

V-Star: Learning Visibly Pushdown Grammars from Program Inputs

Xiaodong Jia and **Gang Tan**

Penn State University

PLDI 2024

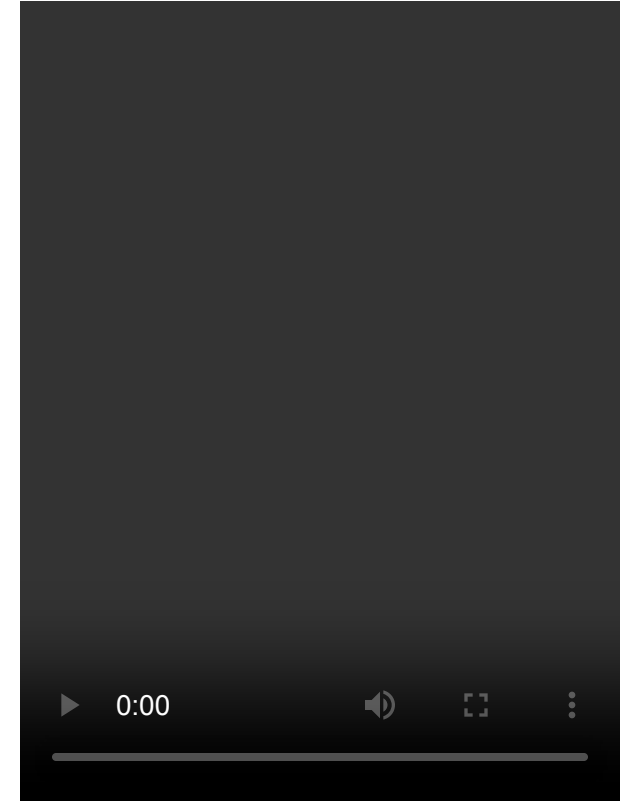
Overview

- Background
- Key Contributions of V-Star
- Evaluation
- Future Work

Program Input Learning

Infer formal grammars of inputs from **black-box programs** and **sample valid inputs**.

- **Oracle:** The black-box program
 - A calculator
 - JSON/XML parser binaries
 - Web server that accepts HTTP requests
- **Seed Strings:** Given valid inputs

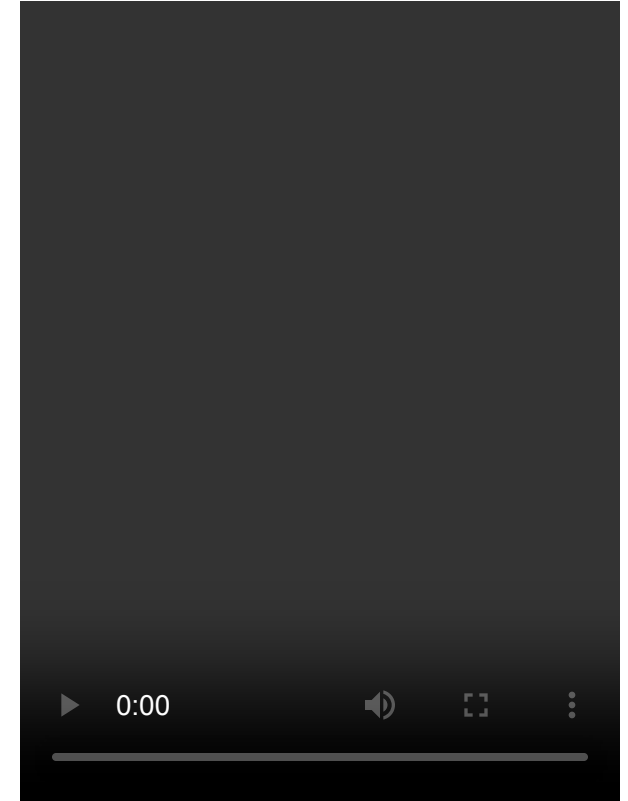


Importance

- Widely applicable
- Improves security and robustness

Application

- Grammar-based fuzzing
- Program validation
- Program comprehension
- Reverse engineering



Related Work

- **Existing Tools**

- Glade (PLDI '17)
- Arvada (ASE '22)
- Learn context-free grammars

- **Limitations:**

- Limited accuracy for many practical grammars
- Do not fully utilize the *nesting structures* in program inputs

V-Star (PLDI '24)

- **Observation:** Using nesting structures can significantly increase model accuracy.
- **Approach:** Exploits *nesting structures* in program inputs to improve accuracy.

