RegexScalpel: Regular Expression Denial of Service (ReDoS) Defense by Localize-and-Fix

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Regular Expression Denial-of-Service

The Server Side

Validate the input email using a vulnerable regex:

`^[a-zA-Z0-9._]+@([a-zA-Z0-9]+.)+com$`

Enter your email:

The Client Side

Normal input :
abc@def.com

Respond immediately

Malicious input :
c@cccccccc...

Denial-of-Service

Regular Expression Denial-of-Service Defense

- Existing Solutions
  - **Regex engine substitution**

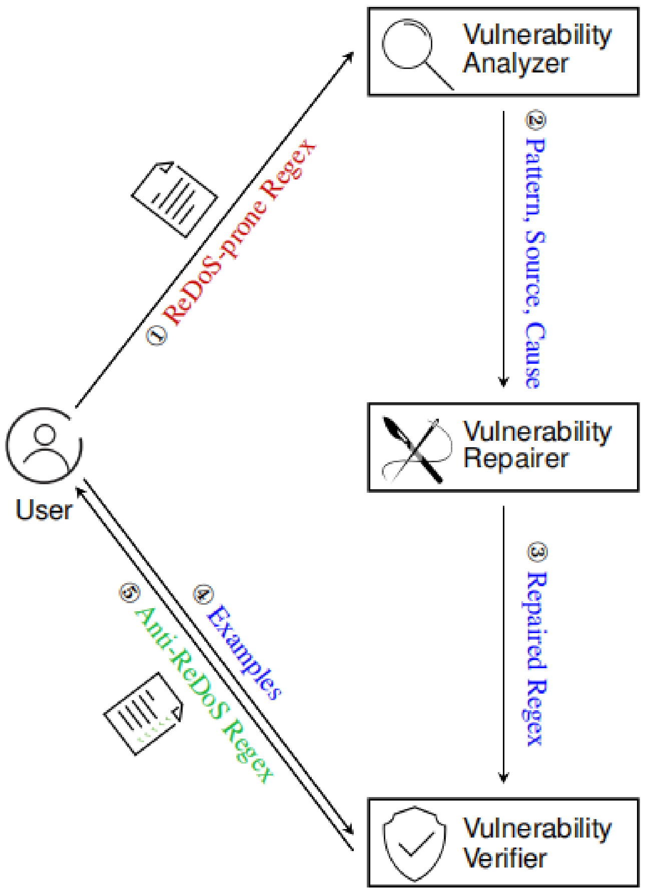
    Omitting extended features, consuming space, bringing semantic differences or incompatibilities.
  - **Input length restriction**

    Facing a dilemma known as "Goldilocks problem".
  - **Regex repair**
    - Repairing vulnerable regexes can greatly mitigate their vulnerabilities.
    - But it's challenging.

Table 13: The proportion of Maintainers' Defense Actions.

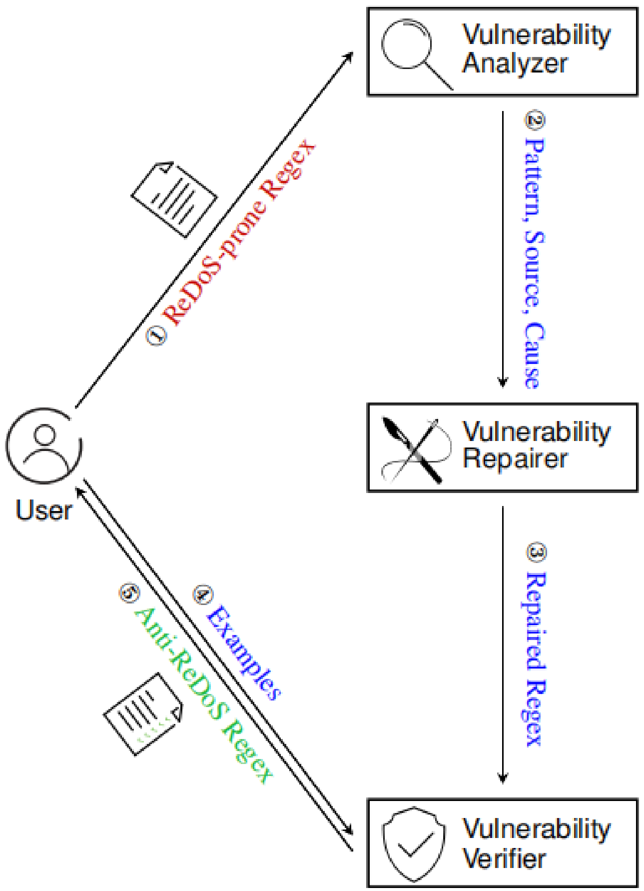
Defense Strategy	SOLA-DA	CVE	Total
Regex Engine Substitution	0 (0%)	1 (0.24%)	1 (0.22%)
Input Length Limit	1 (2.94%)	2 (0.48%)	3 (0.67%)
Code Logic Modification	6 (17.65%)	17 (4.11%)	23 (5.13%)
Regex Repair	**21 (61.76%)**	**392 (94.69%)**	**413 (92.19%)**
No Fix	6 (17.65%)	2 (0.48%)	8 (1.79%)
#Regex	34	414	448

