TDDD38 - Advanced programming in C++

Inheritance & Polymorphism

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Inheritance

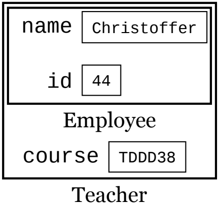
Mental Model

```
class Employee
{
  string name{"Christoffer"};
  int id{44};
};
class Teacher : public Employee
{
  string course{"TDDD38"};
};
Teacher c{};
```

Inheritance

Mental Model

```
class Employee
{
  string name{"Christoffer"};
  int id{44};
};
class Teacher : public Employee
{
  string course{"TDDD38"};
};
Teacher c{};
```



Inheritance

Protected members

```cpp
class Base
{
public:
  Base(int x)
    : x{x} { }

private:
  int x;
};
```

```cpp
struct Derived : Base
{
  Derived(int x)
    : Base{x} { }
  int get()
  {
    return x; // Error!
  }
};
```

Inheritance

Protected members

```cpp
class Base
{
public:
  Base(int x)
    : x{x} { }

protected:
  int x;
};
```

```cpp
struct Derived : Base
{
  Derived(int x)
    : Base{x} { }
  int get()
  {
    return x; // OK!
  }
};
```

Inheritance

Protected members

`protected` members are:

- inaccessible outside the class;
- accessible within derived classes;
- accessible by friends of the class and its subclasses.

Inheritance

Constructors

```cpp
class Base
{
public:
  Base(int x);
private:
  int x;
};

Base::Base(int x)
  : x{x}
{
}
```

```cpp
class Derived : public Base
{
public:
  Derived(int x, double y);
private:
  double y;
};

Derived::Derived(int x, double y)
  : Base{x}, y{y}
{
}
```

Inheritance

Initialization & Destruction

```
class Base
{
  int x{1};
};
class Derived1 : public Base
{
  double y{2.34};
};
class Derived11 final
  : public Derived1
{
  int z{56};
};
```

```
Derived11 obj{};
```

Inheritance

Initialization & Destruction

```
class Base
{
  int x{1};
};
class Derived1 : public Base
{
  double y{2.34};
};
class Derived11 final
  : public Derived1
{
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};
```
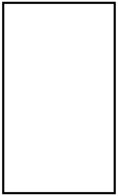

```
Derived11 obj{};
```



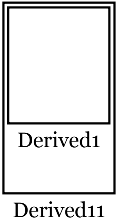
Derived11

Inheritance

Initialization & Destruction

```cpp
class Base
{
  int x{1};
};
class Derived1 : public Base
{
  double y{2.34};
};
class Derived11 final
  : public Derived1
{
  int z{56};
};
```

```cpp
Derived11 obj{};
```



Inheritance

Initialization & Destruction

```
class Base
{
  int x{1};
};
class Derived1 : public Base
{
  double y{2.34};
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  : public Derived1
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  int z{56};
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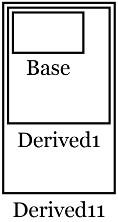

Inheritance

Initialization & Destruction

```
class Base
{
  int x{1};
};
class Derived1 : public Base
{
  double y{2.34};
};
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  : public Derived1
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  int z{56};
};
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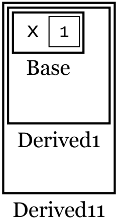

Inheritance

Initialization & Destruction

```
class Base
{
  int x{1};
};
class Derived1 : public Base
{
  double y{2.34};
};
class Derived11 final
  : public Derived1
{
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};
```

```
Derived11 obj{};
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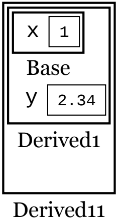

Inheritance

Initialization & Destruction

```
class Base
{
  int x{1};
};
class Derived1 : public Base
{
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Derived11 obj{};
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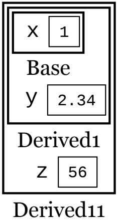

