Principles for Value Annotation Languages

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Introduction

WCET analysis tools require many kinds of *annotations*, like:

- Specifying the environment (hardware, entry points to code, . . .)
- Directing the analysis (context-sensitivity, abstract domain, what kinds of generated information, . . .)
- Specifying value ranges for inputs and program variables
- Specifying flow facts

The two last kinds are both *value annotations* (flow facts $=$ value constraints on IPET execution counters)

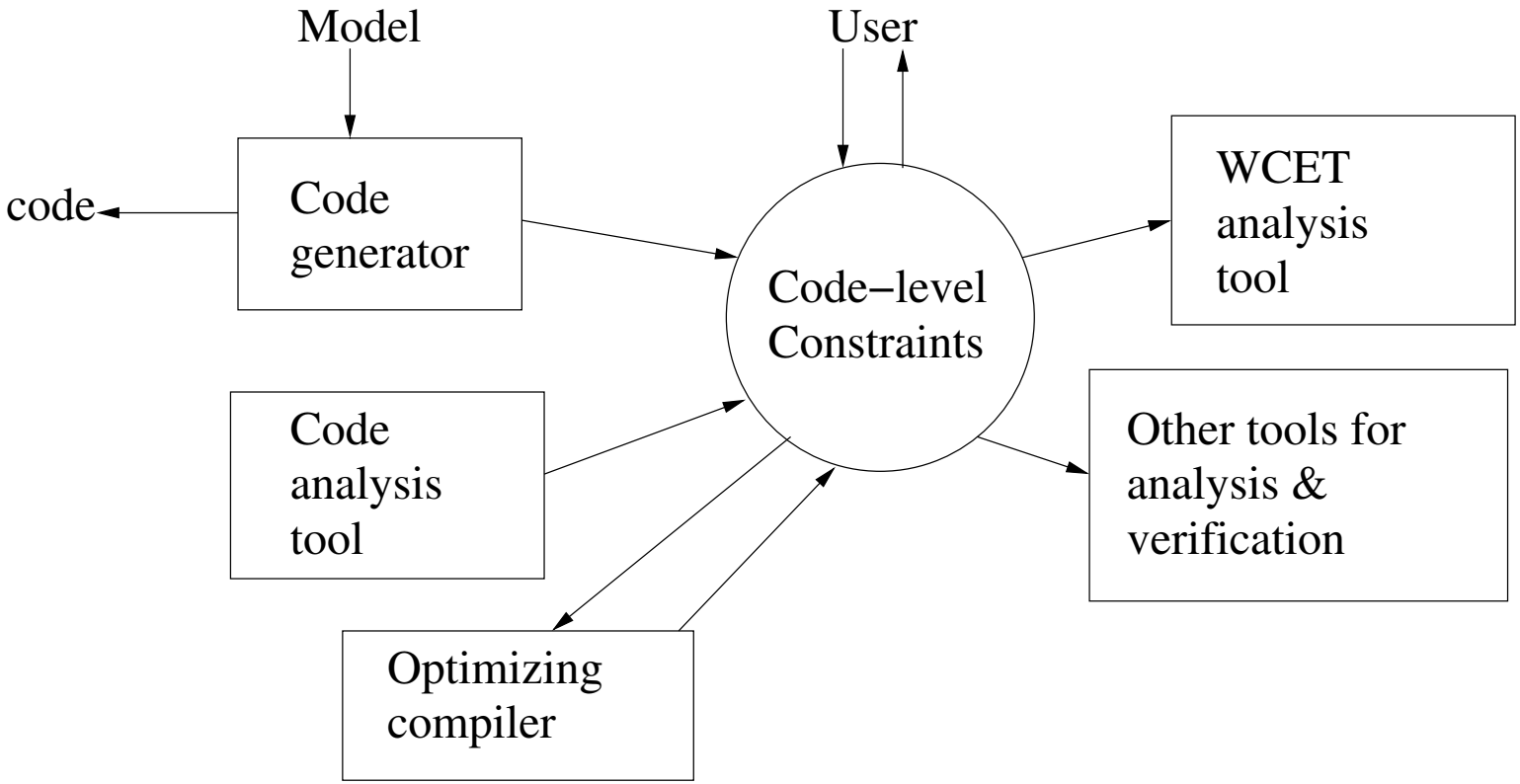
State of Practice

Flow fact and value annotation languages are often defined in an ad-hoc manner:

- Tools have their own languages
- Often designed to fit the capabilities of the tool rather than being general
- Sometimes unclear semantics (usually no formal semantics)

Poor interoperability, harder than necessary to specify constraints

An Ecosystem of Embedded Systems Tools



Wish List for a Language for Code-level Value Constraints

Should work over a wide range of code-level tools

Should work over a wide range of “host” languages, on different levels

General yet simple, few but powerful constructs. Simple and clear semantics

Should have:

- Succinct, natural syntax for humans, as well as
- Easily machine-readable form (XML) for tools

Ability to express contexts where constraints are to hold

Contributions

A core assertion language for value constraints, derived from first principles (Floyd-Hoare logic)

Minimal assumptions on the “host” language

Can express flow facts as value constraints on IPET execution counters

Suggestions for user-friendly syntax

Simple, straightforward formal semantics

A theorem about compositionality of assertions

What Could a Core Language be Good For?

A basis for a standardised assertion language for value annotations and flow facts, shared by many tools (ambitious, not so realistic)

A means to specify and understand the semantics of existing annotation formats (more realistic)

- *Reduce risk of misinterpretations*
- *Helpful when defining translators between different annotation languages*

More thorough understanding how to design such languages (realistic)

- *Will help get future annotation languages right*

The Assertion Language of Floyd-Hoare Logic

A starting point: *Floyd-Hoare logic*

$$\{P\}S\{Q\}$$

Pre-condition – program – post-condition

P and Q express *constraints on states*

States σ map program variables to values (abstraction of memory)

Semantics: if $P(\sigma)$ holds, and if S takes σ to σ', then $Q(\sigma')$ must hold

Example:

$$\{X = i\}X := X + 1\{X = i + 1\}$$

Pre- and post-conditions are expressed in a predicate language on states

It has:

- program variables (like X), which depend on program state,
- *auxiliary* variables (like i), which are independent of state,

Auxiliary variables can be used to relate the values of program variables in pre- and post-conditions

Taking it Further

We take Floyd-Hoare logic as a starting point

But the triples are not suitable. They presume structured (jump-free) code, no good for low-level code.

Solution: make the program point part of the state (add a "PC" variable)

Jumps are now modelled by state transitions that change the PC

Can constrain PC to certain program points in the constraints ("$PC = Label$")

Can be used to express pre- and post-conditions also on low-level code

A Proposed Syntax

A simple language of arithmetic constraints:

$$
\begin{array}{lcl}
a & ::= & n \mid i \mid X \mid a_1 \ a\_op \ a_2 \\
p & ::= & true \mid false \mid p_1 \wedge p_2 \mid p_1 \vee p_2 \mid \neg p \mid a_1 \ r\_op \ a_2 \mid \forall i.p \mid \exists i.p \mid PC = L \\
c & ::= & p_1 \rightarrow p_2
\end{array}
$$

a (arithmetic) expression, p predicate

$p_1 \rightarrow p_2$ are assertions (like the triples in Floyd-Hoare logic). These are our value constraints!