Regular Expression Denial-of-Service Defense



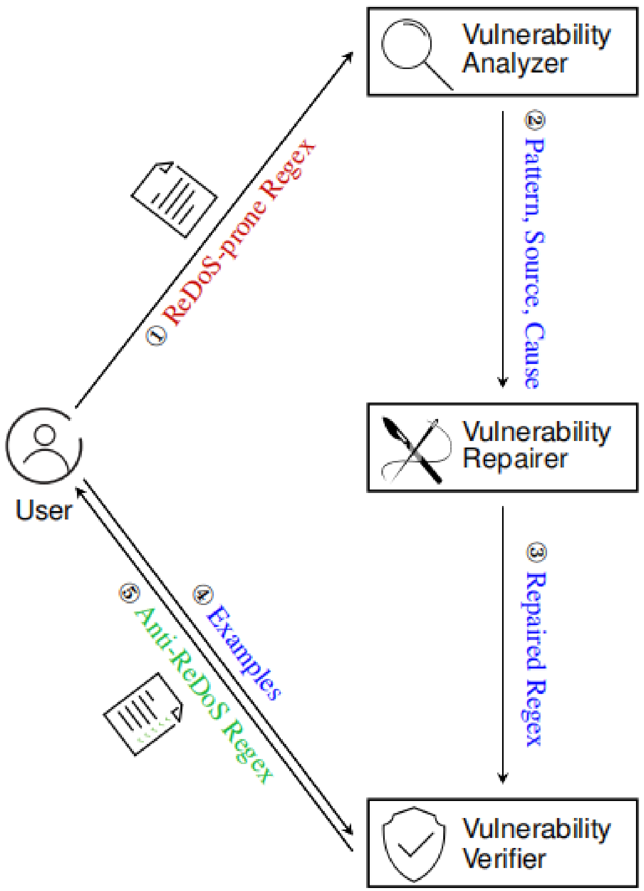
- Our Solution
  - We proposed RegexScalpel, a regex ReDoS vulnerability analysis and repair framework based on localize-and-fix.
  - RegexScalpel can preserve the semantics of the original regex, and the iterative repair method also keeps out vulnerabilities of the repaired regexes.

Regular Expression Denial-of-Service Defense



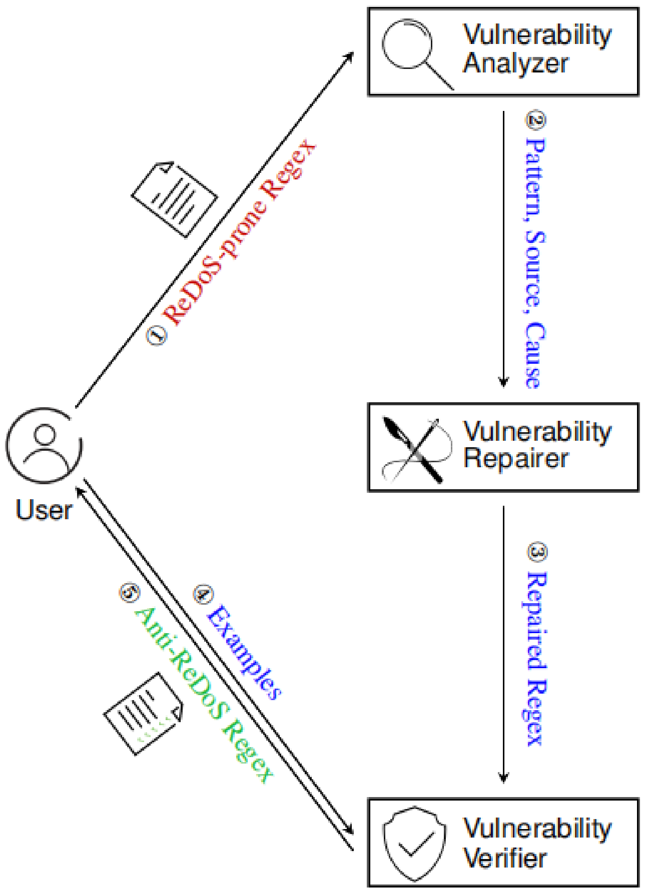
- Our Solution
  - RegexScalpel first leverages the **fine-grained vulnerability patterns** to localize the vulnerabilities and obtain the information for the repair.
  - The information includes their **vulnerable patterns**, **the source** (i.e., the pathological sub-regexes), and **the root causes** (e.g., the overlapping sub-regexes).

Regular Expression Denial-of-Service Defense



- Our Solution
  - RegexScalpel then fixes the pathological sub-regexes according to the **repair patterns** and the information.
  - The repair patterns use **micro-manipulations** (e.g., adding a lookaround, deleting a quantifier or sub-regex, modifying a quantifier or sub-regex) to remove the overlapping paths or reducing the maximum times of backtracking.

Regular Expression Denial-of-Service Defense



- Our Solution
  - RegexScalpel next determines whether the repaired regexes are ReDoS-invulnerable and whether it can pass all the given test cases.
  - If so, the repaired regex is called a successful one. If not, RegexScalpel continues the vulnerability analysis and repairs it.
  - RegexScalpel finally returns a repaired regex randomly chosen from the successful ones.

Vulnerable Patterns

Table 1: The Sub-pattern, Vulnerability Description, Example Regex, and Results from AnaNQ of the Pattern $\mathcal{NQ}$.

