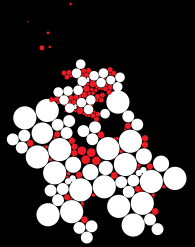
Some Napkin Math

- The day I started on this thesis: June 22th 2019
- Today is April 22th 2020, so that is 305 days (according to Google)
- The summer break was about 30 days, so that is 275 days
- On average, 2 cups of coffee each day
- This thesis equates to about

$$275\ \textit{days} \times\ 2\ \frac{\textit{Cups of Coffee}}{\textit{Day}} \times 0.37\ \frac{\textit{Liters}}{\textit{Cup of Coffee}} = 203.5\ \textit{Liters of Coffee}$$

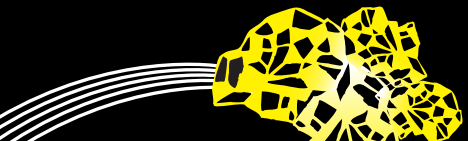
- There are 127 pages in my thesis, so about $\frac{203.5}{127} \approx 1.6\ \frac{\textit{Liters}}{\textit{Page}}$

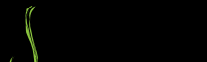
UNIVERSITY OF TWENTE.



Extending Support for Axiomatic Data Types in VerCors

Ömer Faruk Oğuzhan Şakar





Overview

Software Verification

VerCors

Axiomatic Data Types

Maps

Conclusion

Overview

Software Verification

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Axiomatic Data Types

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Conclusion

Software

Software

Software

Software

Software

- *Software is everywhere*

Software

- *Software is everywhere* is a cliché

Software

- *Software is everywhere* is a cliché, but it's true

Cookie Clicker

Cookie Clicker

(homemade by my sister Nisa)

`Clicks:` 0

Cookie Clicker

Clicks: 1

Cookie Clicker

Clicks: 2

Cookie Clicker

Clicks: 3

Cookie Clicker

Clicks: 4

Cookie Clicker

Clicks: 5

```
method youClicked() {
      Clicks <- Clicks + 1

}
```

Cookie Clicker

Clicks: 6

```
method youClicked() {
      Clicks <- Clicks + 1

}
```

Cookie Clicker

Clicks: 7

4_Cookies: ✗

```
method youClicked() {
     Clicks <- Clicks + 1


}
```

Cookie Clicker

Clicks: 7

4_Cookies: ✗

```
method youClicked() {
     Clicks <- Clicks + 1
     if Clicks is larger than 9,

}
```

Cookie Clicker

Clicks: 7

4_Cookies: ✗

```
method youClicked() {
     Clicks <- Clicks + 1
     if Clicks is larger than 9,
          then 4_Cookies <- ✓
}
```

Cookie Clicker

Clicks: 8

4_Cookies: ✗

```
method youClicked() {
     Clicks <- Clicks + 1
     if Clicks is larger than 9,
         then 4_Cookies <- ✓
}
```

Cookie Clicker

Clicks: 9

4_Cookies: ✗

```
method youClicked() {
     Clicks <- Clicks + 1
     if Clicks is larger than 9,
         then 4_Cookies <- ✓
}
```

Cookie Clicker

Clicks: 10

4_Cookies: ✓

```
method youClicked() {
     Clicks <- Clicks + 1
     if Clicks is larger than 9,
         then 4_Cookies <- ✓
}
```

Cookie Clicker

Clicks: 11

4_Cookies: ✓

```
method youClicked() {
     Clicks <- Clicks + 1
     if Clicks is larger than 9,
         then 4_Cookies <- ✓
}
```

Cookie Clicker

Clicks: 12

4_Cookies: ✓

```
method youClicked() {
     Clicks <- Clicks + 1
     if Clicks is larger than 9,
         then 4_Cookies <- ✓
}
```

Software Verification

Software Verification

- Testing: Click and check the outcome

Software Verification

- Testing: Click and check the outcome
- Verification: Proof that it works

Verifying Cookie Clicker

Clicks: ...
4_Cookies: ...

```
method youClicked() {
     Clicks <- Clicks + 1
     if Clicks is larger than 9,
         then 4_Cookies <- ✓
}
```

Verifying Cookie Clicker

Clicks: ...

