Z3-Noodler - An Automata based String Solver
Theory and Practice of SMT Solving

Luís Felipe Ramos Ferreira

What is Z3-Noodler

- Fork of the Z3 theorem prover

What is Z3-Noodler

- ▶ Fork of the Z3 theorem prover
- ▶ String theory solver replaced by *Noodler*

What is Z3-Noodler

- ▶ Fork of the Z3 theorem prover
- ▶ String theory solver replaced by *Noodler*
  - ▶ *Stabilization-based procedure*

What is Z3-Noodler

- Fork of the Z3 theorem prover
- String theory solver replaced by *Noodler*
  - *Stabilization-based procedure*
  - Heavy usage of *non deterministic automata*

Handling automata and regular expressions

- Hard task

Handling automata and regular expressions

- Hard task
- Mata library

Handling automata and regular expressions

- Hard task
- Mata library
  - Union, concatenation, intersection, etc

Handling automata and regular expressions

- Hard task
- Mata library
  - Union, concatenation, intersection, etc
- Very efficient and optimized

Architecture

- Takes advantage of Z3's whole DPLL($\mathcal{T}$) architecture

Architecture

- Takes advantage of Z3's whole DPLL($\mathcal{T}$) architecture
- Parser, rewriter and LIA solver
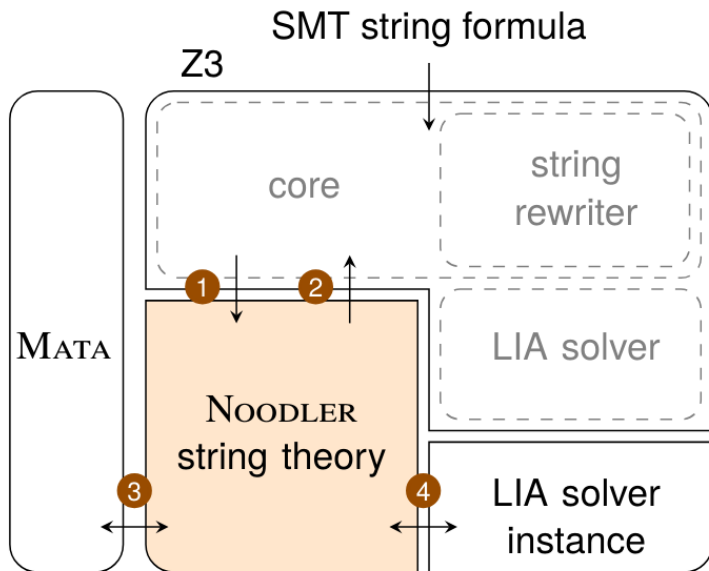
Architecture

Figure 1: Z3-Noodler architecture

String Theory Core

- Axiom Saturation

String Theory Core

- ▶ Axiom Saturation
- ▶ Decision Procedures

String Theory Core

- Axiom Saturation
- Decision Procedures
- Preprocessing

String Theory Core

- Axiom Saturation
- Decision Procedures
- Preprocessing
- Supoorted String Predicates and Limitations

Axiom Saturation

- Goal: optimize the use of Z3's internal LIA solver

Axiom Saturation

- Goal: optimize the use of Z3's internal LIA solver
- Happens during preprocessing (before SAT solver first assignment)

Axiom Saturation

- Goal: optimize the use of Z3's internal LIA solver
- Happens during preprocessing (before SAT solver first assignment)
- $len(t_1) >= 0, len(t_1.t_2) = len(t_1) + len(t_2)$

Axiom Saturation

- Goal: optimize the use of Z3's internal LIA solver
- Happens during preprocessing (before SAT solver first assignment)
- $len(t_1) >= 0, len(t_1.t_2) = len(t_1) + len(t_2)$
- $t_1 = t_2 \implies len(t_1) = len(t_2)$

Axiom saturation

- Goal: deal with string functions/predicates

Axiom saturation

- Goal: deal with string functions/predicates
- Saturates the original formula with an equivalent one composed of:

Axiom saturation

- Goal: deal with string functions/predicates
- Saturates the original formula with an equivalent one composed of:
  - Word (dis)equations

Axiom saturation

- Goal: deal with string functions/predicates
- Saturates the original formula with an equivalent one composed of:
  - Word (dis)equations
  - Regular constraints

Axiom saturation

- Goal: deal with string functions/predicates
- Saturates the original formula with an equivalent one composed of:
  - Word (dis)equations
  - Regular constraints
- $\neg contains(s, "abc")$ becomes $s \notin \Sigma^* abc \Sigma^*$

Decision Procedures: Stabilization Method

- $zyx = xxz \land x \in a^* \land y \in a^+b^+ \land z \in b^*$

Decision Procedures: Stabilization Method

- $zyx = xxz \wedge x \in a^* \wedge y \in a^+ b^+ \wedge z \in b^*$
- $zy = z \wedge y \in a^+ b^+ \wedge z \in b^*$

