Delta-based Verification of Software Product Families

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Verification

of

Software Product Lines

implemented with

Delta Oriented Programming (ABS)

Delta Oriented Programming

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```
1  class C {
2     Int f;
3
4     Unit m(Int x) {
5        this.f = this.f + x;
6     }
7
8     Unit m1(Int x) {
9        this.m(x);
10       this.f = this.f + 1;
11    }
12 }
```

Variants:

{ C }

Delta Oriented Programming

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```
1  delta D1 when Feature1{
2     modifies C {
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4           original(x);
5           this.f = this.f + 2;
6        }
7     }
8  }
```

Variants:

{ C, C.D1 }

Delta Oriented Programming

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```
1  class C {
2     Int f;
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```
1  delta D1 when Feature1{
2     modifies C {
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4           original(x);
5           this.f = this.f + 2;
6        }
7     }
8  }
```

```
1  delta D2 when Feature2{
2     modifies C {
3        modifies Unit m(Int x) {
4           original(x);
5           this.f = this.f + 3;
6        }
7     }
8  }
```

Variants:

{ C, C.D1, C.D2, C.D1.D2 }

Delta Oriented Programming

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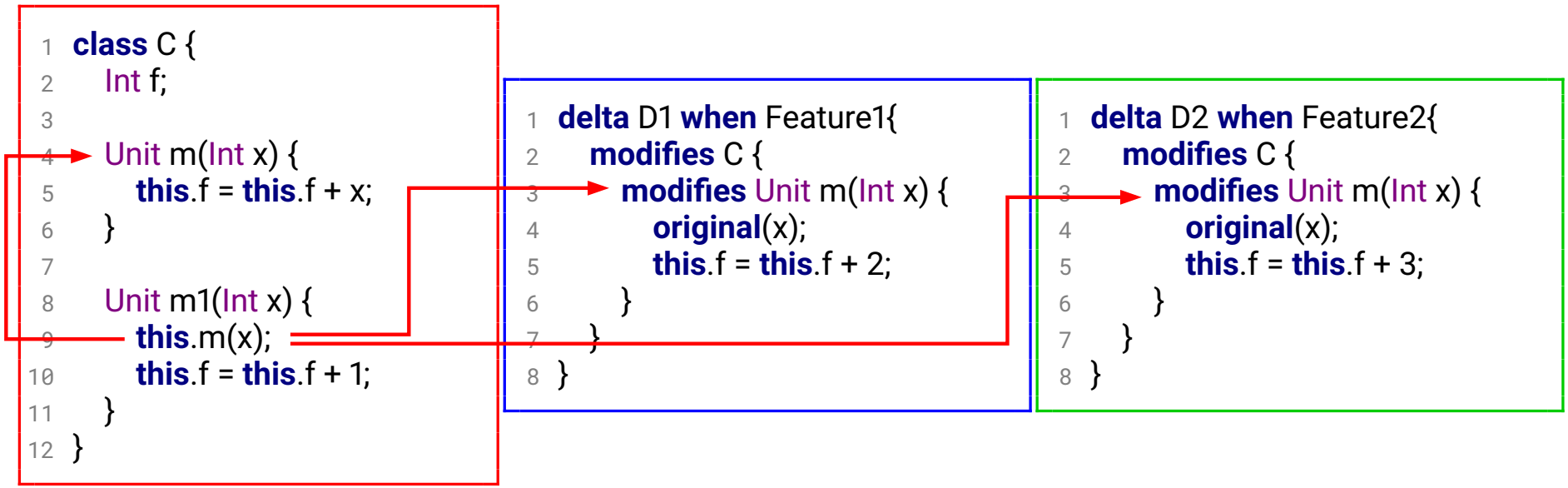

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delta D2 when Feature2{
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Variants:

{ C, C.D1, C.D2, C.D1.D2 }

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Delta Oriented Programming

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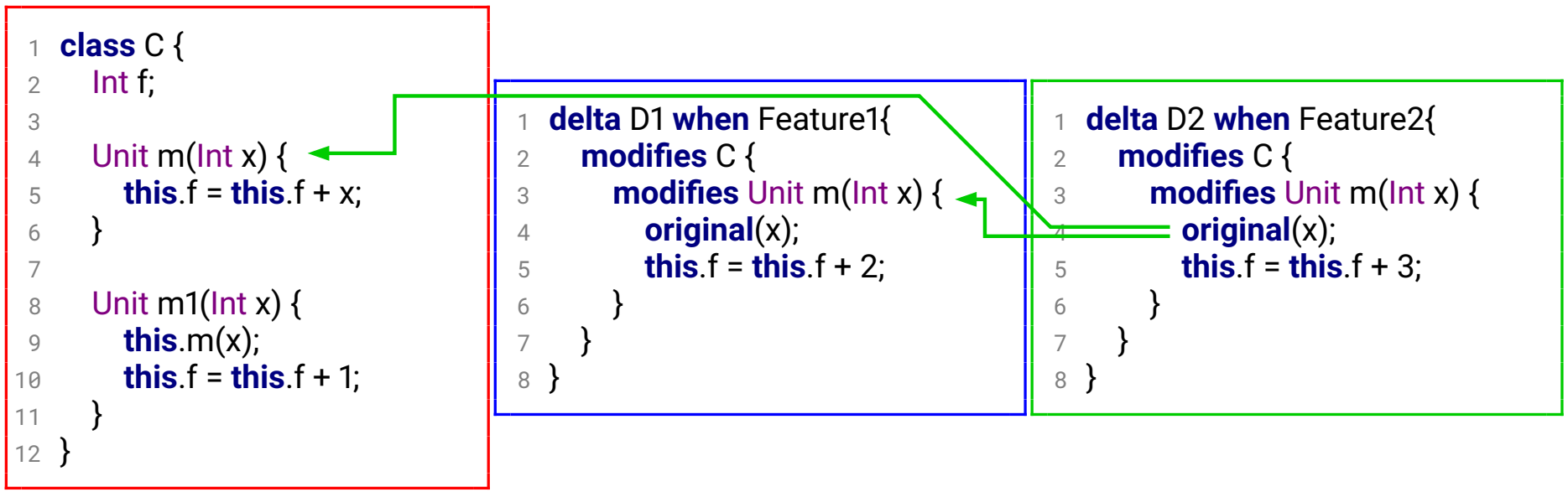

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```
delta D1 when Feature1{
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      }
   }
}
```

```
delta D2 when Feature2{
   modifies C {
      modifies Unit m(Int x) {
         original(x);
         this.f = this.f + 3;
      }
   }
}
```

Variants:

{ C, C.D1, C.D2, C.D1.D2 }

Delta Oriented Programming

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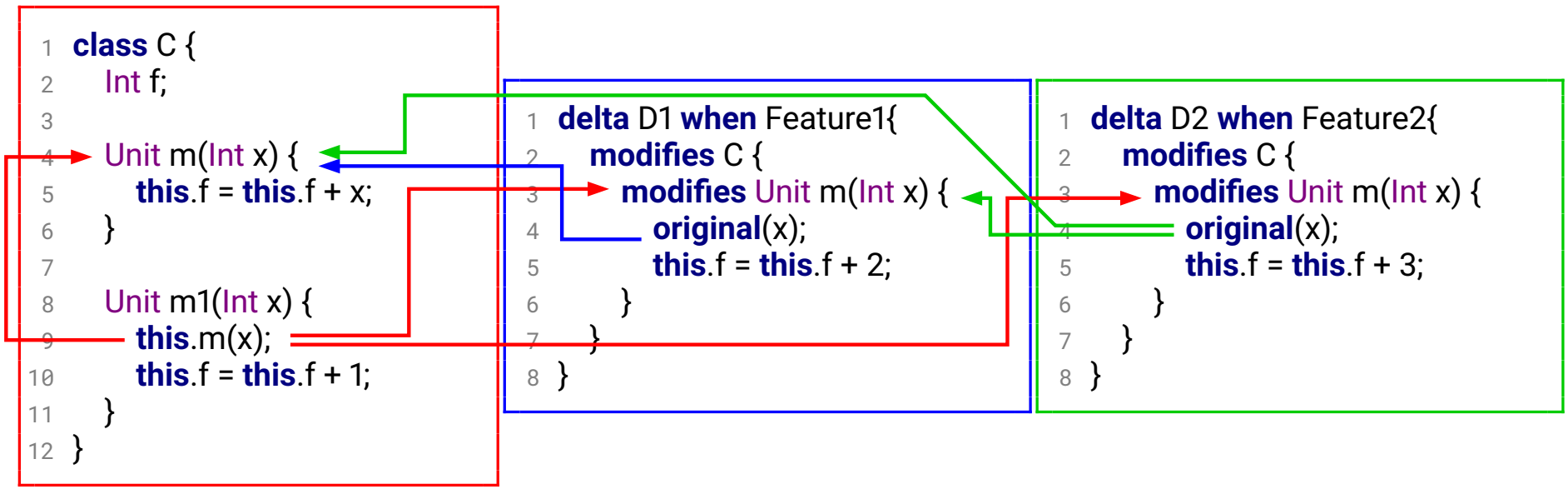

