Synthesizing Program Input Grammars

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Rahul Sharma (Microsoft Research)
Alex Aiken (Stanford)
Percy Liang (Stanford)

Program Input Grammars

```
int main(int argc, char **argv) {
  char *keys;
  size_t keycc, oldcc, keyalloc;
  bool with_filenames;
  size_t cc;
  int opt, prepended;
  int prev_optind, last_recursive;
  int fread_errno;
  intmax_t default_context;
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  exit_failure = EXIT_TROUBLE;
  initialize_main (&argc, &argv);
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  // ...
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$$A_{\mathrm{XML}} \rightarrow A^*_{\mathrm{XML}}$$

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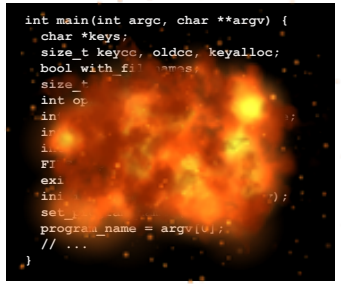
Applications

Applications

Fuzz testing

- Security vulnerabilities
- Differential testing

```
<a>hihi</a>
<a><a></a></a>
<a></a>
...
```



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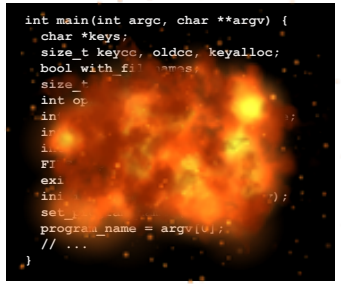
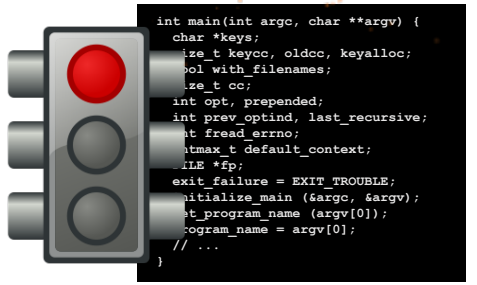


Whitelisting inputs

aa>hi



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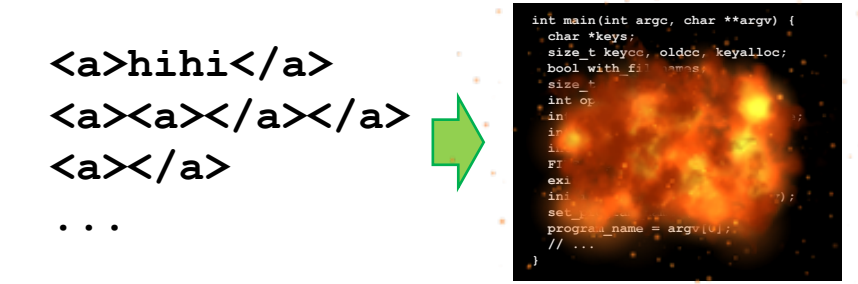

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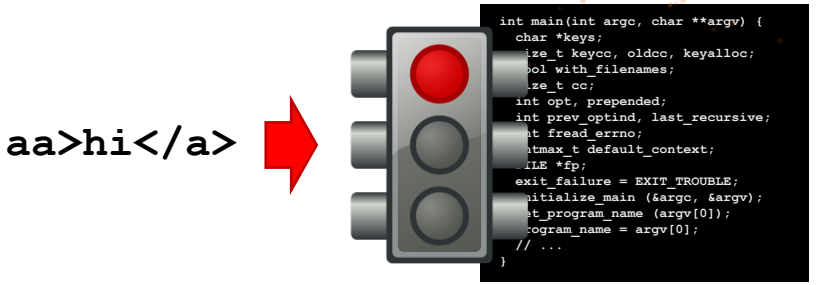

Reverse engineering

Program Input Grammars

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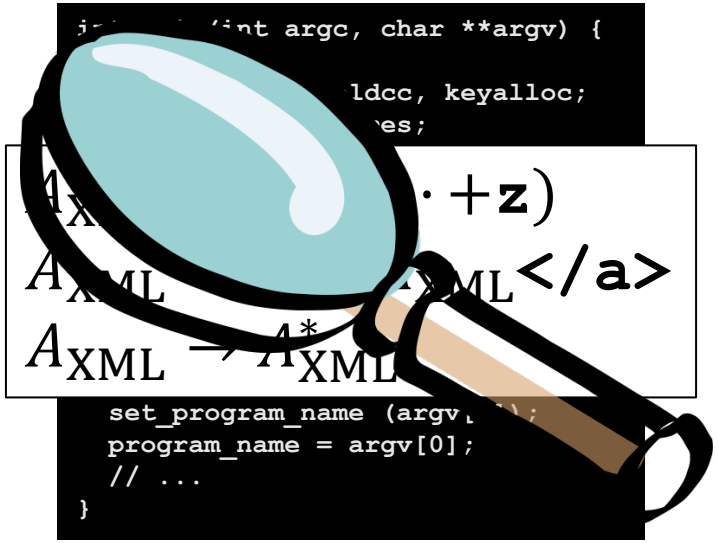
Program Input Grammars



Grammar Synthesis Algorithm

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$\alpha_{\text{in}} =$ `<a>hi</a>`

input example

Grammar Synthesis Algorithm

