

Teaching with Logika

Conceiving and Constructing Correct Software

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Context, Approach and Evolution

Use and Significance of Slang and Logika

Feedback

Discussion

Next Steps

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Software Engineering Curriculum

- Development of *new BSc/MSc curriculum* at Aarhus University (Engineering, Fall 2018)
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 - Introduction to Programming (BSc 10 ECTS – informal)
 - Software Architecture (BSc 5 ECTS – informal)
 - Discrete Mathematics (BSc 5 ECTS – informal)
 - *Programming and Modelling* (BSc 10 ECTS – formal)
 - Declarative Programming (BSc&MSc 10 ECTS – informal/formal)
 - **Software Correctness** (MSc 5 ECTS – formal)

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- Local students are prepared for formal methods thinking
- They see **Slang** and **Logika** in *Programming and Modelling* and **Software Correctness**
 - **Slang**: Scala dialect with verification support
 - **Logika**: Interactive support for programming and verifying with Slang

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- Local students are prepared for formal methods thinking
- They see **Slang** and **Logika** in *Programming and Modelling* and **Software Correctness**
 - **Slang**: Scala dialect with verification support
 - **Logika**: Interactive support for programming and verifying with Slang
- Cohort on MSc level is mixed – **background at MSc level varies**
 - Slang and Logika are well-suited for this situation

Evolution of the Course

- In 2012 started predecessor course (**as programming course**)
 - Using Java, Scheme and Prolog
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 - Started design of new course based on Slang/Logika (*dropping Prolog*)

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 - This worked well, staying focused on **programming** methodology
 - Started design of new course based on Slang/Logika (*dropping Prolog*)
- In 2023 the **new course** Software Correctness was established

Content and Objectives

- Schedule:

- Week 1: Introduction – Reasoning about software (and **tool** installation)
- Week 2: Tracing Facts – Pick up the students **reasoning in familiar ways**
- Week 3: Conditionals – **Progress slowly** discussing different approaches
- Week 4: Contracts (Test) – Ensure **students see benefit** for their programming skills
- Week 5: Contracts (Proof) – Based on preceding week but using compositional **proof**
- Week 6: Loops and Recursion – Some theory: programs are just another kind of formula
- Week 7: Unfolding and Fixpoints – More theory with large and complex formulas
- Week 8: Loops and Recursion Testing – Ensure **students see benefit**
- Week 9: Sequences and Arrays – Increase complexity of programs
- Finally: Verification Examples and Practice – Provide **methodology** backed by examples

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 - Accompanied by a **programming project** where some test and proof is applied (mostly at home)
 - Exercises **only in class** (teacher helps)
- Objectives:
 - Improve **programming** skills, **testing** skills, **documentation** skills, **reasoning** skills
 - Do not limit students' vision to Slang,
so the material becomes relevant **beyond the course**

Context, Approach and Evolution

Use and Significance of Slang and Logika

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A Quick Tour of Slang and Logika

The User Interface

The screenshot shows the Slang and Logika user interface. On the left, there is a file tree with four main categories: Week3, Week4, Week5, and Week7. Under Week3, several Scala files are listed, with one named "maximum_simple.sc" highlighted. Under Week4, there are more Scala files, including "Linear_Combination_Contract_Test_Fault.sc". Under Week5, there are files like "Linear_Function_Impure.sc" and "Swap_Function_Contract.sc". Under Week7, there are files such as "Count_Int_Loop_Rec.sc" and "Fac_Function_Loop_Rec.sc". To the right of the file tree is a code editor window displaying Scala code. The code defines a function that takes two integers x and y, compares them, and swaps them if x is less than y. It then asserts that z equals x or z equals y, and finally asserts that y is less than or equal to z and x is less than or equal to z.

```
// #Sireum #Logika
import org.sireum._

val x: Z = randomInt()
val y: Z = randomInt()

var z: Z = 0
if (x < y) {
    z = y
} else {
    z = x
}
assert(z == x || z == y)
assert(y ≤ z ∧ x ≤ z)
```

