Extending Dynamic Constraint Detection with Disjunctive Constraints

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Dynamic Constraint Detection

- Fixed grammar of universal properties.
  - Serves well for the discovery of a well-defined set of problem-specific, but program-independent properties.
  - Does not allow to capture the logic of a particular program.
- Goal: enable constraint detection to capture the subtle essential properties of a program under analysis.

State Space Partitioning Technique (SSPT)

- Combines static and dynamic program analysis.
- Automatically specializes the language of constraint detection.
- Adds program-specific disjunctive properties.

Introduction: State Space Partitions

```
if (x < 0) {...}
else if (y > 0) {...}
else {...}
```

$$\Rightarrow \quad \begin{aligned} P_1 &\equiv x < 0, \\ P_2 &\equiv x \geq 0 \wedge y > 0, \\ P_3 &\equiv x \geq 0 \wedge y \leq 0 \end{aligned}$$

State space: $\{\langle x, y \rangle \mid -2^{31} \leq x, y < 2^{31}\}$

Three disjoint subspaces, or abstract *states*: P_1, P_2, P_3

Types of Disjunctive Constraints

- Object Invariant
  - Properties a and b are mutually exclusive: $\neg a \vee \neg b$
- Use cases for a method m
  - Method m was called when abstract states s or w hold: $s \vee w$
- Transitions between abstract states induced by a method m, $p \Rightarrow q$
  - p is an abstract state on variables at precondition of m
  - q is a disjunction of abstract states on variables at postcondition of m
- Daikon-inferred implications for a method m, $p \Rightarrow t$
  - p is an abstract state on variables at precondition of m
  - t is an instantiated template

The Calculator Example

```
public class CalcEngine {

//number which appears in the Calculator display
private int displayValue;
//store a running total
private int total;
//true if #'s pressed should overwrite display
private boolean newNumber;
//true if adding
private boolean adding;
//true if subtracting
private boolean subtracting;

public void numberPressed(int number) {
if (newNumber)
    displayValue = number;
else
    displayValue = displayValue * 10 + number;
newNumber = false;
}

public void equals() {
if (adding)
    displayValue = displayValue + total;
else if (subtracting)
    displayValue = total - displayValue;
  ...
}

public void clear() { ... }

public void plus() { ... }

public void minus() { ... }

}
```

State Spaces for the Calculator Example

```
public class CalcEngine {

//number which appears in the Calculator display
private int displayValue;
//store a running total
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    displayValue = displayValue + total;
else if (subtracting)
    displayValue = total - displayValue;
  ...
}

public void clear() { ... }

public void plus() { ... }

public void minus() { ... }

}
```

$$\Pi_1 \equiv \{P_1, P_2\}$$
$$P_1 \equiv \text{newNumber}$$
$$P_2 \equiv \neg\, \text{newNumber}$$

$$\Pi_2 \equiv \{Q_1, Q_2, Q_3\}$$
$$Q_1 \equiv \text{adding}$$
$$Q_2 \equiv \neg\text{adding} \wedge \text{subtracting}$$
$$Q_3 \equiv \neg\text{adding} \wedge \neg\text{subtracting}$$

Constraints for Calculator

```java
public class CalcEngine {

//number which appears in the Calculator display
private int displayValue;
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private int total;
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    displayValue = displayValue + total;
else if (subtracting)
    displayValue = total - displayValue;
  ...
}

public void clear() { ... }

public void plus() { ... }

public void minus() { ... }

}
```

$\Pi_1 \equiv \{P_1, P_2\}$

$P_1 \equiv \text{newNumber}$

$P_2 \equiv \neg\text{newNumber}$

$\Pi_2 \equiv \{Q_1, Q_2, Q_3\}$

$Q_1 \equiv \text{adding}$

$Q_2 \equiv \neg\text{adding} \wedge \text{subtracting}$

$Q_3 \equiv \neg\text{adding} \wedge \neg\text{subtracting}$

Object Invariant:

```
context CalcEngine inv:
(!this.adding || !this.subtracting)
```

