Program Verification

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Summer Term 2021
Program Verification

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Lecture 1: Introduction

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Section 1

Introduction
Outline of the Section on Introduction

- Some Motivation
- Program Verifier
- Motivation
- Challenges
- Content of this Course
Is this program correct?

```
1 int *computeSquares(unsigned int n) {
2     int a[n];
3     int i = 0;
4     while(i <= n) {
5         a[i] = i*i;
6         i++;
7     }
8     return a;
9 }
```

- Quick answer: No. Program does one iteration too much, array accessed beyond its bounds in the last iteration. Typical bug.
- Well-considered answer: Maybe. What is the definition of “correctness”? What is the programming language?
Computers are very good in detecting syntax errors. (Here, Eclipse complains about a missing semicolon). It would be great if tools could also underline bugs that we have seen before.
Is this program correct?

```
var year, days : int;

procedure main()
  modifies year, days;
{
  var leapYear : bool;
  assume year >= 1980;
  assume days >= 0 && days <= 366;
  while (days > 365) {
    call leapYear := isLeapYear(year);
    if (leapYear) {
      if (days > 366) {
        days := days - 366;
        year := year + 1;
      }
    } else {
      days := days - 365;
      year := year + 1;
    }
  }
}
```

Code similar to the code that caused the bug in Microsoft's Zune player.
Program Verification
Motivation
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Course outline
Outline of the Section on Introduction

Some Motivation
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Program Verifier

Typical specifications:
- No division by zero
- Array only accessed within its bounds
- Termination
- Memory safety
- No assert statement is violated
According to the international competition on software verification SV-COMP\(^1\) one of the best verification tools.

Mainly developed by our group\(^2\) at the University of Freiburg. Many student projects and theses improved the tool.

Source code available at GitHub\(^3\).

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\(^1\)SV-COMP: [sv-comp.sosy-lab.org/](https://sv-comp.sosy-lab.org/)

\(^2\)Group of Andreas Podelski: [https://swt.informatik.uni-freiburg.de/](https://swt.informatik.uni-freiburg.de/)

\(^3\)The Ultimate Framework: [https://github.com/ultimate-pa/ultimate/](https://github.com/ultimate-pa/ultimate/)
Some program written in the C language. A specification written in ACSL is given by assert statement in line 6.

```c
unsigned int foo(unsigned int x, unsigned int y) {
    if (x < 1000 || y < 1000) {
        return 1000;
    }
    unsigned int z = x + y;
    //@ assert z >= 1000;
    return z;
}
```

Naive proposition: The program satisfies the specification.

Naive justification: If we add two large numbers the result is a large number.

Ultimate Automizer rightly disagrees: Since the type of `x` and `y` is `unsigned int` the value of `z` is 0 if `y` was 4294966296 and `z` was 0. (If we follow the ISO C11 standard and assume that an `unsigned int` can store values from 0 to 4294967295.)
Let’s try to fix the program as follows.

```c
unsigned long foo(unsigned int x, unsigned int y) {
    if (x < 1000 || y < 1000) {
        return 1000;
    }
    unsigned long z = x + y;
    //@ assert z >= 1000;
    return z;
}
```

- Naive proposition: Now, the program satisfies the specification.
- Naive justification: The range of values of z is now large enough.

Ultimate Automizer rightly disagrees: The type of the expression x+y is still unsigned int and hence the preceding counterexample applies again.
Let's finally fix the program as follows.

```c
unsigned long foo(unsigned int x, unsigned int y) {
    if (x < 1000 || y < 1000) {
        return 1000;
    }
    unsigned long z = (long) x + y;
    //@ assert z >= 1000;
    return z;
}
```

Ultimate Automizer confirms that the program satisfies its specification.
Outline of the Section on Introduction

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More and more devices in our lives are controlled by software.
Software usually has bugs.
Some bugs make the software directly disfunctional, some bugs affect security and are exploited secretly
Software is getting more and more complex.
Higher complexity, more bugs.
Testing is not Always Sufficient

```
int foo(int x, int y) {
    return y / (myHash(x) - 23);
}
```

Unless we test all inputs, we cannot use testing to prove correctness.
Motivation

- Find more software bugs
- Get mathematical proof of correctness
- Speed up software development
Challenge 1: Undecidability

The program verification problem is undecidable.

Do not try to develop algorithms that solve the problem for all programs. Algorithms that solve the problem for some programs are also helpful.
Challenge 2: Ambiguities

Example: What are the values of $x$ and $y$?

\[
\begin{align*}
x & := -7 \div 5; \\
y & := -7 \mod 5;
\end{align*}
\]

<table>
<thead>
<tr>
<th></th>
<th>$x$</th>
<th>$y$</th>
<th>makes sense because</th>
</tr>
</thead>
<tbody>
<tr>
<td>C/C++</td>
<td>-1</td>
<td>-2</td>
<td>$(-1) \cdot 5 + (-2) = 7$</td>
</tr>
<tr>
<td>Python</td>
<td>-2</td>
<td>3</td>
<td>$(-2) \cdot 5 + 3 = 7$</td>
</tr>
<tr>
<td>Javascript</td>
<td>-1.4</td>
<td>-2</td>
<td>$(-1.4) \cdot 5 = 7$</td>
</tr>
</tbody>
</table>

Use mathematical logic to give programming languages a precise semantics. In this course: We develop a small programming language whose semantics can be defined in a couple of slides.
Simple argument for correctness:
The values of $x$ and $y$ are always odd.

We cannot track all executions.
Outline of the Section on Introduction

Some Motivation
Program Verifier
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Content of this Course
Content of this Course

- Mathematical logic
  Propositional logic, First-order logic, SMT-LIB
- Boostan
  A small programming with a precisely defined semantics
- Hoare proof system
  A proof system for programs
- Algorithms for program verification
  Develop algorithms that analyze if a program satisfies a specification
Section 2

Propositional Logic
We presume that all of you know propositional logic. Propositional logic is one of the basic concepts in computer science, it has applications in many areas but there exist several terminology and several notations.

Goals of this section are

- recall the basic ideas of propositional logic
- fix the notation and terminology that we use in this lecture
- ease the presentation of first order logic (next section)
- introduce the idea of a proof system
Definition

Let $\mathcal{V}_{PL}$ be a nonempty set whose elements we call *propositional logical variables*. We define *propositional logic (PL) formulas* inductively as follows.

1. **false** is a PL formula.
2. For each $X \in \mathcal{V}_{PL}$, $X$ is a PL formula.
3. If $F$ is a PL formula, then $\neg F$ is a PL formula.
4. If $F_1$ and $F_2$ are PL formulas, then $(F_1 \land F_2)$ is a PL formula.

Abbreviations

true := $\neg$false

$F_1 \lor F_2$ := $\neg(\neg F_1 \land \neg F_2)$

$F_1 \rightarrow F_2$ := $\neg F_1 \lor F_2$

$F_1 \leftrightarrow F_2$ := $(F_1 \rightarrow F_2) \land (F_2 \rightarrow F_1)$
Terminology

We call true, false atoms.
If \( X \in V_{PL} \), we call \( X \) an atom.
If \( F \) is an atom, we call \( F \) and \( \neg F \) a literal.
We call the symbols \( \neg, \land, \lor, \to, \leftrightarrow \) logical connectives.

Notation

We may omit parentheses.

- Use the following order of precedence for logical connectives:
  \( \neg, \land, \lor, \to, \leftrightarrow \)
- Use the convention that binary operators are right-associative.

Right-associativity means e.g. that \( F_1 \to F_2 \to F_3 \) is \( F_1 \to (F_2 \to F_3) \).
We call true and false truth values and we call a mapping $\rho : \mathcal{V}_{\text{PL}} \rightarrow \{ \text{true}, \text{false} \}$ a variable assignment.

**Definition**

The evaluation is a mapping $\llbracket \cdot \rrbracket$ that takes a PL formula $F$ and a variable assignment $\rho$, and returns a truth value. It is defined as follows.

1. $\llbracket \text{false} \rrbracket_\rho$ is false.
2. For each $X \in \mathcal{V}_{\text{PL}}$, $\llbracket X \rrbracket_\rho$ is $\rho(X)$.
3. $\llbracket \neg F \rrbracket_\rho$ is $\begin{cases} \text{true} & \text{if } \llbracket F \rrbracket_\rho \text{ is false} \\ \text{false} & \text{if } \llbracket F \rrbracket_\rho \text{ is true} \end{cases}$.
4. $\llbracket F_1 \land F_2 \rrbracket_\rho$ is $\begin{cases} \text{true} & \text{if } \llbracket F_1 \rrbracket_\rho \text{ is true and } \llbracket F_2 \rrbracket_\rho \text{ is true} \\ \text{false} & \text{otherwise.} \end{cases}$

**Definition**

1. We call a PL formula $F$ satisfiable if there is a variable assignment $\rho$ such that $\llbracket F \rrbracket_\rho$ is true.
2. We call a PL formula $F$ valid if for all variable assignments $\rho$ the evaluation $\llbracket F \rrbracket_\rho$ is true.
Examples: Satisfiability and Validity

Which of the following formulas is satisfiable, which is valid?

- $F_1 : P \land Q$
  - satisfiable, not valid

- $F_2 : \neg(P \land Q)$
  - satisfiable, not valid

- $F_3 : P \lor \neg P$
  - satisfiable, valid

- $F_4 : \neg(P \lor \neg P)$
  - unsatisfiable, not valid

- $F_5 : (P \rightarrow Q) \land (P \lor Q) \land \neg Q$
  - unsatisfiable, not valid (see next slides)

Is there a formula that is unsatisfiable and valid?
Truth tables
Functions that have finite domain are sometimes visualized or defined via a table. The *truth table* is a table that visualizes the evaluation mapping \([\cdot]\) for a given formula \(F\), i.e., the input is a variable assignment, the output is a truth value. In the truth table (an example is depicted on the next slides), every column is assigned to some subformula of \(F\). The columns are partitioned into two parts. On the left hand side, there is one column for each propositional variable, on the right hand side there is a column for \(F\) and sometimes there are also columns for subformulas of \(F\). A row of the table represents one variable assignment. The rows for subformulas can help to compute the entries for the formula \(F\).
Truth Table: Example

Truth table for the formula $F_5 : (P \to Q) \wedge (P \lor Q) \wedge \neg Q$

<table>
<thead>
<tr>
<th>$P$</th>
<th>$Q$</th>
<th>$(P \to Q)$</th>
<th>$(P \lor Q)$</th>
<th>$\neg Q$</th>
<th>$F_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>false</td>
<td>false</td>
<td>true</td>
<td>false</td>
<td>true</td>
<td>false</td>
</tr>
<tr>
<td>true</td>
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<td>false</td>
</tr>
<tr>
<td>true</td>
<td>true</td>
<td>true</td>
<td>true</td>
<td>false</td>
<td>false</td>
</tr>
</tbody>
</table>

We conclude that $F_5$ is neither satisfiable nor valid.
Truth Tables: Limited Applicability

Unfortunately, the applicability of truth tables is rather limited. A truth table has one row per variable assignment, and there are $2^n$ variable assignments for $n$ variables.

Deciding satisfiability of a PL formula is an NP-complete problem. However, there are many algorithms that work well in practice and that are known to be polynomial on relevant subclasses of PL formulas. Some of these algorithms are discussed in other lectures, e.g., Decision Procedures, and we do not want to discuss the problem in this lecture.
Excursus: Using SMT Solvers for SAT Problem

<table>
<thead>
<tr>
<th>SAT solver</th>
<th>propositional logic</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMT solver</td>
<td>first order logic modulo theories</td>
</tr>
</tbody>
</table>

Example:

\[(P \rightarrow Q) \land (P \lor Q)\]
Tools for checking satisfiability of PL formulas

Finding satisfying assignments for PL formulas can be a time-consuming task. In practice, we use tools to solve this task. Tools that are specialized in finding satisfying assignments for PL formulas are called **SAT solvers**.

Later in this lecture, we will use tools that are called **SMT solvers**. Every SMT solver is also able to find satisfying assignments for PL formulas, but SMT solvers are typically not highly optimized for this task. Since performance is not an issue for us, we will not learn how to use a SAT solver and start to use SMT solvers right now.

Users communicate with an SMT solver via so-called **SMT scripts**. An SMT script is a file that contains a list of commands. In order to get a satisfying assignment for a PL formula $F$, we need only the following four commands.

1. First, we write `(define-fun X Bool)` for each propositional variable $X$ in our formula $F$.
2. Then, we write `(assert $F$)` and have to write the formula $F$ using the prefix (or Polish) notation that is defined at the following URL: [http://smtlib.cs.uiowa.edu/theories-Core.shtml](http://smtlib.cs.uiowa.edu/theories-Core.shtml)
   
   E.g., for PL formulas $F_1, F_2$ we write `(and $F_1$ $F_2$)` instead of $(F_1 \land F_2)$
3. Next, we write `(check-sat)`.
4. Finally, if the formula is satisfiable and we want to see a satisfying assignment, we can write `(get-model)`.

There are several SMT solvers available, we propose to use Z3 because it is also available via a web interface. [https://rise4fun.com/z3/](https://rise4fun.com/z3/)
Implications

Definition

Given a set of PL formulas $\Gamma := \{F_1, \ldots, F_n\}$ and a PL formula $F'$, we say that $\Gamma$ implies $F'$ if for all variable assignments $\rho$ we have that if $\llbracket F_i \rrbracket_\rho = \text{true}$ holds for all $i \in \{1, \ldots, n\}$ then also $\llbracket F' \rrbracket_\rho = \text{true}$ holds. We use $\models$ to denote this binary implication relation and we say that the implication $\Gamma \models F'$ holds if $\Gamma$ implies $F'$.

Example

$\{A, A \rightarrow B\} \models A \land B \quad \{A \rightarrow B\} \models \neg B \rightarrow \neg A$

How can we prove that $\{F_1, \ldots, F_n\}$ implies $F'$?

1. Truth table. (Not doable if number of variables is high)
2. Prove that the PL formula $F_1 \land \ldots \land F_n \rightarrow F'$ is valid. (Requires algorithm for checking validity)
3. Prove that the PL formula $\neg(F_1 \land \ldots \land F_n \rightarrow F')$ is not satisfiable. (Theorem on next slide – requires algorithm for checking satisfiability – implemented in SMT solvers)
4. Use a proof system (next subchapter)
Theorem

The PL formula $F$ is valid iff the PL formula $\neg F$ is not satisfiable.

Proof.

$F$ valid

iff for all variable assignments $\rho$ we have $\llbracket F \rrbracket_\rho = \text{true}$
  (def of validity)

iff for all variable assignments $\rho$ we have $\llbracket \neg F \rrbracket_\rho = \text{false}$
  (def of negation $\neg$)

iff there is no variable assignment $\rho$ such that $\llbracket \neg F \rrbracket_\rho = \text{true}$

iff $\neg F$ not satisfiable
  (def of satisfiability)
Equivalence

**Definition**

We call two PL formulas $F_1$ and $F_2$ *equivalent*, denoted $F_1 \equiv F_2$, if they evaluate to the same truth value under every variable assignment.

**Note**

$$F_1 \equiv F_2 \quad \text{iff} \quad \{ F_1 \} \models F_2 \quad \text{and} \quad \{ F_2 \} \models F_1$$
Proof System (Informally)

- template for giving a proof
- reasoning according to a fixed number of rules
- prove once that every rule is “correct”
- find a proof ↦ find a sequence of rules
Proof system $\mathcal{N}_{\text{PL}}$

- Proof system for implications between PL formulas.
- Proof rules of $\mathcal{N}_{\text{PL}}$ are $(n + 1)$-ary relations over implications denoted as follows:

\[ \Gamma_1 \models F_1 \quad \ldots \quad \Gamma_n \models F_n \quad \Gamma_{n+1} \models F_{n+1} \]

Idea: the rule represents a step in a proof with the following meaning. If $\Gamma_i$ implies $F_i$ for $i \in \{1, \ldots, n\}$ then $\Gamma_{n+1}$ implies $F_{n+1}$. 
Proof rules of $\mathcal{N}_{\text{PL}}$

\[(Ax) \quad \frac{}{\Gamma \cup \{F\} \models F}\]

\[(RAA) \quad \frac{\Gamma \cup \{\neg F\} \models \text{false}}{\Gamma \models F}\]

Introduction rules:

\[(I\land) \quad \frac{\Gamma \models F_1 \quad \Gamma \models F_2}{\Gamma \models F_1 \land F_2}\]

\[(I\lor_i) \quad \frac{\Gamma \models F_i}{\Gamma \models F_1 \lor F_2} \quad i \in \{1, 2\}\]

\[(I\rightarrow) \quad \frac{\Gamma \cup \{F_1\} \models F_2}{\Gamma \models F_1 \rightarrow F_2}\]

\[(I\neg) \quad \frac{\Gamma \cup \{F\} \models \text{false}}{\Gamma \models \neg F}\]

Elimination rules:

\[(E\land_i) \quad \frac{\Gamma \models F_1 \land F_2 \quad i \in \{1, 2\}}{\Gamma \models F_i}\]

\[(E\lor) \quad \frac{\Gamma \models F_1 \lor F_2 \quad \Gamma \cup \{F_1\} \models F_3 \quad \Gamma \cup \{F_2\} \models F_3}{\Gamma \models F_3}\]

\[(E\rightarrow) \quad \frac{\Gamma \models F_1 \quad \Gamma \models F_1 \rightarrow F_2}{\Gamma \models F_2}\]

\[(E\neg) \quad \frac{\Gamma \models F_1}{\Gamma \models \neg F_1}\]

The letters $F, F_1, F_2, F_3$ denote PL formulas.
Proof system $\mathcal{N}_{PL}$

**Definition**

A *derivation* is a tree whose nodes are labelled by implications such that the following holds. If a node labelled by implication $\Gamma_{n+1} \vdash F_{n+1}$ has children that are labelled by implications $\Gamma_1 \vdash F_1 \ldots \Gamma_n \vdash F_n$ then

$$\frac{\Gamma_1 \vdash F_1 \ldots \Gamma_n \vdash F_n}{\Gamma_{n+1} \vdash F_{n+1}}$$

must be an instance of some rule.

**Example**

Let $A, B$ be PL variable, define $\Gamma := \{A, A \to B\}$

\[
\begin{align*}
\Gamma & \vdash A \\
\Gamma & \vdash A \\
\Gamma & \vdash B \\
\Gamma & \vdash A \land B
\end{align*}
\]

\[
\begin{align*}
(A\exists) & \quad \frac{\Gamma \vdash A}{\Gamma \vdash A} \\
(I\lor) & \quad \frac{\Gamma \vdash A \to B}{\Gamma \vdash A} \\
\Gamma & \vdash A \\
\Gamma & \vdash B
\end{align*}
\]

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For derivations: We do not use the typical graph representation of a tree (left, striked out). Instead, we use horizontal lines together with the names of proof rules (right).

We conclude from the preceding definition that a leaf of the derivation can only be labelled by a implication $\Gamma \models F$ such that $\Gamma \models F$ is an instance of some (unary) rule.
By now, we saw several definitions (proof rules of $\mathcal{NP}_L$, derivation) but we may still wonder whether $\mathcal{NP}_L$ is good for something. The following theorem shows us an application: $\mathcal{NP}_L$ can be used to prove implications. Whenever we want to prove an implication, we can find a derivation and conclude that the implication holds.

A consequence: If we have to implement a tool for proving implications, we can solve the task by developing an algorithm for finding derivations.\(^7\)

\(^7\)Please note however that we introduce $\mathcal{NP}_L$ mainly to get familiar with proof systems. State-of-the-art SAT solver implement completely different algorithms [jsat/HeuleJS19].
Theorem (Soundness of $\mathcal{N}_{PL}$)

If a node in a derivation is labelled by $\Gamma \models F_{n+1}$, then the implication $\Gamma \models F_{n+1}$ holds.

Proof.

(Sketch) Show for each rule that the implication below the line holds if all implications above the line hold. Use induction to conclude that the theorem holds.

Theorem (Completeness of $\mathcal{N}_{PL}$)

If the implication $\Gamma \models F_{n+1}$ holds then there exists some derivation in which the root is labelled by $\Gamma \models F_{n+1}$.

Proof difficult, not in the scope of this lecture.
Let’s prove the implication \( \{A, A \rightarrow B\} \models A \land B \):

\[
\begin{align*}
\Gamma \models A & \quad (Ax) \\
\Gamma \models A \land B & \quad (I\land) \\
\Gamma \models A \rightarrow B & \quad (Ax) \\
\Gamma \models B & \quad (E\rightarrow) \\
\Gamma \models A \land B & \quad (Ax) \\
\end{align*}
\]
A guide for proving implications.

1. Goal: Try to construct a derivation whose root node is labelled by the implication that we want to prove.

2. Start building the tree at the root (bottom).

3. For each node in the tree, use the rules to determine the number of children and their labels, because we must never violate the definition of a derivation.

4. Use the Rule $Ax$ as soon as possible because it allow us to construct a leaf of the tree without violating the definition of a derivation.

In the example form the preceding slide we start with a root node that is labelled by $\Gamma \models A \land B$. Since the right hand side of this implication is a conjunction we cannot use the rules $I_\lor 1, I_\lor 1, I_\rightarrow, I_\neg$ to construct the children of our root node. Since $\Gamma$ does not contain $A \land B$ we cannot use the rule $Ax$. Without looking a few steps ahead, we cannot exclude any other rule and have to try all of them. Luckily, this example is rather simple and by looking a few steps ahead we see that the rule $I_\land$ is a good choice.
We note that it is not allowed to replace formulas by equivalent formulas in a derivation. E.g., the following tree is not a derivation (according to the definition), because it is not allowed to swap the operands of the logical connective $\land$.

Rationale: In a proof system, it should be possible to find (and check) derivations by mechanically applying rules without a need for understanding the semantics of formulas. We can e.g., implement a proof system on a computer without teaching the computer to understand the semantics of formulas.
Lecture 3: First-Order Logic

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Monday 26th April
Section 3

First-Order Logic
Like propositional logic, first-order logic (also known as predicate logic) is a basic concept in computer science that has applications in many areas, but there exist several terminology and several notations.

Goals of this section are

▶ recall the basic ideas of first-order logic
▶ fix the notation and terminology that we use in this lecture
▶ get more familiar with proof systems / see proof rules with side-conditions
▶ learn to formalize statements in first-order logic
Before we introduce first-order logic formally, we will have a look at three examples.

On the next two slides you will see three “famous” theorems and a formalization in first-order logic.
Famous Theorems in FOL

- The length of one side of a triangle is less than the sum of the lengths of the other two sides.

\[ \forall x, y, z. \ triangle(x, y, z) \rightarrow length(x) < length(y) + length(z) \]

- Fermat’s Last Theorem.

\[ \forall n. \ integer(n) \land n > 2 \rightarrow \forall x, y, z. \]
\[ \ \ \ \ \integer(x) \land \integer(y) \land \integer(z) \]
\[ \land x > 0 \land y > 0 \land z > 0 \rightarrow x^n + y^n \neq z^n \]
Famous Theorems in FOL

For every regular Language $L$ there is some $n \geq 0$, such that for all words $z \in L$ with $|z| \geq n$ there is a decomposition $z = uvw$ with $|v| \geq 1$ and $|uv| \leq n$, such that for all $i \geq 0$: $uv^iw \in L$.

\[
\forall L. \text{regularlanguage}(L) \rightarrow \\
\exists n. \text{integer}(n) \land n \geq 0 \land \\
\forall z. z \in L \land |z| \geq n \rightarrow \\
\exists u, v, w. \text{word}(u) \land \text{word}(v) \land \text{word}(w) \land \\
z = uvw \land |v| \geq 1 \land |uv| \leq n \land \\
\forall i. \text{integer}(i) \land i \geq 0 \rightarrow uv^iw \in L
\]

Predicate symbols: regularlanguage, integer, word, $\cdot \in \cdot$, $\cdot \leq \cdot$, $\cdot \geq \cdot$, $\cdot = \cdot$
Constant symbols: 0, 1
Function symbols: $| \cdot |$ (word length), concatenation, iteration
Syntax of First-order Logic

Definition

Let a vocabulary \( \mathcal{V} \) be a tuple \((\mathcal{V}_{\text{Var}}, \mathcal{V}_{\text{Const}}, \mathcal{V}_{\text{Fun}}, \mathcal{V}_{\text{Pred}})\) such that

- \( \mathcal{V}_{\text{Var}} \) is a countable set whose elements we call **variables**.
- \( \mathcal{V}_{\text{Const}} \) is a countable set whose elements we call **constant symbols**.
- \( \mathcal{V}_{\text{Fun}} \) is a countable set whose elements we call **function symbols**. Each function symbol \( f \) has a natural number \( \geq 1 \) that we call the **arity** of \( f \).
- \( \mathcal{V}_{\text{Pred}} \) is a countable set whose elements we call **predicate symbols**. Each predicate symbol \( p \) has a natural number \( \geq 0 \) that we call the **arity** of \( p \).

For the following definitions, we fix a vocabulary \( \mathcal{V} = (\mathcal{V}_{\text{Var}}, \mathcal{V}_{\text{Const}}, \mathcal{V}_{\text{Fun}}, \mathcal{V}_{\text{Pred}}) \).

Definition

We define **first-order logic (FOL) terms** inductively as follows.

1. For each \( x \in \mathcal{V}_{\text{Var}} \), \( x \) is a **term**.
2. For each \( c \in \mathcal{V}_{\text{Const}} \), \( c \) is a **term**.
3. If \( t_1, \ldots t_n \) are terms, \( f \in \mathcal{V}_{\text{Fun}} \), \( f \) has arity \( n \), then \( f(t_1, \ldots, t_n) \) is a **term**.
Syntax of First-order Logic

Definition

We define *first-order logic (FOL) formulas* inductively as follows.

1. **false** is a formula.
2. If \( t_1, \ldots, t_n \) are terms, \( p \in \mathcal{V}_{\text{Pred}} \), \( p \) has arity \( n \), then \( p(t_1, \ldots, t_n) \) is a formula.
3. If \( \varphi \) is a formula, then \( \neg \varphi \) is a formula.
4. If \( \varphi_1 \) and \( \varphi_2 \) are formulas, then \( (\varphi_1 \land \varphi_2) \) is a formula.
5. If \( \varphi \) is a formula and \( x \in \mathcal{V}_{\text{Var}} \) then \( \exists x.\varphi \) is a formula.

Abbreviations, Terminology, and Notation

- Analogously to propositional logic we use the abbreviations \( \lor, \to, \iff \).
- Additionally, we introduce \( \forall x.\varphi := \neg \exists x.\neg \varphi \)
- We call the symbols \( \exists \) and \( \forall \) quantifiers. We call formulas of the form \text{true}, \text{false}, and \( p(t_1, \ldots, t_n) \) *atoms*.
- Analogously to propositional logic we may omit parentheses. The precedence of quantifiers is lower than the precedence of logical connectives.
  We may abbreviate \( \exists x_1.\exists x_2.\varphi \) to \( \exists x_1, x_2.\varphi \).
Definition

A model $\mathcal{M} = (\mathcal{D}, \mathcal{I})$ is a pair where $\mathcal{D}$ is a set that we call interpretation domain and $\mathcal{I}$ is a function that we call interpretation function and that has the following properties.

- The domain of $\mathcal{I}$ is $\mathcal{V}_{\text{Const}} \cup \mathcal{V}_{\text{Fun}} \cup \mathcal{V}_{\text{Pred}}$.
- $\mathcal{I}$ maps every constant symbol to an element of $\mathcal{D}$.
- $\mathcal{I}$ maps every $n$-ary function symbol to an $n$-ary function whose domain is $\mathcal{D}^n$ and whose range is $\mathcal{D}$.
- $\mathcal{I}$ maps every $n$-ary predicate symbol to an $n$-ary relation over $\mathcal{D}$.

We call a function $\rho : \mathcal{V}_{\text{Var}} \to \mathcal{D}$ that maps variable symbols to elements of the interpretation domain a variable assignment.

Notation

Let $f : X \to Y$ be a function whose domain is some set $X$ and whose range is some set $Y$. Let $\tilde{x} \in X$ and $\tilde{y} \in Y$, then we use $f \triangleleft \{\tilde{x} \to \tilde{y}\}$ to denote the function that maps all $x \in X \setminus \{\tilde{x}\}$ to $f(x)$ and that maps $\tilde{x}$ to $\tilde{y}$.
Semantics of First-order Logic

Definition

The evaluation of terms is a mapping $[\cdot]_{\mathcal{M},\rho}$ that takes a formula $\varphi$, a model $\mathcal{M} = (D, \mathcal{I})$, and a variable assignment $\rho$, and returns an element of $D$. It is inductively defined as follows.

1. For each $x \in \mathcal{V}_{\text{Var}}$, $[x]_{\mathcal{M},\rho}$ is $\rho(x)$.
2. For each $c \in \mathcal{V}_{\text{Const}}$, $[c]_{\mathcal{M},\rho}$ is $\mathcal{I}(c)$.
3. If $t_1, \ldots, t_n$ are terms, $f \in \mathcal{V}_{\text{Fun}}$, $f$ has arity $n$, then $[f(t_1, \ldots, t_n)]_{\mathcal{M},\rho}$ is $\mathcal{I}(f)([t_1]_{\mathcal{M},\rho}, \ldots, [t_n]_{\mathcal{M},\rho})$. 
Semantics of First-order Logic

**Definition**

The *evaluation of formulas* is a mapping $\llbracket \cdot \rrbracket_{M, \rho}$ that takes a formula $\varphi$, a model $M = (D, I)$, and a variable assignment $\rho$, and returns a truth value. It is inductively defined as follows.

1. $\llbracket \text{false} \rrbracket_{M, \rho}$ is false.

2. $\llbracket p(t_1, \ldots, t_n) \rrbracket$ is \[
\begin{cases}
\text{true} & \text{if } (\llbracket t_1 \rrbracket_{M, \rho}, \ldots, \llbracket t_n \rrbracket_{M, \rho}) \in I(p) \\
\text{false} & \text{otherwise.}
\end{cases}
\]

3. $\llbracket \neg \varphi \rrbracket_{M, \rho}$ is \[
\begin{cases}
\text{true} & \text{if } \llbracket \varphi \rrbracket_{M, \rho} \text{ is false} \\
\text{false} & \text{if } \llbracket \varphi \rrbracket_{M, \rho} \text{ is true.}
\end{cases}
\]

4. $\llbracket \varphi_1 \land \varphi_2 \rrbracket_{M, \rho}$ is \[
\begin{cases}
\text{true} & \text{if } \llbracket \varphi_1 \rrbracket_{M, \rho} \text{ is true and } \llbracket \varphi_2 \rrbracket_{M, \rho} \text{ is true} \\
\text{false} & \text{otherwise.}
\end{cases}
\]

5. $\llbracket \exists x. \varphi \rrbracket_{M, \rho}$ is \[
\begin{cases}
\text{true} & \text{if there exists } v \in D \\
\text{false} & \text{such that } \llbracket \varphi \rrbracket_{M, \rho \downharpoonright \{x \mapsto v\}} \text{ is true}
\end{cases}
\]

otherwise.
Program Verification

Summer Term 2021

Lecture 4: First-Order Logic cont’d

Matthias Heizmann

Wednesday 28th April
Satisfiability and Validity

Definition (Satisfiability)
We call a formula $\varphi$ **satisfiable** if there exists a model $\mathcal{M}$ and a variable assignment $\rho$ such that $\left[\varphi\right]_{\mathcal{M},\rho}$ is **true**.

Definition (Validity)
We call a formula $\varphi$ **valid** if $\left[\varphi\right]_{\mathcal{M},\rho}$ is **true** for all models $\mathcal{M}$ and for all variable assignments $\rho$.

Note
$\varphi$ is valid iff $\neg\varphi$ is unsatisfiable
Implications

Definition

Given a (possibly infinite) set of FOL formulas $\Gamma$ and a FOL formula $\psi$, we say that $\Gamma$ implies $\psi$ if for all models $M$ and for all variable assignments $\rho$ we have that

if $\llbracket \varphi \rrbracket_{M,\rho} = \text{true}$ holds for all $\varphi \in \Gamma$ then also $\llbracket \psi \rrbracket_{M,\rho} = \text{true}$ holds.

We use $\models$ to denote this binary implication relation and we say that the implication $\Gamma \models \psi$ holds if $\Gamma$ implies $\psi$. 
Definition (Free Variables, Bound Variables, Closed Formulas)

Given a FOL term $t$, we define the set of free variables inductively as follows.

$$\text{freevars}(t) = \begin{cases} \{x\} & \text{if } t \text{ is } x \in \mathcal{V}_{\text{Var}} \\ \emptyset & \text{if } t \text{ is } c \in \mathcal{V}_{\text{Const}} \\ \text{freevars}(t_1) \cup \ldots \cup \text{freevars}(t_n) & \text{if } t \text{ is } f(t_1, \ldots, t_n) \end{cases}$$

Given a FOL formula $\psi$, we define the set of free variables inductively as follows.

$$\text{freevars}(\psi) = \begin{cases} \emptyset & \text{if } \psi \text{ is } \text{false} \\ \text{freevars}(t_1) \cup \ldots \cup \text{freevars}(t_n) & \text{if } \psi \text{ is } p(t_1, \ldots, t_n) \\ \text{freevars}(\varphi) & \text{if } \psi \text{ is } \neg \varphi \\ \text{freevars}(\varphi_1) \cup \text{freevars}(\varphi_2) & \text{if } \psi \text{ is } \varphi_1 \land \varphi_2 \\ \text{freevars}(\varphi) \setminus \{x\} & \text{if } \psi \text{ is } \exists x. \varphi \end{cases}$$

We call a variable that occurs in $\psi$ but is not free bound.

We call a formula that does not contain free variables closed.

Note: For a closed formula $\varphi$ the evaluation $[\varphi]_{\mathcal{M}, \rho}$ is independent of the variable assignment $\rho$. 
Notation

- Given a function \( f \), we use \( \text{dom}(f) \) to denote the domain of \( f \).
- Given a function \( f \) that maps variables to terms, we use \( \text{vars}(f) \) to denote the set that contains \( \text{dom}(f) \) and all variables of all terms in the range of \( f \). I.e.,
  \[
  \text{vars}(f) = \text{dom}(f) \cup \bigcup_{x \in \text{dom}(f)} \text{freevars}(f(x))
  \]

Definition (Substitution)

Given a function \( \sigma \) from variable symbols to terms we define the substitution for FOL terms \( t \) and FOL formulas \( \psi \) as follows.

\[
\begin{align*}
  t\sigma &= & \begin{cases} 
    \sigma(x) & \text{if } t \text{ is } x \in \mathcal{V}_{\text{Var}} \text{ and } x \in \text{dom}(\sigma) \\
    t & \text{if } t \text{ is } c \in \mathcal{V}_{\text{Const}} \text{ or if } t \text{ is } x \in \mathcal{V}_{\text{Var}} \text{ and } x \not\in \text{dom}(\sigma) \\
    f(t_1\sigma, \ldots, t_n\sigma) & \text{if } t \text{ is } f(t_1, \ldots, t_n)
  \end{cases}
  \\
  \psi\sigma &= & \begin{cases} 
    \text{false} & \text{if } \psi \text{ is false} \\
    p(t_1\sigma, \ldots, t_n\sigma) & \text{if } \psi \text{ is } p(t_1, \ldots, t_n) \\
    \neg(\varphi\sigma) & \text{if } \psi \text{ is } \neg\varphi \\
    \varphi_1\sigma \land \varphi_2\sigma & \text{if } \psi \text{ is } \varphi_1 \land \varphi_2 \\
    \exists x.\varphi\sigma & \text{if } \psi \text{ is } \exists x.\varphi \text{ and } x \not\in \text{vars}(\sigma) \\
    \exists x'.(\varphi\sigma')\sigma & \text{if } \psi \text{ is } \exists x.\varphi \text{ and } x \in \text{vars}(\sigma)
  \end{cases}
\end{align*}
\]

where \( \sigma' \) is the function that maps \( x \) to \( x' \) and \( x' \) is a fresh variable (i.e., a variable that neither occurs in \( \psi \) nor in \( \text{vars}(\sigma) \)).
If we do not want to specify the substitution function $\sigma$ separately, we write $\varphi[x_1 \mapsto t_1, \ldots, x_n \mapsto t_n]$ instead of $\varphi\sigma$ if $\sigma$ is the function that maps $x_i$ to $t_i$ for $i \in \{1, \ldots, n\}$.