Nesting Structures

```
Program input : <p>      Hello      </p>      World!  
Tokenization  : OPEN_TAG  TEXT       CLOSE_TAG  TEXT
```

Recursion is delimited by special paired symbols, namely *call symbols* and *return symbols*.

Recursion

```
XML -> OPEN_TAG XML CLOSE_TAG XML | TEXT | ε  
      ↑           ↑  
      Call       Return
```

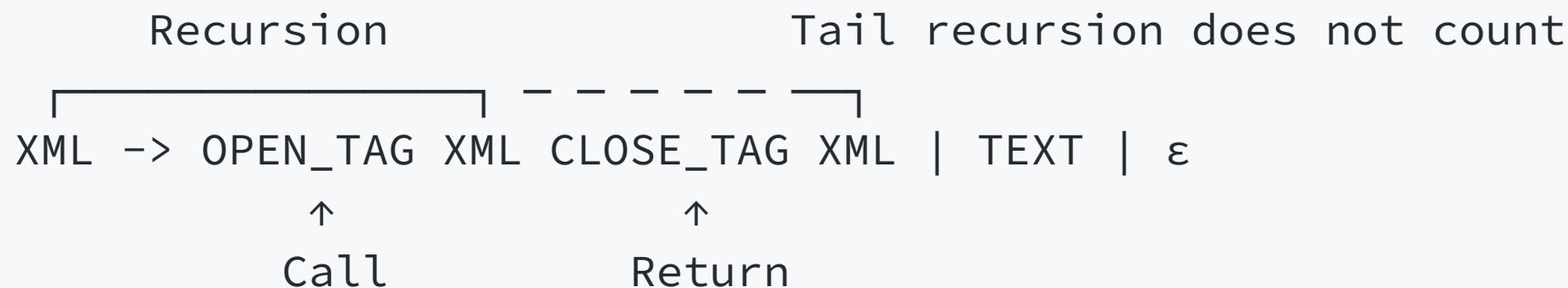
Nesting Structures

```
Program input : <p>      Hello      </p>      World!  
Tokenization  : OPEN_TAG  TEXT      CLOSE_TAG  TEXT
```

Recursion is delimited by special paired symbols, namely *call symbols* and *return symbols*.

```
      Recursion      Tail recursion does not count  
┌───────────┐ ┌───────────┐  
XML -> OPEN_TAG XML CLOSE_TAG XML | TEXT | ε  
      ↑           ↑  
    Call       Return
```

Nesting Structures



Visibly Pushdown Grammars (VPGs) =
Regular Grammars + Nesting Structures

$$L \rightarrow \epsilon$$

$$L \rightarrow cA$$

$$L \rightarrow aAbB$$

Regular Grammar

Models Nesting Structures

Denote Sentences of VPGs

- Sentences in VPGs are normal strings with explicitly denoted call and return symbols, known as *tagging*.

```
<p> Hello </p> World!
```

- **V-Star** learns which substrings need to be colorized, also known as the *tagging function* for program inputs.

From Program Input Learning to Active Learning

- **Oracle:** Answers *membership queries*

$$\mathcal{O} : \text{string } s \mapsto \{\text{true}, \text{false}\}$$

- **Challenges:** With finite queries, exact learning is not guaranteed.
- **Minimally Adequate Teacher (MAT):** Answers *equivalence queries*

$$\mathcal{E} : \text{grammar } G \mapsto \{\text{exact } \text{🎉}, \text{counterexample string } s\}$$

- **Active Learning:** learn grammar from a MAT.

