

Certified Symbolic Finite Transducers: Formalization and Applications to String Manipulation

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Abstract

Finite Transducers (FTs) extend the capabilities of Finite Automata (FAs) by enabling the transformation of input strings into output strings, thereby providing a more expressive framework for operations that encompass both recognition and transformation. FTs have wide applications, including program analysis, string constraint solving, and security-critical sanitizer analysis. However, there is currently no scalable formalization of FTs. This is primarily because transition labels in FTs are not formalized symbolically, resulting in transition explosion and significant performance bottlenecks in practical applications.

In this paper, we present a formalization of FTs in the symbolic setting using Isabelle/HOL, where transition labels can be instantiated with various Boolean algebras, such as intervals and arithmetic predicates. This symbolic approach enables not only efficient FT operations—such as computing the output language of an FT given a regular language—but also supports infinite alphabets. To evaluate the effectiveness of our formalization, we apply the formalized SFTs to two applications: (1) HTMLdecode, a sanitizer used for preventing XSS attacks, and (2) a string solver that models replacement operations with various semantics, including left-most and replace-all matching. Experimental results demonstrate that our approach achieves computational efficiency in constraint-solving scenarios.

1 Introduction

Finite Automata (FA) and Finite Transducers (FT) are fundamental constructs in the theory of formal languages, with extensive applications in programming languages and software engineering. For example, recent advancements in string solvers, as demonstrated by [8], have illustrated the relationship between regular expressions in modern programming languages and various forms of FAs and FTs. Additionally,

FAs and FTs find significant industrial applications, such as in the verification of AWS access control policies [3].

Even though there are various formalizations of FAs and FTs in interactive proof assistants such as Isabelle [2] and Coq [1], these are predominantly based on classical definitions. However, these traditional approaches present certain limitations when applied to practical scenarios. One significant drawback is that transition labels are typically non-symbolic and finite. A conventional transition is represented as $q \xrightarrow{a} q'$, where a is a character from a finite alphabet. This simplistic representation can lead to a phenomenon known as transition explosion. For example, if the alphabet Σ encompasses the entire Unicode range, which is common in modern programming languages, it consists of 0×110000 distinct characters. Defining a transition from state q to q' that accepts any character in Σ would require splitting into 0×110000 individual transitions, rendering the FA and FT operations highly inefficient. Furthermore, in practical applications, it is often necessary to consider infinite alphabets, such as the set of all integers.

Symbolic Finite Automata (SFA) and Symbolic Finite Transducers (SFT) [12, 34] represent advanced extensions of classic FAs and FTs, enhancing their applicability in practical scenarios. These symbolic models utilize transition labels defined by first-order predicates over boolean algebras, allowing for more expressive representations. For example, a transition label might be specified as an interval ($'a' - 'z'$), encompassing all characters from $'a'$ to $'z'$, or as an arithmetic condition ($x \bmod 2 = 0$), denoting all even numbers. This symbolic approach not only provides a more succinct representation but also supports infinite alphabets, thereby extending the expressive capabilities of FAs and FTs.

However, the formalization of transition labels in SFAs and SFTs presents significant challenges within interactive proof assistants. Two fundamental considerations arise: first, the representation of transition labels must be sufficiently expressive to accommodate diverse predicate representations of boolean algebras; second, the formalization framework must be designed with extensibility in mind to facilitate the incorporation of new boolean algebras while minimizing redundant proof efforts.

Prior work of CertiStr [17] has successfully formalized SFAs within Isabelle/HOL, demonstrating both the efficiency and effectiveness of SFAs in practice. However, the formalization of SFTs remains an open challenge, primarily due to their inherent complexity in two aspects: the formalization of transition labels and the specification of transition output

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functions. SFTs constitute a significantly more expressive and powerful theoretical framework compared to SFAs, as evidenced by their capability to model complex string transformations such as replacement operations. Furthermore, numerous studies have demonstrated the broad applicability of SFTs across diverse domains. The work of [34] showcases SFTs in security-critical applications, particularly for cross-site scripting (XSS) prevention. [15] extends this security focus by applying SFTs to web application sanitizer analysis. In system verification, [36] employs SFTs for runtime behavior monitoring, while [16] demonstrates their utility in automated program transformation through systematic inversion techniques.

In this work, we present a comprehensive formalization of SFTs. To address the extensibility challenges inherent in supporting diverse transition label theories, we adopt a refinement-based approach. At the abstraction level, transition labels are formalized through the fundamental mathematical concept of *sets*. This abstraction facilitates subsequent refinement to various representations of Boolean algebras, such as intervals and arithmetic predicates, while maintaining theoretical consistency.

The key operation of our formalization is the product operation between an SFT and an input regular language. Specifically, given an SFA \mathcal{A} representing a regular language and an SFT \mathcal{T} , we define the product operation $\mathcal{T} \times \mathcal{A}$ that characterizes the output language generated by \mathcal{T} when processing inputs from the language recognized by \mathcal{A} .

In the refinement level, we implemented transition labels using an interval-based representation to exemplify the refinement process. The formalization of interval algebra provides efficient set-theoretic operations—including membership checking, intersection, and difference computations—facilitating the refinement of transition labels from abstract sets to concrete intervals. Furthermore, leveraging the data refinement framework [20] in Isabelle/HOL, we store states and transitions using sophisticated data structures such as hashmaps and red-black trees, ensuring efficient automata manipulation.

To evaluate the effectiveness and efficiency of our formalization, we developed a string solver compliant with SMT-LIB language [4], focusing particularly on replacement operations. We evaluated our implementation using a set of benchmarks from the SMT-LIB repository [26]. The experimental results demonstrate that our formalization achieves computational efficiency in constraint-solving scenarios.

In summary, our formalization makes the following contributions:

1. We present the first formalization of symbolic finite transducers in Isabelle/HOL proof assistant.

2. We leverage the refinement framework to create an extensible SFT formalization that is capable of accommodating various boolean algebras, ensuring adaptability to future transition label developments.
3. We develop an interval algebra with efficient set-theoretic operations, enabling refinement of transition labels from abstract sets to concrete intervals.
4. We demonstrate the practical utility of our formalization through its application to string constraint solving, specifically in modeling replacement operations with verified correctness guarantees.

The remainder of this paper is organized as follows: Section 2 introduces the formalization of symbolic finite transducers. Section 3 presents the product operation at the abstract level. Section 4 details the algorithmic refinement of the product operation. Section 5 demonstrates the application to string constraint solving. Section 6 discusses related work. Section 7 concludes with future directions.

2 Formalization of SFTs

We begin by presenting a mathematical definition of SFTs [34], abstracting from the specific implementation details of Isabelle/HOL.

2.1 The Mathematical Definition of SFTs

Let \mathcal{U} be a multi-sorted carrier set or background universe, which is equipped with functions and relations over the elements. We use τ as a sort and \mathcal{U}^τ denotes the sub-universe of elements of type τ . We have a special type \mathbb{B} with $\mathcal{U}^\mathbb{B} = \{\top, \perp\}$, which corresponds to the boolean type.

A lambda term is defined as $\lambda x. t$ of type $\tau_1 \rightarrow \tau_2$. When τ_2 is \mathbb{B} , this lambda term is a predicate. Let ϕ be a predicate. We write $a \in \llbracket \phi \rrbracket$ if $\phi a = \top$. For non-predicate lambda terms, we view them as functions that generate output elements of type τ_2 given input terms of type τ_1 . With these notations and the above definitions, we can define SFTs as follows.

Definition 2.1 (Symbolic Finite Transducer). A Symbolic Finite Transducer over $\tau_1 \rightarrow \tau_2$ is a quadruple $\mathcal{T} = (Q, \Delta, I, \mathcal{F})$, where

- Q is a finite set of states,
- $I \subseteq Q$ is the set of initial states,
- $\mathcal{F} \subseteq Q$ is the set of accepting states,
- Δ is the set of transition relations. Each element in Δ is of the form (q, ϕ, f, q') or written as $q \xrightarrow{\phi, f} q'$, where q and q' are states in Q . ϕ is a predicate of type $\tau_1 \rightarrow \mathbb{B}$. f is a lambda term of type $\tau_1 \rightarrow \tau_2$. f is called an *output function*.