Inheritance

Initialization & Destruction

```
class Base
{
  int x{1};
};
class Derived1 : public Base
{
  double y{2.34};
};
class Derived11 final
  : public Derived1
{
  int z{56};
};
```

```
Derived11 obj{};
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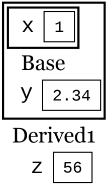
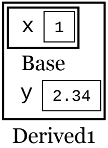


Inheritance

Initialization & Destruction

```
class Base
{
  int x{1};
};
class Derived1 : public Base
{
  double y{2.34};
};
class Derived11 final
  : public Derived1
{
  int z{56};
};
```

```
Derived11 obj{};
```

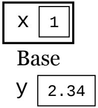


Inheritance

Initialization & Destruction

```
class Base
{
  int x{1};
};
class Derived1 : public Base
{
  double y{2.34};
};
class Derived11 final
  : public Derived1
{
  int z{56};
};
```

```
Derived11 obj{};
```

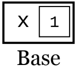


Inheritance

Initialization & Destruction

```cpp
class Base
{
  int x{1};
};
class Derived1 : public Base
{
  double y{2.34};
};
class Derived11 final
  : public Derived1
{
  int z{56};
};
```

```cpp
Derived11 obj{};
```



Inheritance

Initialization & Destruction

```
class Base
{
  int x{1};
};
class Derived1 : public Base
{
  double y{2.34};
};
class Derived11 final
  : public Derived1
{
  int z{56};
};
```

```
Derived11 obj{};
```

x 1

Inheritance

Initialization & Destruction

```
class Base
{
  int x{1};
};
class Derived1 : public Base
{
  double y{2.34};
};
class Derived11 final
  : public Derived1
{
  int z{56};
};
```

```
Derived11 obj{};
```

Inheritance

Initialization & Destruction

An object is initialized in the following order:

1. initialize base classes (call constructors);
2. initialize all data members in declaration order.

An object is destroyed in the following order:

1. destroy all data members in reverse order;
2. destroy base classes in reverse order.

Inheritance

Types of Inheritance

- `public` inheritance
- `protected` inheritance
- `private` inheritance

Inheritance

Types of Inheritance

- `public` inheritance
  - `class Derived : public Base`
  - All public and protected members of `Base` are available as public and protected respectively in `Derived`.
- `protected` inheritance
- `private` inheritance

Inheritance

Types of Inheritance

- `public` inheritance
- `protected` inheritance
  - `class Derived : protected Base`
  - All public and protected members of `Base` are available as protected in `Derived`.
- `private` inheritance

Inheritance

Types of Inheritance

- `public` inheritance
- `protected` inheritance
- `private` inheritance
  - `class Derived : private Base`
  - All members of `Base` are inherited as private and therefore inaccessible from `Derived`.

Inheritance

What will happen? Why?

```
struct Base
{
  ~Base() { cout << "Base" << endl; }
};
struct Derived : public Base
{
  ~Derived() { cout << "Derived" << endl; }
};
int main()
{
  Derived d{};
}
```

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Polymorphism

Dynamic dispatch

```cpp
void print1()
{  cout << "1" << endl; }

struct Base
{
  Base() = default;
  void print()
  {
    foo();
  }

protected:
  using function_t = void (*)();

  Base(function_t foo)
    : foo{foo} { }

private:
  function_t foo{print1};
};
```

```cpp
void print2()
{ cout << "2" << endl; }

struct Derived : public Base
{
  // inherit constructors from Base
  using Base::Base;
  // override default constructor
  Derived()
   : Derived{print2} { }
};
int main()
{
  Base* bp {new Base{}};
  bp->print();
  delete bp;

  bp = new Derived{};
  bp->print();
}
```

Polymorphism

Easier dynamic dispatch

```
struct Base
{
  virtual void print()
  {
    cout << "1" << endl;
  }
};

struct Derived : public Base
{
  void print() override
  {
    cout << "2" << endl;
  }
};
```

```
int main()
{
  Base* bp {new Base{}};
  bp->print();
  delete bp;

  bp = new Derived{};
  bp->print();
}
```

Polymorphism

Polymorphic behaviour

Polymorphic types are;

- types with virtual functions;
- that are called through pointers or references to a base class.

