

Statically Typed String Sanitation Inside a Python (Technical Report)

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Abstract

This report contains supporting evidence for claims put forth and explained in the paper “Statically Typed String Sanitation Inside a Python” [1], including proofs of lemmas and theorems asserted in the paper, examples, additional discussion of the paper’s technical content, and errata.

Keywords: type systems; regular languages; input sanitation; string sanitation

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1 Terminology and Notation

Theorems and lemmas appearing in [1] are numbered correspondingly, while supporting facts appearing only in the Technical Report are lettered.

2 Regular Expressions

The syntax of regular expressions over some alphabet Σ is shown in Figure 1.

Assumption A (Regular Expression Congruences). *We assume regular expressions are implicitly identified up to the following congruences:*

$$\begin{aligned}\epsilon \cdot r &\equiv r \\ r \cdot \epsilon &\equiv r \\ (r_1 \cdot r_2) \cdot r_3 &\equiv r_1 \cdot (r_2 \cdot r_3) \\ r_1 + r_2 &\equiv r_2 + r_1 \\ (r_1 + r_2) + r_3 &\equiv r_1 + (r_2 + r_3) \\ \epsilon^* &\equiv \epsilon\end{aligned}$$

Assumption B (Properties of Regular Languages). *We assume the following properties:*

1. *If $s_1 \in \mathcal{L}\{r_1\}$ and $s_2 \in \mathcal{L}\{r_2\}$ then $s_1 s_2 \in \mathcal{L}\{r_1 \cdot r_2\}$.*
2. *For all strings s and regular expressions r , either $s \in \mathcal{L}\{r\}$ or $s \notin \mathcal{L}\{r\}$.*
3. *Regular languages are closed under reversal.*

3 λ_{RS}

The syntax of λ_{RS} is specified in Figure 2. The static semantics is specified in Figure 4.

3.1 Head and Tail Operations

The following correctness conditions must hold for any definition of $\text{lhead}(r)$ and $\text{ltail}(r)$.

Condition C (Correctness of Head). *If $c_1 s' \in \mathcal{L}\{r\}$, then $c_1 \in \mathcal{L}\{\text{lhead}(r)\}$.*

Condition D (Correctness of Tail). *If $c_1 s' \in \mathcal{L}\{r\}$ then $s' \in \mathcal{L}\{\text{ltail}(r)\}$.*

For example, we conjecture (but do not here prove) that the definitions below satisfy these conditions. Note that these are slightly amended relative to the published paper.

Definition 1 (Definition of $\text{lhead}(r)$). We first define an auxiliary relation that determines the set of characters that the head might be, tracking the remainder of any sequences that appear:

$$\begin{aligned}\text{lhead}(\epsilon, \epsilon) &= \emptyset \\ \text{lhead}(\epsilon, r') &= \text{lhead}(r', \epsilon) \\ \text{lhead}(a, r') &= \{a\} \\ \text{lhead}(r_1 \cdot r_2, r') &= \text{lhead}(r_1, r_2 \cdot r') \\ \text{lhead}(r_1 + r_2, r') &= \text{lhead}(r_1, r') \cup \text{lhead}(r_2, r') \\ \text{lhead}(r^*, r') &= \text{lhead}(r, \epsilon) \cup \text{lhead}(r', \epsilon)\end{aligned}$$

We define $\text{lhead}(r) = a_1 + a_2 + \dots + a_i$ iff $\text{lhead}(r, \epsilon) = \{a_1, a_2, \dots, a_i\}$.

Definition 2 (Brzozowski's Derivative). The *derivative of r with respect to s* is denoted by $\delta_s(r)$ and is $\delta_s(r) = \{t \mid st \in \mathcal{L}\{r\}\}$.

Definition 3 (Definition of $\text{ltail}(r)$). If $\text{lhead}(r, \epsilon) = \{a_1, a_2, \dots, a_i\}$, then we define $\text{ltail}(r) = \delta_{a_1}(r) + \delta_{a_2}(r) + \dots + \delta_{a_i}(r)$.

3.2 Replacement

The following correctness condition must hold for any definition of $\text{lreplace}(r, r_1, r_2)$.

Condition E (Replacement Correctness). If $s_1 \in \mathcal{L}\{r_1\}$ and $s_2 \in \mathcal{L}\{r_2\}$ then

$$\text{replace}(r; s_1; s_2) \in \mathcal{L}\{\text{lreplace}(r, r_1, r_2)\}$$

We do not give a particular definition for $\text{lreplace}(r, r_1, r_2)$ here.

3.3 Small Step Semantics of λ_{RS}

Figure 7 specifies a small-step operational semantics for λ_{RS} .

Lemma F (Canonical Forms). If $\emptyset \vdash v : \sigma$ then:

1. If $\sigma = \text{stringin}[r]$ then $v = \text{rstr}[s]$ and $s \in \mathcal{L}\{r\}$.
2. If $\sigma = \sigma_1 \rightarrow \sigma_2$ then $v = \lambda x.e'$.

Proof. By inspection of the static and dynamic semantics. □

Lemma G (Progress). If $\emptyset \vdash e : \sigma$ either $e = v$ for some v or $e \mapsto e'$ for some e' .

Proof. The proof proceeds by rule induction on the derivation of $\emptyset \vdash e : \sigma$.

λ fragment. Cases SS-T-Var, SS-T-Abs, and SS-T-App are exactly as in a proof of progress for the simply typed lambda calculus.

S-T-Stringin-I. Suppose $\emptyset \vdash \text{rstr}[s] : \text{stringin}[s]$. Then $e = \text{rstr}[s]$.

S-T-Concat. Suppose $\emptyset \vdash \text{rconcat}(e_1; e_2) : \text{stringin}[r_1 \cdot r_2]$ and $\emptyset \vdash e_1 : \text{stringin}[r_1]$ and $\emptyset \vdash e_2 : \text{stringin}[r_2]$. By induction, $e_1 \mapsto e'_1$ or $e_1 = v_1$ and similarly, $e_2 \mapsto e'_2$ or $e_2 = v_2$. If e_1 steps, then SS-E-Concat-Left applies and so $\text{rconcat}(e_1; e_2) \mapsto \text{rconcat}(e'_1; e_2)$. Similarly, if e_2 steps then e steps by SS-E-Concat-Right.

In the remaining case, $e_1 = v_1$ and $e_2 = v_2$. But then it follows by Canonical Forms that $e_1 = \text{rstr}[s_1]$ and $e_2 = \text{rstr}[s_2]$. Finally, by SS-E-Concat, $\text{rconcat}(\text{rstr}[s_1]; \text{rstr}[s_2]) \mapsto \text{rstr}[s_1 s_2]$.

S-T-Case. Suppose $e = \text{rstrcase}(e_1; e_2; x, y.e_3)$ and $\emptyset \vdash e_1 : \text{stringin}[r]$. By induction and Canonical Forms it follows that $e_1 \mapsto e'_1$ or $e_1 = \text{rstr}[s]$. In the former case, e steps by S-E-Case-Left. In the latter case, note that $s = \epsilon$ or $s = at$ for some string t . If $s = \epsilon$ then e steps by S-E-Case- ϵ -Val, and if $s = at$ then e steps by S-E-Case-Concat.

S-T-Replace. Suppose $e = \text{rreplace}[r](e_1; e_2)$, $\emptyset \vdash e : \text{stringin}[\text{lreplace}(r, r_1, r_2)]$ and:

- (1) $\emptyset \vdash e_1 : \text{stringin}[r_1]$
- (2) $\emptyset \vdash e_2 : \text{stringin}[r_2]$

By induction on (1), $e_1 \mapsto e'_1$ or $e_1 = v_1$ for some e'_1 . If $e_1 \mapsto e'_1$ then e steps by SS-E-Replace-Left. Similarly, if e_2 steps then e steps by SS-E-Replace-Right. The only remaining case is where $e_1 = v_1$ and also $e_2 = v_2$. By Canonical Forms, $e_1 = \text{rstr}[s_1]$ and $e_2 = \text{rstr}[s_2]$. Therefore, $e \mapsto \text{rstr}[\text{replace}(r; s_1; s_2)]$ by SS-E-Replace.

