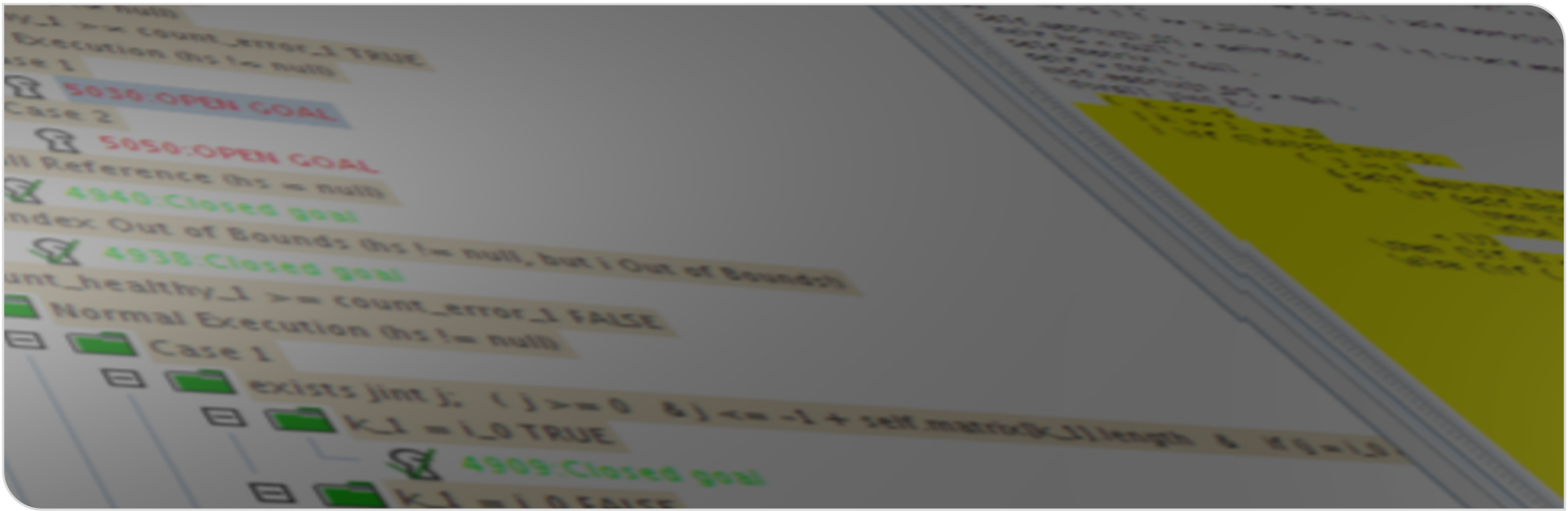
Karlsruhe Institute of Technology

KASTEL

Integrating Source Code, Specification, and Proof State into a Single View in KeY

Wolfram Pfeifer | August 12, 2022



KeY

Karlsruhe Institute of Technology

Deductive verifier for (sequential) Java

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Java Modeling Language (JML)

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Modular specification/verification

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Dynamic Logic (JavaDL), sequent calculus