```
struct Base
{
  virtual void print()
  {cout << "1" << endl;}
};
struct Derived
  : public Base
{
  void print() override
  {cout << "2" << endl;}
};
```

```
int main()
{
  Base* bp{};
  bp = new Base();
  bp->print();
  delete bp;

  bp = new Derived();
  bp->print();
  delete bp;
}
```

Polymorphism

What will happen? Why?

```
struct Base
{
  ~Base() { cout << "Base" << endl; }
};
struct Derived : public Base
{
  ~Derived() { cout << "Derived" << endl; }
};
int main()
{
  Base* bp{new Derived()};
  delete bp;
}
```

Polymorphism

What will happen? Why?

```
struct Base
{
  virtual ~Base() { cout << "Base" << endl; }
};
struct Derived : public Base
{
  ~Derived() { cout << "Derived" << endl; }
};
int main()
{
  Base* bp{new Derived()};
  delete bp;
}
```

Polymorphism

Virtual destructor

- `bp` is of type `Base*` (the *static type* of `bp`);
- deleting `bp` will call the destructor of `Base` regardless of what the *dynamic type* of `bp` is;
- However, if the destructor of base is `virtual` the compiler will use dynamic dispatch to call the overriden destructor from `Derived`, which in turn will call the `Base` destructor.

Therefore we should always declare destructors as virtual for types which will be used through pointers.

Polymorphism

Virtual Table

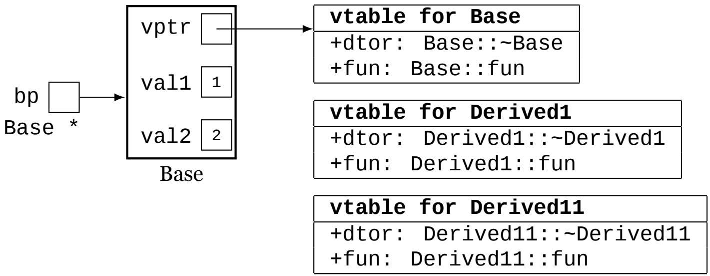
```
struct Base
{
  virtual ~Base();
  virtual void fun();
  int val1{1};
  int val2{2};
};
struct Derived1 : public Base
{
  void fun() override;
  double d{3.4};
};
struct Derived11 : public Derived1
{
  void fun() final;
};
```

```
void Base::fun()
{
  cout << val1 << ' ' << val2;
}

void Derived1::fun()
{
  Base::fun();
  cout << ' ' << d;
}

void Derived11::fun()
{
  cout << "Derived11 ";
  Derived1::fun();
}
```

Polymorphism

Virtual Table

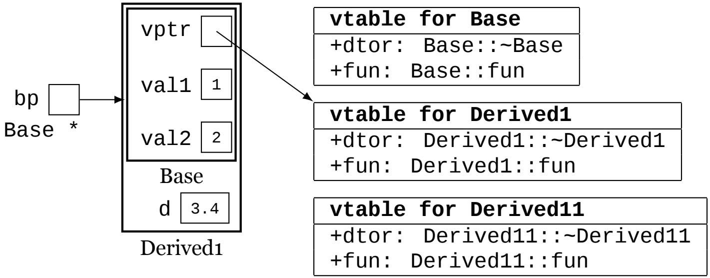
```
Base* bp{new Base{}};
```



Polymorphism

Virtual Table

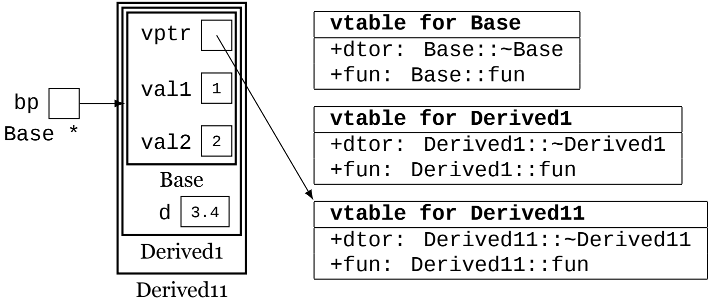
```
Base* bp{new Derived1{}};
```



Polymorphism

Virtual Table