For each transition $q \xrightarrow{\phi, f} q'$, if there exists an element $a \in \llbracket \phi \rrbracket$, where a is called an input, then the application $(f a)$ is the output.

SFTs accept an input word and generate an output word. This can be defined by *runs* of SFTs. An SFT run σ is a sequence $(q_0, \phi_0, f_0, q_1), (q_1, \phi_1, f_1, q_2), \dots, (q_{n-1}, \phi_{n-1}, f_{n-1}, q_n)$ such that $q_0 \in \mathcal{I}$ and $(q_i, \phi_i, f_i, q_{i+1}), 0 \leq i \leq n-1$ is a transition in Δ . σ is an accepting run when q_n is an accepting state.

For a word $w = a_0, \dots, a_{n-1}$, it is accepted by σ if and only if $a_i \in \llbracket \phi_i \rrbracket$ for $0 \leq i \leq n-1$. When w is accepted, run σ generates an output sequence $w' = f_0 a_0, \dots, f_{n-1} a_{n-1}$. We define:

- $(a_0, (f_0 a_0)), \dots, (a_{n-1}, (f_{n-1} a_{n-1}))$ a *trace*,
- a_0, \dots, a_{n-1} the *input* of the trace and $(f_0 a_0), \dots, (f_{n-1} a_{n-1})$ the *output* of the trace.

If a_0, \dots, a_{n-1} is accepted by an accepting run in \mathcal{T} , we say that the trace is an accepting trace of \mathcal{T} . For a trace π , we denote its input as $in(\pi)$ and its output as $out(\pi)$. Given an SFT \mathcal{T} and a word w , we define the *product* operation of \mathcal{T} and w (denoted as $\mathcal{T} \times \{w\}$) as the set of outputs generated by \mathcal{T} with input w . More precisely,

$$\mathcal{T} \times \{w\} = \{w' \mid \exists \pi. \pi \text{ is an accepting trace of } \mathcal{T} \wedge \text{mathit{in}}(\pi) = w \wedge \text{out}(\pi) = w'\}.$$

To make the operation *product* more general, we extend the operation to an SFT and a set of input words represented by a regular language, which can be denoted by an SFA \mathcal{A} . More precisely,

$$\mathcal{T} \times \mathcal{A} = \{w' \mid \exists w. w \in \mathcal{L}(\mathcal{A}) \wedge w' \in \mathcal{T} \times \{w\}\},$$

where $\mathcal{L}(\mathcal{A})$ denotes the language of \mathcal{A} .

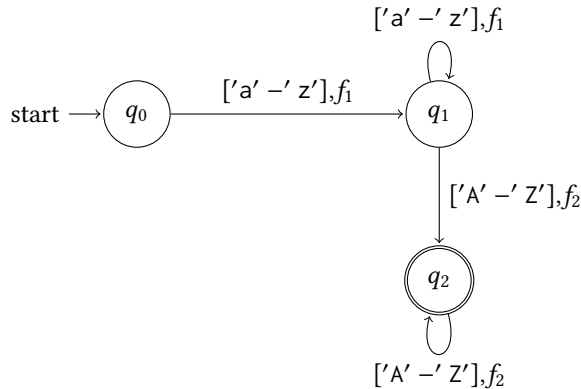


Figure 1. An example of SFT

Figure 1 illustrates an SFT that accepts words matching the regular expression $/[a' -' z'] + [A' -' Z'] + /$. The transition labels utilize intervals of the form $[i-j]$, which are interpreted as predicates $\lambda x. i \leq x \leq j$. The output functions f_1 and f_2 perform case transformations: $f_1 = \lambda x. \text{toUpper}(x)$ converts lowercase letters to uppercase, while $f_2 = \lambda x. \text{toLower}(x)$ performs the inverse operation. For example, given the input string "bigSMALL", this SFT produces the output "BIGsmall".

2.2 The Isabelle/HOL Formalization of SFTs

Firstly, we present the basic idea of our formalization of SFTs in Isabelle/HOL, which consists of three layers.

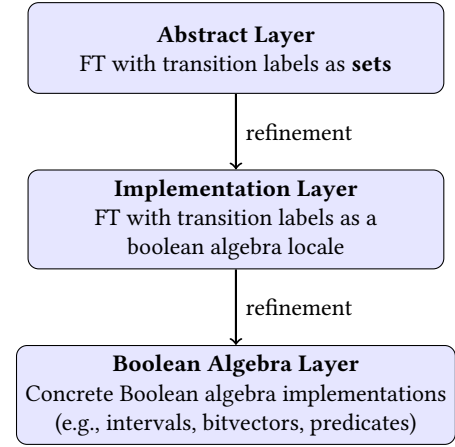


Figure 2. Three-layered formalization of SFTs in Isabelle/HOL. **Abstract Layer:** Transition labels are modeled as sets, representing the most general case. **Locale Layer:** Transition labels are abstracted as a type variable 'a within a locale, supporting any Boolean algebra. **Implementation Layer:** Concrete Boolean algebra instances, such as intervals, bitvectors, or predicates, are provided.

As we have discussed the diversity of transition labels in Section 1, we now present an extensible formalization of SFTs that accommodates this variety. Our approach leverages the refinement framework (Refine_Monadic [19]) in Isabelle/HOL to achieve the flexibility and extensibility of transition labels modeling.

```

1 record ('q, 'a, 'i, 'b) NFT =
2   Q_t :: "'q set"
3   Δ_t :: "('q, 'a, 'i) LTTS"
4   I_t :: "'q set"
5   F_t :: "'q set"
6   M_t :: "'i ⇒ ('a, 'b) Tlabel"
7 type_synonym ('q, 'a, 'i) LTTS = "
8   ('q × ('a set option × 'i) × 'q) set"
9 type_synonym ('a, 'b) Tlabel = "
10   'a option ⇒ 'b set option"

```

Figure 3. The formalization of SFTs in Isabelle/HOL

Figure 3 presents our formalization of SFTs in Isabelle/HOL. While the elements Q_t , I_t , and F_t directly correspond to their counterparts (Q , \mathcal{I} , and \mathcal{F}) in Definition 2.1, the transition relations are not exactly the same. The transition relations are formalized through LTTS (Labeled Transducer Transition System), where each transition is represented as a triple

' $q \times ('a \text{ set option } \times' i) \times' q$. This representation reflects several key design decisions aimed at enhancing the abstraction and flexibility of our SFT formalization.

Firstly, ' $a \text{ set option}$ ' is the input type of the transition, it accepts a set of elements of type ' a ' or `None` corresponding to empty string ϵ . Accepting a set of ' a ' elements aims to express the same but more abstract semantics of the input labels in Definition 2.1, in which an input label is a predicate. A predicate's semantics as introduced before represents a set of elements that make the predicate true. But predicates have various different forms. For instance, the interval $[1 - 9]$ represents the set $\{e \mid 1 \leq e \leq 9\}$. The predicate $\lambda b. b[7] = 1$, where b is a bit vector of length 8, denotes the set of bit vectors that have a 1 in the 7th position. All these different forms of labels are abstracted as sets in our formalization. The value `None` represents the empty string ϵ in our formalization, indicating a transition that consumes no input but may still produce output elements. This design choice facilitates the modeling of real-world applications in SFTs, as we will demonstrate in our application to string solvers.

The second element of type ' i ' serves as an index into the output function space. We use indices instead of functions themselves to enable the reuse of the same output functions for different transitions. The mapping M_t associates each index with a specific output function. These output functions, formalized by `TLabel`, map a single input element to a set of possible output elements rather than to a single element. This design enables non-deterministic output behavior, where the transducer may select any element from the output set randomly or according to specified criteria. Additionally, output functions can produce the empty string ϵ by returning `None`, providing further flexibility in transition behavior.