Variants:

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Contract-based Approach

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```
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5     //@ensures this.f = \old(this.f) + x;
6     //@assignable this.f;
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```

Behavior of `m` specified by

`(m.pre, m.post, m.frame)`

Contract-based Approach

TECHNISCHE UNIVERSITÄT DARMSTADT

```
1   class C {
2     Int f;
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4     //@requires True; ⇐ precondition
5     //@ensures this.f = \old(this.f) + x;
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(True, this.f = \old(this.f) + x, {this.f})
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!! We focus on normal behaviors !!

Compositional Verification

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```
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7     Unit m(Int x) {
8        this.f = this.f + x;
9     }
10
11    //@requires True;
12    //@ensures this.f = \old(this.f) + x  + 1;
13    //@assignable this.f;
14    Unit m1(Int x) {
15       this.m(x);
16       this.f = this.f + 1;
17    }
18 }
```

Compositional Verification

TECHNISCHE UNIVERSITÄT DARMSTADT

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Compositional Verification ??

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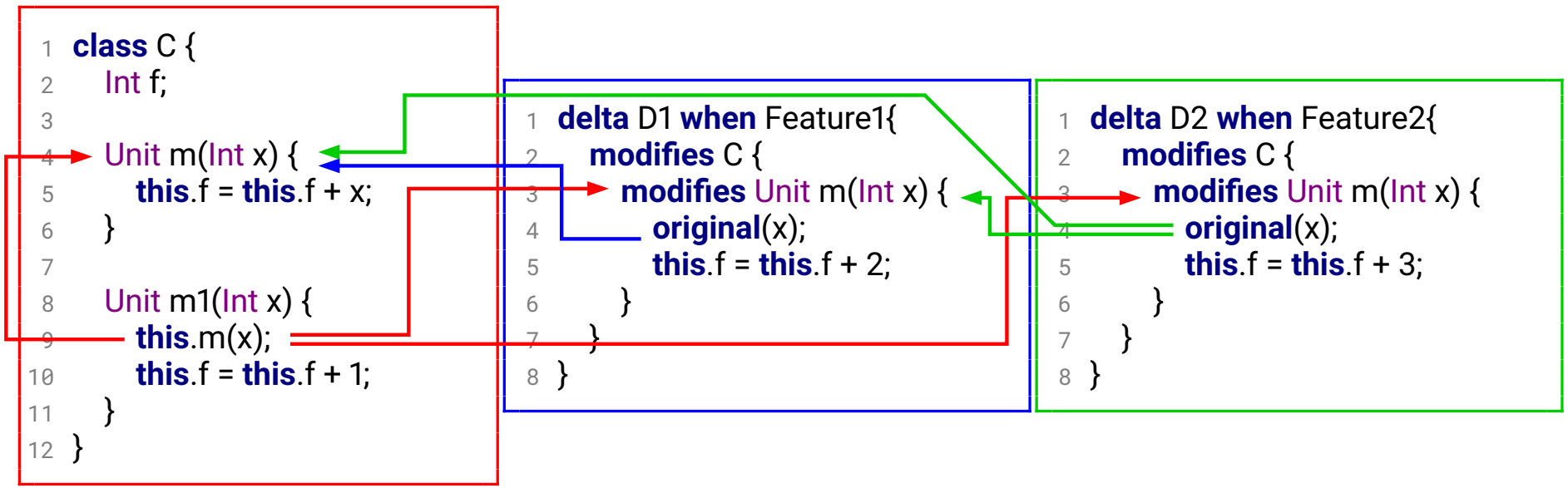

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}
```

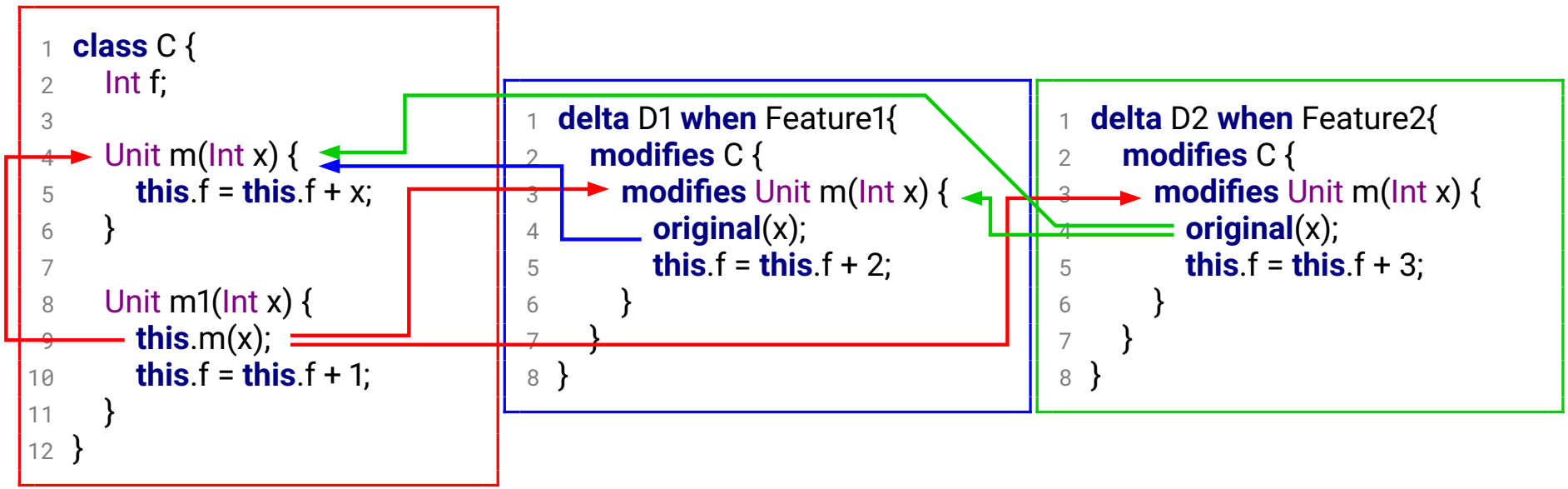
```
delta D1 when Feature1{
    modifies C {
        modifies Unit m(Int x) {
            original(x);
            this.f = this.f + 2;
        }
    }
}
```

```
delta D2 when Feature2{
    modifies C {
        modifies Unit m(Int x) {
            original(x);
            this.f = this.f + 3;
        }
    }
}
```

Straightforward solution: **product-based** verification

Compositional Verification ??

TECHNISCHE UNIVERSITÄT DARMSTADT



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3        modifies Unit m(Int x) {
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6        }
7     }
8  }
```

Straightforward solution: **product-based** verification

⇓

Expensive: **exponential complexity** $O(2^N * M)$

(N nr. of deltas, M nr. of methods)

Liskov Substitution Principle for DOP

Hähnle and Schaefer (2012)

More-general-than Relation ($\succeq$)

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```

`C.m.contract` ***is-more-general-than*** `D1.C.m.contract`

More-general-than Relation ($\succeq$)

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```

`(C.m.preq, C.m.post, C.m.frame)` $\succeq$ `(D1.C.m.preq, D1.C.m.post, D1.C.m.frame)`

More-general-than Relation ($\succeq$)

