Programming Languages

Mixins and Traits

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What modularization techniques are there besides multiple implementation inheritance?
Outline

Design Problems
1. Inheritance vs Aggregation
2. (De-)Composition Problems

Inheritance in Detail
1. A Model for single inheritance
2. Inheritance Calculus with Inheritance Expressions
3. Modeling Mixins

Cons of Implementation Inheritance
1. Lack of finegrained Control
2. Inappropriate Hierarchies

A Focus on Traits
1. Separation of Composition and Modeling
2. Trait Calculus

Mixins in Languages
1. Simulating Mixins
2. Native Mixins

Traits in Languages
1. (Virtual) Extension Methods
2. Squeak
Codelsharing in Object Oriented Systems is often inheritance-centric.

Inheritance itself comes in different flavours:

- single inheritance
- multiple inheritance

All flavours of inheritance tackle problems of *decomposition* and *composition*. 
The Adventure Game

- Door
  - ShortDoor
    - canPass(Person p)
  - LockedDoor
    - canOpen(Person p)
  - ShortLockedDoor
    - canOpen(Person p)
    - canPass(Person p)
The Adventure Game

Door
- canOpen(Person p)
- canPass(Person p)

Short
- canPass(Person p)

Locked
- canOpen(Person p)

<interface>Doorlike
- canPass(Person p)
- canOpen(Person p)

ShortLockedDoor
- canOpen(Person p)
- canPass(Person p)

⚠️ Aggregation & S.-Inheritance
- Door must explicitly provide chaining
- Doorlike must anticipate wrappers

⇒ Multiple Inheritance ✓
The Wrapper

FileStream

write()

read()

SocketStream

write()

read()

SynchRW

acquireLock()

releaseLock()

⚠️ Unclear relations

⇝ Cannot inherit from both in turn with Multiple Inheritance
(Many-to-One instead of One-to-Many Relation)
The Wrapper – Aggregation Solution

Stream
- read()
- write()

FileStream
- read()
- write()

SocketStream
- read()
- write()

SynchRW
- read()
- write()
- acquireLock()
- releaseLock()

⚠️ Aggregation
- Undoes specialization
- Needs common ancestor
With multiple inheritance, read/write Code is essentially *identical but duplicated for each particular wrapper*
Fragility

Inappropriate Hierarchies

Implemented methods (acquireLock/releaseLock) to high
(De-)Composition Problems

All the problems of
- Relation
- Duplication
- Hierarchy

are centered around the question

“How do I distribute functionality over a hierarchy”

→ functional (de-)composition
**Classes and Methods**

The building blocks for classes are
- a countable set of method *names* $\mathcal{N}$
- a countable set of method *bodies* $\mathcal{B}$

Classes map names to elements from the *flat lattice* $\mathcal{B}$ (called bindings), consisting of:
- method bodies $\in \mathcal{B}$ or classes $\in \mathcal{C}$
- $\bot$ abstract
- $\top$ in conflict

and the partial order $\bot \sqsubseteq b \sqsubseteq \top$ for each $b \in \mathcal{B}$

**Definition (Abstract Class $\in \mathcal{C}$)**

A general function $c : \mathcal{N} \mapsto \mathcal{B}$ is called a class.

**Definition (Interface and Class)**

A class $c$ is called

- *interface* iff $\forall n \in \text{pre}(c) \cdot c(n) = \bot$.
- *abstract class* iff $\exists n \in \text{pre}(c) \cdot c(n) = \bot$.
- *concrete class* iff $\forall n \in \text{pre}(c) \cdot \bot \sqsubseteq c(n) \sqsubseteq \top$. 
Definition (Family of classes $C$)

We call the set of all maps from names to bindings the family of classes $C := \mathcal{N} \mapsto \mathcal{B}$.