3 The Product Operation of SFTs

In this section, we formalize the product operation between an SFT \mathcal{T} and an SFA \mathcal{A} , denoted as $\mathcal{T} \times \mathcal{A}$ in Section 2. An additional consideration in this operation is the presence of ϵ -transitions in our SFT formalization, which implies that the resulting automata may also contain ϵ -transitions. Since CertiStr [17] does not include a formalization of SFAs with ϵ -transitions, we extend the framework in CertiStr with a formalization of symbolic SFAs with ϵ -transitions (denoted as ϵ SFA) and provide a verified conversion to standard SFAs. In this paper, we present only the definitions of ϵ SFAs and SFAs, while the complete formalization, including correctness proofs, is available in our Isabelle development.

Figure 4 presents the formalization of both SFAs and ϵ SFAs using Isabelle/HOL record types `NFA` and `eNFA`, respectively. The ϵ SFA formalization extends the standard SFA structure by introducing Δ'_e , which captures ϵ -transitions as pairs of states, while maintaining the same labeled transition relation Δ as in standard SFAs.

```

1 record ('q, 'a) NFA =
2   Q :: "'q set"
3   Δ :: "('q, 'a) LTS"
4   I :: "'q set"
5   F :: "'q set"
6
7 record ('q, 'a) eNFA =
8   Qe :: "'q set"
9   Δe :: "('q, 'a) LTS"
10  Δ'e :: "('q * 'a) set"
11  Ie :: "'q set"
12  Fe :: "'q set"
13
14 type_synonym ('q, 'a) LTS = "'q × 'a set × 'q"

```

Figure 4. The formalization of ϵ SFAs and SFAs

Having established these foundational definitions, we can now formalize the product operation.

```

1 definition productT :: "('q, 'a, 'i, 'b)" NFA ⇒
2   ('q, 'a) NFA ⇒ (('a, 'b) Tlabel ⇒ 'a set
3   ⇒ 'b set option) ⇒ ('q × 'q, 'b) eNFA where
4 "productT T A F = (
5   Qe = Qt T × Q A,
6   Δe = {((p, p'), the (((Mt T) f) None), (q, p')) |
7     p, p', q, f. p' ∈ Q A ∧ (p, (None, f), q) ∈ Δt T
8     ∧ ∃S. (Mt T) f None = Some S} ∪
9     {((p, p'), the (F ((Mt T) f) (σ1 ∩ σ2)), (q, q')) |
10      p, p', q, σ1, σ2, q', f. (p, (Some σ1, f), q) ∈ Δt T ∧
11      (p', σ2, q') ∈ Δ A ∧ σ1 ∩ σ2 ≠ ∅ ∧
12      ∃S. F ((Mt T) f) (σ1 ∩ σ2) = Some S},
13   Δ'e = {((p, p'), (q, p')) | p, p', q, f. p' ∈ Q A ∧
14     (p, (None, f), q) ∈ Δt T ∧
15     (Mt T) f None = None} ∪
16     {((p, p'), (q, q')) | p, p', q, σ1, σ2, q', f.
17      (p, (Some σ1, f), q) ∈ Δt T ∧ (p', σ2, q') ∈ Δ A
18      ∧ σ1 ∩ σ2 ≠ ∅ ∧ ∃x ∈ (σ1 ∩ σ2).
19      ((Mt T) f) (Some x) = None},
20   Ie = It T × I A
21   Fe = Ft T × F A )"

```

Figure 5. The formalization of product operation

Figure 5 depicts the abstract level formalization for the product of an SFT and an SFA. The parameters \mathcal{T} and \mathcal{A} are an SFT and an SFA, respectively. The result of the product operation is an ϵ SFA. But we need to explain the role of parameter F . The output function f for each transition in Δ_t is of type $'a \text{ option} \Rightarrow 'b \text{ set option}$, which applies to a single element of type ' a ' or ϵ . F extends f to apply f to a set of elements. More precisely, let f be an output function, the semantics of F is defined as follows:

$$F f A = \text{Some } \left(\bigcup_{a \in A} (\text{if } f a = \text{Some } S \text{ then } S \text{ else } \emptyset) \right)$$

The transition relations Δ_e and Δ'_e are determined by considering two distinct cases based on the nature of transitions in the SFT: ε -transitions and non- ε -transitions. In both cases, the transition labels in the resulting ε SFA are derived from the composition of the SFT's output function and the SFA's input labels. Let us consider Δ_e first.

1. When $(p, (\text{None}, f), q)$ is a transition in Δ_t , i.e. the input character is ε , and $f \text{ None} \neq \text{None}$. Consequently, the SFA \mathcal{A} remains in its current state, and the product transition produces the output " $((\mathcal{M}_t \mathcal{T}) f) \text{ None}$ ". Remember that f is just an index, $(\mathcal{M}_t \mathcal{T}) f$ is the output function.
2. When $(p, (\text{Some } \sigma_1, f), q)$ is a transition in Δ_t , synchronization is possible only with SFA transitions that share characters with σ_1 , i.e., $\sigma_1 \cap \sigma_2 \neq \emptyset$, where σ_2 represents the input label of the corresponding SFA transition. The resulting output is $F((\mathcal{M}_t \mathcal{T}) f) (\sigma_1 \cap \sigma_2)$.

The transitions in Δ'_e follow a similar pattern with analogous cases for ε and non- ε transitions.

To establish the correctness specification of the product operation, we begin by formalizing the concept of SFT *traces* as introduced in Definition 2.1. In our formalization, traces are represented by the type $('a \text{ option} \times 'b \text{ option}) \text{ list}$, as shown in Figure 6. Given a trace π , we define two key projection functions: (1) `inputE`, which corresponds to $\text{in}(\pi)$ and extracts the input sequence (2) `outputE`, which corresponds to $\text{out}(\pi)$ and extracts the output sequence.

The definition `outputL` generalizes `outputE` to characterize the set of all possible outputs that an SFT \mathcal{T} can generate when processing inputs from the language accepted by the SFA \mathcal{A} . The reachability of a trace π between states q and q' in an SFT \mathcal{T} is verified by the predicate `LTTS_reachable $\mathcal{T} q \pi q'$` .

Figure 7 presents Lemma `productT_correct`, which establishes the correctness of the product operation. The lemma's assumptions, `F_ok1` and `F_ok2`, specify the essential properties of function F . The assumptions `NFT_wf \mathcal{T}` and `NFA \mathcal{A}` ensure that the SFT \mathcal{T} and the SFA \mathcal{A} are well-formed. The conclusion, marked by `shows`, demonstrates that the language of the constructed ε SFA (\mathcal{L}_e denotes the language of ε SFA) from $\mathcal{T} \times \mathcal{A}$ coincides with the mathematical semantics defined by `outputL`, thereby establishing semantic preservation of the product construction.