```
Base* bp{new Derived11{}};
```



Polymorphism

Run-time type information (RTTI)

```
struct Base { virtual ~Base() = default; };
struct Derived1 : public Base { };
struct Derived11 : public Derived1 { };
int main()
{
  Base b;
  Derived1 d1, d2;
  Derived11 d11;
  cout << typeid(b).name() << endl;
  cout << typeid(d1).hash_code() << endl;
  cout << (typeid(d1) == typeid(b)) << endl;
  cout << (typeid(d1) == typeid(d2)) << endl;
  cout << (typeid(d1) == typeid(d11)) << endl;
}
```

Polymorphism

Run-time type information (RTTI)

- `typeid` is used to check the *exact* dynamic type;
- We can use `dynamic_cast` to cast pointers or references to objects into some pointer or reference which is compatible with the dynamic type of the object.

```
struct Base { virtual ~Base() = default; };
struct Derived1 : public Base { };
struct Derived11 : public Derived1 { };
int main()
{
  Base* bp{new Derived1()};
  cout << (dynamic_cast<Base*>(bp) == nullptr) << endl;
  cout << (dynamic_cast<Derived11*>(bp) == nullptr) << endl;
}
```

Polymorphism

Run-time type information (RTTI)

```
struct Base
{
  virtual ~Base() = default;
};
struct Derived1 : public Base
{
  int foo() { return 1; }
};
struct Derived11 : public Derived1 { };
int main()
{
  Base* bp{new Derived1()};
  // won't work, since foo is a non-virtual function in Derived
  cout << bp->foo() << endl;
  // will work, since we converted bp to Derived* which has access to foo
  cout << dynamic_cast<Derived1&>(*bp).foo() << endl;
  // will throw an exception of type std::bad_cast
  cout << dynamic_cast<Derived11&>(*bp).foo() << endl;
}
```

Polymorphism

What will happen? Why?

```
struct Base { virtual ~Base() = default; };
struct Derived1 : public Base { };
struct Derived11 : public Derived1 { };
struct Derived2 : public Base { };
int main()
{
  Base* bp{new Derived1()};
  if (dynamic_cast<Base*>(bp))
    cout << "B ";
  if (dynamic_cast<Derived1*>(bp))
    cout << "D1 ";
  if (dynamic_cast<Derived11*>(bp))
    cout << "D11 ";
  if (dynamic_cast<Derived2*>(bp))
    cout << "D2 ";
}
```

Polymorphism

Slicing

```
struct Base
{
  virtual void print() {cout << x;}
  int x{1};
};
struct Derived : public Base
{
  void print() override {cout << y;}
  int y{2};
};
```

```
void print(Base b)
{
  b.print();
}

int main()
{
  Derived d{};
  print(d);
}
```

Exception Handling

Model

```
int main()
{
  try
  {
    fun1();
    // ...
  }
  catch (std::exception& e)
  {
    cerr << e.what();
  }
}
```

```
void fun1()
{
  // ...
  fun2();
  // ...
  return;
}
```

```
void fun2()
{
  return;
}
```

Exception Handling

Model

```
int main()
{
  try
  {
    fun1();
    // ...
  }
  catch (std::exception& e)
  {
    cerr << e.what();
  }
}
```

```
void fun1()
{
  // ...
  fun2();
  // ...
  return;
}
```

```
void fun2()
{
  return;
}
```

Exception Handling

Model

```cpp
int main()
{
  try
  {
    fun1();
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  {
    cerr << e.what();
  }
}
```

```cpp
void fun1()
{
  // ...
  fun2();
  // ...
  return;
}
```

```cpp
void fun2()
{
  return;
}
```

Exception Handling

Model

```cpp
int main()
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```cpp
void fun1()
{
  // ...
  fun2();
  // ...
  return;
}
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```cpp
void fun2()
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  return;
}
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Exception Handling