4_Cookies: ...

assumes Clicks is positive

```
method youClicked() {
     Clicks <- Clicks + 1
     if Clicks is larger than 9,
         then 4_Cookies <- ✓
}
```

Verifying Cookie Clicker

Clicks: ...

4_Cookies: ...

```
assumes Clicks is positive

method youClicked() {
     Clicks <- Clicks + 1
     if Clicks is larger than 9,
         then 4_Cookies <- ✓
}

ensures Clicks is positive
```

Verifying Cookie Clicker

Clicks: ...

4_Cookies: ...

```
assumes Clicks is positive

method youClicked() {
     Clicks <- Clicks + 1
     if Clicks is larger than 9,
         then 4_Cookies <- ✓
}

ensures Clicks is old Clicks + 1
```

Verifying Cookie Clicker

Clicks: ...
4_Cookies: ...

```
assumes Clicks is positive

method youClicked() {
     Clicks <- Clicks + 1
     if Clicks is larger than 9,
         then 4_Cookies <- ✓
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ensures Clicks is old Clicks + 1
```

```
ensures if Clicks larger than 9,
     then 4_Cookies is ✓
```

Software Verification in a nutshell

My thesis

My thesis

- Extending Support for Axiomatic Data Types (ADTs) in VerCors

Overview

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Maps

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VerCors

VerCors

- Static verification of concurrent/parallel programs.

VerCors

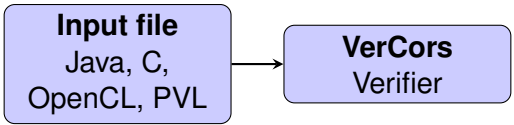
- Static verification of concurrent/parallel programs.
- Developed at the University of Twente

VerCors' Architecture

VerCors' Architecture

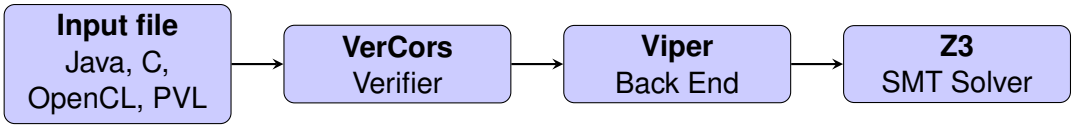
Input file
Java, C,
OpenCL, PVL

VerCors' Architecture



VerCors' Architecture

VerCors' Architecture



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Axiomatic Data Types

Axiomatic Data Types

- Lists/sequences, sets, bags, tuples, integers, doubles, floats, etc.

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- Concrete data types (CDTs)

Axiomatic Data Types

- Lists/sequences, sets, bags, tuples, integers, doubles, floats, etc.
- Concrete data types (CDTs)
- Describe *behavior* instead of *implementation*

Tuple

Tuple

- (`fst`, `snd`)

Tuple

- (`fst`, `snd`)
- Constructor to construct a Tuple

Tuple

- (`fst`, `snd`)
- Constructor to construct a Tuple
- Function to get the first element

Tuple

- (`fst`, `snd`)
- Constructor to construct a Tuple
- Function to get the first element
- Function to get the second element

Tuple CDT (in Java)

```
class Tuple<F,S> {









}
```

Tuple CDT (in Java)

```
class Tuple<F,S> {
    private final F fst;
    private final S snd;









}
```

Tuple CDT (in Java)

```
class Tuple<F,S> {
    private final F fst;
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    public Tuple(F fstArg, S sndArg) {
        fst = fstArg;
        snd = sndArg;
    }



}
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class Tuple<F,S> {
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        fst = fstArg;
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    }

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    public S getSnd() { return snd; }
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    public F getFst() { return fst; }
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}
```

Tuple ADT

```
domain Tuple[F,S] {









}
```

Tuple ADT

```
domain Tuple[F,S] {
    function constructor(f:F, s:S): Tuple[F,S]

}
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Tuple ADT

```
domain Tuple[F,S] {
    function constructor(f:F, s:S): Tuple[F,S]
    function getFst(t:Tuple[F,S]): F
    function getSnd(t:Tuple[F,S]): S









}
```

Tuple ADT

```
domain Tuple[F,S] {
    function constructor(f:F, s:S): Tuple[F,S]
    function getFst(t:Tuple[F,S]): F
    function getSnd(t:Tuple[F,S]): S

    axiom FstAxiom {
        forall f1:F, s1:S :: getFst(constructor(f1,s1)) == f1
    }