We sometimes use $\varphi[x]$ to refer to a formula and a variable. We may then use in this context $\varphi[t]$ to denote $\varphi[x \mapsto t]$. 
Analogously to $\mathcal{N}_{PL}$ for propositional logic there is a proof system for proving implications $\Gamma \models \varphi$ of FOL formulas. We call this proof system *natural deduction for first order logic* and denote it by $\mathcal{N}_{FOL}$. Analogously to $\mathcal{N}_{PL}$ we define the term *derivation* and use this tree as a proof.

For each rule of $\mathcal{N}_{PL}$ there is an analogous rule in $\mathcal{N}_{FOL}$. Additionally we have the four rules that are shown on the next slide. Two of these rules have additional *side conditions* that are written right beneath the rule. A tree is only a *derivation* if all side conditions are satisfied.
Proof rules of \( \mathcal{N}_{\text{FOL}} \)

For each rule of \( \mathcal{N}_{\text{PL}} \) there is an analogous rule in \( \mathcal{N}_{\text{FOL}} \). Additionally we have the following four rules, where \( \varphi \) is some a FOL formula, \( t \) is some FOL term and \( x, y \) are variables.

\[
\begin{align*}
(I\forall) & \quad \frac{\Gamma \models \varphi[x \mapsto y]}{\Gamma \models \forall x. \varphi} \\
(E\forall) & \quad \frac{\Gamma \models \varphi[x \mapsto t]}{\Gamma \models \forall x. \varphi} \\
(I\exists) & \quad \frac{\Gamma \models \varphi[x \mapsto t]}{\Gamma \models \exists x. \varphi} \\
(E\exists) & \quad \frac{\Gamma \models \exists x. \varphi \quad \Gamma \cup \{ \varphi[x \mapsto y] \} \models \psi}{\Gamma \models \psi}
\end{align*}
\]

(a) \( y \notin \text{freevars}(\Gamma) \) and either \( x = y \) or \( y \notin \text{freevars}(\varphi) \)

(b) \( y \notin \text{freevars}(\Gamma \cup \psi) \) and either \( x = y \) or \( y \notin \text{freevars}(\varphi) \)
Example

\[ \Gamma = \{ \forall x, y, z. p(x, y) \land p(y, z) \to p(x, z), \ \forall x, y. p(x, y) \to p(y, x) \} \]

Task: prove that the implication \( \Gamma \vdash p(a, b) \land p(b, c) \to p(c, a) \) is valid.

\[
\begin{align*}
\Gamma' & \vdash p(a, b) \land p(b, c) \\
\hline
\text{(Ax)} & \Gamma' \vdash \forall x. \forall y. \forall z. p(x, y) \land p(y, z) \to p(x, z) \\
\text{(E\forall)} & \Gamma' \vdash \forall y. \forall z. p(a, y) \land p(y, z) \to p(a, z) \\
\text{(E\forall)} & \Gamma' \vdash \forall z. p(a, b) \land p(b, z) \to p(a, b) \\
\text{(E\forall)} & \Gamma' \vdash p(a, b) \land p(b, c) \to p(a, c) \\
\text{(Ax)} & \Gamma' \vdash \forall x. \forall y. p(x, y) \to p(y, x) \\
\text{(E\forall)} & \Gamma' \vdash \forall y. p(a, y) \to p(y, a) \\
\text{(E\forall)} & \Gamma' \vdash p(a, c) \to p(c, a) \\
\end{align*}
\]

In this derivation, we use \( \Gamma' \) as a shorthand for \( \Gamma \cup \{ p(a, b) \land p(b, c) \} \).
Section 4

First-Order Theories
Outline

Introduction

Propositional Logic

First-Order Logic

First-Order Theories

SMT-LIB

Boogie and Boostan

Hoare Proof System

Ultimate Referee

Arrays

Boogie and Boostan – Part 2

Control-flow graphs

Predicate Transformers

Bounded Model Checking

Correctness Specification via Assert Statement

Abstractions – Part 1

Infeasibility Proofs

CEGAR

Trace Abstraction

Constraint-based Invariant Synthesis

Termination Analysis
In practice, symbols like e.g., the constant symbol “0”, the function symbol “+”, or the relation symbol “=” come with a fixed predefined meaning. In this section we will see how we can give symbols in first-order logic a meaning.

What we learn in this section:

- Our intuitive understanding of satisfiability and validity does not always coincide with the classical definition from the last section.
- Finding all axioms that are needed to define the meaning of a symbol is an error-prone and difficult task.
- The expressiveness of an apparently simple theory can be surprisingly high.
- An apparently simple theory can be undecidable.
- There are not only theories for classical arithmetic but also for arithmetic of CPUs.
Outline of the Section on First-Order Theories

Motivation

$T$-Validity and $T$-Satisfiability
Theory of Equality
Theory of Rock-Paper-Scissors
Decidability
Natural Numbers and Integers
Rationals and Reals
Arrays
Combination of Theories
Decidability
**Notation**

We do not only want to use abstract constant symbols $c, d, e, \ldots$ function symbols $f, g, h \ldots$ and predicate symbols $p, q, \ldots$ but also the symbols $0, 1, +, \cdot, /, =, \leq, \ldots$. If we use these symbols, we use an infix notation. E.g., we write $\exists x. y = 2 \cdot x$ instead of $\exists x. = (y, \cdot(2, x))$.

Warning: symbols might not have the expected meaning.
Is the following program correct?

```c
void copyAtoBandC(int a) {
    int b = a;
    int c = b;
    assert (c == a);
}
```

In order to check correctness, we would like to check validity of the following FOL formula.

\[(a = b \land b = c) \rightarrow c = a\]

Problem:
Formula not valid. Counterexample: model \(\mathcal{M} = (\mathcal{D}, \mathcal{I})\) where
\(\mathcal{D} = \{\text{♣}, \text{♠}\}\) and \(\mathcal{I}\) maps the 2-ary predicate symbol \(=\) to the binary relation \(\{(\text{♣}, \text{♠}), (\text{♠}, \text{♣})\} \subseteq \mathcal{D} \times \mathcal{D}\).
First-Order Theories: Motivation

Problem: We do not want to check if $\varphi$ is valid.
We want to check if $\varphi$ holds for some (partial) model $M$.

Solution: Find a set of formulas $A_T$ such that only $M$ (and “similar” models) can make all these formulas valid.
Check if $A_T$ implies $\varphi$.

Example

We will not check if $\varphi : (a = b \land b = c) \rightarrow c = a$ is valid.
Instead we consider the set $A_T$ that contains the following three formulas

$$\forall x. \ x = x,$$
$$\forall x, y. \ x = y \rightarrow y = x,$$
$$\forall x, y, z. \ x = y \land y = z \rightarrow x = z,$$

and check if $A_T$ implies $\varphi$. 
Outline of the Section on First-Order Theories

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T-Validity and T-Satisfiability

Theory of Equality

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A first-order theory $T$ consists of

- A signature $\Sigma$ - set of constant, function, and predicate symbols
- A set of axioms $A_T$ - set of closed (no free variables) $\Sigma$-formulae

A $\Sigma$-formula is a formula constructed of constants, functions, and predicate symbols from $\Sigma$, and variables, logical connectives, and quantifiers.

Idea:

- The symbols of $\Sigma$ are just symbols without prior meaning.
- The axioms of $T$ provide their meaning.
**T-Validity and T-Satisfiability**

**Definition (T-model)**

A model $\mathcal{M}$ is a *T-model*, if $[[\varphi]]_{\mathcal{M},\rho} = \text{true}$ for all $\varphi \in A_T$ and for all variable assignments $\rho$.

**Definition (T-valid)**

A $\Sigma$-formula $\varphi$ is *valid in theory T (T-valid)*, if for every $T$-model $\mathcal{M}$, it holds that $[[\varphi]]_\mathcal{M} = \text{true}$.

**Definition (T-satisfiable)**

A $\Sigma$-formula $\varphi$ is *satisfiable in T (T-satisfiable)*, if there is a $T$-model $\mathcal{M}$ such that $[[\varphi]]_\mathcal{M} = \text{true}$.

**Definition (T-equivalent)**

Two $\Sigma$-formulae $\varphi_1$ and $\varphi_2$ are *equivalent in T (T-equivalent)*, if $\varphi_1 \leftrightarrow \varphi_2$ is $T$-valid.
Lecture 6: First-Order Theories

Matthias Heizmann

Wednesday 5th May
Outline of the Section on First-Order Theories

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$T$-Validity and $T$-Satisfiability

Theory of Equality

Theory of Rock-Paper-Scissors

Decidability

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Decidability
Question: Are the following axioms sufficient for defining the usual meaning of the equality symbol?

\[\forall x. \ x = x, \quad \text{(reflexivity)}\]
\[\forall x, y. \ x = y \rightarrow y = x, \quad \text{(symmetry)}\]
\[\forall x, y, z. \ x = y \land y = z \rightarrow x = z, \quad \text{(transitivity)}\]

Hint: Is the following formula implied by the axioms?
\[a = b \land f(a) = c \rightarrow f(b) = c\]

Answer: These axioms are sufficient if there are no other predicate symbols or function symbols. Otherwise these axioms are not sufficient because we expect that functions return the same outputs for the same inputs.
The theory of equality \( T_E \)

**Signature** \( \Sigma = \{=, a, b, c, \ldots, f, g, h, \ldots, p, q, r, \ldots \} \)

- \( = \), a binary predicate, *interpreted* by axioms.
- all constant, function, and predicate symbols.

**Axioms of \( T_E \):**

1. \( \forall x. \ x = x \)  
   (reflexivity)

2. \( \forall x, y. \ x = y \rightarrow y = x \)  
   (symmetry)

3. \( \forall x, y, z. \ x = y \land y = z \rightarrow x = z \)  
   (transitivity)

4. for each positive integer \( n \) and \( n \)-ary function symbol \( f \),
   \( \forall x_1, \ldots, x_n, y_1, \ldots, y_n. \ \land_i x_i = y_i \rightarrow f(x_1, \ldots, x_n) = f(y_1, \ldots, y_n) \)  
   (congruence)

5. for each positive integer \( n \) and \( n \)-ary predicate symbol \( p \),
   \( \forall x_1, \ldots, x_n, y_1, \ldots, y_n. \ \land_i x_i = y_i \rightarrow (p(x_1, \ldots, x_n) \leftrightarrow p(y_1, \ldots, y_n)) \)  
   (equivalence)
Axiom Schemata

Congruence and Equivalence are *axiom schemata*.

4. for each positive integer \( n \) and \( n \)-ary function symbol \( f \),
\[
\forall x_1, \ldots, x_n, y_1, \ldots, y_n. \quad \bigwedge_i x_i = y_i \rightarrow f(x_1, \ldots, x_n) = f(y_1, \ldots, y_n)
\] (congruence)

5. for each positive integer \( n \) and \( n \)-ary predicate symbol \( p \),
\[
\forall x_1, \ldots, x_n, y_1, \ldots, y_n. \quad \bigwedge_i x_i = y_i \rightarrow (p(x_1, \ldots, x_n) \leftrightarrow p(y_1, \ldots, y_n))
\] (equivalence)

For every function symbol there is an instance of the congruence axiom schema.

*Example:* Congruence axiom for binary function \( f_2 \):
\[
\forall x_1, x_2, y_1, y_2. \quad x_1 = y_1 \land x_2 = y_2 \rightarrow f_2(x_1, x_2) = f_2(y_1, y_2)
\]

\( A_{T_E} \) contains an infinite number of these axioms.
Outline of the Section on First-Order Theories

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Combination of Theories

Decidability
On the next slide, we will next define our own theory and see that this is a difficult task.

**Question 1:** Are axioms 1-3 sufficient?

**Hint 1:** Is the formula \( \neg \exists x. \forall y. x \succ_{\text{win}} y \) (no element wins against all others) valid with respect to these axioms?

**Answer 1:** Axioms 1-3 are not sufficient. A model in which \( \succ_{\text{win}} \) is mapped to a relation that contains all pairs would satisfy the axioms.

**Question 2:** Are axioms 1-9 sufficient?

**Hint 2:** Is the formula \( \neg \exists x. \forall y. x \succ_{\text{win}} y \) valid with respect to axioms 1-9?

**Answer 2:** Axioms 1-9 are not sufficient. A model in which the domain contains also an element *Well* that wins against all others would satisfy the axioms.

As a solution, we also add axiom 10 which however requires that we also add axioms that define the semantics of the equality symbol.
Exercise: Define Theory of Rock-Paper-Scissors

- Signature $\Sigma_{RPS}$
  - Constant symbols: Rock, Paper, Scissors
  - Relation symbol: $\succ_{\text{win}}$

- Axioms $A_{T_{RPS}}$
  1. Rock $\succ_{\text{win}}$ Scissors
  2. Scissors $\succ_{\text{win}}$ Paper
  3. Paper $\succ_{\text{win}}$ Rock
  4. $\neg$Rock $\succ_{\text{win}}$ Rock
  5. $\neg$Rock $\succ_{\text{win}}$ Paper
  6. $\neg$Scissors $\succ_{\text{win}}$ Scissors
  7. $\neg$Scissors $\succ_{\text{win}}$ Rock
  8. $\neg$Paper $\succ_{\text{win}}$ Paper
  9. $\neg$Paper $\succ_{\text{win}}$ Rock
  10. $\forall x. x = \text{Rock} \lor x = \text{Paper} \lor x = \text{Scissors}$

Are the following formulas T-valid?

- $\neg \exists x. \forall y. x \succ_{\text{win}} y$
- $\forall x. \exists y. x \succ_{\text{win}} y$
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Decidability

Reminder

We call a problem \textit{decidable} if there exists an algorithm that terminates on all instances of the problem and gives a correct yes/no answer. We call a problem \textit{semi-decidable} if there exists an algorithm that terminates at least on all “yes”-instances of the problem and gives a correct answer if it terminates.

Example of an undecidable problem: halting problem for Turing machines. Typical way to prove decidability: give an algorithm and prove its correctness. Typical way to prove undecidability: proof via a diagonal argument (e.g., Cantor’s diagonal argument) or proof via reduction.
Decidability

Theorem

Satisfiability of PL formulas is decidable.

Proof not given in this course.
Decision procedure: truth table.

Theorem

Satisfiability of FOL formulas is undecidable.

Proof not given in this course.

Theorem

Validity of FOL formulas is semi-decidable.

Proof not given in this course.
Decision procedure: enumerate trees to find a derivation, semi-decidability follows from soundness and completeness of $N_{\text{FOL}}$.
Decidability of $T_E$

Is it possible to decide $T_E$-validity?

**Theorem**

$T_E$-validity is undecidable.

Proof not given in this course.

If we restrict ourselves to quantifier-free formulae we get decidability:

**Theorem**

*For a quantifier-free formula $T_E$-validity is decidable.*

Proof not given in this course.
Outline of the Section on First-Order Theories

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Natural Numbers and Integers

Natural numbers \( \mathbb{N} = \{0, 1, 2, \ldots \} \)

Integers \( \mathbb{Z} = \{\ldots, -2, -1, 0, 1, 2, \ldots \} \)

Three variations:

- \textit{Peano arithmetic} \( T_{\mathbb{PA}} \): natural numbers with addition and multiplication
- \textit{Presburger arithmetic} \( T_{\mathbb{N}} \): natural numbers with addition
- \textit{Theory of integers} \( T_{\mathbb{Z}} \): integers with +, −, >
Peano Arithmetic $T_{PA}$ (first-order arithmetic)

**Signature:** $\Sigma_{PA} : \{0, 1, +, \cdot, =\}$

**Axioms of $T_{PA}$:** axioms of $T_E$,

1. $\forall x. \neg(x + 1 = 0)$ (zero)
2. $\forall x, y. x + 1 = y + 1 \rightarrow x = y$ (successor)
3. $\varphi[0] \land (\forall x. \varphi[x] \rightarrow \varphi[x + 1]) \rightarrow \forall x. \varphi[x]$ (induction)
4. $\forall x. x + 0 = x$ (plus zero)
5. $\forall x, y. x + (y + 1) = (x + y) + 1$ (plus successor)
6. $\forall x. x \cdot 0 = 0$ (times zero)
7. $\forall x, y. x \cdot (y + 1) = x \cdot y + x$ (times successor)

Line 3 is an axiom schema.
Expressiveness of Peano Arithmetic

$3x + 5 = 2y$ can be written using $\Sigma_{PA}$ as

$$x + x + x + 1 + 1 + 1 + 1 + 1 = y + y$$

We can define $>$ and $\geq$:

- $3x + 5 > 2y$ write as $\exists z. \ z \neq 0 \land 3x + 5 = 2y + z$
- $3x + 5 \geq 2y$ write as $\exists z. \ 3x + 5 = 2y + z$

Examples for valid formulae:

- **Pythagorean Theorem** is $T_{PA}$-valid
  $$\exists x, y, z. \ x \neq 0 \land y \neq 0 \land z \neq 0 \land xx + yy = zz$$

- **Fermat’s Last Theorem** is $T_{PA}$-valid (Andrew Wiles, 1994)
  $$\forall n. \ n > 2 \rightarrow \neg \exists x, y, z. \ x \neq 0 \land y \neq 0 \land z \neq 0 \land x^n + y^n = z^n$$
Expressiveness of Peano Arithmetic (2)

In Fermat’s theorem we used $x^n$, which is not a valid term in $\Sigma_{PA}$. However, there is the $\Sigma_{PA}$-formula $EXP[x, n, r]$ with

1. $EXP[x, 0, r] \leftrightarrow r = 1$
2. $EXP[x, i + 1, r] \leftrightarrow \exists r_1. EXP[x, i, r_1] \land r = r_1 \cdot x$

$$EXP[x, n, r] : \exists d, m. (\exists z. d = (m + 1)z + 1) \land$$
$$\quad (\forall i, r_1. i < n \land r_1 < m \land (\exists z. d = ((i + 1)m + 1)z + r_1) \rightarrow$$
$$\quad \quad r_1x < m \land (\exists z. d = ((i + 2)m + 1)z + r_1 \cdot x)) \land$$
$$\quad r < m \land (\exists z. d = ((n + 1)m + 1)z + r)$$

Fermat’s theorem can be stated as:

$$\forall n. n > 2 \rightarrow \neg \exists x, y, z, rx, ry. x \neq 0 \land y \neq 0 \land z \neq 0 \land$$

$$\quad EXP[x, n, rx] \land EXP[y, n, ry] \land EXP[z, n, rx + ry]$$
Decidability of Peano Arithmetic

Gödel showed that for every recursive function $f : \mathbb{N}^n \rightarrow \mathbb{N}$ there is a $\Sigma_{PA}$-formula $\varphi[x_1, \ldots, x_n, r]$ with

$$\varphi[x_1, \ldots, x_n, r] \leftrightarrow r = f(x_1, \ldots, x_n)$$

$T_{PA}$ is undecidable. (Gödel, Turing, Post, Church)

The quantifier-free fragment of $T_{PA}$ is undecidable. (Matiyasevich, 1970)

Remark: Gödel’s first incompleteness theorem

Peano arithmetic $T_{PA}$ does not capture true arithmetic:

There exist closed $\Sigma_{PA}$-formulae representing valid propositions of number theory that are not $T_{PA}$-valid.

The reason: $T_{PA}$ actually admits nonstandard interpretations.

For decidability: no multiplication.
Presburger Arithmetic $T_\mathbb{N}$

Signature: $\Sigma_\mathbb{N}: \{0, 1, +, =\}$  
no multiplication!

Axioms of $T_\mathbb{N}$: axioms of $T_E$,

1. $\forall x. \neg(x + 1 = 0)$ (zero)
2. $\forall x, y. x + 1 = y + 1 \rightarrow x = y$ (successor)
3. $\varphi[0] \land (\forall x. \varphi[x] \rightarrow \varphi[x + 1]) \rightarrow \forall x. \varphi[x]$ (induction)
4. $\forall x. x + 0 = x$ (plus zero)
5. $\forall x, y. x + (y + 1) = (x + y) + 1$ (plus successor)

3 is an axiom schema.

$T_\mathbb{N}$-satisfiability and $T_\mathbb{N}$-validity are decidable. (Presburger 1929)
Theory of Integers $T_{\mathbb{Z}}$

Signature:
$\Sigma_{\mathbb{Z}} : \{ \ldots, -2, -1, 0, 1, 2, \ldots, -3 \cdot, -2 \cdot, 2 \cdot, 3 \cdot, \ldots, +, -, =, > \}$

where
- $\ldots, -2, -1, 0, 1, 2, \ldots$ are constants
- $\ldots, -3 \cdot, -2 \cdot, 2 \cdot, 3 \cdot, \ldots$ are unary functions
  (intended meaning: $2 \cdot x$ is $x + x$)
- $+, -, =, >$ have the usual meanings.

Relation between $T_{\mathbb{Z}}$ and $T_{\mathbb{N}}$

$T_{\mathbb{Z}}$ and $T_{\mathbb{N}}$ have the same expressiveness:
- For every $\Sigma_{\mathbb{Z}}$-formula there is an equisatisfiable $\Sigma_{\mathbb{N}}$-formula.
- For every $\Sigma_{\mathbb{N}}$-formula there is an equisatisfiable $\Sigma_{\mathbb{Z}}$-formula.

$\Sigma_{\mathbb{Z}}$-formula $\varphi$ and $\Sigma_{\mathbb{N}}$-formula $G$ are equisatisfiable iff:

$\varphi$ is $T_{\mathbb{Z}}$-satisfiable iff $G$ is $T_{\mathbb{N}}$-satisfiable
Example: The $\Sigma_N$-formula

$$\forall x. \exists y. x = y + 1$$

is equisatisfiable to the $\Sigma_Z$-formula:

$$\forall x. x > -1 \rightarrow \exists y. y > -1 \land x = y + 1.$$
Consider the $\Sigma_\mathbb{Z}$-formula

$$F_0 : \forall w, x. \exists y, z. \ x + 2y - z - 7 > -3w + 4$$

Introduce two variables, $v_p$ and $v_n$ (range over the nonnegative integers) for each variable $v$ (range over the integers) of $F_0$

$$F_1 : \forall w_p, w_n, x_p, x_n. \exists y_p, y_n, z_p, z_n.
(x_p - x_n) + 2(y_p - y_n) - (z_p - z_n) - 7 > -3(w_p - w_n) + 4$$

Eliminate $-$ by moving to the other side of $>$

$$F_2 : \forall w_p, w_n, x_p, x_n. \exists y_p, y_n, z_p, z_n.
 x_p + 2y_p + z_n + 3w_p > x_n + 2y_n + z_p + 7 + 3w_n + 4$$

Eliminate $>$ and numbers:

$$F_3 : \forall w_p, w_n, x_p, x_n. \exists y_p, y_n, z_p, z_n. \exists u.
\neg( u = 0) \land x_p + y_p + y_p + z_n + w_p + w_p + w_p
= x_n + y_n + y_n + z_p + w_n + w_n + w_n + u
+ 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1$$

which is a $\Sigma_\mathbb{N}$-formula equisatisfiable to $F_0$. 
Reducing $T_{\mathbb{Z}}$ to $T_{\mathbb{N}}$.

To decide $T_{\mathbb{Z}}$-validity for a $\Sigma_{\mathbb{Z}}$-formula $\varphi$:

- transform $\neg \varphi$ to an equisatisfiable $\Sigma_{\mathbb{N}}$-formula $\neg \psi$,
- decide $T_{\mathbb{N}}$-validity of $\psi$.  

Matthias Heizmann  
Program Verification  
Summer Term 2021  
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Outline of the Section on First-Order Theories

Motivation

T-Validity and T-Satisfiability

Theory of Equality

Theory of Rock-Paper-Scissors

Decidability

Natural Numbers and Integers

Rationals and Reals

Arrays

Combination of Theories

Decidability
Rationals and Reals

\[ \Sigma = \{0, 1, +, -, \cdot, =, \geq\} \]

- **Theory of Reals** \( T_{\mathbb{R}} \) (with multiplication)

  \[ x \cdot x = 2 \implies x = \pm \sqrt{2} \]

- **Theory of Rationals** \( T_{\mathbb{Q}} \) (no multiplication)

  \[ 2x + x = 7 \implies x = \frac{2}{7} \]

*Note: Strict inequality*

\[ \forall x, y. \exists z. x + y > z \]

can be expressed as

\[ \forall x, y. \exists z. \neg(x + y = z) \land x + y \geq z \]
Theory of Reals $T_\mathbb{R}$

Signature: $\Sigma_\mathbb{R}: \{0, 1, +, −, \cdot, =, \geq\}$ with multiplication.

Axioms of $T_\mathbb{R}$: axioms of $T_E$,

1. $\forall x, y, z. (x + y) + z = x + (y + z)$ (+ associativity)
2. $\forall x, y. x + y = y + x$ (+ commutativity)
3. $\forall x. x + 0 = x$ (+ identity)
4. $\forall x. x + (−x) = 0$ (+ inverse)
5. $\forall x, y, z. (x \cdot y) \cdot z = x \cdot (y \cdot z)$ (· associativity)
6. $\forall x, y. x \cdot y = y \cdot x$ (· commutativity)
7. $\forall x. x \cdot 1 = x$ (· identity)
8. $\forall x. x \neq 0 \rightarrow \exists y. x \cdot y = 1$ (· inverse)
9. $\forall x, y, z. x \cdot (y + z) = x \cdot y + x \cdot z$ (distributivity)
10. $0 \neq 1$ (separate identities)
11. $\forall x, y. x \geq y \land y \geq x \rightarrow x = y$ (antisymmetry)
12. $\forall x, y, z. x \geq y \land y \geq z \rightarrow x \geq z$ (transitivity)
13. $\forall x, y. x \geq y \lor y \geq x$ (totality)
14. $\forall x, y, z. x \geq y \rightarrow x + z \geq y + z$ (+ ordered)
15. $\forall x, y. x \geq 0 \land y \geq 0 \rightarrow x \cdot y \geq 0$ (· ordered)
16. $\forall x. \exists y. x = y \cdot y \lor x = −y \cdot y$ (square root)
17. for each odd integer $n$,
   $\forall x_0, \ldots, x_{n−1}. \exists y. y^n + x_{n−1}y^{n−1} \cdots + x_1y + x_0 = 0$ (at least one root)
Decidability of $T_R$

$T_R$ is decidable (Tarski, 1930)
High time complexity: $O(2^{kn})$
Theory of Rationals $T_\mathbb{Q}$

**Signature:** $\Sigma_\mathbb{Q} : \{0, 1, +, -, =, \geq\}$ no multiplication!

**Axioms of $T_\mathbb{Q}$:** axioms of $T_E$,

1. $\forall x, y, z. \ (x + y) + z = x + (y + z)$ (+ associativity)
2. $\forall x, y. \ x + y = y + x$ (+ commutativity)
3. $\forall x. \ x + 0 = x$ (+ identity)
4. $\forall x. \ x + (-x) = 0$ (+ inverse)
5. $1 \geq 0 \land 1 \neq 0$ (one)
6. $\forall x, y. \ x \geq y \land y \geq x \rightarrow x = y$ (antisymmetry)
7. $\forall x, y, z. \ x \geq y \land y \geq z \rightarrow x \geq z$ (transitivity)
8. $\forall x, y. \ x \geq y \lor y \geq x$ (totality)
9. $\forall x, y, z. \ x \geq y \rightarrow x + z \geq y + z$ (+ ordered)
10. For every positive integer $n$: $\forall x. \ \exists y. \ x = y + \cdots + y$ (divisible)
Expressiveness and Decidability of $T_\mathbb{Q}$

Rational coefficients are simple to express in $T_\mathbb{Q}$

*Example:* Rewrite

$$\frac{1}{2}x + \frac{2}{3}y \geq 4$$

as the $\Sigma_\mathbb{Q}$-formula

$$x + x + x + y + y + y + y \geq \underbrace{1 + 1 + \cdots + 1}_{24}$$

$T_\mathbb{Q}$ is decidable.
Efficient algorithm for quantifier free fragment.
Outline of the Section on First-Order Theories

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Theory of Arrays $T_A$

Signature: $\Sigma_A : \{[,], \langle \cdot \triangleleft \cdot \rangle, =\}$, where

- $a[i]$ binary function – read array $a$ at index $i$ (“read($a,i$)”) 
- $a\langle i \triangleleft v \rangle$ ternary function – write value $v$ to index $i$ of array $a$ (“write($a,i,e$)”) 

Axioms

1. the axioms of (reflexivity), (symmetry), and (transitivity) of $T_E$
2. $\forall a, i, j. \ i = j \rightarrow a[i] = a[j]$ (array congruence) 
3. $\forall a, v, i, j. \ i = j \rightarrow a\langle i \triangleleft v \rangle[j] = v$ (read-over-write 1) 
4. $\forall a, v, i, j. \ i \neq j \rightarrow a\langle i \triangleleft v \rangle[j] = a[j]$ (read-over-write 2)
Equality in $T_A$

*Note:* $=$ is only defined for array elements

\[ a[i] = e \rightarrow a\langle i \triangleleft e \rangle = a \]

not $T_A$-valid, but

\[ a[i] = e \rightarrow \forall j. \ a\langle i \triangleleft e \rangle[j] = a[j] , \]

is $T_A$-valid.

Also

\[ a = b \rightarrow a[i] = b[i] \]

is not $T_A$-valid: We only axiomatized a restricted congruence.

$T_A$ is undecidable.

Quantifier-free fragment of $T_A$ is decidable.
Theory of Arrays $T_A^=$ (with extensionality)

Signature and axioms of $T_A^=$ are the same as $T_A$, with one additional axiom

$$\forall a, b. \ (\forall i . \ a[i] = b[i]) \iff a = b \quad \text{(extensionality)}$$

Example:

$$F : \ a[i] = e \rightarrow a\langle i \triangleleft e \rangle = a$$

is $T_A^=$-valid.

$T_A^=$ is undecidable.
Quantifier-free fragment of $T_A^=$ is decidable.
Outline of the Section on First-Order Theories

- Motivation
- $T$-Validity and $T$-Satisfiability
- Theory of Equality
- Theory of Rock-Paper-Scissors
- Decidability
- Natural Numbers and Integers
- Rationals and Reals
- Arrays
- Combination of Theories
- Decidability
Combination of Theories

How do we show that

\[ 1 \leq x \land x \leq 2 \land f(x) \neq f(1) \land f(x) \neq f(2) \]

is \((T_E \cup T_{\mathbb{Z}})\)-unsatisfiable?

Or how do we prove properties about

an array of integers, or

a list of reals . . . ?

Given theories \(T_1\) and \(T_2\) such that

\[ \Sigma_1 \cap \Sigma_2 = \{=\} \]

The **combined theory** \(T_1 \cup T_2\) has

- signature \(\Sigma_1 \cup \Sigma_2\)
- axioms \(A_1 \cup A_2\)
Nelson & Oppen showed that

if satisfiability of qff of $T_1$ is decidable,
satisfiability of qff of $T_2$ is decidable, and
certain technical requirements are met
then satisfiability of qff of $T_1 \cup T_2$ is decidable.
Theory of Bit-vectors

Idea: theory for low-level arithmetic on computer hardware

- Domain: sequences of bits
e.g., 11111111 (which represents the natural number 255 or the integer -1 in two’s complement representation)

- Functions: arithmetic and logical operations on FixedSizeBitvectors
  - bvadd\(_8\)(11111101, 000000100) = 00000001
  - bvand\(_8\)(11111101, 000000100) = 00000100
  - bvshl\(_8\)(11111101, 000000001) = 11111010

- Predicates: comparisons
  - bvult\(_8\)(11111101, 000000100) is **false**
  - bvslt\(_8\)(11111101, 000000100) is **true**

  Meaning of bit-vector as number only given by operator.

Signature \( \Sigma \)

- Constant symbols: 0, 1, 01, 10, 11, 001, ...
- Function symbols: bvadd\(_1\), bvadd\(_2\), bvadd\(_3\) ..., bvmul\(_1\) ...
- Predicate symbols: bvult\(_1\), bvult\(_2\), bvult\(_3\) ..., bvslt\(_1\) ...

Axioms \( A_T \)

Many
Theory of Bit-vectors

```
1 signed char s = 400;
2 unsigned char u1 = 250;
3 unsigned char u2 = 250;
4 if (s >= u1 + u2) {

bvsge32(
    signExtendFrom8To32(s),
    bvadd32(signExtendFrom8To32(u1), signExtendFrom8To32(u1))
)
```
Does the following loop terminate?

```c
for (double d = 0; d != 0.3; d += 0.1) {
}
```
Outline of the Section on First-Order Theories

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Decidability
<table>
<thead>
<tr>
<th>Theory</th>
<th>Decidable</th>
<th>QFF Dec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_E$ Equality</td>
<td>$__$</td>
<td>$\checkmark$</td>
</tr>
<tr>
<td>$T_{PA}$ Peano Arithmetic</td>
<td>$__$</td>
<td>$__$</td>
</tr>
<tr>
<td>$T_N$ Presburger Arithmetic</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
</tr>
<tr>
<td>$T_Z$ Linear Integer Arithmetic</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
</tr>
<tr>
<td>$T_R$ Real Arithmetic</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
</tr>
<tr>
<td>$T_Q$ Linear Rationals</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
</tr>
<tr>
<td>$T_A$ Arrays</td>
<td>$__$</td>
<td>$\checkmark$</td>
</tr>
<tr>
<td>$T_{A=}$ Arrays with Extensionality</td>
<td>$__$</td>
<td>$\checkmark$</td>
</tr>
<tr>
<td>$T_{BV}$ Bitvectors</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
</tr>
<tr>
<td>$T_{Float}$ FloatingPoint</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
</tr>
</tbody>
</table>
Section 5

SMT-LIB
Goals of this section:

- Use a tool to check T-satisfiability (resp. T-validity) of a formula.
  In detail:
  - Get familiar with sorted logics
  - Get familiar with the syntax of the SMT-LIB standard.
  - Translate the syntax of the preceding sections into SMT-LIB and vice versa.
- Fix a semantics for symbols like, e.g., $=, +, -, \cdot, \text{mod}, \leq, \geq$ for the remaining course.
SMT-LIB is an international initiative aimed at facilitating research and development in Satisfiability Modulo Theories (SMT). Since its inception in 2003, the initiative has pursued these aims by focusing on the following concrete goals.

▶ Provide standard rigorous descriptions of background theories used in SMT systems.

▶ Develop and promote common input and output languages for SMT solvers.

▶ Connect developers, researchers and users of SMT, and develop a community around it.

▶ Establish and make available to the research community a large library of benchmarks for SMT solvers.

▶ Collect and promote software tools useful to the SMT community.
SMT Script

- File format that allows you to write commands for SMT solvers.
- File ending .smt2
- Prefix notation

Example:
(set-logic QF_LIA) ← use quantifier-free linear integer arithmetic
(declare-fun x () Int) ← announce that constant x has sort Int
(declare-fun y () Int)
(assert (< x 2)) ← put formula on “assertion stack”
(assert (> x 0))
(check-sat) ← check satisfiability of conjunction of all formulas on assertion stack
(get-model) ← get satisfying assignment
(assert (= x (* y 2)))
(check-sat)
Theories defined by SMT-LIB standard:

- **Integer**
  - -, +, - , *, div, mod, abs, <=, <, > , =, >

- **Reals**
  - -, +, - , *, / , <=, <, > , =, >

- **Arrays** *(will be introduced later in this course)*
  - select, store

- **FixedSizeBitvectors** *(not relevant in this course)*
  - bvadd, bvmul, bvand, bvshl, bvult, ...

- **FloatingPoint** *(not relevant in this course)*
  - fp.add, fp.mul, fp.sqrt, fp.min, fp.leq, fp.isNaN, ...

http://smtlib.cs.uiowa.edu/theories.shtml
Conventions

▶ From now on we use the SMT-LIB definitions for theories.

▶ Let $T$ be the combination of all theories listed on the preceding slide. Instead of $T$-satisfiability (resp. $T$-validity) we will just use the term *satisfiability* (resp. validity).
SMT-LIB: Logics

SMT-LIB logics:

- Describe syntactically and semantically restricted classes of sorted FOL with equality.
- Specify background theories, restrict to quantifier-free formulas, . . .
- Allow solvers to use efficient, specialized techniques.

