Extensions to Clafer Using an SMT Backend

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Abstract

We present a new backend for Clafer - a variability modeling language - using the Z3 Satisfiability Modulo Theory (SMT) solver. Z3 is well respected for its speed and has been shown to outperform other solvers in the domain of partial modeling – one type of modeling within the scope of Clafer. We show that, by retaining the notion of a *scope*, Clafer can generally be expressed within the logic of `QF_UFNRA` (quantifier-free non-linear real arithmetic), however all Clafer models encountered so far can be expressed in `QF_LIA` (quantifier-free linear integer arithmetic). We are capable of supporting language features not previously available in Clafer, including constraints over real numbers, and string constraints, leveraging Z3-Str: a theory extension to Z3. We conclude with a discussion of other extensions we have made, as well as new directions for future work that would not be possible with other Clafer backends.

Contents

1 Introduction

Clafer is a modeling language with first-class support for feature and meta-modeling [1]. In earlier work, Clafer has been translated to two backend solvers 1) Alloy – a bounded relational model checker, and 2) Choco – a library for constraint satisfaction problems. A Clafer specification can be translated to either of these two backends, which produce models of the specification if it is satisfiable, or produce an unsatisfiable core otherwise. Depending on the type of constraints within the Clafer specification, one backend may be more suitable than the other. For example, Alloy does not perform well on arithmetic constraints over large integers, as it deals with them by flattening bounded integers into boolean formulas, however the Choco solver is much more capable on these types of constraints. Furthermore, some desirable language features such as constraints over real numbers and strings are not currently supported by either backend, due to restrictions of the solvers.

In order to address some of these restrictions, we have developed a new translation from Clafer to Z3 [4] – a state-of-the-art SMT solver. Z3 is well known to be a fast solver, motivating our desire to create a new Clafer backend with it. In an experiment by [6], randomly generated partial models were analyzed by four solvers: Alloy, a relational logic solver; Minizinc, a *constraint satisfaction problems* (CSP) solver; Clasp with GrinGo, an *answer set programming* (ASP) solver; and Z3. Z3 was shown to be more efficient (based on solving time) in general, and also scaled better to harder problems. Z3 has also been shown to perform well relative to other SMT solvers, winning the SMTCOMP 2012 competition in the theory categories of `QF_UFLIA`, `QF_UFLRA`, and `QF_BV`, among others[1]. Further, a recent extension to Z3: Z3-Str [7], allows support for some string constraints (*e.g.* length, substring).

In short, this paper makes the following contributions:

1. We describe how Clafer models can be reduced to constraints in logics supported by Z3.

2. We have developed a tool called *ClaferZ3* that reflects the translation described in this work, and can be found at `https://github.com/gsdlab/ClaferZ3`.

3. Our tool supports constraints over real numbers and strings, which are not supported by previous Clafer backends, and thus expands the scope of models that Clafer can analyze.

4. We demonstrate that our tool is sufficient to handle string constraints found in eCos models.

2 Clafer Overview

Clafer is a structural modeling language which is designed for variability modeling. It unifies both feature models and meta-models [**?**]. In Listing 1 we show a specification of a mobile phone in Clafer. `Phone` refers to a top-level clafer of cardinality between 1 and 2 (*e.g.* either 1 or 2 of such phones must exist). `Phone` has an optional feature `PasswordProtection`; its optionality is denoted by the question mark after it. It also has a feature `Apps` that refers to a set of software applications; this is denoted by the `->` symbol following `Apps`.

The star following `SwApps` means that `Apps` refers to a set of software applications of cardinality greater than or equal to zero. Constraints are introduced in square brackets. The constraint denoted by [sum Apps.ref.memory $\leq$ 100], specifies that the sum of the `memory` attributes of all `SwApps` for a given `Phone` instance must be lower than 100. Note that this constraint must be true of *all* `Phone` instances, due to its level of indentation. The dot character in “Apps.ref” in essence serves as a navigation operator, by performing a join between the set `Apps` and the automatically created set `Apps_ref`. This operator is applied again to obtain a set of `memory` values. These values are then added together by the sum operator, and it is enforced that such sum must be less than 100. Finally an unbounded number of `SwApps` are introduced by the clafer `SwApps` followed by a star. Each SwApps contains a `UID` and a `memory` attribute, both of which take integer values. We should note that `SwApps` refers to both the type SwApps as well as defines a set of objects of type SwApps.

[1] Results can be found at `http://www.smtexec.org/exec/?jobs=1004` .

Listing 1: A specification of a mobile phone and its apps in clafer.

```
Phone 1 .. 2
  PasswordProtection  ?
  Apps −> SwApps ∗
  [ sum Apps.ref.memory <= 100 ]

SwApps ∗
  UID : int
  memory : int
```

Listing 2: A generated model of a mobile phone and its apps in clafer from the specification in Listing 1.