A Quick Tour of Slang and Logika

The User Interface

The screenshot shows a user interface for a programming environment. On the left, there is a file tree with four main categories: Week3, Week4, Week5, and Week7. Under Week3, several Scala files are listed, including `absvalue_nn.sc`, `boolor.sc`, `maximum_diff.sc`, `maximum_diff_ded.sc`, `maximum_simple.sc`, `maximum_simple_ded.sc`, `nested_max.sc`, `swap.block.sc`, and `swap_choice.sc`. The file `maximum_simple.sc` is currently selected and highlighted with a blue background. The other categories (Week4, Week5, Week7) also contain similar lists of Scala files.

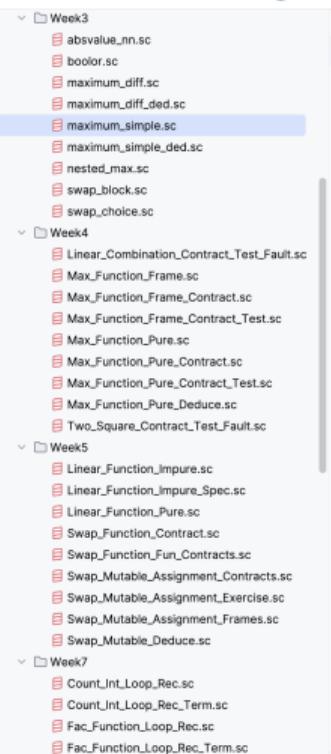
On the right, a code editor displays the contents of the selected file, `maximum_simple.sc`. The code is as follows:

```
1 // #Sireum #Logika
2 import org.sireum._
3 val x: Z = randomInt()
4 val y: Z = randomInt()
5
6 var z: Z = 0
7 if (x < y) {
8
9     z = y
10
11 }
12
13 } else {
14
15     z = x
16
17 }
18
19 }
20 assert(z = x ∨ z = y)
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```

A large callout box with a purple border and text is overlaid on the right side of the code editor. The text reads: "Slang is a dialect of the Scala programming language".

A Quick Tour of Slang and Logika

The User Interface



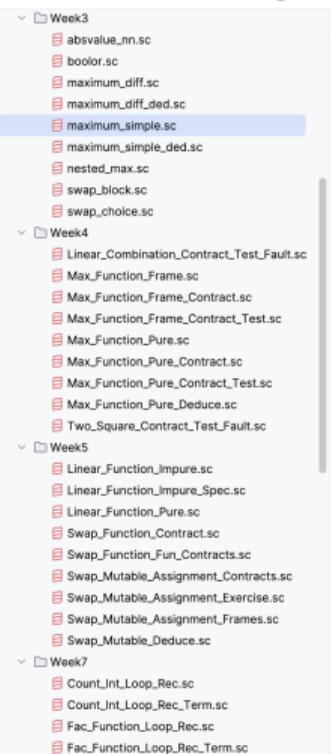
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```

Slang is a dialect of the
Scala programming language

Functional and imperative programming

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The User Interface



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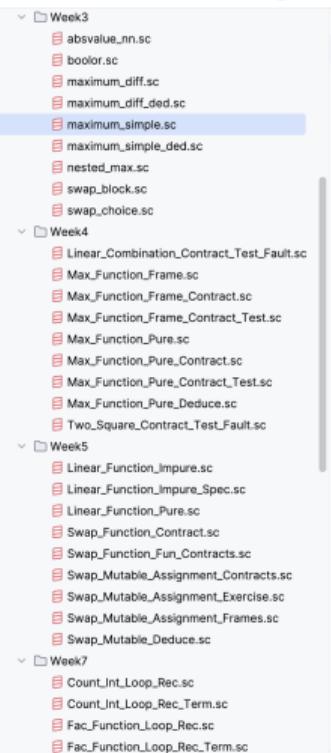
Slang is a dialect of the
Scala programming language

Functional and imperative programming

Dedicated basic data types with
well-defined semantics

A Quick Tour of Slang and Logika

The User Interface



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6 var z: Z = 0
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12     z = x
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15
16 assert(z = x v z)
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19 }
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```

Slang is a dialect of the
Scala programming language

Functional and imperative programming

Dedicated basic data types with
well-defined semantics

Support for algebraic types, records and arrays

A Quick Tour of Slang and Logika

The User Interface

The screenshot shows the Slang and Logika user interface. On the left, there is a file tree with the following structure:

- Week3:
 - absvalue_nn.sc
 - boolor.sc
 - maximum_diff.sc
 - maximum_diff_ded.sc
 - maximum_simple.sc
 - maximum_simple_ded.sc
 - nested_max.sc
 - swap_block.sc
 - swap_choice.sc
- Week4:
 - Linear_Combination_Contract_Test_Fault.sc
 - Max_Function_Frame.sc
 - Max_Function_Frame_Contract.sc
 - Max_Function_Frame_Contract_Test.sc
 - Max_Function_Pure.sc
 - Max_Function_Pure_Contract.sc
 - Max_Function_Pure_Contract_Test.sc
 - Max_Function_Pure_Deduce.sc
 - Two_Square_Contract_Test_Fault.sc
- Week5:
 - Linear_Function_Impure.sc
 - Linear_Function_Impure_Spec.sc
 - Linear_Function_Pure.sc
 - Swap_Function_Contract.sc
 - Swap_Function_Fun_Contracts.sc
 - Swap_Mutable_Assignment_Contracts.sc
 - Swap_Mutable_Assignment_Exercise.sc
 - Swap_Mutable_Assignment_Frames.sc
 - Swap_Mutable_Deduce.sc
- Week7:
 - Count_Int_Loop_Rec.sc
 - Count_Int_Loop_Rec_Term.sc
 - Fac_Function_Loop_Rec.sc
 - Fac_Function_Loop_Rec_Term.sc

On the right, there is a code editor window displaying the following Logika code:

```
1 // #Sireum #Logika
2 import org.sireum._
3 val x: Z = randomInt()
4 val y: Z = randomInt()
5
6 var z: Z = 0
7 Click to show scribed incantations
8
9
10 z = y
11
12
13 } else {
14
15
16 z = x
17
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20 assert(z = x ∨ z = y)
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```

A Quick Tour of Slang and Logika

The User Interface

Week3

- absvalue_nn.sc
- boolor.sc
- maximum_nn.sc
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- maximum_diff_ded.sc
- maximum_simple.sc
- maximum_simple_ded.sc
- nested_max.sc
- swap_block.sc
- swap_choice.sc

Week4

- Linear_Combination_Contract_Test_Fault.sc
- Max_Function_Frame.sc
- Max_Function_Frame_Contract.sc
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9     z = y
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12     z = x
13 }
14
15 assert(z == x || z == y)
16 assert(y <= z & x <= z)

```

Satisfiability check for if-then at [7, 7]: Sat
Satisfiability check for if-else at [7, 7]: Sat

; Satisfiability check for if-then at [7, 7]
; Result: Sat

Claims:

; x == At[Z](".random", 0),
; y == At[Z](".random", 1),
; z == 0,
; x < y
;
(set-logic ALL)

(define-sort B () Bool)
(define-fun |B.unary_!=| ((x B)) B (not x))
(define-fun |B.unary_~| ((x B)) B (not x))
(define-fun |B.==| ((x B) (y B)) B (= x y))
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Logika uses SMT solvers in the background

It also simplifies formulas by rewriting

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Search ...

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There's no magic

```

(define-fun |B.unary_!=| ((x B)) B (not x))
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```

(define-fun |B.| | ((x B) (y B)) B (or x y))
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A Quick Tour of Slang and Logika