S-T-SafeCoerce. Suppose that $\emptyset \vdash \text{rcoerce}[r](e_1) : \text{stringin}[r]$. and $\emptyset \vdash e_1 : \text{stringin}[r']$ for $\mathcal{L}\{r'\} \subseteq \mathcal{L}\{r\}$. By induction, $e_1 = v_1$ or $e_1 \mapsto e'_1$ for some e'_1 . If $e_1 \mapsto e'_1$ then e steps by SS-E-SafeCoerce-Step. Otherwise, $e_1 = v$ and by Canonical Forms $e_1 = \text{rstr}[s]$. In this case, $e = \text{rcoerce}[r](\text{rstr}[s]) \mapsto \text{rstr}[s]$ by SS-E-SafeCoerce.

S-T-Check Suppose that $\emptyset \vdash \text{rcheck}[r](e_0; x.e_1; e_2) : \text{stringin}[r]$ and:

- (3) $\emptyset \vdash e_0 : \text{stringin}[r_0]$
- (4) $\emptyset, x : \text{stringin}[r] \vdash e_1 : \sigma$
- (5) $\emptyset \vdash e_2 : \sigma$

By induction, $e_0 \mapsto e'_0$ or $e_0 = v$. In the former case e steps by SS-E-Check-StepLeft. Otherwise, $e_0 = \text{rstr}[s]$ by Canonical Forms. By Lemma B part 2, either $s \in \mathcal{L}\{r_0\}$ or $s \notin \mathcal{L}\{r_0\}$. In the former case e takes a step by SS-E-Check-Ok. In the latter case e takes a step by SS-E-Check-NotOk.

□

Assumption H (Substitution). *If $\Psi, x : \sigma' \vdash e : \sigma$ and $\Psi \vdash e' : \sigma'$, then $\Psi \vdash [e'/x]e : \sigma$.*

Lemma I (Preservation for Small Step Semantics). *If $\emptyset \vdash e : \sigma$ and $e \mapsto e'$ then $\emptyset \vdash e' : \sigma$.*

Proof. By induction on the derivation of $e \mapsto e'$ and $\emptyset \vdash e : \sigma$.

λ fragment. Cases SS-E-AppLeft, SS-E-AppRight, and SS-E-AppAbs are exactly as in a proof of type safety for the simply typed lambda calculus.

SS-E-Concat-Left. Suppose $e = \text{rconcat}(e_1; e_2) \mapsto \text{rconcat}(e'_1; e_2)$ and $e_1 \mapsto e'_1$. The only rule that applies is S-T-Concat, so $\emptyset \vdash e_1 : \text{stringin}[r_1]$ and $\emptyset \vdash e_2 : \text{stringin}[r_2]$. By induction, $\emptyset \vdash e'_1 : \text{stringin}[r_1]$. Therefore, by S-T-Concat, $\emptyset \vdash \text{rconcat}(e'_1; e_2) : \text{stringin}[r_1 r_2]$.

SS-E-Concat-Right. Suppose $e = \text{rconcat}(e_1; e_2) \mapsto \text{rconcat}(e_1; e'_2)$ and $e_2 \mapsto e'_2$. The only rule that applies is S-T-Concat, so $\emptyset \vdash e_1 : \text{stringin}[r_1]$ and $\emptyset \vdash e_2 : \text{stringin}[r_2]$. By induction, $\emptyset \vdash e'_2 : \text{stringin}[r_2]$. Therefore, by S-T-Concat, $\emptyset \vdash \text{rconcat}(e_1; e'_2) : \text{stringin}[r_1 r_2]$.

SS-E-Concat. Suppose $\text{rconcat}(\text{rstr}[s_1]; \text{rstr}[s_2]) \mapsto \text{rstr}[s_1 s_2]$. The only applicable rule is S-T-Concat, so $\emptyset \vdash \text{rstr}[s_1] : \text{stringin}[r_1]$ and $\emptyset \vdash \text{rstr}[s_2] : \text{stringin}[r_2]$ and $\emptyset \vdash \text{rconcat}(\text{rstr}[s_1]; \text{rstr}[s_2]) : \text{stringin}[r_1 \cdot r_2]$. By Canonical Forms, $s_1 \in \mathcal{L}\{r_1\}$ and $s_2 \in \mathcal{L}\{r_2\}$ from which it follows by Lemma B that $s_1 s_2 \in \mathcal{L}\{r_1 \cdot r_2\}$. Therefore, $\emptyset \vdash \text{rstr}[s_1 s_2] : \text{stringin}[r_1 \cdot r_2]$ by S-T-Rstr.

S-E-Case-Left. Suppose $e \mapsto \text{rstrcase}(e'_1; e_2; x, y.e_3)$ and $\emptyset \vdash e : \sigma$ and $e_1 \mapsto e'_1$. The only rule that applies is S-T-Case, so:

- (6) $\emptyset \vdash e_1 : \text{stringin}[r]$
- (7) $\emptyset \vdash e_2 : \sigma$
- (8) $\emptyset, x : \text{stringin}[\text{lhead}(r)], y : \text{stringin}[\text{ltail}(r)] \vdash e_3 : \sigma$

By (6) and the assumption that $e_1 \mapsto e'_1$, it follows by induction that $\emptyset \vdash e'_1 : \text{stringin}[r]$. This fact together with (7) and (8) implies by S-T-Case that $\emptyset \vdash \text{rstrcase}(e'_1; e_2; x, y.e_3) : \sigma$.

SS-E-Case-Val. Suppose $\text{rstrcase}(e_0; e_2; x, y.e_3) \mapsto e_2$. The only rule that applies is S-T-Case, so $\emptyset \vdash e_2 : \sigma$.

SS-E-Case-Concat. Suppose that $e = \text{rstrcase}(\text{rstr}[as]; e_2; x, y.e_3) \mapsto [\text{rstr}[a], \text{rstr}[s]/x, y]e_3$ and that $\emptyset \vdash e : \sigma$. The only rule that applies is S-T-Case so:

- (9) $\emptyset \vdash \text{rstr}[as] : \text{stringin}[r]$
- (10) $\emptyset \vdash e_2 : \sigma$
- (11) $\emptyset, x : \text{stringin}[\text{lhead}(r)], y : \text{stringin}[\text{ltail}(r)] \vdash e_3 : \sigma$

We know that $as \in \mathcal{L}\{r\}$ by Canonical Forms on (9) Therefore, $a \in \mathcal{L}\{\text{lhead}(r)\}$ by Condition C and $s \in \mathcal{L}\{\text{ltail}(r)\}$ by Condition D.

From these facts about a and s we know by S-T-Rstr that $\emptyset \vdash \text{rstr}[a] : \text{stringin}[\text{lhead}(r)]$ and $\emptyset \vdash \text{rstr}[s] : \text{stringin}[\text{ltail}(r)]$. It follows by Assumption H that $\emptyset \vdash [\text{rstr}[a], \text{rstr}[s]/x, y]e_3 : \sigma$.

Case SS-E-Replace-Left. Suppose that $e = \text{rreplace}[r](e_1; e_2) \mapsto \text{rreplace}[r](e'_1; e_2)$ when $e_1 \mapsto e'_1$. The only rule that applies is S-T-Replace, so $\emptyset \vdash e : \text{stringin}[\text{lreplace}(r, r_1, r_2)]$ where:

$$\begin{aligned} \emptyset \vdash e_1 &: \text{stringin}[r_1] \\ \emptyset \vdash e_2 &: \text{stringin}[r_2] \end{aligned}$$

By induction, $\emptyset \vdash e'_1 : \text{stringin}[r_1]$. Therefore, $\emptyset \vdash \text{rreplace}[r](e'_1; e_2) : \text{stringin}[\text{lreplace}(r, r_1, r_2)]$ by S-T-Replace.