Examples:

- QF_LIA: **Quantifier-Free Linear Integer Arithmetic**
- QF_AX: **Quantifier-Free** formulas over Arrays with eXtensionality
- UFLRA: **Linear Real Arithmetic** with Uninterpreted sort and **Function** symbols
What is a logic?
We have seen *propositional logic* and *first-order logic*, and the previous slide talked about different *SMT-LIB logics*. So what is a logic?
In general, a logic consists of two parts:

1. a language of logical formulas,
2. and an implication relation $\models$ between sets of formulas $\Gamma$ and formulas $\varphi$.

For instance:

- We have defined the *syntax of propositional logic* formulas, and the corresponding implication relation is defined based on the satisfying assignments.

- Similarly, we defined the *syntax of FOL* formulas. The implication relation is defined via models and satisfying assignments.

- In an SMT-LIB logic with background theory $T$, the formulas are a syntactically restricted subset of the FOL formulas over the signature of $T$. The implication relation is $T$-implication: $\Gamma \models_T \psi$ if and only if for every $T$-model $M$ and every assignment $\rho$ we have that if $\llbracket \varphi \rrbracket_{M,\rho} = \text{true}$ for all $\varphi \in \Gamma$, then $\llbracket \psi \rrbracket_{M,\rho} = \text{true}$ also holds.

- Many other logics exist: You may have heard of temporal logics, higher-order logics, intuitionistic logic, ...
SMT-LIB Terms
In the lecture, we defined a (FOL) term inductively to be a variable symbol, a constant symbol, or the application of a function symbol to terms. We defined a (FOL) formula to be the application of a predicate to terms, the negation of a formula, the conjunction of two formulas, and the application of a quantifier to a formula.
In SMT-LIB, every term has a sort. Constants are 0-ary functions, predicates are functions of sort Bool, and logical connectives are functions with argument sort Bool and return sort Bool. Therefore, a formula is just a term of sort Bool as it is an application of a function symbol to terms.
SMT-LIB: Terms

Terms as defined in the lecture:
▶ Constant symbol.
▶ Variable symbol.
▶ Application of a function symbol to terms.

Terms as defined in SMT-LIB:
▶ Constant symbol, variable symbol, function symbol (applied to terms), variable binders applied to terms, annotations on terms.
▶ Only well-sorted terms allowed.
▶ Constant symbols are nullary function symbols.
▶ Predicates are function symbols of sort Bool.
▶ Logical connectives are function symbols, and formulas are terms of sort Bool.
On the previous slide, we have seen an overview about the conceptual differences between (FOL) terms as defined in the lecture and SMT-LIB terms as defined by the SMT-LIB standard. There are also some differences in the notation of terms and formulas. We show how to write terms and formulas as defined in the lecture as SMT-LIB terms on the next slide.
## SMT-LIB: Terms

<table>
<thead>
<tr>
<th>Term or formula</th>
<th>SMT-LIB term</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x )</td>
<td>( x )</td>
</tr>
<tr>
<td>( c )</td>
<td>( c )</td>
</tr>
<tr>
<td>( f(t_1 \ldots t_n) )</td>
<td>( (f \ t_1 \ldots \ t_n) )</td>
</tr>
<tr>
<td><code>false</code></td>
<td><code>false</code></td>
</tr>
<tr>
<td><code>¬F</code></td>
<td><code>(not \( F \))</code></td>
</tr>
<tr>
<td><code>F \land G</code></td>
<td><code>(and \( F \ \ G))</code></td>
</tr>
<tr>
<td><code>\exists x. F</code></td>
<td><code>(exists \( ((x \ \text{Sort})) \) \( (F)\))</code></td>
</tr>
</tbody>
</table>
SMT Solvers

SMT solvers are tools that execute SMT scripts.

- **Z3** [tacas/MouraB08]
  Often used in this course because there is a [Z3 web interface](https://github.com/Z3Prover/z3)

- **SMTInterpol** [spin/ChristHN12]
  Developed in our group at the University of Freiburg by Jochen Hoenicke and Tanja Schindler.

- Many more are available. Check the [list of SMT solvers at the SMT-LIB website](https://www.smt-lib.org) or the [list of SMT solvers at Wikipedia](https://en.wikipedia.org/wiki/List_of_SMT_solvers).

You can submit SMT scripts to the [SMT-LIB benchmark repository](https://www.smt-lib.org) and the annual [SMT competition](https://www.smtcomp.svu.ac.uk) evaluates how SMT solver perform on these benchmarks.
SMT-LIB Commands
We have already seen an example for an SMT script. It consists of several commands that allow us, for instance, to tell the solver which logic to use, which function symbols exist, which formulas to check for satisfiability, and so on.

Communicating with the solver via commands allows to flexibly make use of several functionalities of the solver.

Most solvers provide more functionalities than just checking a formula for satisfiability. In the example script, we have seen the (get-model) command that tells the solver to provide a model for a satisfiable formula. If a formula is unsatisfiable, some solvers can also provide a proof for unsatisfiability (but usually, this requires to set an option that tells the solver to keep track of the proof, as this may be expensive).
Important commands to communicate with the solver:

- **Set solver parameters:**
  ```scheme
  (set-option :produce-models true)
  (set-logic QF_LIA)
  ```

- **Declare sorts and symbols:**
  ```scheme
  (declare-sort U 0)
  (declare-fun x () Int)
  ```

- **Assert formulas:**
  ```scheme
  (assert (> x 0))
  ```

- **Check satisfiability:**
  ```scheme
  (check-sat)
  ```

- **Get models:**
  ```scheme
  (get-model)
  ```
Program Verification

Summer Term 2021

Lecture 7: Boogie, Boostan

Matthias Heizmann

Monday 10th May
Section 6

Boogie and Boostan
Outline

Introduction

Propositional Logic

First-Order Logic

First-Order Theories

SMT-LIB

Boogie and Boostan

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Ultimate Referee

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Boogie and Boostan – Part 2

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Predicate Transformers

Bounded Model Checking

Correctness Specification via Assert Statement

Abstractions – Part 1

Infeasibility Proofs

CEGAR

Trace Abstraction

Constraint-based Invariant Synthesis

Termination Analysis
In this section we introduce the programming languages that are most relevant for this course: Boogie and Boostan.

Goals of this section are:

- understand that real-world programming languages (C, Java, Python) are not a good choice for presenting the material of this course
- recall the basic ideas of context-free grammars
- define the syntax of a new programming language
- define the semantics of this programming language
- define the meaning of “correctness” for programs written in that language
Outline of the Section on Boogie and Boostan

- Boogie and Boostan
- Context-Free Grammars
- Syntax of Boostan
- Excursus: The semantics of C
- Relational Semantics of Boostan
- Precondition-Postcondition Pairs
Which programming language should we choose for our introduction to program verification?

At a first glance it seems reasonable to pick a language that is used by many programmers like e.g., C, Java, or Python. However, if we would do so we would face the following problems.

- The syntax of these languages is very rich and (together with an explanation of its meaning) could not be introduced within a few hours.

- The semantics of these languages is not defined very formally but in hundreds of pages of prose. **TODO cite examples** We would have to formalize these definitions which is a time-consuming task even if we restrict ourselves to a small fragment of the languages syntax. **TODO cite some research**

In this subsection we present the languages that we choose is this course.
Boogie and Boostan

Boogie

- Existing “programming language” optimized for verification.
- Devised by Rustan Leino.
- We will use Boogie for practical examples where we use tools.

Boostan

- Fragment of Boogie.
- (Will be) devised by the participants of this course.
- We will formally define the semantics of Boostan.
- We will use Boostan to formally introduce, discuss and analyze verification techniques.
Boogie

- Developed by Rustan Leino at Microsoft Research
- Programming language vs. verification language
- Intermediate language
- Supported by tools
- Limited features (scopes, side-effects, types, memory allocation, concurrency)

**TODO** Write down what was said in the lecture on each bullet
Boogie Tools: Boogaloo

*Boogaloo* is an interpreter for Boogie developed by Nadia Polikarpova.

- Available via web interface\(^\text{10}\)
- Displays possible executions of a Boogie program
- Use option \(-o\) to control number of executions, e.g. \(-o\ 5\) for 5 executions.
- To get more diverse executions, use \(-n\), e.g. \(-n\ 3\) for at most 3 executions with the same sequence of statements.
- Other interesting options: \(-c=0\) turns off "concrete mode", \(-p\) specifies entry procedure.
- Output with assume \{
  : print "text"
} true
- User Manual available\(^\text{11}\)

\(^\text{10}\) [http://comcom.csail.mit.edu/comcom/#Boogaloo](http://comcom.csail.mit.edu/comcom/#Boogaloo)

Boogie Tools: Boogaloo (Example)

Running the following program through Boogaloo with option `-o 3` produces the output below, listing arguments, output, and return value.

```
1 procedure Square(a : int) returns (square: int) {
2   square := a * a;
3   if (square == 0) {
4     assume {: print "a is zero" } true;
5   } else {
6     assume {: print "a = ", a } true;
7   }
8 }
```

```
1 Execution 0: Square(0) passed
2 a is zero
3 Outs: square → 0
4
5 Execution 1: Square(-1) passed
6 a = -1
7 Outs: square → 1
8
9 Execution 2: Square(1) passed
10 a = 1
11 Outs: square → 1
```
Boogie Tools: Boogaloo (Example)

Running the following program through Boogaloo with options `-o 4 -n 1 -c=0` produces the output below.

```plaintext
procedure ZeroInit(a : [int]int, lo : int, hi : int) returns (b : [int]int)
{
    var i : int;
    b := a;
    i := lo;
    while (i <= hi) {
        b[i] := 0;
        i := i+1;
    }
}
```

1. Execution 0: ZeroInit([], 0, -1) passed
   Outs: b -> []

2. Execution 1: ZeroInit([0 -> 0], 0, 0) passed
   Outs: b -> [0 -> 0]

3. Execution 2: ZeroInit([0 -> 0, 1 -> 0], 0, 1) passed
   Outs: b -> [0 -> 0, 1 -> 0]

4. Execution 3: ZeroInit([0 -> 0, 1 -> 0, 2 -> 0], 0, 2) passed
   Outs: b -> [0 -> 0, 1 -> 0, 2 -> 0]
You can try experimenting with the previous program and different options:

- If you only pass `-o`, Boogaloo will only produce executions with `lo > hi`.

  This is because it first chooses a sequence of statements (go through the loop once), and then searches variable values to fit that sequence. Because there are infinitely many (unlike in the first example), it will never consider another sequence.

- Additionally passing `-n` fixes this problem: It allows only the given number of executions per sequence of statements. However, only 2 instead of 4 executions will be found.

  This is because the number of possible values for the input parameters is restricted (Boogaloo calls this the concrete mode).

- Additionally passing `-c=0` turns off this concrete mode, finally showing the diverse executions on the previous slide.

Different combinations of these options can often help get the desired test cases for a program. However, always using all of them is not necessarily the solution in every case.
The specification of Boogie\textsuperscript{12} \cite{13} has 52 pages and is not written with the formal rigor that we would like to have in this course.

Idea: let us define a (new) language Boostan

- syntax is a fragment of Boogie
- restricted to the needs of this course
- syntax and semantics defined very rigorously using terminology that we know from computer science lectures (context-free grammar, first-order logic)
- semantics compatible to Boogie

For our formal definitions, algorithms, theorems and proofs we will use Boostan. For demonstrations with tools we use Boogie. We will not establish a formal connection between Boogie and Boostan and resort to our intuition to get the connection.

\textsuperscript{12}https://www.microsoft.com/en-us/research/publication/this-is-boogie-2-2/
Outline of the Section on Boogie and Boostan

Boogie and Boostan
Context-Free Grammars
Syntax of Boostan
Excursus: The semantics of C
Relational Semantics of Boostan
Precondition-Postcondition Pairs
Motivation: How can we Formalize Programs?

Sequence of characters vs. tree

\[
\text{while } (i < x) \{ \\
\quad x := x + i; \\
\quad i := i + 1; \\
\} 
\]
The syntax of a programming language is typically defined via a context-free grammar or via a closely related concept.

We will define the syntax of Boostan via a context-free grammar and use a notation that is typically used in lectures on theoretical computer science.

In order to make you (again) familiar with context-free grammars and in order to fix a notation for this course we give a formal definition on the next slides.
Definition

A *context-free grammar* is a 4-tupel $G = (\Sigma, N, P, S)$ such that

- $\Sigma$ is an alphabet, whose elements we call *terminal symbols*,
- $N$ ist a finite set whose elements we call *nonterminal symbols*,
- $P \subseteq N \times (N \cup \Sigma)^*$ ist a finite relation whose elements we call *derivation rules*,
- $S \in N$ is a nonterminal symbol that we call *start symbol* and $\Sigma \cap N \neq \emptyset$.

Example

Consider $G = (\Sigma, N, P, S)$ with $\Sigma = \{a, b\}$, $N = \{S\}$ and

$$P = \{ S \rightarrow aSbS, \
S \rightarrow bSaS, \
S \rightarrow \varepsilon \}. $$
**Definition**

A *derivation tree* is an ordered tree together with a labelling function\(\lambda : V \rightarrow (N \cup \Sigma \cup \{\varepsilon\})\) such that

- a node \(v \in V\) may only have children \(v_1, \ldots, v_n \in V\) if \(\lambda(v) \rightarrow \lambda(v_1) \ldots \lambda(v_n)\) is a rule in \(P\) and
- all leafs are labelled by terminal symbols or by \(\varepsilon\).

**Example**

Consider \(G = (\Sigma, N, P, S)\) with \(\Sigma = \{a, b\}, N = \{S\}\) and

\[
P = \{ S \rightarrow aSbS, \quad S \rightarrow bSaS, \quad S \rightarrow \varepsilon \}.
\]
**Definition**

The *derived word* \( dw \) of a node \( v \) is inductively defined as follows.

\[
dw(v) = \begin{cases} 
\text{dw}(v_1) \ldots \text{dw}(v_n) & \text{if } v \text{ has children } v_1, \ldots, v_n \\
\lambda(v) & \text{otherwise}
\end{cases}
\]

We say that a word \( w \in \Sigma^* \) *can be derived from* a nonterminal symbol \( A \in N \) if there is a derivation tree whose root node \( v \) is labelled by \( A \) and \( \text{dw}(v) = w \).

We call the set of all words that can be derived from the start symbol \( S \) the *language* of \( G \), denoted \( L(G) \).

---

**Example**

Derived word of the tree from preceding slide: \( abba \)

\[
L(G) = \{ w \in \Sigma^* \mid \text{The number of } a \text{'s in } w \text{ is the same as the number of } b \text{'s in } w \}.
\]
Example

See Exercise 3 on Exercise Sheet 05 for another context-free grammar and a derivation tree.
Program Verification

Summer Term 2021

Lecture 8: Boostan, cont’d

Matthias Heizmann

Wednesday 12th May
Exercise: Construct a context-free grammar
\[ G_{\text{TInt}} = (\Sigma_{\text{TInt}}, N_{\text{TInt}}, P_{\text{TInt}}, S_{\text{TInt}}) \]
that generates the language of all FOL terms for the vocabulary \((\mathcal{V}_{\text{Var}}, \mathcal{V}_{\text{Const}}, \mathcal{V}_{\text{Fun}}, \mathcal{V}_{\text{Pred}})\) such that

- \(\mathcal{V}_{\text{Const}}\) is the set of all non-empty words over the alphabet 0–9.
- \(\mathcal{V}_{\text{Var}}\) is the set of all non-empty words over the alphabet a–zA–Z0–9 that are not constant symbols.
- \(\mathcal{V}_{\text{Fun}}\) is the set that contains
  - the unary minus symbol – and
  - the binary symbols +, −, *, div, mod, abs.
Outline of the Section on Boogie and Boostan

Boogie and Boostan
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In this subsection we use context-free grammars to define the syntax of Boostan.

We start with a grammar for numbers and a grammar for variables and extend these grammars incrementally until we have a grammar for statements.

Please note that this is not the final version of Boostan. In the next sections we will extend this section’s definition by arrays, assumptions and nondeterministic assignments. TODO add link
Grammar for Numbers

Problem: We would like to be able to represent every integer, but an alphabet has to be finite.

Solution: Like SMT-LIB, we use digits 0 to 9, a decimal encoding and (later) a unary minus to obtain negative numbers.

Additional requirement: We can tolerate leading zeros, but a number should not be the empty word.

\[ G_{num} = (\Sigma_{num}, N_{num}, P_{num}, S_{num}) \]

\[ \Sigma_{num} = \{0, \ldots, 9\} \]
\[ N_{num} = \{X_{num}, X_{num}'\} \]
\[ P_{num} = \{X_{num} \rightarrow 0X_{num}' | \ldots | 9X_{num}' \}
        \begin{align*}
        &X_{num}' \rightarrow 0X_{num}' | \ldots | 9X_{num}' | \varepsilon \} \\
\end{align*} \]
\[ S_{num} = X_{num} \]
Grammar for Variables

Requirements: Every alphanumerical sequence should be a variable but we do not want to allow the empty word and the set of variables should be disjoint from the set of numbers.

\[ G_{\text{var}} = (\Sigma_{\text{var}}, N_{\text{var}}, P_{\text{var}}, S_{\text{var}}) \]

\[ \Sigma_{\text{var}} = \Sigma_{\text{num}} \cup \{ a, \ldots, z, A, \ldots Z \} \]

\[ N_{\text{var}} = \{ X_{\text{var}}, X_{\text{var}'} \} \]

\[ P_{\text{var}} = \{ X_{\text{var}} \rightarrow aX_{\text{var}'} | \ldots | zX_{\text{var}'} | AX_{\text{var}'} | \ldots | ZX_{\text{var}'} \\ X_{\text{var}'} \rightarrow aX_{\text{var}'} | \ldots | zX_{\text{var}'} | AX_{\text{var}'} | \ldots | ZX_{\text{var}'} | 0X_{\text{var}'} | \ldots | 9X_{\text{var}'} | \varepsilon \} \]

\[ S_{\text{var}} = X_{\text{var}} \]
Grammar for Integer Expressions

Requirements: We would like to have integer expressions that are very similar to integer terms in SMT-LIB. We want an infix notation, we would like to use the symbol `/` instead of `\texttt{div}` and we would like to use the symbol `%` instead of `\texttt{mod}`.

\[ G_I = (\Sigma_I, N_I, P_I, S_I) \]

\[ \Sigma_I = \{-, +, *, /, \%, (, )\} \cup \Sigma_{\text{var}} \cup \Sigma_{\text{num}} \]

\[ N_I = \{X_{iexpr}\} \cup N_{\text{var}} \cup N_{\text{num}} \]

\[ P_I = \{X_{iexpr} \rightarrow (X_{iexpr}) \]
\[ X_{iexpr} \rightarrow -X_{iexpr} \]
\[ X_{iexpr} \rightarrow X_{iexpr} + X_{iexpr} | X_{iexpr} - X_{iexpr} | X_{iexpr} \times X_{iexpr} \]
\[ X_{iexpr} \rightarrow X_{iexpr} / X_{iexpr} | X_{iexpr} \% X_{iexpr} \]
\[ X_{iexpr} \rightarrow X_{\text{var}} \]
\[ X_{iexpr} \rightarrow X_{\text{num}} \} \cup P_{\text{var}} \cup P_{\text{num}} \]

\[ S_I = X_{iexpr} \]
Example

See Exercise 2 on Exercise Sheet 07 for a derivation tree of $G_1$
Grammar for Boolean Expressions

Requirements: We would like to have Boolean expressions that are very similar to Boolean terms in SMT-LIB (resp. formulas in FOL). We want an infix notation, we would like to use the symbol \(!\) instead of \(\text{not}\) (resp. \(\neg\)) and we would like to use the symbol \(\&\&\) instead of \(\text{and}\) (resp. \(\land\)) and we would like to use the symbol \(||\) instead of \(\text{or}\) (resp. \(\lor\)) and we would like to use the symbol \(\implies\) instead of \(\Rightarrow\) (resp. \(\rightarrow\)).

\[ G_B = (\Sigma_B, N_B, P_B, S_B) \]

\[ \Sigma_B = \{ !, \&\&, ||, \implies, <, >, <=, >= \} \cup \Sigma_I \]

\[ N_B = \{ X_{bexpr} \} \cup N_I \]

\[ P_B = \{ \]

\[ X_{bexpr} \rightarrow \ (X_{bexpr}) \]

\[ X_{bexpr} \rightarrow \ ! X_{bexpr} \]

\[ X_{bexpr} \rightarrow \ X_{bexpr} \&\& X_{bexpr} | X_{bexpr} \| X_{bexpr} | X_{bexpr} \implies X_{bexpr} \]

\[ X_{bexpr} \rightarrow \ X_{iexpr} < X_{iexpr} | X_{iexpr} > X_{iexpr} | X_{iexpr} <= X_{iexpr} | X_{iexpr} >= X_{iexpr} \]

\[ X_{bexpr} \rightarrow \ X_{bexpr} == X_{bexpr} | X_{iexpr} == X_{iexpr} \]

\[ X_{bexpr} \rightarrow \ X_{var} \]

\[ X_{bexpr} \rightarrow \ \text{true}\ | \text{false} \} \cup P_I \]

\[ S_B = X_{bexpr} \]
Exercise 1 on [Exercise Sheet 07]
**Terminology**

We call

- a subword that is derived from $X_{var}$ a *(program) variable*,
- a subword that is derived from $X_{iexpr}$ or $X_{bexpr}$ an *expression*,
- a subword that is derived from $X_{stmt}$ a *(program) statement*.
Definition

A Boostan program is a triple \( P = (V, \mu, T) \) where,

- \( V \) is a set of (program) variables,
- \( \mu \) is a map that assigns each variable either \( \mathbb{Z} \) or \{true, false\}
- \( T \) is a derivation tree for the start symbol \( S_{\text{Boo}} \) in the Boostan grammar such that the translation of each expression/type to an SMT term/sort is well-sorted wrt. the map \( \mu \).

Given a variable \( v \in V \) we call \( \mu(v) \) the domain of \( v \).

Example

\( P_{ab} = (V_{ab}, \mu_{ab}, T_{ab}) \) where

- \( V_{ab} = \{a, b\} \),
- \( \mu(a) = \mathbb{Z}, \mu(b) = \mathbb{Z} \), and
- \( T_{ab} \) is the derivation tree for the text on the right.

```plaintext
1  while (!(b == 0)) {
2    if (b >=0) {
3      b := b - 1;
4    } else {
5      b := b + 1;
6    }
7    a := a + 1;
8  }
```
Outline of the Section on Boogie and Boostan

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Question: Do we really have to define all this stuff formally? Isn’t the meaning of a statement intuitively clear to all of us?

Answers:

- Maybe. Depends on your intuition.
- A group of programmers has a problem if at least one programmer has a different intuition.
- Let’s make up our own mind by looking at the following C code.

In all these examples we presume that x is a global variable.
I would guess that non-experts have to study the C standard\textsuperscript{13} for several hours in order to give definite answers.

\textsuperscript{13}E.g., ISO/IEC 9899:2011 informally called C11
Puzzle 1:

```c
int x;
...
x = 5;
int y = x++;```

What is the value of y? 5? 6?

Puzzle 2:

```c
int x;
...
x = 5;
int y = f(x++);
```  

```c
int f(int a) {
    return a + x;
}
```  

What is the value of y? 10? 11? 12?
Program Semantics: Motivation

Puzzle 3:

```c
int x;
...
int y = 23;
x = 5;
if (x++ >= 5 && x++ >= 6) {
    y = 42;
}
```

What is the value of y? 23? 42?

Puzzle 4:

```c
int x;
...
int y = 23;
x = 5;
if (x++ >= 6 && x++ >= 6) {
    y = 42;
}
```

What is the value of x? 5? 6? 7?
Puzzle 5:

```c
1 int f(int a) {
2   return a + x--; 
3 }
```

```c
1 int g(int a, int b) {
2   return a * b; 
3 }
```

```c
1 int x;
2 ...
3 x = 5;
4 int y = g(x++, f(x));
```

What is the value of y? 40? 60?
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There are various ways to define the semantics of a programming language\textsuperscript{14}. We will define the semantics of Boostan via relations. This definition of semantics is sometimes called \textit{relational semantics}. 

\footnote{\url{https://en.wikipedia.org/wiki/Semantics_(computer_science)}}
Idea: assign each statement a binary relation over program states.

Example

```
while (!(b == 0)) {
  if (b >=0) {
    b := b - 1;
  } else {
    b := b + 1;
  }
  a := a + 1;
}
```

We would like to assign to the program $P_{ab}$ a relation that says “Variable $a$’s new value is the sum of the old $a$ and the absolute value of the old $b$. The new value of $b$ is zero.”

Before we can define these relations we have to formally define a program state.
Program State

Definition (Program State)

Given a program $P = (V, \mu, T)$, a program state is a map that assigns each variable $v \in V$ a value of the variable’s domain. We use $S_{V,\mu}$ to denote the set of all program states.

Example

The map that assigns the variable $a$ to 23 and the variable $b$ to 42 is an element of $S_{V_{ab},\mu_{ab}}$.

Notation

There are several notations for maps. We can e.g. write the state above

- as a set of pairs $\{(a, 23), (b, 42)\}$.
- Alternatively, we can write the pairs using an arrow symbol: $\{a \mapsto 23, b \mapsto 42\}$.
- Furthermore, we can give that state a name, e.g., $s$ and define the state via the equalities $s(a) = 23$ and $s(b) = 42$. 
Sets of Program States

Notation/Convention

- We will use FOL formulas to denote sets of program states.
  - The set of variables in our formulas will be the program variables.
  - The constant symbols, function symbols, and predicate symbols are given by the SMT theories.
  - The model $\mathcal{M}$ is defined by the SMT theories.
  - A formula $\varphi$ denotes that set of all program states $s$ such that for $s = \rho$ the evaluation $\llbracket \varphi \rrbracket_{\mathcal{M}, \rho}$ is true.
  - We will introduce the notation for the set of states denoted by a formula later.

Example

- The formula $a = 23 \land b = 42$ denotes the singleton set $\{\{a \mapsto 23, b \mapsto 42\}\} \subseteq S_{\nu_{ab}, \mu_{ab}}$
- We will define a program semantics such that the set of states in which $P_{ab}$ can be after executing the while loop "is" $b = 0$. 
Semantics of Expressions

Idea: assign each expression an SMT formula.

Given an expression $expr$, we define the semantics of the expression, denoted $\llbracket expr \rrbracket$ as the SMT formula that is denoted by the same string.

Exception: The symbols that are not identical in Boostan and SMT formulas: integer division and modulo.
The binary division function $/$ of Boostan will be mapped to the binary division function $div$ of SMT.
The binary modulo function $\%$ of Boostan will be mapped to the binary modulo function $mod$ of SMT.

Example: $\llbracket 2 \times (x \% 16) + 42 \rrbracket$ is $2 \cdot (x \ mod \ 16) + 42$.

Convention

Since Boostan expressions and SMT formulas are so closely related, we may omit the double brackets and will often write $expr$ instead of $\llbracket expr \rrbracket$. 
Semantics of the Assignment Statement

Given a program \( P = (V, \mu, T) \) we define the semantics of an assignment statement \( \llbracket x := \text{expr} \rrbracket \) as the following binary relation over program states.

\[
\left\{ (s_1, s_2) \in S_{V,\mu} \times S_{V,\mu} \mid \llbracket x' = \llbracket \text{expr} \rrbracket \land \bigwedge_{v \in V, v \neq x} v' = v \rrbracket_{M,\rho} \text{ is true} \right. \\
\left. \text{and } \rho = s_1 \cup \text{prime}(s_2) \right\}
\]

Here, prime is the function that takes a state \( s \) and returns a map where every variable \( x \) in the domain of \( s \) is replace by \( x' \). E.g., \( \text{prime}(\{ a \mapsto 23, b \mapsto 42 \}) \) is \( \{ a' \mapsto 23, b' \mapsto 42 \} \).

Example

\( \llbracket a := a + 1 \rrbracket \) is \( \left\{ (s_1, s_2) \mid \llbracket a' = a + 1 \land b' = b \rrbracket_{M,\rho} \text{ and } \rho = s_1 \cup \text{prime}(s_2) \right\} \)
The semantics of the assignment statement $[a := a + 1]$ is $$\{(s_1, s_2) \mid [a' = a + 1 \land b' = b]\}_{M,\rho} \text{ and } \rho = s_1 \cup \text{prime}(s_2)\}.$$ 

E.g., the pair of states $(s_1, s_2)$ where $s_1 = \{a \mapsto 5, b \mapsto 1\}$ and $s_2 = \{a \mapsto 6, b \mapsto 1\}$ is an element of this relation, because for $

\rho = s_1 \cup \text{prime}(s_2) = \{a \mapsto 5, b \mapsto 1, a' \mapsto 6, b' \mapsto 1\}$ the evaluation $[a' = a + 1 \land b' = b]$ is true.

Alternatively, we could write this relation as follows.

$$\{(s_1, s_2) \mid s_2(a) = s_1(a) + 1 \text{ and } s_2(b) = s_1(b)\}.$$
The relational composition of two binary relations $R_1, R_2$ over a set $X$ is defined as follows.

$$R_1 \circ R_2 := \{(x, z) \mid \text{there exists } y \in X \text{ s.t. } (x, y) \in R_1 \text{ and } (y, z) \in R_2\}$$

Example

Let $R_1$ and $R_2$ be the “strictly smaller” relation over $\mathbb{Z}$ (i.e.,

$$R_i = \{(a, b) \in \mathbb{Z} \times \mathbb{Z} \mid a < b\}$$

then we have

$$R_1 \circ R_2 = \{(a, b) \in \mathbb{Z} \times \mathbb{Z} \mid a + 1 < b\}.$$
Semantics of the Concatenation of Statements

Let $st_1$ and $st_2$ be two statements.

We define $[st_1 \; st_2]$ as the relational composition $[st_1] \circ [st_2]$.

Example

See Exercise Sheet 08
Reminder: (Convention)

We defined the formula/term \([ \text{expr} ]\) for an expression \(\text{expr}\). Since expressions and formulas are very similar we will often omit the double brackets.

Notation

Given a program \(P = (V, \mu, st)\) and a formula \(\varphi\) whose free variables are a subset of \(V\), then we will use \(\{\varphi\}\) to denote the set of states that are a satisfying assignment for \(\varphi\).

\[
\{\varphi\} := \{s \in S_{V,\mu} \mid \llbracket \varphi \rrbracket_{M,\rho} \text{ and } \rho = s\}
\]

Warning

A formula in braces like e.g., \(\{\varphi\}\) denotes

- the set that contains the formula \(\varphi\) (you learned that notation in school) and
- a set of states (as defined above).

We have to conclude from the context which meaning is meant.
Semantics of the If-then-else Statement

Let $expr$ be an expression and let $st_1$ and $st_2$ be two statements.

We define

$$[\text{if}(expr)\{st_1\}\text{else}\{st_2\}] \quad \text{as} \quad \left(\{expr\} \times S_{V,\mu}\right) \cap [st_1] \cup \left(\{!expr\} \times S_{V,\mu}\right) \cap [st_2]$$

**Example**

$[\text{if} (b>=0)\{b:=b-1\} \text{else} \{b:=b+1\}]$

$$\left(\{b>=0\} \times S_{V,\mu}\right) \cap \left[\text{b:=b-1}\right] \cup \left(\{!b>=0\} \times S_{V,\mu}\right) \cap \left[\text{b:=b+1}\right]$$

$$\{(s,s')|s(b) \geq 0\} \quad \{(s,s')|s'(b) = s(b) - 1 \quad \text{and} \quad s'(a) = s(a)\} \quad \{(s,s')|s(b) < 0\} \quad \{(s,s')|s'(b) = s(b) + 1 \quad \text{and} \quad s'(a) = s(a)\}$$

$$\{(s, s') | \quad \text{and} \quad (s(b) \geq 0 \text{ and } s'(b) = s(b) - 1) \text{ or } (s(b) < 0 \text{ and } s'(b) = s(b) + 1)\} \quad \text{and} \quad s'(a) = s(a)$$
On Exercise Sheet 06 we recalled the definitions of a binary relation, reflexivity, transitivity and the reflexive transitive closure.

On these slides we will only repeat the definition of the reflexive transitive closure.
Reminder: Reflexive Transitive Closure

Given a binary relation \( R \) over the set \( X \), the reflexive transitive closure, denoted \( R^* \), is the smallest relation such that \( R \subseteq R^* \), \( R^* \) is reflexive and \( R^* \) is transitive.

Example

Let \( R_1 \) and \( R_2 \) be the “strictly smaller” relation over \( \mathbb{Z} \) (i.e., \( R_i = \{ (a, b) \in \mathbb{Z} \times \mathbb{Z} \mid a < b \} \)) then we have
\[
R_1 \circ R_2 = \{ (a, b) \in \mathbb{Z} \times \mathbb{Z} \mid a + 1 < b \}.
\]

We define the identity relation \( id := \{ (x, x) \mid x \in X \} \) and for \( i \in \mathbb{N} \) we define
\[
R^i = \begin{cases} 
  id & \text{if } i = 0 \\
  R \circ R^{i-1} & \text{otherwise}
\end{cases}
\]

Theorem

The reflexive transitive closure \( R^* \) is \( \bigcup_{i \in \mathbb{N}} R^i \)

(Proof not given in this course.)
Semantics of the While Statement

Let \( expr \) be an expression and let \( st \) be a statement.

We define 
\[
\llbracket \textbf{while} (expr) \{ st \} \rrbracket
\]

as
\[
((\{ expr \} \times S_{V,\mu}) \cap \llbracket st \rrbracket)^* \cap (S_{V,\mu} \times \{ !expr \})
\]

Example

\[
\llbracket \textbf{while} (x \geq 0) \{ x := x - 1; y := y + 1; \} \rrbracket
\]

Let us use \( R \) to denote 
\[
((\{ x \geq 0 \} \times S_{V,\mu}) \cap \llbracket x := x - 1; y := y + 1 \rrbracket
\]

\[
\{ (s, s') \mid s(x) \geq 0 \land s'(x) = s(x) - 1 \land s'(y) = s(y) + 1 \}
\]

\[
R^0 = \text{id}
\]

\[
R^1 = \{ (s, s') \mid s(x) \geq 0 \land s'(x) = s(x) - 1 \land s'(y) = s(y) + 1 \}
\]

\[
R^2 = \{ (s, s') \mid s(x) \geq 1 \land s'(x) = s(x) - 2 \land s'(y) = s(y) + 2 \}
\]

\[
\vdots
\]

\[
R^* = \{ (s, s') \mid s = s' \text{ or } (s(x) > s'(x) \geq -1 \land s'(y) - s(y) = s(x) - s'(x)) \}
\]

\[
R^* \cap (S_{V,\mu} \times \{ !x \geq 0 \}) = \{ (s, s') \mid (s = s' \text{ and } s'(x) < 0) \]
\]

or 
\[
(s(x) > s'(x) = -1 \land s'(y) - s(y) = s(x) + 1) \}
Reminder

Idea: assign each statement a binary relation over program states.

Example

