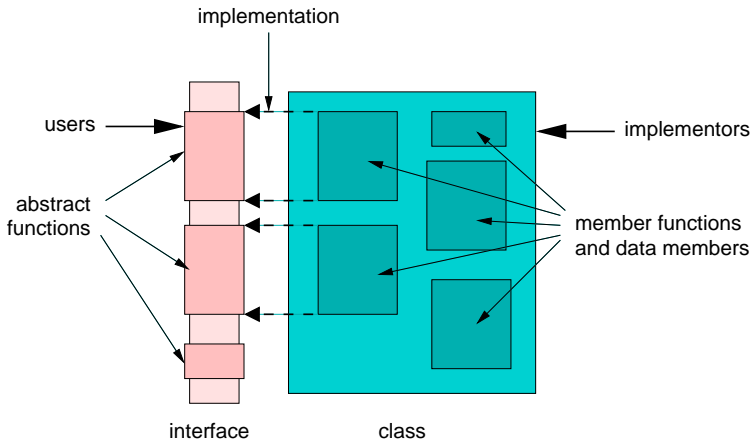
- An **interface** only defines the **signature** of a data type.
  - Names and types of the operations on the type.
  - E.g. an interface `IntStack` with the usual operations for a stack of integer values.
- A (concrete) **class** represents an **implementation** of the data type.
  - Defines its concrete representation and the concrete realization of the operations on the type.
  - E.g. a class `ArrayStack` representing a stack by an array or a class `ListStack` representing a stack by a linked list.
- By an interface, we thus get an **abstract datatype**.
  - `IntStack` serves as the static type for all stack objects.
  - `IntArrayStack` or `IntListStack` are only used when new stack objects are created.

By the use of interfaces, the concrete representation of an abstract datatype can be easily replaced without modifying the program.

# Interfaces

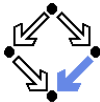


Interfaces represent “shields” for object representations.



Only the functions of the interface are accessible to users of the object.





# An Interface

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An interface is an abstract class with only pure virtual functions.

```
// IntStack.h
class IntStack {
public:
    // a virtual dummy destructor
    virtual ~IntStack { };

    // the operations to be defined by any implementation
    virtual bool isEmpty() = 0;
    virtual void push(int value) = 0;
    virtual int pop() = 0;
    virtual int top() = 0;
};
```

The signature of an abstract datatype “stack of integers”.

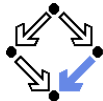
# An Implementation of the Interface



An interface is implemented by deriving from the abstract class a concrete class.

```
// IntArrayStack.h
class IntArrayStack: public IntStack {
private:
    // representation of the stack
    int number;           // by an array 'stack' of length 'size'
    int size;            // with 'number' values stored
    int* stack;
    void resize();
public:
    IntArrayStack();     // the concrete constructor
    virtual ~IntArrayStack(); // implements IntStack operation
    int length();        // not visible in interface
    virtual bool isEmpty(); // implements IntStack operation
    virtual void push(int e); // implements IntStack operation
    virtual int pop();     // implements IntStack operation
    virtual int top();     // implements IntStack operation
}
```

# An Implementation of the Interface



```
// IntArrayStack.cpp
IntArrayStack::IntArrayStack(): number(0), size(10), stack(new int[size]) { }
IntArrayStack::~IntArrayStack() { delete[] stack; }

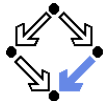
int IntArrayStack::length() { return number; }

bool IntArrayStack::isEmpty() { return length() == 0; }
int IntArrayStack::pop() { number = number-1; return stack[number]; }
int IntArrayStack::top() { return stack[number-1]; }

void IntArrayStack::push(int e) {
    if (number == size) resize();
    stack[number] = e;
    number = number+1;
}

void IntArrayStack::resize() {
    int size0 = 2*size;
    int *stack0 = new int[size0];
    for (int i=0; i<size; i++) stack0[i] = stack[i];
    delete[] stack;
    size = size0; stack = stack0;
}
```

# Another Implementation of the Interface



An interface can be implemented by multiple classes.

```
class IntListStack: public IntStack { // IntListStack.h
private:
    class IntNode; // stack represented by a
    IntNode *head; // sequence of linked nodes
public:
    IntListStack();
    virtual ~IntListStack();
    virtual bool isEmpty();
    virtual void push(int e);
    virtual int pop();
    virtual int top();
};
```

```
class IntListStack::IntNode { // IntListStack.cpp
public:
    int value;
    IntNode* next;
    IntNode(int v, IntNode *n): value(v), next(n) { }
};
```