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SS-E-Replace-Right. Suppose that $e = \text{rreplace}[r](e_1; e_2) \mapsto \text{rreplace}[r](e'_1; e_2)$ when $e_1 \mapsto e'_1$. The only rule that applies is S-T-Replace, so $\emptyset \vdash e : \text{stringin}[\text{lreplace}(r, r_1, r_2)]$ where:

$$\begin{aligned}\emptyset \vdash e_1 &: \text{stringin}[r_1] \\ \emptyset \vdash e_2 &: \text{stringin}[r_2]\end{aligned}$$

By induction, $\emptyset \vdash e'_1 : \text{stringin}[r_1]$. Therefore, $\emptyset \vdash \text{rreplace}[r](r'_1; r_2) : \text{stringin}[\text{lreplace}(r, r_1, r_2)]$ by S-T-Replace.

Case SS-E-Replace.

Suppose $e = \text{rreplace}[r](\text{rstr}[s_1]; \text{rstr}[s_2]) \mapsto \text{rstr}[\text{replace}(r; s_1; s_2)]$. The only applicable rule is S-T-Replace, so

$$\begin{aligned}\emptyset \vdash \text{rstr}[s_1] &: \text{stringin}[r_1] \\ \emptyset \vdash \text{rstr}[s_2] &: \text{stringin}[r_2]\end{aligned}$$

By conanical forms, $s_1 \in \mathcal{L}\{r_1\}$ and $s_2 \in \mathcal{L}\{r_2\}$. Therefore, $\text{lreplace}(r, s_1, s_2) \in \mathcal{L}\{\text{lreplace}(r, r_1, r_2)\}$ by Theorem E. It is finally derivable by S-T-Rstr that:

$$\emptyset \vdash \text{rstr}[\text{lreplace}(r, s_1, s_2)] : \text{stringin}[\text{lreplace}(r, r_1, r_2)].$$

Case SS-E-SafeCoerce. Suppose that $\text{rcoerce}[r](\text{rstr}[s_1]) \mapsto \text{rstr}[s_1]$. The only applicable rule is S-T-SafeCoerce, so $\emptyset \vdash \text{rcoerce}[r](s_1) : \text{stringin}[r]$. By Canonical Forms, $s \in \mathcal{L}\{r\}$. Therefore, $\emptyset \vdash \text{rstr}[s] : \text{stringin}[r]$.

Case SS-E-Check-Ok. Suppose $\text{rcheck}[r](\text{rstr}[s]; x.e_1; e_2) \mapsto [\text{rstr}[s]/x]e_1$, $s \in \mathcal{L}\{r\}$, and $\emptyset \vdash \text{rcheck}[r](\text{rstr}[s]; x.e_1; e_2) : \sigma$. By inversion of S-T-Check, $x : \text{stringin}[r] \vdash e_1 : \sigma$. Note that $s \in \mathcal{L}\{r\}$ implies that $s : \text{stringin}[r]$ by S-T-RStr. Therefore, $\emptyset \vdash [\text{rstr}[s]/x]e_1 : \sigma$.

Case SS-E-Check-NotOk. Suppose $\text{rcheck}[r](\text{rstr}[s]; x.e_1; e_2) \mapsto e_2$, $s \notin \mathcal{L}\{r\}$, and $\emptyset \vdash \text{rcheck}[r](\text{rstr}[s]; x.e_1; e_2) : \sigma$. The only applicable rule is S-T-Check, so $\emptyset \vdash e_2 : \sigma$.

□

Theorem J (Type Safety for small step semantics.). *If $\emptyset \vdash e : \sigma$ then either $e \text{ val}$ or $e \mapsto^* e'$ and $\emptyset \vdash e' : \sigma$.*

Proof. Follows directly from progress and preservation. □

3.3.1 The Security Theorem

Theorem 4 (Correctness of Input Sanitation for λ_{RS}). *If $\emptyset \vdash e : \text{stringin}[r]$ and $e \mapsto^* \text{rstr}[s]$ then $s \in \mathcal{L}\{r\}$.*

Proof. By type safety, $\emptyset \vdash \text{rstr}[s] : \text{stringin}[r]$. Therefore, $s \in \mathcal{L}\{r\}$. □

4 Proofs of Lemmas and Theorems About λ_P

This section follows the same structure as the safety proof for λ_{RS} – we prove type safety for a small-step semantics, prove a semantic correspondence, and then transfer the safety result to the big-step semantics in the paper.

Lemma 5 (Canonical Forms for Target Language).

- If $\emptyset \vdash \iota : \text{regex}$ then $\iota \Downarrow \text{rx}[r]$ such that r is a well-formed regular expression.
- If $\emptyset \vdash \iota : \text{string}$ then $\iota \Downarrow \text{str}[s]$.

Theorem 6 (Progress). If $\emptyset \vdash \iota : \tau$ either $\iota = \dot{v}$ or $\iota \mapsto \iota'$ for some ι' .

Proof. The proof proceeds by induction on the typing assumption. Consider only the string and regex (non- λ) fragments of λ_P .

P-T-Case. Suppose $\emptyset \vdash \text{strcase}(\iota_1; \iota_2; x, y, \iota_3)$. By inversion, $\iota_1 : \text{string}$ and so either $\iota_1 \mapsto \iota'_1$ or by canonical forms, $\iota_1 = \text{str}[s_1]$. Similarly, $\iota_2 \mapsto \iota'_2$ or else $\iota_2 = \text{str}[s_2]$. In the former cases, progress occurs via the compatibility rules. in the case where both are string values, progress occurs via the case concatenation rule.

P-T-Replace. Suppose $\emptyset \vdash \text{replace}(\iota_1; \iota_2; \iota_3)$. By inversion, $\iota_1 : \text{regex}$ and so by canonical forms $\iota_1 = \text{rx}[r]$. By inversion, $\iota_2 : \text{string}$ and so by induction either $\iota_2 \mapsto \iota'_2$ or else $\iota_2 = \text{str}[s_2]$ for some string s_2 . Similarly, either ι_3 steps or else $\iota_3 = \text{str}[s_3]$. In case any steps occur, progress occurs. In the remaining case, PP-E-Replace applies and so progress occurs.

P-T-Check. Finally, suppose $\emptyset \vdash \check{\iota}_x \iota_1 \iota_2 \iota_3$. In case any of these step, then progress occurs. In the remaining cases, applications of inversion and canonical forms for each ι_x and ι_1 implies that the term at hand equals $\text{rx}[r]\text{str}[s]\iota_2\iota_3$, which evaluates to either ι_2 or ι_3 .

□

Lemma K (Substitution Lemma). If $\theta, x : \tau \vdash \iota : \tau'$ and $\theta \vdash \iota' : \tau$ then $\theta \vdash [\iota'/x]\iota : \tau'$.

Theorem 7 (Preservation). If $\emptyset \vdash \iota : \tau$ and $\iota \mapsto \iota'$ then $\emptyset \vdash \iota' : \tau$.

Proof. The proof proceeds by induction of the derivations of $\emptyset \vdash \iota : \tau$ and $\iota \mapsto \iota'$.

We treat only the non-lambda fragment.

Case PS-E-ConcatLeft. Suppose:

$$\begin{aligned} \iota &= \text{rconcat}(\iota_1; \iota_2) \mapsto \text{rconcat}(\iota'_1; \iota_2) \\ \emptyset \vdash \iota : \text{string} \\ \iota &\mapsto \iota' \end{aligned}$$

The only applicable typing rule is P-T-Concat, so $\emptyset \vdash \iota_1 : \text{string}$ and $\emptyset \vdash \iota_2 : \text{string}$. By induction, $\emptyset \vdash \iota'_1 : \text{string}$, so $\emptyset \vdash \text{rconcat}(\iota'_1; \iota_2) : \text{string}$.