Exact Learning: Achievable?

	Regular	VPG	CFG
Positive Examples	Impossible		
Positive + Negative	NP-complete		
Membership Queries	Very Likely NP		
MQ + Seed Strings	Very Likely NP	(V-Star)	(Glade & Arvada)
MAT (MQ + EQ)	Polynomial (Angluin's L^*)	Polynomial	Very Likely NP

V-Star's Contribution

- Learns how to model program inputs as VPGs.
- Learns VPGs using active learning methods.

V-Star Workflow

1. Identify Call and Return Symbols:

- Use oracle and seed strings to infer nesting structures.
- Develop a *tagging function* to recognize call and return symbols.

2. Learn VPA and Convert to VPG:

- Use an L*-like algorithm to learn a Visibly Pushdown Automaton (VPA).
- Convert the VPA into a Visibly Pushdown Grammar (VPG).

V-Star Example: Arithmetic Formula

Seed String:

$(1 + (2 \times 3) / 4)$

What are the Call and Return Symbols?

- Hypothesize recursion as:

$\text{expr} \rightarrow "(" \text{expr} ")" \text{expr} \mid \text{number} \mid \dots$

- Therefore, `(` and `)` are the call and return symbols.

`(1+ (2×3) /4)`

V-Star Example: Arithmetic Formula

Seed String (Encrypted):

□▼●□▼●▼△●▼△

What are the Call and Return Symbols?

- **Nesting Patterns:** Two substrings (x, y) that can be repeated at the same time, and must be repeated at the same time.

□▼●□▼●▼△●▼△

□▼●□□▼●▼△△●▼△

□▼●□□□▼●▼△△△●▼△

...

□▼● (□)^k ▼●▼ (△)^k ●▼△

V-Star Example: Arithmetic Formula

- From valid strings $\square \blacktriangledown \bullet \left(\square \right)^k \blacktriangledown \bullet \blacktriangledown \left(\triangle \right)^k \bullet \blacktriangledown \triangle$, the nesting pattern is $(u, x, z, y, v) = (\square \blacktriangledown \bullet, \square, \blacktriangledown \bullet \blacktriangledown, \triangle, \bullet \blacktriangledown \triangle)$, or simply

$$(x, y) = (\square, \triangle)$$

- Lemma (V-Star):** each nesting pattern (x, y) must contain a call symbol in x , and a return symbol in y .
- Therefore, \square and \triangle are the call and return symbols.

$\square \blacktriangledown \bullet \square \blacktriangledown \bullet \blacktriangledown \triangle \bullet \blacktriangledown \triangle$

- The tagging function:** For any program input, tags \square as call, and \triangle as return symbols.

$\square \blacktriangledown \bullet \blacktriangledown \bullet \blacktriangledown \triangle \bullet \blacktriangledown, \square \blacktriangledown \bullet \blacktriangledown, \dots$

Learn Finite State Automata and Visibly Pushdown Automata

Input	
1	
1×	
1×1	
1×1×1	
1×1×1×1	

- Conjecture: regular expression $(1\times)^* 1$ specifies valid inputs.
- You have learned a formal grammar 🎉

Learn Finite State Automata and Visibly Pushdown Automata

- Learn regular expression
 - Regular expression is equivalent to Finite State Automata (FSA).
- \rightarrow Learn FSA
 - Each state in the automata is an equivalence class.
- \rightarrow Learn Equivalence Classes
 - \rightarrow Angluin's L^* (1987): There is a table-based method!

Learn Finite State Automata and Visibly Pushdown Automata

Fill the Prefix-Suffix Table

Prefix	Suffix		
	ϵ	1	\times 1
ϵ	ϵ	1	\times 1
1	1	11	1 \times 1
1 \times	1 \times	1 \times 1	1 \times \times 1
1 \times 1	1 \times 1	1 \times 11	1 \times 1 \times 1
1 \times 1 \times 1	1 \times 1 \times 1	1 \times 1 \times 11	1 \times 1 \times 1 \times 1

Learn Finite State Automata and Visibly Pushdown Automata

Fill the Prefix-Suffix Table

Prefix	Suffix		
	ϵ	1	$\times 1$
ϵ			
1			
1 \times			
1 \times 1			
1 \times 1 \times 1			

- Each color sequence represents an equivalence class.