```
while (!(b == 0)) {
  if (b >=0) {
    b := b - 1;
  } else {
    b := b + 1;
  }
  a := a + 1;
}
```

We would like to assign to the program $P_{ab}$ a relation that says “Variable $a$’s new value is the sum of the old $a$ and the absolute value of the old $b$. The new value of $b$ is zero.”

On the next slide we compute the relation of the example above.
\[ [b := b-1] = \{ (s, s') \mid [b' = b - 1 \land a' = a]_{\mathcal{M}, \rho} = \text{true} \text{ and } \rho = s \cup \text{prime}(s') \} \]
\[ = \{ (s, s') \mid s'(b) = s(b) - 1 \text{ and } s'(a) = s(a) \} \]
\[ [b := b+1] = \{ (s, s') \mid s'(b) = s(b) + 1 \text{ and } s'(a) = s(a) \} \]
\[ [a := a+1] = \{ (s', s'') \mid s''(a) = s'(a) + 1 \text{ and } s''(b) = s'(b) \} \]
\[ [\text{if/else}] = \{ b \geq 0 \} \times S_{V, \mu} \cap [b := b-1] \cup \{ !b \geq 0 \} \times S_{V, \mu} \cap [b := b+1] \]
\[ = \{ (s, s') \mid s'(a) = s(a) \text{ and } ((s(b) \geq 0 \text{ and } s'(b) = s(b) - 1) \]
\[ \text{ or } (s(b) < 0 \text{ and } s'(b) = s(b) + 1)) \} \]
\[ [\text{loop body}] = \{ (s, s'') \mid \text{ex. } s' \text{ s.t. } (s, s') \in [\text{if/else}], (s', s'') \in [a := a+1] \} \]
\[ = \{ (s, s'') \mid s''(a) = s(a) + 1 \text{ and } ((s(b) \geq 0 \text{ and } s''(b) = s(b) - 1) \]
\[ \text{ or } (s(b) < 0 \text{ and } s''(b) = s(b) + 1)) \} \]
\[ [P_{ab}] = \left( (\{ ! (b == 0) \} \times S_{V, \mu}) \cap [\text{loop body}] \right)^* \cap (S_{V, \mu} \times \{ !! (b == 0) \}) \]
\[ = \{ (s, s') \mid s(b) \neq 0 \text{ and } s'(a) = s(a) + 1 \text{ and } |s'(b)| = |s(b)| - 1 \}^* \]
\[ \cap (S_{V, \mu} \times \{ !! (b == 0) \}) \]
\[ = \{ (s, s') \mid s'(a) + |s'(b)| = s(a) + |s(b)| \text{ and } |s'(b)| \leq |s(b)| \} \]
\[ \cap (S_{V, \mu} \times \{ !! (b == 0) \}) \]
\[ = \{ (s, s') \mid s'(a) = s(a) + |s(b)| \text{ and } s'(b) = 0 \} \]
Example

See Exercise 1 on Exercise Sheet 07 for another example where we compute the relation of a program.
Outline of the Section on Boogie and Boostan

Boogie and Boostan
Context-Free Grammars
Syntax of Boostan
Excursus: The semantics of C
Relational Semantics of Boostan
Precondition-Postcondition Pairs
How can we specify correctness of a Boostan program?

- Now: precondition-postcondition pairs.
- Later: extend Boostan by assert statements.
Precondition-Postcondition Pairs

Given a program $P = (V, \mu, st)$ and a pair of sets of states ($\{\varphi_{pre}\}, \{\varphi_{post}\}$) that we call precondition-postcondition pair, we want to define the following formally. Whenever we run $st$ in some state where $\varphi_{pre}$ holds and the execution of $st$ has come to an end, then we are in some state where $\varphi_{post}$ holds.

**Definition**

We say that program $P$ satisfies the precondition-postcondition pair ($\{\varphi_{pre}\}, \{\varphi_{post}\}$) if the inclusion $\text{post}(\{\varphi_{pre}\}, [st]) \subseteq \{\varphi_{post}\}$ holds.

**Example**

```plaintext
1 while (!( b == 0)) {
2       if (b >= 0) {
3           b := b - 1;
4       } else {
5           b := b + 1;
6       }
7       a := a + 1;
8     }
```

Does $P_{ab}$ satisfy the precondition-postcondition pair ($\{a \cdot b \geq 0\}, \{a \geq 0\}$)?
Post Image

Definition
Given a binary relation $R$ over the set $X$ and a subset of $Y \subseteq X$, the **postimage of $Y$ under $R$**, denoted $\text{post}(Y, R)$, is the set 
\[ \{ x \in X \mid \exists y \in Y \text{ such that } (y, x) \in R \} \]

Example
Let $R$ be the “strictly smaller” relation over $\mathbb{Z}$ (i.e., 
$R = \{(a, b) \in \mathbb{Z} \times \mathbb{Z} \mid a < b\}$) and $Y = \{ y \in \mathbb{Z} \mid y \geq 5 \}$ then 
\[ \text{post}(Y, R) = \{ y \in \mathbb{Z} \mid y \geq 6 \} \]
Precondition-Postcondition Pairs

Example

while (!(b == 0)) {
    if (b >= 0) {
        b := b - 1;
    } else {
        b := b + 1;
    }
    a := a + 1;
}

Does $P_{ab}$ satisfy the precondition-postcondition pair ($\{a \geq 0\}, \{a \geq 0\}$)?

Check $post(\{a \geq 0\}, st) \subseteq \{a \geq 0\}$?

$[st] = \{(s, s') | s'(a) = s(a) + |s(b)| \text{ and } s'(b) = 0\}$

Example

See Exercise 2 on Exercise Sheet 08 for more examples.
Program Verification

Summer Term 2021

Lecture 10: Hoare Proof System

Matthias Heizmann

Wednesday 19th May
Section 7

Hoare Proof System
In this section we will learn to prove correctness of programs.

In more detail:

▶ We set up a proof system that helps us to show that a program satisfies a given precondition-postcondition pair.
▶ We will give a formal proof that the proof system is suitable for this task.
Outline of the Section on Hoare Proof System

Introduction

Rules of the Hoare Proof System

Soundness of the Hoare Proof System
At the beginning of this course, we used the $\mathcal{N}_{PL}$ proof system to derive valid implications of the form $\Gamma \models F$.

In this section we will see a proof system that allows us analogously to derive program statements together with a precondition-postcondition pair such that the program satisfies this precondition-postcondition pair.

This proof system was proposed by the computer scientist Tony Hoare and hence we call it “Hoare proof system”.

Next,

1. we will first define the term Hoare triple,
2. see all rules of the Hoare proof system,
3. define the term “derivation” (analogously to a derivation in $\mathcal{N}_{PL}$),
4. and discuss then each rule in more detail.
Definition (Hoare Triple)

Given a set of states \( \{ \varphi \} \), a program statement \( st \) and a set of states \( \{ \psi \} \), we call the triple \( \{ \varphi \} st \{ \psi \} \) a Hoare triple. We call a Hoare triple \( \{ \varphi \} st \{ \psi \} \) valid if \( st \) satisfies the precondition-postcondition pair \( (\{ \varphi \}, \{ \psi \}) \).

\( \text{TODO} \) Example of a Hoare triple that is valid
\( \text{TODO} \) Example of a Hoare triple that is not valid
Proof Systems of this Course

$\mathcal{N}_{PL}$
proof system for deriving valid PL implications
$\Gamma \vdash F$

$\mathcal{N}_{FOL}$
proof system for deriving valid FOL implications
$\Gamma \vdash \varphi$

Hoare proof system
proof system for deriving valid Hoare triples
${\{\varphi}\, st\, \{\psi\}}$
Outline of the Section on Hoare Proof System

- Introduction
- Rules of the Hoare Proof System
- Soundness of the Hoare Proof System
Rules of the Hoare Proof System – Overview

Assignment axiom

\[(\text{assig}) \quad \{\varphi[x \mapsto \text{expr}]\} x := \text{expr};\{\varphi\}\]

Composition rule

\[(\text{compo}) \quad \{\varphi_1\} \text{st}_1 \{\varphi_2\} \quad \{\varphi_2\} \text{st}_2 \{\varphi_3\} \quad \{\varphi_1\} \text{st}_1 \text{st}_2 \{\varphi_3\}\]

Strengthen precondition rule

\[(\text{strepre}) \quad \{\varphi\} \text{st}\{\psi\} \quad \{\varphi'\} \text{st}\{\psi\} \quad \text{if } \varphi' \models \varphi\]

Weaken postcondition rule

\[(\text{weakpos}) \quad \{\varphi\} \text{st}\{\psi\} \quad \{\varphi\} \text{st}\{\psi'\} \quad \text{if } \psi \models \psi'\]

Conditional rule

\[(\text{condi}) \quad \{\varphi \land \text{expr}\} \text{st}_1 \{\psi\} \quad \{\varphi \land \neg \text{expr}\} \text{st}_2 \{\psi\} \quad \{\varphi\} \text{if(}\text{expr}\text{)}\{\text{st}_1}\text{else}\{\text{st}_2\}\{\psi\}\]

While rule

\[(\text{while}) \quad \{\varphi \land \text{expr}\} \text{st}\{\varphi\} \quad \{\varphi\} \text{while(}\text{expr}\text{)}\{\text{st}\}\{\varphi \land \neg \text{expr}\}\]
Hore Proof System – Derivation

Definition

We define a derivation as a tree whose nodes are labelled by Hoare triples such that the following holds. If a node that is labelled by a Hoare triple \( \{ \varphi_{n+1} \} st_{n+1} \{ \psi_{n+1} \} \) has children that are labelled by Hoare triples \( \{ \varphi_1 \} st_1 \{ \psi_1 \} \ldots \{ \varphi_n \} st_n \{ \psi_n \} \), then

\[
\frac{\{ \varphi_1 \} st_1 \{ \psi_1 \} \ldots \{ \varphi_n \} st_n \{ \psi_n \}}{\{ \varphi_{n+1} \} st_{n+1} \{ \psi_{n+1} \}}
\]

must be an instance of some rule.

Note that this means in particular that leafs of the tree may only be labelled instances of the assignment axiom.

Theorem (Soundness of the Hoare Proof System)

If there is a derivation whose root is labelled by \( \{ \varphi \} st \{ \psi \} \), then the statement \( st \) satisfies the precondition-postcondition pair \( (\{ \varphi \}, \{ \psi \}) \).

Proof. Later, in the last subsection of this section.
The following four rules are sufficient to solve Exercise 3 of Exercise Sheet 09:

- Assignment axiom
- Composition rule
- Strengthen precondition rule
- Weaken postcondition rule

We next discuss the remaining two rules in more detail.
Conditional Rule

\[(\text{condi})\]

\[
\begin{array}{c}
\{\varphi \land expr\} \quad st_1 \quad \{\psi\} \\
\{\varphi \land \neg expr\} \quad st_2 \quad \{\psi\}
\end{array}
\]

\[
\{\varphi\} \quad \text{if} (expr) \quad \{st_1\} \quad \text{else} \quad \{st_2\} \quad \{\psi\}
\]

Example

\[
\begin{array}{c}
\{x=y \land y \geq 0\} \quad y:=y-1; \quad \{x \geq 0 \rightarrow y=x-1\} \land (x < 0 \rightarrow y=x+1) \}\} \\
\{x=y \land \neg (y \geq 0)\} \quad y:=y+1; \quad \{x \geq 0 \rightarrow y=x-1\} \land (x < 0 \rightarrow y=x+1) \}\}
\end{array}
\]

\[
\{y = x\} \quad \text{if}(y\geq 0)\quad \{y:=y-1;\} \quad \text{else} \quad \{y:=y+1;\} \quad \{\varphi\}
\]

Note that for both Hoare triples above the line the postcondition contains one conjunct that seems to be useless. Indeed, these conjuncts are “only” needed to obtain the postcondition for the Hoare triple below the line.
We call the formula $\varphi$ an *inductive loop invariant*.

**Example**

Task: Show that the while loop $\textbf{while}(x>0)\{x:=x-1;y:=y+1;\}$ satisfies the precondition-postcondition pair ($\{z = x + y \land x \geq 0\}, \{z = y\}$).

Solution:

\[
\begin{align*}
\{ z=x+y \land x \geq 0 \} & \quad \begin{aligned} & x:=x-1;y:=y+1; \quad \{ z=x+y \land x \geq 0 \} \\
\{ z=x+y \land x \geq 0 \} & \quad \textbf{while}(x>0)\{x:=x-1;y:=y+1;\} \quad \{ z=x+y \land x \geq 0 \land \neg (x > 0) \} \\
\{ z=x+y \land x \geq 0 \} \quad \textbf{while}(x>0)\{x:=x-1;y:=y+1;\} \quad \{ z = y \}
\end{aligned}
\end{align*}
\]

Typical for a derivation in which we use the while rule:

- We have to combine the while rule with the rules (strepre) and (weakpos).
- The conjunction of the negated condition and the inductive loop invariant restrict some variable to a certain value (here $x = 0$).
Task: prove that $P_{ab}$ satisfies the precondition-postcondition pair $(\{ a \geq 42 \land b \leq -23 \}, \{ a \geq 53 \})$.

We use $\varphi_l$ as an abbreviation for the formula $b \leq 0 \rightarrow a - b \geq 53$.

\[
\begin{aligned}
\{ b \leq 0 \rightarrow a - (b-1) \geq 52 \} & \quad \text{(assig)} \quad \{ b \leq 0 \rightarrow a - b \geq 52 \} & \quad \text{(stpre)} \\
\{ \varphi_l \land b \geq 0 \} & \quad \text{(condi)} \quad \{ \varphi_l \land b \geq 0 \} & \quad \text{(stpre)} \\
\{ \text{if } (b \geq 0) \{ b := b-1; \} \text{ else } \{ b := b+1; \} \{ a := a+1; \} \{ \varphi_l \} \}
\end{aligned}
\]

\[
\begin{aligned}
\{ \varphi_l \} \quad \text{(compo)} \quad \{ \varphi_l \} \quad \text{(stpre)} \\
\{ (\varphi_l) \land \neg (b = 0) \} \quad \text{(weakpos)} \\
\{ a \geq 42 \land b \leq -23 \} \quad \text{(weakpos)} \\
\end{aligned}
\]

where (*) is the following subtree

\[
\begin{aligned}
\{ b \leq 0 \rightarrow a - b \geq 53 \} & \quad \text{(assig)} \\
\{ b \leq 0 \rightarrow a - b \geq 52 \} & \quad \text{(stpre)} \\
\end{aligned}
\]
Example
See Exercise 5 on Exercise Sheet 09 for another examples of a derivation.
Outline of the Section on Hoare Proof System

Introduction

Rules of the Hoare Proof System

Soundness of the Hoare Proof System
This last subsection is dedicated to the proof of the theorem that states that every derived Hoare triple is indeed valid.

We follow the typical approach for proving a theorem about derivations of a proof system:

▶ we state a property of proof rules (here: soundness)
▶ we prove that each proof rule has this property
▶ we conclude via induction that the theorem holds
Reminder: **Theorem (Soundness of the Hoare Proof System)**

If there is a derivation whose root is labelled by \(\{\varphi\} st \{\psi\}\) then the statement \(st\) satisfies the precondition-postcondition pair \((\{\varphi\}, \{\psi\})\).

Reminder: **Definition (Derivation)**

We define a *derivation* as a tree whose nodes are labelled by Hoare triples such that the following holds. If a node that is labelled by a Hoare triple \(\{\varphi_{n+1}\} st_{n+1} \{\psi_{n+1}\}\) has children that are labelled by Hoare triples \(\{\varphi_1\} st_1 \{\psi_1\} \ldots \{\varphi_n\} st_n \{\psi_n\}\), then

\[
\frac{\{\varphi_1\} st_1 \{\psi_1\} \ldots \{\varphi_n\} st_n \{\psi_n\}}{\{\varphi_{n+1}\} st_{n+1} \{\psi_{n+1}\}}
\]

must be an instance of some rule.

**Definition (Sound Rule)**

We call a rule of the form

\[
\frac{\{\varphi_1\} st_1 \{\psi_1\} \ldots \{\varphi_n\} st_n \{\psi_n\}}{\{\varphi_{n+1}\} st_{n+1} \{\psi_{n+1}\}}
\]

*sound* if the following holds. If for all \(i \in \{1, \ldots n\}\) the Hoare triple \(\{\varphi_i\} st_i \{\psi_i\}\) is valid, then the Hoare triple \(\{\varphi_{n+1}\} st_{n+1} \{\psi_{n+1}\}\) is also valid.
Soundness of the Assignment Axiom

Lemma (Soundness of the Assignment Axiom)

The Hoare triple \( \{ \varphi[x \mapsto \text{expr}] \} \ x:=\text{expr}; \ \{ \varphi \} \) is valid.

Reminder

\([x:=\text{expr}]\) is \(\{(s_1, s_2) \in S_{V,\mu} \times S_{V,\mu} \mid \llbracket x' = \llbracket \text{expr} \rrbracket \land \bigwedge_{v \in V, v \neq x} v' = v \rrbracket_{M,\rho} \text{ is true and } \rho = s_1 \cup \text{prime}(s_2)\}\)

Proof. Let \( s' \in \text{post}(\{ \varphi[x \mapsto \text{expr}] \}, \llbracket x:=\text{expr}; \rrbracket) \)

\(\Rightarrow\) There exists \( s \) such that \( s \in \{ \varphi[x \mapsto \text{expr}] \} \) and \( (s, s') \in \llbracket x:=\text{expr}; \rrbracket \)

\(\Rightarrow\) There exists \( s \) such that for \( \rho = s \cup \text{prime}(s') \)

\(\llbracket \varphi[x \mapsto \text{expr}] \land x' = \llbracket \text{expr} \rrbracket \land \bigwedge_{v \in V, v \neq x} v' = v \rrbracket_{M,\rho} \text{ is true} \)

\(\Rightarrow\) for \( \rho = s' \) the evalution \( \llbracket \varphi \rrbracket_{M,\rho} \text{ is true} \)

\(\Rightarrow\) \( s' \in \{ \varphi \} \)
Soundness of the Composition Rule

\[
\begin{align*}
\text{(compo)} & \quad \{\varphi_1\} st_1 \{\varphi_2\} \quad \{\varphi_2\} st_2 \{\varphi_3\} \\
& \quad \{\varphi_1\} st_1 st_2 \{\varphi_3\}
\end{align*}
\]

**Lemma (Soundness of the Composition Rule)**

If the Hoare triple \(\{\varphi_1\} st_1 \{\varphi_2\}\) is valid and the Hoare triple \(\{\varphi_2\} st_2 \{\varphi_3\}\) is valid, then the Hoare triple \(\{\varphi_1\} st_1 st_2 \{\varphi_3\}\) is valid.

Proof. See Exercise 1 on Exercise Sheet 10.
Soundness of the Strengthen Precondition Rule

\[
(\text{strepre}) \quad \frac{\{\varphi\} \text{st} \{\psi\}}{\{\varphi'\} \text{st} \{\psi\}} \quad \text{if } \varphi' \models \varphi
\]

Lemma (Soundness of the Strengthen Precondition Rule)

If the Hoare triple \(\{\varphi\} \text{st} \{\psi\}\) is valid and the side condition \(\varphi' \models \varphi\) is valid, then the Hoare triple \(\{\varphi'\} \text{st} \{\psi\}\) is valid.

Proof. Let \(s' \in \text{post}(\{\varphi'\}, [\text{st}])\)

- \(\Rightarrow\) There exists \(s\) such that \(s \in \{\varphi'\}\) and \((s, s') \in [\text{st}]\).
- \(\Rightarrow\) There exists \(s\) such that \(s \in \{\varphi\}\) and \((s, s') \in [\text{st}]\).
- \(\Rightarrow\) \(s' \in \text{post}(\{\varphi\}, \text{st})\)
- \(\Rightarrow\) \(s' \in \{\psi\}\) (because \(\text{post}(\{\varphi\}, \text{st}) \subseteq \{\psi\}\))
Program Verification

Summer Term 2021

Lecture 12: Hoare Proof System cont’d, Ultimate Referee, Arrays

Matthias Heizmann

Wednesday 2nd June
Soundness of the Weakening Postcondition Rule

\[
(\text{weakpos}) \quad \begin{array}{c}
\{ \varphi \} \text{st} \{ \psi \}
\end{array} \quad \frac{\psi \models \psi'}{\{ \varphi \} \text{st} \{ \psi' \}} \quad \text{if } \psi \models \psi'
\]

Lemma (Soundness of the Weakening Postcondition Rule)

If the Hoare triple \( \{ \varphi \} \text{st} \{ \psi \} \) is valid and the side condition \( \psi \models \psi' \) is valid, then the Hoare triple \( \{ \varphi \} \text{st} \{ \psi' \} \) is valid.

Proof. See Exercise 2 on Exercise Sheet 11.
Soundness of the Conditional Rule

\begin{align*}
\frac{(condi) \{ \varphi \land expr \} \ st_1 \ {\psi} \quad \{ \varphi \land \neg expr \} \ st_2 \ {\psi} \quad \{ \varphi \} \ if(expr)\{st1\} else\{st2\} \ {\psi} }{}
\end{align*}

Lemma (Soundness of the Conditional Rule)

If the Hoare triple \( \{ \varphi \land expr \} \ st_1 \ {\psi} \) is valid and the Hoare triple \( \{ \varphi \land \neg expr \} \ st_2 \ {\psi} \) is valid, then the Hoare triple \( \{ \varphi \} \ if(expr)\{st1\} else\{st2\} \ {\psi} \) is valid.

Proof. See Exercise 3 on Exercise Sheet 11.
Soundness of the While Rule

\[
(\text{while}) \quad \frac{\{\varphi \land expr\} \quad \text{st} \quad \{\varphi\}}{\{\varphi\} \quad \text{while}(expr)\{\text{st}\} \quad \{\varphi \land \neg expr\}}
\]

**Lemma (Soundness of the While Rule)**

If the Hoare triple \(\{\varphi \land expr\} \quad \text{st} \quad \{\varphi\}\) is valid, then the Hoare triple \(\{\varphi\} \quad \text{while}(expr)\{\text{st}\} \quad \{\varphi \land \neg expr\}\) is valid.
Proof. Let \( s' \in \text{post}(\{ \varphi \}, [\textbf{while} (\text{expr})\{ \textit{st} \}]) \), i.e. there exists an \( s \in \{ \varphi \} \) such that

\[(s, s') \in [\textbf{while} (\text{expr})\{ \textit{st} \} ] = ((\{ \text{expr} \} \times S_{V, \mu}) \cap [\textit{st}])^* \cap (S_{V, \mu} \times \{ \text{!expr} \}).\]

Therefore we know that \( s' \in \{ \text{!expr} \}. \)

Let \( R = ((\{ \text{expr} \} \times S_{V, \mu}) \cap [\textit{st}]) \). It holds that \( R^* = \bigcup_{n \in \mathbb{N}_0} R^n \). Thus there exists some \( n \in \mathbb{N}_0 \) such that \( (s, s') \in R^n \).

By induction over \( n \), we show that \( s' \in \{ \varphi \}. \) By the observation above, it follows that \( s' \in \{ \varphi \land \neg \text{expr} \}. \) Thus we will have proven that

\[\text{post}(\{ \varphi \}, [\textbf{while} (\text{expr})\{ \textit{st} \}]) \subseteq \{ \varphi \land \neg \text{expr} \}\]

and thus the While Rule is valid.
\( n = 0 \) We have \( (s, s') \in R^0 = id = \{(s, s') \in S_{\nu, \mu} \times S_{\nu, \mu} \mid s = s'\} \). Hence \( s' = s \), and \( s \in \{\varphi\} \) by assumption.

\( n \to n + 1 \) Assume as induction hypothesis (IH) that for all \( (\tilde{s}, \tilde{s}') \in R^n \) with \( \tilde{s} \in \{\varphi\} \), it holds that \( \tilde{s}' \in \{\varphi\} \).

In our case, \( (s, s') \in R^{n+1} = R^n \circ R \). Thus by definition of composition, there exists some \( s'' \) such that \( (s, s'') \in R^n \) and \( (s'', s') \in R \).

- From the first tuple we derive by (IH) that \( s'' \in \{\varphi\} \).
- From the second tuple and the definition of \( R \), it follows that \( s'' \in \{\text{expr}\} \) and \( (s'', s') \in [\text{st}] \).

Hence it follows that \( s' \in post(\{\varphi \land \text{expr}\}, [\text{st}]) \). By validity of the Hoare triple \( \{\varphi \land \text{expr}\} \text{ st} \{\varphi\} \), we have \( post(\{\varphi \land \text{expr}\}, [\text{st}]) \subseteq \{\varphi\} \). Thus we conclude \( s' \in \{\varphi\} \).
Soundness of the Hoare Proof System

Reminder: **Theorem (Soundness of the Hoare Proof System)**

If there is a derivation whose root is labelled by $\{\varphi\} st \{\psi\}$ then the statement $st$ satisfies the precondition-postcondition pair $(\{\varphi\}, \{\psi\})$

Proof. By definition a Hoare triple, $\{\varphi\} st \{\psi\}$ is valid iff $st$ satisfies the precondition-postcondition pair $(\{\varphi\}, \{\psi\})$. We prove by induction over the height of the derivation that the root node of a derivation is always labelled by a valid Hoare triple.

**Induction hypothesis (IH):** For all derivations of height $\leq n$ the root node is labelled by a valid Hoare triple.

**Base case $n = 0$**. The derivation consists of a single node, labelled by a Hoare triple $\{\varphi\} st \{\psi\}$. By definition of a derivation, $\{\varphi\} st \{\psi\}$ has to be an instance of some rule. The only rule of this form is the assignment axiom. From the lemma on Soundness of the Assignment Axiom we conclude that (IH) holds.
Induction step $n \rightsquigarrow n + 1$. Let $\{\varphi_{m+1}\}st_{m+1}\{\psi_{m+1}\}$ be the label of the root node and $\{\varphi_1\}st_1\{\psi_1\}$ ... $\{\varphi_m\}st_m\{\psi_m\}$ be the labels of the root node’s children. Each child is the root node of derivation of height $\leq n$ and from IH we conclude that it is labelled by a valid Hoare triple. By definition of a derivation,

$$
\begin{align*}
\{\varphi_1\}st_1\{\psi_1\} & \quad \ldots \quad \{\varphi_m\}st_m\{\psi_m\} \\
\{\varphi_{m+1}\}st_{m+1}\{\psi_{m+1}\}
\end{align*}
$$

must be an instance of some rule. The rules of this form are the composition rule, the strengthen precondition rule, the weaken postcondition rule, the conditional rule, and the while rule. For each of these rules one of the lemmas of this subsection lets us conclude that $\{\varphi_{m+1}\}st_{m+1}\{\psi_{m+1}\}$ is a valid hoare triple and hence IH also holds for $n + 1$. ■
Section 8

Ultimate Referee
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In this section we will partially automize the task of checking correctness.

In this section, we will learn to

▶ systematically construct derivations in the Hoare proof system if suitable loop invariants are given

▶ use the Ultimate Referee tool check if given loop invariants are suitable to proof correctness
Guide for Finding a Derivation in the Hoare Proof System
At a first glance it looked like constructing a derivation involves a lot of guessing.

After a closer look it became clear that there is only one rule for each kind of statement and we only have to guess the loop invariant of the while rule and where to put in strepre and weakpos rules.

The following guide teaches us how we can reduce the guesswork to finding suitable loop invariants for the while rule.

Note that however finding a suitable loop invariant is usually the hardest part of the task. This guide just helps us to get the minor obstacles out of the way and helps us to face the real challenge directly.
Guide for Finding a Derivation in the Hoare Proof System

1. Guess “good” loop invariants for all loops
2. Use (weakpos) only for equivalence transformations
   equivalence transformations are sometimes needed to bring a formula syntactically in a form that is required by (condi) or (while)
3. Process sequential composition from right to left
4. Strengthen the precondition (strictly) only before loop invariants
5. Apart from that: use the (strepre) and (weakpos) rules only for equivalence transformations
Finding a derivation usually involves a lot of backtracking. We find out very late that our loop invariants were not sufficient and have to start again. I would be nice, if we could focus on the guesswork and let a computer do everything that can be done algorithmically. (See tool in next subsection.)
Outline of the Section on Ultimate Referee

Guide for Finding a Derivation in the Hoare Proof System

Ultimate Referee
Ultimate Referee is a tool for checking loop invariants.

- Takes as input:
  - program where each loop is annotated by a formula (the potential loop invariants) and
  - a correctness specification (e.g., a precondition-postcondition pair)

Checks if there is some derivation in the Hoare proof system where the formulas are loop invariants of the respective while rules.

- Implemented in the Ultimate framework
- Source code available at GitHub.
- Available via a web interface.
We use the keyword `invariant` in each while loop to state our candidate invariants.

Here our candidate invariant is `invariant y == 0;`

The output of the tool tells us that our candidate invariant is too strong:

Annotation is not valid for all loop-free paths from entry of procedure `main` to loop head at line 7. One counterexample starts in `i=1, j=2` and ends in `i=1, j=2, x=1, y=2.`
Ultimate Referee: Outlook

Ultimate Referee was not only build to support students who are constructing derivations in the Hoare proof system...

- Check results of other verification tools.
- Assume you verify your code with verification tool XYZ. Verification tool XYZ says that your code is correct. Do you trust verification tool XYZ?
- Let verification tool XYZ output all loop invariants and double check its result with Ultimate Referee.

Slightly different than the witness validation [3, 2] implemented in Ultimate. The witness validator is rather lenient and tries to complete proofs that are incomplete.
In this section we will add support for arrays to our formal setting.

Our goals:

▸ Learn about the SMT theory of arrays.
▸ Get familiar with Boogie’s notion of arrays (arrays as maps)
▸ Add support for arrays to the Boostan language.
▸ Add support for this revised Boostan language to the Hoare proof system.
Outline of the Section on Arrays

Motivation for Adding new Features
Arrays as Mathematical Objects
The SMT Theory of Arrays
Arrays in Boogie
Arrays in Boostan
The next slides motivates the need for an SMT theory of arrays.

The diagram contrasts the approach of this lecture with the approach of the Ultimate Automizer verification tool (which we discuss later in this course).

- The verification algorithms of the Ultimate Automizer tool are not (directly) implemented for high-level programming languages. Instead, the tool translates high-level programming languages to the Boogie language. Boogie was designed such that it is closely related to SMT-LIB. Hence, the tool can delegate several sub-tasks to SMT solvers.

- In this lecture, we do not study high-level programming languages. Instead, we take basic features of high-level programming languages and add support for these features to the Boostan language. We design Boostan such that it is closely related to SMT. Hence, we can resort to SMT while defining its semantics.

Arrays are an basic feature of high-level programming languages, hence we want to have SMT support for arrays.
Approach of the Ultimate Automizer verification tool.

High-level imperative programming language. E.g., C.

Approach in this lecture.

High-level imperative programming language. E.g., C.

We need logical formulas whose models are (also) arrays!
Motivation for Adding new Features
Arrays as Mathematical Objects
The SMT Theory of Arrays
Arrays in Boogie
Arrays in Boostan
In school you did some math where the objects were numbers (e.g., natural numbers, reals) or shapes (triangles, circles).

Now, we would now like to do some math where the studied objects are array-like. On one hand, the objects have to be so rich that they are suitable to model arrays of computer programs. On the other hand, the objects have to be so simple that the reasoning can be implemented in tools like e.g., SMT solvers.
**Problem:** Arrays are modifiable.

**Ideas:** Consider an array as a map. Consider an array update as an operation that takes a map and returns a modified map.

**Example (that demonstrates this idea)**

- Let $f_{\text{foo}}$ be the map such that $f_{\text{foo}}(x) = 0$ for all $x$.
- $f_{\text{foo}}$ represents a zero-initialized array.
- After writing the number 23 at index 5 that array is represented by the map $f_{\text{bar}}$ where $f_{\text{bar}}(x) = \begin{cases} 
23 & \text{if } x = 5 \\
0 & \text{otherwise}
\end{cases}$

We use two functions to implement this idea.

- **select**
  - binary function
  - 1st argument: a map
  - 2nd argument: element of map’s domain
  - returns: value of map at that position
  - e.g. $\text{select}(f_{\text{foo}}, 5) = 0$
  - e.g. $\text{select}(f_{\text{bar}}, 5) = 23$

- **store**
  - ternary function
  - 1st argument: a map
  - 2nd argument: element of map’s domain
  - 3rd argument: new value at that position
  - returns: updated map
  - e.g. $\text{store}(f_{\text{foo}}, 5, 23) = f_{\text{bar}}$
Next we compare the theory of arrays that we are going to define with the theory of integers.

Note that the “absolute value” is a function in models of the theory of integers, but can also be an element of the interpretation domain in the theory of arrays.
# Theory of Arrays in Comparison to the Theory of Integers

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<th>Values</th>
<th>Theory of Integers</th>
<th>Theory of Arrays</th>
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<tr>
<td>Numbers, e.g.</td>
<td>23, 42, -17</td>
<td>1-ary maps, e.g., f_foo, f_bar, absolute value (</td>
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<tr>
<td>Functions</td>
<td>+, -, *, abs</td>
<td>select, store</td>
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Outline of the Section on Arrays

- Motivation for Adding new Features
- Arrays as Mathematical Objects
- The SMT Theory of Arrays
- Arrays in Boogie
- Arrays in Boostan
Analogously to our introduction of various SMT theories in the section on First-Order Theories we introduce the theory of arrays.

As an exercise, we should ask ourselves: How can we define the theory of arrays formally? Which symbols and axioms are needed?
Theory of Arrays $T_{arr}$

Signature:
\[ \Sigma_{arr} : \{select, \ store, \ =\} \]

Axioms:
1. the axioms of *reflexivity*, *symmetry*, and *transitivity* of $T_=$
2. array congruence
\[ \forall a, i, j. \ i = j \rightarrow select(a, i) = select(a, j) \]
3. read-over-write 1
\[ \forall a, v, i, j. \ i = j \rightarrow select(store(a, i, v), j) = v \]
4. read-over-write 2
\[ \forall a, v, i, j. \ i \neq j \rightarrow select(store(a, i, v), j) = select(a, j) \]
5. extensionality
\[ \forall a, b. \ (\forall i. \ select(a, i) = select(b, i)) \leftrightarrow a = b \]
The SMT-LIB definition of the theory of arrays can be found at the SMT-LIB website \(^{15}\) We will not discuss details and only look at an example (next slide).

Reminder: SMT-LIB is based on a sorted version of first-order logic. Hence, we have to specify a sort for each variable. The sort of an array whose indices are integers and whose values are Booleans is denoted by \((\text{Array Int Bool})\).

See Exercise Sheet 11 for more examples.

\(^{15}\)http://smtlib.cs.uiowa.edu/theories-ArraysEx.shtml
Arrays in SMT-LIB

Some SMT formula with symbols from the theory of arrays.

\[ a = \text{store}(b, k, v) \land \text{select}(a, i) \neq \text{select}(b, i) \land \text{select}(a, j) \neq \text{select}(b, j) \land i \neq j \]

Some SMT script for checking satisfiability of this formula.

