Contracts: Specification and Verification

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D3S

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Behavior specification using contracts

- Target: program fragment
  - class, object, method (procedure), loop body

- Purpose: define responsibilities
  - Implementation (provider, method, object)
  - Client (caller method, another component)

- Method contract
- Object contract

Method contract

- Precondition
  - Specifies constraints on parameter values and valid states of a target object
  - Logic formula that must hold **at the entry** to the method
  - “caller responsibility”

- Postcondition
  - Specifies constraints on the return value and side effects
    - Captures relation between the initial and final state of the method
  - Logic formula that must hold **at the exit** from the method
  - “implementation responsibility”

Method contract: example

- Program

```
public class ArrayList {
  public void add(int index, Object obj) {
    ...
  }
  public int size() { ... }
}
```

- Textual documentation

  "Value of the `index` parameter has to be greater than or equal to zero. Successful call of `add` increases the size of the array by one."

- Formal contract

```
public void add(int index, Object obj)
  requires index >= 0;
  ensures size = old(size) + 1;
{ ... }
```

Object contract

- Object invariant
  - Specifies valid object states (e.g., values of fields)
  - Logic formula that must hold at the entry and exit of each method defined for the object

How to define contracts

- Three ways
  - Source code comments
  - Explicit annotations
  - Built-in language constructs

- Contract specification languages
  - Spec#, JML, Dafny, Code Contracts, Viper, ...

Spec#

- Programming system
  - Developed by Microsoft Research
  - https://www.microsoft.com/en-us/research/project/spec/
- Main components
  - Programming language
    - Extension of C# with contracts
  - Spec# compiler
    - Inserts run-time checks for contracts into the code
  - Verifier: Boogie

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Spec# language

```
class ArrayList {
  public virtual object Insert(int index, object value)
    requires 0 <= index && index <= Count;
    ensures value == this[index];
    ensures Count == old(Count) + 1;
    ensures result == old(this[index]);
  {
    ...
    int i = count;
    while (i >= index)
      loop invariant i >= index - 1;
    {
      data[i+1] = data[i];
      i--;
    }
  }
}
```

precondition

postcondition

return value

initial value

must hold before and after each iteration

JML: Java Modeling Language

- Contract definition language for Java
  - http://www.eecs.ucf.edu/~leavens/JML/index.shtml
- Differences from Spec#
  - Contracts defined in source comments
    - No built-in Java language constructs
  - Example

```
/*@
  @ requires E1;
  @ ensures E2;
  @*/
public int doSmth() { ... }
```

- Verification tool: ESC/Java2
  - http://kindsoftware.com/products/opensource/ESCJava2/

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Advanced features of Spec# and JML

- Exceptional behavior
  - Constraints on the resulting state when an exception is thrown inside the method
- Model fields (“ghost”)
  - Abstract fields visible only in the contracts
- Quantifiers (∃,∀)
  - Spec#: `Exists` and `Forall`
- Behavioral subtyping
  - Inheritance of contracts
- Frame conditions
  - List of fields which the method can modify

Verification of program against contracts

Verification of program against contracts

- Goal
  - Checking consistency between the method's implementation and its contract
    - φ: precondition ∧ implementation → postcondition
- Approach
  - Intermediate verification language (IVL)
  - Robust and efficient verification engine
    - Based on symbolic exec or verification condition generator
- Example (target platform)
  - Spec#: Boogie program verifier, SMT solver Z3