Method Constraints:

```
context CalcEngine::numberPressed(int number)
pre: P1 || P2, Q1 || Q2 || Q3
post: orig(P1) ==> P2, orig(P2) ==> P2
 orig(Q1) ==> Q1, orig(Q2) ==> Q2
 orig(Q3) ==> Q3
 orig(P1) <==> (displayValue == orig(number))
 orig(P2) ==>
   (displayValue ==
     10*orig(displayValue)+orig(number))
context CalcEngine::clear()
pre: P1 || P2, Q3
post: orig(P1) ==> P1, orig(P2) ==> P1,
 orig(Q3) ==> Q3
```

SSPT:Overview

- Form disjoint partitions of the state spaces of the program variables involved in expressing the `if-then-else` tests.

```
if (adding)
   …
else if (subtracting)

   …
```

$$\Pi_2 \equiv \{Q_1, Q_2, Q_3\}$$

$$Q_1 \equiv \text{adding}$$

$$Q_2 \equiv \neg\text{adding} \wedge \text{subtracting}$$

$$Q_3 \equiv \neg\text{adding} \wedge \neg\text{subtracting}$$

SSPT: Hypothesized Constraints

Let $\Pi = \{P_1, P_2, ..., P_n\}$

- Preconditions: $P_1 \vee P_2 \vee ... \vee P_n$
- Postconditions: $P_i \Rightarrow P_j \vee P_k,\ i, j, k \in [1..n]$
- Object invariants: check whether the *tests* of the corresponding `if-then-else` statement are mutually exclusive.
  - For the Calculator example

```
if (adding)
    …
else if (subtracting)
    …
```

$$
\begin{aligned}
&(\text{adding} \wedge \neg\text{subtracting}) \vee \\
&(\neg\text{adding} \wedge \text{subtracting}) \vee \\
&(\neg\text{adding} \wedge \neg\text{subtracting})
\end{aligned}
$$

SSPT: Constraint Approximation Algorithm

- Let $\Pi = \{P_1, P_2, P_3\}$
- Notation: for $i \in [1..3]$

P_i^{pre} - abstract state P_i over variable values at precondition

P_i^{post} - abstract state P_i over variable values at postcondition

SSPT: Constraint Approximation Algorithm

At the post-condition program point for a method M compute the transitional post-condition for each P_i^{pre}, $i \in [1..3]$, as follows:

1. Assume that $P_i^{pre} \Rightarrow \neg P_1^{post}$, $P_i^{pre} \Rightarrow \neg P_2^{post}$, and $P_i^{pre} \Rightarrow \neg P_3^{post}$ are all possible transitions. Denote this by the set S of indices $S = \{1,\ 2,\ 3\}$.

2. Perform dynamic analysis, and whenever P_i^{pre} and P_j^{post} both hold, remove j from S.

3. Approximate the transitional post-condition for P_i^{pre} with a disjunction of abstract states whose indices are contained in the complement of S, $P_i^{pre} \Rightarrow \bigvee_{k \in S^c} P_k^{post}$.

SSPT: Constraint Approximation Algorithm

Intuition behind the algorithm:

Let $i = 1$ and after step 2, let *S = {1, 3}.*

Then, $P_1^{pre} \Rightarrow \neg P_1^{post}$ and $P_1^{pre} \Rightarrow \neg P_3^{post}$ are consistent with the observed data.

$P_1^{post} \vee P_2^{post} \vee P_3^{post}$ is true by construction.

The transition $P_1^{pre} \Rightarrow P_2^{post}$ follows by propositional logic.

ContExt: Implementation

- Lightweight static analysis of Java source code for abstract state extraction.
- Dynamic analysis tasks are delegated to Daikon.
- ContExt combines the constraints inferred by our approach with those inferred by Daikon in its output.

Transitional Constraint Inference

- A *splitting condition (splitter)* is a boolean expression in terms of some program variables.
- Let T be a program point which has all the variables involved in a splitter a.
- a partitions the data trace into two mutually exclusive subsets:
  - T_a : contains the data values that satisfy a
  - $T_{\neg a}$: contains the data values on which a does not hold.
- Each abstract state P_i^{pre} from a space Π is used as a splitter on the data trace at postcondition program points of the enclosing class.
- Convenient checks when P_i^{pre} and P_j^{post} both hold.