```
1 (set-logic QF_ALIA)
2 (declare-fun i () Int)
3 (declare-fun j () Int)
4 (declare-fun k () Int)
5 (declare-fun v () Int)
6 (declare-fun a () (Array Int Int))
7 (declare-fun b () (Array Int Int))
8 (assert (= b (store a k v)))
9 (assert (not (= (select b i) (select a i))))
10 (assert (not (= (select b j) (select a j))))
11 (check-sat)
12 (get-value (k i j))
13 (assert (not (= j i)))
14 (check-sat)
```
Program Verification
Summer Term 2021
Lecture 13: Arrays cont’d

Matthias Heizmann

Monday 7th June
Outline of the Section on Arrays

- Motivation for Adding new Features
- Arrays as Mathematical Objects
- The SMT Theory of Arrays
- Arrays in Boogie
- Arrays in Boostan
Arrays in Boogie are very similar to arrays in SMT-LIB. An array is a (total) map that assigns each element of the index domain and element of the value domain.

In this course we will use examples to briefly demonstrate the syntax and semantics of Boogie’s arrays, details can be found in the Boogie specification\textsuperscript{16} \textsuperscript{13}.

See Exercise Sheet 11 and Exercise Sheet 12 for more examples.

\textsuperscript{16}https://www.microsoft.com/en-us/research/publication/this-is-boogie-2-2/
Implementation of an insertion sort\textsuperscript{17} algorithm in Boogie:

```
procedure InsertionSort(lo : int, hi : int, a : [int]int) returns (ar : [int]int)
{
  var i, j, temp : int;
  ar := a;
  i := lo+1;
  while (i <= hi) {
    j := i;
    while (j > lo && ar[j] < ar[j-1]) {
      temp := ar[j-1];
      ar[j-1] := ar[j];
      ar[j] := temp;
      j := j-1;
    }
    i := i+1;
  }
}
```

\textsuperscript{17}https://en.wikipedia.org/wiki/Insertion_sort
**Modeling Memory via Arrays**

Feature of many high-level languages: Pointers / References

Simplest way to model in Boogie: global array $\text{mem} : \text{[int]}\text{int}$

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<td>$\text{select}(\text{mem}, \text{ptr})$</td>
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<td>*ptr</td>
<td>$\text{mem}[\text{ptr}]$</td>
<td></td>
</tr>
<tr>
<td>pointer assignment</td>
<td>array assignment</td>
<td>$\text{mem}' = \text{store}(\text{mem}, \text{ptr}, \text{expr})$</td>
</tr>
<tr>
<td>*ptr = expr;</td>
<td>$\text{mem}[\text{ptr}] := \text{expr};$</td>
<td></td>
</tr>
<tr>
<td>reference assignment</td>
<td>assignment</td>
<td>$\text{ptr2}' = \text{ptr}$</td>
</tr>
<tr>
<td>ptr2 = ptr;</td>
<td>$\text{ptr2} := \text{ptr};$</td>
<td></td>
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Outline of the Section on Arrays

Motivation for Adding new Features
Arrays as Mathematical Objects
The SMT Theory of Arrays
Arrays in Boogie
Arrays in Boostan
In this subsection we will add support for arrays to the Boostan language.
Arrays in Boostan

What do we have to extend?

- Syntax
  - expressions
  - assignment statement
- Semantics
  - expressions
  - assignment statement
- Rules of the Hoare proof system
- Soundness proof for the Hoare proof system
Grammar for Boostan with Array Assignment Statement

\[ G_{\text{Boo}} = (\Sigma_{\text{Boo}}, N_{\text{Boo}}, P_{\text{Boo}}, S_{\text{Boo}}) \]

\[ \Sigma_{\text{Boo}} = \{ \text{while}, \text{if}, \text{else}, \{, \} \} \cup \Sigma_{\text{B}} \]

\[ N_{\text{Boo}} = \{ X_{\text{stmt}}, X_{\text{lhs}} \} \cup N_{\text{B}} \]

\[ P_{\text{Boo}} = \{ \]
\[ X_{\text{stmt}} \rightarrow X_{\text{lhs}} := X_{\text{expr}} ; \]
\[ X_{\text{stmt}} \rightarrow X_{\text{stmt}} X_{\text{stmt}} \]
\[ X_{\text{stmt}} \rightarrow \text{if} (X_{\text{expr}}) \{ X_{\text{stmt}} \} \text{ else } \{ X_{\text{stmt}} \} \]
\[ X_{\text{stmt}} \rightarrow \text{while} (X_{\text{expr}}) \{ X_{\text{stmt}} \} \]
\[ X_{\text{lhs}} \rightarrow X_{\text{var}}[X_{\text{expr}}] \]
\[ X_{\text{lhs}} \rightarrow X_{\text{var}} \} \cup P_{\text{B}} \]

\[ S_{\text{Boo}} = X_{\text{stmt}} \]
Semantics of the Array Assignment Statement

Reminder (Assignment Statement)

\[
\begin{align*}
[x := \text{expr};] \text{ is } & \{ (s_1, s_2) \in S_{V, \mu} \times S_{V, \mu} \mid [x' = \text{expr} \land \bigwedge_{v \in V, v \neq x} v' = v]_{M, \rho} \text{ is true} \\
& \quad \text{and } \rho = s_1 \cup \text{prime}(s_2) \}\end{align*}
\]

Given a program \( P = (V, \mu, T) \) we define the semantics of an array assignment statement \([a[i] := \text{expr};]\) as the following binary relation over program states.

\[
\{ (s_1, s_2) \in S_{V, \mu} \times S_{V, \mu} \mid [a' = \text{store}(a, i, \text{expr}) \land \bigwedge_{v \in V, v \neq a} v' = v]_{M, \rho} \text{ is true} \\
& \quad \text{and } \rho = s_1 \cup \text{prime}(s_2) \}\]
An Array Assignment Axiom for the Hoare Proof System

Reminder (Assignment Axiom)

(\textit{assig}) \begin{array}{l}
\{\varphi[x \mapsto \text{expr}]\} \ x:=\text{expr}; \ \{\varphi\}
\end{array}

(\textit{arrassig}) \begin{array}{l}
\{\varphi[a \mapsto \text{store(a,i,expr)}]\} \ a[i]:=\text{expr}; \ \{\varphi\}
\end{array}
Soundness of the Array Assignment Axiom

Lemma (Soundness of the Array Assignment Axiom)

The Hoare triple \( \{ \varphi[a \mapsto \text{store}(a, i, \text{expr})] \} \ a[i] := \text{expr}; \ \{ \varphi \} \) is valid.

Reminder

\[
[a[i] := \text{expr};] \text{ is } \{(s_1, s_2) \in S_V, \mu \times S_V, \mu \mid [a' = \text{store}(a, i, \text{expr}) \land \bigwedge_{v \in V, v \neq a} v' = v]_{\mathcal{M}, \rho} \text{ is true and } \rho = s_1 \cup \text{prime}(s_2)\}
\]

Proof. Analogously to the proof for the proof for the assignment statement.
Boogie and Boostan – Part 2
In this section we will discuss nondeterminism and assumptions.

Our goals:

- Learn that we can model input and other kinds of nondeterminism via Boogie’s havoc statement.
- Add support for the havoc statement to Boostan.
- Learn that we can model additional assumptions via Boogie’s assume statement.
- Add support for the assume statement to Boostan.
Reminder: Many verification tools do not apply their algorithms directly to the input language. Instead, they translate the input program to a program in a language with a sparse syntax (e.g., Boogie) and apply the verification algorithms on the translation output. Hence, language like Boogie must allow one to model all features of high level languages.

We take that into account and add features to Boostan such that we are in principle able to model high-level languages.
Outline of the Section on Boogie and Boostan – Part 2

Nondeterminism and Havoc statement
Nondeterminism

Typical feature of computer programs: input

- user input
- network input
- input from other hardware

How can we model input in a general/abstract way?

- In some sense we already do ...
- Variables are not initialized, may have any value at the beginning
- Can we just use one auxiliary variable per user input?
- No. Input may occur inside a loop.
Modelling Input in Programs

C program:

```c
unsigned char x = 0;
while (x < '1' || x > '9') {
    println("Please input a number from 1 to 9.\n");
    x = readchar();
}
// work with input x
```

Boogie program:

```boogie
var x : int;
x := 0;
while (x < 49 || x > 57) {
    // println("Please input a number from 1 to 9.\n");
    havoc x;
    assume 0 <= x && x <= 255;
}
// work with input x
```

Section 9.2 of the Boogie specification\(^{18}\) explains the assume statement.

Nondeterminism in Boogie

Modelling input in Boogie: In each iteration, an arbitrary value is assigned to the variable $x$.

```boogie
while (x == 3 * y) {
    y := x;
    havoc x;
}
```

**Question:** Does this program satisfy the precondition-postcondition pair ($\{y = 1\}, \{y \leq 81\}$)?

⇒ Let’s ask Ultimate Automizer!

Section 9.4 of the Boogie specification\(^{19}\) explains the havoc statement.

---
\(^{19}\)K. Rustan M. Leino. “This is Boogie 2”. 2008.
What do we have to extend?

- Syntax
- Semantics
- Rules of the Hoare proof system
- Soundness proof for the Hoare proof system
Grammar for Boostan with Havoc Statement

\[ \mathcal{G}_{\text{Boo}} = (\Sigma_{\text{Boo}}, N_{\text{Boo}}, P_{\text{Boo}}, S_{\text{Boo}}) \]

\[ \Sigma_{\text{Boo}} = \{ \text{while, if, else, }, \{, \}, \text{havoc} \} \cup \Sigma_B \]

\[ N_{\text{Boo}} = \{ X_{\text{stmt}}, X_{\text{lhs}} \} \cup N_B \]

\[ P_{\text{Boo}} = \{ X_{\text{stmt}} \rightarrow X_{\text{lhs}} := X_{\text{expr}} ; \\
X_{\text{stmt}} \rightarrow \text{havoc } X_{\text{var}} ; \\
X_{\text{stmt}} \rightarrow X_{\text{stmt}} X_{\text{stmt}} \\
X_{\text{stmt}} \rightarrow \text{if } (X_{\text{expr}}) \{X_{\text{stmt}}\} \text{ else } \{X_{\text{stmt}}\} \\
X_{\text{stmt}} \rightarrow \text{while } (X_{\text{expr}}) \{X_{\text{stmt}}\} \\
X_{\text{lhs}} \rightarrow X_{\text{var}} [X_{\text{expr}}] \\
X_{\text{lhs}} \rightarrow X_{\text{var}} \} \cup P_B \]

\[ S_{\text{Boo}} = X_{\text{Boo}} \]
Semantics of the Havoc Statement

Reminder (Assignment Statement)

\[
[x := \text{expr};] \text{ is } \{(s_1, s_2) \in S_{V, \mu} \times S_{V, \mu} \mid \begin{array}{l}
\land_{v \in V, v \neq x} v' = v]_{\mathcal{M}, \rho} \text{ is true} \\
\text{and } \rho = s_1 \cup \text{prime}(s_2)\}\}
\]

Given a program \( P = (V, \mu, \mathcal{T}) \) we define the semantics of a havoc statement \( [\text{havoc } x;] \) as the following binary relation over program states.

\[
\{(s_1, s_2) \in S_{V, \mu} \times S_{V, \mu} \mid \begin{array}{l}
\land_{v \in V, v \neq x} v' = v]_{\mathcal{M}, \rho} \text{ is true} \\
\text{and } \rho = s_1 \cup \text{prime}(s_2)\}\}
\]
Program Verification

Summer Term 2021

Lecture 14: Havoc, Assume, CFGs

Matthias Heizmann

Wednesday 9th June
A Havoc Axiom for the Hoare Proof System

Reminder (Assignment Axiom)

\[(\text{assign}) \quad \{ \varphi[x \mapsto \text{expr}] \} \ x:=\text{expr}; \ \{ \varphi \}\]

(havoc) \quad \{ \forall x. \varphi \} \ \text{havoc} \ x; \ \{ \varphi \}\]
Soundness of the Havoc Axiom

Lemma (Soundness of the Havoc Axiom)

The Hoare triple $\{\forall x. \varphi\} \texttt{havoc x;} \{\varphi\}$ is valid.

Reminder

$[\texttt{havoc x;}]$ is $\{(s_1, s_2) \in S_{V, \mu} \times S_{V, \mu} \mid \left[ \bigwedge_{v \in V, v \neq x} v' = v \right]_{M, \rho} \text{ is true and }\rho = s_1 \cup \text{prime}(s_2)\}$

Proof. Let $s' \in \text{post}(\{\forall x. \varphi\}, [\texttt{havoc x;}])$

$\Rightarrow$ There exists $s$ such that $s \in \{\forall x. \varphi\}$ and $(s, s') \in [\texttt{havoc x;}]$  
$\Rightarrow$ There exists $s$ such that for $\rho = s \cup \text{prime}(s')$  
$\quad \left[ (\forall x. \varphi) \land \bigwedge_{v \in V, v \neq x} v' = v \right]_{M, \rho} \text{ is true}$  
$\Rightarrow$ There exists $s$ such that for $\rho = s \cup \text{prime}(s')$  
$\quad [\left((\forall x. \varphi)\right)]_{M, \rho} \text{ is true and for all } v \in V \setminus \{x\}, \text{ we have } s(v) = s'(v)$  
$\Rightarrow$ for $\rho = s'$ the evaluation $[\varphi]_{M, \rho} \text{ is true}$  
$\Rightarrow s' \in \{\varphi\}$
Assumptions

How can we restrict input to certain values?

Not a feature of programming languages.
Modelling Input in Programs

C program:

```c
1 unsigned char x = 0;
2 while (x < '1' || x > '9') {
3     println("Please input a number from 1 to 9.");
4     x = readchar();
5 }
6 // work with input x
```

Boogie program:

```boogie
1 var x : int;
2 x := 0;
3 while (x < 49 || x > 57) {
4     // println("Please input a number from 1 to 9.")
5     havoc x;
6     assume 0 <= x && x <= 255;
7 }
8 // work with input x
```

Section 9.2 of the Boogie specification\textsuperscript{18} explains the assume statement.

\textsuperscript{18}K. Rustan M. Leino. “This is Boogie 2”. 2008.
Assumptions in Boostan

What do we have to extend?

- Syntax
- Semantics
- Rules of the Hoare proof system
- Soundness proof for the Hoare proof system
Grammar for Boostan with Assume Statement

\[ g_{\text{Boo}} = (\Sigma_{\text{Boo}}, N_{\text{Boo}}, P_{\text{Boo}}, S_{\text{Boo}}) \]

\[ \Sigma_{\text{Boo}} = \{\text{while, if, else, {}, havoc, assume}\} \cup \Sigma_B \]

\[ N_{\text{Boo}} = \{X_{\text{stmt}}, X_{\text{lhs}}\} \cup N_B \]

\[ P_{\text{Boo}} = \{ \begin{align*}
    X_{\text{stmt}} & \rightarrow X_{\text{lhs}} := X_{\text{expr}} ; \\
    X_{\text{stmt}} & \rightarrow \text{havoc} X_{\text{var}} ; \\
    X_{\text{stmt}} & \rightarrow \text{assume} X_{\text{expr}} ; \\
    X_{\text{stmt}} & \rightarrow X_{\text{stmt}} X_{\text{stmt}} \\
    X_{\text{stmt}} & \rightarrow \text{if} (X_{\text{expr}}) \{X_{\text{stmt}}\} \text{ else } \{X_{\text{stmt}}\} \\
    X_{\text{stmt}} & \rightarrow \text{while} (X_{\text{expr}}) \{X_{\text{stmt}}\} \\
    X_{\text{lhs}} & \rightarrow X_{\text{var}} [X_{\text{expr}}] \\
    X_{\text{lhs}} & \rightarrow X_{\text{var}} \} \cup P_B 
\]
Semantics of the Assume Statement

Given a program $P = (V, \mu, T)$ we define the semantics of an assume statement $\mathbf{[assume \; expr;]}$ as the following binary relation over program states.

$\{(s_1, s_2) \in S_{V,\mu} \times S_{V,\mu} \mid s_1 = s_2 \text{ and } s_2 \in \{expr\}\}$

Alternatively

$\{(s_1, s_2) \in S_{V,\mu} \times S_{V,\mu} \mid \mathbf{[expr \land \bigwedge_{v \in V} v' = v]}_{M,\rho} \text{ is true and } \rho = s_1 \cup \text{prime}(s_2)\}$
An Assume Axiom for the Hoare Proof System

\[(assu)\frac{}{\{\varphi\} \text{assume } expr; \{\varphi \land expr\}}\]
Soundness of the Assume Axiom

Lemma (Soundness of the Assume Axiom)

The Hoare triple \( \{ \varphi \} \text{ assume } \text{expr}; \{ \varphi \land \text{expr} \} \) is valid.

Reminder

\[ [\text{assume expr;}] = \{(s_1, s_2) \in S_{V, \mu} \times S_{V, \mu} \mid s_1 = s_2 \text{ and } s_1 \in \{ \text{expr} \} \} \]

Proof. Let \( s' \in \text{post}(\{ \varphi \}, [\text{assume expr;}]) \)

\[ \Rightarrow \text{ There exists } s \text{ such that } s \in \{ \varphi \} \text{ and } (s, s') \in [\text{assume expr;}]) \]

\[ \Rightarrow \text{ There exists } s \text{ such that } s \in \{ \varphi \} \text{ and } s = s' \text{ and } s \in \{ \text{expr} \} \]

\[ \Rightarrow s' \in \{ \varphi \} \text{ and } s' \in \{ \text{expr} \} \]

\[ \Rightarrow s' \in \{ \varphi \land \text{expr} \} \]
Program Verification

Summer Term 2021

Lecture 15: Control-flow graphs

Matthias Heizmann

Monday 14th June
Section 11

Control-flow graphs
In this section we will see a new formalism for computer programs, namely control-flow graphs. Control-flow graphs are a well-established concept in computer science for which several different but very similar notions exists.

Goals of this section are

- fix our notation of a control-flow graph and the corresponding terminology
- give a characterization of program correctness (in the sense of safety, precondition-postcondition pairs)
- see (again) an example of a complex object is defined by (structural) induction over a context-free grammar
- see (again) an example of a complex proof that is given by (structural) induction over a context-free grammar
Outline of the Section on Control-flow graphs

Motivation
Formal Definition
Program Executions
Proof of the Error Execution Theorem
From the Guide for Finding a Derivation in the Hoare Proof System and the UltimateEliminator tool we learned that it is (at least conceptually) rather easy to give a proof once we found suitable loop invariants.

In the remaining weeks we will see techniques for finding loop invariants but in order to do so we need a new formalism for programs: the control-flow graph.
Relational Semantics vs. Semantics based on control-flow graphs

Relational semantics

- conceptually simple
- suitable for defining the Hoare proof system
- intractable for algorithms (e.g., because we cannot compute the reflexive transitive closure)

Semantics based on control-flow graphs

- more suitable for verification algorithms that do not need loop invariants
- uses relational semantics for “simple statements”

On the next slide, we see an example of a control-flow graph and we probably already have an idea what a control-flow graph should be.

Question: how can we introduce the notion of a control-flow graph formally?
Example: Control-flow Graph

Code of program $P_{ab}$

```c
while (!(b == 0)) {
    if (b >= 0) {
        b := b - 1;
    } else {
        b := b + 1;
    }
    a := a + 1;
}
```

Control-flow graph of $P_{ab}$
Outline of the Section on Control-flow graphs

Motivation
Formal Definition
Program Executions
Proof of the Error Execution Theorem
Definition (Control-Flow Graph)

A \textit{control-flow graph} is a tuple $G = (\text{Loc}, \Delta, \ell_{\text{init}}, \ell_{\text{ex}})$ where

- $\text{Loc}$ is a finite set whose elements we call \textit{locations},
- $\Delta$ is a ternary relation that consists of triples $(\ell, st, \ell')$ where $\ell$ and $\ell'$ are locations and $st$ is either
  - an assignment statement,
  - an array assignment statement,
  - a havoc statement, or
  - an assume statement.
- $\ell_{\text{init}}$ is a location that we call the \textit{initial location}
- $\ell_{\text{ex}}$ is a location that we call the \textit{exit location}

Definition (Control-Flow Graph for a Program)

Given a program $P = (V, \mu, st)$ we say that a control-flow graph $G$ is a \textit{control-flow graph for $P$} if $G$ is a control-flow graph for $st$ which we define inductively on the next slides.
Control-Flow Graph for Simple Statements

Definition:

Let $st$ be

- an assignment statement,
- an array assignment statement,
- a havoc statement, or
- an assume statement,

then $G = (\text{Loc}, \Delta, \ell_{\text{init}}, \ell_{\text{ex}})$ such that

- $\text{Loc} = \{\ell_{\text{init}}, \ell_{\text{ex}}\}$,
- $\Delta = \{(\ell_{\text{init}}, st, \ell_{\text{ex}})\}$, and
- $\ell_{\text{init}} \neq \ell_{\text{ex}}$

is a control-flow graph for $st$.

Example:
Notational Conventions

In order to improve legibility of a control-flow graph, we typically

▶ put a gray box around statements,
▶ omit the “assume” prefix of assume statements (i.e., write $b \geq 0$ instead of $\text{assume } b \geq 0$), and
▶ omit the semicolon at the end of (array-)assume statements and havoc statements.

Control-Flow Graphs are Unique up to Locations

We do not define “the” control-flow graph for a statement, we only define when a graph is “a” control-flow graph of a given statement. We do so because we do not want to fix a naming scheme for the locations. Using the terminology of graph theory we can say that all control-flow graphs for a given statement are isomorphic to each other.
Control-Flow Graph for a Sequential Composition

Let $G^1 = (\text{Loc}^1, \Delta^1, \ell^1_{\text{init}}, \ell^1_{\text{ex}})$ be a control-flow graph for $st_1$, let $G^2 = (\text{Loc}^2, \Delta^2, \ell^2_{\text{init}}, \ell^2_{\text{ex}})$ be a control-flow graph for $st_2$ such that $\text{Loc}^1$ and $\text{Loc}^2$ are disjoint.

Let $G^3 = (\text{Loc}^3, \Delta^3, \ell^3_{\text{init}}, \ell^3_{\text{ex}})$ be the modification of $G^2$ where we replaced every occurrence of $\ell^2_{\text{init}}$ by $\ell^1_{\text{ex}}$, i.e.,

- $\text{Loc}^3 = \text{Loc}^2 \setminus \{\ell^2_{\text{init}}\} \cup \{\ell^1_{\text{ex}}\}$
- $\Delta^3 = \{(\ell^1_{\text{ex}}, st, \ell') \mid (\ell^2_{\text{init}}, st, \ell') \in \Delta^2\}$
  $\cup \{(\ell, st, \ell^1_{\text{ex}}) \mid (\ell, st, \ell^2_{\text{init}}) \in \Delta^2\}$
  $\cup \{(\ell, st, \ell') \mid (\ell, st, \ell') \in \Delta^2 \text{ s.t. } \ell \neq \ell^2_{\text{init}} \text{ and } \ell' \neq \ell^2_{\text{init}}\}$
- $\ell^3_{\text{init}} = \ell^1_{\text{ex}}$
- $\ell^3_{\text{ex}} = \ell^2_{\text{ex}}$

Then $G = (\text{Loc}^1 \cup \text{Loc}^3, \Delta^1 \cup \Delta^3, \ell^1_{\text{init}}, \ell^3_{\text{ex}})$ is a control-flow graph for the sequential composition $st_1st_2$. 
Control-Flow Graph for a Conditional Statement

Let $G^1 = (\text{Loc}^1, \Delta^1, \ell^1_{\text{init}}, \ell^1_{\text{ex}})$ be a control-flow graph for $st_1$, let $G^2 = (\text{Loc}^2, \Delta^2, \ell^2_{\text{init}}, \ell^2_{\text{ex}})$ be a control-flow graph for $st_2$ such that $\text{Loc}^1$ and $\text{Loc}^2$ are disjoint.

The definition of a control-flow graph for the conditional statement

\[
\text{if}(\text{expr})\{st_1\} \text{ else } \{st_2\}
\]

is the task of Exercise 1 on Exercise Sheet 14.
Control-Flow Graph for a While Statement

Let $G = (\text{Loc}, \Delta, \ell_{\text{init}}, \ell_{\text{ex}})$ be a control-flow graph for $st$. Let $\ell_{\text{ex}}^w$ be a location that does not occur in $\text{Loc}$.

Then $G^w = (\text{Loc}^w, \Delta^w, \ell_{\text{init}}^w, \ell_{\text{ex}}^w)$ such that

- $\text{Loc}^w = \text{Loc} \cup \{\ell_{\text{ex}}^w\}$
- $\Delta^w = \Delta \cup \{(\ell_{\text{ex}}, \text{assume}\ expr, \ell_{\text{init}})\} \cup \{(\ell_{\text{ex}}, \text{assume}\ !\ expr, \ell_{\text{ex}}^w)\}$
- $\ell_{\text{init}}^w = \ell_{\text{ex}}$
- $\ell_{\text{ex}}^w = \ell_{\text{ex}}$

is a control-flow graph for the statement

\[ \text{while (expr) \{ st \}.} \]
Example: Control-flow Graph

Code of program $P_{ab}$

```c
while (!(b == 0)) {
    if (b >= 0) {
        b := b - 1;
    } else {
        b := b + 1;
    }
    a := a + 1;
}
```

Control-flow graph of $P_{ab}$
Outline of the Section on Control-flow graphs

- Motivation
- Formal Definition
- Program Executions
- Proof of the Error Execution Theorem
Control-Flow and Data

The control-flow graph is only an alternative syntactic representation of a program. In order to get also an alternative view on the program’s behavior we will make several new definitions in this subsection.

The graph structure of the control-flow graph captures only one aspect of a program, namely it defines the way in which the programmer arranged the statements in the code. This graph structure allows us to specify where the program currently is but this formalism does not (directly) allow us to talk about the data that is stored in the program’s variables.

Our definition of a program state is focused solely on the program’s data but it is not sufficient to specify the situation in which a program currently is, because the state does not provide information about the next statements that can be executed.

We will next give several definitions that combine control-flow aspects and data aspects of a program and allow us to talk about program correctness in our control-flow graph-based formalism.
Let $P = (V, \mu, st)$ be a program and $G = (Loc, \Delta, l_{\text{init}}, l_{\text{ex}})$ be a control-flow graph for $P$.

**Definition (Program Configuration)**

We call a pair $(l, s)$ a program configuration of $P$ if $l \in Loc$ is a location and $s$ is a state of $P$.

**Definition (Execution)**

We call a sequence of program configurations $(l_0, s_0), \ldots, (l_n, s_n)$ an execution of $P$ if there exists a sequence of statements $st_1 \ldots st_n$ such that for each $i \in \{0, \ldots n - 1\}$

$$(l_i, st_{i+1}, l_{i+1}) \in \Delta \text{ and }$$

$$(s_i, s_{i+1}) \in [st_{i+1}]$$
This is a typical (boring) example of an execution. Executions do not have to start at the initial location. Executions do not have to end at the exit location.
Let \((\varphi_{\text{pre}}, \varphi_{\text{post}})\) be a precondition-postcondition pair for \(P\).

**Definition**

We call the program configuration \((\ell, s)\)

- **initial**, if \(\ell = \ell_{\text{init}}\) and \(s \in \{\varphi_{\text{pre}}\}\)
- an **error configuration** if \(\ell = \ell_{\text{ex}}\) and \(s \notin \{\varphi_{\text{post}}\}\)

Note that later in this course we will introduce assert statements and then we will extend the definition of an error configuration.

**Theorem (PppSatAndExec)**

The program \(P = (V, \mu, st)\) satisfies the precondition-postcondition pair \((\varphi_{\text{pre}}, \varphi_{\text{post}})\) iff there exists no execution \((\ell_0, s_0), \ldots, (\ell_n, s_n)\) such that \((\ell_0, s_0)\) is an initial configuration and \((\ell_n, s_n)\) is an error configuration.

We will discuss the proof of this theorem later. First we will see how we can use this theorem.
Does the following program satisfy the given precondition-postcondition pair?

```c
while(x % 1337 != 0) {
    if (y % 37 != 0) {
        x = (3 * x) % (256 * 256);
        y = (- 2 * y + 1) % (256 * 256);
    } else {
        tmp = x;
        x = y;
        y = tmp;
    }
}
```

ϕ\text{pre} : \ x = 1 \land y = 1
ϕ\text{post} : \ y \leq 31337

If a program is correct, we can give a derivation in the Hore proof system. Let’s assume that we tried for hours to find a derivation but failed and now have the impression that the program does not satisfy the precondition-postcondition pair. So far we only had one way to formally show that \((ϕ\text{pre},ϕ\text{post})\) is not satisfied: compute the binary relation over states for this program to check if every pair satisfies the precondition-postcondition pair. Unfortunately, the relation of this program is very complex and we (resp. at least the lecturer) do not have an idea how to compute it efficiently.

Thanks to Theorem PppSatAndExec we now have an alternative within our formal setting: we can give an execution.
Since there is only one single initial configuration we can run the program and in case it terminates we can check the value of the variable y.

```c
#include <stdio.h>

int main(void) {
    unsigned short x = 1;
    unsigned short y = 1;
    while(x % 1337 != 0) {
        if (y % 37 !=0 ) {
            x = (3 * x);
            y = (- 2 * y + 1);
        } else {
            unsigned short tmp = x;
            x = y;
            y = tmp;
        }
        printf("value of x is %d\n", x);
        printf("value of y is %d\n", y);
    }
    return 0;
}
```

In order to do so we implemented the program in C.

The output has 8616 lines, it starts with the lines

value of x is 3
value of y is 65535

and ends with the lines

value of x is 33425
value of y is 43691

We assume optimistically that this C program really mimics the Boostan program from the preceding slide and conclude that the Boo program does not satisfy the given precondition-postcondition pair.
Example

Consider the program $P_{\text{xor}}$ with $V = \{x, y\}$, $\mu(x) = \mu(y) = \{\text{true, false}\}$.

Q: Does the following program satisfy the given precondition-postcondition pair?

```
1 while (x == y) {
2    y := x;
3    havoc x;
4 }
```

ϕ pre : $x$
ϕ post : $x \rightarrow \neg y$

A: Yes. Loop invariant $\text{true}$ is sufficient. If we leave the loop then $x$ and $y$ are disjoint.

Q: Does Theorem PppSatAndExec also allow us to give an alternative proof that uses executions?

A: Not directly. The program has infinitely many executions that start in the initial location and end in the exit location. We cannot check all of them.

The definitions on the next slide will however help us to approach the problem.
Definition (Reachable Program Configuration)

We call a configuration $((\ell, s))$ reachable if there exists a program execution $(\ell_0, s_0), \ldots, (\ell_n, s_n)$ such that $(\ell_0, s_0)$ is an initial configuration and $(\ell_n, s_n) = (\ell, s)$.

Theorem (CorrectIffNoErrorReach)

A program satisfies a given precondition-postcondition pair iff the set of reachable configurations does not contain an error configuration.

Proof. Follows directly from Theorem PppSatAndExec and the definition above.

Can we compute the set of reachable program configurations?
Theorem

The set of reachable configurations $RC$ is the smallest set such that

- each initial configuration is an element of $RC$
- if $(\ell, s) \in RC$, $(\ell, st, \ell') \in \Delta$ and $(s, s') \in \llbracket st \rrbracket$ then $(\ell', s') \in RC$.

Proof. Nontrivial. Later in this course.

This algorithm hints a simple (possibly nonterminating) algorithm for the construction of the set of reachable configurations. For the construction of this set the following graph can be helpful.

Definition

The reachability graph is a pair $(RC, T)$ such that $((\ell, s), st, (\ell', s')) \in T$ iff $(\ell, st, \ell') \in \Delta$ and $(s, s') \in \llbracket st \rrbracket$

Exercise: Construct the reachability graph for the Program $P_{\text{xor}}$. (Exercise Sheet 14)
Outline of the Section on Control-flow graphs

Motivation
Formal Definition
Program Executions
Proof of the Error Execution Theorem
In this subsection, we prove the Theorem PppSatAndExec.

We start by stating the following lemma. The theorem follows directly from this lemma, the definition of an error configuration and the definition of satisfiability of precondition-postcondition pairs.

**Lemma (RelAndExec)**

Let \( G = (\text{Loc}, \Delta, \ell_{\text{init}}, \ell_{\text{ex}}) \) be a control-flow graph for \( st \), then there exists a program execution \((\ell_0, s_0), \ldots, (\ell_n, s_n)\) with \( \ell_0 = \ell_{\text{init}} \) and \( \ell_n = \ell_{\text{ex}} \), iff \((s_0, s_n) \in [st]\).

**Proof.** By induction over the height of \( st \)'s derivation tree. Using the five lemmas from the remaining subsection, the proof can be carried out analogously to the soundness proof for the Hoare proof system.
Lemma (RelAndExec.1)

Let \( st \) be an assignment statement, an array assignment statement, a havoc statement, or an assume statement, and let \( G = (\text{Loc}, \Delta, l_{\text{init}}, l_{\text{ex}}) \) be a control-flow graph for \( st \). There exists a program execution \( (l_0, s_0), \ldots, (l_n, s_n) \) with \( l_0 = l_{\text{init}} \) and \( l_n = l_{\text{ex}} \), iff \( (s_0, s_n) \in \llbracket st \rrbracket \).

Proof.
Since \( st \) is an assignment statement, an array assignment statement, a havoc statement, or an assume statement, the control-flow graph has the form \( G = (\{l_{\text{init}}, l_{\text{ex}}\}, \{(l_{\text{init}}, st, l_{\text{ex}})\}, l_{\text{init}}, l_{\text{ex}}) \).

“\( \Rightarrow \)” By definition of a program execution we have \( (l_i, st_{i+1}, l_{i+1}) \in \Delta \) for each \( i \in \{0, \ldots, n-1\} \). Since \( \Delta \) contains only one element and \( l_{\text{init}} \neq l_{\text{ex}} \), the execution is a sequence of length 2 and has the form \( (l_{\text{init}}, s_0), (l_{\text{ex}}, s_1) \). By definition of a program execution there has to be some statement such \( st_1 \) that \( (l_{\text{init}}, st_1, l_{\text{ex}}) \in \Delta \) and \( (s_0, s_1) \in \llbracket st_1 \rrbracket \). Since there is only one statement in the control-flow graph, \( st_1 \) is \( st \).

“\( \Leftarrow \)” Let \( (s, s') \) be a pair of states for which the assumption \( (s, s') \in \llbracket st \rrbracket \) holds. Since \( (l_{\text{init}}, st, l_{\text{ex}}) \in \Delta \), the sequence \( (l_{\text{init}}, s), (l_{\text{ex}}, s') \) is an execution.
Lemma (RelAndExec.2)

Let \( G = (\text{Loc}, \Delta, \ell_{\text{init}}, \ell_{\text{ex}}) \) be a control-flow graph for the sequential composition \( st_1 st_2 \). There exists a program execution \( (\ell_0, s_0), \ldots, (\ell_n, s_n) \) with \( \ell_0 = \ell_{\text{init}} \) and \( \ell_n = \ell_{\text{ex}} \), iff \( (s_0, s_n) \in \llbracket st_1 st_2 \rrbracket \).

Proof. Exercise 3 on Exercise Sheet 15.
Lemma (RelAndExec.3)

Let $G = (\text{Loc}, \Delta, \ell_{\text{init}}, \ell_{\text{ex}})$ be a control-flow graph for the conditional statement $\text{if}(\text{expr})\{\text{st}_1\}\text{else}\{\text{st}_1\}$. There exists a program execution $(\ell_0, s_0), \ldots, (\ell_n, s_n)$ with $\ell_0 = \ell_{\text{init}}$ and $\ell_n = \ell_{\text{ex}}$, iff $(s_0, s_n) \in \llbracket \text{if}(\text{expr})\{\text{st}_1\}\text{else}\{\text{st}_1\} \rrbracket$.

Proof. Analogously to the other proofs in this subsection. No carried out in the lecture.
Lemma (RelAndExec.4)

Let $G = (\text{Loc}, \Delta, \ell_{\text{init}}, \ell_{\text{ex}})$ be a control-flow graph for the statement \( \text{while}(\text{expr})\{\text{st}\} \). There exists a program execution \((\ell_0, s_0), \ldots, (\ell_n, s_n)\) with \( \ell_0 = \ell_{\text{init}} \) and \( \ell_n = \ell_{\text{ex}} \), iff \((s_0, s_n) \in \llbracket \text{while}(\text{expr})\{\text{st}\} \rrbracket \).

Proof.

Let $G' = (\text{Loc}^{\text{st}}, \Delta^{\text{st}}, \ell_{\text{init}}^{\text{st}}, \ell_{\text{ex}}^{\text{st}})$ be the control flow graph for \( \text{st} \) from which \( G \) is built. Then $\ell_{\text{init}} = \ell_{\text{ex}}^{\text{st}}$. Furthermore, let $R = (\{\text{expr}\} \times S_{\nu, \mu}) \cap \llbracket \text{st} \rrbracket$. 
Let \((s_0, s_n) \in \llbracket \text{while(expr)} \{st\} \rrbracket = R^* \cap (S_{V, \mu} \times \{!expr\})\). Then \(s_n \in \{!expr\}\), and \((s_0, s_n) \in R^k\) for some \(k \in \mathbb{N}_0\). We perform induction over \(k\):

- For \(k = 0\), it follows that \(s_0 = s_n \in \{!expr\}\). By the definition of a CFG for \texttt{while}-statements, \(G\) has an edge \((\ell_{\text{init}}, \texttt{assume !expr;}, \ell_{\text{ex}})\). Hence the sequence \((\ell_{\text{init}}, s_0), (\ell_{\text{ex}}, s_n)\) is a program execution.

- For \(k + 1\), we observe that there exists some \(s'\) such that \((s_0, s') \in R\) and \((s', s_n) \in R^k\). By induction hypothesis, there is an execution \((\ell_m, s_m), \ldots, (\ell_n, s_n)\) with \(s_m = s'\), \(\ell_m = \ell_{\text{init}}\) and \(\ell_n = \ell_{\text{ex}}\).

From \((s_0, s') \in R\) we conclude \(s_0 \in \{\text{expr}\}\) and \((s_0, s') \in \llbracket \text{st} \rrbracket\). By structural induction over the program, it follows that there is an execution \((\ell_1, s_1), \ldots, (\ell_m, s_m)\) with \(\ell_1 = \ell_{\text{init}}^\text{st}, s_1 = s_0, \ell_m = \ell_{\text{ex}}^\text{st}\) and \(s_m = s'\). Furthermore, \((\ell_{\text{init}}, \texttt{assume expr;}, \ell_1) \in \Delta\) and \((s_0, s_1) \in \llbracket \texttt{assume expr;} \rrbracket\). Hence we combine the executions as \((\ell_0, s_0), (\ell_1, s_1), \ldots, (\ell_m, s_m), \ldots, (\ell_n, s_n)\).
Let \((\ell_0, s_0), \ldots, (\ell_n, s_n)\) be such a program execution. We perform the induction over \(k\), the number of occurrences of \(\ell_{\text{ex}} = \ell_{\text{init}}\) among the \(\ell_i\).

- For \(k = 1\) (\(k = 0\) is not possible), we must have \(n = 1\), as the only incoming transition of \(\ell_n = \ell_{\text{ex}}\) is \((\ell_{\text{init}}, \text{assume !expr}, \ell_{\text{ex}})\). Hence we must have \(s_0 = s_n \in \{!\text{expr}\}\) and thus \((s_0, s_n) \in \llbracket \text{while (expr) \{st\}} \rrbracket\).

- For \(k + 1\), let \(m\) be the second occurrence of \(\ell_{\text{init}}\), i.e., \(\ell_m = \ell_{\text{init}}\) with \(m > 0\) and \(\ell_j \neq \ell_{\text{init}}\) for all \(0 < j \leq m\). Then \((\ell_m, s_m), \ldots, (\ell_n, s_n)\) is an execution and by induction \((s_m, s_n) \in \llbracket \text{while(expr)}\{st\} \rrbracket\), i.e., \((s_m, s_n) \in R^*\) and \(s_n \in \{!\text{expr}\}\).

Then \(\ell_1 = \ell_{\text{init}}\), as that is the only other outgoing edge from \(\ell_{\text{init}} = \ell_0\), and hence \((s_0, s_1) \in \llbracket \text{assume expr;} \rrbracket\) and \(s_0 = s_1 \in \{\text{expr}\}\). The sequence \((\ell_1, s_1), \ldots, (\ell_m, s_m)\) is then an execution of \(\text{st}\) (in \(G'\)) with \(\ell_m = \ell_{\text{ex}}\), and by structural induction it follows that \((s_1, s_m) \in \llbracket \text{st} \rrbracket\). Thereby \((s_0, s_m) \in R\).

By sequential composition with \((s_m, s_n)\) we conclude \((s_0, s_n) \in R^*\). Finally, it follows that \((s_0, s_n) \in \llbracket \text{while(expr)}\{st\} \rrbracket\).  

\(\blacksquare\)
Program Verification

Summer Term 2021

Lecture 17: Predicate Transformers

Matthias Heizmann

Monday 21st June
Section 12

Predicate Transformers
In this section we will learn about program transformers\(^{21}\) which will be our main means for analyzing the effect of statements in our control-flow graph-based view on programs.

Goals of this section are

- learn to execute a loop-free program symbolically (i.e., on all inputs in parallel)
- deepen our understanding about the connection between formulas and sets of states
- learn to simplify formulas by eliminating quantifiers

\(^{21}\)https://en.wikipedia.org/wiki/Predicate_transformer_semantics
Outline of the Section on Predicate Transformers

- **Motivation**
- Strongest Post
- Excursus: Formulas and Sets of States
- Excursus: Quantifier Elimination
- Strongest Post And Formulas
- Weakest Precondition
Consider the program $P_{\text{xor}}$ with $V = \{x, y, z\}$, $\mu(x) = \mu(y) = \mu(z) = \mathbb{Z}$.

**Q:** Does the following program satisfy the given precondition-postcondition pair?