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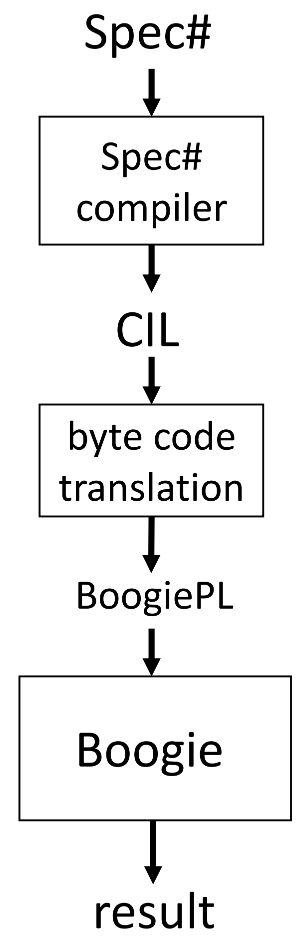
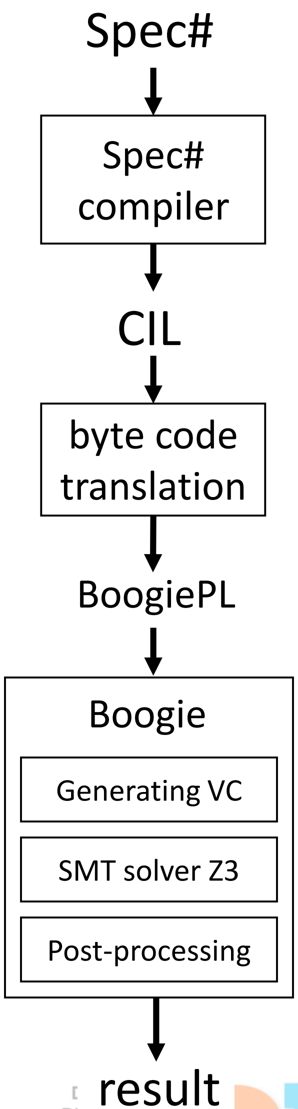
Verifying Spec# contracts with Boogie

- Input
  - Spec# program (C# annotated with contracts)
  - Set of axioms that describe semantics of Spec#
- Axioms
  - Semantics
    - Type system (subtyping)
    - Size of constants
  - Examples
    - All classes are subtypes of `System.Object`
    - `Forall T:type . T <: superclass(T)`



Verifying Spec# contracts with Boogie

- Algorithm
  - Translate Spec# program into BoogiePL
  - Generate verification condition (VC) from the BoogiePL program
  - Run the SMT solver on the VC
    - Result: “no error found” or counterexample
  - Post-processing of the result
    - Mapping counterexample back to the source language (Spec#)



Running example (Spec# program)

```
int M(int x)
  requires 100 <= x;       // precondition
  ensures result == 0;     // postcondition
{
  while (0 < x)
    invariant 0 <= x;      // loop invariant
  {
    x = x - 1;
  }
  return x;
}
```

Example program in Spec# taken from:
M. Barnett and R. Leino. Weakest-Precondition of Unstructured Programs. PASTE 2005, ACM Press

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Translation from Spec# to BoogiePL

```
int M(int x)
  requires 100 <= x;      // precondition
  ensures result == 0;    // postcondition
{
  while (0 < x)
    invariant 0 <= x;     // loop invariant
  {
    x = x - 1;
  }
  return x;
}
```

```
Start:  assume 100 <= x;      // precondition
        goto Head;
Head:   assert 0 <= x;        // loop invariant
        goto Body, After;
Body:   assume 0 < x;         // loop guard
        x := x - 1;
        goto Head;
After:  assume not(0 < x);    // neg loop guard
        r := x;               // return
        assert r = 0;         // postcondition
        goto ;
```

BoogiePL

- Program structure
  - Directed graph of basic blocks (label, statements)
  - Successor blocks are targets of the `goto` statement
- Semantics
  - Program defines a large set of execution traces
  - State = values of all variables + program counter
  - Arbitrary initial values of all program variables
- Important statements
  - `goto label1, label2` ➔ non-deterministic choice
  - `goto ;` ➔ the execution trace terminates successfully
  - `assume E` ➔ filters out execution traces not satisfying *E*
  - `assert E` ➔ if *E* is *false*, then a trace ends with an error

Generating verification condition (VC)

- Construction of an acyclic program (AP)
  - Eliminating loops (back edges in control-flow)
- Transforming into an acyclic passive program (APP)
  - No assignments allowed in APP
- Generating verification condition from the APP

Construction of acyclic program

- What must be still checked in AP
  - Loop invariant holds before the loop starts
  - Any iteration does not break the invariant
- Consequence
  - Loop invariant holds at the exit from the loop
- Eliminating loops
  - Abstraction of an arbitrary number of loop iterations
  - Unrolling the loop body

Abstracting loop iterations

```
Start:  assume 100 <= x;
        assert 0 <= x;          // check loop invariant
        goto Head;
Head:   havoc x;                // reset variables used in the loop
        assume 0 <= x;          // assume loop invariant
        goto Body, After;
Body:   assume 0 < x;
        x := x - 1;
        assert 0 <= x;
        goto ;
After:  assume not(0 < x);
        r := x;
        assert r = 0;
        goto ;
```