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Counterexample generation

Information flow proofs

Testcase generation

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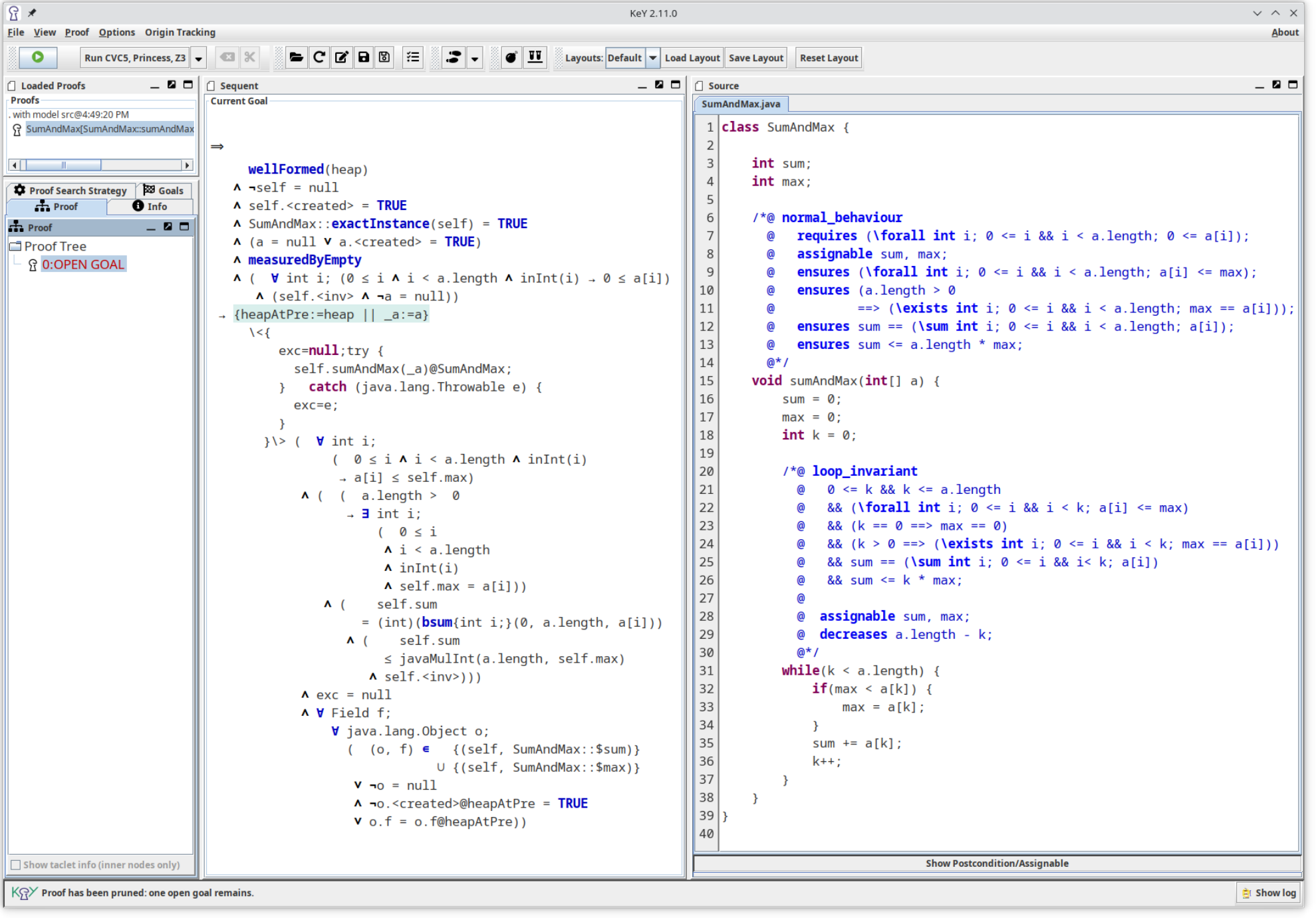
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About
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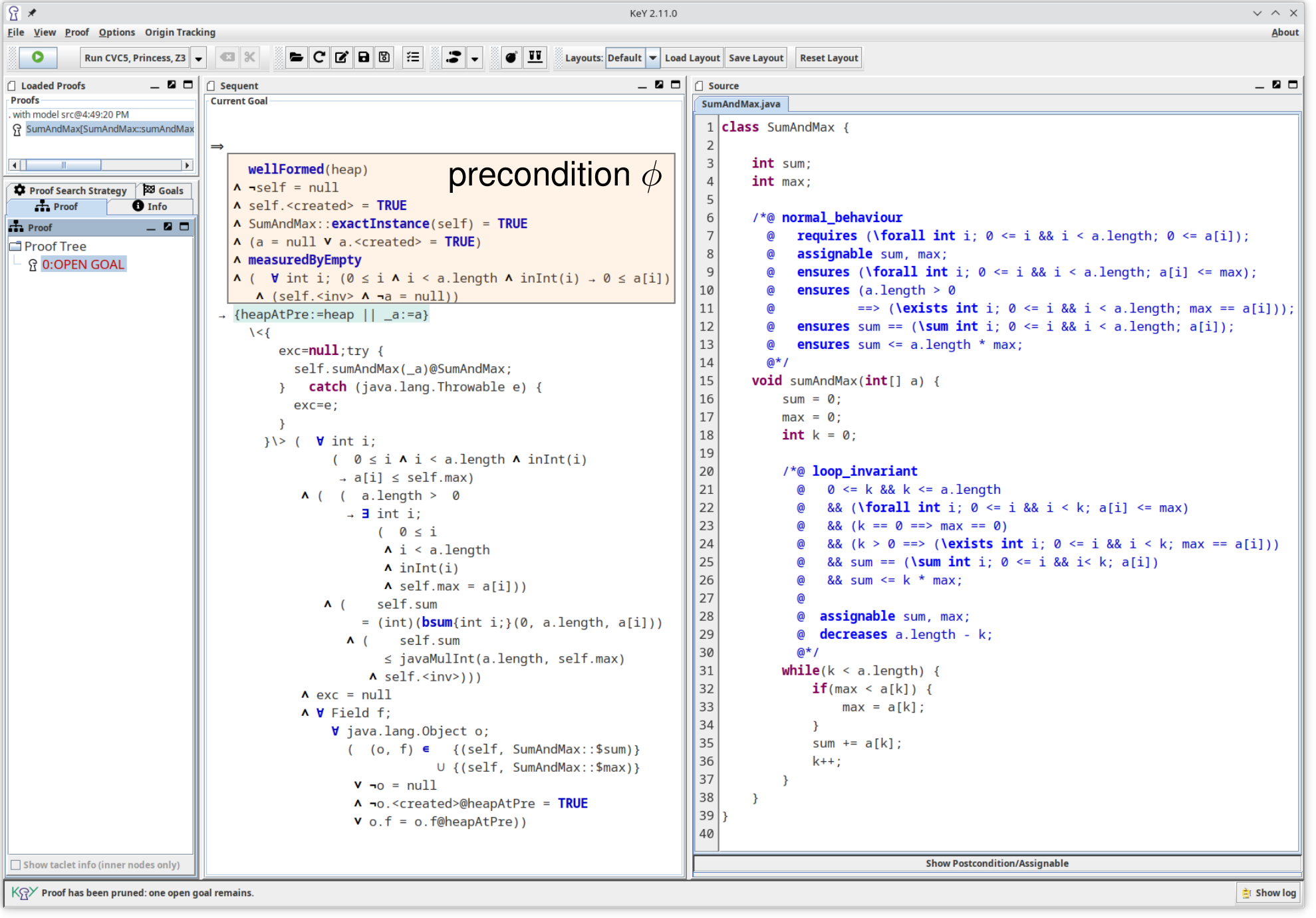
Proof has been pruned: one open goal remains.
Show log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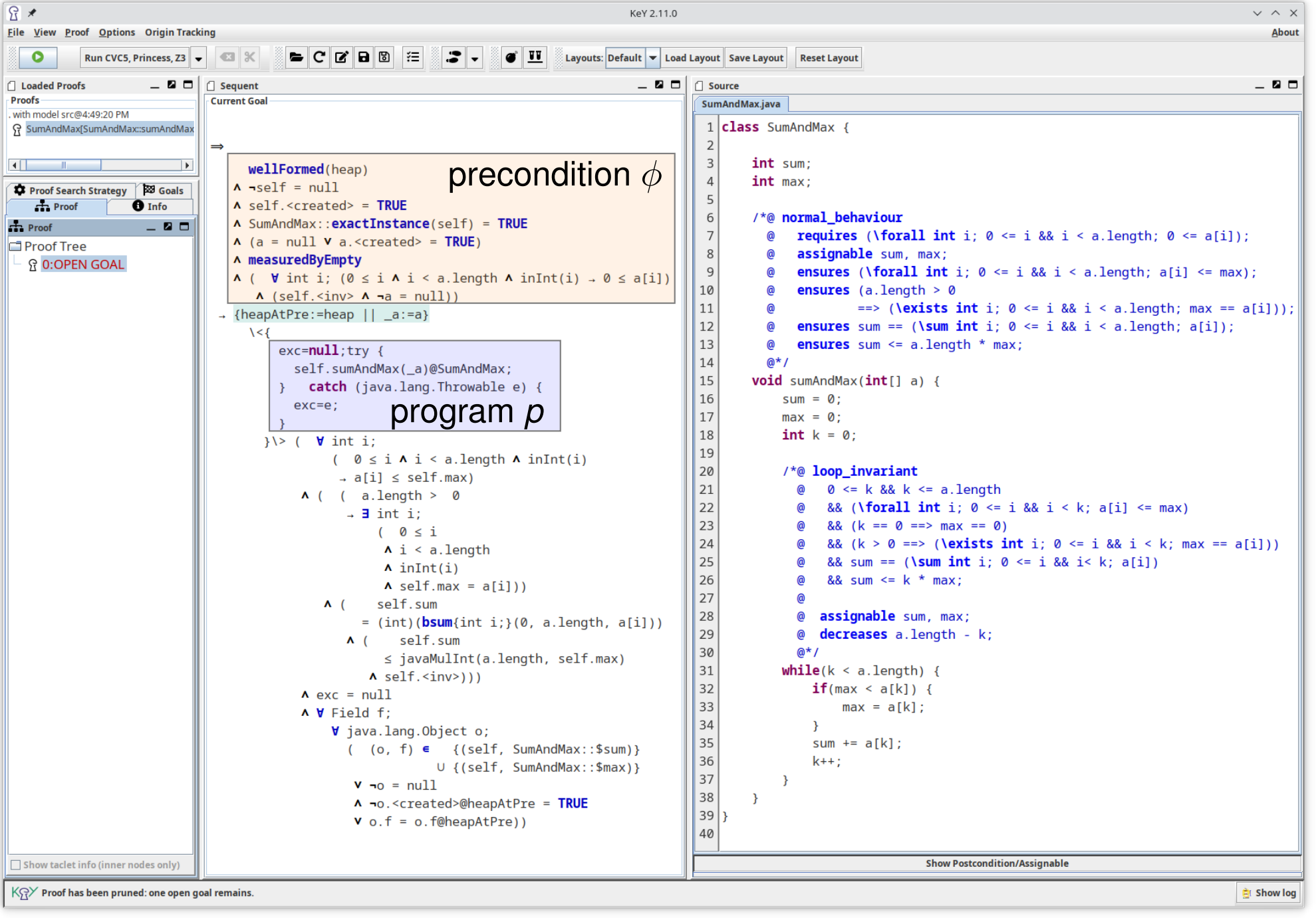
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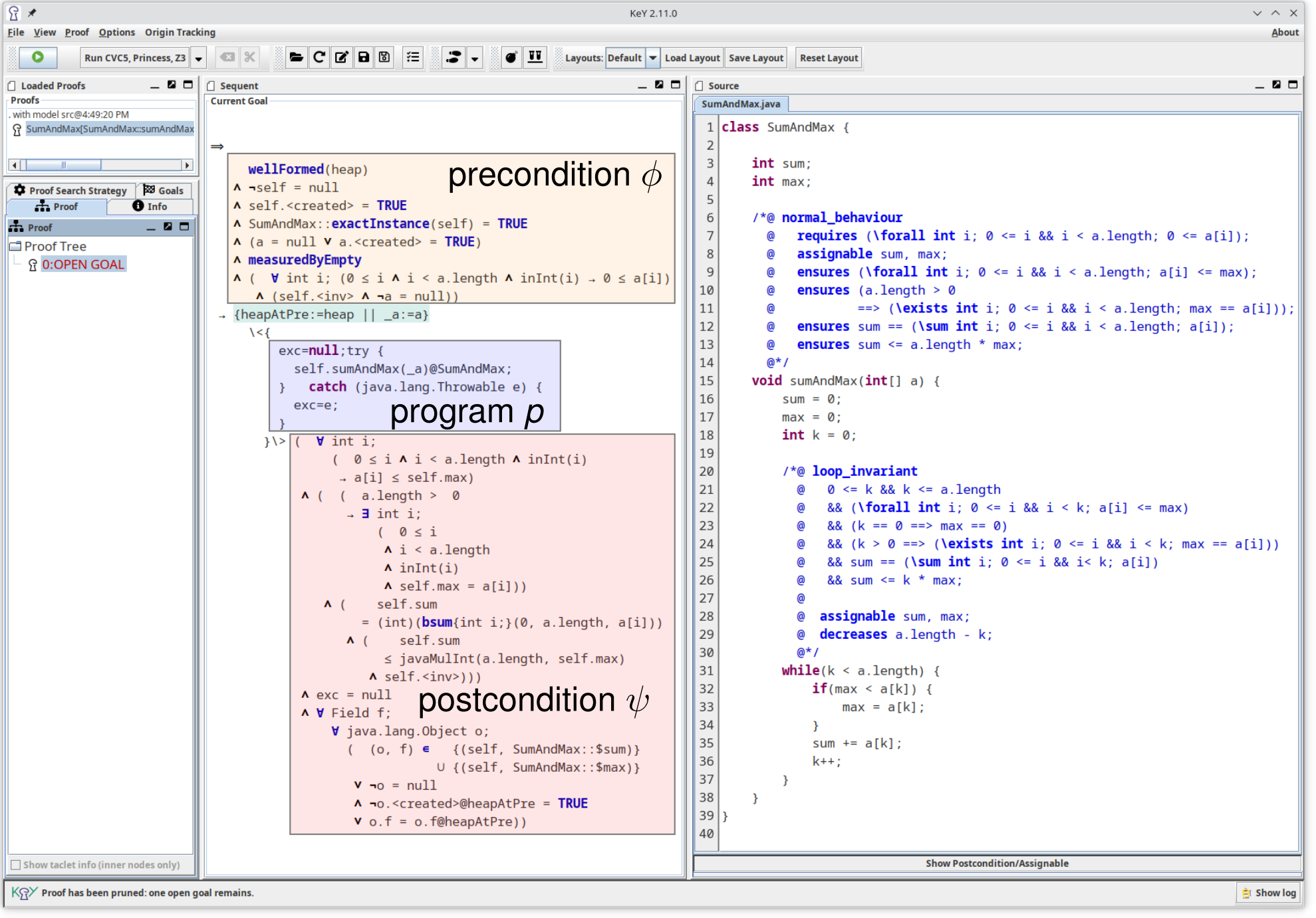
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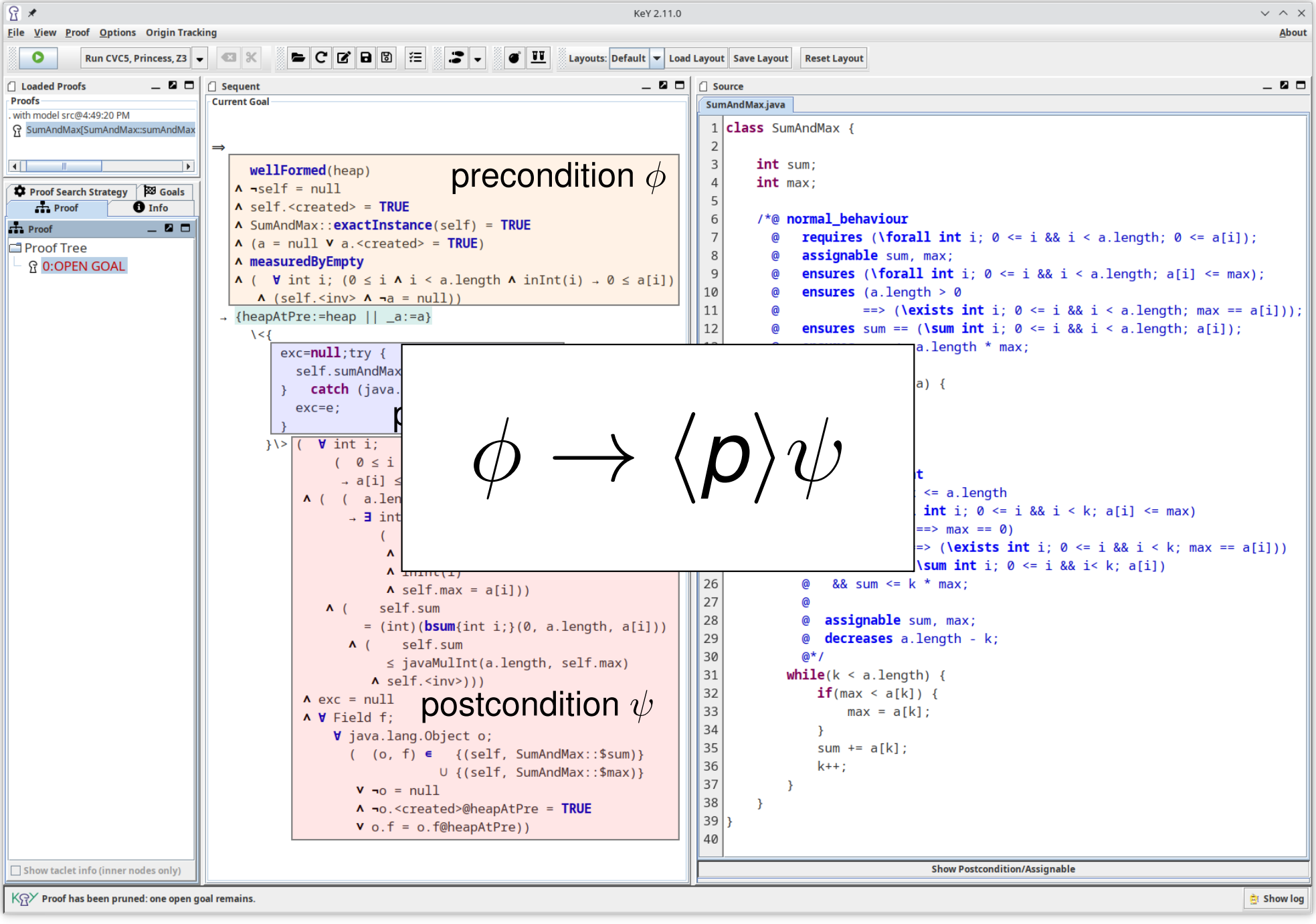
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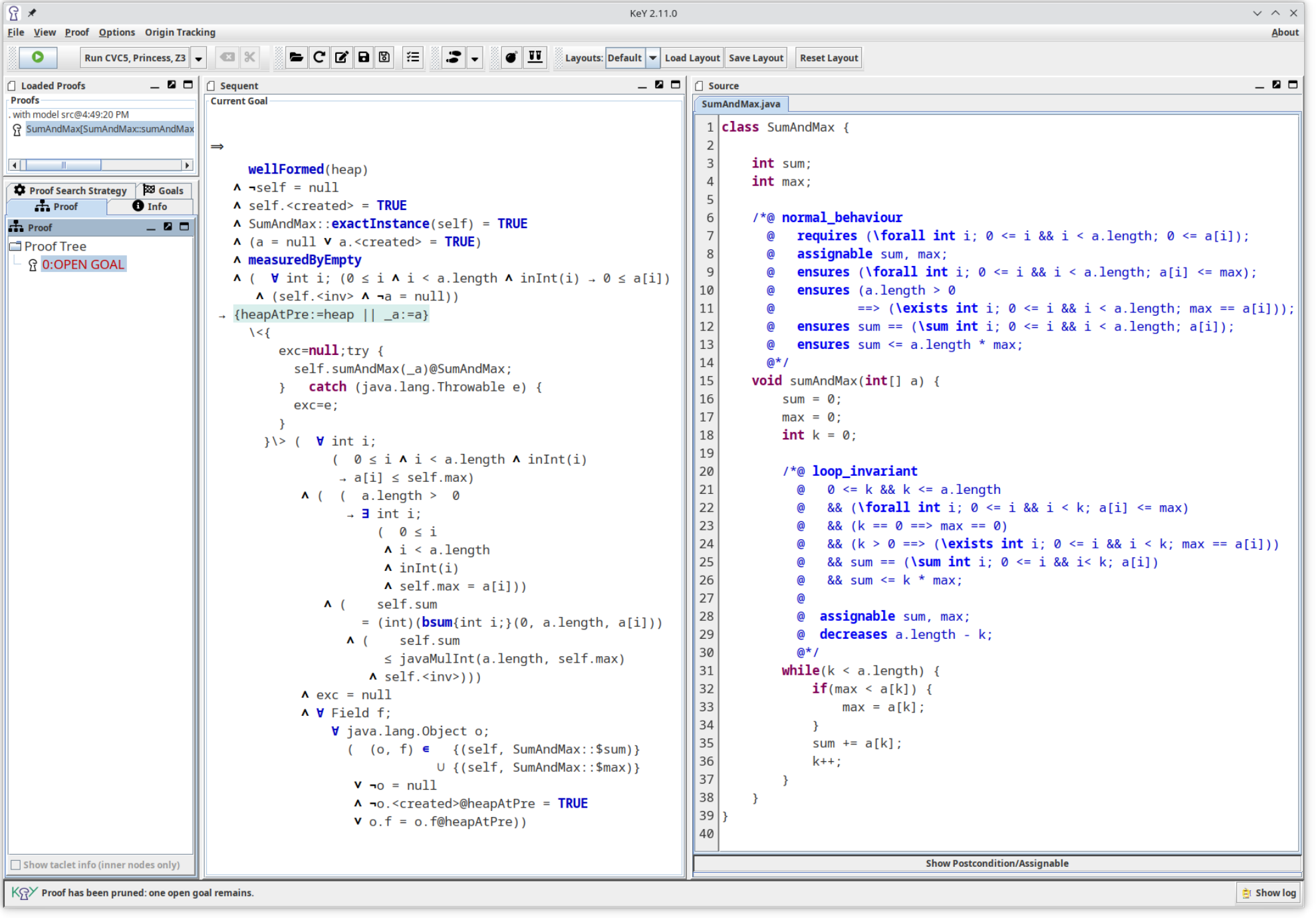
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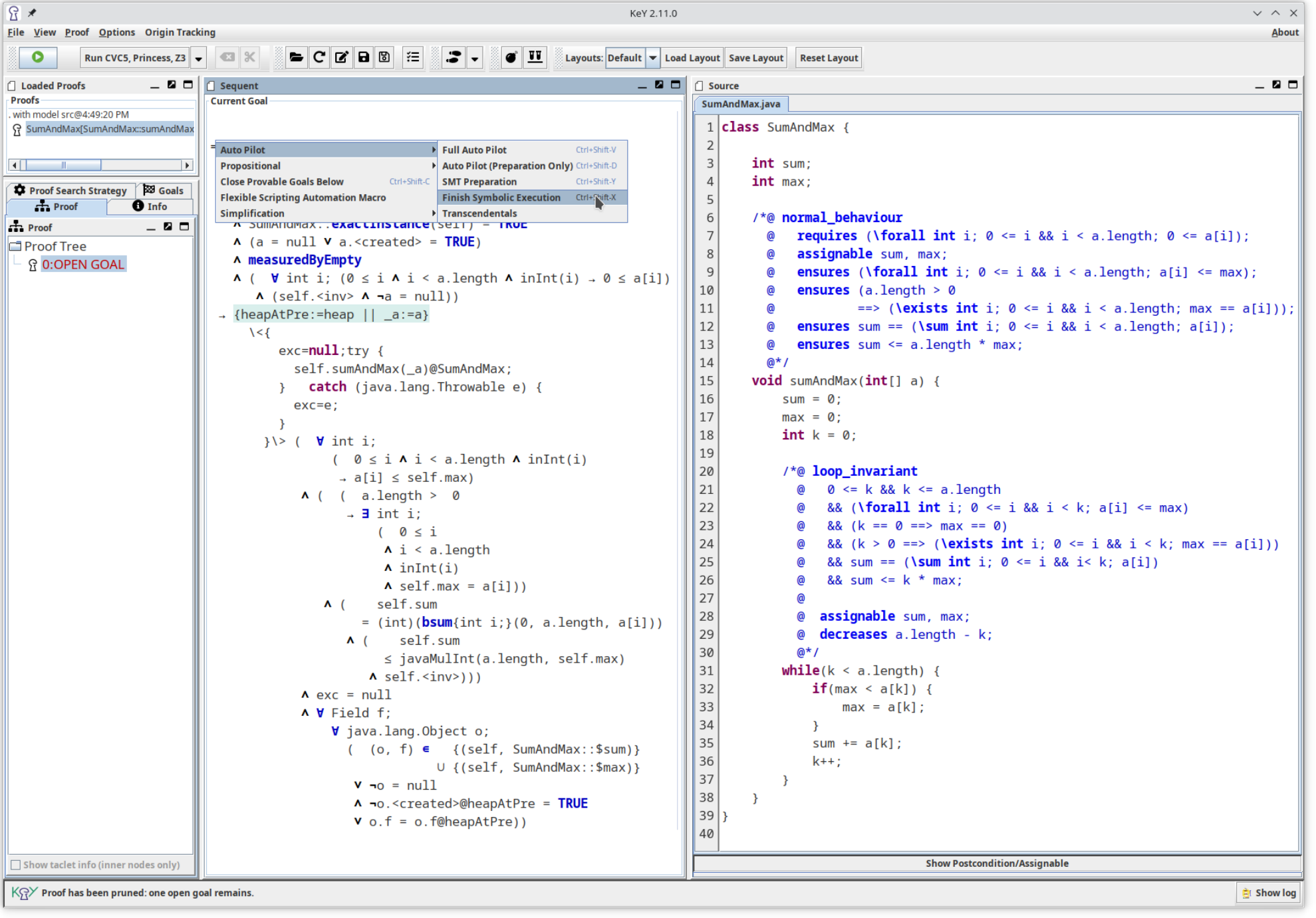
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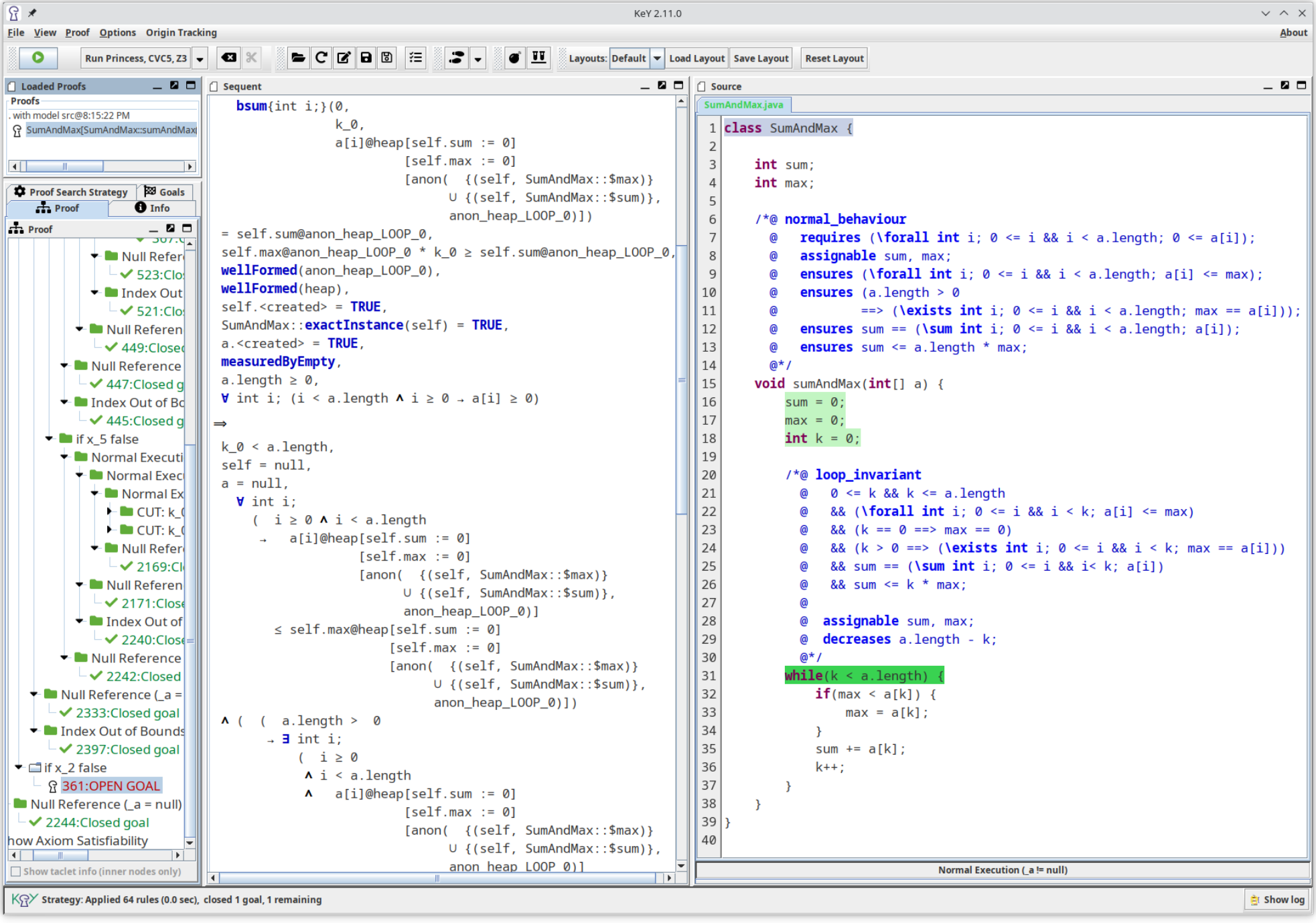
→ {heapAtPre:=heap || _a:=a}
\<{
exc=null;try {
self.sumAndMax(_a)@SumAndMax;
} catch (java.lang.Throwable e) {
exc=e;
}
}\> (∀ int i;
(0 ≤ i ∧ i < a.length ∧ inInt(i)
→ a[i] ≤ self.max)
∧ ((a.length > 0
→ ∃ int i;
(0 ≤ i
∧ i < a.length
∧ inInt(i)
∧ self.max = a[i]))
∧ (self.sum
= (int)(bsum{int i;}(0, a.length, a[i]))
∧ (self.sum
≤ javaMulInt(a.length, self.max)
∧ self.<inv>)))
∧ exc = null
∧ ∀ Field f;
∀ java.lang.Object o;
((o, f) ∈ {(self, SumAndMax::$sum)}
∪ {(self, SumAndMax::$max)}
∨ ¬o = null
∧ ¬o.<created>@heapAtPre = TRUE
∨ o.f = o.f@heapAtPre))
Source
SumAndMax.java
1 class SumAndMax {
2
3 int sum;
4 int max;
5
6 /*@ normal_behaviour
7 @ requires (\forall int i; 0 <= i && i < a.length; 0 <= a[i]);
8 @ assignable sum, max;
9 @ ensures (\forall int i; 0 <= i && i < a.length; a[i] <= max);
10 @ ensures (a.length > 0
11 @ ==> (\exists int i; 0 <= i && i < a.length; max == a[i]));
12 @ ensures sum == (\sum int i; 0 <= i && i < a.length; a[i]);
13 @ ensures sum <= a.length * max;
14 @*/
15 void sumAndMax(int[] a) {
16 sum = 0;
17 max = 0;
18 int k = 0;
19
20 /*@ loop_invariant
21 @ 0 <= k && k <= a.length
22 @ && (\forall int i; 0 <= i && i < k; a[i] <= max)
23 @ && (k == 0 ==> max == 0)
24 @ && (k > 0 ==> (\exists int i; 0 <= i && i < k; max == a[i]))
25 @ && sum == (\sum int i; 0 <= i && i< k; a[i])