Case PS-E-ConcatRight

$$\begin{aligned} e &= \text{rconcat}(e_1; e_2) \mapsto \text{rconcat}(e_1; e'_2) \\ \emptyset \vdash e : \text{string} \\ \iota &\mapsto \iota' \end{aligned}$$

The only applicable typing rule is P-T-Concat, so $\emptyset \vdash \iota_1 : \text{string}$ and $\emptyset \vdash \iota_2 : \text{string}$. By induction, $\emptyset \vdash \iota'_1 : \text{string}$, so $\emptyset \vdash \text{rconcat}(\iota_1; \iota'_2) : \text{string}$.

Case PS-E-Concat Let $e = \text{rconcat}(\text{rstr}[s_1]; \text{rstr}[s_2]) \mapsto \text{rstr}[s_1 s_2]$. The only rule that applies is P-T-Concat, so $\emptyset \vdash e : \text{string}$. By canonical forms, $\emptyset \text{rstr}[s_1 s_2] : \text{string}$.

Case PS-E-CaseLeft Let $\iota = \text{rstrcase}(\iota_1; \iota_2; x, y, \iota_3) \mapsto \text{rstrcase}(\iota'_1; \iota_2; x, y, \iota_3)$ when $\iota_1 \mapsto \iota'_1$. The only rule that applies is P-T-Case, so $\emptyset \vdash \iota : \tau$ where:

$$\begin{aligned} \emptyset \vdash \iota_1 &: \text{string} \\ \emptyset \vdash \iota_2 &: \tau \\ \emptyset, x : \text{string}, y : \text{string} &\vdash \iota_3 : \tau \end{aligned}$$

By induction, $\emptyset \vdash \iota'_1 : \text{string}$. By P-T-Case, $\emptyset \vdash \text{rstrcase}(\iota_1; \iota_2; x, y, \iota_3) : \tau$.

Case PS-E-CaseEpsilon Let $\iota = \text{rstrcase}(\text{rstr}[\epsilon]; \iota_2; x, y, \iota_3) \mapsto \iota_2$. The only rule that applies is P-T-Case, so $\emptyset \vdash \iota : \tau$ where $\iota_2 : \tau$.

Case PS-E-Case Let $\iota = \text{rstrcase}(\text{rstr}[as]; \iota_2; x, y, \iota_3) \mapsto [\text{rstr}[a], \text{rstr}[s]/x, y] \iota_3$. The only rule that applies is P-T-Case, so $\emptyset \vdash \iota : \tau$ where:

$$\begin{aligned} \emptyset \vdash \iota_1 &: \text{string} \\ \emptyset \vdash \iota_2 &: \tau \\ \emptyset, x : \text{string}, y : \text{string} &\vdash \iota_3 : \tau \end{aligned}$$

The result follows by the substitution lemma.

Case PS-E-ReplaceLeft Let $\iota = \text{rreplace}[\iota_1](\iota_2; \iota_3) \mapsto \text{rreplace}[\iota'_1](\iota_2; \iota_3)$ where $\iota_1 \mapsto \iota'_1$. The applicable typing rule is P-T-Replace, so $\emptyset \vdash \iota : \text{string}$ where:

$$\begin{aligned} \emptyset \vdash \iota_1 &: \text{regex} \\ \emptyset \vdash \iota_2 &: \text{string} \\ \emptyset \vdash \iota_3 &: \text{string} \end{aligned}$$

By induction, $\emptyset \vdash \iota'_1 : \text{regex}$. Therefore, $\emptyset \vdash \text{rreplace}[\iota'_1](\iota_2; \iota_3)$.

Case PS-E-ReplaceMid Let $\iota = \text{rreplace}[\iota_1](\iota_2; \iota_3) \mapsto \text{rreplace}[\iota_1](\iota'_2; \iota_3)$ where $\iota_2 \mapsto \iota'_2$. The applicable typing rule is P-T-Replace, so $\emptyset \vdash \iota : \text{string}$ where:

$$\begin{aligned} \emptyset \vdash \iota_1 &: \text{regex} \\ \emptyset \vdash \iota_2 &: \text{string} \\ \emptyset \vdash \iota_3 &: \text{string} \end{aligned}$$

By induction, $\emptyset \vdash \iota'_2 : \text{string}$. Therefore, $\emptyset \vdash \text{rreplace}[\iota_1](\iota'_2; \iota_3)$.

Case PS-E-ReplaceRight Let $\iota = \text{rreplace}[\iota_1](\iota_2; \iota_3) \mapsto \text{rreplace}[\iota_1](\iota_2; \iota'_3)$ where $\iota_3 \mapsto \iota'_3$. The applicable typing rule is P-T-Replace, so $\emptyset \vdash \iota : \text{string}$ where:

$$\begin{aligned} \emptyset \vdash \iota_1 &: \text{regex} \\ \emptyset \vdash \iota_2 &: \text{string} \\ \emptyset \vdash \iota_3 &: \text{string} \end{aligned}$$

By induction, $\emptyset \vdash \iota'_3 : \text{string}$. Therefore, $\emptyset \vdash \text{rreplace}[\iota_1](\iota_2; \iota'_3)$.

Case PS-E-Replace Let $\iota = \text{rreplace}[\text{rx}[r]](\text{rstr}[s_2]; \text{rstr}[s_3]) \mapsto \text{rstr}[\text{lreplace}(r, s_2, s_3)]$. The applicable typing rule is P-T-Replace, so $\emptyset \vdash \iota : \text{string}$. The result follows by canonical forms.

Case PS-E-CheckLeft Let $\iota = \text{rcheck}[\iota_x](\iota_1; \iota_2; \iota_3) \mapsto \text{rcheck}[\iota'_x](\iota_1; \iota_2; \iota_3)$ where $\iota_x \mapsto \iota'_x$. The applicable typing rule is P-T-Check, so $\emptyset \vdash \iota : \tau$ where:

$$\begin{aligned} \emptyset \vdash \iota_x &: \text{regex} \\ \emptyset \vdash \iota_1 &: \text{string} \\ \emptyset \vdash \iota_2 &: \tau \\ \emptyset \vdash \iota_3 &: \tau \end{aligned}$$

By induction, $\iota_x : \text{regex}$. Therefore, $\emptyset \text{rcheck}[\iota'_x](\iota_1; \iota_2; \iota_3) : \tau$.

Case PS-E-CheckRight Let $\iota = \text{rcheck}[\iota_x](\iota_1; \iota_2; \iota_3) \mapsto \text{rcheck}[\iota_x](\iota'_1; \iota_2; \iota_3)$ where $\iota_1 \mapsto \iota'_1$. The applicable typing rule is P-T-Check, so $\emptyset \vdash \iota : \tau$ where:

$$\begin{aligned} \emptyset \vdash \iota_x &: \text{regex} \\ \emptyset \vdash \iota_1 &: \text{string} \\ \emptyset \vdash \iota_2 &: \tau \\ \emptyset \vdash \iota_3 &: \tau \end{aligned}$$

By induction, $\iota'_1 : \text{string}$. Therefore, $\emptyset \text{rcheck}[\iota_x](\iota'_1; \iota_2; \iota_3) : \tau$.

Case PS-E-Check-Ok Let $\iota = \text{rcheck}[\text{rx}[r]](\text{rstr}[s]; \iota_2; \iota_3) \mapsto \iota_2$ and $s \in \mathcal{L}\{r\}$. The applicable typing rule is P-T-Check, so $\emptyset \vdash \iota : \tau$ where $\emptyset \vdash \iota_2 : \tau$.

Case PS-E-Check-NotOk Let $\iota = \text{rcheck}[\text{rx}[r]](\text{rstr}[s]; \iota_2; \iota_3) \mapsto \iota_3$ where $s \notin \mathcal{L}\{r\}$. The applicable typing rule is P-T-Check, so $\emptyset \vdash \iota : \tau$ where $\emptyset \vdash \iota_3 : \tau$.