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`(m.preq, m.post, m.frame)` $\succeq$ `(m.preq, m.post, m.frame)`

if and only if

m.preq $\Rightarrow$ m.preq

m.post $\Leftarrow$ m.post

m.frame $\supseteq$ m.frame

More-general-than Relation ($\succeq$)

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$$\text{True} \Rightarrow \text{True}$$

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```

(m.preq, m.post, m.frame) $\succeq$ (m.preq, m.post, m.frame)

if and only if

True $\Rightarrow$ True

f >= \old(f) + x $\Leftarrow$ f >= \old(f) + x + 2

m.frame $\supseteq$ m.frame

More-general-than Relation ($\succeq$)

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(m.preq, m.post, m.frame) $\succeq$ (m.preq, m.post, m.frame)

if and only if

True $\Rightarrow$ True

f >= \old(f) + x $\Leftarrow$ f >= \old(f) + x + 2

{f} $\supseteq$ {f}

More-general-than Relation ($\succeq$)

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```

`C.m.contract` $\succeq$ `D1.C.m.contract`

then

`D1.m` satisfies `D1.m.contract` $\Longrightarrow$ `D1.m` satisfies `C.m.contract`

More-general-than Relation ($\succeq$)

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```
1  delta D1 when Feature1{
2      modifies C {
3          //@requires True;
4          //@ensures f >= \old(f) + x  + 2;
5          //@assignable f;
6          modifies Unit m(Int x) {
7              original(x);
8              this.f = this.f + 2;
9          }
10     }
11 }
```

A *correct* method `m` **fulfills** every contract more general than its own

More-general-than Relation ($\succeq$)

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```
1  class C {
2      Int f;
3      //@requires True;
4      //@ensures f >= \old(f) + x;
5      //@assignable f;
6      Unit m(Int x) {
7          this.f = this.f + x;
8      }
9
10     //...
11 }
```

```
1  delta D1 when Feature1{
2      modifies C {
3          //@requires True;
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7              original(x);
8              this.f = this.f + 2;
9          }
10     }
11 }
```

A *correct* method `m` **fulfills** every contract more general than its own

When **calling `m`** we can consider its **most general contract**

Liskov Substitution Principle for DOP

Hähnle and Schaefer (2012)

TECHNISCHE UNIVERSITÄT DARMSTADT

For each version of `m`
its contract is **more-specific-than each previous one**

Liskov Substitution Principle for DOP

Hähnle and Schaefer (2012)

TECHNISCHE UNIVERSITÄT DARMSTADT

For each version of `m`
its contract is **more-specific-than each previous one**

+

Each method is **Liskov-verified**:

*for each method call we consider its **most general contract***

Liskov Substitution Principle for DOP

Hähnle and Schaefer (2012)

TECHNISCHE UNIVERSITÄT DARMSTADT

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⇓

Every variant **is correct**

Liskov Substitution Principle for DOP

Hähnle and Schaefer (2012)

TECHNISCHE UNIVERSITÄT DARMSTADT

For each version of `m`
its contract is **more-specific-than each previous one**

+

Each method is **Liskov-verified**:

*for each method call we consider its **most general contract***

⇓

Every variant **is correct**

+

No variant is **generated**: polynomial complexity **O(N*M)**

(N=nr. of deltas, M=nr. of methods)

Liskov Substitution Principle for DOP: PROBLEM

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Program behaviors can **only** become **more specific**

Liskov Substitution Principle for DOP: PROBLEM

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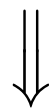
Program behaviors can **only** become **more specific**



All the versions of a method have
the **same** (most general) **behavior**

Liskov Substitution Principle for DOP: PROBLEM

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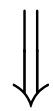
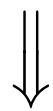
Program behaviors can **only** become **more specific**



All the versions of a method have
the **same** (most general) **behavior**



Deltas **do not modify** method **behaviors**

Idea

TECHNISCHE UNIVERSITÄT DARMSTADT

Goal: Overcome Liskov's restrictions *without increasing costs*

Idea

TECHNISCHE UNIVERSITÄT DARMSTADT

Goal: Overcome Liskov's restrictions *without increasing costs*

How?

Idea

TECHNISCHE UNIVERSITÄT DARMSTADT

Goal: Overcome Liskov's restrictions *without increasing costs*

How?

An **original call** in `m` refers to a **set of versions** of `m`

Idea

TECHNISCHE UNIVERSITÄT DARMSTADT

Goal: Overcome Liskov's restrictions *without increasing costs*

How?

An **original call** in `m` refers to a **set of versions** of `m`

+

Represent this set abstractly:

original calls as *abstract programs*

Idea

TECHNISCHE UNIVERSITÄT DARMSTADT

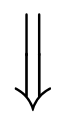
Goal: Overcome Liskov's restrictions *without increasing costs*

How?

An **original call** in `m` refers to a **set of versions** of `m`

+

Represent this set abstractly:
original calls as *abstract programs*



Verifying each delta in isolation

(*delta-based verification*)

How to Deal with Abstract Programs?

TECHNISCHE UNIVERSITÄT DARMSTADT

σ_1

$$x \doteq 0$$
$$y \doteq 2$$

How to Deal with Abstract Programs?

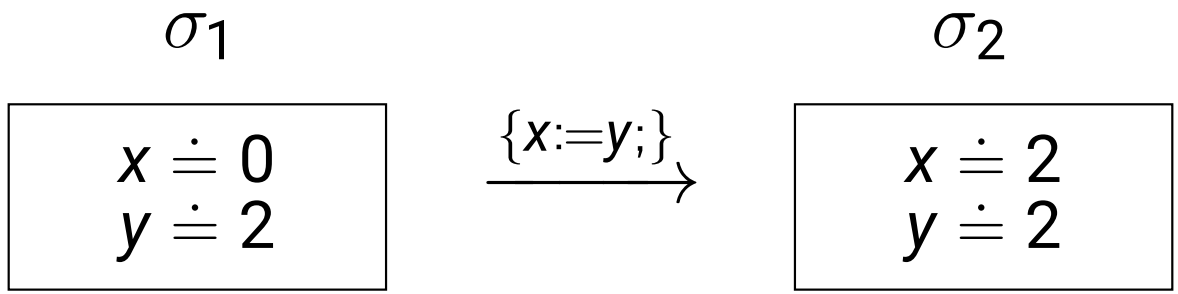
TECHNISCHE UNIVERSITÄT DARMSTADT

$$\sigma_1$$

$$\boxed{\begin{array}{c} x \doteq 0 \\ y \doteq 2 \end{array}} \xrightarrow{\{x := y;\}}$$

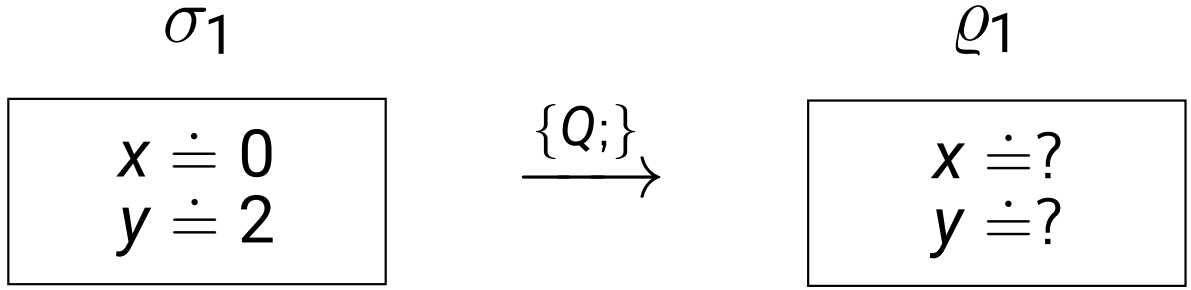
How to Deal with Abstract Programs?