<table>
<tr><th>No.</th><th>Sub-pattern</th><th>Vulnerability Description</th><th>Example Regex</th><th>Returned Triple</th></tr>
<tr><td>#1</td><td>$\mathcal{N}Q_1$</td><td>$r = r_1\{m,n\}$, where $r_1 = r_p\{m_p,n_p\}$, $n_p > 1$, and $n > 1$</td><td>$\delta_1 =$ \[(\d+;)?(\d+)*m (CVE-2015-9239)</td><td>($\mathcal{N}Q_1$, (\d+)*, [+, *])</td></tr>
<tr><td>#2</td><td>$\mathcal{N}Q_2$</td><td>$r = (r_0r_1r_2)\{m,n\}$, where r_0 and r_2 are nullable, $r_1 = r_p\{m_p,n_p\}$, $n_p > 1$, and $n > 1$</td><td>$\delta_2 =$ ^(https?|ftp):\/\/(-\.)?([^\s\/?\.#]+\.?)+(\/[^\s]*)?[^\s\.,]$ (CVE-2021-26272)</td><td>($\mathcal{N}Q_2$, ([^\s\/?\.#]+\.?)+, [+, +])</td></tr>
<tr><td>#3</td><td>$\mathcal{N}Q_3$</td><td>$r = (r_0r_1r_2)\{m,n\}$, where r_0 and r_2 are nullable, $r_1 = (\ldots \mid r_p\{m_p,n_p\} \mid \ldots)$, $n_p > 1$, and $n > 1$</td><td>$\delta_3 =$ D[oD]?(\[[^\[\]]*\]|\s+)+MMMM? (moment)</td><td>($\mathcal{N}Q_3$, (\[[^\[\]]*\]|\s+)+, [+, +])</td></tr>
</table>

- Nested Quantifiers (NQ)
  - ➢ The NQ pattern is a regex with nested quantifiers.
  - ➢ In order to facilitate fixing the pathological regex, we subdivided NQ pattern into three sub-patterns (i.e., NQ1, NQ2 and NQ3).

Vulnerable Patterns

Table 2: The Sub-pattern, Vulnerability Description, Example Regex, and Results from AnaQOD of the Pattern $\mathcal{QOD}$.

<table>
<tr><th>No.</th><th>Sub-pattern</th><th>Vulnerability Description</th><th>Example Regex</th><th>Returned Triple</th></tr>
<tr><td>#1</td><td>$\mathcal{QOD}_1$</td><td>$r = \alpha\{m,n\}$, $\alpha = (r_1 \mid \ldots \mid r_k)$, and $\exists\ \mathcal{L}(\alpha_1) \cap \mathcal{L}(\alpha_2) \neq \emptyset$, where $\alpha_1 = r_{p_1} r_{p_2} \ldots r_{p_t}$, $\alpha_2 = r_{q_1} r_{q_2} \ldots r_{q_s}$, $1 \leq t, s \leq k$, $1 \leq i \leq t$, $1 \leq j \leq s$, $1 \leq p_i, q_j \leq k$, and $p_1 \neq q_1$</td><td>δ4 = <code>^(\d\.|\.\d|\d)+$</code> ([14])</td><td>($\mathcal{QOD}_1$, <code>(\d\.|\.\d|\d)+</code>, <code>[\d\.\d, \d\.\d]</code>)</td></tr>
<tr><td>#2</td><td>$\mathcal{QOD}_2$</td><td>$r = \alpha\{m,n\}$, $\alpha = (r_1 \mid \ldots \mid r_k)$, and $\exists\ \mathcal{L}(r_p) \cap \mathcal{L}(\alpha_1) \neq \emptyset$, $\mathcal{L}(r_l) \cap \mathcal{L}(r_p) = \emptyset$, where $\alpha_1 = r_{q_1} r_{q_2} \ldots r_{q_s}$, $1 \leq i \leq k$, $r_i = r_l r_p$, r_l is not nullable, $1 \leq s \leq k$, $1 \leq j \leq s$, $1 \leq q_j \leq k$</td><td>δ5=<code>(?:[\w-]|\$[-\w]+|#\{\$[-\w]+\})+(?=\s*:)</code> (CVE-2021-23341)</td><td>($\mathcal{QOD}_2$, <code>(?:[\w-]|\$[-\w]+|#\{\$[-\w]+\})+</code>, <code>[[\w-], \$[-\w]+]</code>)</td></tr>
</table>

- Quantified Overlapping Disjunction (QOD)
  - The QOD pattern is a quantified disjunction whose multiple inner sub-regexes overlap.
  - In order to facilitate fixing the pathological regex, we subdivided QOD pattern into two sub-patterns (i.e., QOD1 and QOD2).

Vulnerable Patterns

Table 3: The Sub-pattern, Vulnerability Description, Example Regex, and Results from AnaQOA of the Pattern $\mathcal{QOA}$.