}
```

Tuple ADT

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domain Tuple[F,S] {
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Tuple CDT & ADT

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    public F getFst() { return fst; }
    public S getSnd() { return snd; }
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domain Tuple[F,S] {
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Tuple CDT & ADT

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Tuple CDT & ADT

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class Tuple<F,S> {
    private final F fst;
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```
domain Tuple[F,S] {
    function constructor(f:F, s:S) : Tuple[F,S]
    function getFst(t:Tuple[F,S]) : F
    function getSnd(t:Tuple[F,S]) : S

    axiom FstAxiom {
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            getFst(constructor(f1,s1)) == f1
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    axiom SndAxiom {
        forall f1:F, s1:S ::
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    }
}
```

Soundness

Soundness

- Every formula that can be proven is logically valid

Unsoundness

Unsoundness

```
domain Tuple[F,S] {
     function constructor(f:F, s:S): Tuple[F,S]
     function getFst(t:Tuple[F,S]): F
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     axiom FstAxiom {forall f1:F,s1:S :: getFst(constructor(f1,s1)) == f1}
     axiom SndAxiom {forall f1:F,s1:S :: getSnd(constructor(f1,s1)) == s1}

     axiom UnsoundAxiom {


     }
}
```

Unsoundness

```
domain Tuple[F,S] {
     function constructor(f:F, s:S): Tuple[F,S]
     function getFst(t:Tuple[F,S]): F
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    axiom UnsoundAxiom {
        forall f1:F, s1:S, s2:S ::

    }
}
```

Unsoundness

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domain Tuple[F,S] {
     function constructor(f:F, s:S): Tuple[F,S]
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Unsoundness

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     axiom SndAxiom {forall f1:F,s1:S :: getSnd(constructor(f1,s1)) == s1}

    axiom UnsoundAxiom {
        forall f1:F, s1:S, s2:S ::
            getFst( constructor(f1,s1) ) != getFst( constructor(f1,s2) )
    }
}
```

Unsoundness

```
domain Tuple[F,S] {
     function constructor(f:F, s:S): Tuple[F,S]
     function getFst(t:Tuple[F,S]): F
     function getSnd(t:Tuple[F,S]): S
     axiom FstAxiom {forall f1:F,s1:S :: getFst(constructor(f1,s1)) == f1}
     axiom SndAxiom {forall f1:F,s1:S :: getSnd(constructor(f1,s1)) == s1}

    axiom UnsoundAxiom {
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    }
}
```

Unsoundness

```
axiom UnsoundAxiom {
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}
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Unsoundness

```
axiom UnsoundAxiom {
    forall f1:F, s1:S, s2:S ::
        getFst(constructor(f1,s1)) != getFst(constructor(f1,s2))
}

method myMethod() {









}
```

Unsoundness

```
axiom UnsoundAxiom {
    forall f1:F, s1:S, s2:S ::
        getFst(constructor(f1,s1)) != getFst(constructor(f1,s2))
}

method myMethod() {
    var t1 := constructor(1,2)
    var t2 := constructor(1,3)









}
```

Unsoundness

```
axiom UnsoundAxiom {
    forall f1:F, s1:S, s2:S ::
        getFst(constructor(f1,s1)) != getFst(constructor(f1,s2))
}

method myMethod() {
    var t1 := constructor(1,2)
    var t2 := constructor(1,3)

    assert getFst(t1) == getFst(t2)     // 1 == 1, Verifies


}
```

Unsoundness

```
axiom UnsoundAxiom {
    forall f1:F, s1:S, s2:S ::
        getFst(constructor(f1,s1)) != getFst(constructor(f1,s2))
}

method myMethod() {
    var t1 := constructor(1,2)
    var t2 := constructor(1,3)

    assert getFst(t1) == getFst(t2)     // 1 == 1, Verifies
    assert getSnd(t1) == getSnd(t2)     // 2 == 3, Verifies???

}
```

Unsoundness

```
axiom UnsoundAxiom {
    forall f1:F, s1:S, s2:S ::
        getFst(constructor(f1,s1)) != getFst(constructor(f1,s2))
}

method myMethod() {
    var t1 := constructor(1,2)
    var t2 := constructor(1,3)

    assert getFst(t1) == getFst(t2)     // 1 == 1, Verifies
    assert getSnd(t1) == getSnd(t2)     // 2 == 3, Verifies???
    assert false                        // false ,  Verifies???
}
```