26 @ && sum <= k * max;
27 @
28 @ assignable sum, max;
29 @ decreases a.length - k;
30 @*/
31 while(k < a.length) {
32 if(max < a[k]) {
33 max = a[k];
34 }
35 sum += a[k];
36 k++;
37 }
38 }
39 }
40
Show Postcondition/Assignable
Proof has been pruned: one open goal remains.
Show log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[self.max := 0]
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U {(self, SumAndMax::$sum)},
anon_heap_LOOP_0)])
= self.sum@anon_heap_LOOP_0,
self.max@anon_heap_LOOP_0 * k_0 ≥ self.sum@anon_heap_LOOP_0,
wellFormed(anon_heap_LOOP_0),
wellFormed(heap),
self.<created> = TRUE,
SumAndMax::exactInstance(self) = TRUE,
a.<created> = TRUE,
measuredByEmpty,
a.length ≥ 0,
∀ int i; (i < a.length ∧ i ≥ 0 → a[i] ≥ 0)
⇒
k_0 < a.length,
self = null,
a = null,
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Normal Execution (_a != null)
Strategy: Applied 64 rules (0.0 sec), closed 1 goal, 1 remaining
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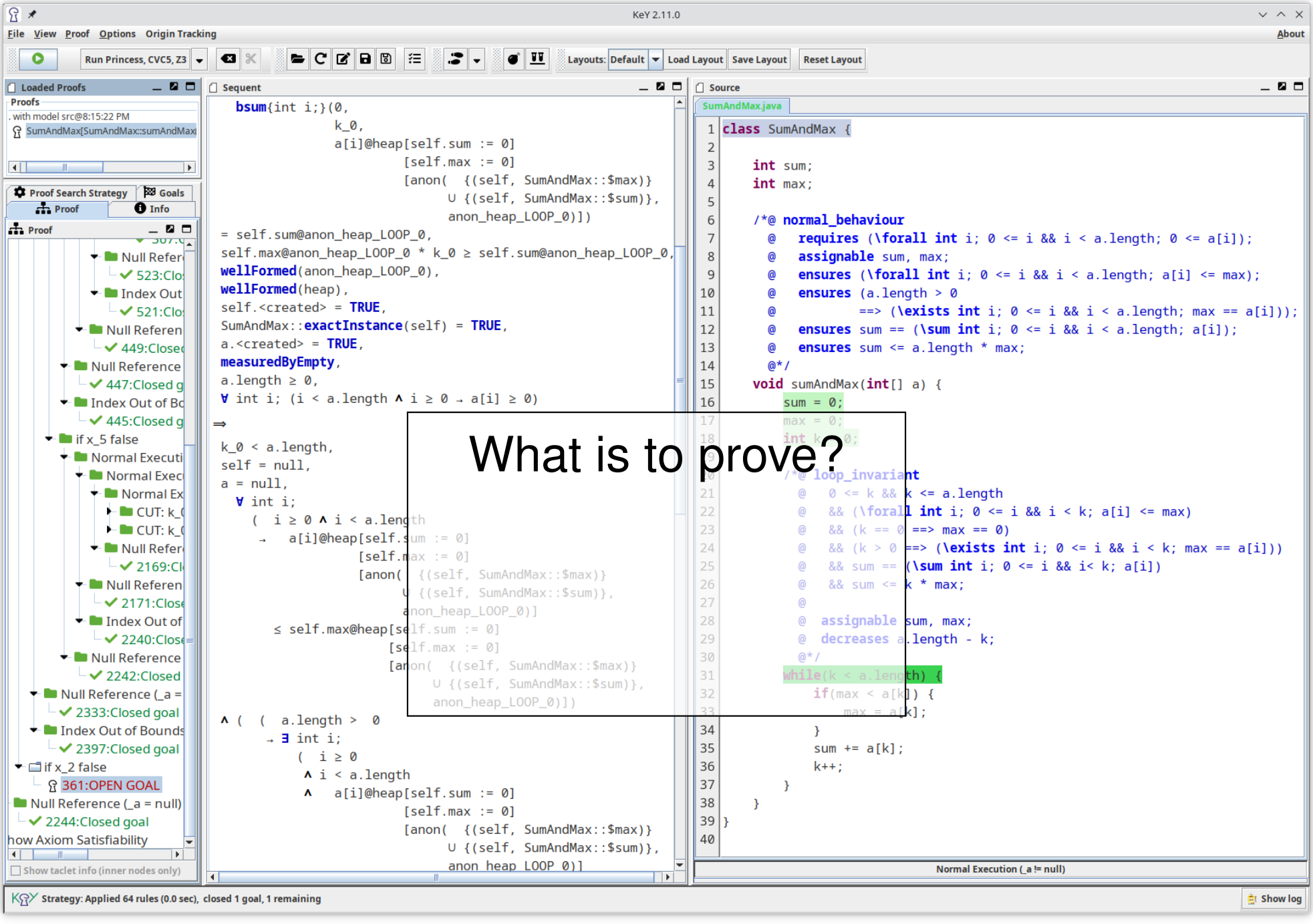
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self.max@anon_heap_LOOP_0 * k_0 ≥ self.sum@anon_heap_LOOP_0,
wellFormed(anon_heap_LOOP_0),
wellFormed(heap),
self.<created> = TRUE,
SumAndMax::exactInstance(self) = TRUE,
a.<created> = TRUE,
measuredByEmpty,
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⇒
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a = null,
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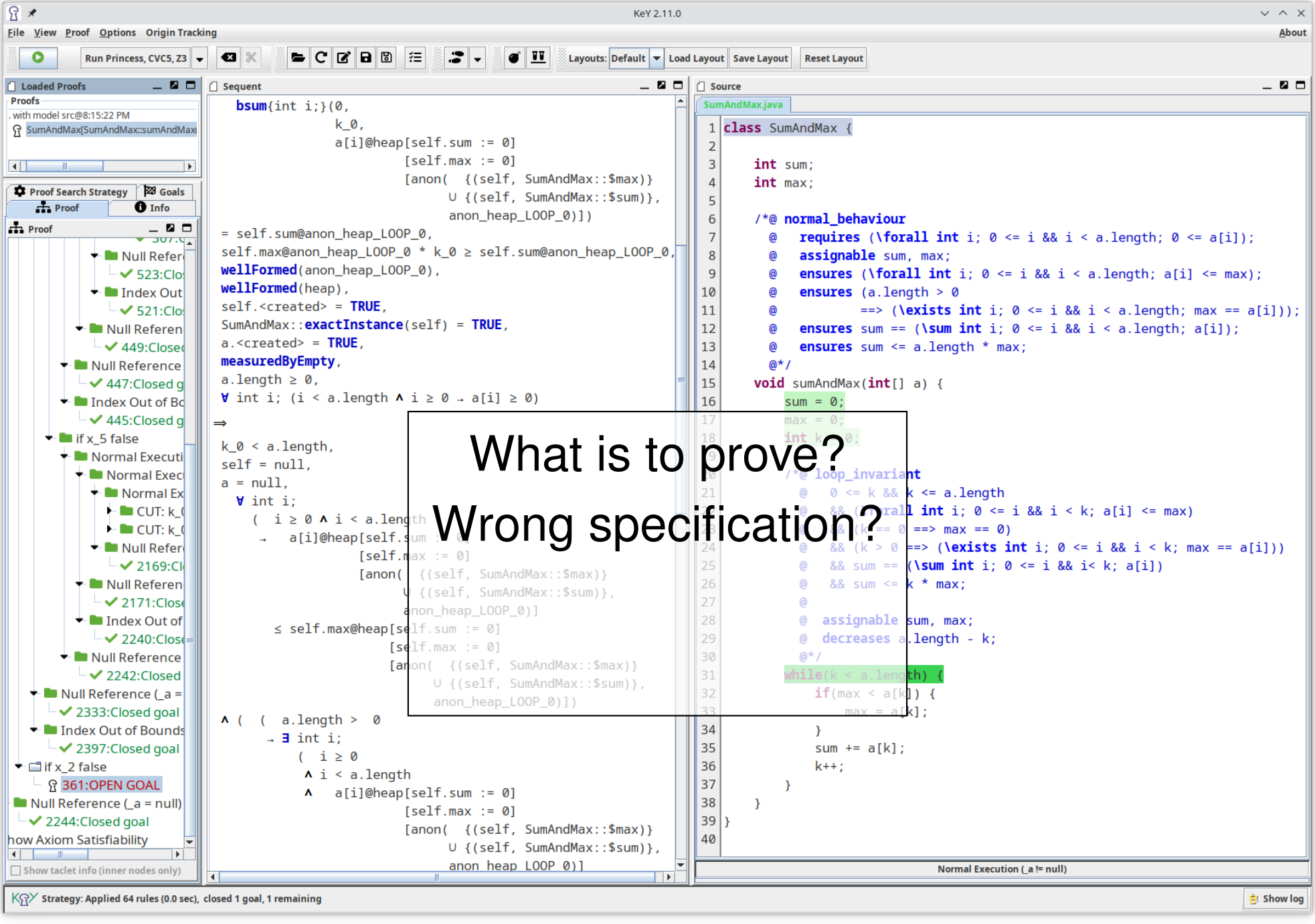
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U {(self, SumAndMax::$sum)},
anon_heap_LOOP_0)])
= self.sum@anon_heap_LOOP_0,
self.max@anon_heap_LOOP_0 * k_0 ≥ self.sum@anon_heap_LOOP_0,
wellFormed(anon_heap_LOOP_0),
wellFormed(heap),
self.<created> = TRUE,
SumAndMax::exactInstance(self) = TRUE,
a.<created> = TRUE,
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class SumAndMax {
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int max;
/*@ normal_behaviour
@ requires (\forall int i; 0 <= i && i < a.length; 0 <= a[i]);
@ assignable sum, max;
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@ ensures (a.length > 0
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@ ensures sum == (\sum int i; 0 <= i && i < a.length; a[i]);
@ ensures sum <= a.length * max;
@*/