TECHNISCHE UNIVERSITÄT DARMSTADT



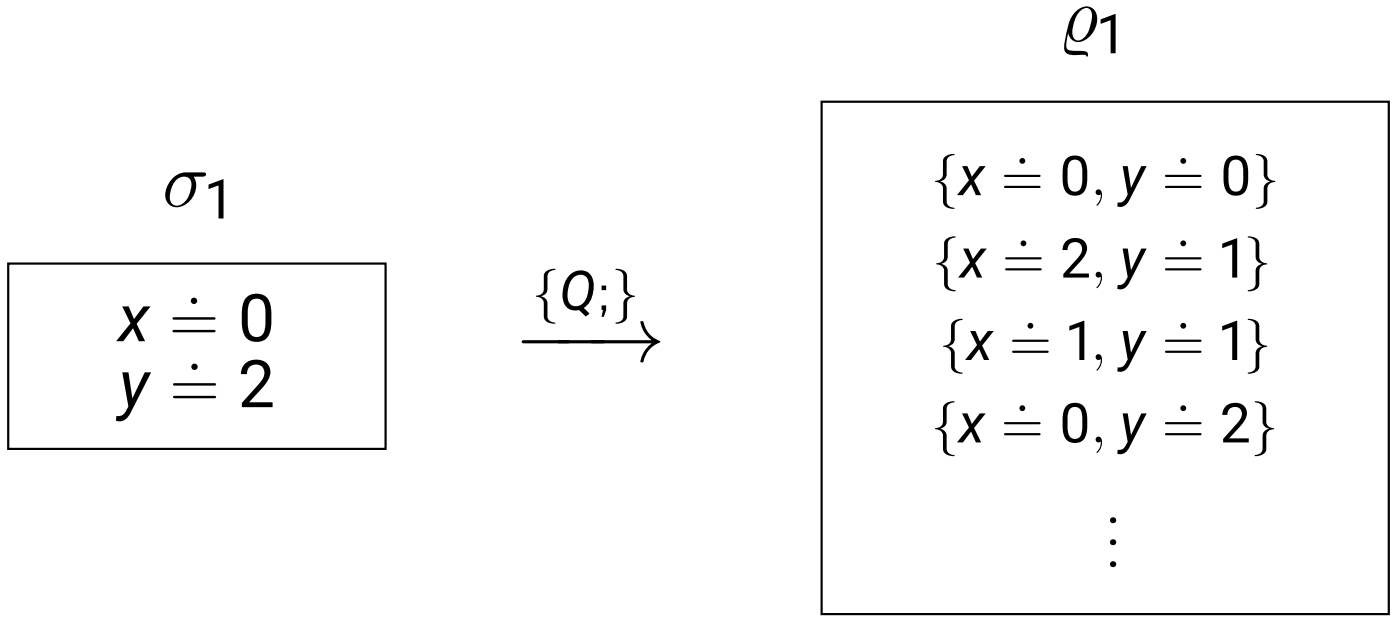
How to Deal with Abstract Programs?

TECHNISCHE UNIVERSITÄT DARMSTADT



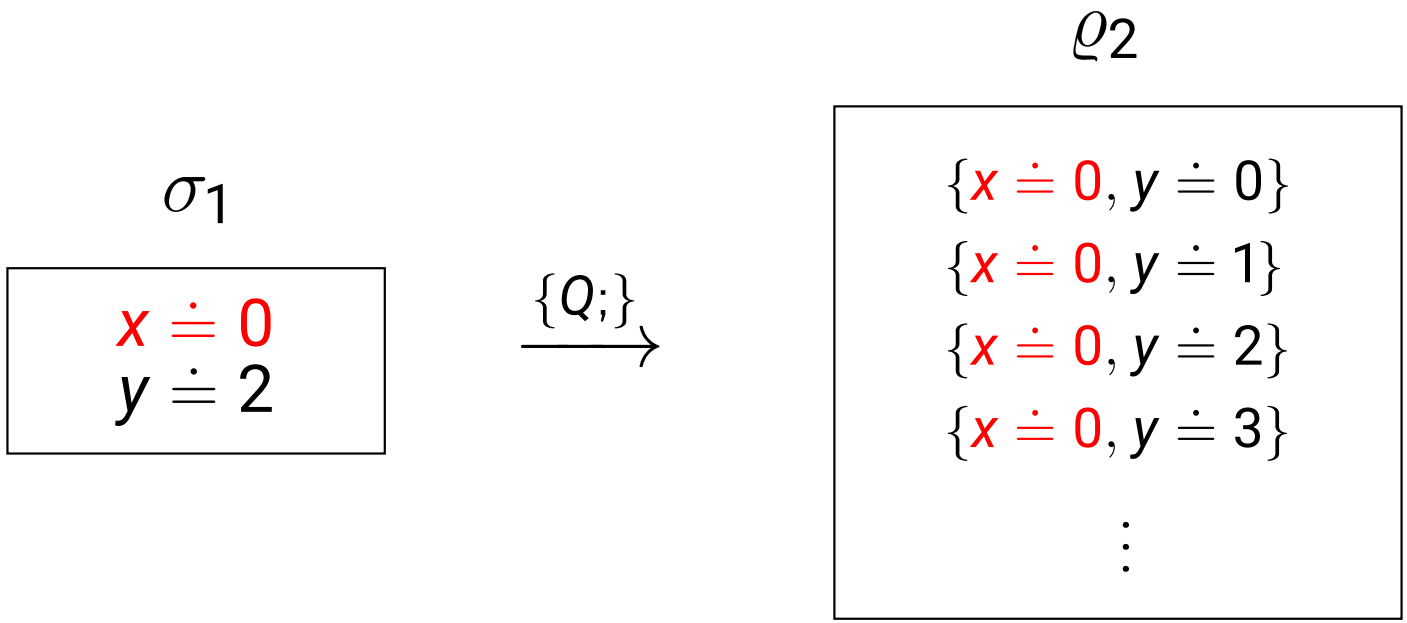
How to Deal with Abstract Programs?

TECHNISCHE UNIVERSITÄT DARMSTADT



How to Deal with Abstract Programs?

TECHNISCHE UNIVERSITÄT DARMSTADT



If Q cannot assign x

Abstract Execution

Steinhöfel and Hähnle (2019)