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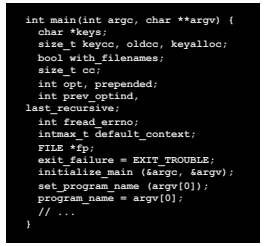

input example &
blackbox access to program

Grammar Synthesis Algorithm

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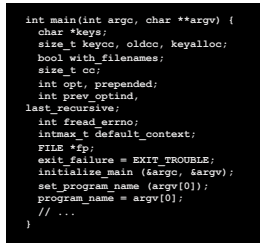
α 

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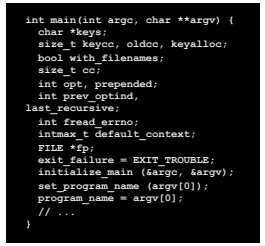
α 

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```

$\alpha \notin L_{\text{XML}}$

input example &
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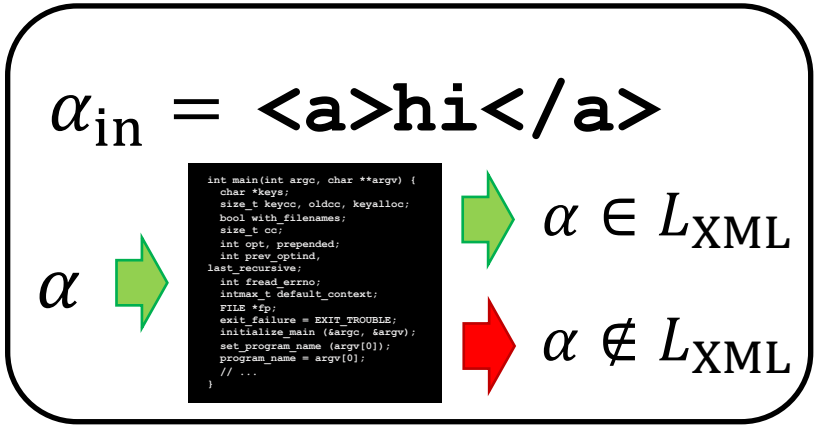
Grammar Synthesis Algorithm



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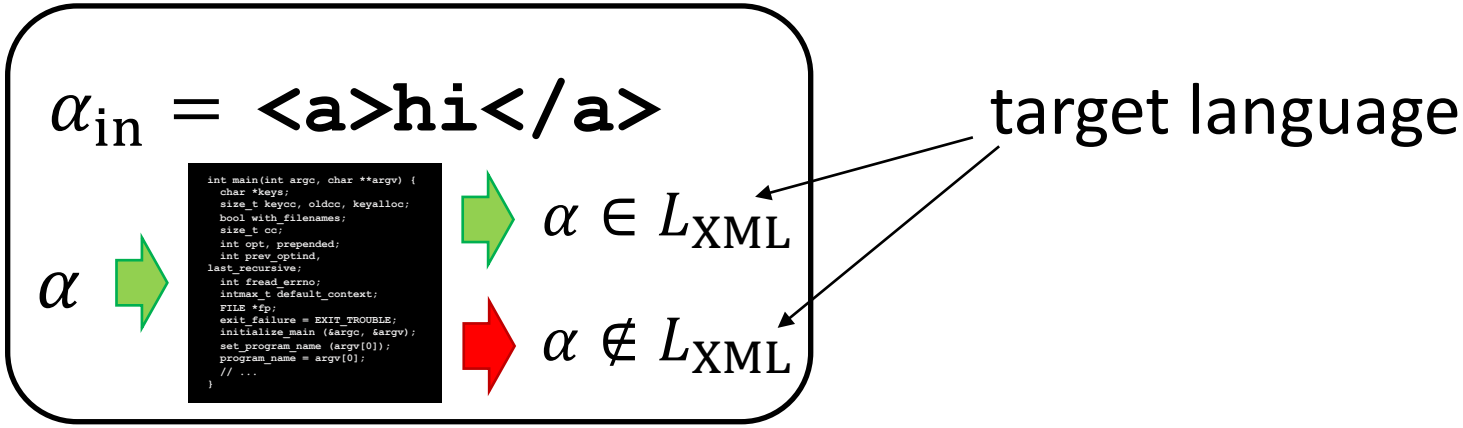

input example &
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Grammar Synthesis Algorithm

$\alpha_{\text{in}} =$ `<a>hi</a>`