void sumAndMax(int[] a) {
sum = 0;
max = 0;
int k = 0;
/*@ loop_invariant
@ 0 <= k && k <= a.length
@ && (\forall int i; 0 <= i && i < k; a[i] <= max)
@ && (k == 0 ==> max == 0)
@ && (k > 0 ==> (\exists int i; 0 <= i && i < k; max == a[i]))
@ && sum == (\sum int i; 0 <= i && i< k; a[i])
@ && sum <= k * max;
@
@ assignable sum, max;
@ decreases a.length - k;
@*/
while(k < a.length) {
if(max < a[k]) {
max = a[k];
}
sum += a[k];
k++;
}
}
}
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What is to prove?
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Strategy: Applied 64 rules (0.0 sec), closed 1 goal, 1 remaining
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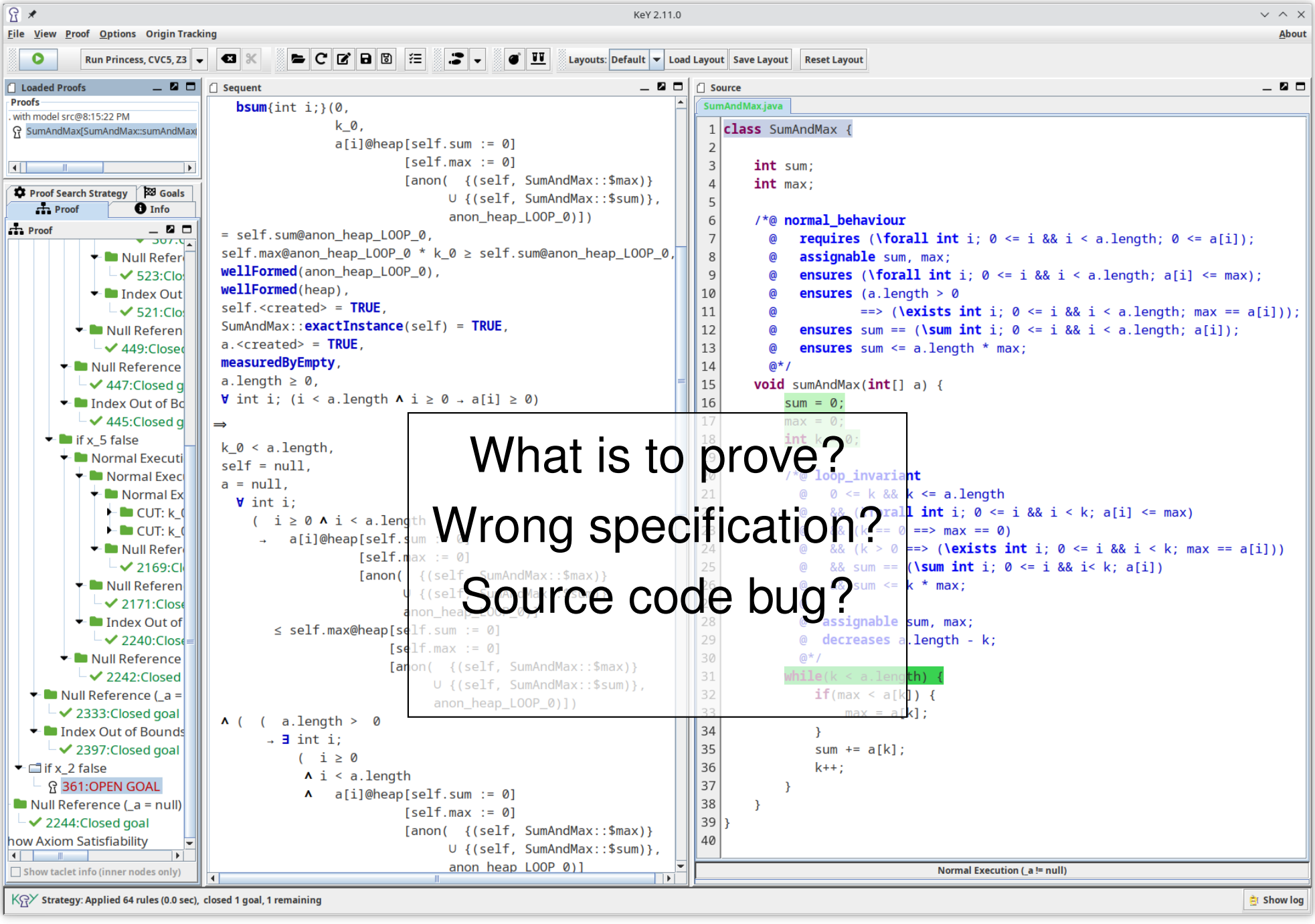
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U {(self, SumAndMax::$sum)},
anon_heap_LOOP_0)])
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wellFormed(heap),
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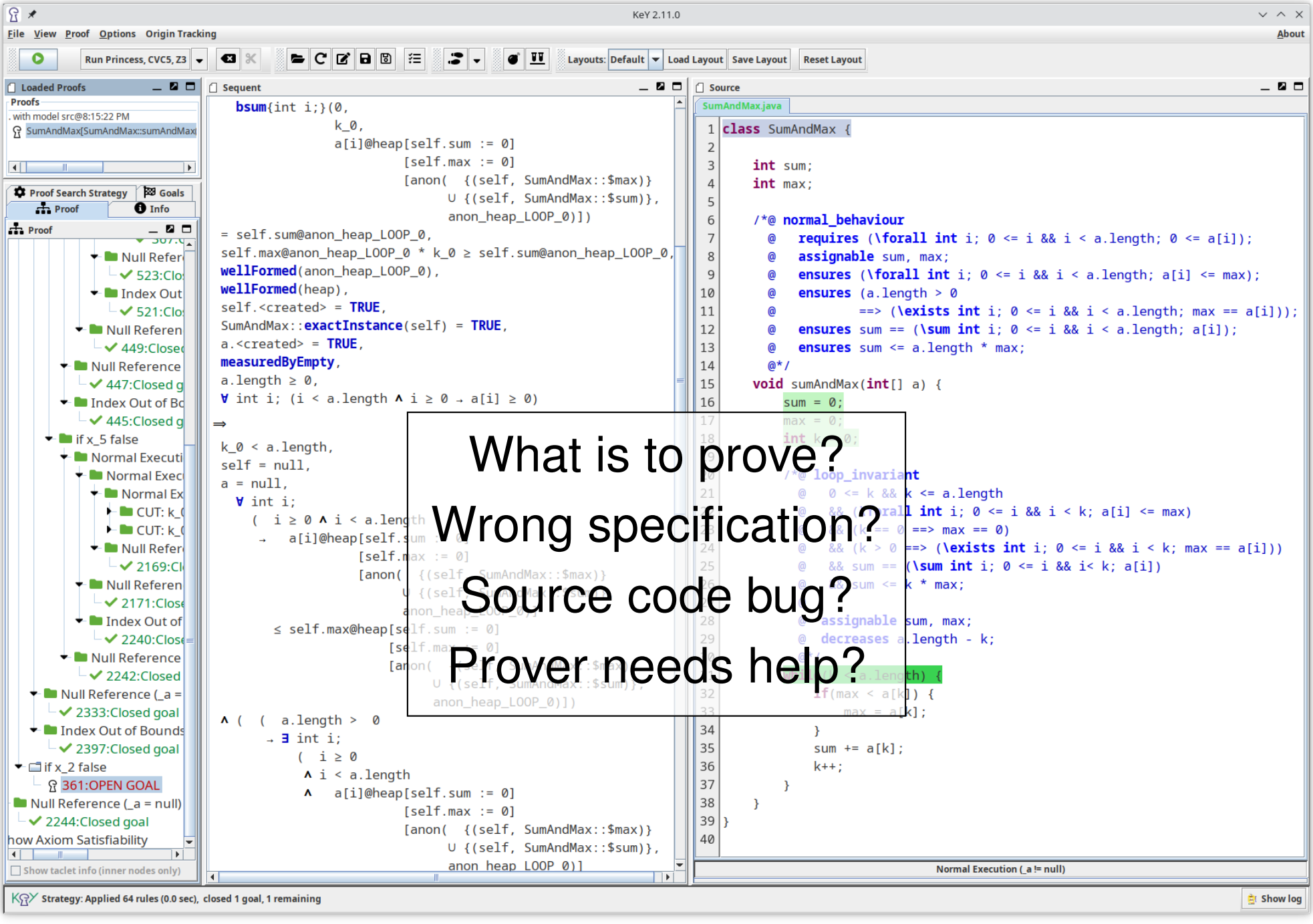
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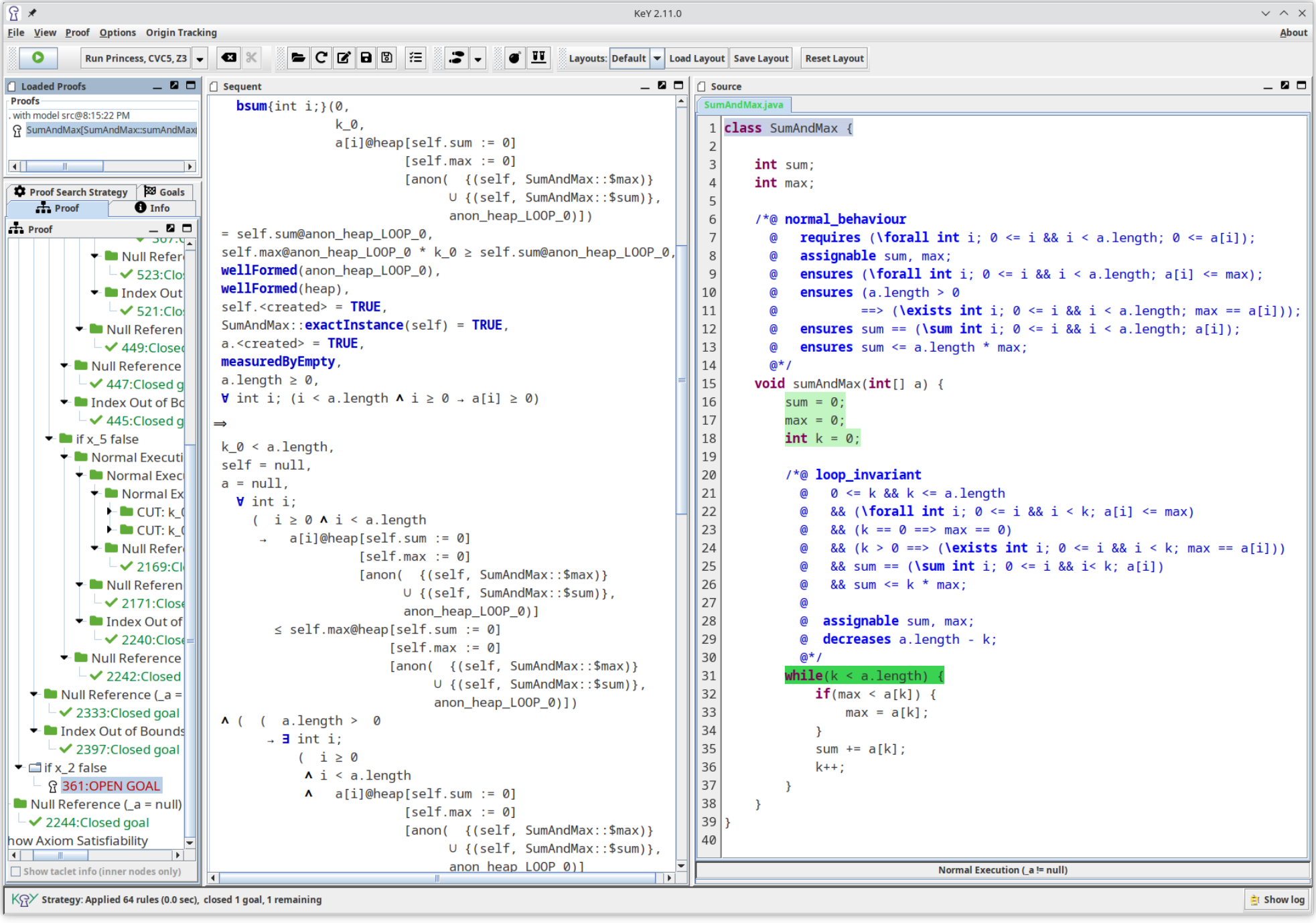
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SumAndMax[SumAndMax::sumAndMax
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521:Clo
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Null Reference
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Index Out of Bo
445:Closed g
if x_5 false
Normal Executi
Normal Exec
Normal Ex
CUT: k_(
CUT: k_(
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Null Referen
2171:Close
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2240:Close
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2242:Closed
Null Reference (_a =
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if x_2 false
361:OPEN GOAL
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how Axiom Satisfiability
Show taclet info (inner nodes only)
Sequent
bsum{int i;}(0,
k_0,
a[i]@heap[self.sum := 0]
[self.max := 0]
[anon({(self, SumAndMax::$max)}
U {(self, SumAndMax::$sum)},
anon_heap_LOOP_0)])
= self.sum@anon_heap_LOOP_0,
self.max@anon_heap_LOOP_0 * k_0 ≥ self.sum@anon_heap_LOOP_0,
wellFormed(anon_heap_LOOP_0),
wellFormed(heap),
self.<created> = TRUE,
SumAndMax::exactInstance(self) = TRUE,
a.<created> = TRUE,
measuredByEmpty,
a.length ≥ 0,
∀ int i; (i < a.length ∧ i ≥ 0 → a[i] ≥ 0)
⇒