The User Interface

Proof commands available in Slang syntax (not in comments)

```

1 // #Sireum #Logika
2 import org.sireum._
3 val x: Z = random
4 val y: Z = random
5
6 var z: Z = 0
7 if (x < y) {
8   Deduce(I $\neg$  (x < y))
9   Deduce(I $\neg$  (x  $\leq$  y))
10  z = y
11  Deduce(I $\neg$  (x  $\leq$  z))
12  Deduce(I $\neg$  (z = y))
13 } else {
14   Deduce(I $\neg$  ( $\neg$ (x < y)))
15   Deduce(I $\neg$  (y  $\leq$  x))
16   z = x
17   Deduce(I $\neg$  (y  $\leq$  z))
18   Deduce(I $\neg$  (z = x))
19 }
20 assert(z = x  $\vee$  z = y)
21 assert(y  $\leq$  z  $\wedge$  x  $\leq$  z)

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Satisfiability check for if-then at [7, 7]: Sat
Satisfiability check for if-else at [7, 7]: Sat

; Result: Sat
; Solver: /Users/au443183/Applications/Sireum/bin
; Arguments: -smt2 -in rlimit=2000000 -t:500
; Time: 0.052s
;
; Claims:
;
; x == At[Z](".random", 0),
; y == At[Z](".random", 1),
; z == 0,
; x < y
;
(set-logic ALL)

(define-sort B () Bool)
(define-fun |B.unary_!=| ((x B)) B (not x))
(define-fun |B.unary_~| ((x B)) B (not x))
(define-fun |B.==| ((x B) (y B)) B (= x y))
(define-fun |B.!=| ((x B) (y B)) B (not (= x y)))
(define-fun |B.&| ((x B) (y B)) B (and x y))
(define-fun |B.||| ((x B) (y B)) B (or x y))
(define-fun |B.^| ((x B) (y B)) B (xor x y))
(define-fun |B._>:| ((x B) (y B)) B ($=>$ x y))
(define-fun |B.->:| ((x B) (y B)) B ($>=$ x y))

A Quick Tour of Slang and Logika

Contracts & Proof

```
1 // #Sireum #Logika
2 import org.sireum._
3
4 def swap(a: ZS, i:Z, j: Z) : Unit = {
5     Contract{
6         Requires(0 ≤ i, i < a.size, 0 ≤ j, j < a.size),
7         Modifies(a),
8         Ensures{
9             a(i) = In(a)(j),
10            a(j) = In(a)(i),
11            ∀(a.indices)(k ⇒ k = i ∨ k = j ∨ a(k) = In(a)(k)),
12            a.size = In(a).size
13        }
14    }
15    val t: Z = a(i)
16    Deduce(⊥ (t = In(a)(i)))
17    a(i) = a(j)
18    Deduce(⊥ (t = In(a)(i)))
19    Deduce(⊥ (a(i) = In(a)(j)))
20    a(j) = t
21    Deduce(⊥ (t = In(a)(i)))
22    Deduce(⊥ (a(j) = t))
23    Deduce(⊥ (a(j) = In(a)(i)))
24    Deduce(⊥ (a(i) = In(a)(j)))
25
26 }
```

Contracts for compositional reasoning

A Quick Tour of Slang and Logika

Contracts & Proof

```
1 // #Sireum #Logika
2 import org.sireum._
3
4 def swap(a: ZS, i:Z, j: Z) : Unit = {
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9             a(i) = In(a)(j),
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11            ∀(a.indices)(k ⇒ k = i ∨ k = j ∨ a(k) = In(a)(k)),
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24    Deduce(⊥ (a(i) = In(a)(j)))
25
26 }
```

Contracts for compositional reasoning

Hoare-style reasoning about imperative commands

A Quick Tour of Slang and Logika

Contracts & Proof

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1 // #Sireum #Logika
2 import org.sireum._
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24    Deduce(⊥ (a(i) = In(a)(j)))
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26 }
```

Contracts for compositional reasoning

Hoare-style reasoning about imperative commands

Proof in Slang as close as possible to programming

A Quick Tour of Slang and Logika

Contracts & Proof

```
1 // #Sireum #Logika
2 import org.sireum._
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4 def swap(a: ZS, i:Z, j: Z) : Unit = {
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23  Deduce(⊥ (a(j) = In(a)(i)))
24  Deduce(⊥ (a(i) = In(a)(j)))
25
26 }
```