4 Algorithm Level Refinement

Having established the abstract definition of the SFT product operation in Section 3, we now present its algorithmic refinement. This section introduces an efficient implementation

```

1 fun inputE ::
2   "('a option × 'b option) list ⇒ 'a list"
3 where
4   "inputE [] = []" |
5   "inputE ((Some a, _) # l) =
6     a # (inputE l)" |
7   "inputE ((None, _) # l) = (inputE l)"
8
9 fun outputE ::
10   "('a option × 'b option) list ⇒ 'b list"
11 where
12   "outputE [] = []" |
13   "outputE (_, Some a) # l) =
14     a # (outputE l)" |
15   "outputE (_, None) # l) = (outputE l)"
16
17 definition outputL ::
18   "('q, 'a, 'i, 'b) NFT ⇒ ('q, 'a) NFA ⇒ 'b list set"
19 where
20   "outputL  $\mathcal{T} \mathcal{A}$  = {outputE  $\pi$  |  $\pi q q'$ .
21      $q \in \mathcal{I}_t \mathcal{T} \wedge q' \in \mathcal{F}_t \mathcal{T} \wedge$ 
22     LTTS_reachable  $\mathcal{T} q \pi q' \wedge \text{inputE } \pi \in \mathcal{L} \mathcal{A}$ }"
    
```

Figure 6. The formalization of traces in SFTs

```

1 lemma productT_correct:
2   fixes  $\mathcal{T} \mathcal{A} F$ 
3   assumes
4     F_ok1: "∀ f s. (∀ e ∈ s. f (Some e) = None) ⟷
5       F f s = None"
6     and F_ok2: "∀ f s. F f s ≠ None ⟶ F f s =
7       Some (⋃ {S | e ∈ S. e ∈ s ∧
8         f (Some e) = Some S})"
9     and wfTA: "NFT_wf  $\mathcal{T} \wedge$  NFA  $\mathcal{A}$ "
10  shows "Le (productT  $\mathcal{T} \mathcal{A} F$ ) = outputL
11     $\mathcal{T} \mathcal{A}$ "
    
```

Figure 7. The correctness lemma of the product operation

of the product construction and refines the abstract representation of transition labels to a concrete interval algebra, enabling practical computation.

4.1 Intervals

An interval is defined as a pair (i, j) (represented as $[i - j]$ as well in the paper) representing the set $\{e \mid i \leq e \leq j\}$. To achieve greater expressiveness, our formalization extends this notion to interval lists of the form $[(i_1, j_1), \dots, (i_n, j_n)]$, which denote the set $\bigcup_{1 \leq k \leq n} \{e \mid i_k \leq e \leq j_k\}$. This generalization offers two key advantages: it enables more compact representation of transitions in SFAs and SFTs through merging, and it allows for efficient handling of interval operations

without unnecessary splitting. For example, the set difference between intervals $(1, 5)$ and $(3, 4)$ can be directly represented as the interval list $[(1, 2), (5, 5)]$, which is also an interval.

Throughout the following discussion, we use the term "interval" to refer to interval lists. Our formalization provides a collection of interval operations through the following interface:

1. `semIs i` : Defines the semantic interpretation of an interval as a set. For an interval (i, j) , `semIs (i, j)` = $\{e \mid i \leq e \leq j\}$.
2. `emptyIs i` : Tests whether an interval represents an empty set, i.e., whether `semIs i` = \emptyset .
3. `nemptyIs i` : Tests whether an interval represents a non-empty set, i.e., whether `semIs i` $\neq \emptyset$.
4. `intersectIs i_1 i_2` : Computes the intersection of two intervals, yielding an interval i such that `semIs i` = `semIs i_1` \cap `semIs i_2` .
5. `diffIs i_1 i_2` : Computes the set difference of two intervals, yielding an interval i such that `semIs i` = `semIs i_1` \setminus `semIs i_2` .

To facilitate formal reasoning and optimize performance, we introduce a canonical form for interval. An interval $[(i_1, j_1), \dots, (i_n, j_n)]$ is in canonical form if it satisfies two key properties:

1. Each (i_k, j_k) is well-formed: $i_k \leq j_k$ for all $k \in \{1, \dots, n\}$
2. Intervals are ordered and non-overlapping: $j_k < i_{k+1}$ for all $k \in \{1, \dots, n-1\}$

We prove that all interval operations preserve canonical form when applied to canonically-formed inputs. This invariant serves two purposes: it simplifies formal proofs by eliminating the need to reason about malformed or overlapping intervals, and it enables more efficient implementations of interval operations by reducing the number of cases to consider.

4.2 Algorithmic Implementation of the Product Operation

In this subsection, we present the algorithmic implementation of the product operation between an SFT and an SFA¹. Figure 8 illustrates the core algorithm `productT_impl`, which is implemented using the *Refine_Monadic* framework. Note that in the implementation, there are some refined operations: `nft_tranfun`, `nfa_states`, `nfa_trans`, `nfa_initial`, and `nfa_accepting`. These are corresponding to the states, transitions, initial states, accepting states, and output function mapping of the SFT.

The operation `prods_imp`, shown in Figure 9, computes the Cartesian product of two state sets. This function employs the `FOREACH` construct, a higher-order iteration operator analogous to OCaml's `Set.fold`. Specifically, given a set

S , a function f of type ' $a \Rightarrow b \Rightarrow b$ ', and an initial accumulator I of type ' b ', the expression `FOREACH S f I` systematically applies f to each element in S , accumulating results in a principled manner.

```
1 definition productT_impl where
2 "productT_impl  $\mathcal{T}$   $\mathcal{A}$  F fe = do {
3   Q  $\leftarrow$  prods_imp (nft_states  $\mathcal{T}$ )
4   (nfa_states  $\mathcal{A}$ );
5   (D1, D2)  $\leftarrow$  trans_comp_imp
6   (nft_tranfun  $\mathcal{T}$ ) F fe (nft_trans  $\mathcal{T}$ )
7   (nfa_trans  $\mathcal{A}$ ) (nfa_states  $\mathcal{A}$ );
8   I  $\leftarrow$  prods_imp (nft_initial  $\mathcal{T}$ )
9   (nfa_initial  $\mathcal{A}$ );
10  F  $\leftarrow$  prods_imp (nft_accepting  $\mathcal{T}$ )
11  (nfa_accepting  $\mathcal{A}$ );
12  RETURN (Q, D1, D2, I, F)
13 }"
```

Figure 8. The computation of SFT product

```
1 definition prods_imp where
2 "prods_imp Q1 Q2 =
3   FOREACH { $q$ .  $q \in Q1$ } ( $\lambda$  q Q. do {
4     S  $\leftarrow$  FOREACH { $q$ .  $q \in Q2$ }
5     ( $\lambda$  q' Q'. RETURN ( $\{(q, q')\} \cup Q'$ ))  $\emptyset$ ;
6     RETURN (Q  $\cup$  S)
7   })  $\emptyset$ "
```

Figure 9. The computation of Cartesian product of two state sets

```
1 definition trans_comp_imp where
2 "trans_comp_imp M F fe T1 T2 Q =
3   FOREACH { $t$ .  $t \in T1$ }
4   ( $\lambda$ ( $q, (\alpha, f), q'$ ) (D1, D2).
5     (if ( $\alpha = \text{None}$ ) then
6       (subtrans_comp_ε M q f q' F fe
7         T2 D1 D2)
8     else
9       (subtrans_comp M q (the  $\alpha$ ) f
10        q' F fe T2 D1 D2))) ( $\emptyset, \emptyset$ )"
```

Figure 10. The computation of `trans_comp_imp`

A central algorithmic challenge in our implementation lies in the computation of transition sets $D1$ (corresponding to Δ_e) and $D2$ (corresponding to Δ'_e) in Figure 8. As shown in Figure 10, we implement this computation through the function `trans_comp_imp`, which computes the synchronization

¹For clarity of presentation, we show a simplified version of the Isabelle/HOL implementation while preserving the essential algorithmic structure.

of transitions between the SFT and SFA. This function decomposes the synchronization process into two distinct cases, each handled by a specialized function:

1. `subtrans_comp_ε`: Processes ε -transitions in the SFT, where transitions consume no input but may produce output
2. `subtrans_comp`: Processes standard transitions in the SFT, where both input consumption and output generation may occur

```

1 definition subtrans_comp where
2   "subtrans_comp M q α f q' F fe T D1 D2 =
3     FOREACH {t.t∈T} (λ (q1,α',q1') (D1,D2).
4       (if (nemptyIs (intersectIs α α')) then
5         do {
6           D1 ←
7             (if (F (M f) (intersectIs α α'))
8               ≠ None) then
9               let αi = the (F (M f)
10                 (intersectIs α α')) in
11                 RETURN {(q,q1), αi, (q',q1'))}
12                 ∪ D1
13             else RETURN D1);
14           D2 ←
15             (if fe (M f) (intersectIs α α')
16               then
17                 RETURN {(q,q1), (q',q1'))} ∪ D2
18             else RETURN D2);
19           RETURN (D1, D2) }
20     else (RETURN (D1, D2)))) (D1, D2)"
    
```

