# Z3str4 String Solver: System Description

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***Abstract*—In this document we introduce and describe our Z3str4 string solver submitted to the SMTCOMP competition 2020. We briefly review the key insights that underpin the algorithmic design of Z3str4, as well as its setup.**

## I. System Overview

Z3str4 is a *multi-armed* solver that incorporates 3 sub-solvers, namely, Z3str3, the length abstraction solver LAS, and Z3seq (a string solver from the Z3 team at Microsoft Research). Of these, the Z3str3 and the LAS solvers were developed by the authors. Z3str3 is built on top of the Z3 theorem prover, from Microsoft Research. The Z3str4 solver additionally makes use of other existing, unmodified components of Z3 [1], namely, the core, bit-vector, and linear arithmetic solvers.

The architecture of Z3str4 is illustrated in Fig. 1. Our solver includes two pre-defined "arms", or sequences of algorithms. The algorithms in these arms are always executed in sequence (as shown), with the possibility of clauses learnt from the previous solver passed on as input to the subsequent one in the sequence. Further, only one arm is ever executed in a run of Z3str4. A arm is chosen using a heuristic we refer to as a "probe", that analyzes the input formula and predicts which of the two arms would have a smaller runtime.

If an algorithm in an arm answers SAT or UNSAT, this answer is returned by Z3str4. Otherwise, a timeout has been reached for that algorithm and the next algorithm in the sequence is called, first augmenting the input formula with certain learned constraints from the previous algorithm in the arm. This allows each algorithm to benefit from the work done by earlier ones, even if they were unable to solve the problem.

As described above, each arm includes three possible algorithms: a length abstraction solver (LAS), described in the following section; Z3str3, which uses the well-known "arrangement" method for solving strings [2], [3] and Z3seq, with certain modifications as described below.

## II. Arm Selection

The arm selection method or the "probe" uses static features of the instance to determine which arm to invoke. At a high level, the method checks whether any of the following terms appear in the input formula: string disequalities; negated `prefixof` and `suffixof` terms; and any `contains`, `replace`, or regular expression terms. The intuition here is that the occurrence of these terms generally produce formulas that are hard for the bit-vector solver to handle due to disjunctions of constraints. If these terms do not occur, an arm is chosen in which algorithms that use the bit-vector reduction (LAS and Z3str3) are called before algorithms that don't (Z3seq). Otherwise, the opposite priority is used.

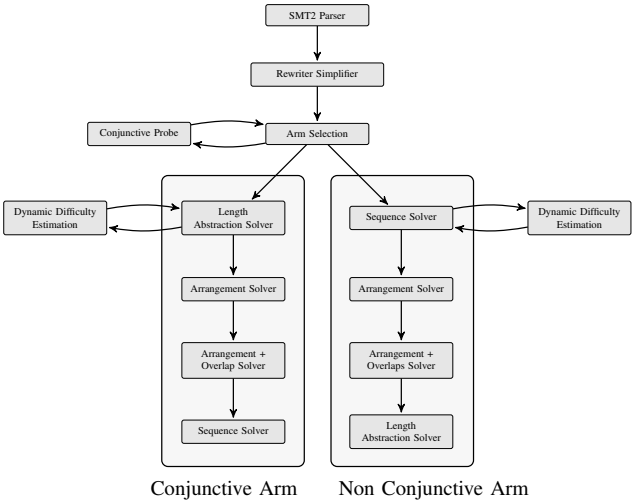


Fig. 1. Architecture of the Z3str4 tool.

## III. Length Abstraction Solver (LAS)

The length abstraction solver (LAS) is a novel CEGAR-style algorithm we developed for Z3str4 that can quickly solve string formulas based on abstractions and refinements of integer constraints implied by string equations. LAS abstracts word equations and other input constraints into length (in)equalities, and uses Z3's built-in arithmetic solver to solve them. Briefly, LAS first constructs an integer over-approximation of the input formula based on implied length constraints and checks if it is satisfiable. If it is unsatisfiable, then it follows that the input is unsatisfiable as well. Otherwise, the solver refines this over-approximation appropriately. This process is repeated until either the solver converges to the correct satisfying assignment or a maximum number of attempts is reached.

## IV. Z3 String Solver (Z3str3)

Z3str3 is part of the Z3-str family of string solvers, including Z3-str and Z3str2. Z3str3 reduces the input string constraints to an arrangement (disjunction) of conjunctions of derived string equations. (This algorithm is described in more detail in our

previous work [3].) Then, for each arrangement, the solver queries the Z3 arithmetic solver to obtain consistent length assignments to the string variables in them, and reduces the resulting fixed-length equations to a bit-vector representation. This formula is then solved by Z3's bit-vector solver. If the formula is satisfiable, the bit-vector solution can be translated directly to a satisfying assignment for the original string equation. Otherwise, the solver learns a clause that avoids the current length assignment in a conflict-driven clause learning loop, and continues searching for either a different length assignment or a different arrangement.

The hybrid approach we use in Z3str3 combines the efficiency of an unfolding-based strategy (reduction of fixed-length word equations to bit-vectors) with the ability of a word-based strategy to reason about string terms of unbounded length (the arrangement method).

## V. Z3 Sequence Solver (Z3seq)

At a high level, Z3seq works as a series of "checks". If a check fails, then a corresponding action is taken (for example, asserting an implied formula) and the process repeats. If all checks pass, then the query is solved. We have modified Z3seq with a heuristic referred to as "dynamic difficulty estimation". Briefly, Z3seq has over 20 checks that it performs, and queries that are solved efficiently by the sequence solver rarely, in practice, fail later checks. Our difficulty estimation heuristic keeps track of the last failing check, and forces the algorithm to give up if certain later checks fail.

## References


[1] L. De Moura and N. Bjørner, "Z3: An efficient smt solver," in *International conference on Tools and Algorithms for the Construction and Analysis of Systems*. Springer, 2008, pp. 337–340.

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[3] Y. Zheng, V. Ganesh, S. Subramanian, O. Tripp, M. Berzish, J. Dolby, and X. Zhang, "Z3str2: an efficient solver for strings, regular expressions, and length constraints," *Formal Methods in System Design*, vol. 50, no. 2-3, pp. 249–288, 2017. [Online]. Available: https://doi.org/10.1007/s10703-016-0263-6