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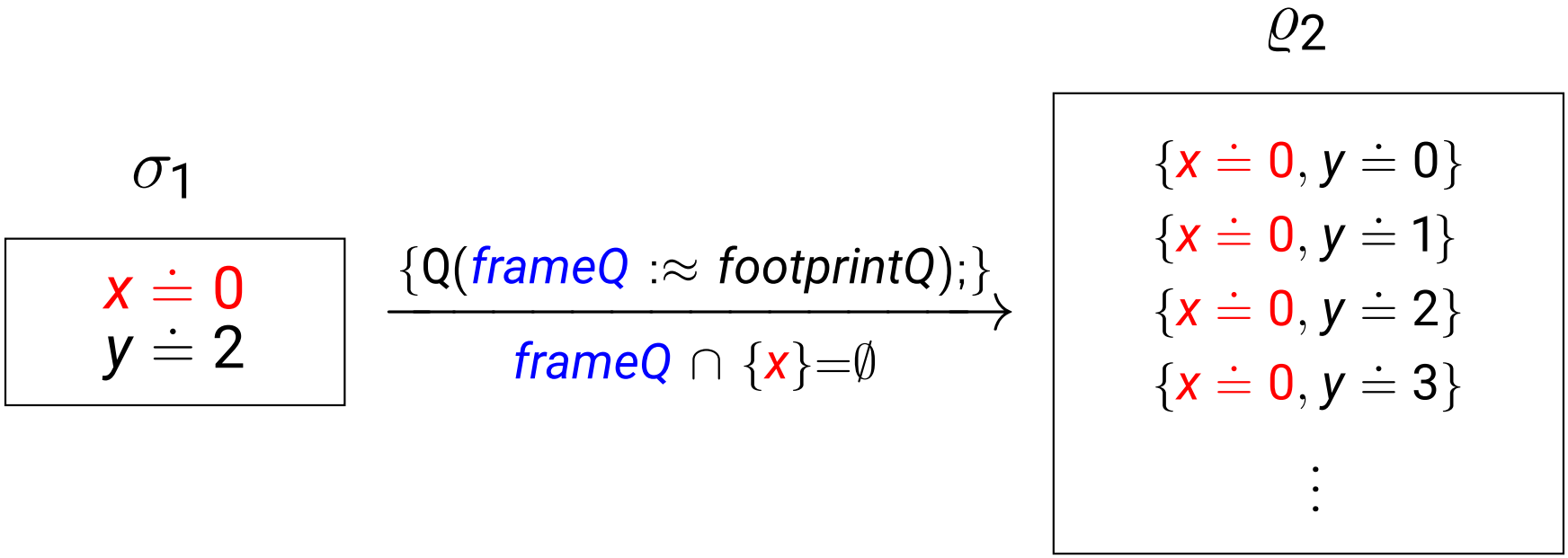
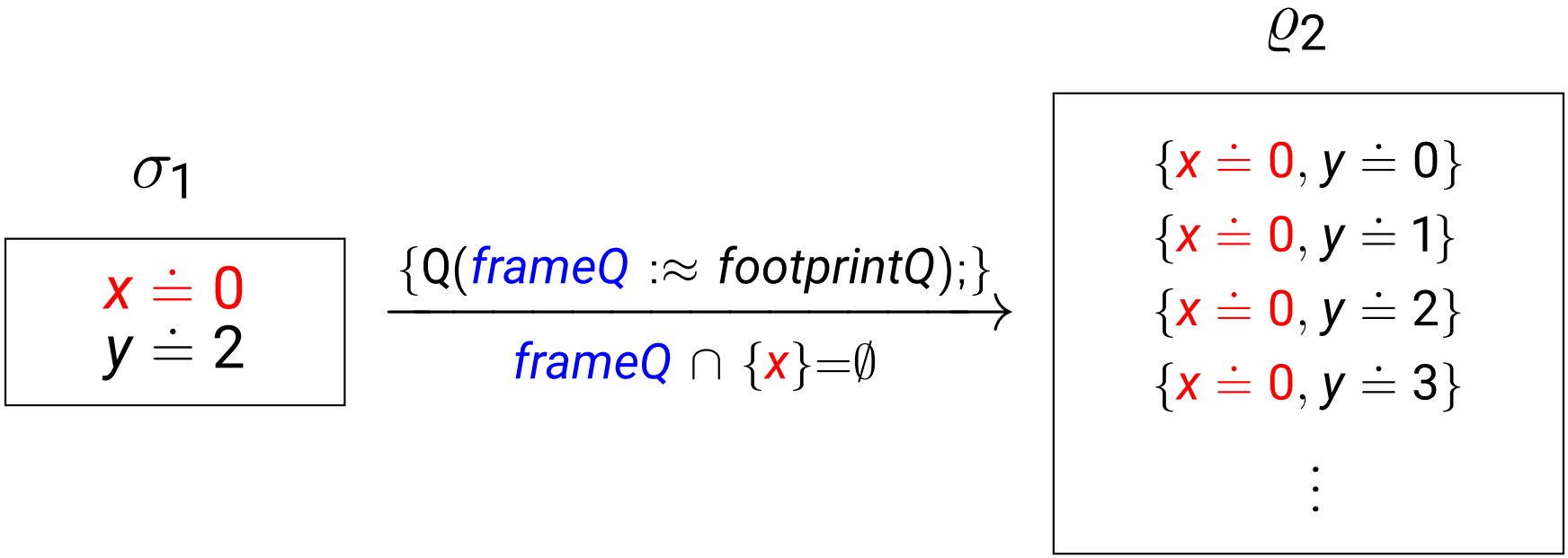


Q is modelled as an **Abstract Statement**

Abstract Execution

Steinhöfel and Hähnle (2019)

TECHNISCHE UNIVERSITÄT DARMSTADT



Proving Universal Behavioral Properties

$x \doteq$ `\old(x)` after executing Q(*frameQ* :≈ *footprintQ*)

Modelling Original Calls as Abstract Statements

TECHNISCHE UNIVERSITÄT DARMSTADT

```
1 delta D {
2     modifies C {
3         modifies Unit m(Int x) {
4             label : original(x);
5             //...
6         }
7     }
8 }
```

Modelling Original Calls as Abstract Statements

TECHNISCHE UNIVERSITÄT DARMSTADT

```
1 delta D {
2     modifies C {
3         modifies Unit m(Int x) {
4             label : original(x);
5             //...
6         }
7     }
8 }
```

$\texttt{Original}(\mathit{frameO} :\approx \mathit{footprintO})$
$x \notin \mathit{frameO}$

Modelling Original Calls as Abstract Statements

TECHNISCHE UNIVERSITÄT DARMSTADT

```
1 delta D {
2     modifies C {
3         modifies Unit m(Int x) {
4             label: original(x);
5             //...
6         }
7     }
8 }
```

`Original(`*frameO* $:\approx$ *footprintO*`)`
$x \notin$ frameO

`\old (field, label)`

Verifying Deltas with Abstract Execution

TECHNISCHE UNIVERSITÄT DARMSTADT

```
1  class C {
2     Int f1;
3     Unit m(Int x){/*...*/}
4  }
5
6  delta D {
7     modifies C {
8        adds Int f2;
9        //@ensures f2 == \old(f2) + 1
10       //@      && f1 == \old(f1, l) + 1;
11       modifies Unit m(Int x) {
12          f2 = f2 + 1;
13          l : original(x);
14          f1 = f1 + 1;
15       }
16    }
17 }
```

Verifying Deltas with Abstract Execution

TECHNISCHE UNIVERSITÄT DARMSTADT

```
1  class C {
2     Int f1;
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5
6  delta D {
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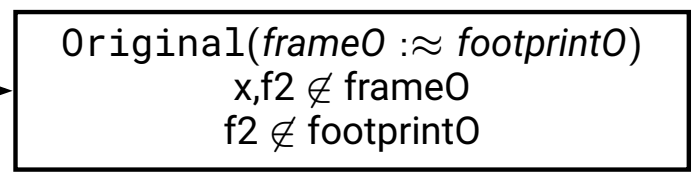
11       modifies Unit m(Int x) {
12          f2 = f2 + 1;
13          l : original(x);
14          f1 = f1 + 1;
15       }
16    }
17 }
```



Verifying Deltas with Abstract Execution

TECHNISCHE UNIVERSITÄT DARMSTADT

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1  class C {
2     Int f1;
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6  delta D {
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9        //@ensures f2 == \old(f2) + 1
10       //@      && f1 == \old(f1, l) + 1;
11       modifies Unit m(Int x) {
12          f2 = f2 + 1;
13          l : original(x);
14          f1 = f1 + 1;
15       }
16    }
17 }
```

Original(*frame0* :≈ *footprint0*)

x,f2 ∉ frame0

f2 ∉ footprint0

Beyond Liskov!

Verifying Deltas with Abstract Execution

TECHNISCHE UNIVERSITÄT DARMSTADT

```
1  class C {
2     Int f1;
3     Unit m(Int x){/*...*/}
4  }
5
6  delta D {
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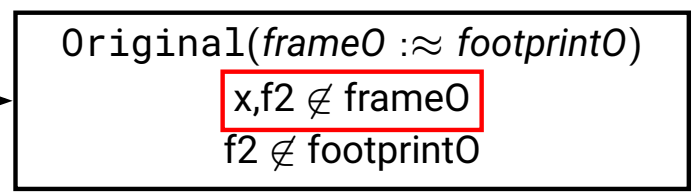
16    }
17 }
```



Verifying Deltas with Abstract Execution

TECHNISCHE UNIVERSITÄT DARMSTADT

```
1  class C {
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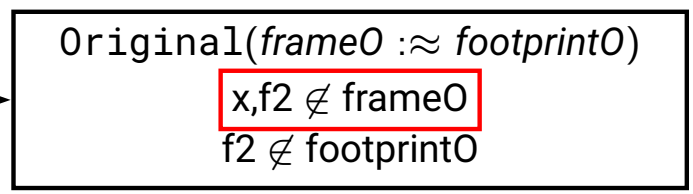

This contract **cannot be invalidate** by delta applications

Behavior Preserving Method

TECHNISCHE UNIVERSITÄT DARMSTADT

```
1  class C {
2     Int f;
3
4     //@ensures this.f == \old(this.f) + 1;
5     Unit m1(){ f = f + 1; }
6
7     //@ensures this.f >= \old(this.f) + 3;
8     Unit m2() {
9        m1();
10       f = f + 2;
11    }
12
13    //@ensures this.f == \old(this.f) + 5;
14    Unit m3() {
15       m2();
16       f = f + 2;
17    }
18
19    //@ensures this.f == −1;
20    Unit m4(){ f = −1; }
21 }
```

```
1  delta D {
2     modifies C {
3
4        //@ensures this.f >= \old(this.f) + 7;
5        modifies Unit m2() {
6           original();
7           f = f + 4;
8        }
9
10       //@ensures this.f == 1;
11       modifies Unit m4() { f = 1; }
12
13    }
14 }
```