<table>
<tr><th>No.</th><th>Sub-pattern</th><th>Vulnerability Description</th><th>Example Regex</th><th>Returned Triple</th></tr>
<tr><td>#1</td><td>$\mathcal{QOA}_1$</td><td>$r = (\ldots r_1 r_2 \ldots)\{m,n\}$, where $r_1 = r_p\{m_p,n_p\}$, $r_2 = r_q\{m_q,n_q\}$, $\mathcal{L}(r_1) \cap \mathcal{L}(r_2) \neq \emptyset$</td><td>$\delta_6$ = ^__[^\W_]+\w+__$ (pylint)</td><td>($\mathcal{QOA}_1$, [^\W_]+\w+, [[^\W_]+, \w+])</td></tr>
<tr><td>#2</td><td>$\mathcal{QOA}_2$</td><td>$r = (\ldots r_1 r_2 r_3 \ldots)\{m,n\}$, where $r_2 = r_t\{m_t,n_t\}$ is nullable, $r_1 = r_p\{m_p,n_p\}$, $r_3 = r_q\{m_q,n_q\}$, $\mathcal{L}(r_1) \cap \mathcal{L}(r_3) \neq \emptyset$</td><td>$\delta_7$ = ^(>=?|<=?)\s*(\d*\.?\d+)%$ (CVE-2021-23364)</td><td>($\mathcal{QOA}_2$, \d*\.?\d+, [\d*, \d+])</td></tr>
<tr><td>#3</td><td>$\mathcal{QOA}_3$</td><td>$r = (r_1 \ldots r_2)\{m,n\}$, where $r_1 = r_p\{m_p,n_p\}$, $r_2 = r_q\{m_q,n_q\}$, $n > 1$, $\mathcal{L}(r_1) \cap \mathcal{L}(r_2) \neq \emptyset$</td><td>$\delta_8$ = @([\w\-]+\.[\w\-:]+)+[:/]</td><td>($\mathcal{QOA}_3$, ([\w\-]+\.[\w\-:]+)+, [[\w\-]+, [\w\-:]+])</td></tr>
<tr><td>#4</td><td>$\mathcal{QOA}_4$</td><td>$r = (r_1 \ldots r_2 r_3)\{m,n\}$, where $r_3 = r_t\{m_t,n_t\}$ is nullable, $r_1 = r_p\{m_p,n_p\}$, $r_2 = r_q\{m_q,n_q\}$, $n > 1$, $\mathcal{L}(r_1) \cap \mathcal{L}(r_2) \neq \emptyset$</td><td>$\delta_9$ = ^([ab]+d[ac]+e?)+$</td><td>($\mathcal{QOA}_4$, ([ab]+d[ac]+e?)+, [[ab]+, [ac]+])</td></tr>
<tr><td>#5</td><td>$\mathcal{QOA}_5$</td><td>$r = (r_1 r_2 \ldots r_3)\{m,n\}$, where $r_1 = r_t\{m_t,n_t\}$ is nullable, $r_2 = r_p\{m_p,n_p\}$, $r_3 = r_q\{m_q,n_q\}$, $n > 1$, $\mathcal{L}(r_2) \cap \mathcal{L}(r_3) \neq \emptyset$</td><td>$\delta_{10}$ = ^(;(([\t]*[0-9a-zA-Z]+=[\x21-\x7E]*)*)[\t]*)?$</td><td>($\mathcal{QOA}_5$, ([\t]*[0-9a-zA-Z]+=[\x21-\x7E]*)*, [[0-9a-zA-Z]+, [\x21-\x7E]*])</td></tr>
</table>

- Quantified Overlapping Adjacent (QOA)
  - The QOA pattern is a quantified regex containing two adjacent overlapping sub-regexes.
  - In order to facilitate fixing the pathological regex, we subdivided QOA pattern into five sub-patterns (i.e., QOA1, QOA2, QOA3, QOA4, and QOA5).

Vulnerable Patterns

Table 4: The Sub-pattern, Vulnerability Description, Example Regex, and Results from AnaSLQ of the Pattern $\mathcal{SLQ}$.

No.	Sub-pattern	Vulnerability Description	Example Regex	Returned Triple
#1	$\mathcal{SLQ}_1$	Starting with $r = r_1$, where $r_1 = r_q\{m_q, n_q\}$, and $n_q > 1$	$\delta_{11} =$ `([A-Z]+)([A-Z][a-z])` (CVE-2021-3820)	($\mathcal{SLQ}_1$, `[A-Z]+`, `[A-Z]+`)
#2	$\mathcal{SLQ}_2$	Starting with $r = r_1 r_2$, where $r_1 = r_p\{m_p, n_p\}$ is nullable, $r_2 = r_q\{m_q, n_q\}$, and $n_q > 1$	$\delta_{12} =$ `\$?[A-Z]+` (PrismJS)	($\mathcal{SLQ}_2$, `\$?[A-Z]+`, `[A-Z]+`)
#3	$\mathcal{SLQ}_3$	Starting with $r = r_1 r_2$, where $r_1 = r_p\{m_p, n_p\}$ is not nullable, $r_2 = r_q\{m_q, n_q\}$, and $\mathcal{L}(r_1) \cap \mathcal{L}(r_2) \neq \emptyset$	$\delta_{13} =$ `{([\s\S]+?)}` (CVE-2021-3777)	($\mathcal{SLQ}_3$, `{([\s\S]+?)`, [{, `[\s\S]+`])
#4	$\mathcal{SLQ}_4$	Starting with $r = r_1 r_2$, where $r_1 = r_p\{m_p, n_p\}$ is not nullable, $r_2 = r_q\{m_q, n_q\}$, $r_q = r_{q_1} r_{q_2}$, r_{q_1} is not nullable, $r_{q_2} = r_t\{m_t, n_t\}$, and $\mathcal{L}(r_{q_2}) \cap \mathcal{L}(r_1) \neq \emptyset$	$\delta_{14} =$ `[ab](ca+)+d`	($\mathcal{SLQ}_4$, `[ab](ca+)+`, [`[ab]`, `a+`])
#5	$\mathcal{SLQ}_5$	Starting with $r = r_1 r_2$, where $r_1 = r_p\{m_p, n_p\}$ is not nullable, $r_2 = r_q\{m_q, n_q\}$, $r_q = r_{q_1} r_{q_2} r_{q_3}$, r_{q_1} and r_{q_3} are not nullable, $r_{q_2} = r_t\{m_t, n_t\}$, and $\mathcal{L}(r_{q_2}) \cap \mathcal{L}(r_1) \neq \emptyset$	$\delta_{15} =$ `[ab](ca{1,2}da)+e`	($\mathcal{SLQ}_5$, `[ab](ca{1,2}da)+`, [`[ab]`, `a{1,2}`])

- Starting with Large Quantifier (SLQ)
  - ➢ The SLQ pattern is a regex starting with a sub-regex with a large quantifier.
  - ➢ In order to facilitate fixing the pathological regex, we subdivided SLQ pattern into three sub-patterns (i.e., SLQ1, SLQ2, SLQ3, SLQ4, and SLQ5).