Learn Finite State Automata and Visibly Pushdown Automata

Fill the Prefix-Suffix Table

Prefix	Suffix		
	ϵ	1	$\times 1$
ϵ			
1			
1 \times			
1 \times 1			
1 \times 1 \times 1			

- ϵ is equivalent to 1 \times .

Learn Finite State Automata and Visibly Pushdown Automata

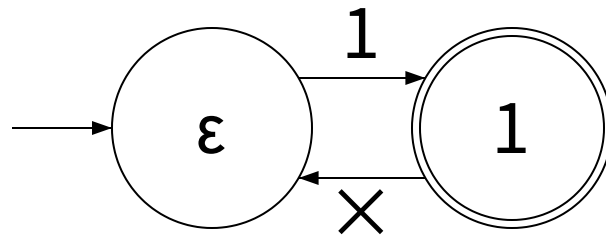
Fill the Prefix-Suffix Table

Prefix	Suffix		
	ϵ	1	$\times 1$
ϵ			
1			
1 \times			
1 \times 1			
1 \times 1 \times 1			

- 1 is equivalent to 1 \times 1 and 1 \times 1 \times 1 .

Build an FSA

- The equivalence classes can be convert to an FSA directly.



- The FSA above is equivalent to regular expression $(1X)^*1$.

Learn Finite State Automata and Visibly Pushdown Automata

Doesn't work for VPG

Prefix	Suffix					
	ϵ	$\times 1)$	$\times 1)\times 1)$	\dots	$\times 1)\dots\times 1)$	\dots
ϵ	ϵ	$\times 1)$	$\times 1)\times 1)$	\dots	$\times 1)\times 1)\times 1)$	\dots
$(1$	$(1$	(1×1)	$(1\times 1)\times 1)$	\dots	$(1\times 1)\times 1)\times 1)$	\dots
$((1$	$((1$	$((1\times 1)$	$((1\times 1)\times 1)$	\dots	$((1\times 1)\times 1)\times 1)$	\dots
\dots	\dots	\dots	\dots	\dots	\dots	\dots
$(\dots(1$	$((((1$	$((((1\times 1)$	$((((1\times 1)\times 1)$	\dots	$(\dots(1\times 1)\dots\times 1)$	\dots
\dots	\dots	\dots	\dots	\dots	\dots	\dots

- Infinite number of equivalence classes.

Learn Finite State Automata and Visibly Pushdown Automata

Infix	Left Context, Right Context		
	ϵ, ϵ	$\epsilon, \times 1$	$(, \times 1)$
ϵ	ϵ	$\times 1$	$(\times 1)$
1	1	1 \times 1	(1 \times 1)
1 \times	1 \times	1 $\times \times$ 1	(1 $\times \times$ 1)
(1 \times 1)	(1 \times 1)	(1 \times 1) \times 1	((1 \times 1) \times 1)

- Each infix must be well-matched.
- The number of equivalence classes becomes finite.

More Info in the Paper

- **Hierarchy:**
 - Regular Grammar < VPGs < CFGs
- **Formal Definition of VPGs and VPA**
- **Conversions and Learning:**
 - From Finite State Automata (FSA) to Visibly Pushdown Automata (VPA)
 - How to identify nesting structures using nesting patterns
 - How to learn Visibly Pushdown Automata (VPA)
- **Partial Tokenizer:**
 - What is it?
 - How does it help?

- **Evaluation Methodology**

- Replicated the artifact of Arvada (ASE '22).
- Includes oracle grammars, evaluation datasets, and seed strings.