Unrolling loop body

```
Start:  assume 100 <= x;
        assert 0 <= x;          // check loop invariant
        goto Head;
Head:   havoc x;                // reset variables used in the loop
        assume 0 <= x;          // assume loop invariant
        goto Body, After;
Body:   assume 0 < x;
        x := x - 1;
        assert 0 <= x;          // check loop invariant
        goto ;                  // back edge removed
After:  assume not(0 < x);
        r := x;
        assert r = 0;
        goto ;
```

AP: acyclic program

```
Start:  assume 100 <= x;
        assert 0 <= x;          // check loop invariant
        goto Head;
Head:   havoc x;                // reset variables used in the loop
        assume 0 <= x;          // assume loop invariant
        goto Body, After;
Body:   assume 0 < x;
        x := x - 1;
        assert 0 <= x;          // check loop invariant
        goto ;                  // back edge removed
After:  assume not(0 < x);
        r := x;
        assert r = 0;
        goto ;
```

Transforming into acyclic passive programs

- Passive program
  - No destructive update allowed

- Two steps
  - Rewrite into a single-assignment form
  - Removing all assignment statements

Rewriting into single-assignment form

```
Start:  assume 100 <= x0;
        assert 0 <= x0;
        goto Head;
Head:   skip; // "havoc x1" not necessary anymore
        assume 0 <= x1;
        goto Body, After;
Body:   assume 0 < x1;
        x2 := x1 - 1;
        assert 0 <= x2;
        goto ;
After:  assume not(0 < x1);
        r1 := x1;
        assert r1 = 0;
        goto ;
```

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Rewriting into single-assignment form

- Problem
  - Join points (after choice)

```
x0 := ...;
if (E) { x1 := ...}
else { x2 := ...}
```

Q: how to solve this problem ?

Rewriting into single-assignment form

- Problem
  - Join points (after choice)

```
x0 := ...;
if (E) { x1 := ...}
else { x2 := ...}
```

- Solution (ϕ-functions)

```
x0 := ...;
if (E) { x1 := ...; x3 := x1 }
else { x2 := ...; x3 := x2 }
```

Removing assignment statements

```
Start:  assume 100 <= x0;
        assert 0 <= x0;
        goto Head;
Head:   skip;
        assume 0 <= x1;.
        goto Body, After;
Body:   assume 0 < x1;
        assume x2 = x1 - 1;
        assert 0 <= x2;
        goto ;
After:  assume not(0 < x1);
        assume r1 = x1;
        assert r1 = 0;
        goto ;
```

APP: acyclic passive program

```
Start:  assume 100 <= x0;
        assert 0 <= x0;
        goto Head;
Head:   skip;
        assume 0 <= x1;.
        goto Body, After;
Body:   assume 0 < x1;
        assume x2 = x1 - 1;
        assert 0 <= x2;
        goto ;
After:  assume not(0 < x1);
        assume r1 = x1;
        assert r1 = 0;
        goto ;
```

Encoding control flow into logic formula

- Boolean variable B_{ok} is defined for each basic block *B*
  - $B_{ok} = true$ ➔ all possible executions of B and its successors from the current state are correct
- Block equation B_{be} is defined for each basic block *B*

$$Start_{be}:\ Start_{ok} \leftrightarrow 100 <= x0 \Rightarrow (0 <= x0 \land Head_{ok})$$

$$Head_{be}:\ Head_{ok} \leftrightarrow 0 <= x1 \Rightarrow (Body_{ok} \land After_{ok})$$

$$Body_{be}:\ Body_{ok} \leftrightarrow 0 < x1 \Rightarrow (x2 = x1 - 1 \Rightarrow 0 <= x2)$$

$$After_{be}:\ After_{ok} \leftrightarrow \neg(0 < x1) \Rightarrow (r1 = x1 \Rightarrow r1 = 0)$$