Repair Patterns

Table 5: The Repair Patterns for Nested Quantifiers ($\mathcal{NQ}$).

No.	Repair Pattern	
τ_1	$\dfrac{\mathcal{L}(r) = \mathcal{L}(r_p\{m_p \times m, n_p \times n\})}{r \Longrightarrow (r_p\{m_p \times m, n_p \times n\})\cancel{\{m,n\}}}$	$(\mathcal{N}Q_1)$
τ_2	$\dfrac{\mathcal{L}(r) = \mathcal{L}((r_0 r_p \cancel{\{m_p,n_p\}} r_2)\{m,n\})}{r \Longrightarrow (r_0 r_p \cancel{\{m_p,n_p\}} r_2)\{m,n\}}$	$(\mathcal{N}Q_2)$
τ_3	$\dfrac{\mathcal{L}(r) = \mathcal{L}((r_0(\ldots \mid r_p\cancel{\{m_p,n_p\}} \mid \ldots)r_2)\{m,n\})}{r_1 \Longrightarrow (\ldots \mid r_p\cancel{\{m_p,n_p\}} \mid \ldots)}$	$(\mathcal{N}Q_3)$

- Nested Quantifiers (NQ)
  - The NQ pattern has a redundant quantifier by nature. So to fix NQ pattern, we can remove the redundant quantifier.

Repair Patterns

Table 6: The Repair Patterns for Quantified Overlapping Disjunction ($\mathcal{QOD}$).

No.	Repair Pattern	No.	Repair Pattern	No.	Repair Pattern
τ_4	$\dfrac{\mathcal{L}(r)=\mathcal{L}((r_1\|\ldots\|r_q\|\ldots\|r_k)\{m,n\})}{\alpha \implies (r_1\|\ldots\|r_q\|\ldots\|r_k)}\ (\mathcal{QOD}_1)$	τ_5	$\dfrac{t>1}{r_{p_1} \implies r_{p_1}(?!\Phi(r_{p_2}))}\ (\mathcal{QOD}_1)$	τ_6	$\dfrac{s>1}{r_{q_1} \implies r_{q_1}(?!\Phi(r_{q_2}))}\ (\mathcal{QOD}_{\{1,2\}})$
τ_7	$\dfrac{}{r_{p_1} \implies (?!\Phi(\alpha_2))r_{p_1}}\ (\mathcal{QOD}_1)$	τ_8	$\dfrac{}{r_{q_1} \implies (?!\Phi(\alpha_1))r_{q_1}}\ (\mathcal{QOD}_1)$	τ_9	$\dfrac{\mathrm{scs}(\alpha_1)=true,\quad \Sigma_{\alpha_1}\setminus \mathrm{first}(r_{q_1})\neq\emptyset}{\alpha_1 \implies \Theta(\Sigma_{\alpha_1}\setminus \mathrm{first}(r_{q_1}))}\ (\mathcal{QOD}_1)$
τ_{10}	$\dfrac{\mathrm{scs}(\alpha_2)=true,\quad \Sigma_{\alpha_2}\setminus \mathrm{first}(r_{p_1})\neq\emptyset}{\alpha_2 \implies \Theta(\Sigma_{\alpha_2}\setminus \mathrm{first}(r_{p_1}))}\ (\mathcal{QOD}_1)$	τ_{11}	$\dfrac{}{r_p \implies r_p(?<!\Phi(\alpha_1))}\ (\mathcal{QOD}_2)$	τ_{12}	$\dfrac{}{r_{q_1} \implies (?!\Phi(r_p))r_{q_1}}\ (\mathcal{QOD}_2)$
τ_{13}	$\dfrac{\mathrm{scs}(\alpha_1)=true,\quad \Sigma_{\alpha_1}\setminus \mathrm{first}(r_p)\neq\emptyset}{\alpha_1 \implies \Theta(\Sigma_{r_{q_1}}\setminus \mathrm{first}(r_p))}\ (\mathcal{QOD}_2)$	τ_{14}	$\dfrac{r_p=r_u\{m_u,n_u\},\quad \mathrm{scs}(r_u)=true,\quad \Sigma_{r_u}\setminus \mathrm{first}(r_{q_1})\neq\emptyset}{r_p \implies \Theta(\Sigma_{r_u}\setminus \mathrm{first}(r_{q_1}))}\ (\mathcal{QOD}_2)$		

- Quantified Overlapping Disjunction (QOD)
  - ➢ The QOD pattern has multiple matching paths across the overlapping disjunctions for a string.
  - ➢ We proposed three strategies, namely, deleting one overlapping disjunction, adding a lookaround constraint to one overlapping disjunction, and modifying one overlapping disjunction by subtracting the first set of the other one.

Repair Patterns

Table 7: The Repair Patterns for Quantified Overlapping Adjacency ($\mathcal{QOA}$).