Behavior Preserving Method

TECHNISCHE UNIVERSITÄT DARMSTADT

```
1  class C {
2     Int f;
3
4     //@ensures this.f == \old(this.f) + 1;
5     Unit m1(){ f = f + 1; } ⇐ NOT MODIFIED
6
7     //@ensures this.f >= \old(this.f) + 3;
8     Unit m2() {
9        m1(); ⇐ NOT MODIFIED
10       f = f + 2;
11    }
12
13    //@ensures this.f == \old(this.f) + 5;
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15       m2();
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```

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1  delta D {
2     modifies C {
3
4        //@ensures this.f >= \old(this.f) + 7;
5        modifies Unit m2() {
6           original();
7           f = f + 4;
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10       //@ensures this.f == 1;
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13    }
14 }
```

Behavior Preserving Method

TECHNISCHE UNIVERSITÄT DARMSTADT

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2     Int f;
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4     //@ensures this.f == \old(this.f) + 1;
5     Unit m1(){ f = f + 1; } ⇐ NOT MODIFIED
6
7     //@ensures this.f >= \old(this.f) + 3;
8     Unit m2() { ⇐ LISKOV
9        m1(); ⇐ NOT MODIFIED
10       f = f + 2;
11    }
12
13    //@ensures this.f == \old(this.f) + 5;
14    Unit m3() {
15       m2();⇐ LISKOV
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```
1  delta D {
2     modifies C {
3
4        //@ensures this.f >= \old(this.f) + 7;
5        modifies Unit m2() { ⇐ LISKOV
6           original();⇐ LISKOV
7           f = f + 4;
8        }
9
10       //@ensures this.f == 1;
11       modifies Unit m4() { f = 1; }
12
13    }
14 }
```

Behavior Preserving Method

TECHNISCHE UNIVERSITÄT DARMSTADT

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1  class C {
2     Int f;
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5     Unit m1(){ f = f + 1; } ⇐ NOT MODIFIED
6
7     //@ensures this.f >= \old(this.f) + 3;
8     Unit m2() { ⇐ LISKOV
9        m1(); ⇐ NOT MODIFIED
10       f = f + 2;
11    }
12
13    //@ensures ??;
14    Unit m3() {
15       m4(); ⇐ NON LISKOV
16       f = f + 2;
17    }
18
19    //@ensures this.f == −1;
20    Unit m4(){ f = −1; } ⇐ NON LISKOV
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```

```
1  delta D {
2     modifies C {
3
4        //@ensures this.f >= \old(this.f) + 7;
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12
13    }
14 }
```

Behavior Preserving Method

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Definition (Behavior Preserving Method)

A *Behavior Preserving Method*:

- does **not call non Behavior Preserving methods**
- is either
  - non **modified**
  - **modified** and **fulfilling Liskov**

Definition (Behavior Preserving Sequence)

Sequence of statements **without calls to non Behavior Preserving methods**

Behavior Preserving Method

TECHNISCHE UNIVERSITÄT DARMSTADT

Definition (Behavior Preserving Method)

A *Behavior Preserving Method*:

- does **not call non Behavior Preserving methods**
- is either
  - non **modified**
  - **modified** and **fulfilling Liskov**

Definition (Behavior Preserving Sequence)

Sequence of statements **without calls to non Behavior Preserving methods**

$\Rightarrow$ Its behavior **cannot be modified** by delta application

Behavior Preserving Method

TECHNISCHE UNIVERSITÄT DARMSTADT

```
1  class C {
2     Int f;
3
4     //@ensures this.f == \old(this.f) + 1;
5     Unit m1(){ f = f + 1; } ⇐ NOT MODIFIED
6
7     //@ensures this.f >= \old(this.f) + 3;
8     Unit m2() { ⇐ LISKOV
9        m1(); ⇐ NOT MODIFIED
10       f = f + 2;
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```

```
1  delta D {
2     modifies C {
3
4        //@ensures this.f >= \old(this.f) + 7;
5        modifies Unit m2() { ⇐ LISKOV
6           original();⇐ LISKOV
7           f = f + 4;
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9
10       //@ensures this.f == 1;
11       modifies Unit m4() { f = 1; }⇐ NON LISKOV
12
13    }
14 }
```

Behavior Preserving Method

TECHNISCHE UNIVERSITÄT DARMSTADT

```
1  class C {
2     Int f;
3
4     //@ensures this.f == \old(this.f) + 1;
5     Unit m1(){ f = f + 1; } ⇐ BP
6
7     //@ensures this.f >= \old(this.f) + 3;
8     Unit m2() { ⇐ BP
9        m1(); ⇐ BP
10       f = f + 2;
11    }
12
13    //@ensures ??;
14    Unit m3() {⇐ NON BP
15       m4(); ⇐ NON BP
16       f = f + 2;
17    }
18
19    //@ensures this.f == −1;
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21 }
```

```
1  delta D {
2     modifies C {
3
4        //@ensures this.f >= \old(this.f) + 7;
5        modifies Unit m2() { ⇐ BP
6           original();⇐ BP
7           f = f + 4;
8        }
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13    }
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```

Behavior Preserving Method

TECHNISCHE UNIVERSITÄT DARMSTADT

```
1  class C {
2     Int f;
3
4     //@ensures this.f == \old(this.f) + 1;
5     Unit m1(){ f = f + 1; } ⇐ BP
6
7     //@ensures this.f >= \old(this.f) + 3;
8     Unit m2() { ⇐ BP
9        m1(); ⇐ BP ⇐ BP-SEQUENCE
10       f = f + 2;
11    }
12
13    //@ensures ??;
14    Unit m3() {⇐ NON BP
15       m4(); ⇐ NON BP
16       f = f + 2;
17    }
18
19    //@ensures this.f == −1;
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21 }
```

```
1  delta D {
2     modifies C {
3
4        //@ensures this.f >= \old(this.f) + 7;
5        modifies Unit m2() { ⇐ BP
6           original();⇐ BP
7           f = f + 4;
8        }
9
10       //@ensures this.f == 1;
11       modifies Unit m4() { f = 1; }⇐ NON BP
12
13    }
14 }
```

Shallow Single Original Normal Form

TECHNISCHE UNIVERSITÄT DARMSTADT

```
1  class C {
2     Int f1;
3     Unit m(Int x){/*...*/}
4  }
5
6  delta D {
7     modifies C {
8        adds Int f2;
9        //@ensures f2 == \old(f2) + 1
10       //@      && f1 == \old(f1, l) + 1;
11       modifies Unit m(Int x) {
12          f2 = f2 + 1;
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```

Shallow Single Original Normal Form

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10       //@      && f1 == \old(f1, l) + 1;
11       modifies Unit m(Int x) {
12          f2 = f2 + 1; ⇐ BP-SEQUENCE
13          l : original(x);
14          f1 = f1 + 1; ⇐ BP-SEQUENCE
15       }
16    }
17 }
```

Shallow Single Original Normal Form

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```
1  class C {
2     Int f1;
3     Unit m(Int x){/*...*/}
4  }
5
6  delta D {
7     modifies C {
8        adds Int f2;
9        //@ensures f2 == \old(f2) + 1
10       //@      && f1 == \old(f1, l) + 1;
11       modifies Unit m(Int x) {
12          f2 = f2 + 1; ⇐ BP-SEQUENCE
13          l : original(x); ⇐ original call
14          f1 = f1 + 1; ⇐ BP-SEQUENCE
15       }
16    }
17 }
```

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TECHNISCHE UNIVERSITÄT DARMSTADT

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14          f1 = f1 + 1; ⇐ BP-SEQUENCE
15       }
16    }
17 }
```

Definition

The body of $\delta.\mathtt{m}$ is

$$\{ S_1 \; ; \; \textbf{original}(\overline{p}) \; ; \; S_2 \; ; \}$$

with S_1,S_2 BP-sequences

Refactoring to Normal Form

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Refactorable