My thesis

My thesis

- Extending Support for Axiomatic Data Types (ADTs) in VerCors

My thesis

- Extending Support for Axiomatic Data Types (ADTs) in VerCors
- List of features on ADTs to support

Overview

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Maps

Maps

collection of key/value pairs with unique keys

Maps

, immutable collection of key/value pairs with unique keys

Maps

, finite, immutable collection of key/value pairs with unique keys

Maps

- Unordered, finite, immutable collection of key/value pairs with unique keys

Maps

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- Based on the Dafny map axiomatization
- 10 functions and 23 axioms

Modeling a map

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- get (m:Map[K,V], k: K): V

Map constructors

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- empty(): Map[K,V]

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- empty (): Map[K,V]
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  empty()

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  build(empty(), 1, 1)

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  build(build(empty(), 1, 1), 2, 4)

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- build (m: Map[K,V], k: K, v: V): Map[K,V]
- A map with pairs $1 \rightarrow 1$, $2 \rightarrow 4$ and $3 \rightarrow 9$
- build(build(build(empty(), 1, 1), 2, 4), 3, 9)

Axioms on the `empty` function

```
axiom Ax1 {



}
```

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```
axiom Ax1 {
     forall k1: K ::


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```

Axioms on the `empty` function

```
axiom Ax1 {
     forall k1: K ::
          !(k1 in keys(empty())) &&

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Axioms on the `empty` function

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axiom Ax1 {
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          !(k1 in keys(empty())) &&
          |keys(empty())| == 0
}
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         !(k1 in keys(empty())) &&
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Axioms on the `empty` function

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axiom Ax1 {
     forall k1: K ::
         !(k1 in keys(empty())) &&
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}

axiom Ax2 {
     forall v1: V ::
         !(v1 in values(empty())) &&
         |values(empty())| == 0
}
```

Axiom on the `build` function

```
axiom Ax3 {

}
```

Axiom on the `build` function

```
axiom Ax3 {
     forall k1: K, v1: V, m1: Map[K,V] ::


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```
axiom Ax3 {
     forall k1: K, v1: V, m1: Map[K,V] ::
          k1 in keys(build(m1, k1, v1)) &&

}
```

Axiom on the `build` function

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axiom Ax3 {
     forall k1: K, v1: V, m1: Map[K,V] ::
         k1 in keys(build(m1, k1, v1)) &&
         get(build(m1, k1, v1), k1) == v1
}
```

In practice

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- How does Z3 use these axioms

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- How does Z3 use these axioms
- For Universal Quantifiers:

In practice

- How does Z3 use these axioms
- For Universal Quantifiers: Candidates

Triggers

```
function f(i: Int): Int
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assume forall k: Int :: f(f(k)) == f(k*k)+1
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Good trigger

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function f(i: Int): Int

assume forall k: Int :: {f(f(k))} f(f(k)) == f(k*k)+1
assert f(f(3)) == f(9)+1 // Verifies
```

Good trigger

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function f(i: Int): Int

assume forall k: Int :: {f(f(k))} f(f(k)) == f(k*k)+1
assert f(f(3)) == f(9)+1 // Verifies

bound k to 3
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Good trigger

```
function f(i: Int): Int

assume forall k: Int :: {f(f(k))} f(f(k)) == f(k*k)+1
assert f(f(3)) == f(9)+1 // Verifies

bound k to 3, so f(f(3)) == f(3*3)+1
```

Restrictive trigger

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assume forall k: Int :: {f(f(f(k)))} f(f(k)) == f(k*k)+1
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Restrictive trigger

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assume forall k: Int :: {f(f(f(k)))} f(f(k)) == f(k*k)+1
assert f(f(3)) == f(9)+1 // Fails
```

Looping trigger

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assume forall k: Int :: {f(k)} f(f(k)) == f(k*k)+1
assert f(f(3)) == f(9)+1 // Verifies
assert f(f(3)) == f(4)+1 // Times out
```

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bound k to f(3)
```