Several possibilities for composing maps $C \uplus C$:

- the symmetric join $\uplus$, defined componentwise:

  \[
  (c_1 \uplus c_2)(n) = b_1 \uplus b_2 = \begin{cases} 
  b_2 & \text{if } b_1 = \bot \text{ or } n \notin \text{pre}(c_1) \\
  b_1 & \text{if } b_2 = \bot \text{ or } n \notin \text{pre}(c_2) \\
  b_2 & \text{if } b_1 = b_2 \\
  \top & \text{otherwise}
  \end{cases}
  \]

  where $b_i = c_i(n)$

- in contrast, the asymmetric join $\uplus$, defined componentwise:

  \[
  (c_1 \uplus c_2)(n) = \begin{cases} 
  c_1(n) & \text{if } n \in \text{pre}(c_1) \\
  c_2(n) & \text{otherwise}
  \end{cases}
  \]
Example: Smalltalk-Inheritance

*Smalltalk* inheritance
- children’s methods dominate parents’ methods
- is the archetype for inheritance in mainstream languages like Java or C#
- inheriting smalltalk-style establishes a reference to the parent

**Definition (Smalltalk inheritance (\(\triangleright\))):**

Smalltalk inheritance is the binary operator \(\triangleright: C \times C \mapsto C\), defined by
\[
c_1 \triangleright c_2 = \{\text{super } \mapsto c_2\} \sqcup (c_1 \sqcup c_2)
\]

**Example: Doors**

\[
\text{Door} = \{\text{canPass } \mapsto \bot, \text{canOpen } \mapsto \bot\}
\]
\[
\text{LockedDoor} = \{\text{canOpen } \mapsto 0x4204711\} \triangleright \text{Door}
\]
\[
= \{\text{super } \mapsto \text{Door}\} \sqcup (\{\text{canOpen } \mapsto 0x4204711\} \sqcup \text{Door})
\]
\[
= \{\text{super } \mapsto \text{Door}, \text{canOpen } \mapsto 0x4204711, \text{canPass } \mapsto \bot\}
\]
Excursion: Beta-Inheritance

In Beta-style inheritance
- the design goal is to provide security wrt. replacement of a method by a different method.
- methods in parents dominate methods in subclass
- the keyword inner explicitly delegates control to the subclass

Definition (Beta inheritance (◁))

Beta inheritance is the binary operator ◁ : C × C ↦ C, defined by
\[ c_1 ◁ c_2 = \{ \text{inner} \mapsto c_1 \} \uplus (c_2 \uplus c_1) \]

Example (equivalent syntax):

```java
class Person {
    String name = "Axel Simon";
    public String toString() { return name + inner.toString(); }
};
class Graduate extends Person {
    public extension String toString() { return ", Ph.D."; }
};
```
So what do we really want?
Adventure Game with Code Duplication

Door
- LockedDoor
  - canOpen(Person p)
- ShortDoor
  - canPass(Person p)
- ShortLockedDoor
  - canOpen(Person p)
  - canPass(Person p)
Adventure Game with Mixins

<mixin>Locked
canOpen(Person p)

<mixin>Short
canPass(Person p)

ShortLockedDoor
canOpen(Person p)
canPass(Person p)

Door
canOpen(Person p)
canPass(Person p)

compose
mixin
class Door {
    boolean canOpen(Person p) { return true; };
    boolean canPass(Person p) { return p.size() < 210; };
}
mixin Locked {
    boolean canOpen(Person p){
        if (!p.hasItem(key)) return false; else return super.canOpen(p);
    }
}
mixin Short {
    boolean canPass(Person p){
        if (p.height()>1) return false; else return super.canPass(p);
    }
}
class ShortDoor = Short(Door);
class LockedDoor = Locked(Door);
mixin ShortLocked = Short o Locked;
class ShortLockedDoor = Short(Locked(Door));
class ShortLockedDoor2 = ShortLocked(Door);
Back to the blackboard!
Abstract model for Mixins

A Mixin is a *unary second order type expression*. In principle it is a curried version of the Smalltalk-style inheritance operator. In certain languages, programmers can create such mixin operators:

**Definition (Mixin)**

The mixin constructor $\textit{mixin} : C \mapsto (C \mapsto C)$ is a unary class function, creating a unary class operator, defined by:

$$\textit{mixin}(c) = \lambda x. c \triangleright x$$

⚠️ Note: Mixins can also be composed $\circ$:

