An Algebra for Features and Feature Composition

Sven Apel (University of Passau)

Christian Lengauer (University of Passau)

Don Batory (UT Austin)

Bernhard Möller (University of Augsburg)

Christian Kästner (University of Magdeburg)

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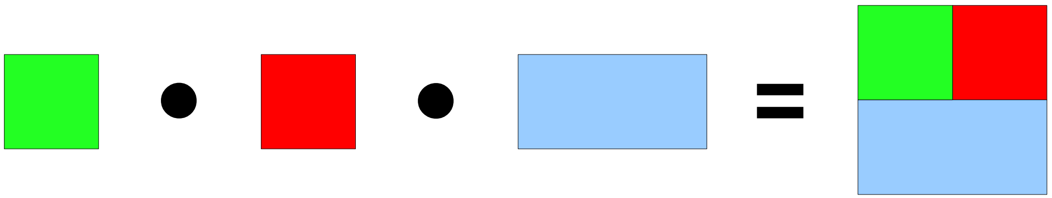
Feature-Oriented Software Development

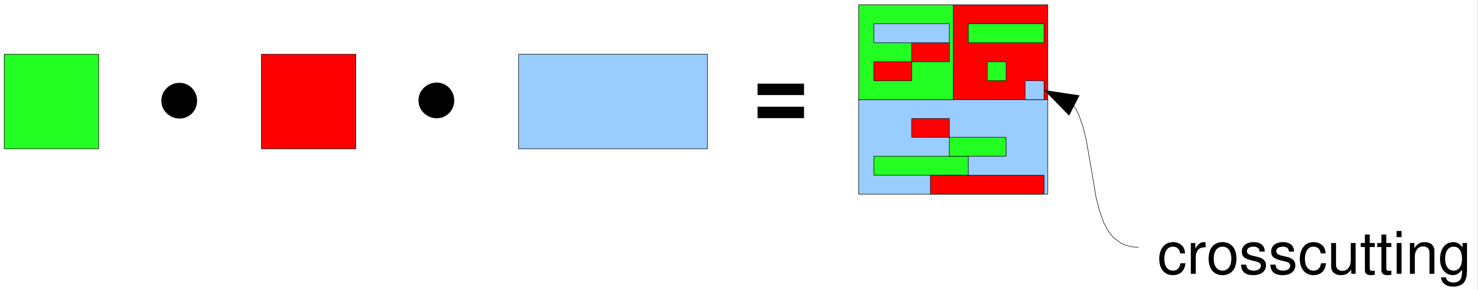
- What is a feature?
  - Increment in program functionality
  - Maps to a requirement
  - Used to distinguish different programs
- Idea: represent features explicitly in design and code
  - Each feature is encapsulated in a module
  - A feature refines a (possibly empty) program
  - A final program is composed of a series of features

Feature Composition

- A simple model of feature composition (•)



- The reality is more complicated



Diverse Implementation Approaches

- Components
- Collaboration-based design
- Aspect-oriented programming
- Generative programming
- Frames
- ...

➔ What are the essence and the principles of features and feature composition?