k_0 < a.length,
self = null,
a = null,
∀ int i;
(i ≥ 0 ∧ i < a.length
→ a[i]@heap[self.sum := 0]
[self.max := 0]
[anon({(self, SumAndMax::$max)}
U {(self, SumAndMax::$sum)},
anon_heap_LOOP_0)]
≤ self.max@heap[self.sum := 0]
[self.max := 0]
[anon({(self, SumAndMax::$max)}
U {(self, SumAndMax::$sum)},
anon_heap_LOOP_0)])
∧ ((a.length > 0
→ ∃ int i;
(i ≥ 0
∧ i < a.length
∧ a[i]@heap[self.sum := 0]
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[anon({(self, SumAndMax::$max)}
U {(self, SumAndMax::$sum)},
anon_heap_LOOP_0)]
Source
SumAndMax.java
1 class SumAndMax {
2
3 int sum;
4 int max;
5
6 /*@ normal_behaviour
7 @ requires (\forall int i; 0 <= i && i < a.length; 0 <= a[i]);
8 @ assignable sum, max;
9 @ ensures (\forall int i; 0 <= i && i < a.length; a[i] <= max);
10 @ ensures (a.length > 0
11 @ ==> (\exists int i; 0 <= i && i < a.length; max == a[i]));
12 @ ensures sum == (\sum int i; 0 <= i && i < a.length; a[i]);
13 @ ensures sum <= a.length * max;
14 @*/
15 void sumAndMax(int[] a) {
16 sum = 0;
17 max = 0;
18 int k = 0;
19
20 /*@ loop_invariant
21 @ 0 <= k && k <= a.length
22 @ && (\forall int i; 0 <= i && i < k; a[i] <= max)
23 @ && (k == 0 ==> max == 0)
24 @ && (k > 0 ==> (\exists int i; 0 <= i && i < k; max == a[i]))
25 @ && sum == (\sum int i; 0 <= i && i< k; a[i])
26 @ && sum <= k * max;
27 @
28 @ assignable sum, max;
29 @ decreases a.length - k;
30 @*/
31 while(k < a.length) {
32 if(max < a[k]) {
33 max = a[k];
34 }
35 sum += a[k];
36 k++;
37 }
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39 }
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Strategy: Applied 64 rules (0.0 sec), closed 1 goal, 1 remaining
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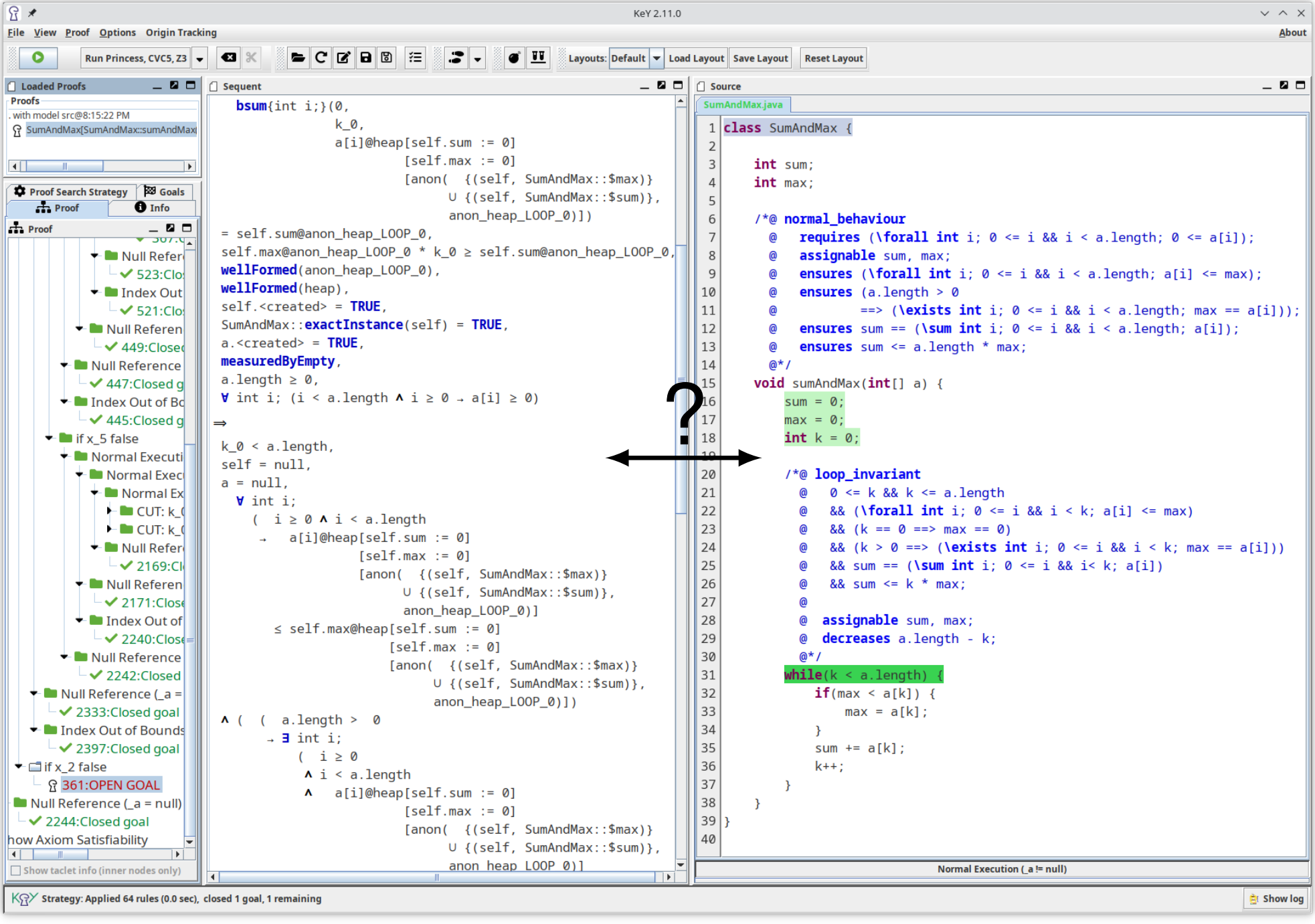
KeY 2.11.0
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= self.sum@anon_heap_LOOP_0,
self.max@anon_heap_LOOP_0 * k_0 ≥ self.sum@anon_heap_LOOP_0,
wellFormed(anon_heap_LOOP_0),
wellFormed(heap),
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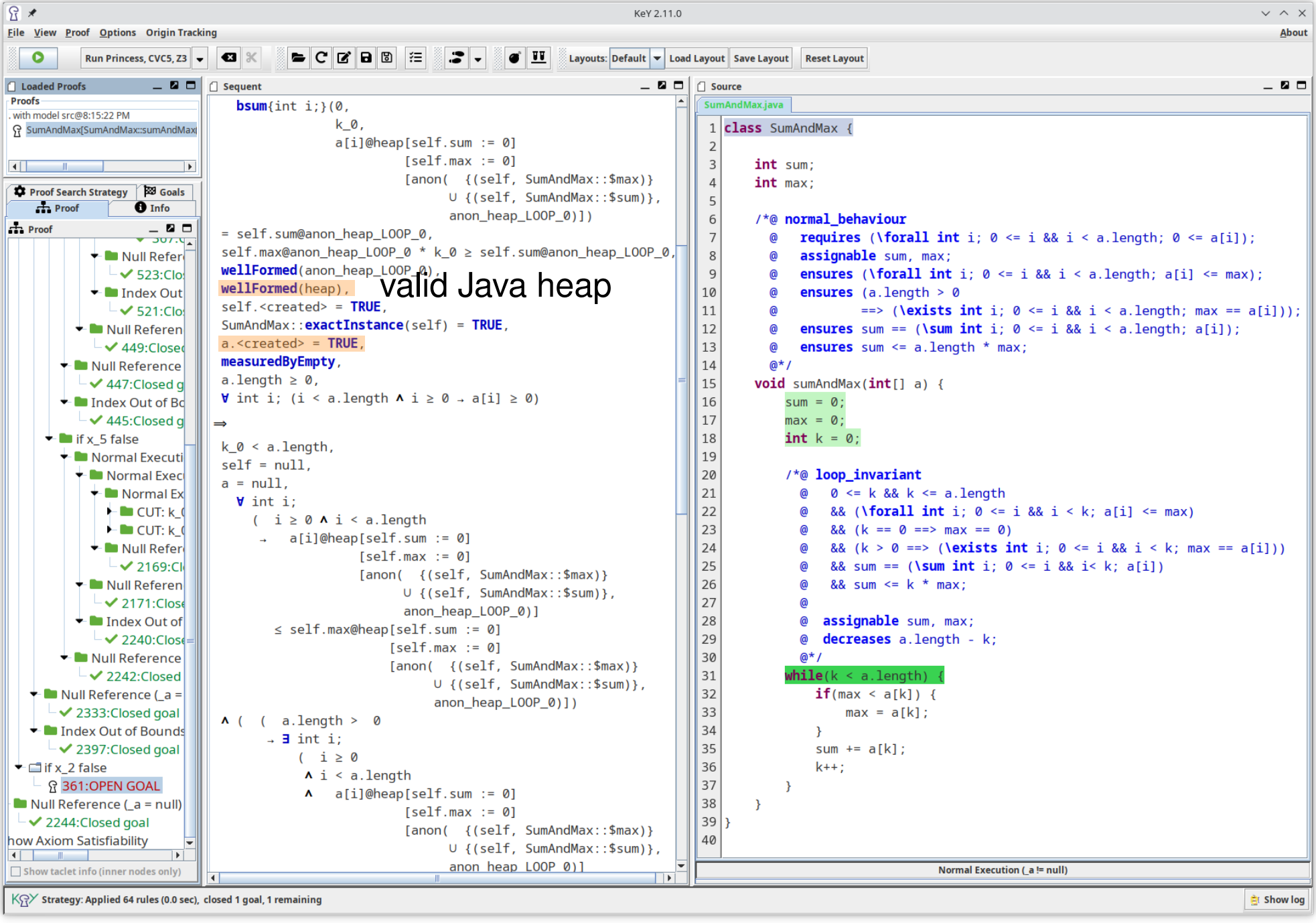
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self.max@anon_heap_LOOP_0 * k_0 ≥ self.sum@anon_heap_LOOP_0,
wellFormed(anon_heap_LOOP_0),
wellFormed(heap),
self.<created> = TRUE,
SumAndMax::exactInstance(self) = TRUE,
a.<created> = TRUE,
measuredByEmpty,