# Another Implementation of the Interface

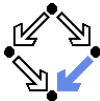


```
// IntListStack.cpp
#define NULL (0)

IntListStack::IntListStack() { head = NULL; }
IntListStack::~IntListStack() { while (head != NULL) pop(); }

bool IntListStack::isEmpty() { return head == NULL; }
void IntListStack::push(int e) { head = new IntNode(e, head); }
int IntListStack::top() { return head->value; }

int IntListStack::pop() {
    int result = head->value;
    IntNode *next = head->next;
    delete head;
    head = next;
    return result;
}
```



# The Use of the Interface

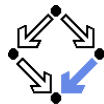
```
// a generic function on stacks
public void push(IntStack* s, int n, int v) {
    for (int i=0; i<n; i++) s->push(v);
}

int main() { / original program
    IntStack* stack = new IntArrayStack();
    push(stack, 10, 5); cout << stack.pop();
    // cout << stack.length(); // illegal, length() not in interface
    delete stack;
}

int main() { // program with new data representation
    IntStack* stack = new IntListStack();
    push(stack, 10, 5); cout << stack.pop();
    delete stack;
}
```

Use interfaces to make programs independent of data representations.

# Application Frameworks

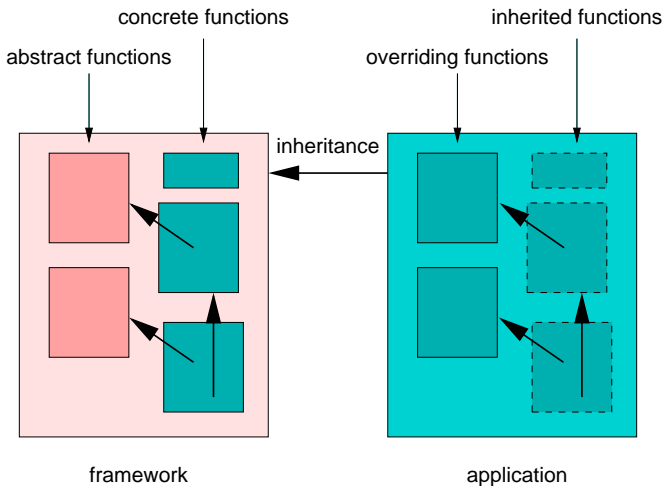
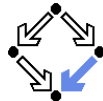


An abstract class need not be just an interface without own functionality.

- **(Application) framework:** an abstract class  $A$  that also has some concrete functions.
  - The concrete functions provide actual application functionality.
  - The abstract functions are “hooks” for customizing this functionality.
- **Some concrete functions of  $A$  call the abstract functions.**
  - Functionality depends on how abstract functions are overridden.
- **Application:** a concrete class  $C$  that is derived from  $A$ .
  - Has to override the abstract functions of  $A$  by concrete functions.
  - Inherits the functionality of  $A$  with appropriate customization.

**Application frameworks allow the development of “generic applications”.**

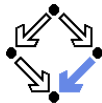
# Application Frameworks



Framework provides "hooks" for customization of application.



# Example Framework

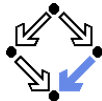


```
class Printer { // an application framework
public:
    Printer() { } ;
    virtual ~Printer() { };
    void print(int n);           // functionality of framework
    virtual char* getText() = 0; // hook for customization
};

// print n lines containing the denoted text
void Printer::print(int n)
{
    for(int i=0; i<n; i++)
    {
        cout << getText() << "\n";
    }
}
```

A framework for printing text in a formatted manner.

# Example Application



```
class IntPrinter: public Printer { // an application
    int i;
    char text[20];
public:
    IntPrinter(int i) { this->i = i; }
    virtual char* getText(); // customization of framework
};

char* IntPrinter::getText() {
    sprintf(text, "%d", i);
    return text;
}

int main() {
    IntPrinter p(7);
    p.print(3); // 7 7 7
    p.print(5); // 7 7 7 7 7
}
```

An application for printing integers in a formatted manner.