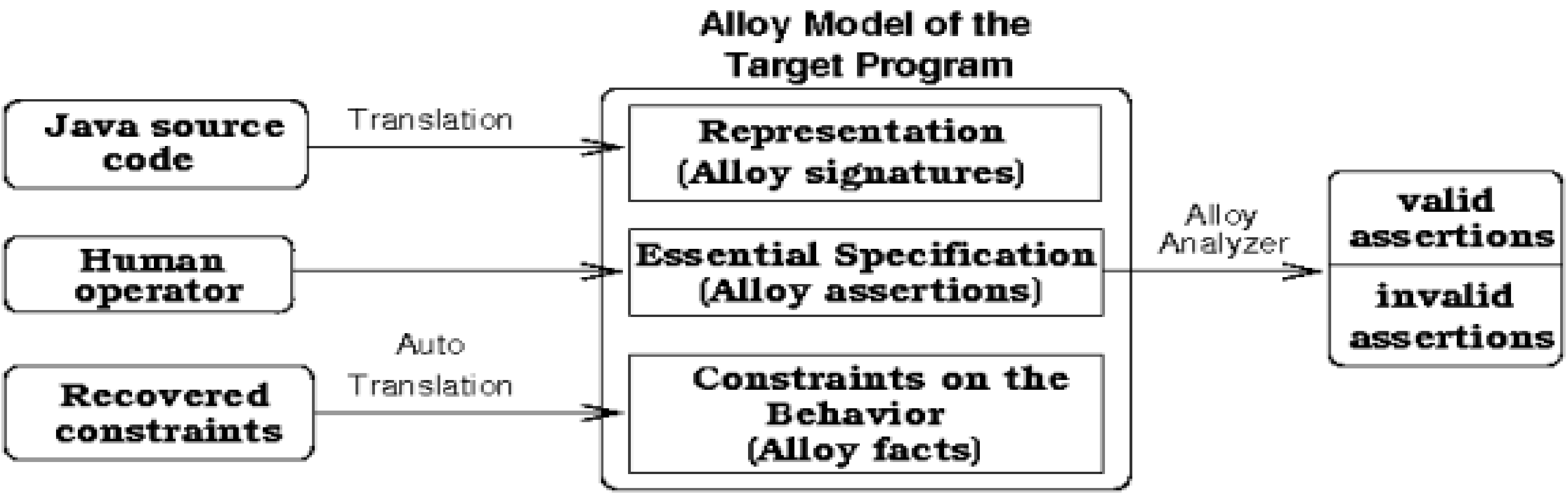
Limitations

- Our approach is primarily a dynamic analysis.
  - The reported constraints are unsound.
  - Potentially stronger constraints are reported.
- Increase in the number of accidental constraints reported and loss of precision.
- Given the same test suite, our approach may not infer some unconditional constraints that Daikon would.
- Requires the presence of source code.
- The technique has been applied to only one class at a time.

Evaluation Challenge

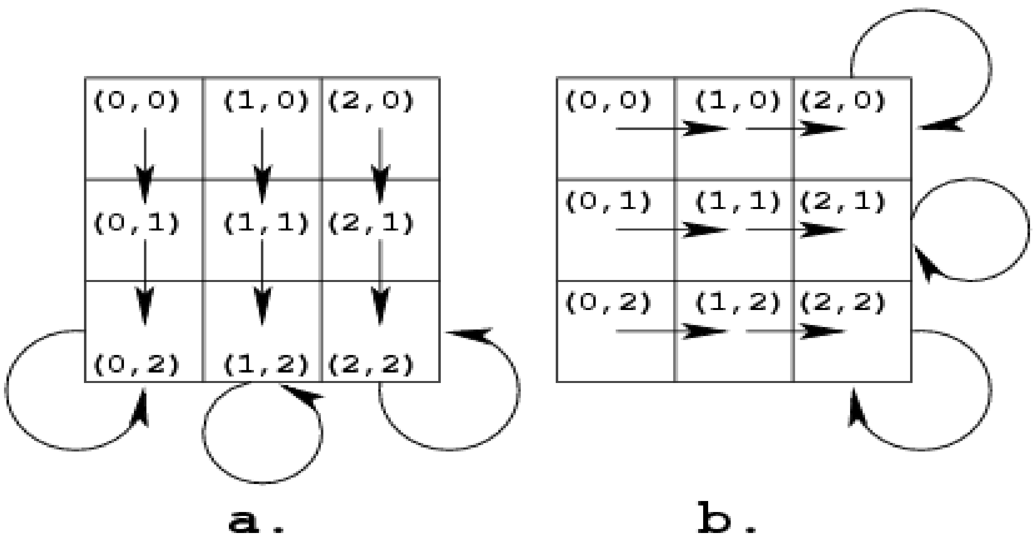
- Quantitative measurement of the quality of inferred constraints is challenging.
- Propose a methodology for a quantitative evaluation of constraint inference techniques based on a modeling language Alloy.
- Concentrate on recall.
- Apply it to comparatively evaluate Daikon and ContExt on two examples.