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[self.max := 0]
[anon({(self, SumAndMax::$max)}
U {(self, SumAndMax::$sum)},
anon_heap_LOOP_0)]
valid Java heap
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SumAndMax.java
1 class SumAndMax {
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3 int sum;
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7 @ requires (\forall int i; 0 <= i && i < a.length; 0 <= a[i]);
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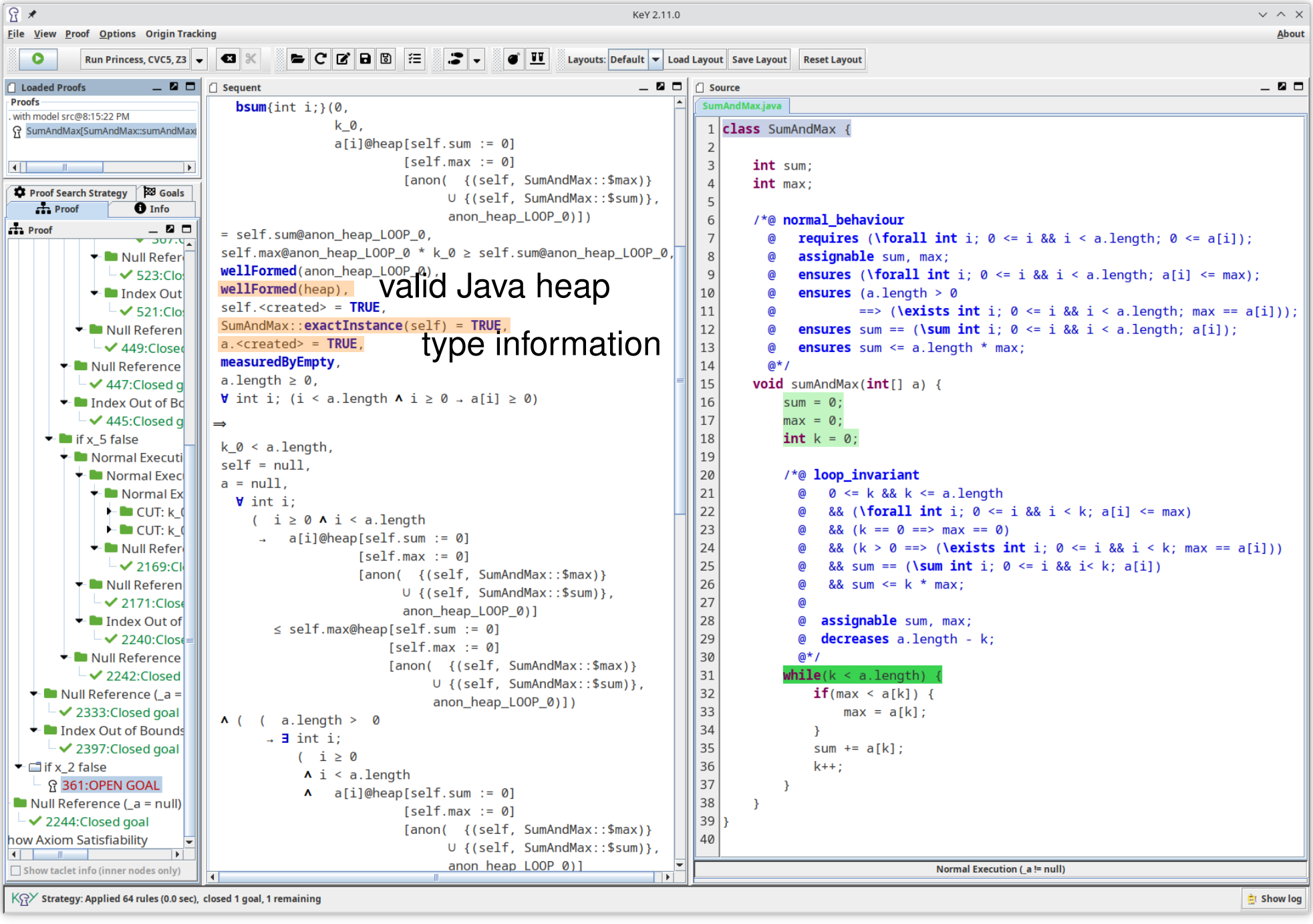
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[anon({(self, SumAndMax::$max)}
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= self.sum@anon_heap_LOOP_0,
self.max@anon_heap_LOOP_0 * k_0 ≥ self.sum@anon_heap_LOOP_0,
wellFormed(anon_heap_LOOP_0),
wellFormed(heap),
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SumAndMax::exactInstance(self) = TRUE,
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U {(self, SumAndMax::$sum)},
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valid Java heap
type information
Source
SumAndMax.java
1 class SumAndMax {
2
3 int sum;
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5
6 /*@ normal_behaviour
7 @ requires (\forall int i; 0 <= i && i < a.length; 0 <= a[i]);
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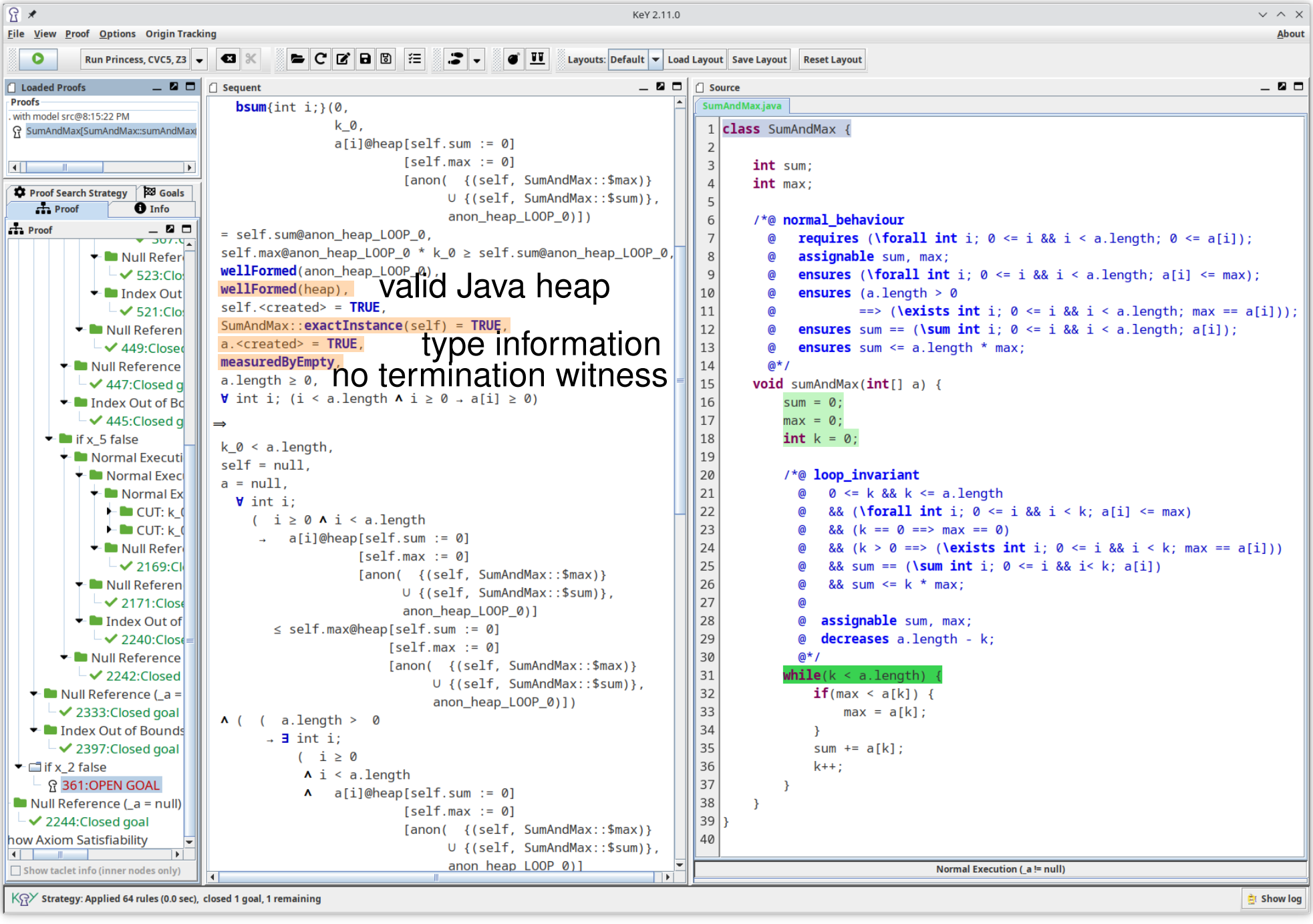
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valid Java heap
type information
no termination witness
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SumAndMax.java
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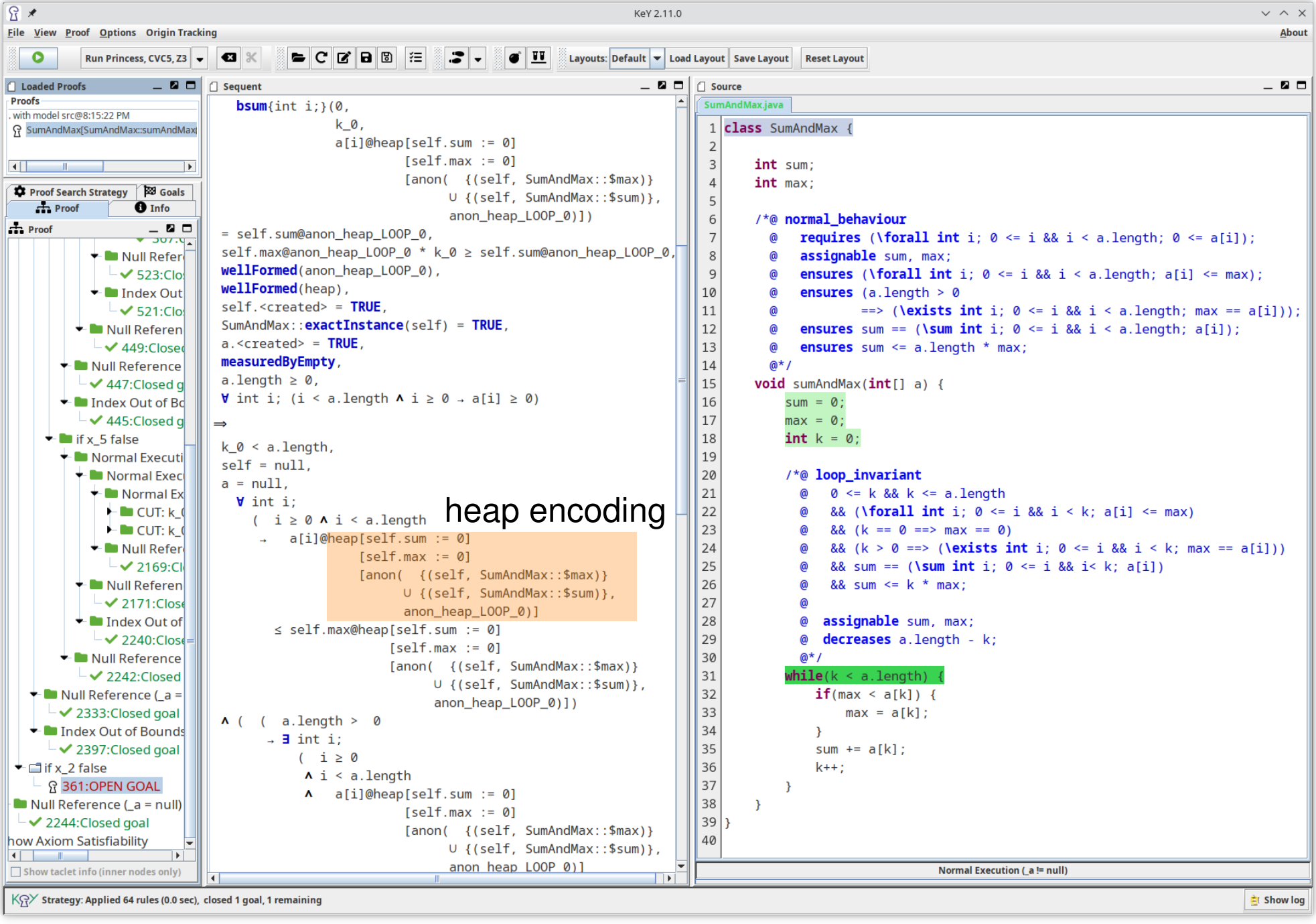
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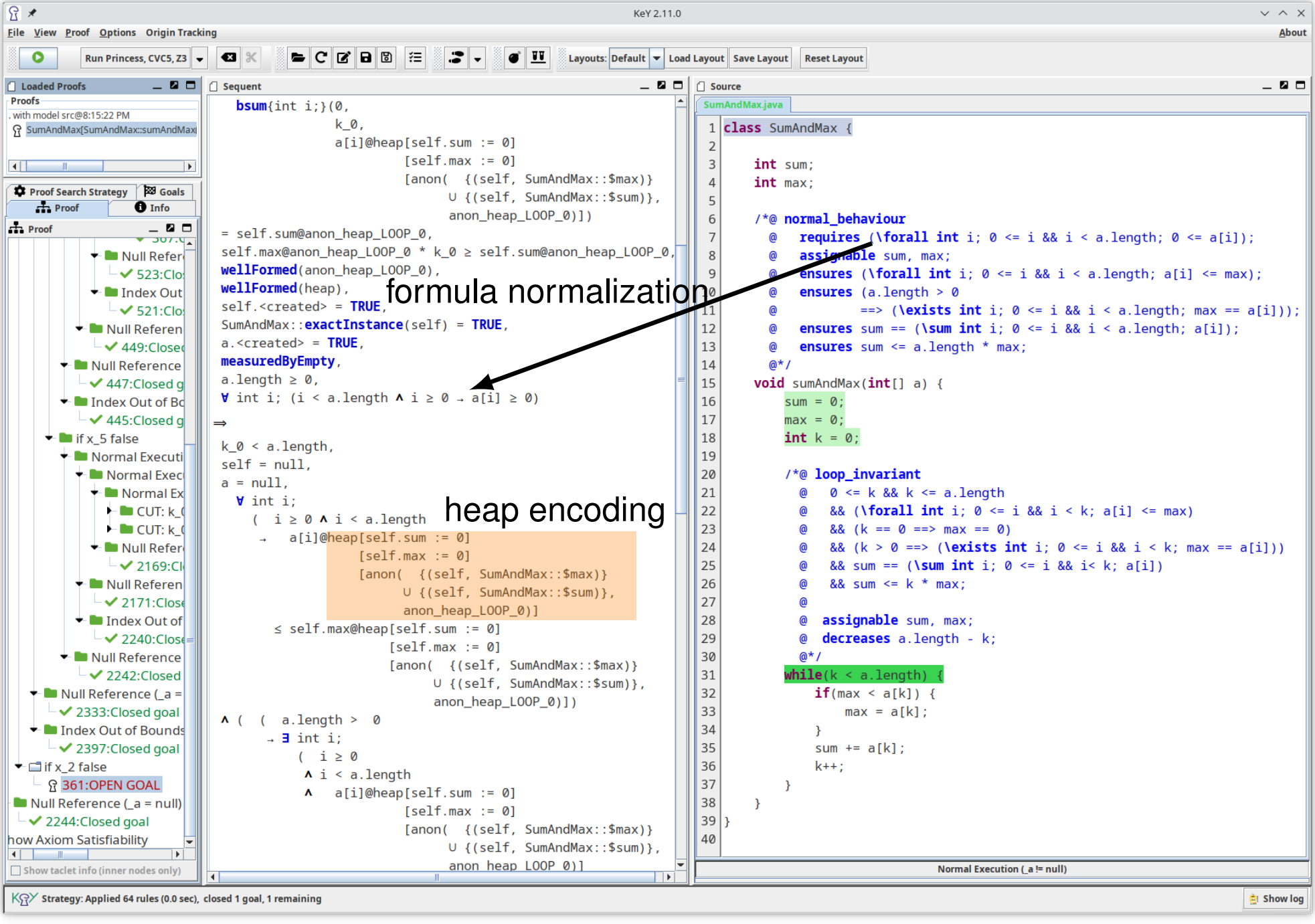
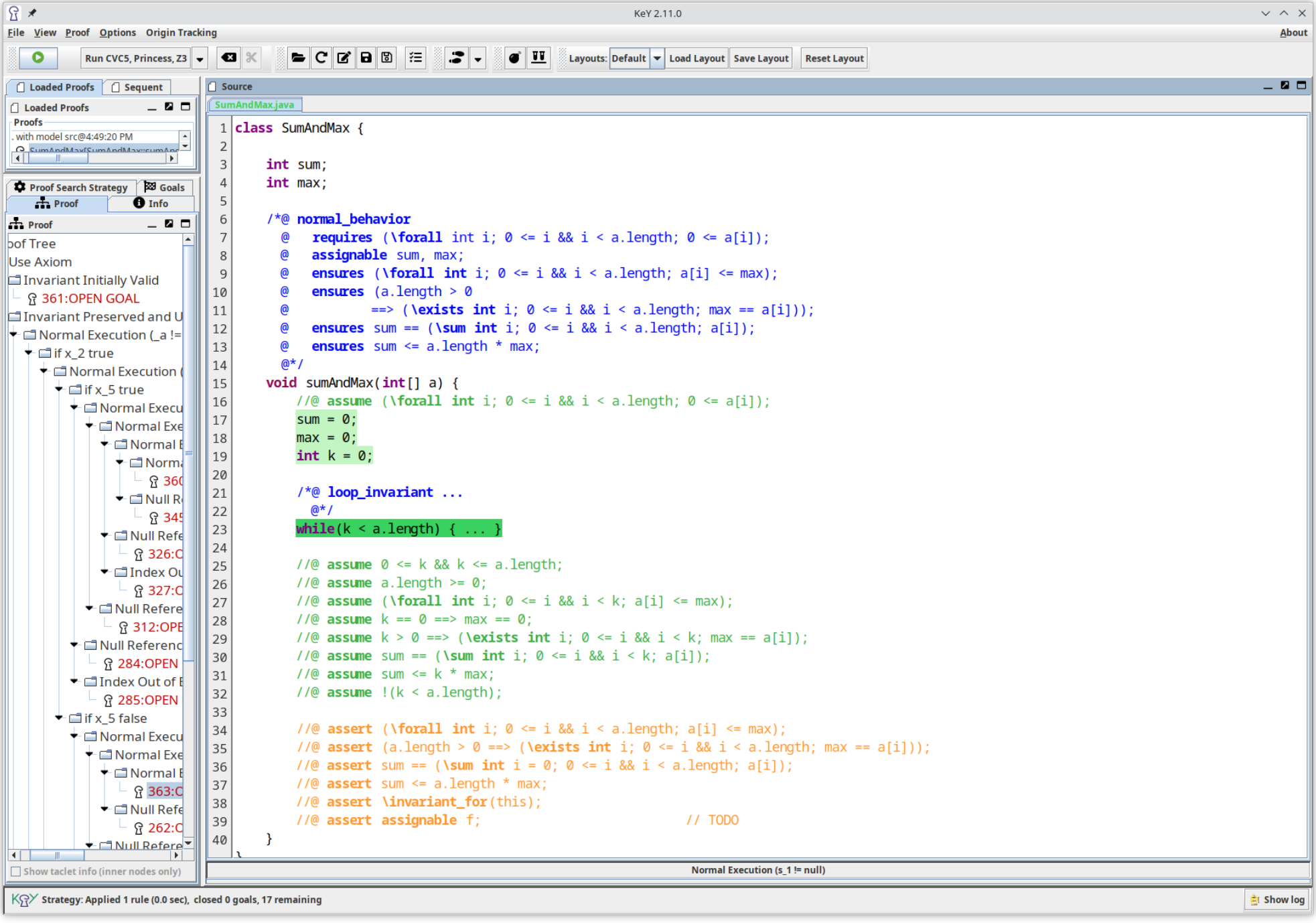
20 /*@ loop_invariant
21 @ 0 <= k && k <= a.length
22 @ && (\forall int i; 0 <= i && i < k; a[i] <= max)
23 @ && (k == 0 ==> max == 0)
24 @ && (k > 0 ==> (\exists int i; 0 <= i && i < k; max == a[i]))
25 @ && sum == (\sum int i; 0 <= i && i< k; a[i])
26 @ && sum <= k * max;
27 @
28 @ assignable sum, max;
29 @ decreases a.length - k;
30 @*/
31 while(k < a.length) {
32 if(max < a[k]) {
33 max = a[k];
34 }
35 sum += a[k];
36 k++;
37 }
38 }
39 }
40
Normal Execution (_a != null)
Strategy: Applied 64 rules (0.0 sec), closed 1 goal, 1 remaining
Show log