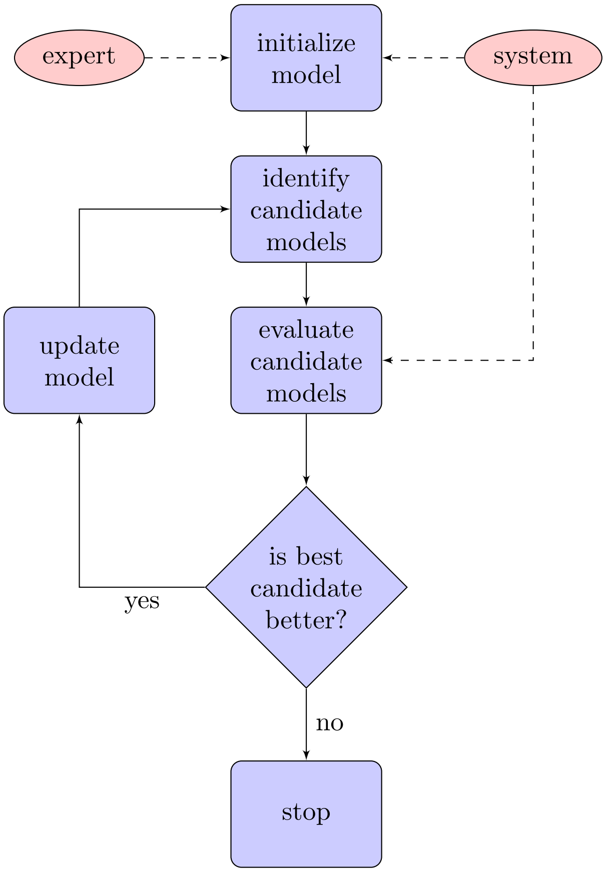
```
Phone0
  PasswordProtection0
  Apps0 −> SwApps0
  Apps1 −> SwApps1

SwApps0
  UID0=5
  memory1=15

SwApps1
  UID1=6
  memory1=26
```

Listing 3: The integer variables associated with each clafer in Z3 and corresponding to Listing 2.

```
Phone: [0, 1]
PasswordProtection: [0, 2]
Apps: [0, 0, 2, 2]
Apps_ref: [0, 1, 4, 4]
SwApps: [0, 0, 1, 1]
UID: [0, 1, 4, 4]
UID_ref: [5, 6, 0, 0]
memory: [0, 1, 4, 4]
memory_ref: [15, 26, 0, 0]
```


expert
initialize model
system
identify candidate models
update model
evaluate candidate models
is best candidate better?
yes
no
stop

Listing 4: A more complex mobile phone specification in clafer.

```
SwApps ∗
  memory : int

IPhoneApps −> SwApps ∗
  [ this.ref.memory < 15 ]
AndroidApps −> SwApps ∗

[ sum AndroidApps.ref.memory <= 100 ]
```

3 Solution Overview

For consistency (and due to large amounts of overlapping terminology), we define the following terms and notations: 1) we use capitalized *Clafer* to denote the language Clafer itself, and lowercase *clafer* to denote individual components of the input (*e.g.* `Phone` in Listing 1); 2) we call the Clafer input the *specification* (*e.g.* Listing 1); 3) an output that conforms to the specification (e.g. Listing 2) is a *model*, and; 4) individual occurrences of a clafer in the model are *instances* (*e.g. Phone0* in Listing 2).

The logic of Clafer can essentially be reduced to the following main components:

- Finite sets, and operations over them (e.g. set union). For the translation to Z3, we use a finite list of bounded integer variables to represent a given clafer[2]. Abstractly, each integer in the list corresponds to a *potential* instance of that clafer in the outputted model. An instance is part of the model if Z3 returns a value for it not equal to a predefined *sentinel* number for that clafer (more details are further described in the following section). We then need to add constraints over these sets, such that if a satisfying assignment is returned from Z3 for these variables, then it can be mapped back to a Clafer model conforming to the specification. For example, these constraints must ensure that the number of instances of a clafer are within the specified cardinality, and that all bracketed constraints are satisfied.

- Basic arithmetic constraints (e.g. addition, multiplication) and boolean constraints (e.g. *and*, *or*, *not*), which have direct translations to Z3.

Most of the difficulty lies in creating constraints over the finite sets in such a way that the integer variables can be mapped to a model conformant to the specification. We discuss some details of this next.

4 Detailed Solution Overview

This section describes the Z3 constraints that are generated to represent a Clafer specification in Z3. We begin with our representation of a clafer in Section 4.1. The remaining sections constrain this representation to conform to all restrictions of the specification (*e.g.* cardinality constraints, bracketed constraints, etc.).

[2] Since our integers have bounded ranges, bitvectors should be sufficient as well, and may increase performance. We discuss this in Section **??**.