□

5 Proofs and Lemmas and Theorems About Translation

Theorem 8 (Translation Correctness). *If $\Psi \vdash e : \sigma$ then there exists an ι such that $\llbracket e \rrbracket = \iota$ and $\llbracket \Psi \rrbracket \vdash \iota : \llbracket \sigma \rrbracket$. Furthermore, if $e \mapsto^* v$ then $\iota \mapsto^* \dot{v}$ such that $\llbracket v \rrbracket = \dot{v}$.*

Proof. We present a proof by induction on the structure of e . We write $e \rightsquigarrow \iota$ as shorthand for the final property.

Case $e = \text{rstr}[s]$. Suppose $\Theta \vdash \text{rstr}[s] : \sigma$.

By examination the syntactic structure of conclusions in the relation S-T, we know this is true just in case $\sigma = \text{stringin}[r]$ for some r such that $s \in \mathcal{L}\{r\}$; and of course, there is always such an r .

There are no free variables in $\text{rstr}[s]$, so we might as well proceed from the fact that $\emptyset \vdash \text{rstr}[s] : \text{stringin}[r]$.

This proof needs to be changed to use only the small-step semantics.

By definition of the translation ($\llbracket \cdot \rrbracket$) the following statements hold:

- $$\begin{aligned} (12) \quad & \llbracket \text{rstr}[s] \rrbracket = \text{str}[s] \\ (13) \quad & \llbracket \text{stringin}[r] \rrbracket = \text{string} \\ (14) \quad & \llbracket \emptyset \rrbracket = \emptyset \end{aligned}$$

Note that $\emptyset \vdash \text{str}[s] : \text{string}$ by P-T-Str. Recall that contexts are standard and, in particular, can be weakened. So since $\llbracket \Theta \rrbracket$ is either a weakening of \emptyset or \emptyset itself, $\llbracket \Theta \rrbracket \vdash \text{str}[s] : \text{string}$ by weakening.

Summarily, $\text{str}[s]$ is a term of λ_P such that $\llbracket \Theta \rrbracket \vdash \text{str}[s] : \llbracket \sigma \rrbracket$

It remains to be shown that there exist v, \dot{v} such that $\text{rstr}[s] \Downarrow v$, $\text{string}s \Downarrow \dot{v}$, and $\llbracket v \rrbracket = \dot{v}$. But this is immediate because each term evaluates to itself and we have already established the equality.

Case $e = \text{rconcat}(e_1; e_2)$. By induction.

Case $e = \text{rstrcase}(e_1; e_2; x, y.e_3)$. This case relies on our definition of context translation.

Suppose $\Psi \vdash \text{rstrcase}(e_1; e_2; x, y.e_3) : \sigma$. By inversion of the typing relation it follows that $\Psi \vdash e_1 : \text{stringin}[r]$, $\Psi \vdash e_2 : \sigma$ and $\Psi, x : \text{stringin}[\text{lhead}(r)], y : \text{stringin}[\text{ltail}(r)] \vdash e_3 : \sigma$.

By induction, there exists an ι_1 such that $\llbracket e_1 \rrbracket = \iota_1$, $\llbracket \Psi \rrbracket \vdash \iota_1 : \llbracket \sigma \rrbracket$, and $e_1 \rightsquigarrow \iota_1$. Similarly for e_2 and some ι_2 .

By canonical forms, $e_1 \Downarrow \text{rstr}[s]$ and so $\iota_1 \Downarrow \text{str}[s]$ by \rightsquigarrow .

Choose $\iota = \text{concat}(\iota_1; \iota_2)x, y.\iota_3$ and note that by the properties established via induction, $\llbracket e \rrbracket = \iota$ and $\llbracket \Psi \rrbracket \vdash \iota : \llbracket \sigma \rrbracket$.

Suppose $s = \epsilon$. Then $e \Downarrow v$ where $e_2 \Downarrow v$ and $\iota \Downarrow \dot{v}$ where $\iota_2 \Downarrow \dot{v}$. But recall that $e_2 \rightsquigarrow v_2$ and so $\llbracket v \rrbracket = \dot{v}$.

Suppose otherwise that $s = at$ for some character a and string t . Then $e \Downarrow v$ where $[a, t/x, y]e_3 \Downarrow v$. Similarly, $\iota \Downarrow \dot{v}$ where $[a, t/x, y]\iota_3 \Downarrow \dot{v}$.

Case $e = \text{rreplace}[r](e_1; e_2)$. There is only one applicable typing rule, so suppose $\Psi \vdash \text{rreplace}[r](e_1; e_2) : \text{stringin}[\text{lreplace}(r, e_1, e_2)]$. Let $\psi = \llbracket \Psi \rrbracket$. Note that $\llbracket \text{rreplace}[r](e_1; e_2) \rrbracket = \text{replace}(\text{rx}[r]; \iota_1; \iota_2)$ when by induction $\llbracket e_1 \rrbracket = \iota_1$ and $\llbracket e_2 \rrbracket = \iota_2$ such that $\psi \vdash \iota_1$ and $\psi \vdash \iota_2$. It follows by P-T-Replace that $\psi \vdash \text{replace}(\text{rx}[r]; \iota_1; \iota_2) : \text{string}$. Finally, note that $\llbracket \text{stringin}[\text{lreplace}(r, e_1, e_2)] \rrbracket = \text{string}$.

For evaluation correspondence, note that $\llbracket \text{rstr}[\text{lreplace}(r, s_1, s_2)] \rrbracket = \text{rstr}[\text{lreplace}(r, s_1, s_2)]$ and so it suffices to show that $\text{replace}(\text{rx}[r]; \iota_1; \iota_2) \Downarrow \text{rstr}[r]s_1s_2$. Note that $\text{lreplace}(r, e_1, e_2) \Downarrow \text{rstr}[\text{lreplace}(r, s_1, s_2)]$ where $e_1 \Downarrow \text{rstr}[s_1]$, $e_2 \Downarrow \text{rstr}[s_2]$, $r \Downarrow r$. By induction, $\iota_1 \Downarrow \text{rstr}[s_1]$, $\iota_2 \Downarrow \text{rstr}[s_2]$, and $\text{rx}[r] \Downarrow \text{rx}[r]$. So by S-E-Replace, the sufficient condition holds.

Case $e = \text{rcoerce}[r](e')$. The only applicable typing rule is S-T-SafeCoerce, so suppose $\Psi \vdash \text{rcoerce}[r](e') : \text{stringin}[r]$ where $\Psi \vdash e' : \text{stringin}[r']$ and $\mathcal{L}\{r'\} \subseteq \mathcal{L}\{r\}$. By induction, $e' \rightsquigarrow \iota$ for some ι . Therefore, $\llbracket \text{rcoerce}[r](e') \rrbracket = \iota$ by Tr-SafeCoerce.

For evaluation correspondence, note that $e \Downarrow v$ where $e' \Downarrow v$. The result follows by induction because $e' \rightsquigarrow \iota$.