$$\mathcal{O}_{\text{XML}}(\alpha) = \begin{cases} 1 & \text{if } \alpha \in L_{\text{XML}} \\ 0 & \text{otherwise} \end{cases}$$

input example &
membership oracle

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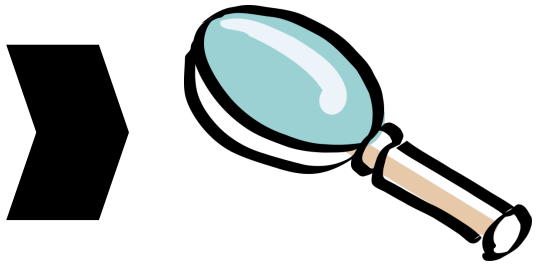

grammar synthesis
algorithm

Grammar Synthesis Algorithm

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grammar synthesis
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grammar approximating
the target language

Idea: Construct a series of increasingly general languages

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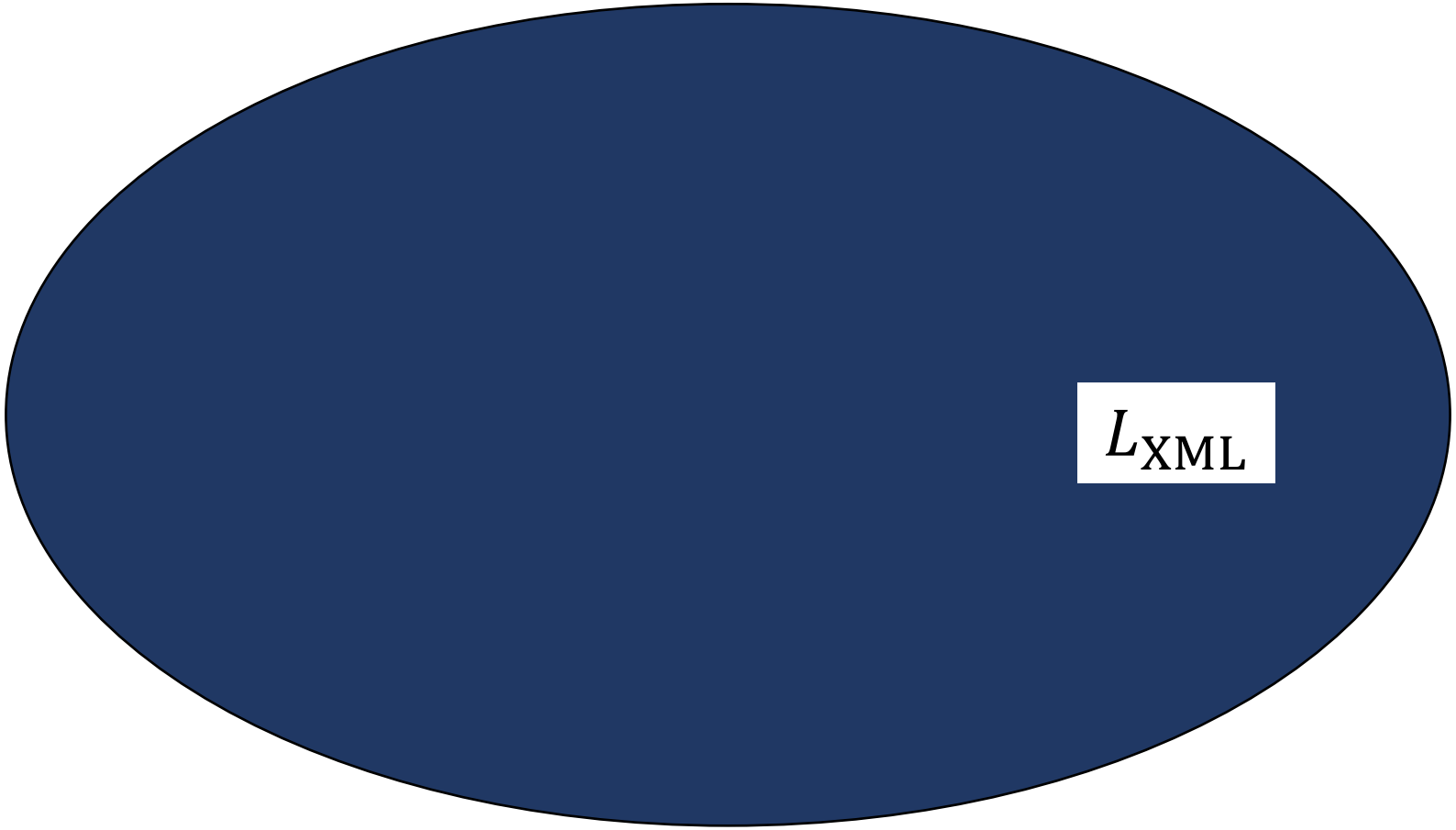

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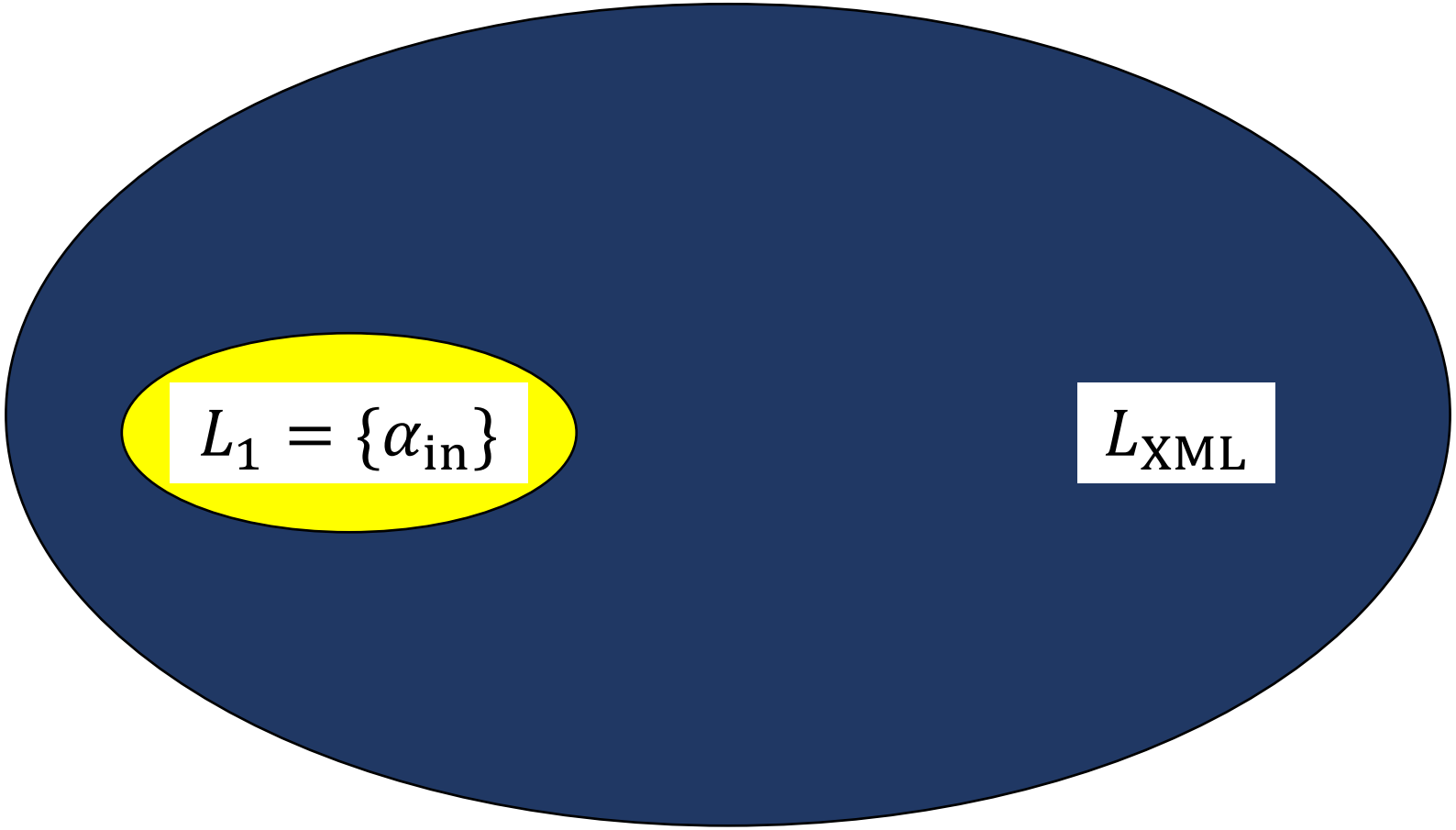

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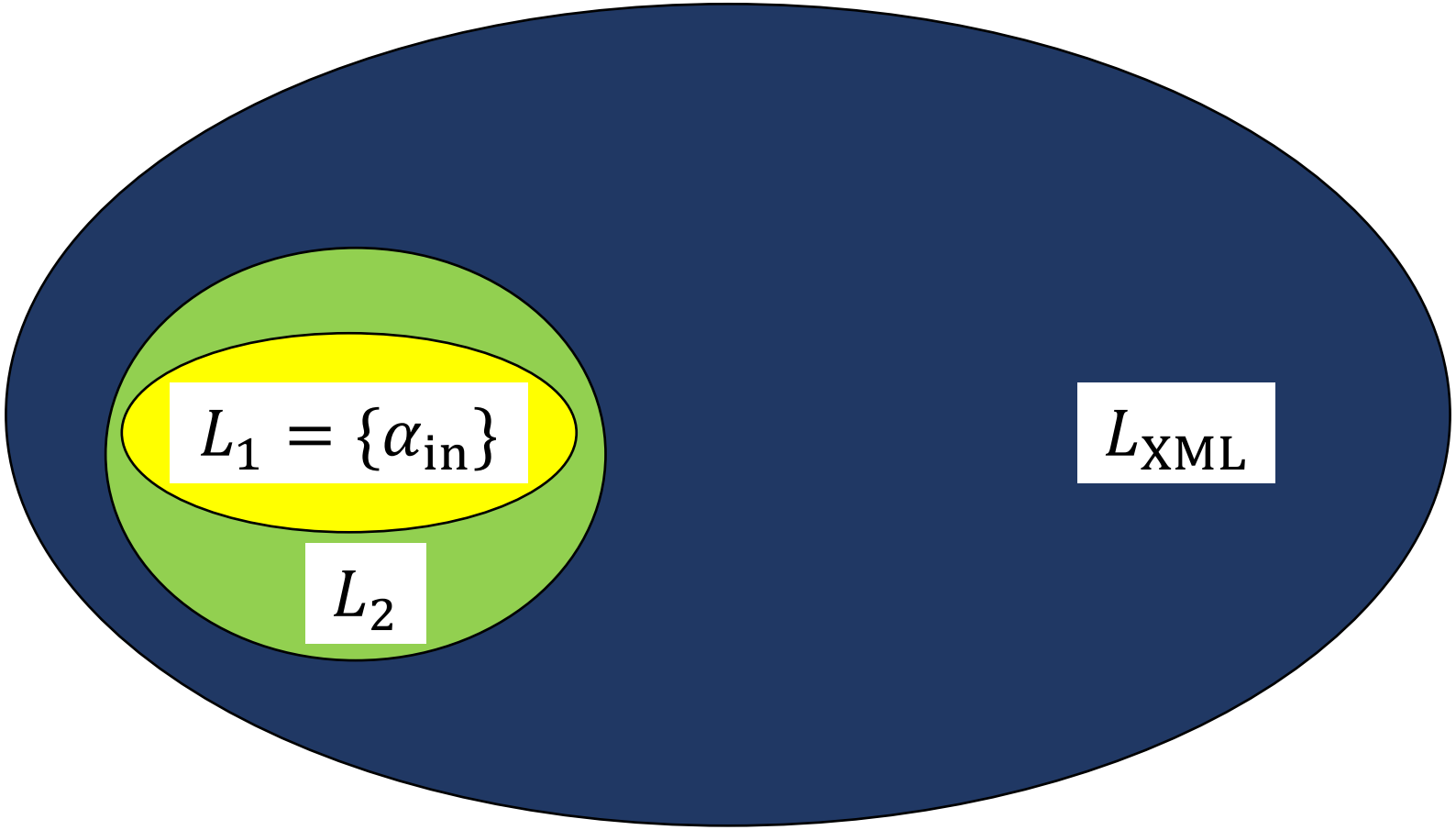

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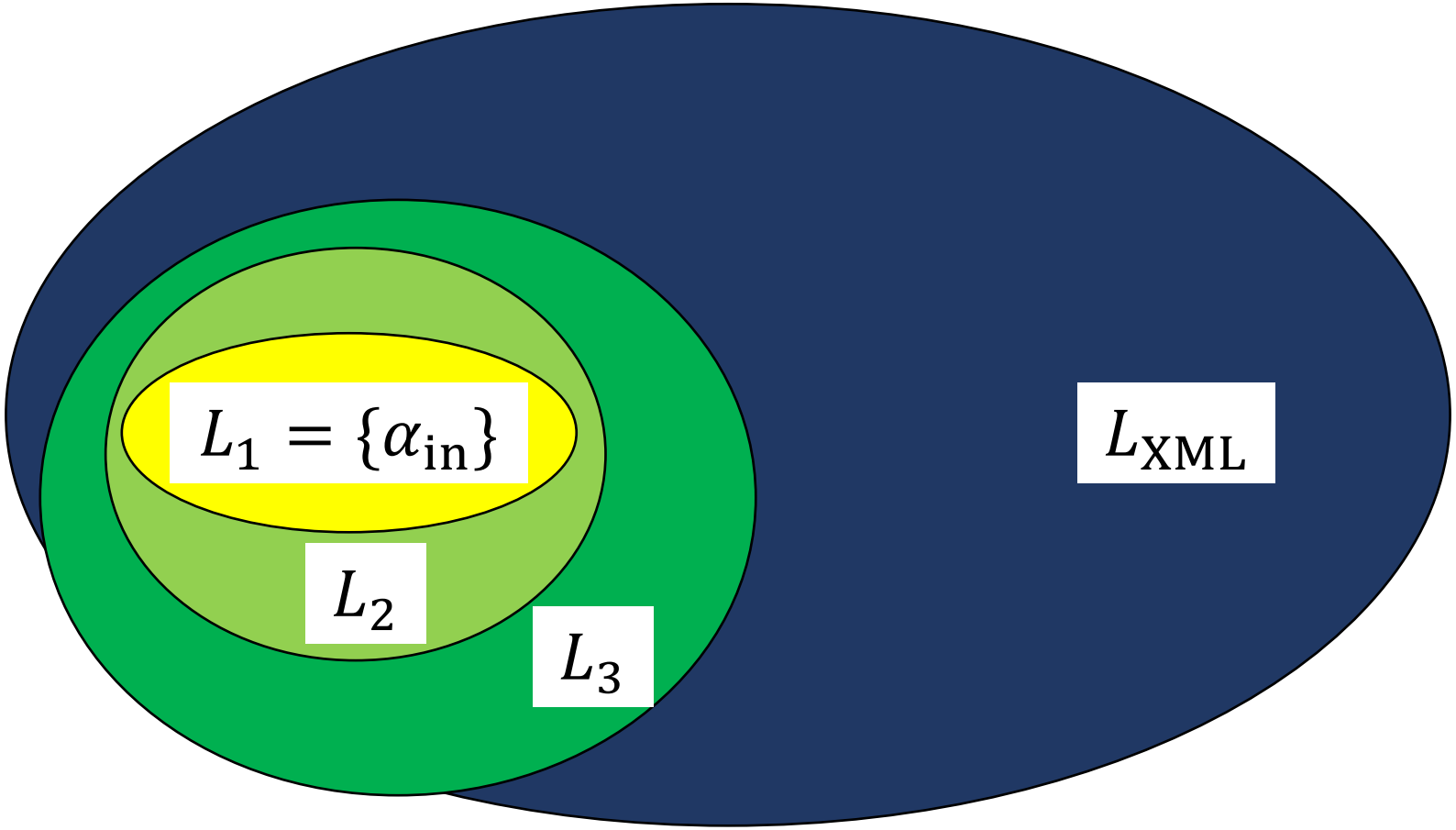