Familiar Interface for students

k: Z

Example

🔗 ⋮

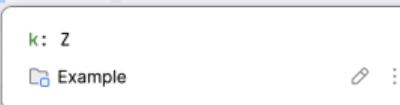
A Quick Tour of Slang and Logika

Contracts & Proof

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25
26 }
```

Familiar Interface for students

Interactive inspection of all elements, including formulas and proof



A Quick Tour of Slang and Logika

Proof Information

```
5  @pure def sorted(seq: ISZ[Z]): B = {
6    Contract(
7      Ensures(Res = All(1 until seq.size)(i => seq(i-1) ≤ seq(i)))
8    )
9    var res: B = true
10   var k: Z = 1
11   while (k < seq.size) {
12     Invariant(
13       Modifies(k, res),
14       k ≥ 1,
15       k-1 ≥ 0,
16       k-1 ≤ seq.size,
17       seq.size ≥ 2 || res = true,
18       seq.size < 2 ∨ k ≤ seq.size,
19       seq.size < 2 || res = All(1 until k)(i => seq(i-1) ≤ seq(i))
20     )
21     Deduce(¬ (seq.size ≥ 2))
22     if (seq(k - 1) > seq(k)) {
23       res = false
24     }
25     k = k + 1
26   }
27   Deduce(¬ (seq.size ≥ 2 || res = All(1 until seq.size)(i => seq(i-1) ≤ seq(i))))
28   Deduce(¬ (seq.size < 2 || res = All(1 until seq.size)(i => seq(i-1) ≤ seq(i))))
29   return res
30 }
31 }
```

Proof information available **interactively**

A Quick Tour of Slang and Logika

Proof Information

```
5  v @pure def sorted(seq: ISZ[Z]): B = {
6    v Contract(
7      Ensures(Res = All(1 until seq.size)(i => seq(i-1) ≤ seq(i)))
8    )
9    v res: B = true
10   v k: Z = 1
11   v while (k < seq.size) {
12     v Invariant(
13       Modifies(k, res),
14       k ≥ 1,
15       k-1 ≥ 0,
16       k-1 ≤ seq.size,
17       seq.size ≥ 2 || res = true,
18       seq.size < 2 ∨ k ≤ seq.size,
19       seq.size < 2 || res = All(1 until k)(i => seq(i-1) ≤ seq(i))
20     )
21   v Deduce(¬ (seq.size ≥ 2))
22   v if (seq(k - 1) > seq(k)) {
23     v Click to show some hints else
24     v }
25     v k = k + 1
26   v
27   v Deduce(¬ (seq.size ≥ 2 || res = All(1 until seq.size)(i => seq(i-1) ≤ seq(i))))
28   v Deduce(¬ (seq.size < 2 || res = All(1 until seq.size)(i => seq(i-1) ≤ seq(i))))
29   v return res
30   v
31 }
```

Proof information available **interactively**

“Click the *light bulb*”

A Quick Tour of Slang and Logika

Proof Information

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5  @pure def sorted(seq: ISZ[Z]): B = {
6    Contract(
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29   return res
30 }
31 }
```

// State claims at line 23
At(res, 0) = T;
At(k, 0) = 1;
k < seq.size;
k ≥ 1;
k - 1 ≥ 0;
k - 1 ≤ seq.size;
seq.size ≥ 2;
seq.size < 2 ∨
k ≤ seq.size;
¬(seq.size < 2);
res = ∀(1 until k)(i => seq(i - 1) ≤ seq(i));
seq(k - 1) > seq(k)

Filter claims ...