Figure 11. The computation of `subtrans_comp`

We now present the implementation of `subtrans_comp` in detail, as shown in Figure 11 (the implementation of `subtrans_comp_ε` follows analogous principles). For a transition $(q, (\text{Some } \alpha, f), q')$ in the SFT, this function traverses all transitions in the SFA, represented by the set T . For each transition $(q_1, \alpha', q'_1) \in T$, the function performs two key operations when the intersection of input labels is non-empty ($\alpha \cap \alpha' \neq \emptyset$, verified using `nemptyIs`):

1. Computes non- ε -transitions ($D1$): When the output function applied to the intersection $\alpha \cap \alpha'$ yields a non-empty set, a new transition is added to $D1$ with the computed output label.
2. Generates ε -transitions ($D2$): When there exists at least one input in the intersection $\alpha \cap \alpha'$ that produces an empty string (verified by checking if $M f$ maps any element to `None`. The checking is implemented by `fe`), a corresponding ε -transition is added to $D2$.

The correctness of the product computation is established through a refinement proof, demonstrating that `productT_imp`

```

1 lemma productT_imp_correct:
2   assumes finite_TT: "finite (Δt T)"
3     and finite_TA: "finite (Δ A)"
4     and finite_Q: "finite (Q A)"
5     and finite_TQ: "finite (Qt T)"
6     and finite_I: "finite (I A)"
7     and finite_TI: "finite (It T)"
8     and finite_F: "finite (F A)"
9     and finite_TF: "finite (Ft T)"
10  shows "productT_imp T A F fe ≤
11        SPEC (λA. A = productT T A F)"
    
```

Figure 12. The refinement relation between `productT_imp` and `productT`

(Figure 8) correctly implements the abstract specification `productT` (Figure 5). This refinement relationship is formally specified in Figure 12, where we leverage the *Refine_Monadic* framework's data refinement.

The refinement is expressed through the relation $C \leq \text{SPEC } A$, which asserts that the concrete implementation C is an element of the abstract specification A . More precisely, the concrete implementation must produce an ε SFA that is structurally equivalent or isomorphic to the one produced by the abstract algorithm `productT`.

To establish this equivalence, we must prove that the ε SFAs produced by `productT_imp` and `productT` are isomorphic in all essential components: the set of states, transition relations, ε -transition relations, initial and accepting state sets.

The implementation of `productT_imp` follows *Refine_Monadic* framework's interfaces for sets to store states and transition relations. The *Refine_Monadic* framework provides a way to automatically refine these interfaces to more efficient data structure, such as red-black trees or hashmaps. In our formalization, we refine the sets of storing states and transitions to red-black trees.

5 An Application to String Solving

In this section, we demonstrate the practical application of our formalized SFTs to string constraint solving, specifically focusing on replacement operations. While *CertiStr* [17] provides a verified framework for string constraint solving using SFAs, its capabilities are inherently limited by the expressiveness of SFAs. In particular, SFAs cannot directly model string transformation operations such as replacement.

Our string solver is based on *CertiStr* [17] by extending it with the modeling of replacement operations. *CertiStr* exploits forward-propagation to solve the string constraints. Our SFT modeling for replacement operations can seamlessly be integrated into *CertiStr*'s forward-propagation framework.

5.1 Modeling the Replacement Operation

The string replacement operation, denoted as $\text{replace}(\text{str}, \text{pattern}, \text{replacement})$, is a fundamental string transformation that takes three parameters:

- **str**: The input string to be transformed.
- **pattern**: A regular expression defining the matching criteria.
- **replacement**: The string to be substituted for the matched substring.

The semantics of the replacement operation can be formally characterized by two distinct cases:

1. When there exists at least one substring s' in str such that s' matches pattern , then s' is replaced with replacement .
2. When no substring of str matches pattern , the operation returns str unchanged.

The first case can be modeled by SFTs. We illustrate this case by an example. Given a replacement operation $\text{replace}(s, /[0-9]+/, \text{"NUM"})$, which means replacing a occurrence of the substring that matches the regular expression $/[0-9]+/$ with the string "NUM". We model this replacement operation by an SFT with the following 3 steps:

1. First, construct an SFA that recognizes the regular expression pattern $/[0-9]+/$. Transform this SFA into an SFT by augmenting each transition with an output function $f = \lambda x. \text{None}$ that produces the empty string.
2. Second, construct an SFA that accepts the replacement string "NUM". Since a constant string can be viewed as a specialized regular expression, we can construct its SFA representation. Convert this SFA into an SFT by adding ϵ -transitions and appropriate output functions that emit the characters of "NUM" in sequence.
3. Finally, compose the two SFTs through concatenation and augment the resulting transducer with self-loop transitions at the initial and final states. These additional transitions, labeled with Σ (the set of all characters in the alphabet) and the identity function $\text{id} = \lambda x. x$, enable the SFT to process arbitrary prefixes and suffixes of the input string while preserving the replacement behavior on matched substrings.

Step 1. Figure 13 illustrates the construction of the pattern-matching component. The left side shows the SFA that recognizes the regular expression $/[0-9]+/$, while the right side presents its transformation into an SFT. This transformation is achieved by augmenting each transition with the output function $f = \lambda x. \text{None}$, which consistently produces the empty string, effectively "consuming" the matched digits without generating output.

Step 2. Figure 14 depicts the automata for the replacement string "NUM". The left side shows the SFA that accepts this constant string, while the right side presents its SFT transformation. The transformation employs an indexed output

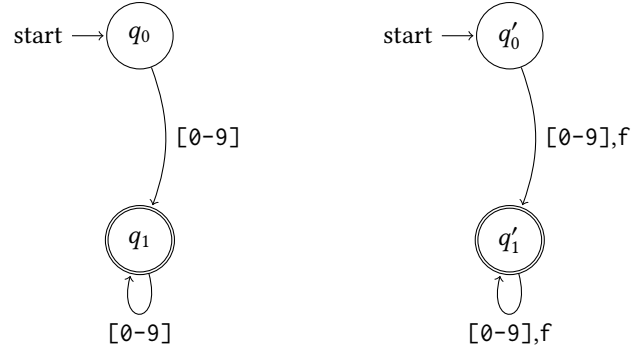


Figure 13. Corresponding SFA and SFT for $/[0-9]+/$

function g that emits characters of the replacement string sequentially:

$$g = \lambda i x. \text{match } i \text{ with } \begin{cases} 1 \mapsto [(78, 78)] & (\text{ASCII for 'N'}) \\ 2 \mapsto [(85, 85)] & (\text{ASCII for 'U'}) \\ 3 \mapsto [(77, 77)] & (\text{ASCII for 'M'}) \\ _ \mapsto \text{None} \end{cases}$$

This function maps transition indices to their corresponding character outputs, using ASCII codes to represent the string "NUM" character by character.