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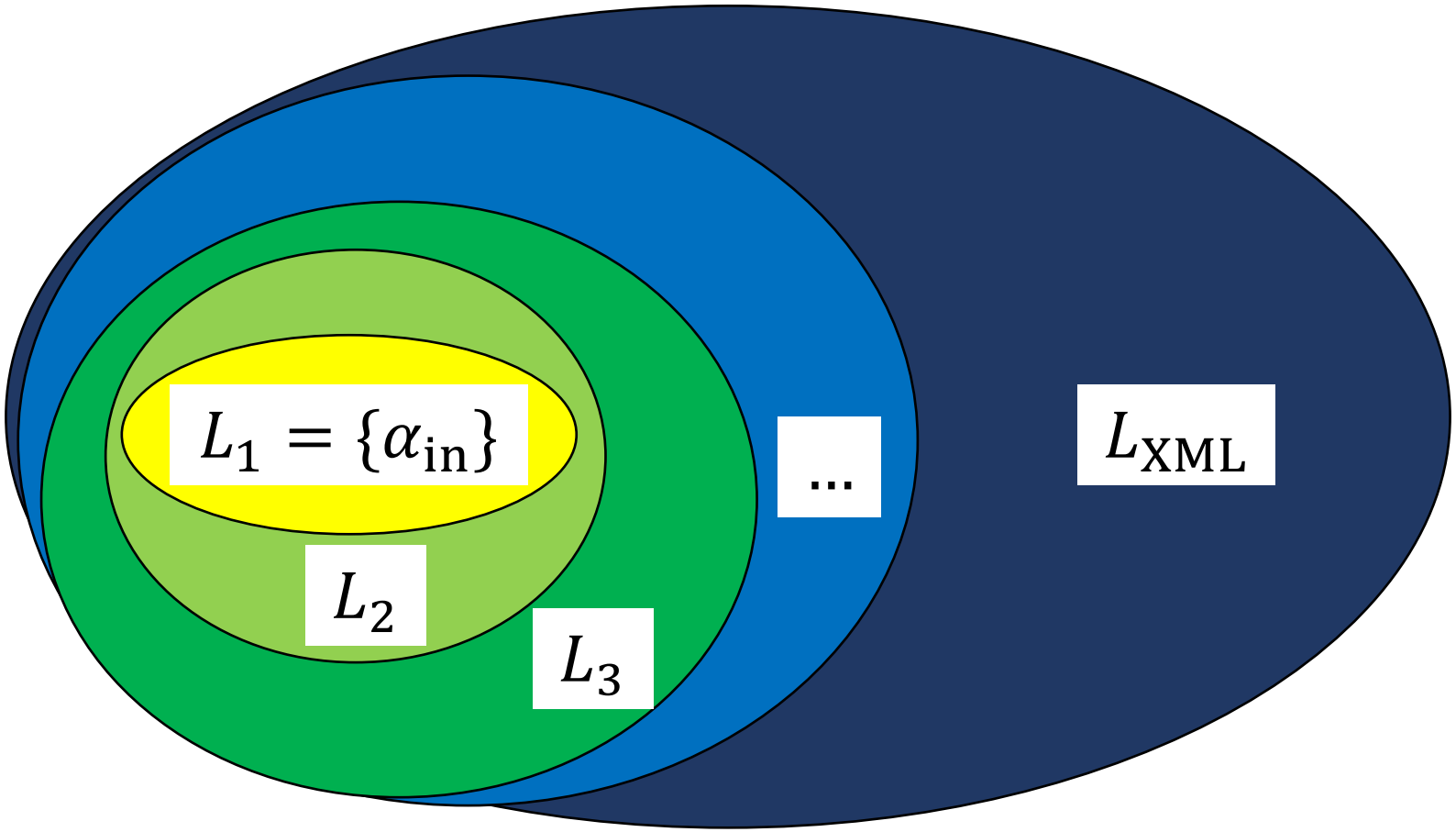

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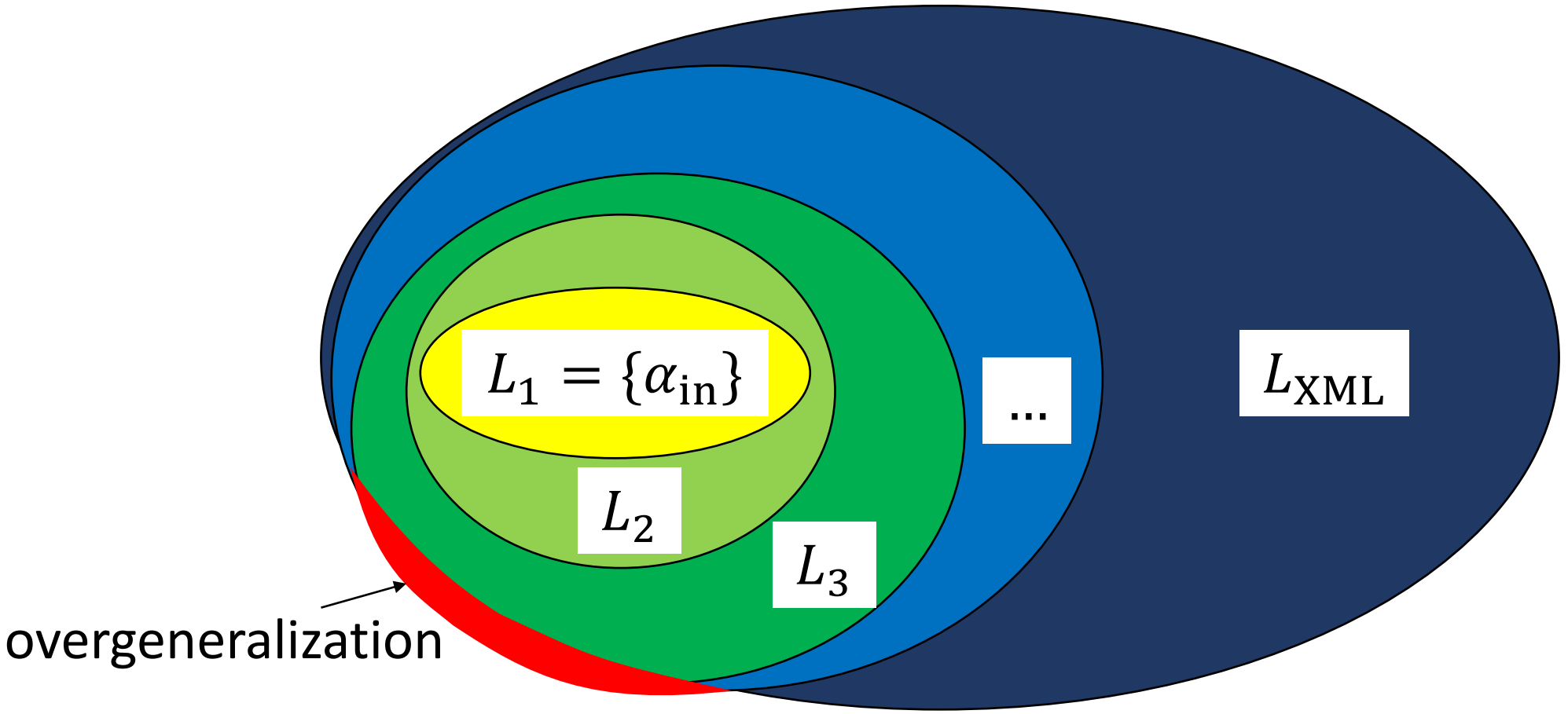

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$\alpha_{\text{in}} =$ `<a>hi</a>`

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$$\alpha_{\text{in}} = \texttt{<a>hi} \subseteq (\texttt{<a>hi})^* \subseteq (\texttt{<a>}(\texttt{hi})^*\texttt{})^*$$

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$$\alpha_{\text{in}} = \texttt{<a>hi} \subseteq (\texttt{<a>hi})^* \subseteq (\texttt{<a>}(\texttt{hi})^*\texttt{})^* \subseteq \ldots$$

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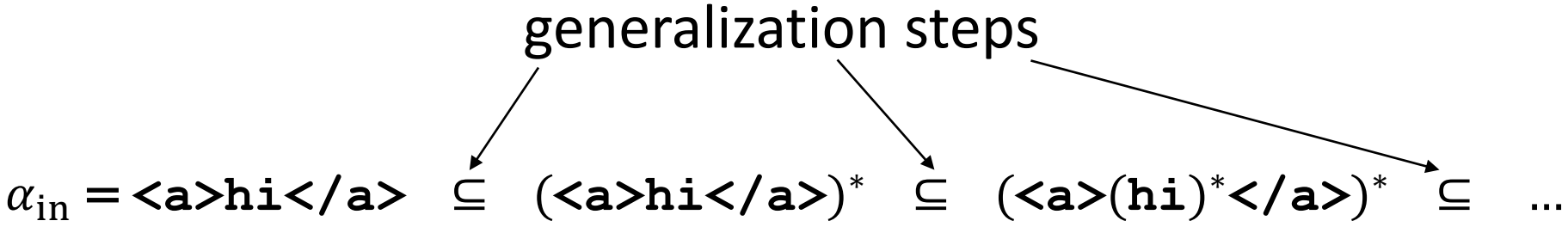

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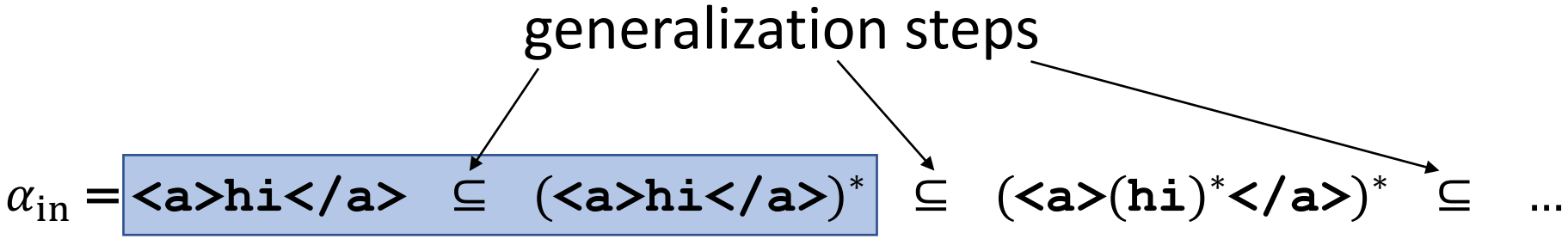