```
1  modifies Unit m(Int x) {
2     if (x > 0) {
3        field1 += 1;
4        m1(); ⇐ BP
5        original(x);
6     } else {
7        original(x);
8        field2 += 1;
9     }
10 }
```

Refactoring to Normal Form

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Refactoring to Normal Form

TECHNISCHE UNIVERSITÄT DARMSTADT

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10 }
```

$\Longrightarrow$

Refactored

```
1  modifies Unit m(Int x) {
2     if (x > 0) {
3        field1 += 1;
4        m1(); ⇐ BP
5     }
6     original(x);
7     if (x<=0) {
8        field2 += 1;
9     }
10 }
```

Refactoring to Normal Form

TECHNISCHE UNIVERSITÄT DARMSTADT

Refactorable

```
1  modifies Unit m(Int x) {
2    if (x > 0) {
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4      m1(); ⇐ BP
5      original(x);
6    } else {
7      original(x);
8      field2 += 1;
9    }
10 }
```

$\Longrightarrow$

Refactored

```
1  modifies Unit m(Int x) {
2    if (x > 0) {
3      field1 += 1;   ⇐ BP-SEQUENCE S1
4      m1(); ⇐ BP
5    }
6    original(x);     ⇐ original call
7    if (x<=0) {
8      field2 += 1;   ⇐ BP-SEQUENCE S2
9    }
10 }
```

Refactoring to Normal Form

TECHNISCHE UNIVERSITÄT DARMSTADT

Refactorable

```
1  modifies Unit m(Int x) {
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4        m1(); ⇐ BP
5        original(x);
6     } else {
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8        field2 += 1;
9     }
10 }
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$\Longrightarrow$

Refactored

```
1  modifies Unit m(Int x) {
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4        m1(); ⇐ BP
5     }
6     original(x);      ⇐ original call
7     if (x<=0) {
8        field2 += 1;   ⇐ BP-SEQUENCE S2
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```

Using **Abstract Execution** to prove **correctness of refactoring**

Change Old Behavior Principle

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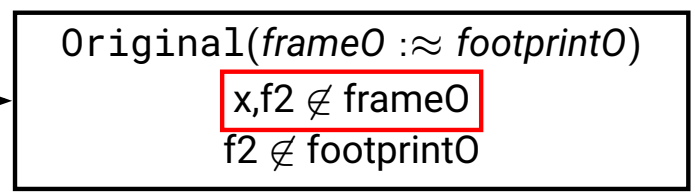

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16    }
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```

Definition

The body of δ `.m` is either:

a) in normal form
$\{ S_1 \; ; \; \textbf{original}(\overline{p}) \; ; \; S_2 \; ; \}$
where $\mathbf{S_1}$ **assigns new fields**, *or*

b) a BP-sequence.

`Original`(*frame0* :≈ *footprint0*)
x,f2 ∉ frame0
f2 ∉ footprint0

Change Old Behavior Principle

TECHNISCHE UNIVERSITÄT DARMSTADT

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where $\mathbf{S_1}$ **assigns new fields**, *or*

b) a BP-sequence.

`Original`(*frameO* :≈ *footprintO*)
x,f2 ∉ frameO
f2 ∉ footprintO

The behavior of $\delta.m$ **cannot be affected** by delta application

Theorem

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The following theorem guarantees the correctness of this approach.

Theorem

Assume the following:

Theorem

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   - 2.1 *m is modified*

Theorem

TECHNISCHE UNIVERSITÄT DARMSTADT

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Theorem

Assume the following:

1. *Each method in the core is a BP-sequence, and verified.*
2. *For each δ.m one of the following holds:*
   - 2.1 *m is modified*
     - *fulfills Change Old Behavior Principle, and is verified,* ***or***

Theorem

TECHNISCHE UNIVERSITÄT DARMSTADT

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Theorem

Assume the following:

1. *Each method in the core is a BP-sequence, and verified.*
2. *For each δ.m one of the following holds:*
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     - *fulfills Change Old Behavior Principle, and is verified,* ***or***
     - *is a BP-method, and is Liskov-verified*

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     - *is a BP-method, and is Liskov-verified*
   - 2.2 *m is not modified (added), its body is a BP-sequence and is verified*

Theorem

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Assume the following:

1. *Each method in the core is a BP-sequence, and verified.*
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   - 2.2 *`m` is not modified (added), its body is a BP-sequence and is verified*
3. *No contract can call a non BP-method.*

Theorem

TECHNISCHE UNIVERSITÄT DARMSTADT

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Theorem

Assume the following:

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3. *No contract can call a non BP-method.*

Then each variant is correct.

Normal Form and **Abstract Execution** enable **delta-based verification**

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+

original is the only callable non BP-method

Normal Form and **Abstract Execution** enable **delta-based verification**

+

original is the only callable non BP-method

⇓

Deltas **cannot affect** the behavior of **non modified methods**

Delta-based Verification of Software Product Families

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Normal Form and **Abstract Execution** enable **delta-based verification**

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Once a contract is proved it **cannot be invalidate** by delta applications

Delta-based Verification of Software Product Families

TECHNISCHE UNIVERSITÄT DARMSTADT

Normal Form and **Abstract Execution** enable **delta-based verification**

+

original is the only callable non BP-method

⇓

Deltas **cannot affect** the behavior of **non modified methods**

⇓

Once a contract is proved it **cannot be invalidate** by delta applications

⇓

Each contract has to be **proven once**: **polynomial complexity O(N*M)**
(N=nr. of deltas, M=nr. of methods)

Case Studies

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Expressiveness and Performance?

Expressiveness

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Specification and verification of

- **BankAccountSPL** Thüm et al. (2012)
- **MinePumpPL** Apel et al. (2013)

Expressiveness

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Specification and verification of

- **BankAccountSPL** Thüm et al. (2012)
- **MinePumpPL** Apel et al. (2013) Performance?

Performance

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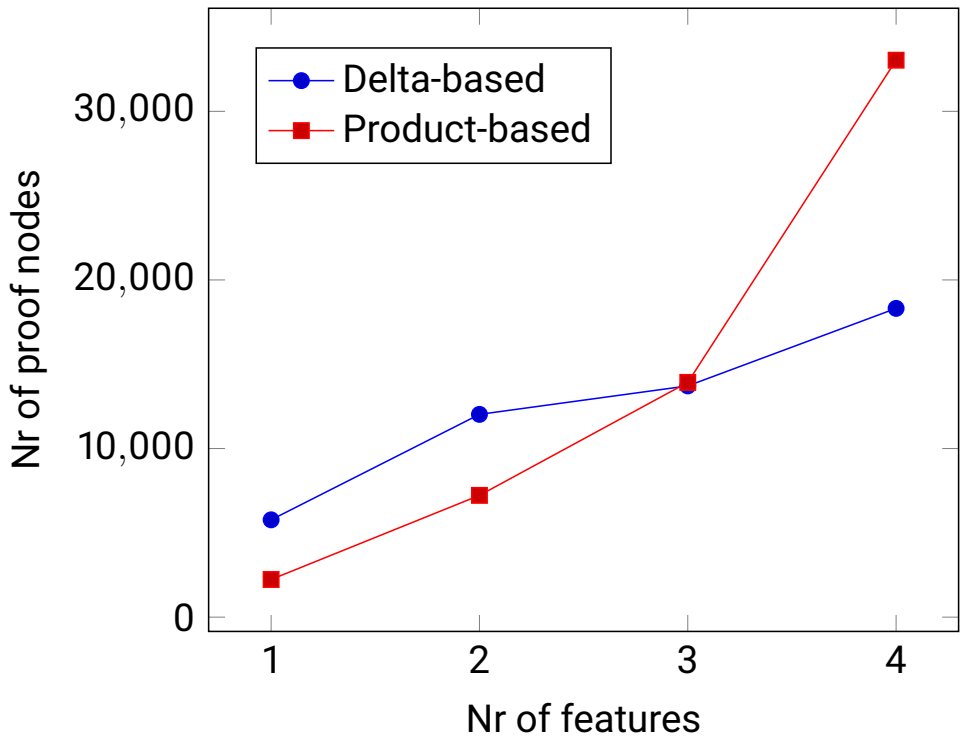