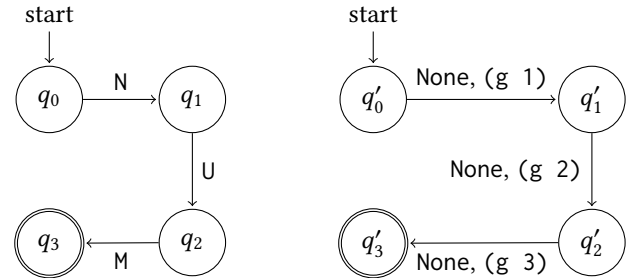


Figure 14. Corresponding SFA and SFT for "NUM"

Step 3. Figure 15 presents the complete SFT construction, obtained by composing the pattern-matching SFT (Fig. 13) with the replacement-generating SFT (Fig. 14). The composition process involves two key modifications:

1. Connect the two SFTs by adding ϵ -transitions (labeled with "None, f") from each accepting state of the pattern-matching SFT to the initial state of the replacement-generating SFT
2. Augment the resulting transducer with self-loop transitions at both ends, labeled with " Σ, id ", where Σ represents the full alphabet. For the string solver, Σ is the set of all unicode characters. These transitions enable the SFT to process arbitrary input prefixes and suffixes while preserving the matched substring for replacement

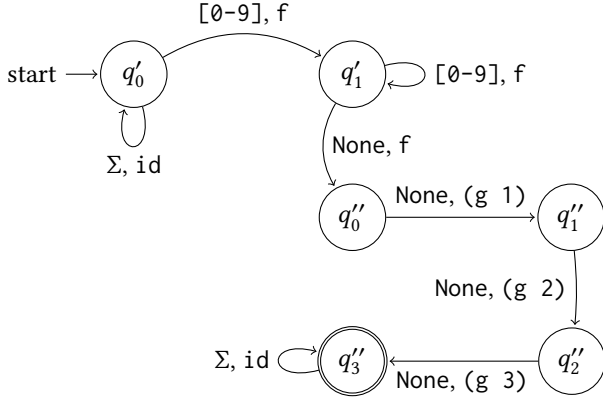


Figure 15. The SFT for the replacement operation $\text{replace}(s, /[0-9]+/, \text{"NUM"})$

Having constructed the SFT, we can now compute the forward image of the replacement operation. Consider the string constraint $s' = \text{replace}(s, /[0-9]+/, \text{"NUM"})$, where we aim to characterize the possible values of s' . Let \mathcal{T} denote the constructed SFT modeling the replacement operation, and let \mathcal{A} be the SFA representing the domain of possible values for the input string s . The forward image of this replacement operation is given by the product $\mathcal{T} \times \mathcal{A}$, which precisely captures the set of all possible output strings that can be produced by applying the replacement operation to any input string accepted by \mathcal{A} . Our string solver uses this forward image to do forward propagation for further string solving.

Comparison with SMT-LIB Semantics. It is important to note that our formalization differs from the standard SMT-LIB semantics for the replacement operation. In SMT-LIB, the `str.replace` operation is defined to replace only the *first* occurrence of a substring matching the given pattern. In contrast, our semantics allows for a more general interpretation where any matching substring may be replaced. But it still replaces only one occurrence of them.

5.2 Experiments

We have implemented CertiStrR, an extension of CertiStr [17], to support string replacement operations. While the core solving algorithm maintains the certification guarantees of CertiStrR, the frontend components are implemented using established non-certified OCaml libraries: `dolmen` [24] for SMT-LIB parsing and `ocaml-re-nfa` [35] for regular expression to NFA conversion.

CertiStrR implements two kinds of SMT-LIB's replacement operations: `str.replace s p r`: a string-based replacement where pattern p is a constant string. `str.replace_re s p r`: a regular expression-based replacement where pattern p is a regular expression

Listing 1 demonstrates the regular expression variant through an example that replaces numeric sequences with the string "NUM". The constraints are satisfiable because the input string $a = \text{"2024,2025"}$ contains a substring "2025" that matches the regular expression `re.+ (re.range "0" "9")` (equivalent to `/[0-9]+/`), and replacing this match with "NUM" yields the expected output string $b = \text{"2024,NUM"}$.

As discussed in the previous subsection, our replacement semantics differs from the SMT-LIB standard semantics. Run the SMT solver CVC5 [30] with the code in Listing 1, the result is UNSAT because CVC5 only matches the first occurrence of the pattern.

```

1 (set-logic QF_S)
2 (declare-fun a () String)
3 (declare-fun b () String)
4 (assert (= a "2024,2025"))
5 (assert (= b "2024,NUM"))
6 (assert (= b (str.replace_re a
7   (re.+ (re.range "0" "9")) "NUM")))
8 (check-sat)
    
```

Listing 1. Example SMT-LIB Code

We evaluate CertiStrR using benchmarks from SMT-LIB 2024 [26], focusing on the QF_S and QF_SLIA logic fragments. The benchmarks are divided into two categories based on the replacement operations: (1) string-based replacement (`str.replace`) and (2) regular expression-based replacement (`str.replace_re`). Due to CertiStrR's current front-end limitations in supporting the full SMT-LIB language, we preprocess certain operations. For instance, conjunctive assertions of the form `(assert (and c1 c2))` are decomposed into separate assertions `(assert c1)` and `(assert c2)` when $c1$ and $c2$ are string constraints supported by CertiStrR.

	SAT/UNSAT/Inc	Time (s)	Tests
<code>replace_str</code>	142/173/8	0.27	323
<code>replace_re</code>	84/4/10	0.36	98

Table 1. Experimental results

The experimental evaluation was conducted on a laptop with an Apple M4 processor and 24 GB of memory, with a time limit of one minute per test. The results show average execution times of 0.27 seconds for `str.replace_str` and 0.36 seconds for `str.replace_re` operations. Test outcomes were classified into three categories: SAT (satisfiable), UNSAT (unsatisfiable), and Inconclusive. An "Inconclusive" result indicates that the solver cannot determine satisfiability, not due to timeout (all tests are finished in one minute) but rather due to inherent limitations of the forward-propagation algorithm inherited from CertiStr [17]. Specifically, when the string constraints do not satisfy the tree property defined in [17], the forward-propagation algorithm may be unable

to reach a definitive conclusion, even when the variable domains remain non-empty after propagation.

Our performance analysis revealed that while the SFT-based replacement operation modeling is efficient, the primary computational bottleneck stems from automata accumulation during forward-propagation. Consider the following string constraints:

$$x = x_1 ++ x_2; \quad x = \text{replace}(x_3, p, r);$$

$$x = x_4; \quad x = \text{replace_re}(x_5, p_1, r_1);$$

where $++$ denotes string concatenation. The variable x appears multiple times on the left-hand side of the equations, causing the forward-propagation algorithm to accumulate automata representations for all constraints: $x_1 ++ x_2$, $\text{replace}(x_3, p, r)$, x_4 , and $\text{replace_re}(x_5, p_1, r_1)$. Each accumulation step requires computing the product of the current automaton with the previous result. Given that the product operation has a worst-case complexity of $O(n^2)$, where n represents the automaton size, this repeated accumulation can lead to state explosion.

5.3 Effort of Certified Development

We discuss the effort of certified SFT development in this subsection. Table 2 provides an overview. The abstract-level development means all formalizations in Section 2 and 3, including SFTs and ε SFAs. The implementation-level development means all formalizations in Section 4 including the refinement of the product operation. The last row corresponds to the effort of the interval formalization. The most difficult part is the correctness proof of the product operation at the abstract level (Figure 7). Interval formalization complexity dramatic increase in CertiStrR compared to the interval formalization in CertiStr [17] due to the extension of intervals to a list.

	Defs	Lemmas	Proofs (LOC)
Abstract	17	21	3274
Implementation	51	43	2700
Interval	15	29	1500

Table 2. Overview of the effort of certified development

6 Related Work

Symbolic Automata and Transducers. Symbolic Automata and Transducers [10–12, 27, 34] represent a significant advancement in automata theory, offering improved efficiency in operations and enhanced expressiveness through algebraic theories that support infinite alphabets. This symbolic framework has been progressively extended to accommodate more complex structures: symbolic tree transducers [32] handle

hierarchical data structures, while symbolic pushdown automata [9] manage nested word structures. Recent developments in 2024 have further expanded the scope of symbolic techniques to include Büchi automata and omega-regular languages [31], enabling verification of infinite-state systems and analysis of non-terminating computations.