No.	Repair Pattern	No.	Repair Pattern	No.	Repair Pattern
τ_{15}	$\frac{\mathcal{L}(r_p)=\mathcal{L}(r_q)}{r_1 r_2 \implies r_p\{m_p+m_q, n_p+n_q\}}\ (\mathcal{QOA}_1)$	τ_{16}	$\frac{}{r_1 \implies r_1(?<!\Phi(r_q))}\ (\mathcal{QOA}_1)$	τ_{17}	$\frac{}{r_2 \implies (?!\Phi(r_p))r_2}\ (\mathcal{QOA}_1)$
τ_{18}	$\frac{n \leq 1}{n_p \implies n_\mu, n_q \implies n_\mu}\ (\mathcal{QOA}_{\{1,2\}})$	τ_{19}	$\frac{\mathrm{scs}(r_p)=true,\quad \Sigma_{r_p} \setminus \mathrm{first}(r_q) \neq \emptyset}{r_p \implies \Theta(\Sigma_{r_p} \setminus \mathrm{first}(r_q))}\ (\mathcal{QOA}_{\{1,3\}})$	τ_{20}	$\frac{\mathrm{scs}(r_q)=true,\quad \Sigma_{r_q} \setminus \mathrm{first}(r_p) \neq \emptyset}{r_q \implies \Theta(\Sigma_{r_q} \setminus \mathrm{first}(r_p))}\ (\mathcal{QOA}_{\{1,3\}})$
τ_{21}	$\frac{\mathrm{scs}(r_p)=true,\quad \Sigma_{r_p} \setminus \mathrm{first}(r_q) \neq \emptyset,\quad m_p \geq 1}{r_1 \implies r_p\{m_p-1, n_p-1\}\Theta(\Sigma_{r_p} \setminus \mathrm{first}(r_q))}\ (\mathcal{QOA}_1)$	τ_{22}	$\frac{\mathrm{scs}(r_q)=true,\quad \Sigma_{r_q} \setminus \mathrm{first}(r_p) \neq \emptyset,\quad m_q \geq 1}{r_2 \implies \Theta(\Sigma_{r_q} \setminus \mathrm{first}(r_p))r_q\{m_q-1, n_q-1\}}\ (\mathcal{QOA}_1)$	τ_{23}	$\frac{}{r_1 \implies (?!\Phi(r_q))r_1}\ (\mathcal{QOA}_3)$
τ_{24}	$\frac{}{r_2 \implies r_2(?<!\Phi(r_p))}\ (\mathcal{QOA}_3)$	τ_{25}	$\frac{\mathrm{scs}(r_p)=true,\quad \Sigma_{r_p} \setminus \mathrm{first}(r_q) \neq \emptyset,\quad m_p \geq 1}{r_1 \implies \Theta(\Sigma_{r_p} \setminus \mathrm{first}(r_q))r_p\{m_p-1, n_p-1\}}\ (\mathcal{QOA}_3)$	τ_{26}	$\frac{\mathrm{scs}(r_q)=true,\quad \Sigma_{r_q} \setminus \mathrm{first}(r_p) \neq \emptyset,\quad m_q \geq 1}{r_2 \implies r_q\{m_q-1, n_q-1\}\Theta(\Sigma_{r_q} \setminus \mathrm{first}(r_p))}\ (\mathcal{QOA}_3)$
τ_{27}	$\frac{m_t=0}{r \implies r_1 r_3 \mid r_1 r_t\{1,n_t\} r_3}\ (\mathcal{QOA}_2)$	τ_{28}	$\frac{m_t=0}{r_2 r_3 \implies r_2 \mid r_2 r_t\{1,n_t\}}\ (\mathcal{QOA}_4)$	τ_{29}	$\frac{m_t=0}{r_1 r_2 \implies r_2 \mid r_t\{1,n_t\} r_2}\ (\mathcal{QOA}_5)$

- Quantified Overlapping Adjacent (QOA)
  - The QOA pattern contains the corresponding two overlapping adjacencies.
  - We proposed three repair strategies, that is, merging the overlapping adjacencies, adding a lookaround constraint to one overlapping adjacency, and modifying one overlapping adjacency.

Repair Patterns

Table 8: The Repair Patterns for Starting with Large Quantifier ($\mathcal{SLQ}$).

No.	Repair Pattern	No.	Repair Pattern	No.	Repair Pattern
τ_{30}	$\dfrac{}{r \Longrightarrow \hat{}r}\ (\mathcal{SLQ}_{\{1,2,3,4,5\}})$	τ_{31}	$\dfrac{}{n_q \Longrightarrow n_\mu}\ (\mathcal{SLQ}_{\{1,2,3,4,5\}})$	τ_{32}	$\dfrac{m_p = 0}{r \Longrightarrow r_2 \mid r_p\{1,n_p\}r_2}\ (\mathcal{SLQ}_2)$
τ_{33}	$\dfrac{}{r_p \Longrightarrow (?!\Phi(r_q))r_p}\ (\mathcal{SLQ}_3)$	τ_{34}	$\dfrac{}{r_q \Longrightarrow (?!\Phi(r_p))r_q}\ (\mathcal{SLQ}_3)$	τ_{35}	$\dfrac{\mathrm{scs}(r_p) = true,\quad \Sigma_{r_p} \setminus \mathrm{first}(r_q) \neq \emptyset}{r_p \Longrightarrow \Theta(\Sigma_{r_p} \setminus \mathrm{first}(r_q))}\ (\mathcal{SLQ}_3)$
τ_{36}	$\dfrac{\mathrm{scs}(r_q) = true,\quad \Sigma_{r_q} \setminus \mathrm{first}(r_p) \neq \emptyset}{r_q \Longrightarrow \Theta(\Sigma_{r_q} \setminus \mathrm{first}(r_p))}\ (\mathcal{SLQ}_3)$	τ_{37}	$\dfrac{}{r_p \Longrightarrow r_p(?<!\Phi(r_t))}\ (\mathcal{SLQ}_{\{4,5\}})$	τ_{48}	$\dfrac{}{r_t \Longrightarrow (?!\Phi(r_p))r_t}\ (\mathcal{SLQ}_{\{4,5\}})$
τ_{39}	$\dfrac{\mathrm{scs}(r_p) = true,\quad \Sigma_{r_p} \setminus \mathrm{first}(r_t) \neq \emptyset}{r_p \Longrightarrow \Theta(\Sigma_{r_p} \setminus \mathrm{first}(r_t))}\ (\mathcal{SLQ}_{\{4,5\}})$	τ_{40}	$\dfrac{\mathrm{scs}(r_t) = true,\quad \Sigma_{r_t} \setminus \mathrm{first}(r_p) \neq \emptyset}{r_t \Longrightarrow \Theta(\Sigma_{r_t} \setminus \mathrm{first}(r_p))}\ (\mathcal{SLQ}_{\{4,5\}})$		