**Example: Doors**

\[
\begin{align*}
\text{Locked} &= \{ \text{canOpen} \mapsto 0x1234 \} \\
\text{Short} &= \{ \text{canPass} \mapsto 0x4711 \} \\
\text{Composed} &= \textit{mixin}(\text{Short}) \circ (\textit{mixin}(\text{Locked})) = \lambda x. \text{Short} \triangleright (\text{Locked} \triangleright x) \\
&= \lambda x. \{ \text{super} \mapsto (\text{Locked} \triangleright x) \} \uplus (\{ \text{canOpen} \mapsto 0x1234, \text{canPass} \mapsto 0x4711 \} \triangleright x)
\end{align*}
\]
Wrapper with Mixins

Mixins for wrappers

- avoids duplication of read/write code
- keeps specialization
- even compatible to single inheritance systems
class Door {
  boolean canOpen(Person p)...
  boolean canPass(Person p)...
}
mixin Locked {
  boolean canOpen(Person p)...
}
mixin Short {
  boolean canPass(Person p)...
}
class ShortDoor
  = Short(Door);
class ShortLockedDoor
  = Short(Locked(Door));
...
Surely multiple inheritance is powerful enough to simulate mixins?
Simulating Mixins in C++

template <class Super>
class SyncRW : public Super {
    public: virtual int read() {
        acquireLock();
        int result = Super::read();
        releaseLock();
        return result;
    };
    virtual void write(int n) {
        acquireLock();
        Super::write(n);
        releaseLock();
    };
    // ... acquireLock & releaseLock
};
template <class Super>
class LogOpenClose : public Super {
    public: virtual void open()
    {
        Super::open();
        log("opened");
    }
    virtual void close()
    {
        Super::close();
        log("closed");
    }
    protected: virtual void log(char*s) { ... };
};
class MyDocument : public SyncRW<LogOpenClose<Document>> {};
## True Mixins vs. C++ Mixins

<table>
<thead>
<tr>
<th>True Mixins</th>
<th>C++ Mixins</th>
</tr>
</thead>
<tbody>
<tr>
<td>super natively supported</td>
<td>Mixins reduced to templated superclasses</td>
</tr>
<tr>
<td>Composable mixins</td>
<td>Can be seen as coding pattern</td>
</tr>
<tr>
<td>Hassle-free simple alternative to multiple inheritance</td>
<td>C++ Type system not modular</td>
</tr>
<tr>
<td></td>
<td>⇝ Mixins have to stay source code</td>
</tr>
</tbody>
</table>

### Common properties of Mixins

- Linearization is necessary
- ⇝ Exact sequence of Mixins is relevant
Ok, ok, show me a language with native mixins!
class Person
  attr_accessor :size
  def initialize
    @size = 160
  end
  def hasKey
    true
  end
end

class Door
  def canOpen (p)
    true
  end
  def canPass(person)
    person.size < 210
  end
end

module Short
  def canPass(p)
    p.size < 160 and super(p)
  end
end

module Locked
  def canOpen(p)
    p.hasKey() and super(p)
  end
end

class ShortLockedDoor < Door
  include Short
  include Locked
end

p = Person.new
d = ShortLockedDoor.new
puts d.canPass(p)
class Door
  def canOpen(p)
    true
  end
  def canPass(person)
    person.size < 210
  end
end

module Short
  def canPass(p)
    p.size < 160 and super(p)
  end
end

module Locked
  def canOpen(p)
    p.hasKey() and super(p)
  end
end

module ShortLocked
  include Short
  include Locked
end

class Person
  attr_accessor :size
  def initialize
    @size = 160
  end
  def hasKey
    true
  end
end

p = Person.new
d = Door.new
d.extend ShortLocked
puts d.canPass(p)
Is Inheritance the Ultimate Principle in Reusability?
Control

- Common base classes are shared or duplicated at class level
Lack of Control

- Common base classes are shared or duplicated at class level
- super as ancestor reference vs. qualified specification
- No fine-grained specification of duplication or sharing
Inappropriate Hierarchies

- High up specified methods *turn obsolete*, but there is no statically safe way to remove them.
Inappropriate Hierarchies

- High up specified methods *turn obsolete*, but there is no statically safe way to remove them

⚠️ Liskov Substitution Principle!
Is Implementation Inheritance even an *Anti-Pattern*?
Excerpt from the Java 8 API documentation for class Properties:

“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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⚠️ Misuse of Implementation Inheritance

Implementation Inheritance itself as a pattern for code reusage is often misused!