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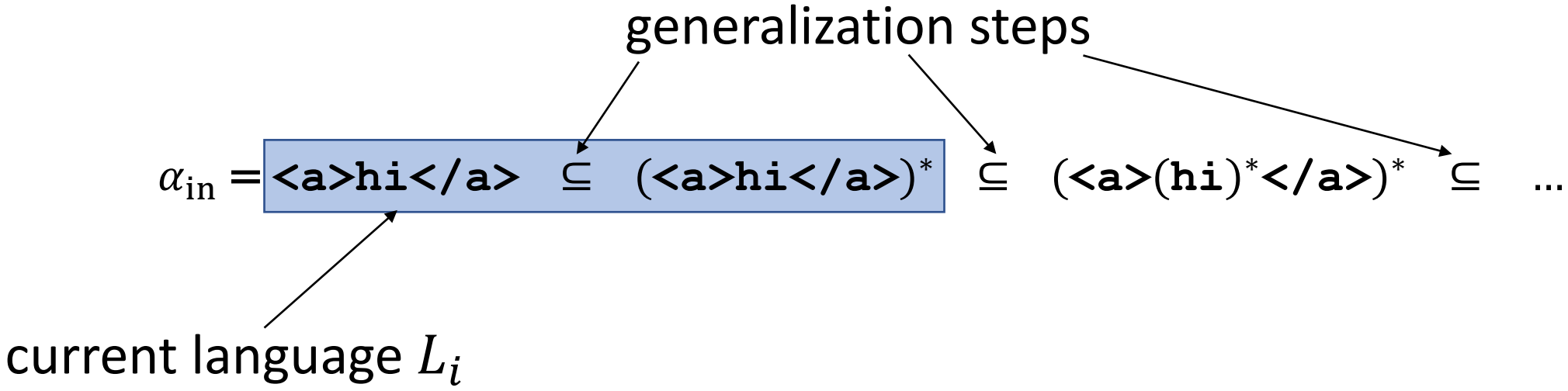

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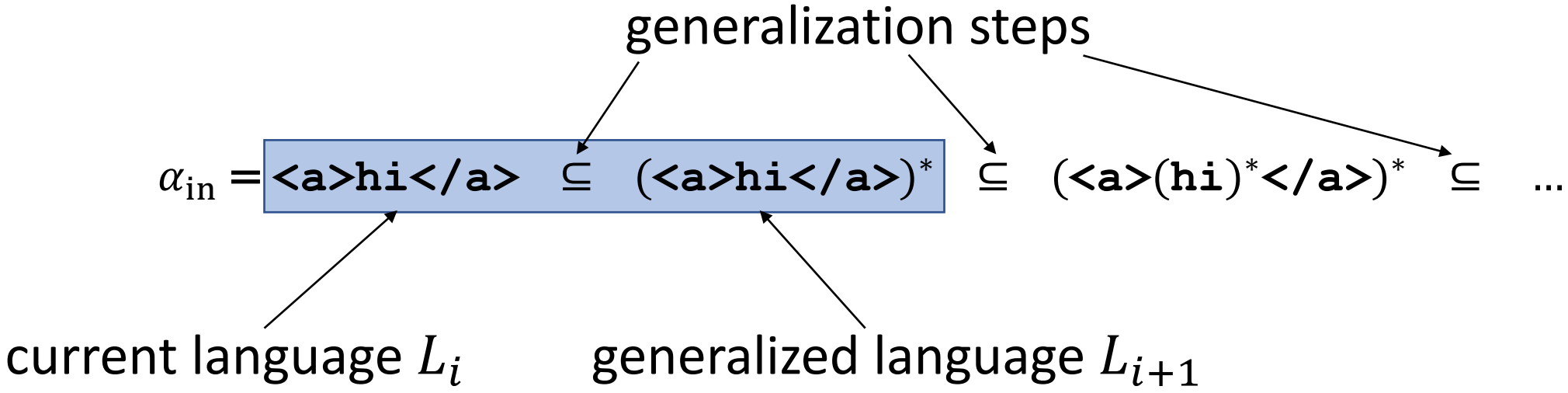

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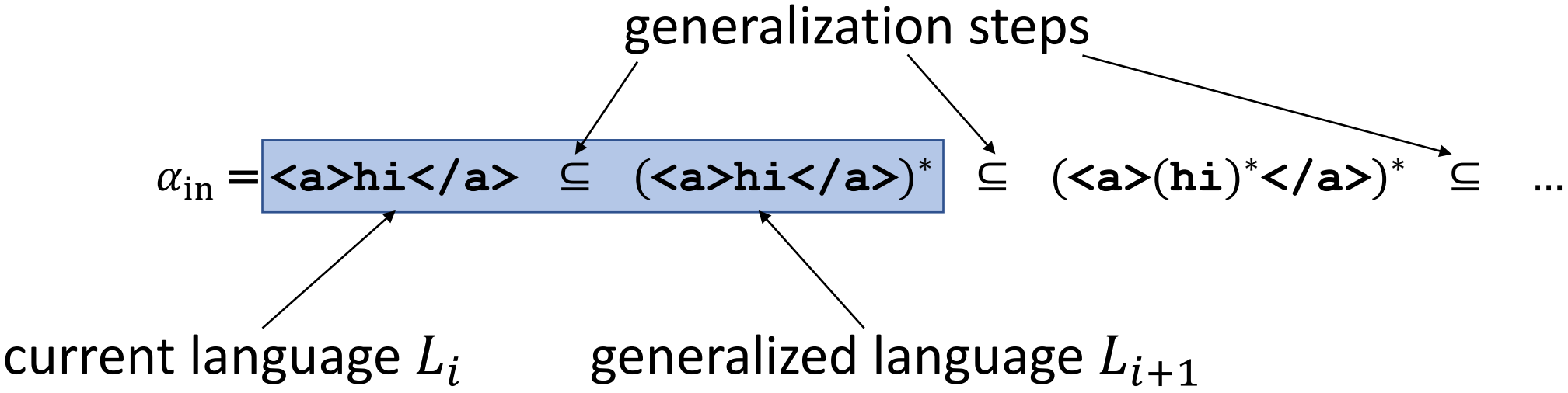
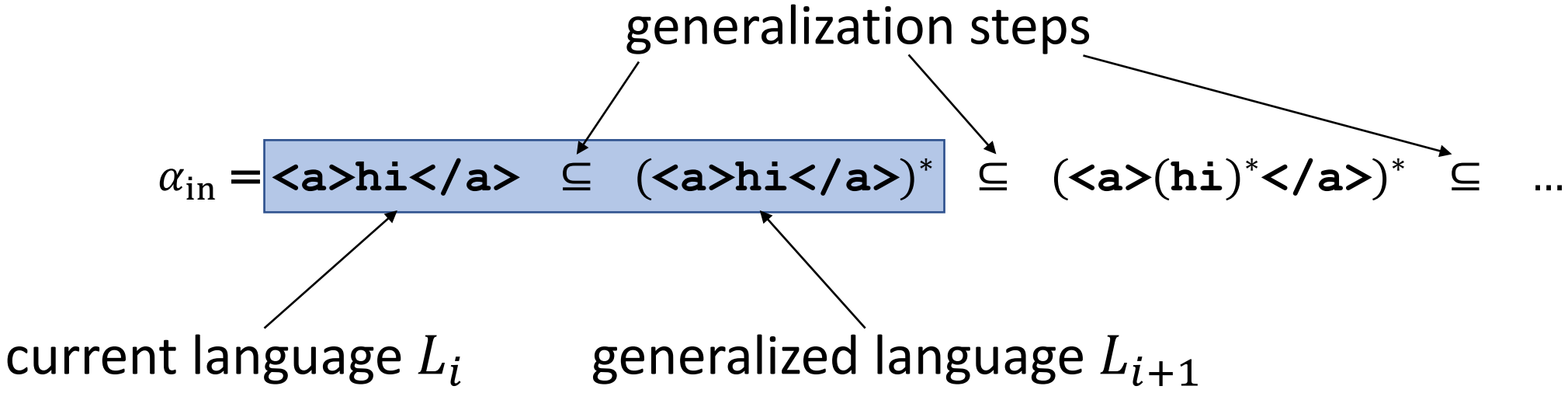


Monotone: $L_{i+1} \supseteq L_i$

Idea: Construct a series of increasingly general languages

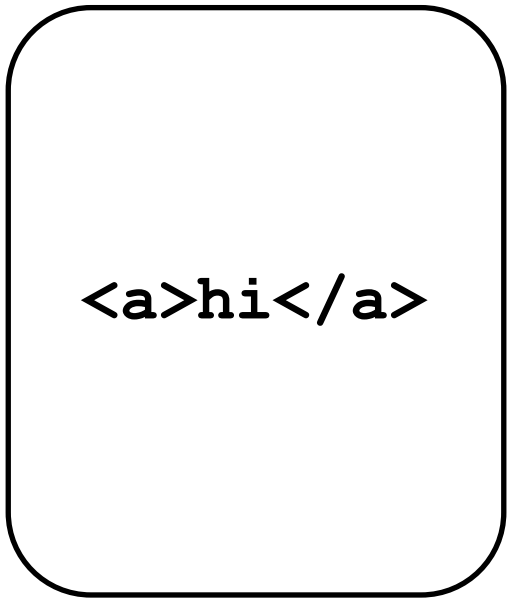


Monotone: $L_{i+1} \supseteq L_i$

Precise: $L_{i+1} \subseteq L_{\text{XML}}$

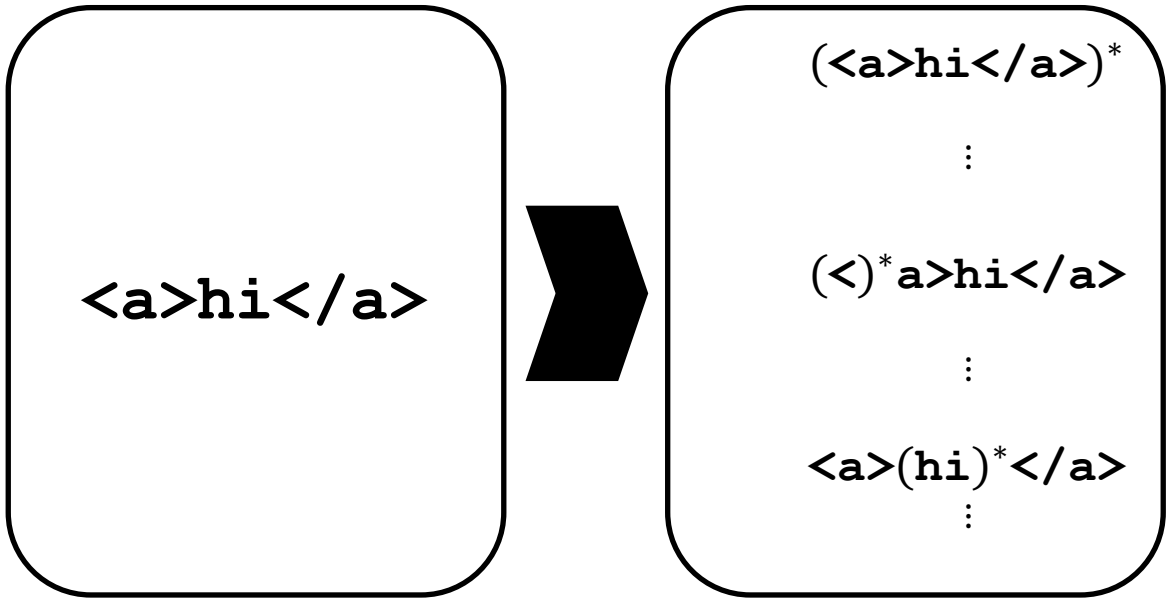
Generalization Step

Generalization Step



current
language

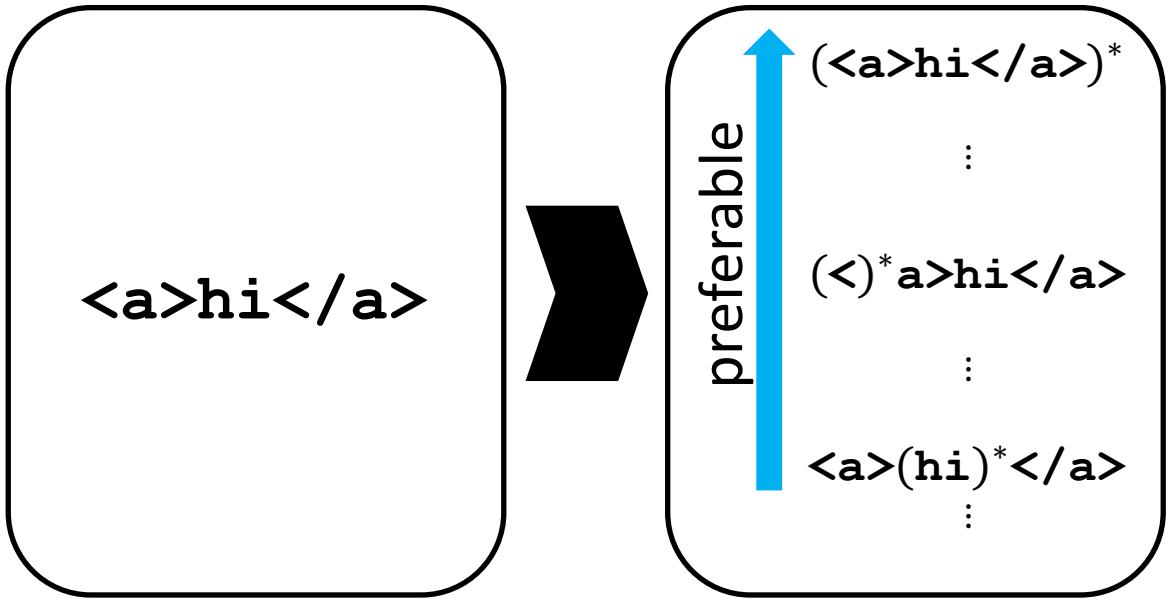
Generalization Step



current language

candidates

Generalization Step