- **Selected Grammars**

- Five Grammars: JSON, LISP, XML, While, MathExpr
- Chosen because they are VPGs

Evaluation: Accuracy

- **Recall** $\frac{|L \cap L_{\mathcal{O}}|}{|L|}$: Probability that a string of the oracle is accepted by the learned grammar G .
- **Precision** $\frac{|L \cap L_{\mathcal{O}}|}{|L_{\mathcal{O}}|}$: Probability that a string in G is accepted by the oracle.
- **F-1 Score** $\frac{2}{1/\text{recall} + 1/\text{prec}}$: Harmonic mean of precision and recall, indicating overall accuracy.

Grammar	GLADE			Arvada			V-Star		
	Recall	Prec	F-1	Recall	Prec	F-1	Recall	Prec	F-1
JSON	0.42	0.98	0.59	0.97 \pm 0.09	0.92 \pm 0.08	0.94 \pm 0.05	1.00	1.00	1.00
Lisp	0.23	1.00	0.38	0.38 \pm 0.26	0.95 \pm 0.08	0.50 \pm 0.18	1.00	1.00	1.00
XML	0.26	1.00	0.42	0.99 \pm 0.02	1.00 \pm 0.00	1.00 \pm 0.01	1.00	1.00	1.00
While	0.01	1.00	0.02	0.91 \pm 0.20	1.00 \pm 0.00	0.94 \pm 0.14	1.00	1.00	1.00
MathExpr	0.18	0.98	0.31	0.72 \pm 0.24	0.96 \pm 0.03	0.80 \pm 0.16	1.00	1.00	1.00

Evaluation: Efficiency

- **#Queries:** The number of unique membership queries made during the learning process.
- **Time:** The overall running time for each tool.
- **#Seeds:** The number of seed strings (i.e., valid strings) shared by all tools.

Grammar	#Seeds	GLADE		Arvada		V-Star	
		#Queries	Time	#Queries	Time	#Queries	Time
JSON	71	11 K	21 s	$6.8 \text{ K} \pm 394$	$25 \text{ s} \pm 2 \text{ s}$	541 K	33 min
Lisp	26	3.8 K	7 s	$2.2 \text{ K} \pm 307$	$8 \text{ s} \pm 2 \text{ s}$	16 K	77 s
XML	62	15 K	21 s	$12 \text{ K} \pm 1 \text{ K}$	$61 \text{ s} \pm 5 \text{ s}$	208 K	16 min
While	10	9.2 K	13 s	$5.4 \text{ K} \pm 563$	$15 \text{ s} \pm 1 \text{ s}$	1440 K	1.5 h
MathExpr	40	19 K	42 s	$6.6 \text{ K} \pm 421$	$24 \text{ s} \pm 2 \text{ s}$	4738 K	6 h

Evaluation: More Statistics of V-Star

- **%Queries(Token)**: Percentage of membership queries made for token inference.
- **%Queries(VPA)**: Percentage of membership queries made for VPA learning.
- **#TestString**: The number of test strings sampled from the seed strings by V-Star.

Grammar	#Queries	%Q(Token)	%Q(VPA)	#TestString	Time
JSON	541 K	2.71%	97.29%	8043	33 min
Lisp	16 K	1.37%	98.63%	693	77 s
XML	208 K	94.93%	5.07%	682	16 min
While	1440 K	9.40%	90.60%	119	1.5 h
MathExpr	4738 K	0.11%	99.89%	2602	6 h

Most time is spent on VPA learning, not token inference, as short seed strings lead to shorter nesting patterns and a smaller search space.

Conclusion and Future Work

- **Conclusion:** V-Star is more accurate compared to other tools but requires more time due to VPA learning.
- **Future Work:**
 - **Performance:** Improve V-Star's efficiency to reduce VPA learning time.
 - **Evaluation:** Test V-Star on more practical grammars.
 - **Alternative Algorithms:** Explore other VPA learning methods.
 - **Readability:** Enhance the readability of the learned grammar.
 - **CFG Learning:** Use V-Star as a starting point for learning Context-Free Grammars.