Generating verification condition

$\textbf{\textit{Start}}_{be}$: $Start_{ok} \leftrightarrow 100 <= x0 \Rightarrow (0 <= x0 \land Head_{ok})$
$\textbf{\textit{Head}}_{be}$: $Head_{ok} \leftrightarrow 0 <= x1 \Rightarrow (Body_{ok} \land After_{ok})$
$\textbf{\textit{Body}}_{be}$: $Body_{ok} \leftrightarrow 0 < x1 \Rightarrow (x2 = x1 - 1 \Rightarrow 0 <= x2)$
$\textbf{\textit{After}}_{be}$: $After_{ok} \leftrightarrow \neg(0 < x1) \Rightarrow (r1 = x1 \Rightarrow r1 = 0)$

⬇

VC: $Axioms \land Start_{be} \land Head_{be} \land Body_{be} \land After_{be} \Rightarrow Start_{ok}$

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What does the verification condition mean

a run of the program according to semantics of Spec#

$$Axioms \wedge Start_{be} \wedge Head_{be} \wedge Body_{be} \wedge After_{be} \Rightarrow Start_{ok}$$

postcondition not violated

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Contracts and procedure calls

- Idea: use contracts of individual procedures

- Procedure calls

```
...
call M    ➡    assert precondition of M
               havoc fields modified by M
...            assume postcondition of M
```

Verification of contracts: limitations

- Incompleteness
  - First-order predicate calculus is semi-decidable
    - Verification tool may run forever on some inputs (programs)
  - Making tools less precise ➔ spurious warnings

- Modular verification
  - Analyze procedures separately (one at a time)
  - Cannot detect errors depending on internal behavior of other procedures (with partial contracts)
  - Better performance and scalability
    - Verification applicable to real-world programs

Tools

- Dafny
  - Verification-ready programming language
  - Builds upon the ideas (algorithm) of Spec#
  - https://dafny.org/
  - https://github.com/dafny-lang/dafny

- VCC: Verifier for Concurrent C
  - https://www.microsoft.com/en-us/research/project/vcc-a-verifier-for-concurrent-c/
  - Target domain: low-level concurrent systems (e.g., OS)
  - Challenge: verify programs with threads and pointers
  - Solution: **object ownership**
    - Thread can write only to objects that it owns in the given state
    - Thread can read only objects that it owns or does not change

Tools

- Viper: Verification Infrastructure for Permission-based Reasoning
  - http://viper.ethz.ch/
  - Contract language + set of verification tools
    - Limited support for object-oriented programming
  - Features: ownership, **access permissions**
  - Usage: plugin for VSCode, online interface
  - Examples: http://viper.ethz.ch/examples/
    - Sorted List (basic access permissions)
    - Linked List (with recursive predicates)

Tools

- KeY program verifier
  - Java programs with JML spec
  - Developer support (nice IDE)
  - https://www.key-project.org/
  - https://github.com/KeYProject/key

Disclaimer

- Code Contracts
  - Similar definition language
    - Method preconditions and postconditions, invariants
  - Different verification algorithm
    - Mostly based on abstract interpretation (lecture 9)

Automated inference of contracts

- Backward symbolic analysis (execution)
  - Propagating weakest preconditions
  - From desired property (negated error)

- Bi-abduction
  - Enables modular compositional verification
  - https://cacm.acm.org/research/separation-logic/

Deductive methods in SW verification

- Mechanized program verification
  - Proofs for complicated algorithms
  - Languages and tool support
    - Coq proof assistant: https://coq.inria.fr/

Further reading

- M. Barnett, K.R.M. Leino, and W. Schulte. **The Spec# Programming System: An Overview**. CASSIS 2004
- M. Barnett, B.-Y. E. Chang, R. DeLine, B. Jacobs, and K.R.M. Leino. **Boogie: A Modular Reusable Verifier for Object-Oriented Programs**. FMCO 2005
- M. Barnett and K.R.M. Leino. **Weakest-Precondition of Unstructured Programs**. PASTE 2005, ACM

- K.R.M. Leino. **Dafny: An Automatic Program Verifier for Functional Correctness**. LPAR 2010
  - https://www.microsoft.com/en-us/research/project/dafny-a-language-and-program-verifier-for-functional-correctness/

- P. Muller, M. Schwerhoff, and A.J. Summers. **Viper: A Verification Infrastructure for Permission-Based Reasoning**. VMCAI 2016

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Literature (books)

- Software Foundations
  - https://softwarefoundations.cis.upenn.edu/
- Formal Reasoning about Programs
  - http://adam.chlipala.net/frap/