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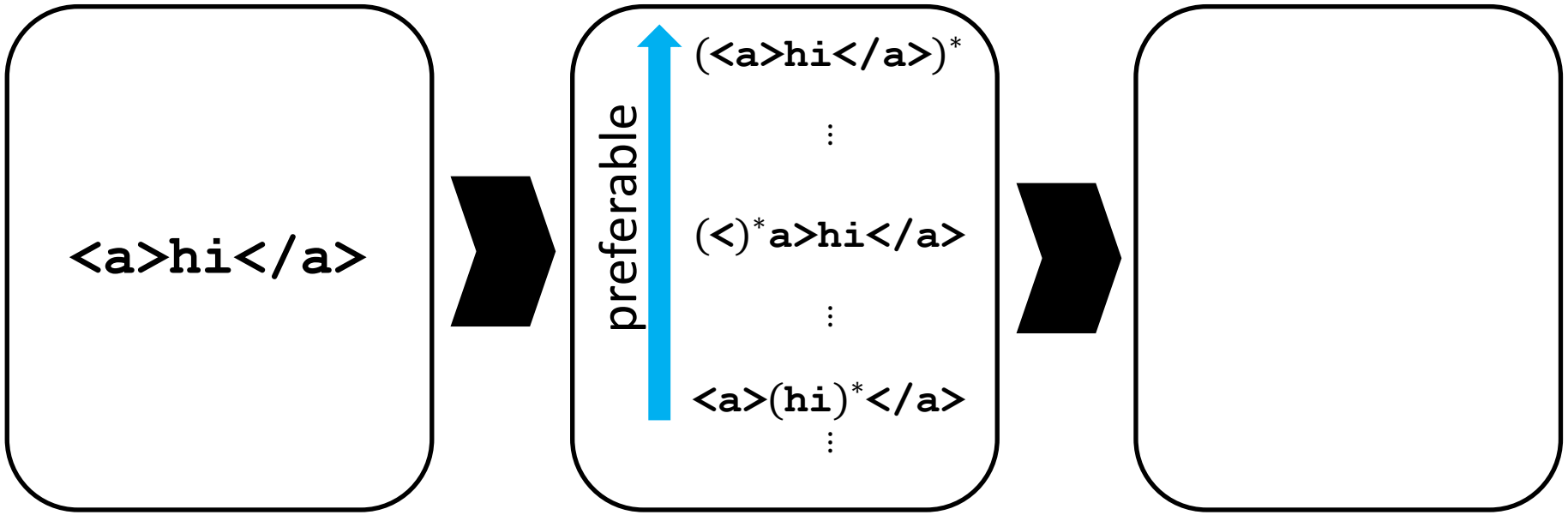
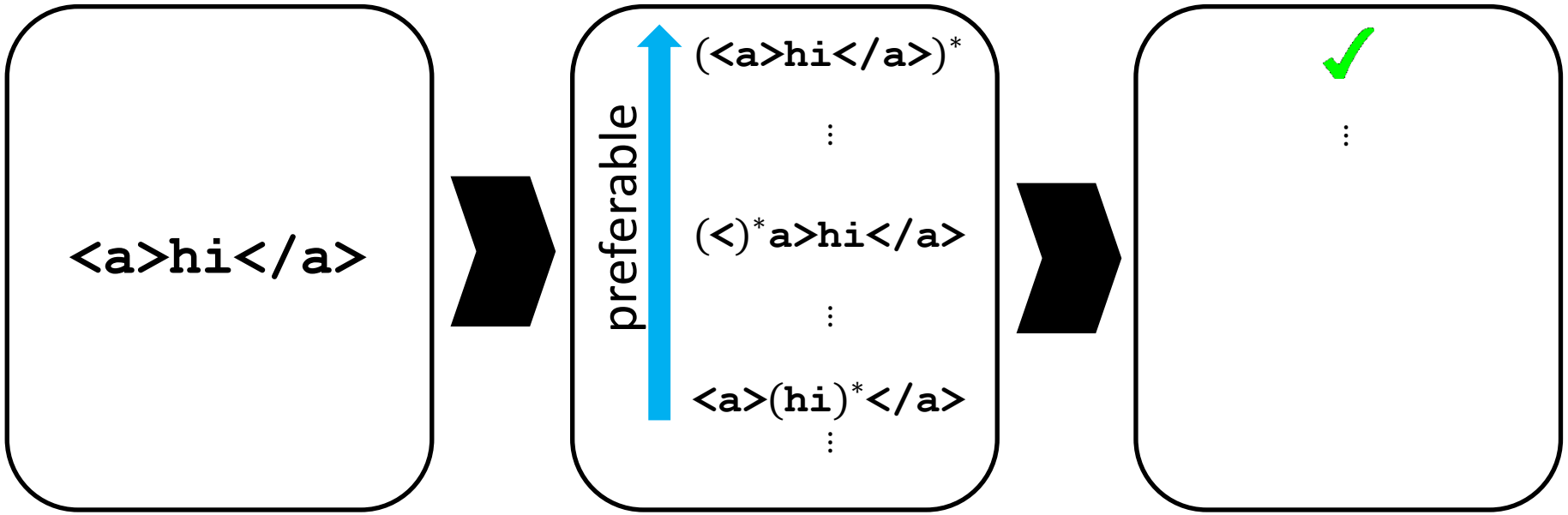


current language

candidates

check precision

Generalization Step



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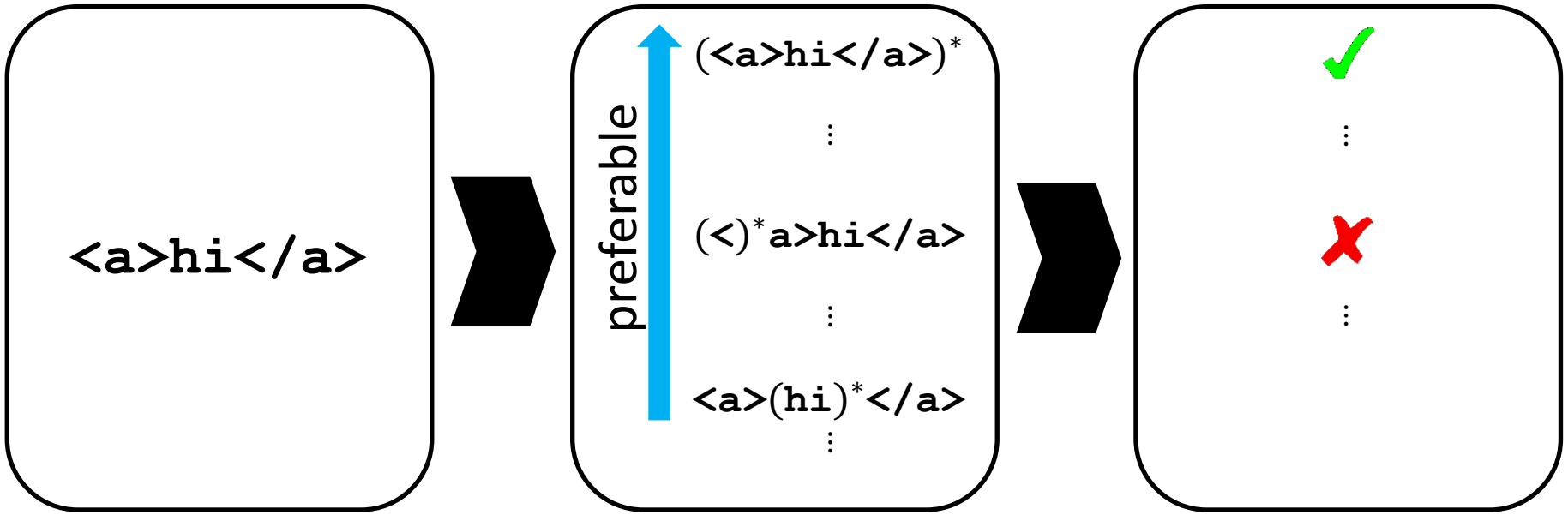

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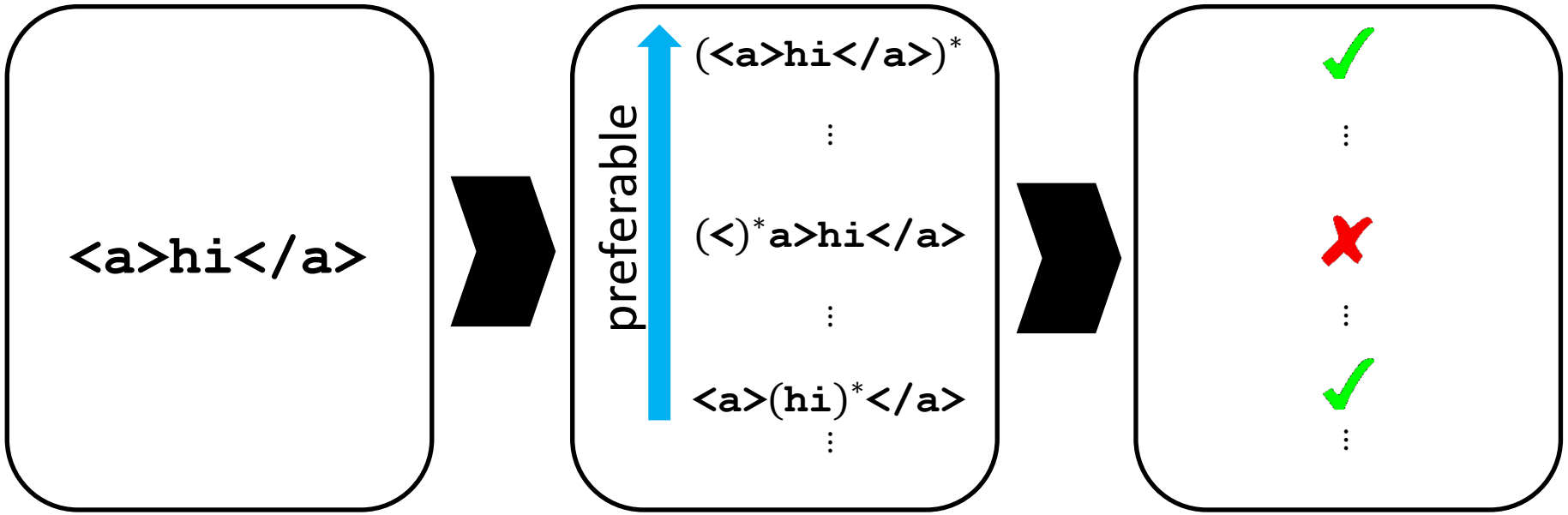

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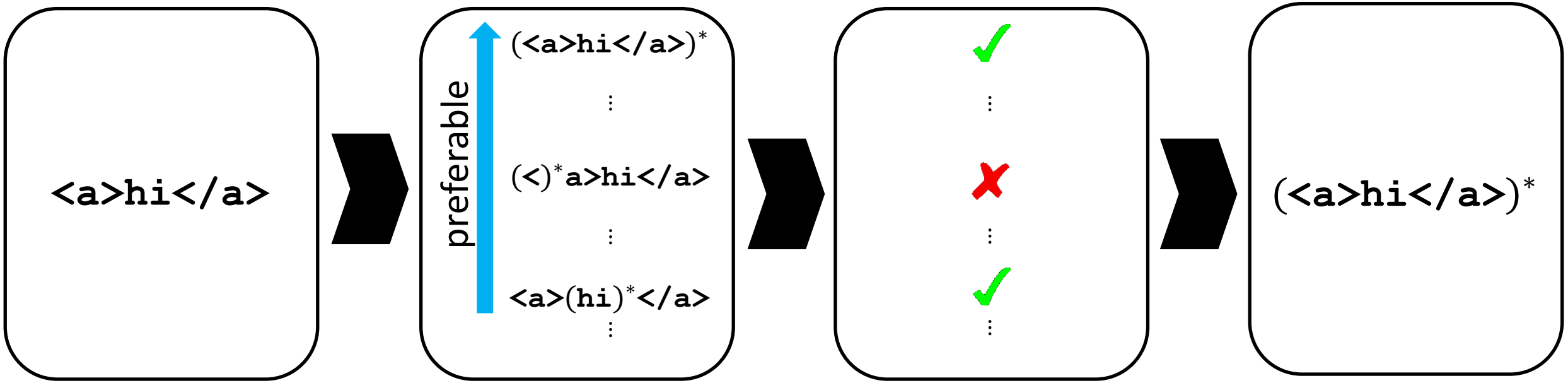


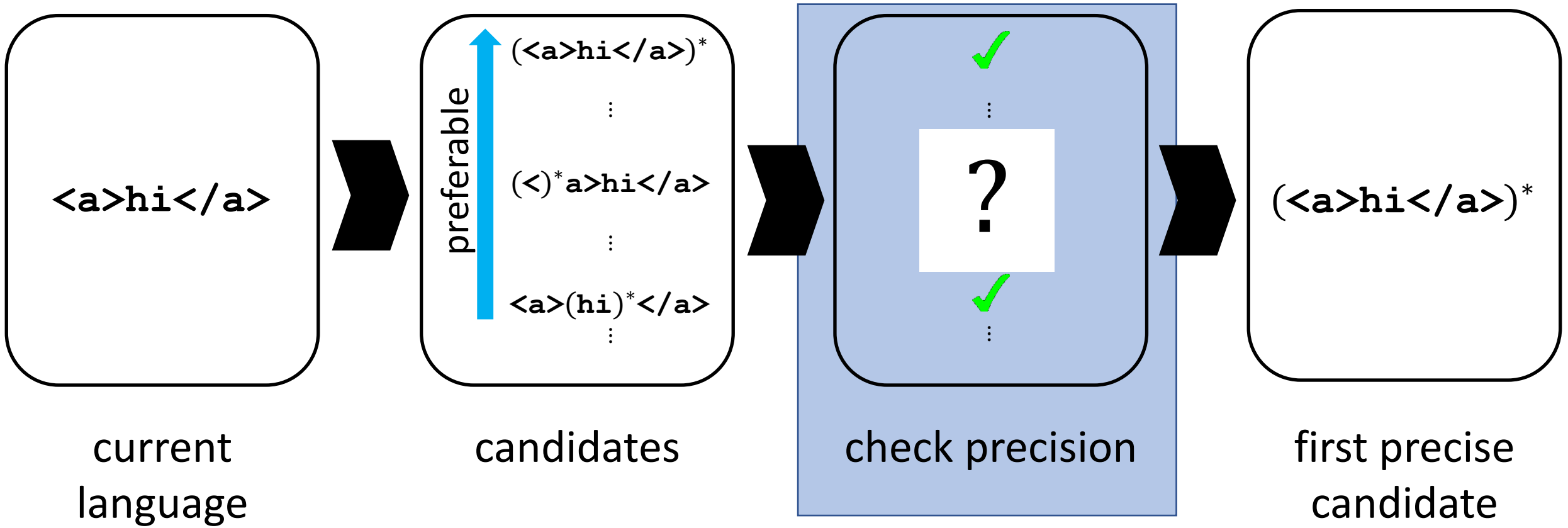
current language

candidates

check precision

first precise candidate

Generalization Step



Check Precision

For every $\alpha \in$ (<a>hi)*:

$$\alpha \in L_{\text{XML}}$$

Check Precision

For every $\alpha \in$ (<a>hi)*:

$$\mathcal{O}_{\mathrm{XML}}(\alpha) = 1$$

Check Precision

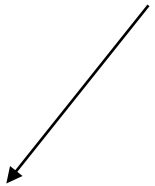
infinite!