Decision Procedures: Stabilization Method

- $zyx = xxz \land x \in a^* \land y \in a^+ b^+ \land z \in b^*$
- $zy = z \land y \in a^+ b^+ \land z \in b^*$
- Regular constraints enforce *UNSAT*

Decision Procedures: Stabilization Based

- Solves word (dis)equations with regular and length constraints

Decision Procedures: Stabilization Based

- Solves word (dis)equations with regular and length constraints
- For every variable, creates a NFA enconding regular contraints of the variable

Decision Procedures: Stabilization Based

- ▶ Solves word (dis)equations with regular and length constraints
- ▶ For every variable, creates a NFA enconding regular contraints of the variable
- ▶ Iteratively refines the NFA according to word equations until stability is achieved

Decision Procedures: Stabilization Based

- ▶ Solves word (dis)equations with regular and length constraints
- ▶ For every variable, creates a NFA enconding regular contraints of the variable
- ▶ Iteratively refines the NFA according to word equations until stability is achieved
- ▶ Stability: for every word equation $s_1 = s_2$, the language of the NFA of s_1 equals the language of the NFA of s_2

Decision Procedures: Stabilization Based

- Solves word (dis)equations with regular and length constraints
- For every variable, creates a NFA enconding regular contraints of the variable
- Iteratively refines the NFA according to word equations until stability is achieved
- Stability: for every word equation $s_1 = s_2$, the language of the NFA of s_1 equals the language of the NFA of s_2
- After stability, length constraints are added and fed to the LIA solver

Decision Procedures: Nielsen Transformation

- Efficient for quadratic equations

Decision Procedures: Nielsen Transformation

- ▶ Efficient for quadratic equations
- ▶ Creates a graph encoding the system and reason about it

Decision Procedures: Nielsen Transformation

- Efficient for quadratic equations
- Creates a graph encoding the system and reason about it
- Complex

Preprocessing

- Each DP aforementioned employs different preprocessing steps

Preprocessing

- Each DP aforementioned employs different preprocessing steps
- Simple unsatisfiable patterns are checked for early termination

Preprocessing

- Each DP aforementioned employs different preprocessing steps
- Simple unsatisfiable patterns are checked for early termination
- $xy = zw \land len(x) = len(z) \implies y = w$

Supported String Predicates and Limitations

- *replace*, *substr*, *at*, *indexof*, *prefix*, *suffix*, *contains*

Supported String Predicates and Limitations

- *replace*, *substr*, *at*, *indexof*, *prefix*, *suffix*, *contains*
- Limited support for ¬*contains*

Supported String Predicates and Limitations

- *replace*, *substr*, *at*, *indexof*, *prefix*, *suffix*, *contains*
- Limited support for ¬*contains*
- Don't support *replace_all* and *to*/*from_int*

Supported String Predicates and Limitations

- *replace*, *substr*, *at*, *indexof*, *prefix*, *suffix*, *contains*
- Limited support for ¬*contains*
- Don't support *replace_all* and *to*/*from_int*
- Z3-Noodler is complete for the chain-free fragment with unbounded disequations, regular constraints and quadratic equations

Supported String Predicates and Limitations

- *replace*, *substr*, *at*, *indexof*, *prefix*, *suffix*, *contains*
- Limited support for ¬*contains*
- Don't support *replace_all* and *to*/*from_int*
- Z3-Noodler is complete for the chain-free fragment with unbounded disequations, regular constraints and quadratic equations
- Outside of this, the theory is sound but not complete

Experiments

- ▶ Three sets of benchmarks: *Regex*, *Equations* and *Predicates Small*

Experiments

- ▶ Three sets of benchmarks: *Regex*, *Equations* and *Predicates Small*
- ▶ Z3-Noodler is good in the *Regex* group in number of solved instances as well in average runtime

Experiments

- Three sets of benchmarks: *Regex*, *Equations* and *Predicates Small*
- Z3-Noodler is good in the *Regex* group in number of solved instances as well in average runtime
- The same happens in the *Equations* group

Experiments

- ▶ Three sets of benchmarks: *Regex*, *Equations* and *Predicates Small*
- ▶ Z3-Noodler is good in the *Regex* group in number of solved instances as well in average runtime
- ▶ The same happens in the *Equations* group
- ▶ cvc5 is the best one in *Predicates Small*, while Z3-Noodler performed poorly

Experiments

- Three sets of benchmarks: *Regex*, *Equations* and *Predicates Small*
- Z3-Noodler is good in the *Regex* group in number of solved instances as well in average runtime
- The same happens in the *Equations* group
- cvc5 is the best one in *Predicates Small*, while Z3-Noodler performed poorly
- Z3-Noodler could, however, be further improved by proper axiom saturation for predicates or lazy predicate evaluation

The end

- Thanks!