```
1  z := y + x;
2  assume x <= -25;
3  x := z * z - 2;
4  assume x < 0;
5  havoc x;
6  assume (z*(y % 23) < -20);
```

$\varphi_{\text{pre}} : \ y \geq 1$

$\varphi_{\text{post}} : \ y \geq 45$
From Theorem PppSatAndExec we know that we can disprove correctness by finding an execution that starts in an initial configuration and ends in an error configuration. On the next slide we will try to find such an execution.

Unlike a program from the last section this program has more than one initial states.

- We do not really know where we should start, apply an naive approach where we pick some state and run the program.
- The execution “gets stuck” at the first assume statement. We wonder if only this execution does not reach the error configuration or if all executions cannot reach an error configuration. We realize that we could have passed the first assume statement if we would have started in a different state. We pick a different initial configuration and restart do construct an execution.
- The execution “gets stuck” at the second assume statement. We wonder if only this execution does not reach the error configuration or if all executions cannot reach an error configuration. We realize that we could have passed the second assume statement if we would have started in a different state. We pick a different initial configuration and restart do construct an execution.
- ...
Example

$z := y + x$

$x := z^2 - 2$

$x < 0$

havoc $x$

$z \cdot (y \% 23) < -20$
In order to find a suitable execution you probably did (maybe implicitly) compute the set of all states that are reachable after each of the statements. The next slide shows formulas whose satisfying variable assignments are exactly the reachable sets of states.

In the next subsection we define the *strongest post predicate transformer* which allows us to compute these formulas.
Example

\[ z := y + x \]
\[ x \leq -25 \]
\[ z = y + x \land x \leq -25 \]
\[ x := z^2 - 2 \land z - y \leq -25 \]
\[ x = z^2 - 2 \land x < 0 \land z - y \leq -25 \]
\[ \text{havoc } x \]
\[ -1 \leq z \land z \leq 1 \land z - y \leq -25 \]
\[ z*(y\%23) < -20 \]
\[ z = -1 \land y \geq 24 \land (y\%23) > 20 \]
Outline of the Section on Predicate Transformers

Motivation

Strongest Post

Excursus: Formulas and Sets of States

Excursus: Quantifier Elimination

Strongest Post And Formulas

Weakest Precondition
First, we state informally the properties that our definition of the strongest post operator $sp$ should have. Then we discuss how we could give a formal definition.

Idea:
Given a set of states $S$ and a statement $st$, the strongest postcondition $sp(S, st)$ is the set of states for which the following holds. If there is a state $s \in S$

- in which we can execute $st$,
- in which $st$ terminates, and
- $s'$ is a successor after executing $st$
then $s' \in sp(S, st)$. 
Given a binary relation $R$ over the set $X$ and a subset of $Y \subseteq X$, the
*postimage of $Y$ under $R$*, denoted $\text{post}(Y, R)$, is the set
\[
\{ x \in X \mid \text{exists } y \in Y \text{ such that } (y, x) \in R \}
\]

**Example**

Let $R$ be the “strictly smaller” relation over $\mathbb{Z}$ (i.e.,
\[ R = \{(a, b) \in \mathbb{Z} \times \mathbb{Z} \mid a < b \}\]) and $Y = \{y \in \mathbb{Z} \mid y \geq 5\}$ then
\[
\text{post}(Y, R) = \{y \in \mathbb{Z} \mid y \geq 6\}
\]
**Definition (Strongest Postcondition)**

Given a set of states $S$ and a statement $st$ the *strongest postcondition* is the post image of $S$ under the relation $\llbracket st \rrbracket$, i.e.

$$sp(S, st) = post(S, \llbracket st \rrbracket).$$

**Example**

See Exercise Sheet 16.

In one of the next subsections we will see some special cases in which the resulting state of the strongest postcondition can be represented by a formula if the input was represented by a formula.
Outline of the Section on Predicate Transformers

- Motivation
- Strongest Post
- **Excursus: Formulas and Sets of States**
- **Excursus: Quantifier Elimination**
- Strongest Post And Formulas
- Weakest Precondition
The goal of this short subsection/excursus is to deepen/recap our understanding of the connection between formulas and sets of states.
Reminder (Implication)

Given a (possibly infinite) set of FOL formulas $\Gamma$ and a PL formula $\psi$, we say that $\Gamma$ implies $\psi$ if for all models $M$ and for all variable assignments $\rho$ the following holds.

If $[\varphi]_{M,\rho}$ is true for all $\varphi \in \Gamma$ then also $[\psi]_{M,\rho}$ is true

We use $\models$ to denote this binary implication relation and we say that the implication $\Gamma \models \psi$ holds if $\Gamma$ implies $\psi$. Furthermore, we say that $\varphi$ implies $\psi$, written $\varphi \models \psi$, if the implication $\{\varphi\} \models \psi$ holds.

Reminder: Since the end of our introduction to logics we consider only models $M$ in which the axioms of all SMT-LIB theories are valid.

Theorem (Duality of Implication and Subset)

$\varphi$ implies $\psi$ iff $\{\rho \mid [\varphi]_{M,\rho}$ is true$\} \subseteq \{\rho \mid [\psi]_{M,\rho}$ is true$\}$

Reminder (Sets of Program States)

Given a program $P = (V, \mu, T)$ we defined $\{\varphi\} := \{s \in S_{V,\mu} \mid [\varphi]_{M,\rho}$ is true for $\rho = s\}$

Corollary (Duality of Implication and Subset)

$\varphi$ implies $\psi$ iff $\{\psi\} \subseteq \{\varphi\}$
\[
\begin{align*}
true &= y \geq 23 \lor x = 42 \\
false &= y \geq 23 \land x = 42 \\
\end{align*}
\]
Outline of the Section on Predicate Transformers

Motivation
Strongest Post
Excursus: Formulas and Sets of States
Excursus: Quantifier Elimination
Strongest Post And Formulas
Weakest Precondition
Quantified formulas are notoriously difficult to solve. Later in this section we have to deal with quantified formulas. In this subsection we will learn about quantifier elimination which is the task of finding an equivalent quantifier-free formula for a given formula.
Quantifier Elimination

Theorem (Destructive Equality Resolution 1)

If the variable $x$ does not occur in the term $t$ then the formula $\exists x. \varphi \wedge x = t$ and the formula $\varphi[x \mapsto t]$ are equivalent.

Proof. Not given in this course. Follows directly from the axioms of equality and the semantics of existential quantification and conjunction.

Problem: Formula does not have required form.
Solution: Do equivalence transformation which solves equality for subject $\hat{x}$.

Example

$\exists \hat{x}. (\hat{x} \% 2) = 0 \wedge x = \hat{x} + 1$

Equivalent to

$\exists \hat{x}. (\hat{x} \% 2) = 0 \wedge \hat{x} = x - 1$

Equivalent to

$(x - 1) \% 2 = 0$
Problem: Since \( \hat{x} \) is an integer we cannot simply divide by 2.
Solution: We can divide by 2 if we add the conjunct \((x\%2) = 0\).

Example

Let \( x, \hat{x} \) be variable symbols whose sort is \( \text{Int} \).

\[
\exists \hat{x}. \text{select}(a, \hat{x}) = 23 \land x = 2 \cdot \hat{x}
\]

equivalent to \( \exists \hat{x}. \text{select}(a, \hat{x}) = 23 \land \hat{x} = x \text{ div } 2 \land (x\%2) = 0 \)

equivalent to \( \text{select}(a, x \text{ div } 2) = 23 \land (x\%2) = 0 \)

Problem: Since \( y \) could be 0, we cannot simply divide by \( y \).
Solution: Case distinction. (Does eliminate quantifier but reduces its scope.)

Example

Let \( x, \hat{x}, y \) be variable symbols whose sort is \( \text{Real} \).

\[
\exists \hat{x}. \text{select}(a, \hat{x}) = 23 \land x = y \cdot \hat{x}
\]

equivalent to \( \exists \hat{x}. \text{select}(a, \hat{x}) = 23 \land x = y \cdot \hat{x} \land y \neq 0 \)

\( \lor \) \( \text{select}(a, \hat{x}) = 23 \land x = y \cdot \hat{x} \land y = 0 \)

equivalent to \( \text{select}(a, x/y) = 23 \land y \neq 0 \)

\( \lor \) \( (\exists \hat{x}. \text{select}(a, \hat{x}) = 23) \land x = 0 \land y = 0 \)
Quantifier Elimination

**Theorem (Destructive Equality Resolution 2)**

*If the variable* \( x \) *does not occur in the term* \( t \) *then the formula* \( \forall x. \varphi \lor x \neq t \) *and the formula* \( \varphi[x \mapsto t] \) *are equivalent.*

**Proof.** Negate und and use the destructive equality resolution theorem for existential quantification. Discussed only very briefly in the lecture.
Outline of the Section on Predicate Transformers

Motivation
Strongest Post
Excursus: Formulas and Sets of States
Excursus: Quantifier Elimination
Strongest Post And Formulas
Weakest Precondition
In practice we represent sets of states by formulas and we would like to let a machine compute the strongest post operator. The definition of the strongest post operator does not directly tell us how we can implement the operator.

In this subsection we will see characterizations of the strongest post operator that will ease an implementation of the operator. For these characterizations, we consider each kind of statement individually and we always consider the special case where the set of states is given by a formula.
Theorem (Strongest Post of the Assignment Statement)

\[ sp(\{\varphi\}, \text{ x := expr}) \text{ is } \{ \exists \hat{x}. \varphi[x \mapsto \hat{x}] \land x = expr[x \mapsto \hat{x}] \} \]

Reminder (Semantics of the Assignment Statement)

\[ \llbracket x := expr; \rrbracket \text{ is } \{(s_1, s_2) \in S_{V, \mu} \times S_{V, \mu} \mid \llbracket x' = expr \land \bigwedge_{v \in V, v \neq x} v' = v \rrbracket_{M, \rho} \text{ is true} \text{ and } \rho = s_1 \cup \text{prime}(s_2)\} \]

Proof.

\[ sp(\{\varphi\}, \text{ x := expr;}) \]
\[ = \{s_2 \mid \text{exists } s_1 \in \{\varphi\} \text{ and } (s_1, s_2) \in \llbracket x := expr; \rrbracket \} \]
\[ = \{s_2 \mid \text{exists } s_1 \in S_{V, \mu} \text{ and } \llbracket \varphi \land x' = expr \land \bigwedge_{v \in V, v \neq x} v' = v \rrbracket_{M, \rho} \text{ is true} \text{ and } \rho = s_1 \cup \text{prime}(s_2)\} \]
\[ = \{s_2 \mid \llbracket \exists \hat{v}_1 \ldots \exists \hat{v}_n. \varphi[v_1 \mapsto \hat{v}_1, \ldots, v_n \mapsto \hat{v}_n] \land x = expr[v_1 \mapsto \hat{v}_1, \ldots, v_n \mapsto \hat{v}_n] \land \bigwedge_{v \in V, v \neq x} v = \hat{v} \rrbracket_{M, \rho} \text{ is true and } \rho = s_2 \} \]
\[ = \{s_2 \mid \llbracket \exists \hat{x}. \varphi[x \mapsto \hat{x}] \land x = expr[x \mapsto \hat{x}] \rrbracket_{M, \rho} \text{ is true and } \rho = s_2 \} \]
\[ = \{ \exists \hat{x}. \varphi[x \mapsto \hat{x}] \land x = expr[x \mapsto \hat{x}] \} \]
Theorem (Strongest Post of the Havoc Statement)

\[ sp(\{\varphi\}, \text{havoc } x;) \text{ is } \{\exists x. \varphi\} \]

Reminder (Semantics of the Havoc Statement)

\[ [\text{havoc } x;] \text{ is } \{(s_1, s_2) \in S_{V,\mu} \times S_{V,\mu} \mid [x' = expr \land \bigwedge_{v \in V, v \neq x} v' = v]_{M,\rho} \text{ is true} \text{ and } \rho = s_1 \cup \text{prime}(s_2)\} \]

Proof. Very similar to the proof for the Assignment Statement.
Theorem (Strongest Post of the Assume Statement)

\[ sp(\{\text{\varphi}\}, \text{assume } \text{expr};) \text{ is } \{\varphi \land \text{expr}\} \]

Reminder (Semantics of the Assume Statement)

\[[\text{assume } \text{expr};]\text{ is } \{s_1, s_2 \in S_{V,\mu} \times S_{V,\mu} \mid s_1 = s_2 \text{ and } s_2 \in \{\text{expr}\}\}\]

Proof.

\[ sp(\{\varphi\}, \text{assume } \text{expr};) \]
\[ = \{s_2 \mid \exists s_1 \in \{\varphi\} \text{ and } (s_1, s_2) \in [[\text{assume } \text{expr};]]\} \]
\[ = \{s_2 \mid \exists s_1 \in \{\varphi\} \text{ and } s_1 = s_2 \text{ and } s_2 \in \{\text{expr}\}\} \]
\[ = \{\varphi \land \text{expr}\} \]
Theorem (Strongest Post of the Sequential Composition)

If $st$ is an sequential composition of the form $st_1st_2$, then $sp(S, st)$ is $sp(sp(S, st_1), st_2)$.

Reminder (Semantics of the Sequential Composition)

$[st_1st_2]$ is $[st_1] \circ [st_2]$ “the relational composition”

Reminder (Post Image)

\[
post(Y, R) = \{ x \in X \mid \text{exists } y \in Y \text{ such that } (y, x) \in R \}
\]

Proof.

\[
sp(S, st_1st_2)
\]
\[
= \{ s_3 \in S_{V,\mu} \mid \text{exists } s_1 \in \{\varphi\} \text{ such that } (s_1, s_3) \in \llbracket st_1st_2 \rrbracket \}
\]
\[
= \{ s_3 \in S_{V,\mu} \mid \text{exists } s_1 \in \{\varphi\}, \text{exists } s_2 \in S_{V,\mu} \text{ such that } (s_1, s_2) \in \llbracket st_1 \rrbracket \\
\text{and } (s_2, s_3) \in \llbracket st_2 \rrbracket \}
\]
\[
= \{ s_3 \in S_{V,\mu} \mid \text{exists } s_2 \in sp(\{\varphi\}, st_1) \text{ such that } (s_2, s_3) \in \llbracket st_2 \rrbracket \}
\]
\[
= sp(sp(S, st_1), st_2)
\]
Theorem (Strongest Post of the Conditional Statement)

See Exercise 1 of Exercise Sheet 17.
In general, we cannot express the strongest post of the while statement as a formula. However, we give a characterization that motivates that the strongest post of a while statement can be very complex in some cases and that is can also be computed in some special cases.

We define the \textit{k-th iterative application application} of the strongest post operator \( sp(\ldots sp(S, st)\ldots) \) formally as follows.

\textbf{Notation}

\[
sp^k(S, st) = \begin{cases} 
S & \text{if } k = 0 \\
sp(sp^{k-1}(S, st), st) & \text{if } k > 0 
\end{cases}
\]

\textbf{Theorem}

\textit{If } \textit{st} \textit{is a while statement of the form } while(expr)\{st\} \textit{then } sp(S, st) \textit{is}

\[
\bigcup_{k \in \mathbb{N}} sp(sp^k(S, \text{assume expr; st}), \text{assume !expr; })
\]
There are however several examples in which the strongest post of a while statement can be expressed by a formula.

**Example**

```
sp({i = 0}, while(b){i := i+1; havoc b;}) is {¬b ∧ i ≥ 0}
```

**Example**

```
sp({i = 0 ∧ i ≥ n}, while(i<n){a[i] := 0; i := i+1;}) is 
{i = n ∧ (∀k.(0 ≤ k ∧ k < n) → select(a, k) = 0)}
```

TODO Say something about the research area of loop acceleration.
Analogously to the strongest post predicate transformer $sp$, we defined the weakest precondition predicate transformer $wp$ in Exercise 4 of Exercise Sheet 17.
Program Verification
Summer Term 2021
Lecture 19: Bounded Model Checking

Matthias Heizmann

Monday 28th June
Section 13

Bounded Model Checking
Outline

Introduction

Propositional Logic

First-Order Logic

First-Order Theories

SMT-LIB

Boogie and Boostan

Hoare Proof System

Ultimate Referee

Arrays

Boogie and Boostan – Part 2

Control-flow graphs

Predicate Transformers

Bounded Model Checking

Correctness Specification via Assert Statement

Abstractions – Part 1

Infeasibility Proofs

CEGAR

Trace Abstraction

Constraint-based Invariant Synthesis

Termination Analysis
In this section we will learn the bounded model checking [ac/BiereCCSZ03] verification technique. We give a rather non-standard introduction to the topic because we use want to use definition that we need later in this course.

Goals of this section are

- set formal basis for the later sections on abstractions
- learn that positive tests results can be deceptive even if we have a high test coverage
- see an algorithm that can find bugs in erroneous programs
In this subsection we will only see two definitions. This definitions will be the basis for the following subsection that the basis for the sections on abstractions. There will be no examples in this subsection but we will see several examples in the remaining course. **TODO add links to examples**
Let $G = (\text{Loc}, \Delta, \ell_{\text{init}}, \ell_{\text{ex}})$ be a control-flow graph for a program $P = (V, \mu, st)$.

**Definition**

An **abstract (program) configuration** is a pair $(\ell, \{\varphi\})$ where $\ell$ is a location and $\varphi$ is a formula over the program’s variables.

**Definition**

An **abstract reachability graph** is a pair $(AC, T)$ such that $AC$ is a set of abstract configurations such that

1. for each abstract configuration $(\ell, \{\varphi\})$ for which $\varphi \neq \text{false}$ and there exists $(\ell, st, \ell') \in \Delta$, there is a abstract configuration $(\ell', \{\varphi'\})$ such that $sp(\{\varphi\}, st) \subseteq \{\varphi'\}$ and $((\ell, \{\varphi\}), st, (\ell', \{\varphi'\})) \in T$

2. $(\ell_{\text{init}}, \{\varphi_{\text{pre}}\}) \in AC$, and

3. for each abstract configuration $(\ell, \{\varphi\})$ there is a path from $(\ell_{\text{init}}, \{\varphi_{\text{pre}}\})$ to $(\ell, \{\varphi\})$.

We will come back to the (general) abstract reachability graph later and next consider a special case first.
Outline of the Section on Bounded Model Checking

Abstract Reachability Graph
Precise Abstract Reachability Graph
Algorithms for Constructing Graphs
A precise abstract reachability graph is an abstract reachability graph \((AC, T)\) such that for each \( (\ell, \{\varphi\}), st, (\ell', \{\varphi'\}) \) the equality \( sp(\{\varphi\}, st) = \{\varphi'\} \) holds.

- This definition is very similar to the definition of the abstract reachability graph but the inclusion in the first bullet point is always an equality.
- A precise abstract reachability graph for a given control-flow graph is unique up to the formulas that represent the set of state at each location.
We will next consider an implementation of the greatest common divisor (GCD) (see Exercise 1 on Exercise Sheet 06) and wonder if the implementation is correct.

We have seen in Exercise 1 of Exercise Sheet 05 that formulas that express the GCD are rather complex and hence we take as the postcondition only one property of the GCD. Rationale: if this property is violated, our implementation is bad and if the property is satisfied, we can strengthen the property.

In order to check correctness, we proceed as follows. We first run some tests. For each test, we pick an initial program configuration, construct an execution that starts with that initial configuration and check if the execution ends in an error configuration.

In order to improve legibility, we depict the tests as tables and omit the values of the variables $a_{\text{in}}$ and $b_{\text{in}}$. 
Example: a (faulty?) Implementation of the GCD

```c
while (!(a == b)) {
    if (a >= b) {
        a := (a - b) / 2;
    } else {
        b := (b - a) / 2;
    }
}
```

ϕ\textsubscript{pre} : \(a\text{\_in} = a \land b\text{\_in} = b \land a\text{\_in} > 0 \land b\text{\_in} > 0\)

ϕ\textsubscript{post} : \(a\text{\_in}\%a == 0 \land b\text{\_in}\%b == 0\)

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None of the three tests showed a violation of the postcondition. Furthermore these tests look like they cover most of the program’s behavior.

- Every statement is covered by some test.
- We have a test that takes the if-branch first, and we have a test that takes the else-branch first.
- We have a test for the corner case that both inputs are prime numbers.
- We have a test for the corner case that the result consists of several similar prime factors.

We might be tempted to believe that the program is correct.

However, if we start to build the precise abstract reachability graph, we see after a few iterations that there is an abstract program configuration whose set of states is not a subset of the postcondition.
Control-flow graph of our GCD implementation

\[
\begin{align*}
\ell_1 & \quad (a==b) \quad \ell_7 \\
\ell_5 & \quad ! (a==b) \quad \ell_3 \\
\ell_2 & \quad ! (a>=b) \quad \ell_1 \\
\end{align*}
\]

\[
\begin{align*}
b:= (b-a)/2 \\
a:= (a-b)/2 \\
! (a>=b) \\
! (a==b) \\
a>=b \\
a==b
\end{align*}
\]

Part of precise abstract reachability graph

\[
\begin{align*}
(\ell_1, \{a_{in} > 0 \land b_{in} > 0 \land a_{in} = a \land b_{in} = b\}) \\
\quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \ quart
Definition (Abstract Error Configuration)

Let $(\varphi_{\text{pre}}, \varphi_{\text{post}})$ be a precondition-postcondition pair. We call an abstract configuration $(\ell, \{\varphi\})$ an abstract error configuration if $\ell$ is the exit location and the inclusion $\{\varphi\} \subseteq \{\varphi_{\text{post}}\}$ does not hold.

Example

The abstract configuration

$$(\ell_7, \{a_{\text{in}} > 0 \wedge b_{\text{in}} > 0 \wedge b_{\text{in}} = b \wedge a_{\text{in}} > b \wedge a = (a_{\text{in}} - b)/2 \wedge a = b\})$$

from the preceding slide is an abstract error configuration.

There is an abstract error configuration in our example. The next lemma and the next theorem explain the consequences.
Let $P$ be a program and let $G$ be a control-flow graph for $P$.

**Theorem**

Let $(\varphi_{\text{pre}}, \varphi_{\text{post}})$ be a precondition-postcondition pair. The program $P$ satisfies $(\varphi_{\text{pre}}, \varphi_{\text{post}})$ iff the precise abstract reachability graph for $G$ does not contain an abstract error configuration.

Proof. Follows directly from Theorem CorrectIffNoErrorReach and the next Lemma.

**Lemma**

The set of reachable configurations contains an error configuration iff the precise abstract reachability graph for $G$ contains an abstract error configuration.

Proof. TODO
Additional exercises: (Difficult there are not always clear “yes”/“no” answers.)

1. How can we check if an abstract configuration is an abstract error configuration?
2. Is this check decidable?
3. How many nodes does an precise abstract reachability graph have?
4. Which direction of the theorem from the preceding slide is usually important?
5. In which cases is the other direction also important?
Outline of the Section on Bounded Model Checking

- Abstract Reachability Graph
- Precise Abstract Reachability Graph
- Algorithms for Constructing Graphs
In this subsection we will see

- an algorithm for the construction of the reachability graph \((RC, T)\) and
- an algorithm for the construction of the precise abstract reachability graph \((AC, T)\).

**Todo** Explain the algorithms: BFS traversal of the graph while it is build, perhaps no surprises if you are familiar with BFS traversal of graphs.
procedure \textsc{ConstructRC}((Loc, \Delta, l_{\text{init}}, l_{\text{ex}}) : CFG, \varphi_{\text{pre}} : Precondition) returns \((RC, T)\)

1. \(RC \leftarrow \emptyset, T \leftarrow \emptyset, \text{worklist} \leftarrow \emptyset\)
2. \(\text{for all } s \in \{\varphi_{\text{pre}}\} \text{ do}\)
3. \(\quad RC \leftarrow RC \cup \{(l_{\text{init}}, s)\}\)
4. \(\quad \text{worklist} \leftarrow \text{worklist} \cup \{(l_{\text{init}}, s)\}\)
5. \(\text{end for}\)
6. \(\text{while } \text{worklist} \neq \emptyset \text{ do}\)
7. \(\quad (l, s) \leftarrow \text{RemoveFirst}(\text{worklist})\)
8. \(\quad \text{for all } l', st \text{ with } (l, st, l') \in \Delta \text{ do}\)
9. \(\quad \quad \text{for all } s' \text{ with } (s, s') \in [st] \text{ do}\)
10. \(\quad \quad \quad T \leftarrow T \cup \{(l, s, st, l', s')\}\)
11. \(\quad \quad \text{if } (l', s') \notin RC \text{ then}\)
12. \(\quad \quad \quad RC \leftarrow RC \cup \{(l', s')\}\)
13. \(\quad \quad \text{worklist} \leftarrow \text{worklist} \cup \{(l', s')\}\)
14. \(\quad \quad \text{end if}\)
15. \(\quad \text{end for}\)
16. \(\quad \text{end for}\)
17. \(\text{end while}\)
18. \(\text{end procedure}\)
procedure CONSTRUCTAC((Loc, Δ, \(l_{\text{init}}\), \(l_{\text{ex}}\)) : CFG, \(\varphi_{\text{pre}}\) : Precondition)
returns \((AC, T)\)

2: \(T \leftarrow \emptyset\)
3: \(AC \leftarrow \{(\ell_{\text{init}}, \{\varphi_{\text{pre}}\})\}\)
4: worklist \(\leftarrow \{(\ell_{\text{init}}, \{\varphi_{\text{pre}}\})\}\)

5: while worklist \(\neq \emptyset\) do
6: \((\ell, S) \leftarrow \text{REMOVEFIRST}(\text{worklist})\)
7: for all \(\ell', st\) with \((\ell, st, \ell') \in \Delta\) do
8: \(S' \leftarrow sp(S, st)\)
9: \(T \leftarrow T \cup \{((\ell, S), st, (\ell', S'))\}\)
10: if \((\ell', S') \notin AC\) then
11: \(AC \leftarrow AC \cup \{(\ell', S')\}\)
12: if \(S' \neq \{\text{false}\}\) then
13: worklist \(\leftarrow\) worklist \(\cup\) \{((\ell', S'))\}
14: end if
15: end if
16: end for
17: end while
18: end procedure
Algorithm for Bounded Model Checking

Apply the algorithm $\text{ConstructAC}$ with the following modifications.

- Check if $(\ell', S)$ is an error configuration while adding it to the graph.
- If $(\ell', S)$ is an error configuration, then discontinue to build the graph and tell the user that his program is not safe.
- Construct a path $(\ell_0, S_0), \ldots, (\ell_0, S_0)$ such that $(\ell_0, S_0)$ is $(\ell_{\text{init}}, \{\varphi_{\text{pre}}\})$ and $(\ell_n, S_n)$ is the error configuration $(\ell', S)$.
- Let $st_1, \ldots s_n$ be a sequence of statements such that $(\ell_{i-1}, st_i, \ell_i) \in \Delta$ for each $i \in \{1, \ldots, n\}$. Return $st_1, \ldots s_n$ to the user as a counterexample to safety of his program.

Guarantees correctness up to a bound:

After we explored all nodes whose distance to the initial node is smaller than $k$, we can guarantee the program cannot reach an error by executing less than $k$ statements.
Program Verification

Summer Term 2021

Lecture 20: Assert, Abstractions

Matthias Heizmann

Wednesday 30th June
Section 14

Correctness Specification via Assert Statement
In Boogie, Java, Python and many other programming languages there is an *assert statement* \(^{22}\). The assert statement consists of a Boolean expression that is evaluated when the program executes the statement. If the expression is evaluated to *true* the execution continues regularly. If the expression is evaluated to *false* the program is considered erroneous and e.g., an exception is thrown.

```
1 assume p != 0;
2 while (n >= 0) {
3   assert p != 0;
4   if (n == 0) {
5     p := 0;
6   }
7   n := n - 1;
8 }
```

Example of some Boogie code whose correctness is specified by the assert statement in line 3. This code is correct, if the value of the variable \( p \) is never zero in line 3.

We will extend Boostan by an assert statement. We will not define the relational semantics for this statement and use it only in contexts where we work with control-flow graphs. In Exercise 3 of Exercise Sheet 18 we will see that we can translate every specification given by assert statements into a specification given by a precondition-postcondition pair if we also allow a minor modification of the program.

\(^{22}\)Wikipedia: Assertion
Grammar for Boostan with Assert Statement

\[ G_{ Boo } = (\Sigma_{ Boo }, N_{ Boo }, P_{ Boo }, S_{ Boo }) \]

\[ \Sigma_{ Boo } = \{ \text{while, if, else, }, \{, \}, \text{havoc, assume, assert} \} \cup \Sigma_{ B } \]

\[ N_{ Boo } = \{ X_{ stmt }, X_{ lhs } \} \cup N_{ B } \]

\[ P_{ Boo } = \{ \]
\[ X_{ stmt } \rightarrow X_{ lhs } := X_{ expr } ; \]
\[ X_{ stmt } \rightarrow \text{havoc } X_{ var } ; \]
\[ X_{ stmt } \rightarrow \text{assume } X_{ expr } ; \]
\[ X_{ stmt } \rightarrow \text{assert } X_{ expr } ; \]
\[ X_{ stmt } \rightarrow X_{ stmt } X_{ stmt } \]
\[ X_{ stmt } \rightarrow \text{if } ( X_{ expr } ) \{ X_{ stmt } \} \text{ else } \{ X_{ stmt } \} \]
\[ X_{ stmt } \rightarrow \text{while } ( X_{ expr } ) \{ X_{ stmt } \} \]
\[ X_{ lhs } \rightarrow X_{ var } [ X_{ expr } ] \]
\[ X_{ lhs } \rightarrow X_{ var } \} \cup P_{ B } \]

\[ S_{ Boo } = X_{ Boo } \]
A control-flow graph is a tuple $G = (\text{Loc}, \Delta, \ell_{\text{init}}, \ell_{\text{ex}})$ where

- $\text{Loc}$ is a finite set whose elements we call locations,
- $\Delta$ is a ternary relation that consists of triples $(\ell, st, \ell')$ where $\ell$ and $\ell'$ are locations and $st$ is either
  - an assignment statement,
  - an array assignment statement,
  - a havoc statement, or
  - an assume statement.
- $\ell_{\text{init}}$ is a location that we call the initial location
- $\ell_{\text{ex}}$ is a location that we call the exit location

A control-flow graph with error locations is a tuple $G = (\text{Loc}, \Delta, \ell_{\text{init}}, \ell_{\text{ex}}, \text{Loc}_{\text{err}})$ where

- $G = (\text{Loc}, \Delta, \ell_{\text{init}}, \ell_{\text{ex}})$ is a control-flow graph and
- $\text{Loc}_{\text{err}} \subseteq \text{Loc}$ is a subset of locations that we call error locations
Definition (Control-Flow Graph With Error Locations for a Program)

Given a program $P = (V, \mu, st)$ we define the control-flow graph with error locations for $P$ analogously to the control-flow graph for $P$. We always take the union of error locations of “sub control-flow graphs” and define the control-flow graph for an assert statement below.

Definition:
Let $st$ be an assert statement of the form