Model

```
int main()
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  try
  {
    fun1();
    // ...
  }
  catch (std::exception& e)
  {
    cerr << e.what();
  }
}
```

```
void fun1()
{
  // ...
  fun2();
  // ...
  return;
}
```

```
void fun2()
{
  return;
}
```

Exception Handling

Model

```cpp
int main()
{
  try
  {
    fun1();
    // ...
  }
  catch (std::exception& e)
  {
    cerr << e.what();
  }
}
```

```cpp
void fun1()
{
  // ...
  fun2();
  // ...
  return;
}
```

```cpp
void fun2()
{
  throw std::exception{""};
}
```

Exception Handling

Model

```
int main()
{
  try
  {
    fun1();
    // ...
  }
  catch (std::exception& e)
  {
    cerr << e.what();
  }
}
```

```
void fun1()
{
  // ...
  fun2();
  // ...
  return;
}
```

```
void fun2()
{
  throw std::exception{""};
}
```

Exception Handling

Model

```
int main()
{
  try
  {
    fun1();
    // ...
  }
  catch (std::exception& e)
  {
    cerr << e.what();
  }
}
```

```
void fun1()
{
  // ...
  fun2();
  // ...
  return;
}
```

```
void fun2()
{
  throw std::exception{""};
}
```

Exception Handling

Model

```cpp
int main()
{
  try
  {
    fun1();
    // ...
  }
  catch (std::exception& e)
  {
    cerr << e.what();
  }
}
```

```cpp
void fun1()
{
  // ...
  fun2();
  // ...
  return;
}
```

```cpp
void fun2()
{
  throw std::exception{""};
}
```

Exception Handling

Lifetime & Stack Unwinding

```cpp
int foo()
{
  int z{};
  throw z;
}
struct Cls
{
  Cls() try
    : y{foo()}
  {
  }
  catch (int i)
  {
    cerr << i;
    throw "cls error";
  }
  int y;
};
```

```cpp
int main() try
{
  int x{};
  Cls c{};
  // ...
}
catch (char const* str)
{
  cerr << str;
}
catch (std::exception& e)
{
  cerr << e.what();
}
catch (...)
{
  cerr << "Unknown error";
}
```

Exception Handling

Exception usage

- Exceptions are very slow when they are thrown;
- should only be thrown in *exceptional* situations;
- don't use exceptions for control flow, it will severely slow down your program.

Exception Handling

noexcept

- Due to stack unwinding, the compiler have to generate some extra code to handle exceptions;
- this extra generated code can be costly, especially if it is not used;
- the `noexcept`-specifier tells the compiler that no exceptions will be thrown from a function;
- declaring functions as `noexcept` will allow the compiler to not generate code for exception handling.

Exception Handling

noexcept

```
void fun() noexcept;
```

Exception Handling

noexcept

```
void fun() noexcept;
```

- A function declared `noexcept` is allowed to call throwing functions, as long as the exception is caught before it reaches the `noexcept` function;

Exception Handling

noexcept

```
void fun() noexcept;
```

- A function declared `noexcept` is allowed to call throwing functions, as long as the exception is caught before it reaches the `noexcept` function;
- If an exception is thrown inside a `noexcept` function, `std::terminate` is called, thus aborting the program.

1 Inheritance
2 Polymorphism
3 Exception Handling
4 Smart Pointers

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Smart Pointers

Exceptions and Memory Management

```cpp
int* get(int x)
{
  if (x < 0)
    throw std::out_of_range{""};
  return new int{x};
}
struct Cls
{
  Cls(int x, int y) : data1{get(x)}, data2{get(y)} { }
  ~Cls()
  {
    delete data1;
    delete data2;
  }
  int* data1;
  int* data2;
};
```

Smart Pointers

Exceptions and Memory Management

```
struct Cls
{
  Cls(int x, int y) try
    : data1{get(x)}, data2{get(y)}
  {
  }
  catch (...)
  {
    delete data1;
    throw;
  }
  ~Cls()
  {
    delete data1;
    delete data2;
  }
  int* data1;
  int* data2;
};
```