Evaluation Methodology



Case Study 1: Puzzle

- The Puzzle class represents an environment with an agent.



Puzzle Specification

Assertion in Alloy	English-language specification

assert moveForward_1 {
all p′ : Puzzle, p : Puzzle |
(p in (p′.moveForward.Unit)) =>
(p′.yPosition = p.yPosition <=> p′.yPosition = 0)
}
	The y-coordinate of the agent is to remain the same only when it attempts a moveForward from the top edge of the board (y is 0).

assert moveForward_2 {
all p′ : Puzzle, p : Puzzle |
(p in (p′.moveForward.Unit)) =>
(p′.yPosition - 1 = p.yPosition <=> p′.yPosition > 0)
}
	Otherwise, an agent moves forward exactly one square (y-coordinate decreases by one).

assert moveForward_3 {
all p′ : Puzzle, p : Puzzle |
(p in (p′.moveForward.Unit)) =>
p.yPosition =< p′.yPosition
}
	The y-position of the agent at the post-condition of the moveForward method is less than or equal to the y-position at pre-condition.

assert moveForward_4 {
all p′ : Puzzle, p : Puzzle |
(p in (p′.moveForward.Unit)) =>
(p.xPosition = p′.xPosition)
}
	Moving forward does not affect the x-coordinate of the agent.

Puzzle Evaluation

	number of assertions	number of checked assertions	number of facts
Daikon	35	18 (51%)	35
Daikon (w/split)	35	23 (66%)	124
ContExt	35	28 (80%)	554

Comparative evaluation of the inferred constraints for ContExt and Daikon on the `Puzzle` example

Case Study 2: Employee Example

	number of assertions	number of checked assertions	number of facts
Daikon	15	12 (80%)	55
ContExt	15	15 (100%)	89

Comparative evaluation of the inferred constraints for ContExt and Daikon on the `Employee` example

Related Work

- Csallner et al. employ a dynamic symbolic execution technique to obtain program-specific constraints.
  - performs symbolic execution over an existing test suite.
- Engler et al. and Yang et al. focus on recovering a relatively small number of error-revealing properties.
- Dallmaier et al. use a combination of static and dynamic analysis to construct state machines that represent an object's behavior in terms of its inspector and mutator methods.
- Arumuga Nainar et al. are interested in finding relevant boolean formulae.
  - The formulae partition the program state space into only two subspaces, one in which a bug is exibited, and the other one in which it is not.

Conclusions

- State Space Partitioning Technique combines lightweight static and dynamic analysis to provide for the inference of program-specific disjunctive properties.
- Proposed an evaluation methodology for the quality of inferred constraints based on the Alloy modeling language.

Comparative Complexity

- Generalized disjunctive template:
  - 2^k, where k is the number of hypothesized non-disjunctive constraints.

Comparative Complexity

P	Number of program points in the target program.
C	Number of hypothesized constraints at a program point.
L	Number of data samples observed.

- Daikon (approximated with those of the simple incremental algorithm) :
  - Space complexity: $S = O(P * C)$
  - Time complexity: $T = O\,(P * C * L)$

Comparative Complexity

P	Number of program points in the target program.
C	Number of hypothesized constraints at a program point.
L	Number of data samples observed.
m	Number of class-scoped partitions.
n	The maximum number of states per class-scoped partition.

- ContExt:
  - $P' = m * n * P, C' = m * n + C$
  - Space complexity: $S = O(P' * C') = O(mnP * (mn + C))$
  - Time complexity: $T = O(P' * C' * L) = O(mnP * (mn + C) * L)$