Our Approach

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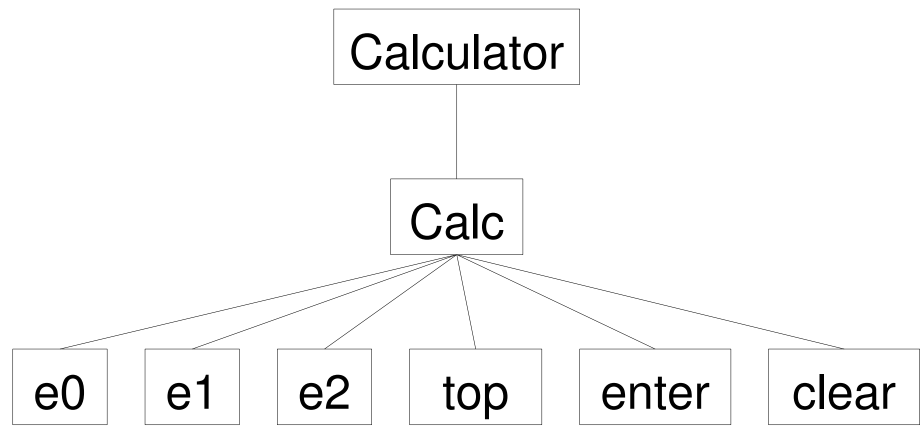
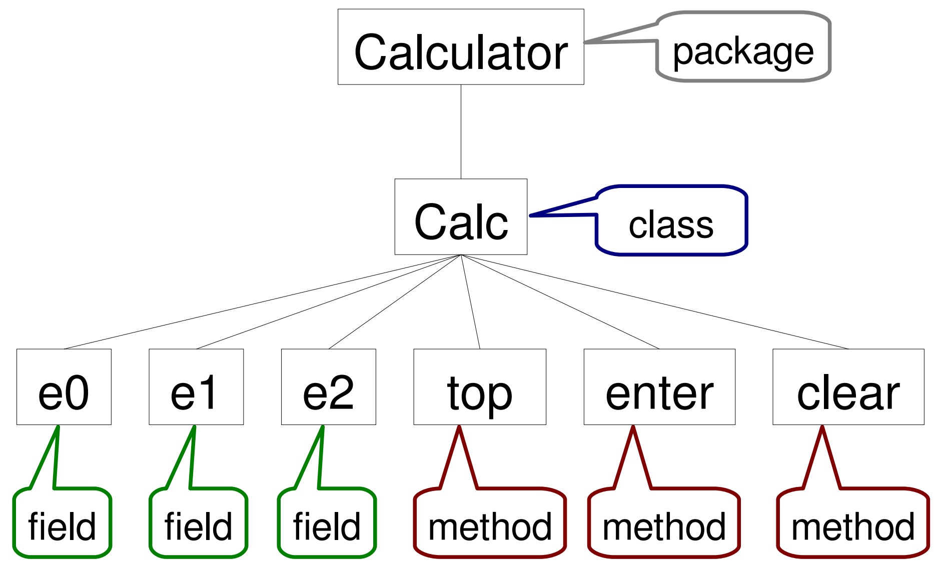
Features are Trees

```
class Calc {
  int e0 = 0, e1 = 0, e2 = 0;
  void enter(int val) {
    e2 = e1; e1 = e0; e0 = val;
  }
  void clear() {
    e0 = e1 = e2 = 0;
  }
  String top() {
    return String.valueOf(e0);
  }
}
```



Nodes Have Different Types

```
class Calc {
  int e0 = 0, e1 = 0, e2 = 0;
  void enter(int val) {
    e2 = e1; e1 = e0; e0 = val;
  }
  void clear() {
    e0 = e1 = e2 = 0;
  }
  String top() {
    return String.valueOf(e0);
  }
}
```



Feature Composition is Tree Superimposition

```
package Calculator;
class Calc {
  void add() {
    e0 = e1 + e0; e1 = e2;
  }
}
```

feature: Add

•

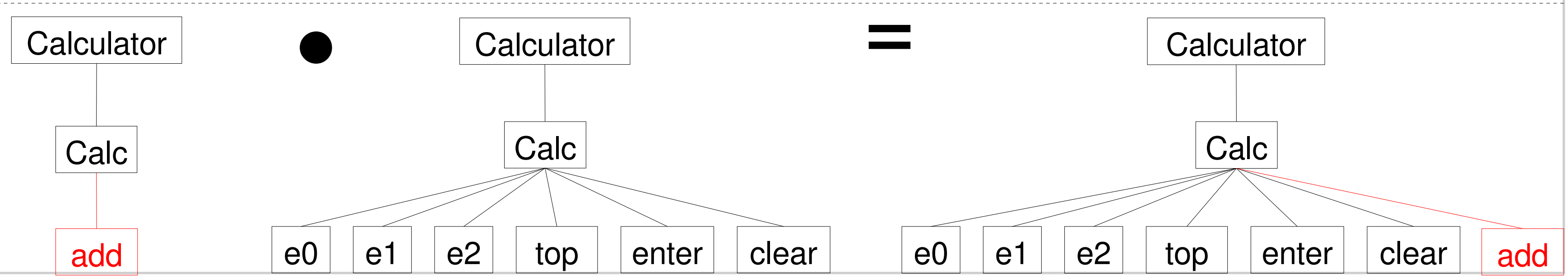
```
package Calculator;
class Calc {
  int e0 = 0, e1 = 0, e2 = 0;
  void enter(int val) {
    e2 = e1; e1 = e0; e0 = val;
  }
  void clear() {
    e0 = e1 = e2 = 0;
  }
  String top() {
    return String.valueOf(e0);
  }
}
```