KeY 2.11.0
File View Proof Options Origin Tracking
About
Run Princess, CVC5, Z3
Layouts: Default
Load Layout
Save Layout
Reset Layout
Loaded Proofs
Proofs
. with model src@8:15:22 PM
SumAndMax[SumAndMax::sumAndMax
Proof Search Strategy
Goals
Proof
Info
Proof
Null Refer
523:Clo
Index Out
521:Clo
Null Referen
449:Close
Null Reference
447:Closed g
Index Out of Bo
445:Closed g
if x_5 false
Normal Executi
Normal Exec
Normal Ex
CUT: k_(
CUT: k_(
Null Refer
2169:Cl
Null Referen
2171:Close
Index Out of
2240:Close
Null Reference
2242:Closed
Null Reference (_a =
2333:Closed goal
Index Out of Bounds
2397:Closed goal
if x_2 false
361:OPEN GOAL
Null Reference (_a = null)
2244:Closed goal
how Axiom Satisfiability
Show taclet info (inner nodes only)
Sequent
bsum{int i;}(0,
k_0,
a[i]@heap[self.sum := 0]
[self.max := 0]
[anon({(self, SumAndMax::$max)}
U {(self, SumAndMax::$sum)},
anon_heap_LOOP_0)])
= self.sum@anon_heap_LOOP_0,
self.max@anon_heap_LOOP_0 * k_0 ≥ self.sum@anon_heap_LOOP_0,
wellFormed(anon_heap_LOOP_0),
wellFormed(heap),
self.<created> = TRUE,
SumAndMax::exactInstance(self) = TRUE,
a.<created> = TRUE,
measuredByEmpty,
a.length ≥ 0,
∀ int i; (i < a.length ∧ i ≥ 0 → a[i] ≥ 0)
⇒
k_0 < a.length,
self = null,
a = null,
∀ int i;
(i ≥ 0 ∧ i < a.length
→ a[i]@heap[self.sum := 0]
[self.max := 0]
[anon({(self, SumAndMax::$max)}
U {(self, SumAndMax::$sum)},
anon_heap_LOOP_0)]
≤ self.max@heap[self.sum := 0]
[self.max := 0]
[anon({(self, SumAndMax::$max)}
U {(self, SumAndMax::$sum)},
anon_heap_LOOP_0)])
∧ ((a.length > 0
→ ∃ int i;
(i ≥ 0
∧ i < a.length
∧ a[i]@heap[self.sum := 0]
[self.max := 0]
[anon({(self, SumAndMax::$max)}
U {(self, SumAndMax::$sum)},
anon_heap_LOOP_0)]
formula normalization
heap encoding
Source
SumAndMax.java
1 class SumAndMax {
2
3 int sum;
4 int max;
5
6 /*@ normal_behaviour
7 @ requires (\forall int i; 0 <= i && i < a.length; 0 <= a[i]);
8 @ assignable sum, max;
9 @ ensures (\forall int i; 0 <= i && i < a.length; a[i] <= max);
10 @ ensures (a.length > 0
11 @ ==> (\exists int i; 0 <= i && i < a.length; max == a[i]));
12 @ ensures sum == (\sum int i; 0 <= i && i < a.length; a[i]);
13 @ ensures sum <= a.length * max;
14 @*/
15 void sumAndMax(int[] a) {
16 sum = 0;
17 max = 0;
18 int k = 0;
19
20 /*@ loop_invariant
21 @ 0 <= k && k <= a.length
22 @ && (\forall int i; 0 <= i && i < k; a[i] <= max)
23 @ && (k == 0 ==> max == 0)
24 @ && (k > 0 ==> (\exists int i; 0 <= i && i < k; max == a[i]))
25 @ && sum == (\sum int i; 0 <= i && i< k; a[i])
26 @ && sum <= k * max;
27 @
28 @ assignable sum, max;
29 @ decreases a.length - k;
30 @*/
31 while(k < a.length) {
32 if(max < a[k]) {
33 max = a[k];
34 }
35 sum += a[k];
36 k++;
37 }
38 }
39 }
40
Normal Execution (_a != null)
Strategy: Applied 64 rules (0.0 sec), closed 1 goal, 1 remaining
Show log