A Quick Tour of Slang and Logika

Proof Information

```
5  @pure def sorted(seq: ISZ[Z]): B = {
6    Contract(
7      Ensures(Res = All(1 until seq.size)(i => seq(i-1) ≤ seq(i)))
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k ≤ seq.size;
¬(seq.size < 2);
res = ∀(1 until k)(i => seq(i - 1) ≤ seq(i));
seq(k - 1) > seq(k)
}

Proof information shown to student
close to the program text

Filter claims ...

A Quick Tour of Slang and Logika

Proof Information

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5  @pure def sorted(seq: ISZ[Z]): B = {
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seq.size < 2 ∨
k ≤ seq.size;
¬(seq.size < 2);
res = ∀(1 until k)(i => seq(i - 1) ≤ seq(i));
seq(k - 1) > seq(k)
}

Proof information shown to student
close to the program text

Easy to match program text to formulas
(also large formulas)

Filter claims ...

A Quick Tour of Slang and Logika

Informal vs Formal

```
1 // #Sireum #Logika
2 import org.sireum.-
3
4 val m: Z = randomInt();
5 val n: Z = randomInt()
6 val z: Z = m + n
7 // deduce z == m + n (consequence of assignment)
8 val y: Z = z - n
9 // deduce z == m + n (old fact)
10 // deduce y == z - n (consequence of assignment)
11 // deduce y == m (proof by algebra)
12 //           (y == z - n
13 //           == (m + n) - n
14 //           == m)
15 val x: Z = z - y
16 // deduce z == m + n (old fact)
17 // deduce y == m (old fact)
18 // deduce x == z - y (consequence of assignment)
19 // deduce x == n (proof by algebra)
20 //           (x == z - y
21 //           == (m + n) - m
22 //           == n)
23 assert(x == n & y == m)
24
```

Informal proofs in comments useable
without tool support

A Quick Tour of Slang and Logika

Informal vs Formal

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20 //           (x == z - y
21 //           == (m + n) - m
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```

Informal proofs in comments useable
without tool support

Also used on white board

A Quick Tour of Slang and Logika

Informal vs Formal

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1 // #Sireum #Logika
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4 ✨ val m: Z = randomInt();
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```

Logika can do many proofs fully automatic

✓ Logika Verified
Proof is accepted

A Quick Tour of Slang and Logika

Informal vs Formal

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Logika can do many proofs fully automatic

Beginning students benefit from this

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A Quick Tour of Slang and Logika

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Logika can do many proofs fully automatic

Beginning students benefit from this

If they know that it can be proved,
Logika confirms or refutes their deductions

✓ Logika Verified
Proof is accepted

A Quick Tour of Slang and Logika

Informal vs Formal

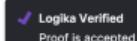
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21 //           = (m + n) - m
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23 ✨ assert(x == n & y == m)
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```

Logika can do many proofs fully automatic

Beginning students benefit from this

If they know that it can be proved,
Logika confirms or refutes their deductions

The students can use Logika like a teacher



Context, Approach and Evolution

Use and Significance of Slang and Logika

Feedback

Discussion

Next Steps

Student Feedback

It was nice with a little mini-project to use some of the techniques learned in the course

Student Feedback

It was nice with a little mini-project to use some of the techniques learned in the course

It was really nice to have exercises during the lecture and that [the teacher] walked around to help us if we were struggling with some of the proofs. I really liked that!

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It was nice with a little mini-project to use some of the techniques learned in the course

It was really nice to have exercises during the lecture and that [the teacher] walked around to help us if we were struggling with some of the proofs. I really liked that!

[The teacher] was really good at explaining the subjects and always made sure that the class was understanding the theory

I am not sure if I am going to use what I have learned

Context, Approach and Evolution
oooo

Use and Significance of Slang and Logika
ooooo

Feedback
oo

Discussion
●oo

Next Steps
oo

Context, Approach and Evolution

Use and Significance of Slang and Logika

Feedback

Discussion

Next Steps

Discussion

- A good **user-friendly tool** that the students are familiar with is **essential**
- Students look for the **benefit** they get out of a course
- They **don't** have a strong background in maths and logics
- It's better if taught material **does not look like formal methods**
- Concerning proof, **in-class attention** by teacher is required
- Using theorem provers directly **did not work well**
- Notation and methodology should be as close to **programming** as possible
- The students rate this course **very high**: 4.4 out of 5
(but response rate needs to be improved)
- **Despite its title** “Software Correctness” high number of inscriptions
(20 students)
- Lecture materials for the course are **publicly available**
(<https://github.com/santoslab/software-correctness-course-materials>)

Much More Material Available From Kansas State University

S 301: Logical Foundations of Programming

Search... X

Propositional Logic Proofs

Predicate Logic Translations

Predicate Logic Proofs

Mathematical Induction

Intro to Programming Logic

Functions and Loops

9.1. Functions

9.2. Recursion

9.3. Loops

9.4. Logika Facts

9.5. Summary

Sequences, Globals, and Iteration

U Auto

Using Hugo and Hugo Relearn Theme.

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Functions and Loops > Loops