Applications of Symbolic Transducers. The efficiency, scalability, and expressive power of symbolic automata and transducers have led to their widespread adoption in numerous real-world applications. These applications span diverse domains, including: constraint solving for program analysis [33], security-critical sanitizer analysis for web applications [15], runtime verification of system behaviors [36], and automated program inversion for software transformation [16]. Each application leverages the symbolic approach’s ability to handle complex patterns and infinite alphabets efficiently.

Formalization of Symbolic Automata and Transducers. While classical automata theories have been extensively formalized in interactive theorem provers [7, 13, 18, 29], with some work on transducer formalization [21], the symbolic variants of automata and transducers remain largely unexplored in formal verification. To our knowledge, CertiStr [17] represents the only existing work on symbolic automata formalization in a proof assistant. Our work advances this frontier by extending the formal treatment to both SFTs and ε SFAs.

String Solving. A significant application of our certified transducer framework is in string constraint solving, a field that has seen intensive research development over the past decade. While our work provides formal verification guarantees, there exists a rich ecosystem of non-certified string solvers, each with distinct capabilities: Kaluza [23] specializes in JavaScript analysis, CVC5 [30], Z3-str3 [5] builds on the Z3 framework, S3P [28], Ostrich [8], and SLOTH [14]. As more and more bugs have been uncovered in existing string solvers [6] and SMT solvers [22] We believe that our work will benefit the community by providing a formal foundation for string solvers development.

Certified SMT Solvers. Beyond string theories, certification efforts in SMT solving have extended to other domains. For example, the work by Shi et al. [25], who developed a certified SMT solver for quantifier-free bit-vector theory, demonstrating the broader applicability of interactive theorem proving in certified SMT solver development.

7 Conclusion

In this paper, we have presented the first formalization of symbolic finite transducers in the proof assistant Isabelle/HOL. Our formalization provides flexible interfaces that facilitate diverse applications through two key features: support for ε -transitions in both inputs and outputs, and extensibility to various boolean algebras via the refinement framework.

To demonstrate the practical utility of our formalization, we developed CertiStrR, an extension of CertiStr [17]. This

implementation adds support for string replacement operations and has been evaluated on benchmarks from SMT-LIB 2024 [26]. The experimental results confirm both the efficiency and effectiveness of our approach. While we focused on string solving applications, our extensible framework for transition labels is broadly applicable to other domains, including program verification.

Future work includes extending our symbolic formalization in two key directions: (1) Enriching the boolean algebra framework to support more complex theories, such as arithmetic constraints. (2) Incorporating prioritized transitions into SFTs, which would enable precise modeling of SMT-LIB's standard semantics for replacement operations, particularly the first-match behavior. These extensions will further enhance the expressiveness and practical applicability of our formalization while maintaining its formal verification guarantees.

References

- [1] Coq Homepage. <https://coq.inria.fr/>.
- [2] Isabelle Proof Assistant, 2013. <https://isabelle.in.tum.de/>.
- [3] John Backes, Pauline Bolignano, Byron Cook, Catherine Dodge, Andrew Gacek, Kasper Søe Luckow, Neha Rungta, Oksana Tkachuk, and Carsten Varming. Semantic-based automated reasoning for AWS access policies using SMT. In Nikolaj Bjørner and Arie Gurfinkel, editors, *2018 Formal Methods in Computer Aided Design, FMCAD 2018, Austin, TX, USA, October 30 - November 2, 2018*, pages 1–9. IEEE, 2018. doi:10.23919/FMCAD.2018.8602994.
- [4] Clark Barrett, Pascal Fontaine, and Cesare Tinelli. The SMT-LIB Standard: Version 2.6. Technical report, Department of Computer Science, The University of Iowa, 2017. Available at www.SMT-LIB.org.
- [5] Murphy Berzish, Vijay Ganesh, and Yunhui Zheng. Z3str3: A string solver with theory-aware heuristics. In Daryl Stewart and Georg Weissenbacher, editors, *2017 Formal Methods in Computer Aided Design, FMCAD 2017, Vienna, Austria, October 2-6, 2017*, pages 55–59. IEEE, 2017. doi:10.23919/FMCAD.2017.8102241.
- [6] Dmitry Blotsky, Federico Mora, Murphy Berzish, Yunhui Zheng, Ifaz Kabir, and Vijay Ganesh. Stringfuzz: A fuzzer for string solvers. In Hana Chockler and Georg Weissenbacher, editors, *Computer Aided Verification - 30th International Conference, CAV 2018, Held as Part of the Federated Logic Conference, FloC 2018, Oxford, UK, July 14-17, 2018, Proceedings, Part II*, volume 10982 of *Lecture Notes in Computer Science*, pages 45–51. Springer, 2018. doi:10.1007/978-3-319-96142-2_6.
- [7] Julian Brunner. Transition Systems and Automata Isabelle Library. *Arch. Formal Proofs*, 2017. https://www.isa-afp.org/entries/Transition_Systems_and_Automata.html.
- [8] Taolue Chen, Alejandro Flores-Lamas, Matthew Hague, Zhilei Han, Denghang Hu, Shuanglong Kan, Anthony W. Lin, Philipp Rümmer, and Zhilin Wu. Solving string constraints with regex-dependent functions through transducers with priorities and variables. *Proc. ACM Program. Lang.*, 6(POPL):1–31, 2022. doi:10.1145/3498707.
- [9] Loris D'Antoni and Rajeev Alur. Symbolic visibly pushdown automata. In Armin Biere and Roderick Bloem, editors, *Computer Aided Verification - 26th International Conference, CAV 2014, Held as Part of the Vienna Summer of Logic, VSL 2014, Vienna, Austria, July 18-22, 2014. Proceedings*, volume 8559 of *Lecture Notes in Computer Science*, pages 209–225. Springer, 2014. doi:10.1007/978-3-319-08867-9_14.
- [10] Loris D'Antoni, Zachary Kincaid, and Fang Wang. A symbolic decision procedure for symbolic alternating finite automata. In Sam Staton, editor, *Proceedings of the Thirty-Fourth Conference on the Mathematical Foundations of Programming Semantics, MFPS 2018, Dalhousie University, Halifax, Canada, June 6-9, 2018*, volume 341 of *Electronic Notes in Theoretical Computer Science*, pages 79–99. Elsevier, 2018. URL: <https://doi.org/10.1016/j.entcs.2018.03.017>, doi:10.1016/J.ENTCS.2018.03.017.
- [11] Loris D'Antoni and Margus Veanes. Minimization of symbolic automata. In Suresh Jagannathan and Peter Sewell, editors, *The 41st Annual ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages, POPL '14, San Diego, CA, USA, January 20-21, 2014*, pages 541–554. ACM, 2014. doi:10.1145/2535838.2535849.
- [12] Loris D'Antoni and Margus Veanes. The power of symbolic automata and transducers. In Rupak Majumdar and Viktor Kuncak, editors, *Computer Aided Verification - 29th International Conference, CAV 2017, Heidelberg, Germany, July 24-28, 2017, Proceedings, Part I*, volume 10426 of *Lecture Notes in Computer Science*, pages 47–67. Springer, 2017. doi:10.1007/978-3-319-63387-9_3.
- [13] Christian Doczkal, Jan-Oliver Kaiser, and Gert Smolka. A constructive theory of regular languages in coq. In Georges Gonthier and Michael Norrish, editors, *Certified Programs and Proofs - Third International Conference, CPP 2013, Melbourne, VIC, Australia, December 11-13, 2013, Proceedings*, volume 8307 of *Lecture Notes in Computer Science*, pages 82–97. Springer, 2013. doi:10.1007/978-3-319-03545-1_6.
- [14] Lukás Holík, Petr Janku, Anthony W. Lin, Philipp Rümmer, and Tomás Vojnar. String constraints with concatenation and transducers solved efficiently. *Proc. ACM Program. Lang.*, 2(POPL):4:1–4:32, 2018. doi:10.1145/3158092.
- [15] Pieter Hooimeijer, Benjamin Livshits, David Molnar, Prateek Saxena, and Margus Veanes. Fast and precise sanitizer analysis with BEK. In *20th USENIX Security Symposium, San Francisco, CA, USA, August 8-12, 2011, Proceedings*. USENIX Association, 2011. URL: http://static.usenix.org/events/sec11/tech/full_papers/Hooimeijer.pdf.
- [16] Qinheping Hu and Loris D'Antoni. Automatic program inversion using symbolic transducers. In Albert Cohen and Martin T. Vechev, editors, *Proceedings of the 38th ACM SIGPLAN Conference on Programming Language Design and Implementation, PLDI 2017, Barcelona, Spain, June 18-23, 2017*, pages 376–389. ACM, 2017. doi:10.1145/3062341.3062345.
- [17] Shuanglong Kan, Anthony Widjaja Lin, Philipp Rümmer, and Michal Schrader. Certistr: a certified string solver. In Andrei Popescu and Steve Zdancewic, editors, *CPP '22: 11th ACM SIGPLAN International Conference on Certified Programs and Proofs, Philadelphia, PA, USA, January 17 - 18, 2022*, pages 210–224. ACM, 2022. doi:10.1145/3497775.3503691.
- [18] P. Lammich. The CAVA automata library. *Arch. Formal Proofs*, 2014, 2014.
- [19] Peter Lammich. Refinement for monadic programs. *Archive of Formal Proofs*, January 2012. https://isa-afp.org/entries/Refine_Monadic.html, Formal proof development.
- [20] Peter Lammich. Automatic Data Refinement. In Sandrine Blazy, Christine Paulin-Mohring, and David Pichardie, editors, *Interactive Theorem Proving - 4th International Conference, ITP 2013, Rennes, France, July 22-26, 2013. Proceedings*, volume 7998 of *Lecture Notes in Computer Science*, pages 84–99. Springer, 2013. doi:10.1007/978-3-642-39634-2_9.
- [21] Alexander Lochmann, Bertram Felgenhauer, Christian Sternagel, René Thiemann, and Thomas Sternagel. Regular tree relations. *Arch. Formal Proofs*, 2021, 2021. URL: https://www.isa-afp.org/entries/Regular_Tree_Relations.html.
- [22] Muhammad Numair Mansur, Maria Christakis, Valentin Wüstholtz, and Fuyuan Zhang. Detecting critical bugs in SMT solvers using blackbox mutational fuzzing. In Prem Devanbu, Myra B. Cohen, and Thomas Zimmermann, editors, *ESEC/FSE '20: 28th ACM Joint European Software Engineering Conference and Symposium on the Foundations of Software Engineering, Virtual Event, USA, November 8-13, 2020*, pages