```plaintext
assert expr;
```

then $G = (Loc, \Delta, l_{init}, l_{ex}, Loc_{err})$ such that

- $Loc = \{l_1, l_2, l_3\}$,
- $\Delta = \{(l_{init}, assume !expr; , l_{err}), (l_{init}, assume expr; , l_{ex})\}$,
- $l_{init} = l_1$,
- $l_{ex} = l_3$,
- $Loc_{err} = \{l_2\}$,
- $l_{init} \neq l_{err}, l_{init} \neq l_{ex},$ and $l_{ex} \neq l_{err}$.

is a control-flow graph for $st$.

Example:
We defined the notion of an error configuration for programs with precondition-postcondition pairs. We will next extend this definition to programs with assert statements.

Definition (Error Configuration)

We call a program configuration \((\ell, s)\) an **error configuration** if \(\ell \in \text{Loc}_{\text{err}}\).

Similarly, we extend the notion of an abstract error configuration which was originally given for programs with precondition-postcondition pairs to programs with assert statements.

Definition (Abstract Error Configuration)

We call an abstract configuration \((\ell, \{\varphi\})\) an **abstract error configuration** if \(\ell \in \text{Loc}_{\text{err}}\) and \(\{\varphi\} \neq \emptyset\).

Please note that it is bad practice to extend an existing definition.
Please note that it is bad practise to extend an existing definition.

From the error configuration’s point of view it would have been straightforward to introduce the content of the lecture in the following order.

1. Boostan and its relational semantics.
2. Assert statements.
3. Control flow graph with error locations.
4. Only then: Discussion about correctness, precondition-postcondition pairs.
5. Definition of error configurations for both kinds of specifications at.

Now, we have to check that theorems and lemmas that we gave so far also hold for our extended definitions.

If we think it becomes clear form the context, we will always explicitly state whether correctness was specified by assert statements or precondition-postcondition pairs.
Section 15

Abstractions – Part 1
Outline

Introduction

Propositional Logic

First-Order Logic

First-Order Theories

SMT-LIB

Boogie and Boostan

Hoare Proof System

Ultimate Referee

Arrays

Boogie and Boostan – Part 2

Control-flow graphs

Predicate Transformers

Bounded Model Checking

Correctness Specification via Assert Statement

Abstractions – Part 1

Infeasibility Proofs

CEGAR

Trace Abstraction

Constraint-based Invariant Synthesis

Termination Analysis
In this section we will learn a kind of correctness proof that is based on the control-flow graph.

In this section we see

- that bounded model checking is typically not sufficient to prove correctness of a program
- how abstractions help to prove correctness

(This section is directly build upon the preceding section on bounded model checking.)
Consider the program on the following slide.

- The program has infinitely many configurations. Infinitely many configurations are reachable, we cannot draw a reachability graph.
- The precise abstract reachability graph has infinitely many configurations too. Our bounded model checking algorithm will fail.
- Observation: The variable $x$ is initially zero. We only increment $x$. Hence $x$ can never become -1 and the program satisfies its precondition-postcondition pair.

Consider the graph on the following slide.

- Each node represents a configuration of the program. Different rows represent different evaluations of the variables. Different columns represent different locations. The initial configurations are highlighted blue, the error configurations are highlighted red.
- This graph is not a reachability graph because we show also non-reachable configurations.

Idea of our abstraction:
Partition configurations into finitely many equivalence classes (here: light blue boxes). Build a graph whose nodes are the equivalence classes. Connect two equivalence classes $C_1, C_2$ by an edge if there are configurations $c_1 \in C_1$ and $c_2 \in C_2$ that are connected by an edge. Call an equivalence class initial if it contains an initial configuration. Call an equivalence class error if it contains an error configuration. If there is no path from an initial equivalence class to an error equivalence class, there is also no path from an initial configuration to an error configuration and the analyzed program is correct. Unfortunately, the contrary direction does not hold. If there is a path from an initial equivalence class to an error equivalence class, the program might be incorrect but it might also be the case the we have chosen a partition that is not helpful.
The program flow is as follows:

- $\ell_4 \xrightarrow{!b} \ell_1 \xrightarrow{b} \ell_2 \xrightarrow{\text{havoc } b} \ell_3$
  - $x := x + 1$

**Precondition ($\varphi_{\text{pre}}$):**

$x = 0$

**Postcondition ($\varphi_{\text{post}}$):**

$x \neq -1$

The states and transitions are as follows:

- $\ell_4$: $\{b \mapsto \text{true}, x \mapsto 2\}$, $\{b \mapsto \text{false}, x \mapsto 2\}$
- $\ell_1$: $\{b \mapsto \text{true}, x \mapsto 1\}$, $\{b \mapsto \text{false}, x \mapsto 1\}$
- $\ell_2$: $\{b \mapsto \text{true}, x \mapsto 0\}$, $\{b \mapsto \text{false}, x \mapsto 0\}$
- $\ell_3$: $\{b \mapsto \text{true}, x \mapsto -1\}$, $\{b \mapsto \text{false}, x \mapsto -1\}$, $\{b \mapsto \text{true}, x \mapsto -2\}$, $\{b \mapsto \text{false}, x \mapsto -2\}$
Next, we will rephrase our ideas for an abstraction in our formal setting.

We will use **abstract configurations** as equivalence classes (i.e., like in the example above we will never have different locations in one equivalence class).

We note that these lemma/theorem are slightly more general than the idea mentioned above. The abstract **abstract reachability graph** does not require that its abstract configurations form a partition of the program’s configurations.
Let $P$ be a program and let $G$ be a control-flow graph for $P$.

**Lemma**

*If some abstract reachability graph for $G$ does not contain an abstract error configuration, then the set of reachable configurations does not contain an error configuration.*

Note that there is an existential quantification: it is sufficient to find *some* abstract reachability graph that does not contain an abstract error configuration.

**Theorem**

*Let $(\varphi_{pre}, \varphi_{post})$ be a precondition-postcondition pair. If some abstract reachability graph for $G$ does not contain an abstract error configuration, then $P$ satisfies $(\varphi_{pre}, \varphi_{post})$.*

As a consequence we make the following definition. We will prove the theorem later and consider next some examples.

**Definition**

We call an abstract reachability graph for $G$ a *safety proof* if it does not contain an abstract error configuration.
We will discuss these lemma/theorem using the following program.

todo Explain the following program

► motivated by ...  
► correct because ...
Example

Program code and control-flow graph of the program $P_{\text{goanna}}$

```plaintext
assume p != 0;
while (n >= 0) {
    assert p != 0;
    if (n == 0) {
        p := 0;
    }
    n := n - 1;
}
```
Some abstract reachability graph that is suitable to show that the assert statement of $P_{\text{goanna}}$ is always valid.

- ($\ell_0$, \{true\})
  - $p \neq 0$
    - ($\ell_1$, \{p \neq 0 \lor n = -1\})
      - $n < 0$
        - ($\ell_6$, \{true\})
      - $n \geq 0$
        - ($\ell_2$, \{p \neq 0\})
          - $p = 0$
            - ($\ell_{\text{err}}$, \{false\})
          - $p \neq 0$
            - ($\ell_5$, \{p \neq 0 \lor n = 0\})
              - $n = 0$
                - ($\ell_4$, \{n = 0\})
              - $n \neq 0$
                - $p := 0$

- $n := n - 1$
- $p = 0$
- $n > 0$
- $p := 0$
- $n = 0$
- $p \neq 0$
- $n \neq 0$
The abstract reachability graph of the preceding slide is sufficient to prove safety of the program because all (resp. the only) abstract configuration whose location is $\ell_{\text{err}}$ has an empty set of states.

The graph structure of this abstract reachability graph coincides with the graph structure of the control-flow graph. The reason for that is that the lecturer tried to find a small abstract reachability graph. We will later see examples for abstract reachability graphs of the same programs that are larger.

Note that we have not yet seen an algorithm for inferring an abstract reachability graph. What we learned in the lecture allow us only the check that the above graph is indeed an abstract reachability graph for $P_{\text{goanna}}$ and to check that this abstract reachability graph is a safety proof for $P_{\text{goanna}}$. 
From a technical point of few that lecture has not made any progress since the presentation of the Hoare proof system. The Hoare proof system allowed us to give a correctness proof in case we guessed “good” loop invariants. The notion of an abstract reachability graph allows us to give a correctness proof in case we guessed “good” abstract configurations.

So, for the task of finding correctness proofs, the last sections on graph-based representations gave us only a new formalism but the task seems to be as hard as before.

In the next slides we present a approach that reduces the guesswork to the task of finding a set of formulas $B$. We will see an algorithm that uses the set of formulas $B$ to construct an abstract reachability graph. If the set of formulas $B$ was “good” the abstract reachability graph will be a safety proof.
Given a finite set of formulas $B$ we define the *abstract strongest post* operator as follows.

$$sp_B^#(\{\psi\}, st) = \{ \bigwedge \{ \varphi \in B \mid sp(\{\psi\}, st) \subseteq \{\varphi\}\} \}$$

If the set $B$ is empty, the abstract strongest post operator is always $\{\bigwedge\{\}\}$, i.e., the set of states for which the formula $\bigwedge\{}$ holds. This formula is called the “empty conjunction” and one usually uses the convention that the empty conjunction is $\textbf{true}$. We follow this convention.\footnote{The convention to define the empty conjunction as $\textbf{true}$ is a rather random choice and cannot be concluded from other definitions. This choice is however sometimes convenient because then e.g., the formula $\varphi \land \bigwedge B$ and the formula $\bigwedge (B \cup \{\varphi\})$ are equivalent. Analogously, the empty disjunction is $\textbf{false}$. In general, the convention is that the result for an empty set of operands is the neutral element. E.g., for real numbers, the empty sum is 0 and the empty product is 1.}
todo Explain also all of the remaining slides
Definition

We call an abstract reachability graph \((AC, T)\) **precise for** \(B\) if for each \((\ell, \{\varphi\}), st, (\ell', \{\varphi'\}))\) the equality \(sp_B^\#(\{\varphi\}, st) = \{\varphi'\}\) holds.
1: procedure CONSTRUCTACB((Loc, Δ, ℓinit, ℓex) : CFG, ϕpre, B : formulas)
   returns (AC, T)
2:   T ← ∅
3:   AC ← \{((ℓinit, {ϕpre})}\}
4:   worklist ← \{((ℓinit, {ϕpre})}\}
5:   while worklist \neq ∅ do
6:     (ℓ, S) ← REMOVEFIRST(worklist)
7:     for all ℓ', st with (ℓ, st, ℓ') ∈ Δ do
8:       S' ← sp_B^♯(S, st)
9:       T ← T \cup \{((ℓ, S), st, (ℓ', S'))\}
10:      if (ℓ', S') \notin AC then
11:         AC ← AC \cup \{((ℓ', S'))\}
12:         if S' \neq \{false\} then
13:            worklist ← worklist \cup \{((ℓ', S'))\}
14:         end if
15:     end if
16:   end for
17:  end while
18: end procedure
Abstract reachability graph that is precise for
\( B = \{ p \neq 0, n = 0, n = -1, \text{true, false} \} \):

\[ (\ell_0, \{ \text{true} \}) \]
\[ p \neq 0 \rightarrow (\ell_1, \{ p \neq 0 \}) \]
\[ n < 0 \rightarrow (\ell_6, \{ p \neq 0 \}) \]
\[ (\ell_1, \{ n = -1 \}) \] \( n < 0 \rightarrow (\ell_6, \{ n = -1 \}) \)
\[ n \geq 0 \rightarrow (\ell_2, \{ p \neq 0 \}) \]
\[ p = 0 \rightarrow (\ell_{\text{err}}, \{ \text{false} \}) \]
\[ (\ell_2, \{ \text{false} \}) \]
\[ n := n-1 \]
\[ (\ell_3, \{ p \neq 0 \}) \]
\[ n = 0 \rightarrow (\ell_4, \{ p \neq 0 \land n = 0 \}) \]
\[ (\ell_5, \{ p \neq 0 \}) \]
\[ p := 0 \rightarrow (\ell_5, \{ n = 0 \}) \]
\[ (\ell_5, \{ n = 0 \}) \]
Abstract reachability graph that is precise for
\( B = \{ p \neq 0, n \geq 0, n = -1, \text{true}, \text{false}\} \):
Program Verification

Summer Term 2021

Lecture 21: Infeasibility Proofs

Matthias Heizmann

Monday 5th July
Section 16

Infeasibility Proofs
Motivation

Program Verification
↓
Finding Loop Invariants
↓
Finding “good” formulas for construction of an abstract reachability graph
How can we get a set of formulas $B$?

**Naive approach:** Take all Boolean expressions that occur in the program.

**Problem:** Insufficient in many cases.

**Workaround:** Take also variations.

**Problem:** In the worst case the size of an abstract reachability graph (that is precise for $B$) grows exponentially in the size of $B$. 
We use the next slides to discuss an idea for obtaining useful formulas.

If we want to know whether a sequence of statements has an execution or not, we can compute $sp$ for the sequence and check if the resulting formula is logically equivalent to false. This does not yet help us for constructing a “good” abstract reachability graph because we need a formula after every statement.

Hence we devise a new kind of proof for the non-existence of an execution. In this new kind of proof, we have a formula after each statement and the $i$-formula denotes a superset of the states that are reachable after executing the first $i$ statements.

We can obtain such a proof by applying $sp$ iteratively (see middle column). However there is also a simpler proof (see right column).
Idea: Consider Proofs for sequences of statements

<table>
<thead>
<tr>
<th>sequence of statements that leads from initial location to error location</th>
<th>proof that there is no execution</th>
<th>simplified proof</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p \neq 0 )</td>
<td>( \varphi_0 ) true</td>
<td>( \varphi_0 ) true</td>
</tr>
<tr>
<td>( n \geq 0 )</td>
<td>( \varphi_1 ) ( p \neq 0 )</td>
<td>( \varphi_1 ) ( p \neq 0 )</td>
</tr>
<tr>
<td>( p = 0 )</td>
<td>( \varphi_2 ) ( p \neq 0 \land n \geq 0 )</td>
<td>( \varphi_2 ) ( p \neq 0 )</td>
</tr>
</tbody>
</table>

Next: a formalism for generating “simple proofs”
Definition (Trace, Feasibility)
We call a sequence of statements a *trace*. We call a trace $\pi$ *feasible* if there is some execution for $\pi$.

Definition (Inductive sequence of sets of states)
Given a sequence of statements $\pi = st_1, \ldots, st_n$, we call a sequence of sets of states $\{\varphi_0\}, \ldots, \{\varphi_n\}$ inductive for $\pi$ if $sp(\{\varphi_i\}, st_{i+1}) \subseteq \{\varphi_{i+1}\}$ for all $i \in \{0, \ldots, n - 1\}$

Theorem
*If there exists a sequence of sets of states $\{\varphi_0\}, \ldots, \{\varphi_n\}$ that is inductive for $\pi$ such that $\varphi_0$ is true and $\varphi_n$ is false, then $\pi$ is infeasible.*

Definition (Proof of infeasibility)
We call a sequence of sets of states $\{\varphi_0\}, \ldots, \{\varphi_n\}$ a *proof of infeasibility* if the sequence is inductive for $\pi$, $\varphi_0$ is true, and $\varphi_n$ is false.
Definition (Abstraction of a statement)

We define the *abstraction of a statement* \( \text{abstract}(st) \) as follows.

\[
\text{abstract}(st) = \begin{cases} 
\text{assume true} & \text{if } st \text{ is of the form } \text{assume } \psi \\
\text{havoc } x & \text{if } st \text{ is of the form } x := e \\
\text{havoc } x & \text{if } st \text{ is of the form } \text{havoc } x
\end{cases}
\]

Definition (Abstraction of a trace)

We call a trace \( \pi^\# = st_1^\#, \ldots, st_n^\# \) an *abstraction of a trace* \( \pi = st_1, \ldots, st_n \) if each \( st_i^\# \) is either the statement \( st_i \) or the abstraction \( \text{abstract}(st_i) \).

Theorem

*If \( \pi^\# \) is an abstraction of \( \pi \) and \( \{ \varphi_0 \}, \ldots, \{ \varphi_n \} \) is a proof of infeasibility for \( \pi^\# \), then \( \{ \varphi_0 \}, \ldots, \{ \varphi_n \} \) is a proof of infeasibility for \( \pi \).*
On the next two slides we see two examples for the construction of a “simplified proof”.

The first column shows a trace. The second column shows the (unnecessarily large) infeasibility proof that is obtained by an iterative application of $sp$. The third column shows an abstraction of the trace in which we highlighted the abstracted statements in orange. The last column shows the proof that is obtained by applying $sp$ to the abstraction of the trace.
<table>
<thead>
<tr>
<th>trace $\pi$</th>
<th>sp for $\pi$</th>
<th>abstract trace $\pi^#$</th>
<th>sp for $\pi^#$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$st_1$ $p \neq 0$</td>
<td>$\varphi_0$ <strong>true</strong></td>
<td>$p \neq 0$</td>
<td>$\varphi_0$ <strong>true</strong></td>
</tr>
<tr>
<td>$st_2$ $n \geq 0$</td>
<td>$\varphi_1$ $p \neq 0$</td>
<td><strong>true</strong></td>
<td>$\varphi_1$ $p \neq 0$</td>
</tr>
<tr>
<td>$st_3$ $p = 0$</td>
<td>$\varphi_2$ $p \neq 0 \land n \geq 0$</td>
<td>$p = 0$</td>
<td>$\varphi_2$ $p \neq 0$</td>
</tr>
<tr>
<td></td>
<td>$\varphi_3$ <strong>false</strong></td>
<td></td>
<td>$\varphi_3$ <strong>false</strong></td>
</tr>
<tr>
<td>trace $\pi$</td>
<td>sp for $\pi$</td>
<td>abstract trace $\pi#$</td>
<td>sp for $\pi#$</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>$st_1$ $p \neq 0$</td>
<td>$\varphi_0$ <code>true</code></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$st_2$ $n \geq 0$</td>
<td>$\varphi_1$ <code>true</code></td>
<td>$\varphi_0$ <code>true</code></td>
<td></td>
</tr>
<tr>
<td>$st_3$ $p \neq 0$</td>
<td>$\varphi_2$ <code>true</code></td>
<td></td>
<td>$\varphi_1$ <code>true</code></td>
</tr>
<tr>
<td>$st_4$ $n = 0$</td>
<td>$\varphi_3$ <code>true</code></td>
<td></td>
<td>$\varphi_2$ <code>true</code></td>
</tr>
<tr>
<td>$st_5$ $p := 0$</td>
<td>$\varphi_4$ <code>true</code></td>
<td></td>
<td>$\varphi_3$ <code>true</code></td>
</tr>
<tr>
<td>$st_6$ $n := n-1$</td>
<td>$\varphi_5$ <code>true</code></td>
<td></td>
<td>$\varphi_4$ <code>n = 0</code></td>
</tr>
<tr>
<td>$st_7$ $n \geq 0$</td>
<td>$\varphi_6$ <code>false</code></td>
<td></td>
<td>$\varphi_5$ <code>false</code></td>
</tr>
<tr>
<td>$st_8$ $p = 0$</td>
<td>$\varphi_7$ <code>false</code></td>
<td></td>
<td>$\varphi_6$ <code>false</code></td>
</tr>
</tbody>
</table>
Question: How can we construct the abstract trace $\pi^\#$?

Naive Approach: Iteratively abstract statements and check if abstract trace is still infeasible.

Advanced Approaches: (not discussed in this course) Encode trace as logical formula such that the formula is satisfiable iff the trace is feasible (SSA form). Use then either unsatisfiable cores or Craig interpolation. In the worst case, the “advanced approaches” are not better than the “naive approach”.
Good Infeasibility Proofs

<table>
<thead>
<tr>
<th>trace $\pi$</th>
<th>abstract trace $\pi_2^#$</th>
<th>sp for $\pi_2^#$</th>
<th>abstract trace $\pi_1^#$</th>
<th>sp for $\pi_1^#$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$st_1$ $a[0]:=x^2$</td>
<td>havoc $a[0]$</td>
<td>$\varphi_0$ true</td>
<td>$a[0]:=x^2$</td>
<td>$\varphi_0$ true</td>
</tr>
<tr>
<td>$st_2$ $n:=1000$</td>
<td>$n:=1000$</td>
<td>$\varphi_1$ true</td>
<td>havoc $n$</td>
<td>$\varphi_1$ $a[0]=x^2$</td>
</tr>
<tr>
<td>$st_3$ !(n&gt;=0)</td>
<td>!(n&gt;=0)</td>
<td>$\varphi_2$ $n=1000$</td>
<td>true</td>
<td>$\varphi_2$ $a[0]=x^2$</td>
</tr>
<tr>
<td>$st_4$ $a[k]=-1$</td>
<td>true</td>
<td>$\varphi_3$ false</td>
<td>$a[k]=-1$</td>
<td>$\varphi_3$ $a[0]=x^2$</td>
</tr>
<tr>
<td>$st_5$ $k=0$</td>
<td>true</td>
<td>$\varphi_4$ false</td>
<td>$k=0$</td>
<td>$\varphi_4$ $a[0]=x^2 \land a[k]=-1$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\varphi_5$ false</td>
<td></td>
<td>$\varphi_5$ false</td>
</tr>
</tbody>
</table>
### Good Infeasibility Proofs

```plaintext
1 \ a[0] = x \times x;
2 \ n := 1000;
3 \ while (n \geq 0) {
4      \ n := n - 1;
5  }
6 \ if (a[k] == -1) {
7    \ assert k != 0;
8  }
```

<table>
<thead>
<tr>
<th>(\pi_2^#)</th>
<th>sp for (\pi_2^#)</th>
<th>(\pi_1^#)</th>
<th>sp for (\pi_1^#)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\varphi_0)</td>
<td>true</td>
<td>(\varphi_0)</td>
<td>true</td>
</tr>
<tr>
<td>havoc (a[0])</td>
<td></td>
<td>a[0] := (x^2)</td>
<td></td>
</tr>
<tr>
<td>(\varphi_1)</td>
<td>true</td>
<td>(\varphi_1)</td>
<td>(a[0] = x^2)</td>
</tr>
<tr>
<td>(n := 1000)</td>
<td></td>
<td>havoc (n)</td>
<td></td>
</tr>
<tr>
<td>(\varphi_2)</td>
<td>(n = 1000)</td>
<td>true</td>
<td>(\varphi_2)</td>
</tr>
<tr>
<td>!(n \geq 0)</td>
<td></td>
<td></td>
<td>true</td>
</tr>
<tr>
<td>(\varphi_3)</td>
<td>false</td>
<td>(\varphi_3)</td>
<td>(a[0] = x^2)</td>
</tr>
<tr>
<td>true</td>
<td>a[k]=-1</td>
<td>true</td>
<td></td>
</tr>
<tr>
<td>(\varphi_4)</td>
<td>false</td>
<td>(\varphi_4)</td>
<td></td>
</tr>
<tr>
<td>true</td>
<td>k=0</td>
<td>(a[0] = x^2) \land a[k] = -1</td>
<td></td>
</tr>
<tr>
<td>(\varphi_5)</td>
<td>false</td>
<td>(\varphi_5)</td>
<td>false</td>
</tr>
</tbody>
</table>
```
Section 17

CEGAR
In this section we will see an approach that can be used to develop a verification algorithm. The approach is called CEGAR which stands for CounterExample-Guided Abstraction Refinement.

The approach is motivated by the following two facts.

- We do not know how to construct a set of formulas $B$ that is suitable for a program $P$.
- We do know how we can construct a set of formulas that is suitable for a sequence of statements.

The idea is that we start with an empty set of formulas $B$ and that we iteratively enlarge this set by formulas that we obtain from the analysis of traces.
Definition

Given an abstract reachability graph \((AC, T)\), we call a sequence of statements \(st_1, \ldots, st_n\) an error trace in \((AC, T)\) if there exists a sequence of abstract configurations \((ℓ_0, \{ϕ_0\}), \ldots, (ℓ_n, \{ϕ_n\})\) such that

- \((ℓ_0, \{ϕ_0\})\) is the initial abstract configuration,
- \(((ℓ_i, \{ϕ_i\}), st_{i+1}, (ℓ_{i+1}, \{ϕ_{i+1}\})) \in T\) for \(i \in \{0, \ldots, n - 1\}\), and
- \((ℓ_n, \{ϕ_n\})\) is an abstract error configuration.

Intuitively an error trace is a sequence of labelings along a path from the initial abstract configuration to an abstract error configuration.
Let us prove that $P_{goanna}$ is correct.

Start with $B = \emptyset$, construct abstract reachability graph that is precise for $B$. 
Abstract reachability graph for $B = \emptyset$:

1. $(\ell_0, \{\text{true}\})$
   - $p \neq 0$
     - $(\ell_1, \{\text{true}\})$
       - $n < 0$
         - $(\ell_6, \{\text{true}\})$
       - $n = 0$
         - $(\ell_2, \{\text{true}\})$
           - $p = 0$
             - $(\ell_{\text{err}}, \{\text{true}\})$
           - $p \neq 0$
             - $(\ell_3, \{\text{true}\})$
               - $n = 0$
                 - $(\ell_4, \{\text{true}\})$
               - $n \neq 0$
                 - $(\ell_5, \{\text{true}\})$
                   - $p := 0$
                     - $(\ell_5, \{\text{true}\})$

2. $n := n - 1$

3. $p := 0$
Abstract reachability graph for $B = \{p \neq 0, \text{false}\}$:
Abstract reachability graph that is precise for
\( B = \{ p \neq 0, n = 0, n = -1, \text{true}, \text{false}\} : \)

\[
\begin{align*}
(l_0, \{\text{true}\}) & \quad \text{p} \neq 0 \\
(l_1, \{p \neq 0\}) & \quad \text{n} < 0 \quad (l_6, \{p \neq 0\}) \\
(l_1, \{n = -1\}) & \quad \text{n} < 0 \quad (l_6, \{n = -1\}) \\
(l_2, \{p \neq 0\}) & \quad \text{p} = 0 \quad (l_{\text{err}}, \{\text{false}\}) \\
(l_2, \{\text{false}\}) & \quad \text{n} \geq 0 \\
(l_3, \{p \neq 0\}) & \quad \text{n} \geq 0 \\
(l_3, \{p \neq 0\}) & \quad \text{n} = 0 \\
(l_4, \{p \neq 0 \land n = 0\}) & \quad \text{n} \neq 0 \\
(l_5, \{p \neq 0\}) & \quad \text{p} := 0 \\
(l_5, \{n = 0\}) & \quad \text{p} : = 0 \\
(l_5, \{n = 0\}) & \quad \text{n} := \text{n} - 1 \\
(l_6, \{p \neq 0\}) & \quad \text{n} := \text{n} - 1
\end{align*}
\]
The CEGAR Approach (Pseudocode)

Step 1: Set $B$ to the empty set.

Step 2: Construct an abstract reachbility graph $ARG$ that is precise for $B$.

Step 3: Check if $ARG$ is safe.
   If yes, report that $P$ satisfies its specification and return.
   If no, construct an error trace $\pi$ of $ARG$.

Step 4: Check if $\pi$ is feasible.
   If yes, report that $P$ does not satisfy its specification, construct an execution for $\pi$, and return.
   If no, construct an infeasibility proof $\{\varphi_0\}, \ldots, \{\varphi_n\}$ for $\pi$, add the set of formulas $\{\varphi_0, \ldots, \varphi_n\}$ to $B$, and continue with Step 2.
The CEGAR Approach (Diagram)

program $P$

$B := \emptyset$

$\text{Is } ARG(P, B) \text{ a proof of correctness?}$

$\text{is } \pi \text{ feasible?}$

Construct infeasibility proof for $\pi$
Add formulas to $B$

Pick new error trace $\pi$

"$P$ is correct"

"$P$ is incorrect"

where $ARG(P, B)$ is an abstract reachability graph of $P$ that is precise for $B$. 
Lemma

Let \( \pi \) be a trace. If \( \{ \varphi_0 \}, \ldots, \{ \varphi_n \} \) is an infeasibility proof for \( \pi \) and \( B \supseteq \{ \varphi_0, \ldots, \varphi_n \} \) then \( \pi \) is not an error trace in an abstract reachability graph that is precise for \( B \).

Proof. Let \((AC, T)\) be an abstract reachability graph that is precise for \( B \). We prove by induction over the length \( k \) of prefixes of the trace \( \pi = st_1, \ldots, st_n \) the following. If there is a path \((\ell_1, \{ \psi_1 \}), \ldots, (\ell_k, \{ \psi_k \})\) such that \(( (\ell_i, \{ \psi_i \}), st_i, (\ell_{i+1}, \{ \psi_{i+1} \}) ) \) \( \in T \) for \( i \in \{1, \ldots, k\} \) then \( \{ \psi_k \} \subseteq \{ \varphi_k \} \).

We conclude that there is no path for \( \pi \) or that for the last element of the path \((\ell_n, \{ \psi_n \})\) the formula \( \psi_n \) is equivalent to \text{false} and hence \((\ell_n, \{ \psi_n \})\) is not an abstract error configuration.

Theorem (Progress property)

If an algorithm follows the CEGAR approach and \( \pi \) is the error trace that is analyzed in iteration \( i \) then \( \pi \) will not be an error trace of the abstract reachability graph in further iterations.
The theorem in the preceding slide is stated rather informally..
Shortcomings of predicate abstraction

We need a “good” set of formulas \( B \).

My opinion:

- yet, no good “solution” known
- many promising approaches that mitigate the problem
- for every program that was considered, someone found an algorithm that works for this program
Shortcomings of predicate abstraction

The computation of $sp^#_B$ is costly.
Computed in every iteration, for every abstract configuration, one SMT solver call per element of $B$. Especially costly for “expensive” SMT theories or theory combinations, e.g., floats, bitvectors, and arrays.

Reminder (Abstract Strongest Post)

$$sp^#_B(\{\psi\}, st) = \{\land \{\varphi \in B \mid sp(\{\psi\}, st) \subseteq \{\varphi\}\}\}$$

Optimizations:

▶ Use different sets $B$ for different locations.
▶ Do not use general SMT formulas and an SMT solver, but certain classes of formulas (“domains”, e.g., intervals, octagon, polyhedra) and specialized algorithms for construction of $sp^#_B$.
▶ Do not construct ARG explicitly. Construct a tree that represents the breadth-first search for new counterexamples. Label nodes with formulas. Reuse tree in next iteration.
▶ Use the partial order on formulas induced by implication. If there are two nodes $(\ell, \{\varphi_1\})$ and $(\ell, \{\varphi_2\})$ such that $\varphi_2 \vDash \varphi_1$, we can ignore $(\ell, \{\varphi_2\})$. We say that $(\ell, \{\varphi_2\})$ is already “covered” by $(\ell, \{\varphi_1\})$. 

Matthias Heizmann
Program Verification
Summer Term 2021
Section 18

Trace Abstraction
Outline

Introduction

Propositional Logic

First-Order Logic

First-Order Theories

SMT-LIB

Boogie and Boostan

Hoare Proof System

Ultimate Referee

Arrays

Boogie and Boostan – Part 2

Control-flow graphs

Predicate Transformers

Bounded Model Checking

Correctness Specification via Assert Statement

Abstractions – Part 1

Infeasibility Proofs

CEGAR

Trace Abstraction

Constraint-based Invariant Synthesis

Termination Analysis
A Floyd-Hoare annotation is a mapping that assigns each location $l_i$ a formula $\varphi_i$ such that there is an edge

\[ \varphi_i \xrightarrow{\text{stmt}} l_j \xrightarrow{\varphi_j} \]

only if the Hoare triple

\[ \{ \varphi_i \} \text{ stmt } \{ \varphi_j \} \]

is valid.

**Theorem**

Given a program $P$, if there is a Floyd-Hoare annotation such that

- every initial location is labeled with $\text{true}$ and
- every error location is labeled with $\text{false}$

then $P$ is safe.

Example:

Floyd-Hoare annotation for $P_{\text{goanna}}$
Idea

While analyzing a program $P$, consider automata whose alphabet $\Sigma$ is the set of all statements that occur in $P$’s control-flow graph.

Define a Floyd-Hoare annotation for such an automaton analogously to the definition of a Floyd-Hoare annotation for a control-flow graph.

Definition

We call an automaton $\mathcal{A} = (Q, \Sigma, \Delta, Q_{\text{init}}, F)$ a *Floyd-Hoare automaton* if there exists a Floyd-Hoare annotation $\beta : Q \rightarrow \text{Fmrl}(V)$ such that

- $\beta(q) = \text{true}$ for all $q \in Q_{\text{init}}$ and
- $\beta(q) = \text{false}$ for all $q \in F$.

Theorem

*Every trace that is accepted by a Floyd-Hoare automaton is infeasible.*
Let $A_P$ be the automaton whose graph structure is similar to the control-flow graph.

**Theorem**

*If there are Floyd-Hoare automata $A_1, \ldots, A_n$ such that the inclusion*

$$L(A_P) \subseteq L(A_1) \cup \ldots \cup L(A_n)$$

*holds then the program $P$ is safe.*
We’ve omitted the proofs of the previous two theorems in the lecture. However, they are not difficult:

- Every trace that is accepted by a Floyd-Hoare automaton is infeasible. Proof: Let \( \tau \) be a trace that is accepted by a Floyd-Hoare automaton \( A \) with annotation \( \beta \). Then there exists an accepting run \( q_0 \ldots q_n \) for \( \tau \). By the definition of Floyd-Hoare automata, \( \beta(q_0) \ldots \beta(q_n) \) is an infeasibility proof for \( \tau \).

- The second theorem follows directly: Every error trace in \( P \) is accepted by one of the Floyd-Hoare automata \( A_i \). Thus it is infeasible, and thus no error configuration can be reached.
“A program defines a language over the alphabet of statements.”

- **Set of statements:** alphabet of formal language
  e.g., \( \Sigma = \{ p \neq 0, n \geq 0, n = 0, p := 0, n \neq 0, \\
p = 0, n--, n < 0, \} \)

- **Control flow graph:** automaton over the alphabet of statements
- **Error location:** accepting state of this automaton
- **Error trace of program:** word accepted by this automaton
Note that in this formalism, infeasible traces (i.e., traces for which there exists no execution of the program $P$) may still be accepted by the automaton $A_P$. The finite automaton cannot distinguish between feasible and infeasible traces.

In fact, the verification task consists precisely of showing that all the traces accepted by $A_P$ are infeasible.
Trace Abstraction: Example

```
1 assume p != 0;
2 while (n >= 0) {
3   assert p != 0;
4   if (n == 0) {
5     p := 0;
6   }
7   n := n - 1;
8 }
```

Source Code
Trace Abstraction: Example

1. take trace $\pi_1$

```
\[
p \neq 0 \\
n \geq 0 \\
p \equiv 0
\]
```
Trace Abstraction: Example

1. take trace $\pi_1$
2. consider trace as automaton $A_1$

\[\text{Diagram:} \quad \begin{align*}
&\text{p} \neq 0 \\
&\text{n} \geq 0 \\
&\text{p} = 0
\end{align*}\]
Trace Abstraction: Example

1. take trace $\pi_1$
2. consider trace as automaton $A_1$
3. analyze correctness of $A_1$, compute Floyd-Hoare annotation
1. take trace $\pi_1$
2. consider trace as automaton $A_1$
3. analyze correctness of $A_1$, compute Floyd-Hoare annotation
4. generalize automaton $A_1$
   - add transitions

\[
\{ p \neq 0 \} \text{ n-- } \{ p \neq 0 \} \quad \text{is valid Hoare triple}
\]
\[
\{ p \neq 0 \} \text{ n != 0 } \{ p \neq 0 \} \quad \text{is valid Hoare triple}
\]
\[
\{ p \neq 0 \} \text{ n >= 0 } \{ p \neq 0 \} \quad \text{is valid Hoare triple}
\]
1. take trace $\pi_1$
2. consider trace as automaton $A_1$
3. analyze correctness of $A_1$, compute Floyd-Hoare annotation
4. generalize automaton $A_1$
   ▶ add transitions
Trace Abstraction: Example

1. take trace $\pi_1$
2. consider trace as automaton $A_1$
3. analyze correctness of $A_1$, compute Floyd-Hoare annotation
4. generalize automaton $A_1$
   ▶ add transitions
Trace Abstraction: Example

1. take trace $\pi_1$
2. consider trace as automaton $A_1$
3. analyze correctness of $A_1$, compute Floyd-Hoare annotation
4. generalize automaton $A_1$
   - add transitions
   - merge states with same annotation
Consider only traces in set theoretic difference $\mathcal{L}(\mathcal{A}_P) \setminus \mathcal{L}(\mathcal{A}_1)$.
Trace Abstraction: Example

1. take trace $\pi_2$

\[
\begin{align*}
\text{p} & \neq 0 \\
\text{n} & \geq 0 \\
\text{n} & = 0 \\
\text{p} & := 0 \\
\text{n} & := 0 \\
\text{n} & \geq 0 \\
\text{p} & := 0
\end{align*}
\]
Trace Abstraction: Example

1. take trace $\pi_2$
2. consider trace as automaton $A_2$
1. take trace $\pi_2$
2. consider trace as automaton $A_2$
3. analyze correctness of $A_2$, compute annotation
1. take trace $\pi_2$
2. consider trace as automaton $A_2$
3. analyze correctness of $A_2$, compute annotation
4. generalize automaton $A_2$
   - add transitions
   - merge states with same annotation
Trace Abstraction: Example

\[
\mathcal{L}(\mathcal{A}_P) \subseteq \mathcal{L}(\mathcal{A}_1) \cup \mathcal{L}(\mathcal{A}_2)
\]

- **Program** \( P \)
  - \( \ell_0 \):
    - \( p \neq 0 \)
    - \( n > 0 \) to \( \ell_1 \)
    - \( n > 0 \) to \( \ell_3 \)
    - \( n = 0 \) to \( \ell_2 \)
    - \( n -= 0 \) to \( \ell_4 \)

- **Automaton** \( \mathcal{A}_1 \)
  - \( q_0 \) to all
  - \( p \neq 0 \)
  - \( n -= 0 \) to \( q_1 \)
  - \( p = 0 \)
  - \( n -= 0 \) to \( q_2 \)
  - \( n > 0 \) to \( q_3 \)

- **Automaton** \( \mathcal{A}_2 \)
  - \( q_0 \) to all
  - \( n = 0 \)
  - \( n -= 0 \) to \( q_1 \)
  - \( n -= 0 \) to \( q_2 \)
  - \( n > 0 \) to \( q_3 \)
Trace Abstraction: Verification Algorithm

1. Program $P$
2. $\mathcal{L}(A_P) \subseteq \mathcal{L}(A_1) \cup \cdots \cup \mathcal{L}(A_n)$
3. Is $\pi$ feasible?
   - Yes:
     - “$P$ is correct”
   - No: Pick new error trace $\pi$
4. Construct infeasibility proof for $\pi$
   - Yes: Construct generalized automaton $A_i$
   - No: Pick new error trace $\pi$
Lecture 23: Invariant Synthesis

Matthias Heizmann

Monday 12th July
Section 19

Constraint-based Invariant Synthesis
Motivation Part I

The next slide motivates the general idea of invariant synthesis.