4.1 Representation of a clafer

We borrow two key ideas from a previous translation of Clafer to Choco [**?**]: 1) clafers are represented as a finite number of integers; and 2) clafers that extend abstract clafers have a direct mapping to their supers (we discuss this point later).

We reprensent a clafer as a finite list of integers. Consider the `Phone` clafer in Listing 1. Since our outputted Clafer model will have at most two `Phone` clafers, we can represent it with a list of two integer variables, say $[phone0, phone1]$.

For star-cardinalities (as in the reference clafer `Apps`), we place a finite *scope s* on the clafer, indicating that only s instances can occur in the model. For the sake of example, let us assume that the scope of all unbounded clafers is 4. Then we can represent the clafer `Apps` with the list $[Apps0, Apps1, Apps2, Apps3]$.

Semantically, the values of these integer variables represent *parent pointers*, indicating where the clafer should be placed in the outputted model. For example, if the variable $Apps0$ is set to 0 by the solver, then it should fall directly beneath $Phone0$ in the hierarchy of the outputted model. Likewise, if $Apps0 = 1$, then $Apps0$ would be placed under $Phone1$.

A clafer instance is *excluded* from the model if its integer variable is set to a pre-defined *sentinel* value, which equals the total number of instance variables of the clafer's parent. For example, since the `Apps` clafer is directly underneath `Phone`, and `Phone` has two instances variables, any `Apps` instance set to 2 will not be included in the model. In Fig. 1c, since *Apps2* and *Apps3* both equal 2, they do not appear in the model in Fig. 1b. For *top-level clafers* that do not have a parent, the instance is included if its corresponding variable is set to 0, and not included if set to 1. For simplicity in the remainder of the paper, given a clafer `x`, an instance x_i is excluded if $x_i = x_{sentinel}$ ($Apps2 = Apps_{sentinel}$ in our example).

Reference clafers (e.g. `Apps`) require an additional integer variable associated with each instance, which corresponds to where the reference points. For a reference clafer instance x_i, we label its reference x_i_ref. For example, in Listing 2, $Apps0$ points to $SwApps0$, indicating that $Apps0\_ref$ in the Z3 output equaled 0. Each reference variable is bounded by the number of instances of the referenced clafer. A reference exists *iff* its corresponding clafer exists (e.g. $Apps0 \neq Apps_{sentinel} \Leftrightarrow Apps0\_ref \neq SwApps_{sentinel}$).

Integer clafers (*e.g.* memory) can be treated similarly to reference clafers, however their references are unbounded. Also, if an integer clafer is not present in the model, we set its reference to 0 to facilitate other set operations, such as summation.

As a larger example, once again consider Listing 2, along with the corresponding output of Z3 in Listing 3. For space limitations, each line of Listing 3 corresponds to all instances of the specified clafer; the line "Apps: [0,0,2,2]" is shorthand for $Apps0 = 0, Apps1 = 0, Apps2 = 2, Apps3 = 2$. Since $Apps0 = Apps1 = 0$, they are both beneath $Phone0$, however $Apps2$ and $Apps3$ are not present in the model (since $Apps_{sentinel} = 2$). Since $Apps0\_ref = 0$, $Apps0$ must reference $SwApps0$. Furthermore, since $Apps2$ and $Apps3$ are not present in the model, $Apps2\_ref = Apps3\_ref = SwApps_{sentinel}$.

4.2 Bracketed Constraints

We must also support Clafer's bracketed constraints (as in [*sum Apps.ref.memory* <= 100] from Listing 1), which we only discuss at a very high-level. To generate this constraint, we must first compute each of the joins in $Apps.ref.memory$. which is intuitively the set of `memory` clafers that are beneath any `SwApp` referenced by an `Apps` instance. We must then ensure that the sum of this set of `memory` instances is less than 100. Note that this is indeed the case in our example, since $memory0 + memory1 = 41 \leq 100$.

Although this example is not too difficult to convert to Z3 constraints, more complicated expressions and language features make set constraints challenging. Consider the specification in Listing 4. Both `IphoneApps` and `AndroidApps` reference `SwApps`, however when considering the summation on the last line, we must only consider instances of `SwApps` referenced by instances of `AndroidApps`. As another example, two previously unmentioned Clafer keywords are `this` and `parent`, which essentially allows one to consider each instance of a clafer individually. For example, the constraint: $[this.ref.memory = 15]$ in Listing 4 essentially states that the `memory` field of any `SwApp` referenced by an `IphoneApp` must be equal to 15. This requires us to generate constraints corresponding to *all* individual instances of `IphoneApp`.

5 Extensions to Clafer

One of the most notable differences of our work to previous backends of Clafer is the ability to handle constraints on real numbers[3]. Z3 handles real numbers naturally, so incorporating constraints over them into our translation required minimal effort. We therefore do not discuss further details.