- 701–712. ACM, 2020. doi:10.1145/3368089.3409763.
- [23] Prateek Saxena, Devdatta Akhawe, Steve Hanna, Feng Mao, Stephen McCamant, and Dawn Song. A symbolic execution framework for JavaScript. In *S&P*, pages 513–528, 2010. doi:10.1109/SP.2010.38.
- [24] Gabriel Scherer and contributors. Dolmen: A library and binary for parsing, typechecking, and evaluating languages used in automated deduction. <https://github.com/Gbury/dolmen>, 2023. Accessed: 2023-10-15.
- [25] Xiaomu Shi, Yu-Fu Fu, Jiaxiang Liu, Ming-Hsien Tsai, Bow-Yaw Wang, and Bo-Yin Yang. Coqqfbv: A scalable certified SMT quantifier-free bit-vector solver. In Alexandra Silva and K. Rustan M. Leino, editors, *Computer Aided Verification - 33rd International Conference, CAV 2021, Virtual Event, July 20-23, 2021, Proceedings, Part II*, volume 12760 of *Lecture Notes in Computer Science*, pages 149–171. Springer, 2021. doi:10.1007/978-3-030-81688-9_7.
- [26] SMT-LIB. Smt-lib benchmarks. <https://smt-lib.org/benchmarks>. Accessed: 2023-10-17.
- [27] Hellis Tamm and Margus Veanes. Theoretical aspects of symbolic automata. In A Min Tjoa, Ladjel Bellatreche, Stefan Biffl, Jan van Leeuwen, and Jiri Wiedermann, editors, *SOFSEM 2018: Theory and Practice of Computer Science - 44th International Conference on Current Trends in Theory and Practice of Computer Science, Krems, Austria, January 29 - February 2, 2018, Proceedings*, volume 10706 of *Lecture Notes in Computer Science*, pages 428–441. Springer, 2018. doi:10.1007/978-3-319-73117-9_30.
- [28] Minh-Thai Trinh, Duc-Hiep Chu, and Joxan Jaffar. S3: A symbolic string solver for vulnerability detection in web applications. In Gail-Joon Ahn, Moti Yung, and Ninghui Li, editors, *Proceedings of the 2014 ACM SIGSAC Conference on Computer and Communications Security, Scottsdale, AZ, USA, November 3-7, 2014*, pages 1232–1243. ACM, 2014. doi:10.1145/2660267.2660372.
- [29] Thomas Tuerk. A Formalisation of Finite Automata in Isabelle / HOL. <https://www.thomas-tuerk.de/assets/talks/cava.pdf>, 2012.
- [30] Stanford University and University of Iowa. cvc5: An efficient open-source automatic theorem prover for smt problems. <https://cvc5.github.io/>, 2023. Accessed: 2023-10-15.
- [31] Margus Veanes, Thomas Ball, Gabriel Ebner, and Ekaterina Zhuchko. Symbolic automata: Omega-regularity modulo theories. *Proc. ACM Program. Lang.*, 9(POPL):33–66, 2025. doi:10.1145/3704838.
- [32] Margus Veanes and Nikolaj S. Bjørner. Symbolic tree transducers. In Edmund M. Clarke, Irina B. Virbitskaite, and Andrei Voronkov, editors, *Perspectives of Systems Informatics - 8th International Andrei Ershov Memorial Conference, PSI 2011, Novosibirsk, Russia, June 27-July 1, 2011, Revised Selected Papers*, volume 7162 of *Lecture Notes in Computer Science*, pages 377–393. Springer, 2011. doi:10.1007/978-3-642-29709-0_32.
- [33] Margus Veanes, Nikolaj S. Bjørner, and Leonardo Mendonça de Moura. Symbolic automata constraint solving. In Christian G. Fermüller and Andrei Voronkov, editors, *Logic for Programming, Artificial Intelligence, and Reasoning - 17th International Conference, LPAR-17, Yogyakarta, Indonesia, October 10-15, 2010. Proceedings*, volume 6397 of *Lecture Notes in Computer Science*, pages 640–654. Springer, 2010. doi:10.1007/978-3-642-16242-8_45.
- [34] Margus Veanes, Pieter Hooimeijer, Benjamin Livshits, David Molnar, and Nikolaj S. Bjørner. Symbolic finite state transducers: algorithms and applications. In John Field and Michael Hicks, editors, *Proceedings of the 39th ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages, POPL 2012, Philadelphia, Pennsylvania, USA, January 22-28, 2012*, pages 137–150. ACM, 2012. doi:10.1145/2103656.2103674.
- [35] Jeremy Yallop and contributors. ocaml-re-nfa: Ocaml code to construct an nfa from a regular expression. <https://github.com/yallop/ocaml-re-nfa>, 2023. Accessed: 2023-10-15.
- [36] Nofel Yaseen, Behnaz Arzani, Ryan Beckett, Selim Ciraci, and Vincent Liu. Aragog: Scalable runtime verification of shardable networked systems. In *14th USENIX Symposium on Operating Systems Design and Implementation, OSDI 2020, Virtual Event, November 4-6, 2020*, pages 701–718. USENIX Association, 2020. URL: <https://www.usenix.org/conference/osdi20/presentation/yaseen>.