Smart Pointers

Exceptions and Memory Management

```
struct Cls
{
  Cls(int x, int y) try
    : data1{get(x)}, data2{get(y)}
  {
  }
  catch (...)
  {
    delete data1;
    throw;
  }
  ~Cls()
  {
    delete data1;
    delete data2;
  }
  int* data1;
  int* data2;
};
```

Segmentation Fault

Smart Pointers

Exceptions and Memory Management

```
struct Cls
{
  Cls(int x, int y) : data1{get(x)}
  {
    try
    {
      data2 = get(y);
    }
    catch (...)
    {
      delete data1;
      throw;
    }
  }
  ~Cls()
  {
    // ...
  }
  // ...
};
```

Smart Pointers

Exceptions and Memory Management

```
struct Cls
{
  Cls(int x, int y) : data1{get(x)}
  {
    try
    {
      data2 = get(y);
    }
    catch (...)
    {
      delete data1;
      throw;
    }
  }
  ~Cls()
  {
    // ...
  }
  // ...
};
```

Painfully Tedious

Smart Pointers

Smart Pointers

- Use RAII to automatically handle allocated memory;
- two variants: shared and unique;
- both types reside in `<memory>`;
- `std::unique_ptr`
- `std::shared_ptr`

Smart Pointers

Smart Pointers

- Use RAII to automatically handle allocated memory;
- two variants: shared and unique;
- both types reside in `<memory>`;
- `std::unique_ptr`
    - Represent ownership;
    - each `unique_ptr` points to a unique object;
    - when the pointer is destroyed, the object is deallocated;
    - cannot be copied, only moved.
- `std::shared_ptr`

Smart Pointers

Smart Pointers

- Use RAII to automatically handle allocated memory;
- two variants: shared and unique;
- both types reside in `<memory>`;
- `std::unique_ptr`

```
// hand off manually allocated memory
std::unique_ptr<int> ptr1{new int{5}};
// let the smart pointer handle it
std::unique_ptr<int> ptr2{make_unique<int>(5)};
// move ptr2 to ptr3
std::unique_ptr<int> ptr3{std::move(ptr2)};
// ptr2 is now null
```

- `std::shared_ptr`

Smart Pointers

Smart Pointers

- Use RAII to automatically handle allocated memory;
- two variants: shared and unique;
- both types reside in `<memory>`;
- `std::unique_ptr`
- `std::shared_ptr`
  - Represent shared ownership on an object;
  - Can be copied;
  - Will deallocate the memory when all shared pointers have been destroyed;
  - Should be avoided if possible since it is quite expensive.

Smart Pointers

Smart Pointers

- Use RAII to automatically handle allocated memory;
- two variants: shared and unique;
- both types reside in `<memory>`;
- `std::unique_ptr`
- `std::shared_ptr`

```
std::shared_ptr<int> ptr1{new int{5}};
std::shared_ptr<int> ptr2{make_shared<int>(5)};
std::shared_ptr<int> ptr3{ptr2};
// both ptr2 and ptr3 point to the same object
// the object will be deallocated once both ptr2 and ptr3
// have been destroyed.
```

Smart Pointers

Nice solution

```
std::unique_ptr<int> get(int x)
{
  if (x < 0)
    throw std::out_of_range{""};
  return std::make_unique<int>(x);
}
struct Cls
{
  Cls(int x, int y) : data1{get(x)}, data2{get(y)} { }
  ~Cls() = default;
  std::unique_ptr<int> data1;
  std::unique_ptr<int> data2;
};
```

Smart Pointers

Nice solution

```
std::unique_ptr<int> get(int x)
{
  if (x < 0)
    throw std::out_of_range{""};
  return std::make_unique<int>(x);
}
struct Cls
{
  Cls(int x, int y) : data1{get(x)}, data2{get(y)} { }
  ~Cls() = default;
  std::unique_ptr<int> data1;
  std::unique_ptr<int> data2;
};
```

Perfection!

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