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bound k to f(3), so f(f(f(3))) == f(f(3)*f(3))+1
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bound k to 3, so f(f(3)) == f(3*3)+1
bound k to 4
```

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function f(i: Int): Int

assume forall k: Int :: {f(k)} f(f(k)) == f(k*k)+1
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assert f(f(3)) == f(4)+1 // Times out

bound k to f(3), so f(f(f(3))) == f(f(3)*f(3))+1
bound k to 3, so f(f(3)) == f(3*3)+1
bound k to 4, so f(f(4)) == f(4*4)+1
```

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bound k to 3, so f(f(3)) == f(3*3)+1
bound k to 4, so f(f(4)) == f(4*4)+1
bound k to 16
```

Looping trigger

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bound k to f(3), so f(f(f(3))) == f(f(3)*f(3))+1
bound k to 3, so f(f(3)) == f(3*3)+1
bound k to 4, so f(f(4)) == f(4*4)+1
bound k to 16, so f(f(16)) == f(16*16)+1
```

Map triggers

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```
void m7() {



}
```

Map triggers

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void m7() {
     map<int,int> myMap = map<int,int> {1 -> 1, 2 -> 4, 3 -> 9};




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void m7() {
     map<int,int> myMap = map<int,int> {1 -> 1, 2 -> 4, 3 -> 9};
     assert !(0 in keys(myMap));
     assert 1 in keys(myMap);
     assert 2 in keys(myMap);
     assert 3 in keys(myMap);
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```

Axiom Profiler

Axiom Profiler

- A tool to debug and understand SMT quantifier instantiation
- Developed at ETH Zürich

Graph for trigger-based proof

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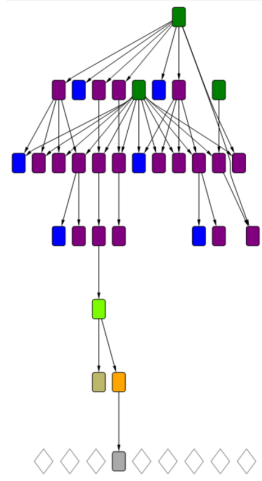

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     forall k1: K, v1: V, m1: Map[K,V] ::
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}
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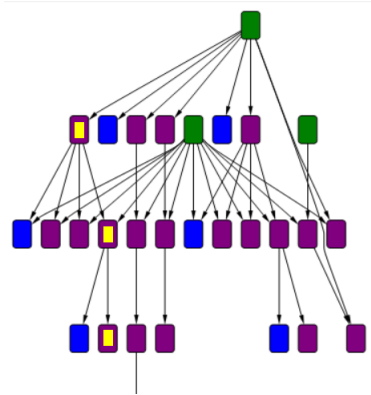

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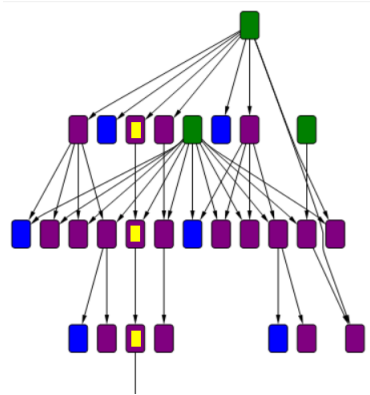

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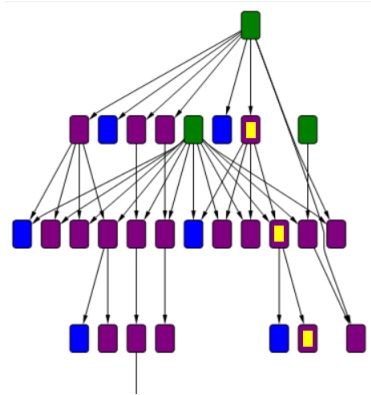

Graph for arith/basic theorem prover

Graph for arith/basic theorem prover

```
requires (\forall int i; 0 <= i && i < 100; i in keysMap(a) && a[i] == i*i);
void m3(map<int, int> a) {
     assert a[20] == 400;
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Knowledge :

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- Introduce new integer i' (introduced by Viper)

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- a[i'] == i' $\times$ i'
- $0 \leq 20 < 100$
- $20 \times 20 == 400$

Overview

Software Verification

VerCors

Axiomatic Data Types

Maps

Conclusion

Implemented features on ADTs

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- Checks if its argument is empty

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- Append/prepend a single value to a sequence

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- Set comprehension
- Maps
- Generic classes and functions

Questions