feature: CalcBase

=

```
package Calculator;
class Calc {
  int e0 = 0, e1 = 0, e2 = 0;
  void enter(int val) {
    e2 = e1; e1 = e0; e0 = val;
  }
  void clear() {
    e0 = e1 = e2 = 0;
  }
  String top() {
    return String.valueOf(e0);
  }
  void add() {
    e0 = e1 + e0; e1 = e2;
  }
}
```

feature: CalcAdd



Feature Composition

- Recursive composition of the elements of a feature
  - *package* • *package* → *package* (also for subpackages)
  - *class* • *class* → *class* (also for inner classes)
  - *interface* • *interface* → *interface* (also for inner interfaces)
  - *method* • *method* → ?
  - *field* • *field* → ?

What About Fields and Methods?

- If the same signature, there are two options:
  1. Consider these compositions errors
  2. Allow these compositions under some circumstances
     - *method* • *method* → *method* if one method calls **`original`**
     - *field* • *field* → *field* if one field is abstract (no value assigned)

Composition of Fields and Methods

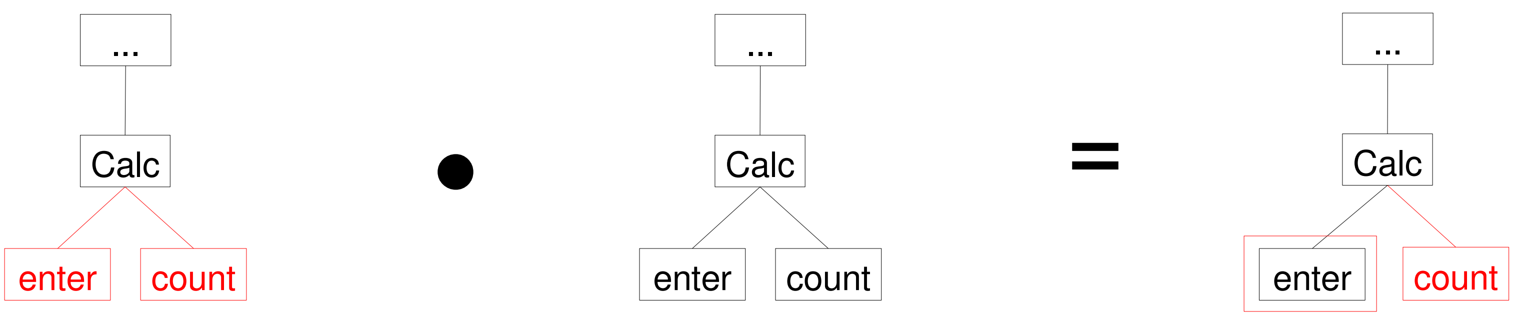
```
class Calc {
  int count = 0;
  void enter(int val) {
    original.enter(val);
    count++;
  }
}
```

•

```
class Calc {
  int count;
  void enter(int val) {
    e2 = e1; e1 = e0; e0 = val;
  }
}
```

=

```
class Calc {
  int count = 0;
  void enter(int val) {
    e2 = e1; e1 = e0; e0 = val;
    count++;
  }
}
```



A Feature Algebra

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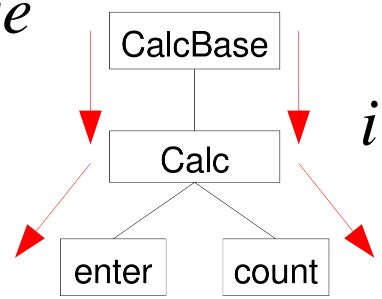
Paths and Introductions

- A feature is represented as a tree
- Each path in the tree, starting at the root, is called an introduction