- Starting with Large Quantifier (SLQ)
  - ➢ The SLQ pattern contains the sub-regex starting with a large quantifier (for SLQ1 and SLQ2) or the overlapping sub-regexes (for SLQ3, SLQ4 and SLQ5).
  - ➢ We proposed four strategies, namely, adding a start-of-line anchor, replacing the large quantifier with a small one, adding a lookaround to one sub-regex, and modifying one sub-regex by subtracting the first set of the other one.

Case Exhibition

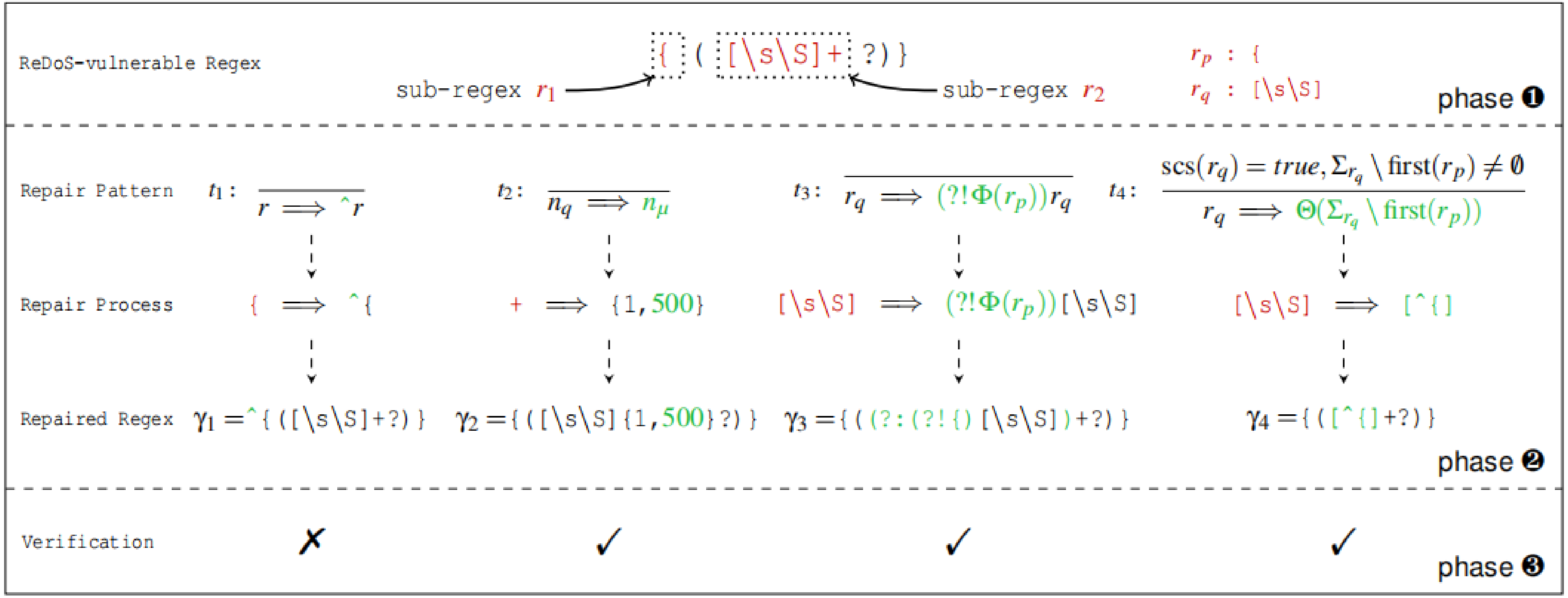


Figure 2: An Example for Repairing the ReDoS-vulnerable Regex {([\s\S]+?)}.

- The NPM package nodejs-tmpl (6,858,130 weekly downloads) used this regex, which aims to match the simple string formatting using {}.

Experiment Setup

- Evaluation Datasets
  - ➢ Our evaluation was conducted on the ReDoS-vulnerable regexes collected from two widely-used sources: (i) the SOLA-DA benchmark and (ii) real-world CVEs.

Table 9: The ReDoS-vulnerable Regex Sets for Evaluation.

Benchmark	#Regex	Description
SOLA-DA [34]	34	ReDoS-vulnerable regexes in NPM modules found by the Software Lab at TU Darmstadt
CVE [9]	414	ReDoS-vulnerable regexes extracted from 70 ReDoS-related CVEs in recent three years
Total	448	

Experiment Setup

- Evaluation Approaches
  - We selected three state-of-the-art tools belonging to three paradigms, i.e., regex engine substitution (RE2), input length restriction (LLI), and regex repair (FlashRegex).