This extension allows many domains that require real numbers to be modeled naturally. For example, any models involving probabilities or percentages can be modeled using reals. One applicable domain that has previously been modeled in Clafer is that of banking. Previous work investigated the family of available Scotiabank mortgage options, which included interest rates and monetary amount, both of which can be naturally modeled with reals[4].

An argument against the usefulness of reals is that, when the precision of all numbers in the model is known, all numbers could be multiplied by some power of 10 to convert them to integers. We argue that this approach makes models less intuitive to comprehend (*e.g.* an interest rate represented as 1.43 is more comprehensible than if it were 143).

We discuss further extensions allowing string constraints, such as length, concatenation, and substring. We also propose a new algorithm to prevent the generation of models that are isomorphic to previously generated models.

5.1 String Constraints

6 Related and Previous Work

This work most closely resembles that of [**?**]. Their work translates Clafer to Choco, a CSP language. We have borrowed components from that work, particularly in our representation of clafers and inherited clafers. We are able to extend Clafer with constraints over strings and real numbers, which neither the Choco nor Alloy backend currently support. Z3 also allows us to handle arbitrarily larger integers, which neither of the other backends support. In addition, in the future we intend to extend this project in order to eliminate the need for scopes on unbounded clafers. We discuss this in Section **??**.

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The work of Michel et. al. [3] discusses how configuration problems can be encoded in SMT using TVL [2] – a text based feature modeling language similar to Clafer. TVL supports many of the components of feature modeling, including hierarchy, group cardinality, attributes,

[3] Due to complications with the Clafer frontend grammar, we have only been able to prototype these constraints with small hand-generated models. This also applies to string constraints. These restrictions will be addressed in the near future.

[4] See `http://gsd.uwaterloo.ca/node/356`.

enums, and cross-tree constraints. However, several aspects of Clafer make the translation to an SMT solver much more difficult than that of TVL in [3]. Most notably, Clafer supports many set constraints that make translation much more difficult.

A previous project [5] within the GSD lab was capable of translating a small subset of Clafer to Z3, in order to support attributed feature models for multi-objective optimization. The primary components of Clafer necessary for this domain include hierarchical constraints, fixed-size cardinalities (e.g. [0..1]), and basic arithmetic constraints. This project subsumes that translation by allowing arbitrary Clafer constraints.

7 Future Work

This project utilized only a small subset of the available features of Z3. For example, Z3 has support for uninterpreted functions and data types. We would like to modify our translation to take advantage of these features. With this approach, we may be able to eliminate the need for scopes in our implementation.

One particular reason we did not take this approach yet is due to translation efficiency. As an example, in an early version of this project we used an uninterpreted function to represent cardinality constraints. Given a clafer, the function would restrict its instances to conform to the cardinality constraints. By blasting this function into basic propositional logic (which we can do since we have a bounded number of instances), our translation times were significantly decreased[5], even for small models. We emphasize that here we are referring to *translation time*; Z3 took approximately the same time to solve models whether or not functions were used.

8 Conclusions

We have developed a translation from Clafer to Z3. We extend capabilities of Clafer with string constraints using Z3-Str, as well as constraints over real numbers.

References

[1] K. Bk, K. Czarnecki, and A. Wsowski. Feature and meta-models in Clafer: mixed, specialized, and coupled. *Software Language Engineering*, 2011.

[2] A. Classen, Q. Boucher, and P. Heymans. A text-based approach to feature modelling: Syntax and semantics of TVL. *Science of Computer Programming*, 76(12):1130–1143, Dec. 2011.

[3] R. Michel, A. Hubaux, V. Ganesh, and P. Heymans. An SMT-based Approach to Automated Configuration. *SMT Workshop 2012 10th . . .* , pages 107–117, 2012.

[4] L. D. Moura and N. Bjø rner. Z3: An efficient SMT solver. *Tools and Algorithms for the Construction and . . .* , 2008.

[5] R. Olaechea. *Comparison of Exact and Approximate Multi-Objective Optimization for Software Product Lines*. PhD thesis, 2013.

[6] P. Saadatpanah, M. Famelis, J. Gorzny, N. Robinson, M. Chechik, and R. Salay. Comparing the effectiveness of reasoning formalisms for partial models. *Proceedings of the Workshop on Model-Driven Engineering, Verification and Validation - MoDeVVa '12*, 1(c):41–46, 2012.

[5] Although time differences were not recorded, some relatively small specifications required 2-3 additional seconds.

[7] Y. Zheng, X. Zhang, and V. Ganesh. Z3-str: a z3-based string solver for web application analysis. *Proceedings of the 2013 9th Joint Meeting on Foundations of Software Engineering - ESEC/FSE 2013*, page 114, 2013.