Semantics: if $p_1(\sigma)$ holds, and $\sigma \rightarrow^* \sigma'$, then $p_2(\sigma')$ must hold

Relation to the Host Language

Minimal assumptions on the host language:

- Its programs have *states* σ, and *state transitions* $\sigma \rightarrow \sigma'$
- It has *program variables* X. States σ map program variables X to (numerical) values $\sigma(X)$
- It has a dedicated program variable PC that holds the current position in the code (a *label*). Labels can be basically anything that identifies a program point

Examples:

- C: program variables are C variables, labels are C labels or (line number, column number) pairs
- Linked binaries: program variables and labels are addresses

Some examples

(Assume labels "$entry$", "$exit$" for the entry and exit point of the host program)

- $(PC = entry) \rightarrow (PC = L \implies X < 17)$: for all states reachable from the start of the program, if at label L then $X < 17$;
- $(PC = entry \wedge 1 \leq X \leq 10) \rightarrow (PC = exit \implies Y \leq 100)$: if the program is started with $1 \leq X \leq 10$ then, at exit, $Y \leq 100$;
- $(PC = entry) \rightarrow X < 32768$: a global invariant, in all reachable states holds that $X < 32768$.

Some Syntactic Sugar

Let $@L$ stand for $PC = L$ (common to constrain to a certain label)

Let p stand for $@entry \rightarrow p$ (common to consider all states reachable from the entry point)

Some examples revisited:

- $(@entry \wedge 1 \leq X \leq 10) \rightarrow (@exit \implies Y \leq 100)$
- $X < 32768$ (understood, for all states reachable from the entry point)
- $@L \implies X < 17$ (ditto)

IPET Execution Counters and Flow Facts

For any label L, a global IPET execution counter $\#L$

Can be used in constraints expressing flow facts:

- $@exit \implies \#L < 100$: a simple capacity constraint;
- $@exit \implies \#L = 99$: an exact capacity constraint;
- $@exit \implies \#L_1 + \#L_2 \leq 1$: a mutual exclusivity constraint;
- $(@entry \wedge 1 \leq X \leq 10) \rightarrow (@exit \implies \#L \leq 100)$: a capacity constraint under the condition that the value of X lies in the range $[1 \ldots 10]$ at entry;
- $(@entry \wedge X = n) \rightarrow (@exit \implies \#L \leq 2 \cdot n + 1)$: a parametric constraint relating the number of executions of L to the value of X at entry;

Time

The state could contain time (represented, say, by program variable T)

An example of a real-time constraint. Assume that L, L' are labels in a loop with loop counter I. Then

$$(@L \wedge T = t \wedge I = i) \rightarrow (@L' \wedge I = i \implies T - t \leq 7)$$

expresses that for each iteration, L' is reached at most 7 time units after L

Uses auxiliary variables i, t for "old" values of I, T (in pre-condition). Could use "$X.old$" to refer to value of X in pre-condition. Example becomes

$$@L \rightarrow (@L' \wedge I = I.old \implies T - T.old \leq 7)$$

Semantics

The language can be given a formal semantics

Completely standard, I will not bring it up here

Important to have to make the notation well-defined

Also makes it possible to prove certain laws

Theorem 1 (compositionality of assertions):

$p_1 \rightarrow p_2 \wedge p_2 \rightarrow p_3 \implies p_1 \rightarrow p_3$.

Context-sensitivity

We can define call-strings as sequences of labels that are call sites for functions

Let S be a call-string. $p \to p'\ through\ S$ means that if $p(\sigma)$ holds, and σ' can be reached from σ through a sequence of transitions visiting the labels in S, then $p'(\sigma')$ must hold

Can be used to “qualify” assertions to hold only for certain contexts

Theorem 1 can be extended to context-sensitive assertions:

Theorem 2:

$$p_1 \to p_2\ through\ S \wedge p_2 \to p_3\ through\ S' \implies p_1 \to p_3\ through\ S \cdot S'.$$

Conclusions

A simple core language for value constraints

Like Floyd-Hoare logic, but not restricted to structured (jump-free) languages

Minimal assumptions on the host language

Can express very general value constraints, including general flow facts

Formal semantics, exact meaning, no room for misinterpretations

Straightforward to extend to context-sensitive constraints

Not restricted per se to WCET analysis tools, any code level tool could potentially use it