The theorem that we revisit on this slide says that a Floyd-Hoare annotation of a certain form is a sufficient criterion for safety of the analyzed program.

In the violet box we restate this sufficient criterion by expanding the definition of a Floyd-Hoare annotation. We replaced all statements on the validity of a Hoare triple \( \{ \varphi \}, st, \{ \varphi' \} \) by the equivalent statement that the inclusion \( sp(\{ \varphi \}, st) \subseteq \{ \varphi' \} \) holds.

In the orange box we generalize this sufficient condition from sets of states that are denoted by a formula to arbitrary sets, furthermore we expand the definition of the inclusion and the strongest postcondition.

On the right we see an example of a control-flow graph and an instantiation of the violet box for this control-flow graph. We note that we picked this control-flow graph because of its simplicity but there is no Boostan program that has this control-flow graph.
Reminder (Theorem)

Given a program $P$, if there is a Floyd-Hoare annotation such that
- every initial location is labeled with $\text{true}$ and
- every error location is labeled with $\text{false}$
then $P$ is safe.

There exist formulas $\varphi_{\ell_1}, \ldots, \varphi_{\ell_n}$ such that
- $\varphi_{\ell_{\text{init}}}$ is $\text{true}$
- for each $(\ell, st, \ell') \in \Delta$ : $sp(\{\varphi_{\ell}\}, st) \subseteq \{\varphi_{\ell'}\}$
- for each $\ell \in Loc_{\text{err}}$ : $\varphi_{\ell}$ is $\text{false}$

There exist sets of states $S_{\ell_1}, \ldots, S_{\ell_n}$ such that
- $S_{\ell_{\text{init}}}$ is $S_{V, \mu}$
- for each $(\ell, st, \ell') \in \Delta$ : for all $s \in S_{V, \mu} . s \in S_{\ell}$ and $(s, s') \in \llbracket st \rrbracket$ implies $s' \in S_{\ell'}$
- for each $\ell \in Loc_{\text{err}}$ : $S_{\ell}$ is $\emptyset$
Motivation Part II

The presentation on the preceding slide gives rise to the following question:

“Can we formalize the condition in the violet box or the condition in the orange box as a formula in some logic and obtain a Floyd-Hoare annotation as a satisfying assignment of this formula?”

In this course we will consider possibilities to formalize the condition (violet box, orange box) as an SMT formula. There are two obstacles.

**Obstacle 1:** The relation $[[s]]$ that defines the meaning of a statement $s$ is not given as a formula.

**Obstacle 2:** The condition quantifies over states, sets of states and both sorts are related via the ’is element’ relation. This is usually impossible in first-order logic and can only be done in second-order logic.

On the next slide we demonstrate how we overcome Obstacle 1. We define the *transition formula* which is a formula that denotes the relation $[[s]]$ for a given statement $s$. We note that such a formula does not always exist (difficult to prove) and is not unique (make yourself an example).

The schematic examples show that for every simple statement there exists a transition formula. (We call the transition formulas given in the table *canonical transition formulas.*) Since a control-flow graph contains only simple statements we overcame Obstacle 1.
**Definition (Transition Formula)**

We call a formula $\tau$ over primed and unprimed program variables a *transition formula* for $st$ if the relation $[[st]]$ coincides with the following relation.

$$\{(s_1, s_2) \mid [[\tau]]_{M, \rho} \text{ is true and } \rho = s_1 \cup \text{prime}(s_2)\}$$

**Example**

<table>
<thead>
<tr>
<th>statement $st$</th>
<th>canonical transition formula $\tau_{st}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x := \text{expr};$</td>
<td>$x' = \text{expr} \land \bigwedge_{v \in V, v \neq x} v' = v$</td>
</tr>
<tr>
<td>$a[i] := \text{expr};$</td>
<td>$a' = \text{store}(a, i, \text{expr}) \land \bigwedge_{v \in V, v \neq a} v' = v$</td>
</tr>
<tr>
<td>havoc $x;$</td>
<td>$\bigwedge_{v \in V, v \neq x} v' = v$</td>
</tr>
<tr>
<td>assume $\text{expr};$</td>
<td>$\text{expr} \land \bigwedge_{v \in V} v' = v$</td>
</tr>
</tbody>
</table>
On the next slide we demonstrate a way to overcome Obstacle 2.

The quantification of set variables is existential and the outermost quantification in the orange box. We can always drop the outermost existential quantification (we introduce a Skolem constant\(^{24}\)) by replacing the quantified variables by other symbols and obtain an equisatisfiable formula.

If quantification is not required, we can use a predicate symbol to represent a set. E.g., over the integers, the set of even numbers is a (resp. the only) satisfying assignment for the predicate symbol \(p\) in the following formula.

\[
\forall x. p(x) \leftrightarrow \exists y. x = 2 \cdot y
\]

Using these two observations, we rephrase the conditions from the orange box as SMT formulas (see blue box in the next slide). In order to improve legibility we use \(\vec{v}\) to denote the list of all program variables. We call these formulas \textit{constraints}.

We note that the constraints do not encode the existence of a Floyd-Hoare annotation but something weaker: for a Floyd-Hoare annotation we require additionally that the solutions for sets of states can be represented as a FOL formula.

\(^{24}\)see \textit{Skolem normal form}
There exist \( p_{\ell_1}, \ldots, p_{\ell_n} \) such that

\[
\forall \vec{v}.\; p_{\ell\text{init}}(\vec{v}) \leftrightarrow \text{true}
\]

\[
\bigwedge_{(\ell, st, \ell') \in \Delta} \forall \vec{v}, \forall \vec{v}'.\; p_\ell(\vec{v}) \land \tau_{st}(\vec{v}, \vec{v}') \rightarrow p_{\ell'}(\vec{v}')
\]

\[
\bigwedge_{\ell \in \text{Locerr}} \forall \vec{v}.\; p_\ell(\vec{v}) \leftrightarrow \text{false}
\]

Example:

\[
\forall x.\; p_{\ell_1}(x) \leftrightarrow \text{true}
\]

\[
\forall x, x'.\; p_{\ell_1}(x) \land x' = 5 \rightarrow p_{\ell_2}(x')
\]

\[
\forall x, x'.\; p_{\ell_2}(x) \land x' = x + 1 \rightarrow p_{\ell_2}(x')
\]

\[
\forall x, x'.\; p_{\ell_2}(x) \land x = -1 \land x' = x \rightarrow p_{\ell_3}(x')
\]

\[
\forall x.\; p_{\ell_3}(x) \leftrightarrow \text{false}
\]

We are searching for \( \varphi_i \) such that \( \llbracket \varphi_i \rrbracket \) is a solution for \( p_{\ell_i} \).

In order to check satisfiability of the constraints above we write an SMT-LIB script (see next slide) and pass it to an SMT solver.
A satisfying assignment for \( p_1, p_2 \) and \( p_3 \) that can be denoted as an SMT formula is a Floyd-Hoare annotation for the running example in the section Invariant Synthesis.

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Date: 2019-07-22

(set-logic UFLIA)

(declare-fun p1 (Int) Bool)
(declare-fun p2 (Int) Bool)
(declare-fun p3 (Int) Bool)

(assert (forall ((|x| Int)) (= (p1 |x|) true)))
(assert (forall ((|x| Int) (|x'| Int))
  (= > (and (p1 |x|) (= |x'| 5)) (p2 |x'|))))
(assert (forall ((|x| Int) (|x'| Int))
  (= > (and (p2 |x|) (= |x'| (+ |x| 1))) (p2 |x'|))))
(assert (forall ((|x| Int) (|x'| Int))
  (= > (and (p2 |x|) (= |x'| (- 1)) (= |x'| |x|)) (p3 |x'|))))
(assert (forall ((|x| Int)) (= (p3 |x|) false)))

(check-sat)
(get-model)
The result is devastating. By today (2019-07-22) neither CVC4\(^{25}\), nor Princess\(^{26}\), nor SMTInterpol\(^{27}\), nor Z3\(^{28}\) is able to provide a response for the check-sat command. This means that our idea is rather useless, because the constraints are already too complicated for small and simple control flow graphs.

(In case you are planning to do a PhD please note that this situation is typical. You had an idea. It looked promising. You spend time and effort on the idea. It did not work out in practice.)

Now, our options are:

1. Wait (month, years, decades, ...) until SMT solvers are powerful enough.
2. Give up on this idea.
3. Find a simpler problem for which our approach works.
4. Get a brilliant idea.

We go for the third option...

\(^{25}\)http://cvc4.cs.stanford.edu/web/
\(^{26}\)http://www.philipp.ruemmer.org/princess.shtml
\(^{27}\)https://ultimate.informatik.uni-freiburg.de/smtinterpol/
\(^{28}\)https://github.com/Z3Prover/z3
General idea:
Do not check if some Floyd-Hoare annotation exists, check only if some Floyd-Hoare annotation of a specific form exists.

Instance of this idea that we pursue:
Replace each $p_\ell(\vec{v})$ by a linear inequality whose variables are the variables of the program and whose coefficients are the unknowns for which we want to find a solution.

E.g., if our program has two integer variables $x$ and $y$, then we replace the predicate symbol $p_\ell(x, y)$ by

$$a_\ell \cdot x + b_\ell \cdot y + c_\ell \geq 0$$

+ The SMT solver does not have to find a solution for predicate symbols but only for first-order variables $a_\ell, b_\ell, c_\ell$.
- We can only find a Floyd-Hoare annotation $\beta$ if for each $\ell \in Loc$ the formula $\beta(\ell)$ is a linear inequality.

We carry out this idea in the blue box on the next slide. In order to improve legibility we consider the special case where the program has only one variable. The extension to multiple variables is straightforward.
There exist $a_{\ell_1}, \ldots, a_{\ell_n}, b_{\ell_1}, \ldots, b_{\ell_n}$ such that

\[ \forall x. a_{\ell_{\text{init}}} \cdot x + b_{\ell_{\text{init}}} \geq 0 \iff \text{true} \]

\[ \bigwedge_{(\ell, st, \ell') \in \Delta} \forall x, x'. a_{\ell} \cdot x + b_{\ell} \geq 0 \land \tau_{st}(x, x') \rightarrow a_{\ell'} \cdot x' + b_{\ell'} \geq 0 \]

\[ \bigwedge_{\ell \in \text{Loc}_{\text{err}}} \forall x. a_{\ell} \cdot x + b_{\ell} \geq 0 \iff \text{false} \]

Again, we write an SMT-LIB script (see next slide) and pass it to an SMT solver.
(set-logic UFNIA)

(declare-fun a1 () Int)
(declare-fun b1 () Int)
(declare-fun a2 () Int)
(declare-fun b2 () Int)
(declare-fun a3 () Int)
(declare-fun b3 () Int)

(assert (forall ((|x| Int))
  (= (>= (+ (* a1 |x|) b1) 0) true)))

(assert (forall ((|x| Int) (|x'| Int)) (=>
  (and (>= (+ (* a1 |x|) b1) 0) (= |x'| 5))
  (> (>= (+ (* a2 |x'|) b2) 0))))

(assert (forall ((|x| Int) (|x'| Int)) (=>
  (and (and (>= (+ (* a2 |x|) b2) 0)) (= |x'| (+ |x| 1)))
  (> (>= (+ (* a2 |x'|) b2) 0))))

(assert (forall ((|x| Int) (|x'| Int)) (=>
  (and (>= (+ (* a2 |x|) b2) 0)) (= |x'| |x| (- 1)) (= |x'| |x|)
  (> (>= (+ (* a3 |x'|) b3) 0))))

(assert (forall ((|x| Int))
  (= (>= (+ (* a3 |x|) b3) 0) false)))

(check-sat)

(get-model)
Again, the result is devastating. By today (2019-07-22) neither CVC4\textsuperscript{29}, nor Princess\textsuperscript{30}, nor Z3\textsuperscript{31} is able to provide a response for the check-sat command. This means that our idea is rather useless, because the constraints are already too complicated for small and simple control flow graphs.

(In case you are planning to do a PhD please note that this situation is typical. You had an idea. It looked promising. You spend time and effort on the idea. It did not work out in practice.)

Let us consider the constraints again and reflect why they are difficult to solve.

- **Quantifier alternation.** Since we are searching for a satisfying assignment of a non-closed formula, the formula is implicitly existentially quantified and we have to solve a problem that involves quantifier alternation.

- **Nonlinear arithmetic (i.e., multiplication of variables).**

Now, our options are:

1. Wait (month, years, decades, ... ) until SMT solvers are powerful enough.
2. Give up on this idea.
3. Find a simpler problem for which our approach works.
4. Get a brilliant idea.

This time, we can go for the fourth option because someone already had a brilliant idea.

\begin{itemize}
\item \texttt{http://cvc4.cs.stanford.edu/web/}
\item \texttt{http://www.philipp.ruemmer.org/princess.shtml}
\item \texttt{https://github.com/Z3Prover/z3}
\end{itemize}
In the following lemma, \( A \) denotes a matrix and \( A \cdot \vec{x} \leq \vec{b} \) denotes a conjunction of linear inequalities. E.g., \( \begin{pmatrix} 1 & 0 \\ -1 & 0 \\ 1 & -1 \end{pmatrix} \cdot \begin{pmatrix} x \\ x' \end{pmatrix} \leq \begin{pmatrix} -1 \\ -1 \\ 0 \end{pmatrix} \) denotes the conjunction \( x \leq -1 \land -x \leq -1 \land x - x' \leq 0 \land x' - x \leq 0 \) which is a transition formula for the statement \( x = -1 \).

**Lemma (Farkas)**

\[
\exists \vec{x} \quad A \cdot \vec{x} \leq \vec{b} \quad \text{implies} \quad \forall \vec{x} \quad (A \cdot \vec{x} \leq \vec{b} \rightarrow \vec{c}^T \cdot \vec{x} \leq \delta) \quad \iff \quad \exists \vec{\lambda} \quad (\vec{\lambda} \geq 0 \land \vec{\lambda}^T \cdot A = \vec{c}^T \land \vec{\lambda}^T \cdot \vec{b} \leq \delta)
\]

We use this lemma to transform our formulas into equisatisfiable formulas that are simpler for SMT solvers.

The left-hand side of the lemma’s succedent has the same form as our formulas. First, we consider the subformula that has the form of the lemma’s antecedent. If this subformula is unsatisfiable the implication holds trivially and can be replaced by true. If this subformula is satisfiable, we can replace the formula by the corresponding instance of the right-hand side of the lemma’s succedent. Hence, we obtain formulas without quantifier alternation.
Success
Using Farkas’ Lemma\textsuperscript{32} we can transform our constraints into a form such that SMT solvers can find satisfying assignments. We have not seen an example in the lecture but this transformation is implemented in Ultimate and helped to find invariants for many examples.

Extension to more complex invariants
The limitation to annotations of the form $a_\ell \cdot x + b_\ell \cdot y + c_\ell \geq 0$ is very restrictive. Using a single inequality we are not even able to state an equality like, e.g., $x = 0$. A straightforward extension is to use a boolean combination of linear inequalities. We note however that for Farkas’ Lemma we need a form that is very similar to a conjunctive normal form and that hence the size of the final formula grows exponentially in the size of this Boolean combination of linear inequalities.

References
The idea to use Farkas’ Lemma for solving universally quantified constraints was first introduced by Colón and Sipma [tacas/ColonS01]. Their application was the synthesis of linear ranking functions. The synthesis of invariants that we saw in the lecture was published later by Colón, Sankaranarayanan and Sipma [cav/ColonSS03]. An invited paper by Rybalchenko [cav/Rybalchenko10] summarizes these approaches, and shows examples.

\textsuperscript{32}Wikipedia: Julias Farkas 1847-1930
Program Verification

Summer Term 2021

Lecture 24: Termination

Matthias Heizmann

Wednesday 14th July
Section 20

Termination Analysis
Outline

Introduction
 Propositional Logic
 First-Order Logic
 First-Order Theories
 SMT-LIB
 Boogie and Boostan
 Hoare Proof System
 Ultimate Referee
 Arrays

Boogie and Boostan – Part 2

Control-flow graphs
 Predicate Transformers
 Bounded Model Checking
 Correctness Specification via Assert Statement
 Abstractions – Part 1
 Infeasibility Proofs
 CEGAR
 Trace Abstraction
 Constraint-based Invariant Synthesis
 Termination Analysis
How should we define “termination” of a computer program?

We will next discuss four properties of programs.
1. Can the program reach the exit location?
   Is there some input for which the program reaches the exit location?
2. Can the program stop?
   Is there some input for which the program stops?
3. Does the program always reach the exit location?
   Does the program reach the exit location for all inputs?
4. Does the program always stop?
   Does the program stop for all inputs?
Results of the discussion:

- The properties are not stated precisely enough to give definite answers.

- On Exercise Sheet 23 we define four properties of the Boostan language and use the terminology from the definition of Boostan’s semantics.

- The first two properties and the last two properties are fundamentally different: we can state the first two using techniques that we saw in this course. (E.g., if we want to check the first property we could put an assert false at the end of the program.)

- Differences between “stopping” and “reaching the error location”. In C: program crashing. In Boogie or Boostan: assume statements.

- If we consider Boostan programs without assume statements there is no difference between Property 1 and Property 3 (resp. Property 2 and Property 4).

- Property 4 is the property that we want to call “termination”. We will give the formal definition for Boostan on the next slides.
Infinite Executions

Let $P = (V, \mu, st)$ be a program and $G = (Loc, \Delta, l_{\text{init}}, l_{\text{ex}})$ be a control-flow graph for $P$.

**Definition (Infinite Execution)**

We call a sequence of program configurations $(\ell_0, s_0), \ldots$ an *infinite execution* of $P$ if there exists an infinite sequence of statements $st_1 \ldots$ such that for each $i \in \mathbb{N}$

- $(\ell_i, st_{i+1}, l_{i+1}) \in \Delta$ and
- $(s_i, s_{i+1}) \in [st_{i+1}]$

**Definition**

We call $P$ *terminating* if $P$ does not have an infinite execution that starts in an initial configuration.
For the forthcoming definition of a ranking function we need the notion of a well-founded relation which was introduced in Exercise Sheet 22.

**Definition**

Let $X$ be a set. We call a binary relation $R \subseteq X \times X$ well-founded if there is no infinite sequence $x_1, x_2, \ldots$ such that $(x_i, x_{i+1}) \in R$ for all $i \in \mathbb{N}$. 
Our main means for proving termination will be *ranking functions*. We will first give a formal definition without further motivation and discuss its applications afterwards.

Informally, a ranking function for a loop is a function whose value is bounded from below but decreasing in every iteration. (Hence, we can conclude by reductio ad absurdum that only a finite number of loop iterations is possible).

On Wikipedia ranking functions are called *Loop variants*. In the research community on termination analysis, the term ranking function is however used more often.
Definition (Ranking Function)

Given a program $P = (V, \mu, st)$, a while loop `while(expr){st}` and a set $W$ together with a well-founded relation $R \subseteq W \times W$, we call a function $f : S_{V,\mu} \rightarrow W$ a ranking function if for each pair of states $(s, s') \in \llbracket \text{assume expr; st} \rrbracket$ the relation $(f(s), f(s')) \in R$ holds.

Example:

1. `while (x + y < 100) {
2. \hspace{1em} x := x + 1;
3. }

If we choose $(W, R)$ as $(\mathbb{N}, >)$ then

$$f(s) = 100 - s(x) - s(y)$$

is a ranking function for this program.

Notation:

In order to improve legibility, people usually write

$$f(x, y) = 100 - x - y$$

instead of $f(s) = 100 - s(x) - s(y)$. In this course we will also use both notations.
In Exercise 2 of Exercise Sheet 23 the task was to find ranking functions for programs.

In fact, if we require that a ranking function is a total function we typically cannot use \( \mathbb{N} \) as the range of the function. We discuss the problem of a ranking function’s range a couple of slides later.
**Question:** Is every loop that has a ranking function terminating?  

**Answer:** No. There might be a nonterminating loop inside a loop that has a ranking function.

```plaintext
1 while (x < 100) {
2   x := x + 1;
3   while (y < 100) {
4     y := y -1;
5   }
6 }
```
**Theorem**

*Let P be a program. If every while loop of P has a ranking function then P is terminating.*

Proof. (Not given in the lecture)
(Informally) Assume there is an infinite execution \((\ell_0, s_0), (\ell_1, s_1), \ldots\) that starts in an initial configuration. Let \(\ell'_0, \ell'_1, \ldots\) be the subsequence of all locations that are loop heads (definition of loop head was introduced on Exercise Sheet 23). Because of the structure of control flow graphs the sequence \(\ell'_0, \ell'_1, \ldots\) is an infinite subsequence (a formal proof would need more details here). Because there a only finitely many different locations in a control-flow graph, at least one loop head occurs infinitely often. Let \(\hat{\ell}\) be a loop head that occurs infinitely often in the sequence. Between each two visits of \(\hat{\ell}\) the ranking function of the corresponding loop is decreasing which is a contradiction to well-foundedness.
In the remaining section on termination, we will discuss the following questions.

- Are ranking functions into \((\mathbb{N}, >)\) always convenient?
- How can we check if a function \(f\) is a ranking function?
- What if a ranking function is only decreasing for reachable states?
- How can we compute ranking functions?
- How can we build an algorithm for checking termination?
- How can we find nonterminating executions?
- What is more difficult? Safety or termination?
Question: Are ranking functions into \((\mathbb{N}, >)\) always convenient?

Problem: Negative return value of function after the last loop iteration.

For \((\mathbb{N}, >)\) the function
\[ f(x) = x \]

is not a ranking function because after the last loop iteration the function returns \(-1\).
\[ f(x) = x + 1 \]
is a ranking function.

For \((\mathbb{N}, >)\) the function
\[ f(x, y) = x \]
is not a ranking function.
\[ f(x, y) = x + y \]
is a ranking function.

For \((\mathbb{N}, >)\) there is no ranking function.

Solution: Do not use \((\mathbb{N}, >)\) but \((\mathbb{Z}, >_{\mathbb{N}})\) whose relation we define as follows.

\[ x >_{\mathbb{N}} y \iff x > y \text{ and } x \in \mathbb{N} \]

This relation also solves another problem: If we require that the function \(f\) is defined for all states \(s \in S_{V,\mu}\) (i.e., \(f\) is a total function) then the functions that we saw so far were in fact not well-defined.
**Question:** How can we check if a function \( f \) is a ranking function?

We present a solution for the schematic example on the right where we assume

1. we have one loop in the loop body,
2. the program's variables are \( x_1, \ldots, x_n \),
3. that we can express the function as an expression \( f_{expr}(x_1, \ldots, x_n) \) over the program's variables, and
4. the range of \( f \) is \( \mathbb{Z} \) and we consider the well-founded ordering \( \succ_N \).

We introduce a new variable \( oldf \) whose values are integers and transform the program above to the program on the left. The function \( f \) is a ranking function for the outer while loop iff the program on the left is safe.
On the preceding slide we made four assumptions.

- The generalization where we drop the first two assumptions is obviously straightforward.

- The third assumption is a vital restriction since not every function is computable (no proof given in lecture).

- Whenever there is a computable ranking function, there is also a (computable) lexicographic ranking function (see Exercise 2 on Exercise Sheet 23) where each lexicographic component is $\mathbb{Z}, >_{\mathbb{N}}$. If the function $f$ is given in that form we can drop the fourth assumption, introduce an additional variable for each lexicographic component and modify lines 1, 8, and 9 accordingly.
Question: What if a ranking function is only decreasing for reachable states? The discussion of this question was mainly done on Exercise Sheet 23.

Consider the following program which is obviously terminating.

\begin{verbatim}
1 assume(y >= 1);
2 while (x >= 0) {
3   x := x - y;
4 }
\end{verbatim}

Q: Is $f(x, y) = x$ a ranking function for this loop? 
A: No. The value of $x$ is increasing if $y$ is negative.

Q: Is there a ranking function that allows us to prove termination of this program? 
A: Our first definition of a ranking function refers only to a loop. In order to prove termination of the program above, we also have to take the reachable states into account.
Definition (Loop Entry)

Given a while loop \(\text{while}(\text{expr})\{\text{st}\}\) and a control-flow graph \(G = (\text{Loc}, \Delta, \ell_{\text{init}}, \ell_{\text{ex}})\) for this while loop, we call \(\ell_{\text{init}}\) the entry location of the while loop.

If we would do this section with more formal rigor, we would redo the definition of a control flow graph and add to the tuple \((\text{Loc}, \Delta, \ell_{\text{init}}, \ell_{\text{ex}})\) a partial function that maps entry locations to the respective while loops.
Definition (Ranking Function)

Given a program $P = (V, \mu, st)$, a Floyd-Hoare annotation $\beta$ for $P$, a while loop `while(expr){st}` whose loop head is the location $\ell$, and a set $W$ together with a well-founded relation $R \subseteq W \times W$, we call a function $f : S_{V,\mu} \to W$ a ranking function if for each pairs of states where $s \in \{\beta(\ell)\}$ and $(s, s') \in \llbracket \text{assume expr; st} \rrbracket$ the relation $(f(s), f(s')) \in R$ holds.

Theorem

Let $P$ be a program and $\beta$ be a Floyd-Hoare annotation for $P$. If every while loop of $P$ has a ranking function for $\beta$ then $P$ is terminating.

Proof. (Not given in the lecture)

Analogously to the proof for the theorem on termination that does not yet have a name. Additionally we have to argue that the Floyd-Hoare annotation denotes a superset of the reachable states at each location.
Question: How can we compute ranking functions?

- For general programs: very difficult.

  Although there is some research that follows this direction [popl/CousotC12, esop/UrbanM14, tacas/UrbanGK16]. See e.g., the FUNCTION tool of Caterina Urban.

- For infinite traces: sometimes doable.

  For several termination analyses TODO cite some it is sufficient to compute ranking functions for ultimately periodic traces. An ultimately periodic trace is an infinite trace in which some (finite) sequence of statements is repeated infinitely often. E.g., the trace where \( x>0, y>0, y:=y-1 \) is repeated infinitely often is an ultimately periodic trace of the Program \( P_2 \) from Exercise 2 on Exercise Sheet 23. This ultimately periodic trace is then considered as a program that consists of a single while loop. For programs of this form several approaches are available [tacas/ColonS01, vmcai/PodelskiR04, cav/BradleyMS05, tacas/CookKRW10, popl/Ben-AmramG13, atva/HeizmannHLP13, tacas/LeikeH14, cav/Ben-AmramG17]. We outline the basic idea of these approaches on the next slides.
“Synthesize” ranking functions analogously to the synthesis of invariants.

Compute one transition formula $\tau_{\text{loop}}$ for all statements on the path from the loop entry to the loop entry.

Do not set up constraints that encode the existence of a general ranking function. Set up constraints that encode the existence of a ranking function that has a certain form.

If the variables of the program are $x$ and $y$ and $r_x, r_y, r_0 \in \mathbb{Z}$ then we call $r_x \cdot x + r_y \cdot y + r_0$ a linear function.

Constraints for the existence of a linear ranking function.

There exist $r_x, r_y, r_0$ such that

- $\forall x, y, x', y'. \tau_{\text{loop}}(x, x') \rightarrow (r_x \cdot x + r_y \cdot y + r_0) - (r_x \cdot x' + r_y \cdot y' + r_0) \geq 1$
- $\forall x, y, x', y'. \tau_{\text{loop}}(x, x') \rightarrow r_x \cdot x + r_y \cdot y + r_0 \geq 0$

The first line states that the function $f(x, y) = r_x \cdot x + r_y \cdot y + r_0$ is decreasing in every iteration. The second line states that the function $f(x, y) = r_x \cdot x + r_y \cdot y + r_0$ is bounded from below.

Use Farkas’ Lemma to simplify the constraints.

Apply an SMT solver to the resulting constraints. E.g., in the schematic example above we use the satisfying assignments to $r_x, r_y, r_0$ to build our linear ranking function.
Usually, the part of an ultimately periodic trace that is infinitely often repeated is preceded by a sequence of statements. E.g., if you consider the (there is only one) infinite trace that starts at the initial location of the program from Exercise 4 on Exercise Sheet 23 the infinite repetition of $x \geq 0$, $x := x - y$ is preceded by $y \geq 1$.

We translate these infinite traces into a while loop that is preceded by a sequence of statements and call these programs lasso programs because their control flow graphs have the shape of a lasso.
In lasso programs the loop sometimes does not have a ranking function but there is a ranking function for the combination of the loop and a given Floyd-Hoare annotation.

See [discussion on ranking functions for reachable states](#).

For these program we synthesize a ranking function together with a loop invariant \([\text{cav/BradleyMS05, atva/HeizmannHLP13}]\).

The constraints for the special case where we are searching for a ranking function of the form \(\vec{r}^T \cdot \vec{v} + r_0\) and an invariant of the form \(\vec{s}^T \cdot \vec{v} + s_0\) are given below.

In order to shorten the presentation, we use \(\vec{r}^T\) to denote the coefficients of the ranking function and \(\vec{s}^T\) to denote the coefficients of the invariant. We use \(\tau_{\text{stem}}\) to denote a transition formula of the sequential composition of all statements before the loop.

There exist \(\vec{r}, r_0, \vec{s}, s_0\) such that

\[
\forall \vec{v} \vec{v}'. \quad \tau_{\text{stem}}(\vec{v}, \vec{v}') \rightarrow \vec{s}^T \cdot \vec{v}' + s_0 \geq 0
\]

\[
\forall \vec{v} \vec{v}'. \quad \vec{s}^T \cdot \vec{v} + s_0 \geq 0 \land \tau_{\text{loop}}(\vec{v}, \vec{v}') \rightarrow \vec{s}^T \cdot \vec{v}' + s_0 \geq 0
\]

\[
\forall \vec{v} \vec{v}'. \quad \vec{s}^T \cdot \vec{v} + s_0 \geq 0 \land \tau_{\text{loop}}(\vec{v}, \vec{v}') \rightarrow \vec{r}^T \cdot \vec{v} - \vec{r}^T \cdot \vec{v}' \geq 1
\]

\[
\forall \vec{v} \vec{v}'. \quad \vec{s}^T \cdot \vec{v} + s_0 \geq 0 \land \tau_{\text{loop}}(\vec{v}, \vec{v}') \rightarrow \vec{r}^T \cdot \vec{v} + r_0 \geq 0
\]
Synthesis of ranking functions available in Ultimate: **LASSO RANKER**

- Supports synthesis of ranking functions together with invariants \([atva/HeizmannHLP13]\) and various kinds of ranking functions \([tacas/LeikeH14]\). E.g., linear ranking functions, nested ranking functions, multiphase ranking functions, lexicographic ranking functions or piecewise ranking funtions. Implements an approach based on trace abstraction \([cav/HeizmannHP14, pldi/ChenHLLTTZ18]\) that uses Büchi automata.

- Frontend currently supports the languages Boogie and C.

- Available via web interface.
Question: How can we build an algorithm for checking termination?

Basic idea of the approach of the Terminator tool [pldi/CookPR06].

Iteratively collect ranking functions until termination of all loops is shown.

1. Start with the empty set of ranking functions.
2. Pick an ultimately periodic trace for which termination is not yet shown (if termination is not yet proven).
3. Compute a ranking function for this trace and add it to our collection (if the trace does not have an infinite execution).
4. Check if the collection of ranking functions is sufficient to prove termination and continue with the second step.

A strength of Terminator’s approach is that it does not need one (possibly complicated) ranking function for each loop but that it can use a combination of several ranking functions to prove termination of a single loop. The theoretical basis for this are *disjunctively well-founded transition invariants* [lics/PodelskiR04]. In this lecture we will only demonstrate the basic idea on one example.
Let us prove that the program whose code is depicted on the right is terminating. The `if (*)` means that the computer which runs the program can nondeterministically pick one of the two branches. This is a syntax of Boogie that we did not introduce in Boostan.

We will need three iterations and two ranking functions.

Initially, our set of ranking functions is empty. We construct the first program depicted on the next slide and pass it to a tool that checks safety (resp. that every assert statement is valid). The safety checker tells us that the assert is reachable via the `if`-branch and we conclude that there is an ultimately periodic infinite trace that repeats the `if`-branch. We pass this trace to a tool that infers ranking functions and obtain $f_1(x, y) = x$.

In the second iteration we construct the second program of the next slide in order to check whether $f_1$ is sufficient to prove termination. This second safety check looks similar to the check that we discussed a few slides ago but the (re-)initialization of the old $f_1$ variable is done nondeterministically. The safety checker tells us that the assert can be violated by an execution that takes the `else` branch. We conclude that there is an ultimately periodic trace that repeats the `else`-branch whose termination cannot be shown by the ranking function $f_1$. We pass this trace to a tool that infers ranking functions and obtain $f_2(x, y) = y$. 

```c
while (x > 0 && y > 0) {
    if (*) {
        x := x - 1;
        havoc y;
    } else {
        y := y - 1;
    }
}
```
In the third iteration we construct the third program of the next slide in order to check whether the combination of $f_1$ and $f_2$ is sufficient to prove termination. The safety checker tells us that the assert statement is valid and we conclude termination of the original program.

We note that the expression of the assert statement is a disjunction; we do not require that both ranking functions are decreasing, we only require that at least one of ranking function is decreasing. For concluding termination the nondeterministic assignments to $\text{oldf1}$ and $\text{oldf1}$ are vital. The safety proof does not only show that in each iteration the function $f_1$ or the function $f_2$ is decreasing, the safety proof shows that between every two (not necessarily consecutive) visits of the loop head the function $f_1$ or the function $f_2$ is decreasing.
while (x > 0 && y > 0) {
  if (*) {
    x := x - 1;
    havoc y;
  } else {
    y := y - 1;
  }
  assert false;
}

if (*) {
  oldf1 := f1(x, y);
}
while (x > 0 && y > 0) {
  if (*) {
    x := x - 1;
    havoc y;
  } else {
    y := y - 1;
  }
  assert oldf1 > f1(x, y) &&
  oldf1 >= 0;
  if (*) {
    oldf1 := f1(x, y);
  }
}

if (*) {
  oldf2 := f2(x, y);
}
while (x > 0 && y > 0) {
  if (*) {
    x := x - 1;
    havoc y;
  } else {
    y := y - 1;
  }
  assert (oldf1 > f1(x, y) &&
          oldf1 >= 0)
       || (oldf2 > f2(x, y) &&
            oldf2 >= 0);
  if (*) {
    oldf1 := f1(x, y);
    oldf2 := f2(x, y);
  }
}

assert oldf1 > f1(x, y) &&
oldf1 >= 0;
if (*) {
  oldf1 := f1(x, y);
}

f1(x, y) = x
f2(x, y) = y
Development of Termination has been discontinued, successor is the T2 tool.
There are several other tools and approaches for termination analysis. TODO cite some

Termination analysis available in Ultimate: Büchi Automizer

- Implements an approach based on trace abstraction [cav/HeizmannHP14, pldi/ChenHLLTTZ18] that uses Büchi automata.
- Frontend currently supports the languages Boogie and C.
- Won the termination category at the Competition on Software Verification (SV-COMP) several times.
- Available via web interface. (Because of a bug, one has to use the command line version to see the ranking functions)
Question: How can we prove nontermination?

In the lecture, we discussed the poster on the Geometric Nontermination Arguments approach [tacas/LeikeH18] very briefly.

Not relevant for exam. Mainly shown to attract students that like linear algebra.
Question: What is more difficult? Safety or termination?

For both kinds of properties it is undecidable whether the property holds for a given program.

There exists a small program for which yet no one could prove or disprove termination.

Given a starting value $a_0$, let us consider the infinite series of integers $a_0, a_1, \ldots$ such that

$$a_{i+1} = \begin{cases} 
\frac{a_i}{2} & \text{if } a_i \text{ is even} \\
3 \cdot a_i + 1 & \text{if } a_i \text{ is odd}
\end{cases}$$

Collatz conjecture: For any starting value, the sequence will finally reach 1.

The Collatz conjecture is correct if and only if the program on the right is terminating.

Although many people tried, yet no one could prove or disprove the conjecture.

To the best of my knowledge, no small safety problem with the same level of difficulty is known.

```java
1    while (x != 1) {
2        if (x%2==0) {
3            x := x/2;
4        } else {
5            x := 3x+1
6        }
7    }
```


References II