For a subset of **MinePumpPL**

Performance

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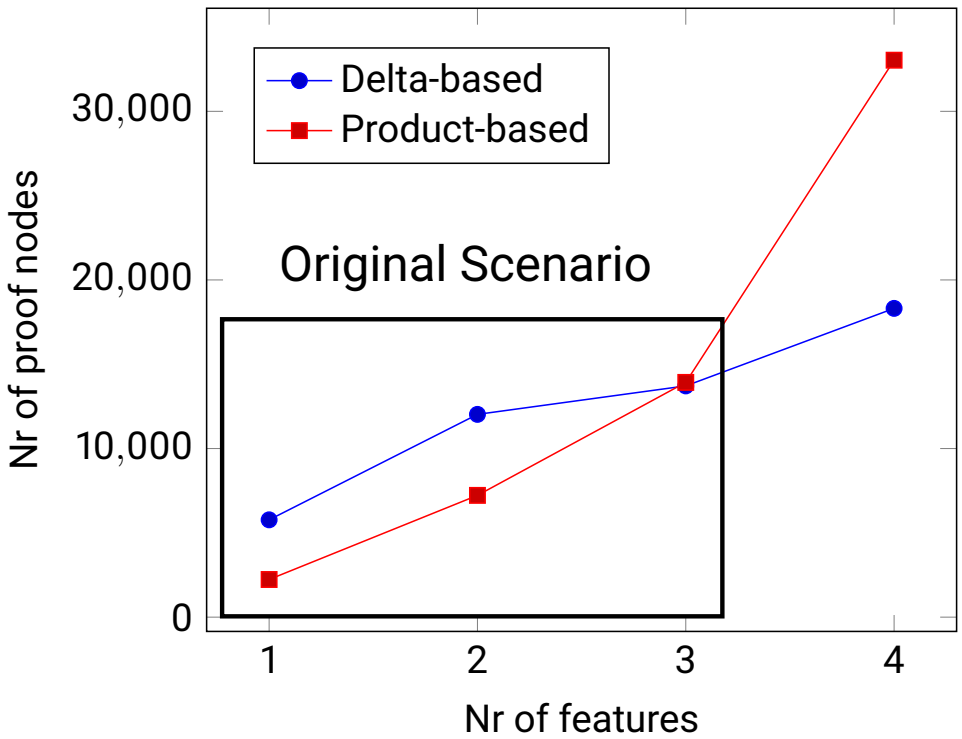

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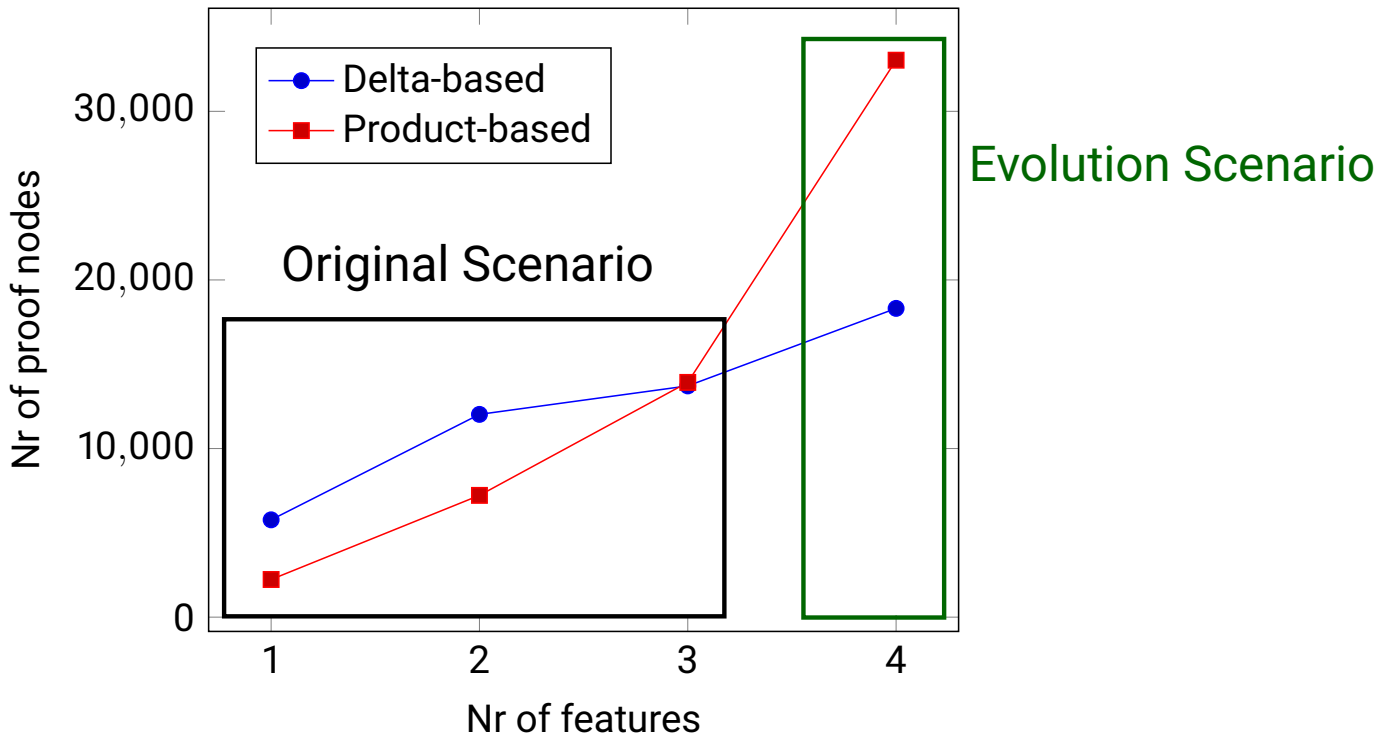

For a subset of **MinePumpPL**

Conclusion

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Achievement

Overcome Liskov's restrictions *without increasing costs*

How?

Conclusion

TECHNISCHE UNIVERSITÄT DARMSTADT

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Overcome Liskov's restrictions *without increasing costs*

How?

Delta-based Verification:
Normal Form $\Rightarrow$ Abstract Execution

Expressiveness and Performance?

Conclusion

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Achievement

Overcome Liskov's restrictions *without increasing costs*

How?

Delta-based Verification:
Normal Form $\Rightarrow$ **Abstract Execution**

Expressiveness and Performance?

$\Rightarrow$ **Expressive** enough to specify existing product lines
$\Rightarrow$ **Outperforms** product-based analysis, **suitable for evolving SPLs**

References I

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Achieving Normal Form with AE

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```
1  //before refactoring
2  modifies Unit m(p) {
3
4     if ( p1 == 0 ) {
5        field1 = 1;
6        m1(p1); //BP−method
7        original(p);
8        field2 +=1;
9     } else {
10       field1 = 2;
11       original(p);
12       m2(p2); //BP−method
13       field2 +=2;
14    }
15 }
```

⇝

```
1  //after refactoring
2  modifies Unit m(p) {
3     Bool cond = p1 == 0;
4     if ( cond ) {
5        field1 = 1;
6        m1(p1); //BP−method
7     } else {
8        field1 = 2;
9     }
10    original(p);
11    if (cond) {
12       field2 +=1;
13    } else {
14       m2(p2); //BP−method
15       field2 +=2;
16    }
17 }
```

Achieving Normal Form with AE (cont'd)

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Transformation rules:

1. Conditional Statement Condition Extraction (CSCE)
2. Unfold If Branch Prefix
3. Unfold Else Branch Prefix
4. Consolidate Duplicate Conditional Fragments (Extract Prefix)
5. Split Conditional Statement

```
if ( e^boolean(frameE :≈ footprintE) ) {
    Q1(frameQ1 :≈ footprintQ1);
} else {
    Q2(frameQ2 :≈ footprintQ2);
}
```

CSCE ⟶

```
/*@ ae_constraint
    @ x ∉ frameQ1 && x ∉ footprintQ1 &&
    @ x ∉ frameQ2 && x ∉ footprintQ2;
    @*/
x = e^boolean(frameE :≈ footprintE);
if (x) {
    Q1(frameQ1 :≈ footprintQ1);
} else {
    Q2(frameQ2 :≈ footprintQ2);
}
```