KeY 2.11.0
File View Proof Options Origin Tracking
About
Run CVC5, Princess, Z3
Layouts: Default
Load Layout
Save Layout
Reset Layout
Loaded Proofs
Sequent
Loaded Proofs
Proofs
. with model src@4:49:20 PM
Proof Search Strategy
Goals
Proof
Info
Proof
pof Tree
Use Axiom
Invariant Initially Valid
361:OPEN GOAL
Invariant Preserved and U
Normal Execution (_a !=
if x_2 true
Normal Execution (
if x_5 true
Normal Execu
Normal Exe
Normal E
Norma
360
Null R
345
Null Refe
326:O
Index Ou
327:O
Null Refere
312:OPE
Null Referenc
284:OPEN
Index Out of E
285:OPEN
if x_5 false
Normal Execu
Normal Exe
Normal E
363:O
Null Refe
262:O
Null Refere
Show taclet info (inner nodes only)
Source
SumAndMax.java
1 class SumAndMax {
2
3 int sum;
4 int max;
5
6 /*@ normal_behavior
7 @ requires (\forall int i; 0 <= i && i < a.length; 0 <= a[i]);
8 @ assignable sum, max;
9 @ ensures (\forall int i; 0 <= i && i < a.length; a[i] <= max);
10 @ ensures (a.length > 0
11 @ ==> (\exists int i; 0 <= i && i < a.length; max == a[i]));
12 @ ensures sum == (\sum int i; 0 <= i && i < a.length; a[i]);
13 @ ensures sum <= a.length * max;
14 @*/
15 void sumAndMax(int[] a) {
16 //@ assume (\forall int i; 0 <= i && i < a.length; 0 <= a[i]);
17 sum = 0;
18 max = 0;
19 int k = 0;
20
21 /*@ loop_invariant ...
22 @*/
23 while(k < a.length) { ... }
24
25 //@ assume 0 <= k && k <= a.length;
26 //@ assume a.length >= 0;
27 //@ assume (\forall int i; 0 <= i && i < k; a[i] <= max);
28 //@ assume k == 0 ==> max == 0;
29 //@ assume k > 0 ==> (\exists int i; 0 <= i && i < k; max == a[i]);
30 //@ assume sum == (\sum int i; 0 <= i && i < k; a[i]);
31 //@ assume sum <= k * max;
32 //@ assume !(k < a.length);
33
34 //@ assert (\forall int i; 0 <= i && i < a.length; a[i] <= max);
35 //@ assert (a.length > 0 ==> (\exists int i; 0 <= i && i < a.length; max == a[i]));
36 //@ assert sum == (\sum int i = 0; 0 <= i && i < a.length; a[i]);
37 //@ assert sum <= a.length * max;
38 //@ assert \invariant_for(this);
39 //@ assert assignable f; // TODO
40 }
}
Normal Execution (s_1 != null)
Strategy: Applied 1 rule (0.0 sec), closed 0 goals, 17 remaining
Show log

Summary

Idea

Combined view for source, specification, and proof state

- that facilitates understanding of the current proof situation,
- which the user can interact with,
- with which (hopefully) most Java programs can be verified.

Open Questions

- How can formulas be represented that relate multiple heap states?
- How can framing clauses be represented?
- What about multiple modalities (queries, information flow, . . .)?