$$i_1 = CalcBase$$



$$i_2 = CalcBase.Calc$$

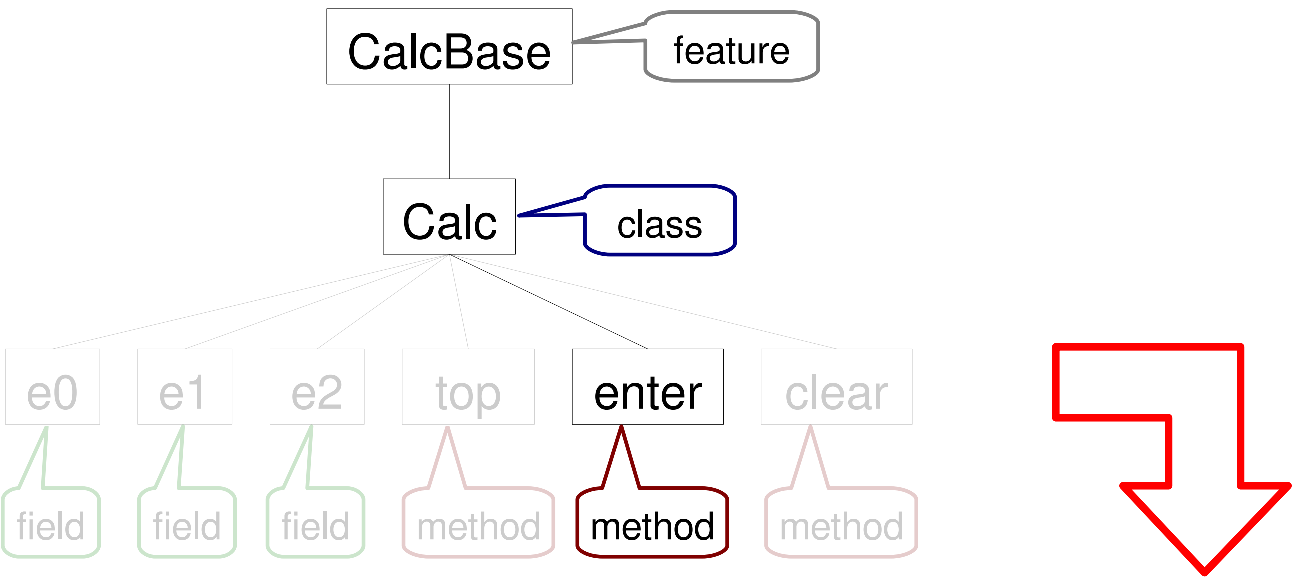
$$i_3 = CalcBase.Calc.enter$$

$$i_4 = CalcBase.Calc.count$$

- The hierarchical structure is encoded in the identifiers

Introductions Encode Type Information

- Similarly to trees that represent features, an introduction encodes type information in its identifier



$$i = CalcBase^{feature}.Calc^{class}.enter^{method}$$

Features and Introductions

- A feature is a sum of introductions ($\oplus$)

$$
\begin{aligned}
F = & \, CalcBase \\
& \oplus CalcBase.Calc \\
& \oplus CalcBase.Calc.e0 \\
& \oplus CalcBase.Calc.e1 \\
& \oplus CalcBase.Calc.e2 \\
& \oplus CalcBase.Calc.enter \\
& \oplus CalcBase.Calc.clear \\
& \oplus CalcBase.Calc.top
\end{aligned}
$$

A compiler can evaluate this meta-expression and synthesize the according code

the set of summands is prefix-closed

Introduction Sum

- Introduction sum over the set of introductions I forms an **idempotent non-commutative monoid (I, $\oplus$)**
  - Closure: composing introductions creates new introductions
  - Associativity: $(a \oplus b) \oplus c = a \oplus (b \oplus c)$
  - Identity: $\xi \oplus a = a \oplus \xi = a$ (ξ is the empty introduction)
  - Non-commutativity: $a \oplus b \neq b \oplus a$
  - Distant idempotence: $a \oplus b \oplus a = b \oplus a$
    - implies direct idempotence: $a \oplus a = a$

Feature Composition is Introduction Sum

- Features are composed by introduction sum

$$F = \underbrace{i_1 \oplus \ldots \oplus i_{m_0}}_{F_0} \oplus \ldots \oplus \underbrace{i_1 \oplus \ldots \oplus i_{m_n}}_{F_n}$$

Semantics of Introduction Sum

- An introduction adds a new path to a tree
- Introductions are composed recursively
- Nodes with the same name and type are merged
  - Node wrapping
  - Subtree merging

Applications of Introductions

- Node wrapping
  - Extend methods via overriding
  - Shield field accesses
  - Declare new superclasses and interfaces
- Subtree merging
  - Add new packages, classes, interfaces, methods, fields

