Inheritance

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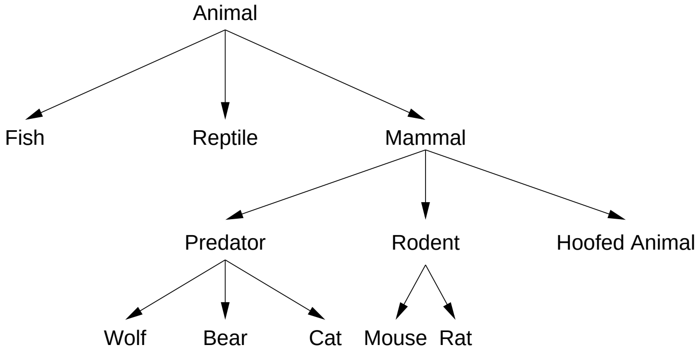
Class Hierarchies

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

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.

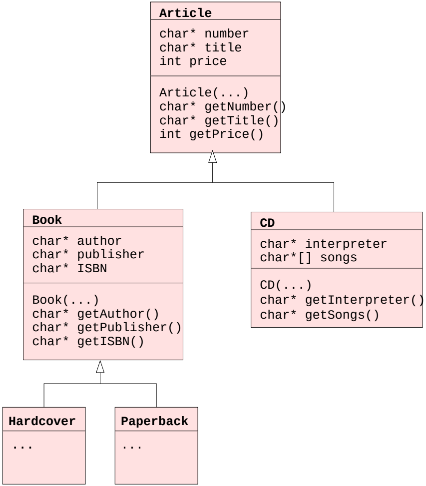
Derived Classes

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.

Copy Assignment Operators

```
class Article {
    ...
    // this definition is automatically generated
    Article& operator=(const Article& a) {
      number = a.number; title = a.title; price = a.price;
      return *this;
    }
};

class Book : public Article { // Book is derived from Article
    ...
    // this definition is automatically generated
    Book& operator=(const Book& b) {
       Article::operator=(b);
       number = a.number; title = a.title; price = a.price;
       return *this;
     }
};
```

Also the copy assignment operator of a base class is not inherited.

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.

1. Deriving Classes from Base Classes

2. **Generic Methods and Types**

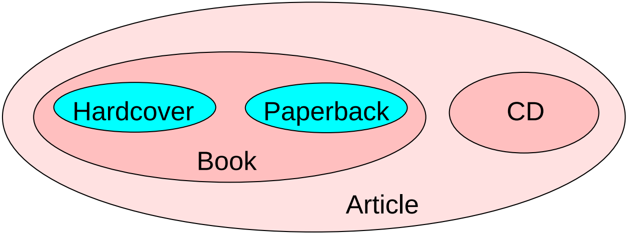
3. Virtual Functions and Overriding

4. Abstract Classes, Interfaces, Frameworks

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 prefered 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;
}
```

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

A virtual function need not have a definition.

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

```
// concrete class
class Derived: public Base {
  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

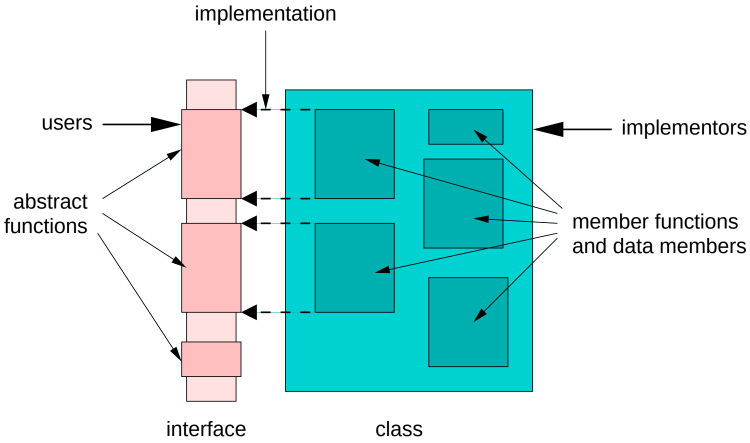
Abstract classes can represent interfaces.

- 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

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:                              // stack represented by a
    class IntNode;                      // sequence of linked nodes
    IntNode *head;
  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.

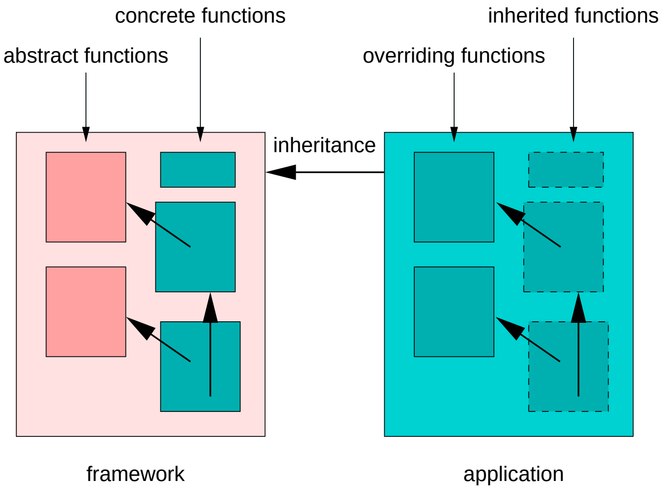
Application Frameworks

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 containg 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 formated 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 formated manner.