〜〜 All that is not explicitely prohibited will eventually be done!
The Idea Behind Traits

- A lot of the problems originate from the coupling of implementation and modelling
- Interfaces seem to be hierarchical
- Functionality seems to be modular

Central idea

Separate object *creation* from *modelling* hierarchies and *composing* functionality.

〜〜 Use interfaces to design hierarchical signature propagation
〜〜 Use *traits* as modules for assembling functionality
〜〜 Use classes as frames for entities, which can create objects
A class $t$ is without attributes is called trait.

The **trait sum** $+ : \mathcal{T} \times \mathcal{T} \mapsto \mathcal{T}$ is the componentwise least upper bound:

\[
(c_1 + c_2)(n) = b_1 \sqcup b_2 = \begin{cases} 
b_2 & \text{if } b_1 = \bot \lor n \notin \text{pre}(c_1) \\
b_1 & \text{if } b_2 = \bot \lor n \notin \text{pre}(c_2) \\
b_2 & \text{if } b_1 = b_2 \\
\top & \text{otherwise}
\end{cases}
\]

with $b_i = c_i(n)$

**Trait-Expressions** also comprise:

- **exclusion** $- : \mathcal{T} \times \mathcal{N} \mapsto \mathcal{T}$:
  \[
  (t - a)(n) = \begin{cases} 
  \text{undef} & \text{if } a = n \\
  t(n) & \text{otherwise}
  \end{cases}
  \]

- **aliasing** $[\rightarrow] : \mathcal{T} \times \mathcal{N} \times \mathcal{N} \mapsto \mathcal{T}$:
  \[
  t[a \rightarrow b](n) = \begin{cases} 
  t(n) & \text{if } n \neq a \\
  t(b) & \text{if } n = a
  \end{cases}
  \]

Traits $t$ can be connected to classes $c$ by the asymmetric join:

\[
(c \sqcup t)(n) = \begin{cases} 
  c(n) & \text{if } n \in \text{pre}(c) \\
  t(n) & \text{otherwise}
  \end{cases}
  \]

Usually, this connection is reserved for the last composition level.
# Traits – Concepts

## Trait composition principles

<table>
<thead>
<tr>
<th>Flat ordering</th>
<th>All traits have the same precedence under $+$ under $\triangleright$ explicit disambiguation with aliasing and exclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precedence</td>
<td>Under asymmetric join $\sqcup$, class methods take precedence over trait methods</td>
</tr>
<tr>
<td>Flattening</td>
<td>After asymmetric join $\sqcup$: Non-overridden trait methods have the same semantics as class methods</td>
</tr>
</tbody>
</table>

## Conflicts ...

Conflicts arise if composed traits map methods with identical names to different bodies.

## Conflict treatment

- Methods can be aliased ($\rightarrow$)
- Methods can be excluded ($\leftarrow$)
- Class methods override trait methods and sort out conflicts ($\sqcup$)
Can we augment classical languages by traits?
Extension Methods (C#)

Central Idea:
Uncouple method definitions from class bodies.

Purpose:
- retrospectively add methods to complex types
  ~⇒ external definition
- especially provide definitions of interface methods
  ~⇒ poor man's multiple inheritance!

Syntax:
1. Declare a static class with definitions of static methods
2. Explicitly declare first parameter as receiver with modifier `this`
3. Import the carrier class into scope (if needed)
4. Call extension method in *infix form* with emphasis on the receiver
public class Person{
    public int size = 160;
    public bool hasKey() { return true;}
}

public interface Short {}
public interface Locked {}

public static class DoorExtensions {
    public static bool canOpen(this Locked leftHand, Person p){
        return p.hasMore();
    }

    public static bool canPass(this Short leftHand, Person p){
        return p.size<160;
    }
}

public class ShortLockedDoor : Locked,Short {
    public static void Main() {
        ShortLockedDoor d = new ShortLockedDoor();
        Console.WriteLine(d.canOpen(new Person()));
    }
}
Extension Methods as Traits