Modification – A Further Element of a Feature

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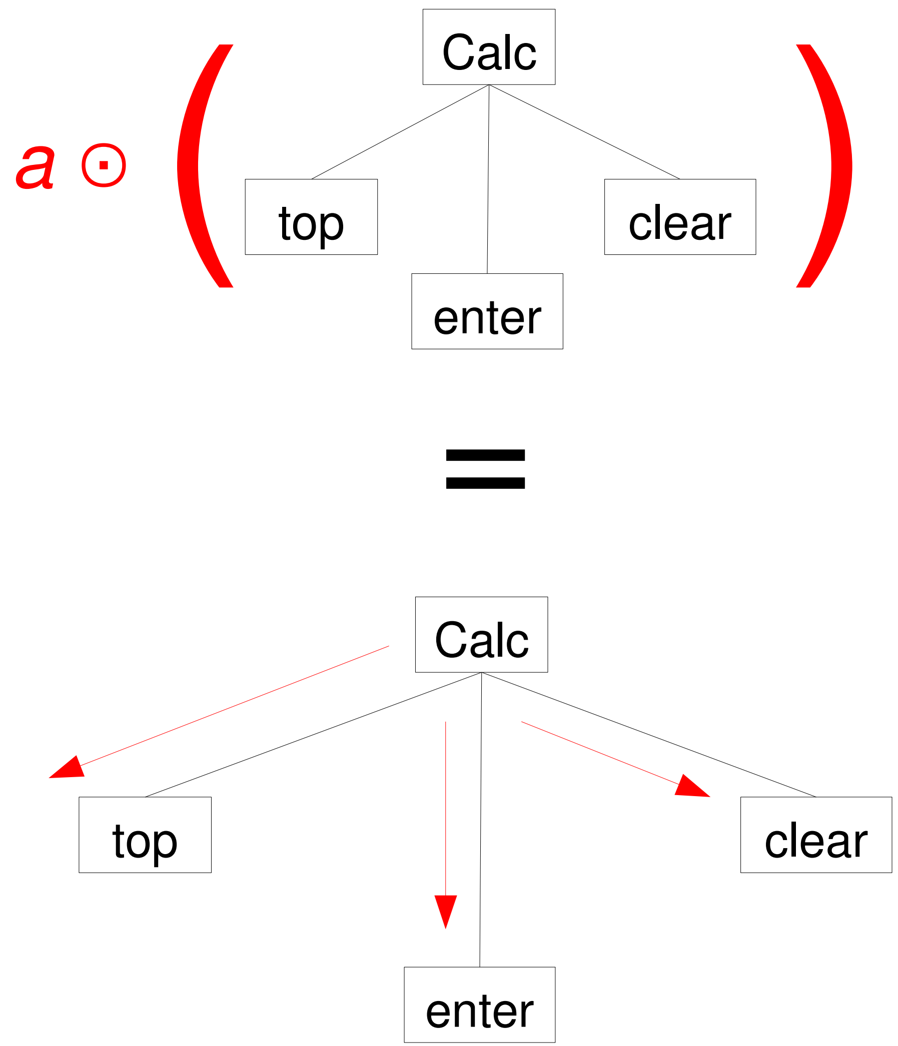
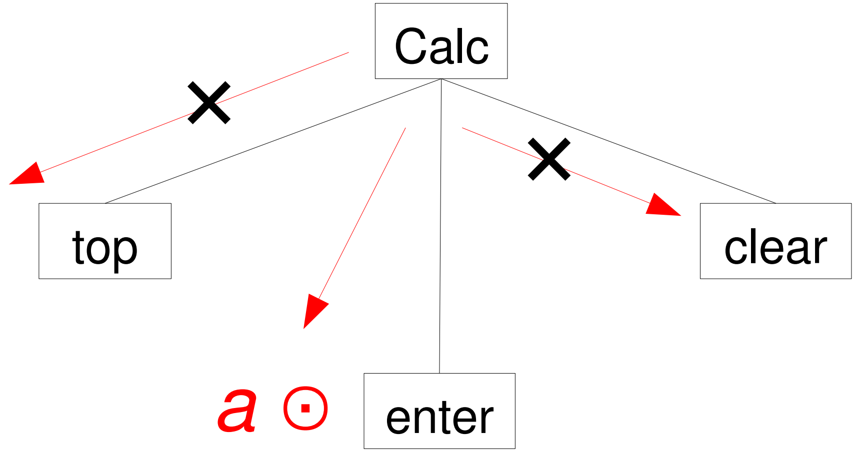
Modifications

- Meta-level entities / meta-programming constructs
- Quantify over introductions
- Apply changes to a feature declaratively
- General form of modifications
  - Where does something happen?
  - What happens?
  - (What conditions must hold?)