```
val x: Z = Z.read()
val y: Z = Z.read()

var sum: Z = 0
var count: Z = 0

//prove the invariant before the loop begins
Deduce(
    1 (      sum == 0          ) by Premise,           //from the "sum = 0" assignment
    2 (      count == 0        ) by Premise,           //from the "count = 0" assignment
    3 (      sum == count*x ) by Algebra*(1, 2)       //proved EXACTLY the loop invariant
)

while (count != y) {
    Invariant(
        Modifies(sum, count),
        sum == count * x
    )

    Deduce(
        1 (      sum == count*x   ) by Premise,           //the loop invariant holds
                                                       //at the beginning of an iteration
    )

    sum = sum + x

    Deduce(
        1 (      sum == Old(sum) + x   ) by Premise,           //from "sum = sum + x" assignment
        2 (      Old(sum) == count*x ) by Premise,           //loop invariant WAS true, but sum
                                                       //has changed
        3 (      sum == count*x + x ) by Algebra*(1,2)       //current knowledge without using
    )

    count = count + 1

    Deduce(
        1 (      count == Old(count)+ 1 ) by Premise,           //from "count = count + 1" assignment
        2 (      sum == Old(count)*x + x ) by Premise,           //from previous "sum = count*x + x"
                                                       //but count has changed
        3 (      sum == (count-1)*x + x ) by Algebra*(1,2),
        4 (      sum == count*x - x + x ) by Algebra*(3),
        5 (      sum == count*x         ) by Algebra*(4)       //loop invariant holds at end of
    )
}
```

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Functions and Loops

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9.2. Recursion

9.3. Loops

9.4. Logika Facts

9.5. Summary

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Functions and Loops > Loops

val x: Z = Z.read()
val y: Z = Z.read()

var sum: Z = 0
var count: Z = 0

//prove the invariant before the loop begins

Deduce(
 1 (sum == 0) by Premise,
 2 (count == 0) by Premise,
 3 (sum == count*x) by Algebra*(1, 2)
)

while (count != y) {
 Invariant(
 Modifies(sum, count),
 sum == count * x
)

Deduce(
 1 (sum == count*x) by Premise, //the loop invariant holds
 //at the beginning of an iteration
)

sum = sum + x

Deduce(
 1 (sum == Old(sum) + x) by Premise, //from "sum = sum + x" assignment
 2 (Old(sum) == count*x) by Premise, //loop invariant WAS true, but sum
 3 (sum == count*x + x) by Algebra*(1,2) //current knowledge without using
)

count = count + 1

Deduce(
 1 (count == Old(count)+ 1) by Premise, //from "count = count + 1" assignment
 2 (sum == Old(count)*x + x) by Premise, //from previous "sum = count*x + x"
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Visit John's presentation on Logika later today!



Context, Approach and Evolution

Use and Significance of Slang and Logika

Feedback

Discussion

Next Steps

Next Steps

- Extend the number of **examples**
- Improve support for **self-study**
- improve presentation of **more advanced verification**
- Improve presentation of **proof methodology**
- Rely on discussion and **feedback from students** for improvements
- The course **evolves gradually** – material, tool and students change