Extension Methods

- transparently extend arbitrary types externally
- provide quick relief for plagued programmers

...but not traits

- Interface declarations empty, thus kind of purposeless
- Flattening not implemented
- Static scope only

Static scope of extension methods causes unexpected errors:

```csharp
public interface Locked {
    public bool canOpen(Person p);
}
public static class DoorExtensions {
    public static bool canOpen(this Locked leftHand, Person p) {
        return p.hasKey();
    }
}
```
Extension Methods as Traits

**Extension Methods**
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}

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    public static bool canOpen(this Locked leftHand, Person p) {
        return p.hasKey();
    }
}
```
Java 8 advances one step further:

```java
interface Door {
    boolean canOpen(Person p);
    boolean canPass(Person p);
}
interface Locked {
    default boolean canOpen(Person p) { return p.hasKey(); } 
}
interface Short {
    default boolean canPass(Person p) { return p.size<160; } 
}
public class ShortLockedDoor implements Short, Locked, Door {
}
```

**Implementation**

...consists in adding an interface phase to `invokevirtual`'s name resolution

**Precedence**

Still, default methods do not override methods from `abstract classes` when composed
**Central Idea**

Separate class generation from hierarchy specification and functional modelling

1. model hierarchical relations with interfaces
2. compose functionality with traits
3. adapt functionality to interfaces and add state via glue code in classes

**Simplified multiple Inheritance without adverse effects**
So let’s do the language with real traits?!
Squeak

Squeak is a smalltalk implementation, extended with a system for traits.

Syntax:

- `name: param1 and: param2`
  declares method name with param1 and param2

- `| ident1 ident2 |`
  declares Variables ident1 and ident2

- `ident := expr`
  assignment

- `object name: content`
  sends message name with content to object (≡ call: object.name(content))

- `.`
  line terminator

- `^ expr`
  return statement
Trait named: `#TRStream` uses: `TPositionableStream`  

- **on:** aCollection
  - `self setStart.`

- **next**
  - `self atEnd`
    - `ifTrue: [nil]`
    - `ifFalse: [self collection at: self nextPosition].`

Trait named: `#TSynch` uses: `{}`

- **acquireLock**
  - `self semaphore wait.`

- **releaseLock**
  - `self semaphore signal.`

Trait named: `#TSyncRStream` uses: `TSynch+(TRStream@(#readNext -> #next))`

- **next**
  - `| read |`
  - `self acquireLock.`
  - `read := self readNext.`
  - `self releaseLock.`
  - `^ read.`
Disambiguation

Traits vs. Mixins vs. Class-Inheritance

All different kinds of type expressions:

- Definition of curried *second order type operators* + Linearization

Explicitly: Traits differ from Mixins

- Traits are applied to a class *in parallel*, Mixins *sequentially*
- Trait *composition is unordered*, avoiding linearization effects
- Traits do *not contain attributes*, avoiding state conflicts
- With traits, *glue code* is concentrated in single classes
Disambiguation

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Traits vs. Mixins vs. Class-Inheritance

All different kinds of type expressions:

- Definition of curried *second order type operators* + Linearization
- Finegrained flat-ordered *composition of modules*
- Definition of (local) partial order on precedence of types wrt. MRO
- Combination of principles

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Lessons learned

Mixins

- Mixins as *low-effort* alternative to multiple inheritance
- Mixins lift type expressions to *second order type expressions*

Traits

- Implementation Inheritance based approaches leave room for improvement in modularity in real world situations
- Traits offer *fine-grained control* of composition of functionality
- Native trait languages offer *separation of composition* of functionality from *specification* of interfaces
Further reading...


Stéphane Ducasse, Oscar Nierstrasz, Nathanael Schärli, Roel Wuyts, and Andrew P. Black. Traits: A mechanism for fine-grained reuse. *ACM Transactions on Programming Languages and Systems (TOPLAS)*, 2006.


Nathanael Schärli, Stéphane Ducasse, Oscar Nierstrasz, and Andrew P. Black. Traits: Composable units of behaviour. *European Conference on Object-Oriented Programming (ECOOP)*, 2003.