Case $e = \text{rcheck}[r](e_1; x.e_2; e_3)$. The applicable typing rule is S-T-Check, so $\psi \vdash e : \sigma$ where $\psi \vdash e_1 : \text{stringin}[r]$, $\psi, x : \text{stringin}[r] \vdash e_2 : \sigma$, and $\psi \vdash e_3 : \sigma$. By induction and a corresponding

hand wave
lots and
lots of
symbol
pushing.

substitution principle there exists $\iota_1, \iota_2, \iota_3$ such that $e_1 \rightsquigarrow \iota_1$, $e_2 \rightsquigarrow \iota_2$ in context $\psi, s : \text{stringin}[r]$, and $e_3 \rightsquigarrow \iota_3$. Choose $\iota = \text{check}(\text{rx}[r]; \iota_1; \lambda x. \iota_2; \iota_3)$. The result follows by induction.

hand wave

□

Theorem 9 (Correctness of Input Sanitation for Translated Terms). *If $\llbracket e \rrbracket = \iota$ and $\emptyset \vdash e : \text{stringin}[r]$ then $\iota \Downarrow \text{str}[s]$ for $s \in \mathcal{L}\{r\}$.*

Proof. By Theorem 8 and the rules given, $\iota \Downarrow \text{str}[s]$ implies that $e \Downarrow \text{rstr}[s]$. Theorem 4 together with the assumption that e is well-typed implies that $s \in \mathcal{L}\{r\}$. □

References

- [1] N. Fulton, C. Omar, and J. Aldrich. Statically typed string sanitation inside a python. SPLASH '14. ACM, 2014.

$$r ::= \epsilon \mid . \mid a \mid r \cdot r \mid r + r \mid r^* \quad a \in \Sigma$$

Figure 1: Regular expressions over the alphabet Σ .

$$\begin{aligned} \sigma &::= \sigma \rightarrow \sigma \mid \text{stringin}[r] && \text{source types} \\ e &::= x \mid v && \text{source terms} \\ &\quad \mid \text{rconcat}(e; e) \mid \text{rstrcase}(e; e; x, y.e) && s \in \Sigma^* \\ &\quad \mid \text{rreplace}[r](e; e) \mid \text{rcoerce}[r](e) \mid \text{rcheck}[r](e; x.e; e) \\ v &::= \lambda x.e \mid \text{rstr}[s] && \text{source values} \end{aligned}$$

Figure 2: Syntax of λ_{RS} .

$$\begin{aligned} \tau &::= \tau \rightarrow \tau \mid \text{string} \mid \text{regex} && \text{target types} \\ \iota &::= x \mid \dot{v} && \text{target terms} \\ &\quad \mid \text{concat}(\iota; \iota) \mid \text{strcase}(\iota; \iota; x, y.\iota) \\ &\quad \mid \text{rx}[r] \mid \text{replace}(\iota; \iota; \iota) \mid \text{check}(\iota; \iota; \iota; \iota) \\ \dot{v} &::= \lambda x.\iota \mid \text{str}[s] \mid \text{rx}[r] && \text{target values} \end{aligned}$$

Figure 3: Syntax for the target language, λ_P , containing strings and statically constructed regular expressions.

$$\boxed{\Psi \vdash e : \sigma} \quad \Psi ::= \emptyset \mid \Psi, x : \sigma$$

$$\begin{array}{c} \text{S-T-VAR} \\ \frac{x : \sigma \in \Psi}{\Psi \vdash x : \sigma} \end{array} \quad \begin{array}{c} \text{S-T-ABS} \\ \frac{\Psi, x : \sigma_1 \vdash e : \sigma_2}{\Psi \vdash \lambda x.e : \sigma_1 \rightarrow \sigma_2} \end{array} \quad \begin{array}{c} \text{S-T-APP} \\ \frac{\Psi \vdash e_1 : \sigma_2 \rightarrow \sigma \quad \Psi \vdash e_2 : \sigma_2}{\Psi \vdash e_1(e_2) : \sigma} \end{array} \quad \begin{array}{c} \text{S-T-STRINGIN-I} \\ \frac{s \in \mathcal{L}\{r\}}{\Psi \vdash \text{rstr}[s] : \text{stringin}[r]} \end{array}$$

$$\begin{array}{c} \text{S-T-CONCAT} \\ \frac{\Psi \vdash e_1 : \text{stringin}[r_1] \quad \Psi \vdash e_2 : \text{stringin}[r_2]}{\Psi \vdash \text{rconcat}(e_1; e_2) : \text{stringin}[r_1 \cdot r_2]} \end{array}$$

$$\begin{array}{c} \text{S-T-CASE} \\ \frac{\Psi \vdash e_1 : \text{stringin}[r] \quad \Psi \vdash e_2 : \sigma \quad \Psi, x : \text{stringin}[\text{lhead}(r)], y : \text{stringin}[\text{ltail}(r)] \vdash e_3 : \sigma}{\Psi \vdash \text{rstrcase}(e_1; e_2; x, y.e_3) : \sigma} \end{array}$$

$$\begin{array}{c} \text{S-T-REPLACE} \\ \frac{\Psi \vdash e_1 : \text{stringin}[r_1] \quad \Psi \vdash e_2 : \text{stringin}[r_2]}{\Psi \vdash \text{rreplace}[r](e_1; e_2) : \text{stringin}[\text{lreplace}(r, r_1, r_2)]} \end{array} \quad \begin{array}{c} \text{S-T-SAFECOERCE} \\ \frac{\Psi \vdash e : \text{stringin}[r'] \quad \mathcal{L}\{r'\} \subseteq \mathcal{L}\{r\}}{\Psi \vdash \text{rcoerce}[r](e) : \text{stringin}[r]} \end{array}$$

$$\begin{array}{c} \text{S-T-CHECK} \\ \frac{\Psi \vdash e_0 : \text{stringin}[r] \quad \Psi, x : \text{stringin}[r] \vdash e_1 : \sigma \quad \Psi \vdash e_2 : \sigma}{\Psi \vdash \text{rcheck}[r](e_0; x.e_1; e_2) : \sigma} \end{array}$$

Figure 4: Typing rules for λ_{RS} . The typing context Ψ is standard.

$$\boxed{e \Downarrow v}$$

$\frac{\text{S-E-ABS}}{\lambda x.e \Downarrow \lambda x.e}$	$\frac{\text{S-E-APP} \quad e_1 \Downarrow \lambda x.e_3 \quad e_2 \Downarrow v_2 \quad [v_2/x]e_3 \Downarrow v}{e_1(e_2) \Downarrow v}$	$\frac{\text{S-E-RSTR}}{\text{rstr}[s] \Downarrow \text{rstr}[s]}$	$\frac{\text{S-E-CONCAT} \quad e_1 \Downarrow \text{rstr}[s_1] \quad e_2 \Downarrow \text{rstr}[s_2]}{\text{rconcat}(e_1; e_2) \Downarrow \text{rstr}[s_1 s_2]}$
$\frac{\text{S-E-CASE-}\epsilon \quad e_1 \Downarrow \text{rstr}[\epsilon] \quad e_2 \Downarrow v_2}{\text{rstrcase}(e_1; e_2; x, y.e_3) \Downarrow v_2}$		$\frac{\text{S-E-CASE-CONCAT} \quad e_1 \Downarrow \text{rstr}[as] \quad [\text{rstr}[a], \text{rstr}[s]/x, y]e_3 \Downarrow v_3}{\text{rstrcase}(e_1; e_2; x, y.e_3) \Downarrow v_3}$	
$\frac{\text{S-E-REPLACE} \quad e_1 \Downarrow \text{rstr}[s_1] \quad e_2 \Downarrow \text{rstr}[s_2]}{\text{rreplace}[r](e_1; e_2) \Downarrow \text{rstr}[\text{replace}(r; s_1; s_2)]}$		$\frac{\text{S-E-SAFE} \text{COERCE} \quad e \Downarrow \text{rstr}[s]}{\text{rcoerce}[r](e) \Downarrow \text{rstr}[s]}$	
$\frac{\text{S-E-CHECK-OK} \quad e \Downarrow \text{rstr}[s] \quad s \in \mathcal{L}\{r\} \quad [\text{rstr}[s]/x]e_1 \Downarrow v}{\text{rcheck}[r](e; x.e_1; e_2) \Downarrow v}$		$\frac{\text{S-E-CHECK-NOTOK} \quad e \Downarrow \text{rstr}[s] \quad s \notin \mathcal{L}\{r\} \quad e_2 \Downarrow v}{\text{rcheck}[r](e; x.e_1; e_2) \Downarrow v}$	

Figure 5: Big step semantics for λ_{RS} .

$$\boxed{e \mapsto e}$$

$\frac{\text{SS-E-APPLEFT} \quad e_1 \mapsto e'_1}{e_1(e_2) \mapsto e'_1(e_2)}$	$\frac{\text{SS-E-APPRIGHT} \quad e_2 \mapsto e'_2}{v_1 \mapsto v_1}$	$\frac{\text{SS-E-APPABS}}{(\lambda x : \tau_{11}.t_{12})v_2 \mapsto [v_2/x]t_{12}}$
---	---	--

$$\boxed{e \mapsto^* e}$$

$\frac{\text{RT-REFL}}{e \mapsto^* e}$	$\frac{\text{RT-TRANS} \quad e \mapsto^* e' \quad e' \mapsto e''}{e \mapsto^* e''}$
--	---

Figure 6: Call-by-name small step Semantics for λ and its reflexive, transitive closure.

