Bachelor’s Thesis

Converting between ACSL Annotations and Witness Invariants

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Motivation (1)

```
int main() {
    int a = 1, b = 1;
    while(b < 1000) {
        a += a;
        b += b;
    }
    if (a != b) {
        ERROR: return 1;
    }
    return 0;
}
```

Example program with
loop invariant $b == a$

Motivation (1)

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int main() {
    int a = 1, b = 1;
    while(b < 1000) {
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    }
    if (a != b) {
        ERROR: return 1;
    }
    return 0;
}
```

Example program with loop invariant $b == a$


```
...
<node id="N9">
  <data key="invariant">( b == a )</data>
  <data key="invariant.scope">main</data>
</node>
<edge source="N2" target="N9">
  <data key="enterLoopHead">true</data>
  <data key="startline">2</data>
  <data key="endline">2</data>
  <data key="startoffset">28</data>
  <data key="endoffset">32</data>
</edge>
...
```


GraphML-based correctness witness containing the invariant

Motivation (2)

Advantages of Annotations:

- Easy to understand/modify for a human
- No need for additional files
- Might create compatibility with other tools

```
int main() {
    int a = 1, b = 1;
    //@ loop invariant b == a;
    while(b < 1000) {
        a += a;
        b += b;
    }
    if (a != b) {
        ERROR: return 1;
    }
    return 0;
}
```

Overview

- Preliminaries
- ACSL $\Leftrightarrow$ Witness
- Evaluation
- Summary

ACSL

- **A**NSI/ISO **C** **S**pecification **L**anguage
- Used by the Frama-C framework
- Specification as special comments in the program:
  `/*@ ... */` or `//@ ...`
- Several kinds of annotations, e.g.
  - Function Contracts
  - Loop Annotations
  - Assertions

ACSL - Logic Expressions

- Building blocks of ACSL annotations
- Roughly correspond to C Expressions
- Distinction between *Terms* and *Predicates*, e.g.
  - `x` and `1+2+3` are terms
  - `\true` and `x == 0` are predicates

ACSL - Assertions

- Structure: `//@ assert <predicate>;`
- Contained predicate should evaluate to true where the assertion is located
- Example:

```
int x = 1;
//@ assert x == 1;
int y = 5;
//@ assert x + y < 10;
...
```

ACSL - Function Contracts

- Specify properties of functions
- Made of different kinds of *clauses*, e.g.
  - *requires* clauses describe properties of the pre-state
  - *ensures* clauses describe properties of the post-state
- Example:

```
/*@ requires y <= x;
    ensures x >= 0; */
int natural_subtraction(int x, int y) {
  ...
}
```

Correctness Witnesses

- Observe the state space exploration of the verifier
- May provide invariants that hold at certain program locations
- Invariants used in the GraphML-based witness exchange format
  - must be valid C expressions
  - must evaluate to an int
  - may contain conjunction/disjunction
  - may not contain function calls

Witness Invariants ⇒ ACSL Annotations

- Witness invariants are valid ACSL predicates
  → Conversion is easy
- Example:
  x == 0 becomes `assert x == 0;`
- But: Where to put assertions?
  - Use location information from witness
  - Run observer analysis on the program with the witness as observer automaton

ACSL Annotations ⇒ Witness Invariants (1)

- Basic idea: Represent annotations by predicates
- ACSL predicates are often equivalent to C expressions
- ACSL assertion can simply be represented by contained predicate → Conversion is straightforward
- Example:
  `assert x => y;` can be converted to *!x || y*

ACSL Annotations ⇒ Witness Invariants (2)

- How to represent the following?

```
/*@ requires y <= x;
    ensures x >= 0; */
int natural_subtraction(int x, int y) {
  x = x - y;
  return x;
}
```

ACSL Annotations ⇒ Witness Invariants (3)

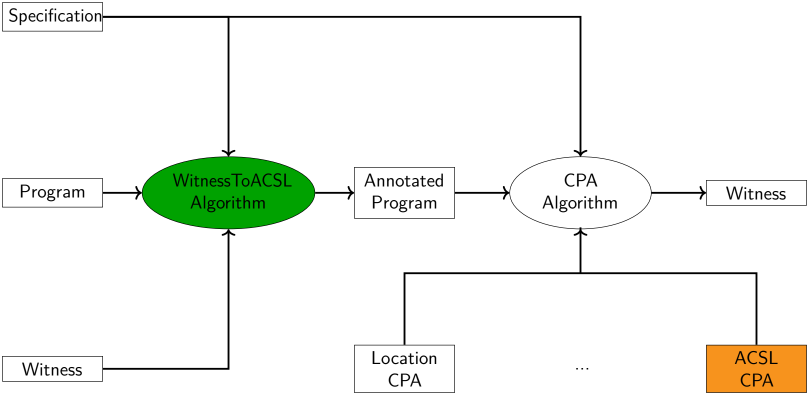
- Split up contract into several assertions:

```
/*@ requires y <= x;
    ensures x >= 0; */
int natural_subtraction
    (int x, int y) {
  x = x - y;
  return x;
}
```

```
int natural_subtraction
    (int x, int y) {
  //@ assert y <= x;
  x = x - y;
  //@ assert x >= 0;
  return x;
}
```

- Translate assertions like before

Implementation



Evaluation - Goals

1. Generate valid ACSL annotations from correctness witnesses
2. Parse ACSL annotations and create witnesses containing derived invariants
3. Validate generated ACSL annotations/witnesses

Evaluation - Results (1)

Generate valid ACSL annotations from correctness witnesses

- Good performance of the actual algorithm ✓
- Often no result because invariants are not found ✗
- Found invariants can usually be converted successfully ✓

input witnesses	10387
algorithm done	9775
generated programs	5387
with annotations	4685

Evaluation - Results (2)

Parse ACSL annotations and create witnesses containing derived invariants

- ACSL annotations can be parsed and are interpreted correctly ✓
- Parsing annotations is apparently inefficient ✗
- Conversion is often possible and performed correctly ✓
- Many annotations are skipped because they are invalid ✗

input programs	4685
produced witnesses	3392
with invariant	1585

Evaluation - Results (2)

Parse ACSL annotations and create witnesses containing derived invariants

- ACSL annotations can be parsed and are interpreted correctly ✓
- Parsing annotations is apparently inefficient ✗
- Conversion is often possible and performed correctly ✓
- Many annotations are skipped because they are invalid ✗

input programs	4685
produced witnesses	3392
with invariant	1585

```
...
int i = 0;
for (int j = 10; j > 0; j--) {
  i++;
}
//@ assert j == 0 && i == 10;
...
```

Invalid ACSL assertion for which no correct location exists

Evaluation - Results (3)

Validate generated ACSL annotations/witnesses

- Validation of produced ACSL annotations usually successful ✓
- Validation of produced witnesses succeeds almost always ✓
- No incorrect invariants after roundtrip ✓

input programs	4685
Frama-C-SV true	3188
Frama-C-SV unknown	1445
Frama-C-SV other	52

input witnesses	3483
true	3463
ERROR (recursion)	19
TIMEOUT	1

Summary

- Conversion Witness Invariant ⇒ ACSL Annotation
  - Easy in theory: Just use invariant as predicate in ACSL assertion
  - Several approaches to find correct location for assertion
  - There might not be a correct location
- Conversion ACSL Annotation ⇒ Witness Invariant
  - Represent annotations by predicates
  - Predicates can then be converted to invariants
  - Bigger contracts can be split up into multiple assertions before conversion
- Future Work
  - Better way to extract invariants from witnesses
  - Improve parsing of ACSL annotations