Modifications are Tree Walks



Where is a Modification Applied?



a = *.enter

Effects of Modifications

- Same as introduction sum
  - Add new children to a node
  - Wrapping of nodes

So What is the Difference Between Introductions and Modifications?

- Both can wrap nodes and add subtrees
- The difference between both is how this is expressed
  - Where does something happen?
  - What happens?

Back to our Feature Algebra

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Operations on Modifications

- Modifications can be added (just like introductions)

$$\oplus : A \times A \rightarrow A$$

- Modifications can be composed like functions

$$\odot : A \times A \rightarrow A$$

- Modifications can be applied to introductions

$$\odot : A \times I \rightarrow I$$

Modification Sum

- $\oplus : A \times A \rightarrow A$
- Modifications consist of two parts
  - Where does something happen?
    - The sum modifies the union of join points
  - What happens?
    - Disjoint sets of join points
      - Wrappers and subtree introductions can be merged to one set
    - Overlapping join points
      - Wrappers are nested based on the summation order
      - Subtrees are merged based on the summation order

Modification Application

- $\odot : A \times I \to I$

- Modifications are applied to sums of introductions

$$a \odot (i \oplus j) = (a \odot i) \oplus (a \odot j) \quad \text{with} \quad a \in A \quad \text{and} \quad i, j \in I$$

Modification Composition

- $\odot : A \times A \rightarrow A$

- Modification composition is successive modification application

$$(a \odot b) \odot i = a \odot (b \odot i) \quad \text{with} \quad a, b \in A \quad \text{and} \quad i \in I$$

Algebraic Properties of Modifications

- Modifications and their operations form a **binoid** $(A, \oplus, \odot)$
  - $(A, \oplus)$ with $\oplus: A \times A \to A$ is an **idempotent monoid**
    - Associativity: $(a \oplus b) \oplus c = a \oplus (b \oplus c)$
    - Identity: $\zeta \oplus a = a \oplus \zeta = a$ (ζ is the empty modification)
    - Non-commutativity: $a \oplus b \neq b \oplus a$
    - Distant idempotence: $a \oplus b \oplus a = b \oplus a$
      - implies direct idempotence: $a \oplus a = a$
  - $(A, \odot)$ with $\odot: A \times A \to A$ is a **monoid**
    - Associativity: $(a \odot b) \odot c = a \odot (b \odot c)$
    - Identity: $\zeta \odot a = a \odot \zeta = a$ (ζ is the empty modification)
    - Non-commutativity: $a \odot b \neq b \odot a$

Algebraic Properties of Features

(I, $\oplus$) is a **semimodul** over the **binoid** (A, $\oplus$, $\odot$)

$$a \odot (i \oplus j) = (a \odot i) \oplus (a \odot j) \quad \text{with} \quad a \in A \quad \text{and} \quad i, j \in I$$

$$(a \oplus b) \odot i = (a \odot i) \oplus (b \odot i) \quad \text{with} \quad a, b \in A \quad \text{and} \quad i \in I$$

$$(a \odot b) \odot i = a \odot (b \odot i) \quad \text{with} \quad a, b \in A \quad \text{and} \quad i \in I$$

Quarks

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Two Interpretations of Modifications

- **Local modifications** (*a*) affect only introductions of the features applied before

$$F_3 \bullet F_2 \bullet F_1 \bullet X = i_3 \oplus a_3 \odot (i_2 \oplus a_2 \odot (i_1 \oplus a_1 \odot X))$$

- **Global modifications** (*g*) may affect all introductions of a series of features

$$F_3 \bullet F_2 \bullet F_1 \bullet X = (g_3 \odot g_2 \odot g_1) \odot (i_3 \oplus i_2 \oplus i_1 \oplus X)$$

Quarks

- A feature consists of introductions and local / global modifications of different orders
- Composition of features is not obvious ➔ ***quarks***
- A quark is a triple and represents a feature

$$q = \langle g, i, a \rangle$$

Quark Composition

$$\langle g_1, i_1, a_1\rangle\langle g_2, i_2, a_2\rangle = \langle g_1 \odot g_2, i_1 \oplus (a_1 \odot i_2), a_1 \odot a_2\rangle$$

Conclusions