$e \mapsto e$ (Continues figure 6)

$\frac{\text{SS-E-CONCAT-LEFT} \quad e_1 \mapsto e'_1}{\text{rconcat}(e_1; e_2) \mapsto \text{rconcat}(e'_1; e_2)}$	$\frac{\text{SS-E-CONCAT-RIGHT} \quad e_2 \mapsto e'_2}{\text{rconcat}(v_1; e_2) \mapsto \text{rconcat}(v_1; e'_2)}$
$\frac{\text{SS-E-CONCAT}}{\text{rconcat}(\text{rstr}[s_1]; \text{rstr}[s_2]) \mapsto \text{rstr}[s_1 s_2]}$	$\frac{\text{SS-E-CASE-LEFT} \quad e_1 \mapsto e'_1}{\text{rstrcase}(e_1; e_2; x, y.e_3) \mapsto \text{rstrcase}(e'_1; e_2; x, y.e_3)}$
$\frac{\text{SS-E-CASE-}\epsilon\text{-VAL}}{\text{rstrcase}(\text{rstr}[\epsilon]; e_2; x, y.e_3) \mapsto e_2}$	$\frac{\text{SS-E-CASE-CONCAT}}{\text{rstrcase}(\text{rstr}[as]; e_2; x, y.e_3) \mapsto [\text{rstr}[a], \text{rstr}[s]/x, y]e_3}$
$\frac{\text{SS-E-REPLACE-LEFT} \quad e_1 \mapsto e'_1}{\text{rreplace}[r](v_1; e_2) \mapsto \text{rreplace}[r](v'_1; e_2)}$	$\frac{\text{SS-E-REPLACE-RIGHT} \quad e_2 \mapsto e'_2}{\text{rreplace}[r](e_1; e_2) \mapsto \text{rreplace}[r](e_1; e'_2)}$
$\frac{\text{SS-E-REPLACE}}{\text{rreplace}[r](\text{rstr}[s_1]; \text{rstr}[s_2]) \mapsto \text{rstr}[\text{replace}(r; s_1; s_2)]}$	$\frac{\text{SS-E-SAFE COERCE-STEP} \quad e \mapsto e'}{\text{rcoerce}[r](e) \mapsto \text{rcoerce}[r](e')}$
$\frac{\text{SS-E-SAFE COERCE}}{\text{rcoerce}[r](\text{rstr}[s]) \mapsto \text{rstr}[s]}$	$\frac{\text{SS-E-CHECK-STEP LEFT} \quad e \mapsto e'}{\text{rcheck}[r](e; x.e_1; e_2) \mapsto \text{rcheck}[r](e'; x.e_1; e_2)}$
$\frac{\text{SS-E-CHECK-OK} \quad s \in \mathcal{L}\{r\}}{\text{rcheck}[r](\text{rstr}[s]; x.e_1; e_2) \mapsto [\text{rstr}[s]/x]e_1}$	$\frac{\text{SS-E-CHECK-NOT OK} \quad s \notin \mathcal{L}\{r\}}{\text{rcheck}[r](\text{rstr}[s]; x.e_1; e_2) \mapsto e_2}$

Figure 7: Small step semantics for λ_{RS} . Extends 6.

$$\boxed{\Theta \vdash \iota : \tau} \quad \Theta ::= \emptyset \mid \Theta, x : \tau$$

$\frac{\text{P-T-VAR}}{x : \tau \in \Theta \quad \Theta \vdash x : \tau}$	$\frac{\text{P-T-ABS}}{\Theta, x : \tau_1 \vdash \iota_2 : \tau_2 \quad \Theta \vdash \lambda x. \iota_2 : \tau_1 \rightarrow \tau_2}$	$\frac{\text{P-T-APP}}{\Theta \vdash \iota_1 : \tau_2 \rightarrow \tau \quad \Theta \vdash \iota_2 : \tau_2 \quad \Theta \vdash \iota_1(\iota_2) : \tau}$	$\frac{\text{P-T-STRING}}{\Theta \vdash \text{str}[s] : \text{string}}$
	$\frac{\text{P-T-REGEX}}{\Theta \vdash \text{rx}[r] : \text{regex}}$	$\frac{\text{P-T-CONCAT}}{\Theta \vdash \iota_1 : \text{string} \quad \Theta \vdash \iota_2 : \text{string} \quad \Theta \vdash \text{concat}(\iota_1; \iota_2) : \text{string}}$	
	$\frac{\text{P-T-CASE}}{\Theta \vdash \iota_1 : \text{string} \quad \Theta \vdash \iota_2 : \tau \quad \Theta, x : \text{string}, y : \text{string} \vdash \iota_3 : \tau \quad \Theta \vdash \text{strcase}(\iota_1; \iota_2; x, y. \iota_3) : \tau}$		
	$\frac{\text{P-T-REPLACE}}{\Theta \vdash \iota_1 : \text{regex} \quad \Theta \vdash \iota_2 : \text{string} \quad \Theta \vdash \iota_3 : \text{string} \quad \Theta \vdash \text{replace}(\iota_1; \iota_2; \iota_3) : \text{string}}$		
	$\frac{\text{P-T-CHECK}}{\Theta \vdash \iota_x : \text{regex} \quad \Theta \vdash \iota_1 : \text{string} \quad \Theta \vdash \iota_2 : \tau \quad \Theta \vdash \iota_3 : \tau \quad \Theta \vdash \text{check}(\iota_x; \iota_1; \iota_2; \iota_3) : \tau}$		

Figure 8: Typing rules for λ_P . The typing context Θ is standard.

$$\boxed{\iota \Downarrow \dot{v}}$$

$\frac{\text{P-E-ABS}}{\lambda x. e \Downarrow \lambda x. e}$	$\frac{\text{P-E-APP}}{\iota_1 \Downarrow \lambda x. \iota_3 \quad \iota_2 \Downarrow \dot{v}_2 \quad [\dot{v}_2/x] \iota_3 \Downarrow \dot{v}_3 \quad \iota_1(\iota_2) \Downarrow \dot{v}_3}$	$\frac{\text{P-E-STR}}{\text{str}[s] \Downarrow \text{str}[s]}$	$\frac{\text{P-E-RX}}{\text{rx}[r] \Downarrow \text{rx}[r]}$
$\frac{\text{P-E-CONCAT}}{\iota_1 \Downarrow \text{str}[s_1] \quad \iota_2 \Downarrow \text{str}[s_2] \quad \text{concat}(\iota_1; \iota_2) \Downarrow \text{str}[s_1 s_2]}$	$\frac{\text{P-E-CASE-}\epsilon}{\iota_1 \Downarrow \text{str}[\epsilon] \quad \iota_2 \Downarrow \dot{v}_2 \quad \text{strcase}(\iota_1; \iota_2; x, y. \iota_3) \Downarrow \dot{v}_2}$		$\frac{\text{P-E-CASE-CONCAT}}{\iota_1 \Downarrow \text{str}[as] \quad [\text{str}[a], \text{str}[s]/x, y] \iota_3 \Downarrow \dot{v} \quad \text{strcase}(\iota_1; \iota_2; x, y. \iota_3) \Downarrow \dot{v}}$
$\frac{\text{P-E-REPLACE}}{\iota_1 \Downarrow \text{rx}[r] \quad \iota_2 \Downarrow \text{str}[s_2] \quad \iota_3 \Downarrow \text{str}[s_3] \quad \text{replace}(\iota_1; \iota_2; \iota_3) \Downarrow \text{str}[\text{replace}(r; s_2; s_3)]}$		$\frac{\text{P-E-CHECK-OK}}{\iota_x \Downarrow \text{rx}[r] \quad \iota \Downarrow \text{str}[s] \quad s \in \mathcal{L}\{r\} \quad \iota_1 \Downarrow \dot{v}_1 \quad \text{check}(\iota_x; \iota; \iota_1; \iota_2) \Downarrow \dot{v}_1}$	
$\frac{\text{P-E-CHECK-NOTOK}}{\iota_x \Downarrow \text{rx}[r] \quad \iota \Downarrow \text{str}[s] \quad s \notin \mathcal{L}\{r\} \quad \iota_2 \Downarrow \dot{v}_2 \quad \text{check}(\iota_x; \iota; \iota_1; \iota_2) \Downarrow \dot{v}_2}$			