- Evaluation Metrics
  - A defense is considered successful if it (i) passes all the given test cases, and (ii) is free from ReDoS attack.
  - The success defense rate is calculated by dividing the number of successful defenses by the total number of vulnerable regexes under defense.

Comparing State-of-the-art tools

Table 10: Success Defense Rate Across Automated Tools.

Tool	SOLA-DA	CVE	Total
RE2	18 (52.94%)	35 (8.45%)	53 (11.83%)
LLI(100)	22 (64.71%)	45 (10.87%)	67 (14.96%)
LLI(500)	26 (76.47%)	18 (4.35%)	44 (9.82%)
LLI(5000)	26 (76.47%)	19 (4.59%)	45 (10.04%)
FlashRegex	4 (11.76%)	91 (21.98%)	95 (21.20%)
RegexScalpel	**33 (97.06%)**	**410 (99.03%)**	**443 (98.88%)**
#Regex	34	414	448

Regex engine substitution

Input length restriction

Input length restriction

Our method

- RegexScalpel can effectively defend 98.88% of vulnerable regexes, compared with 21.20% achieved by the best work.

Comparing Maintainers' Repairs

Table 14: Success Defense Rate of the Repairs by Maintainers and RegexScalpel.

	SOLA-DA	CVE	Total
Manual Repair	14 (66.67%)	305 (77.81%)	319 (77.23%)
RegexScalpel	**21 (100%)**	**388 (98.98%)**	**409 (99.03%)**
#Regex	21	392	413

Input length restriction

Our method

- Among the repaired vulnerable regexes handcrafted by the maintainers, only 77.23% are ReDoS free. RegexScalpel outperforms manual fixing, and successfully repairs 99.03% of regexes.

Usefulness to Maintainers

Table 17: Demographics of New Vulnerabilities Repaired by RegexScalpel.

No.	Project	Disclosure Date	CVE ID	#Vuln. Regex
#1	Python	Jan 30th, 2021	CVE-2021-3733	1
#2	NLTK	Sep 5th, 2020	–	1
#3	pylint	Sep 3rd, 2020	–	2
#4	mpmath	Oct 8th, 2021	CVE-2021-29063	1
#5	browserslist	Apr 28th, 2021	CVE-2021-23364	6
#6	code-server	Sep 17th, 2021	CVE-2021-3810	1
#7	ansi-regex	Sep 12th, 2021	CVE-2021-3807	1
#8	nth-check	Sep 17th, 2021	CVE-2021-3803	1
#9	nodejs-tmpl	Sep 15, 2021	CVE-2021-3777	1
#10	jspdf	Feb 12th, 2021	CVE-2021-23353	1
			Total	16

- RegexScalpel detected and repaired 16 new ReDoS regexes in ten popular projects.
- All the 16 repairs were accepted by the maintainers and merged into subsequent project releases, resulting in 8 confirmed CVEs.

Semantics Preservation

- We used the following equation to calculate the semantic similarities between the repaired regexes and the original ones.

$$Sim(r_1, r_2) = \frac{|\mathcal{L}(r_1) \cap \mathcal{L}(r_2)|}{|\mathcal{L}(r_1) \cup \mathcal{L}(r_2)|}$$

$$Sim(r_1, r_2) = \lim_{\lambda \to +\infty} \frac{|\mathcal{L}(r_1)^{\leq \lambda} \cap \mathcal{L}(r_2)^{\leq \lambda}|}{|\mathcal{L}(r_1)^{\leq \lambda} \cup \mathcal{L}(r_2)^{\leq \lambda}|}$$

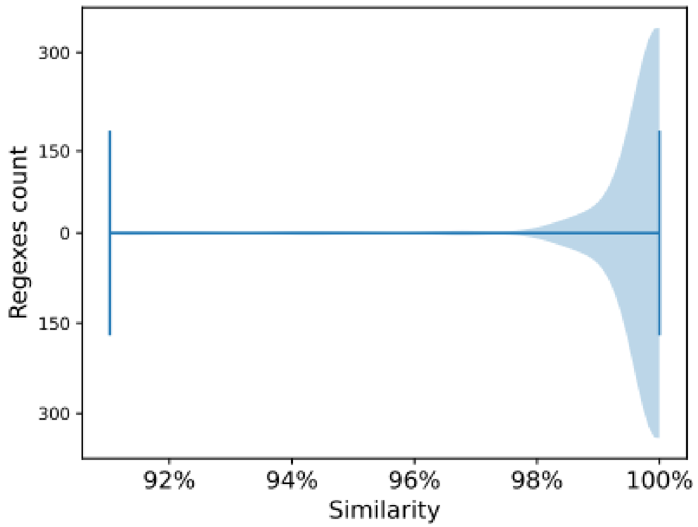


Figure 3: Semantic similarities between the vulnerable regexes and the repaired ones.

- For the benchmarks, most similarities go beyond 98%. On average, the semantic similarity is 99.57%, meaning that the semantics of regexes are well-preserved after the repair.

Summary

- We proposed RegexScalpel, which can defend ReDoS attacks by automatically localizing and repairing vulnerable regexes.
- The evaluation exhibits the remarkable effectiveness of RegexScalpel. It achieves 98.88% successful repair ratio, compared with 21.20% achieved by the best existing work.
- RegexScalpel helped to repair 16 ReDoS vulnerabilities in the ten real-world projects and got confirmed by the maintainers, resulting in 8 confirmed CVEs.
- RegexScalpel can synthesize repaired regexes preserving the semantics of the original ones and keeping the semantics as close as possible to the original ones.

THANKS

Q&A

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