Figure 9: Big step semantics for λ_P

$$\boxed{\ell \mapsto \ell}$$

$\frac{\text{PS-E-CONCATLEFT} \quad \ell_1 \mapsto \ell'_1}{\text{concat}(\ell_1; \ell_2) \Downarrow \text{concat}(\ell'_1; \ell_2)}$	$\frac{\text{PS-E-CONCATRIGHT} \quad \ell_2 \mapsto \ell'_2}{\text{concat}(\ell_1; \ell_2) \Downarrow \text{concat}(\ell_1; \ell'_2)}$	$\frac{\text{PS-E-CONCAT}}{\text{concat}(\text{str}[s_1]; \text{str}[s_2]) \Downarrow \text{str}[s_1 s_2]}$
$\frac{\text{PS-E-CASELEFT} \quad \ell_1 \mapsto \ell'_1}{\text{strcase}(\ell_1; \ell_2; x, y. \ell_3) \mapsto \text{strcase}(\ell'_1; \ell_2; x, y. \ell_3)}$		$\frac{\text{PS-E-CASE-EPSILON}}{\text{strcase}(\epsilon; \ell_2; x, y. \ell_3) \mapsto \ell_2}$
$\frac{\text{PS-E-CASE}}{\text{strcase}(\text{str}[as]; \ell_2; x, y. \ell_3) \mapsto \text{str}[as]}$		$\frac{\text{PS-E-REPLACELLEFT} \quad \ell_1 \mapsto \ell'_1}{\text{replace}(\ell_1; \ell_2; \ell_3) \mapsto \text{replace}(\ell'_1; \ell_2; \ell_3)}$
$\frac{\text{PS-E-REPLACEMID} \quad \ell_2 \mapsto \ell'_2}{\text{replace}(\text{rx}[r]; \ell_2; \ell_3) \mapsto \text{replace}(\text{rx}[r]; \ell'_2; \ell_3)}$	$\frac{\text{PS-E-REPLACERIGHT} \quad \ell_3 \mapsto \ell'_3}{\text{replace}(\text{rx}[r]; \text{str}[s_2]; \ell_3) \mapsto \text{replace}(\text{rx}[r]; \text{str}[s_2]; \ell'_3)}$	
$\frac{\text{PS-E-REPLACE}}{\text{replace}(\text{rx}[r]; \text{str}[s_2]; \text{str}[s_3]) \mapsto \text{str}[\text{replace}(r; s_2; s_3)]}$		$\frac{\text{PS-E-CHECKLEFT} \quad \ell_x \mapsto \ell'_x}{\text{rcheck}[\ell_x](\ell; \ell_1; \ell_2) \mapsto \text{rcheck}[\ell'_x](\ell; \ell_1; \ell_2)}$
$\frac{\text{PS-E-CHECKRIGHT} \quad \ell \mapsto \ell'}{\text{rcheck}[\text{rx}[r]](\ell; \ell_1; \ell_2) \mapsto \text{rcheck}[\text{rx}[r]](\ell'; \ell_1; \ell_2)}$		$\frac{\text{PS-E-CHECK-OK} \quad s \in \mathcal{L}\{r\}}{\text{rcheck}[\text{rx}[r]](\text{str}[s]; \ell_1; \ell_2) \mapsto \ell_1}$
	$\frac{\text{PS-E-CHECK-NOTOK} \quad s \notin \mathcal{L}\{r\}}{\text{rcheck}[\text{rx}[r]](\text{str}[s]; \ell_1; \ell_2) \mapsto \ell_2}$	

Figure 10: Small step semantics for λ_P (extends L-E rules)

$$\boxed{\llbracket \sigma \rrbracket = \tau}$$

$$\frac{\text{TR-T-STRING}}{\llbracket \text{stringin}[r] \rrbracket = \text{string}}$$

$$\frac{\text{TR-T-ARROW} \quad \llbracket \sigma_1 \rrbracket = \tau_1 \quad \llbracket \sigma_2 \rrbracket = \tau_2}{\llbracket \sigma_1 \rightarrow \sigma_2 \rrbracket = \tau_1 \rightarrow \tau_2}$$

$$\boxed{\llbracket \Psi \rrbracket = \Theta}$$

$$\frac{\text{TR-T-CONTEXT-EMP}}{\llbracket \emptyset \rrbracket = \emptyset}$$

$$\frac{\text{TR-T-CONTEXT-EXT} \quad \llbracket \Psi \rrbracket = \Theta \quad \llbracket \sigma \rrbracket = \tau}{\llbracket \Psi, x : \sigma \rrbracket = \Theta, x : \tau}$$

$$\boxed{\llbracket e \rrbracket = \iota}$$

$$\frac{\text{TR-VAR}}{\llbracket x \rrbracket = x}$$

$$\frac{\text{TR-ABS} \quad \llbracket e \rrbracket = \iota}{\llbracket \lambda x. e \rrbracket = \lambda x. \iota}$$

$$\frac{\text{TR-APP} \quad \llbracket e_1 \rrbracket = \iota_1 \quad \llbracket e_2 \rrbracket = \iota_2}{\llbracket e_1(e_2) \rrbracket = \iota_1(\iota_2)}$$

$$\frac{\text{TR-CASE} \quad \llbracket e_1 \rrbracket = \iota_1 \quad \llbracket e_2 \rrbracket = \iota_2 \quad \llbracket e_3 \rrbracket = \iota_3}{\llbracket \text{rstrcase}(e_1; e_2; x, y. e_3) \rrbracket = \text{strcase}(\iota_1; \iota_2; x, y. \iota_3)}$$

$$\frac{\text{TR-STRING}}{\llbracket \text{rstr}[s] \rrbracket = \text{str}[s]}$$

$$\frac{\text{TR-CONCAT} \quad \llbracket e_1 \rrbracket = \iota_1 \quad \llbracket e_2 \rrbracket = \iota_2}{\llbracket \text{rconcat}(e_1; e_2) \rrbracket = \text{concat}(\iota_1; \iota_2)}$$

$$\frac{\text{TR-SUBST} \quad \llbracket e_1 \rrbracket = \iota_1 \quad \llbracket e_2 \rrbracket = \iota_2}{\llbracket \text{rreplace}[r](e_1; e_2) \rrbracket = \text{replace}(\text{rx}[r]; \iota_1; \iota_2)}$$

$$\frac{\text{TR-SAFECOERCE} \quad \llbracket e \rrbracket = \iota}{\llbracket \text{rcoerce}[r'](e) \rrbracket = \iota}$$

$$\frac{\text{TR-CHECK} \quad \llbracket e \rrbracket = \iota \quad \llbracket e_1 \rrbracket = \iota_1 \quad \llbracket e_2 \rrbracket = \iota_2}{\llbracket \text{rcheck}[r](e; x. e_1; e_2) \rrbracket = \text{check}(\text{rx}[r]; \iota; (\lambda x. \iota_1)(\iota); \iota_2)}$$

Figure 11: Translation from source terms (e) to target terms (ι).