For every $\alpha \in$ `(<a>hi</a>)`*:

$$\mathcal{O}_{\mathrm{XML}}(\alpha) = 1$$

Check Potential Precision

finite subset of **checks**



For every $\alpha \in S \subseteq (\texttt{<a>hi})^*$:

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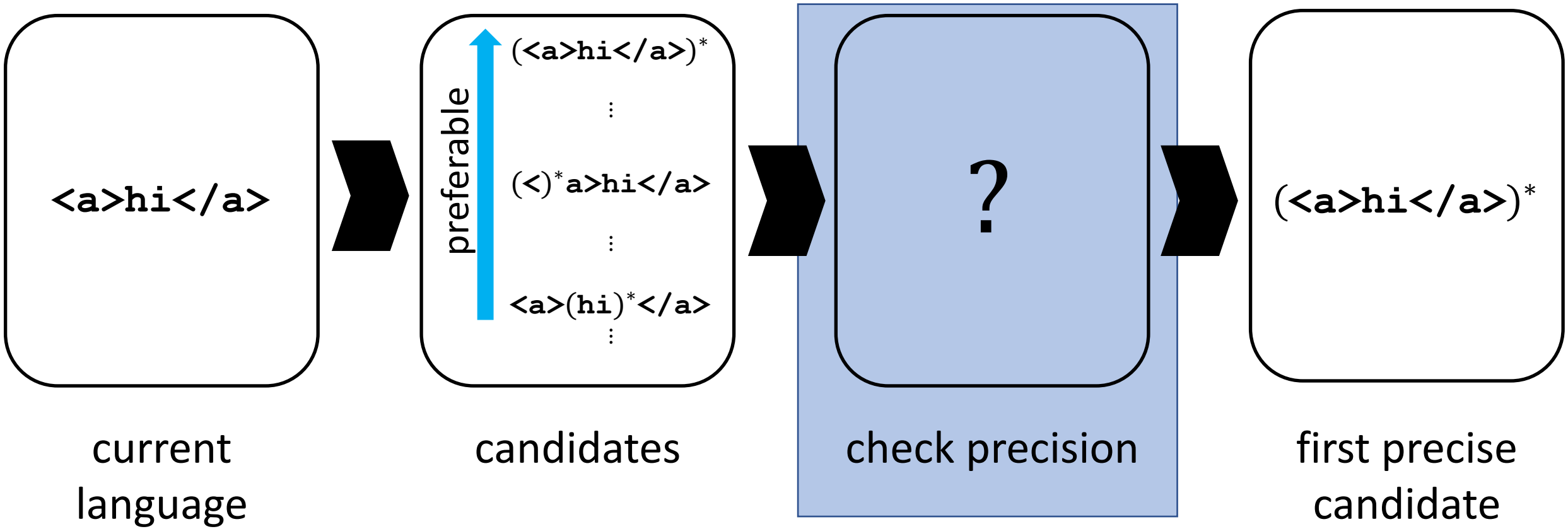
Generalization Step



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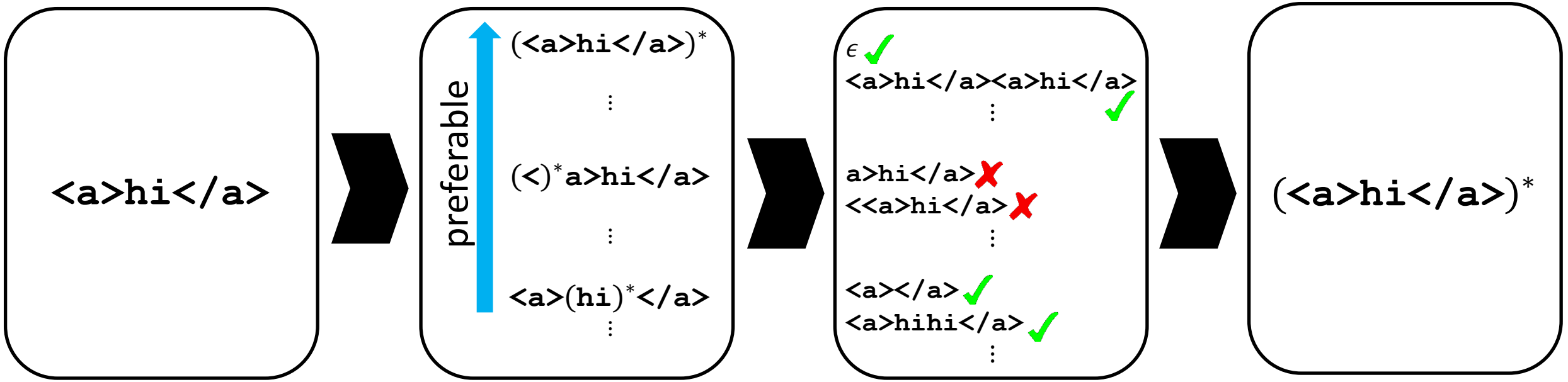

current language

candidates

check potential precision

first potentially precise candidate

Check Potential Precision

For every $\alpha \in S \subseteq (\texttt{<a>hi})^*$:

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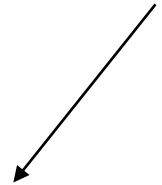
Check Potential Precision

what if we made mistakes earlier?



For every $\alpha \in S \subseteq (\texttt{<a>hi})^*$:

$$\mathcal{O}_{\mathrm{XML}}(\alpha) = 1$$

Precise: $L_{i+1} \subseteq L_{\mathrm{XML}}$

ignore past mistakes

Precise: $L_{i+1} \setminus L_i \subseteq L_{\mathrm{XML}}$

Check Potential Precision

For every $\alpha \in S \subseteq (\texttt{<a>hi})^*$:

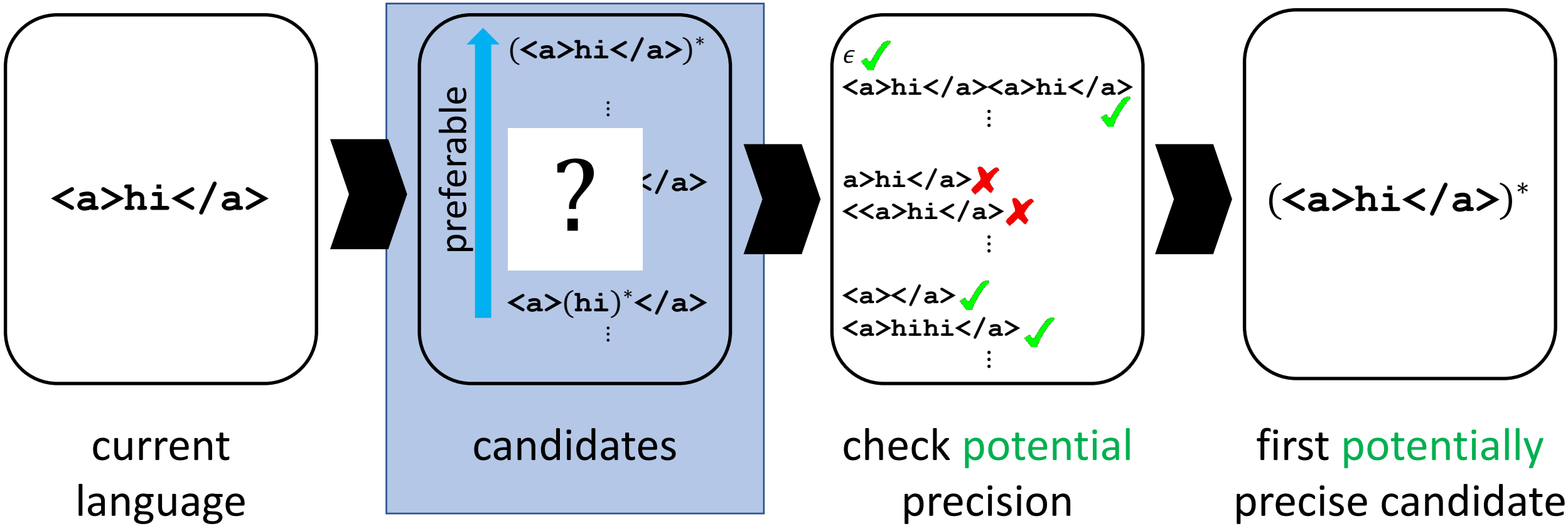
$$\mathcal{O}_{\mathrm{XML}}(\alpha) = 1$$

Check Potential Precision

For every $\alpha \in S \subseteq (\texttt{<a>hi})^* \setminus \texttt{<a>hi}$:

$$\mathcal{O}_{\mathrm{XML}}(\alpha) = 1$$

Generalization Step



input example `<a>hi</a>`

input example { **<a>hi**

regular expression { $\Rightarrow$ (**<a>hi**)*

$\Rightarrow$ (**<a>**(**hi**)*****)*

$\Rightarrow$ (**<a>**(**h**+**i**)*****)*

input example

<a>hi

regular expression

$\Rightarrow$ $(\texttt{<a>hi})^*$

$\Rightarrow$ $(\texttt{<a>}(\texttt{hi})^*\texttt{})^*$

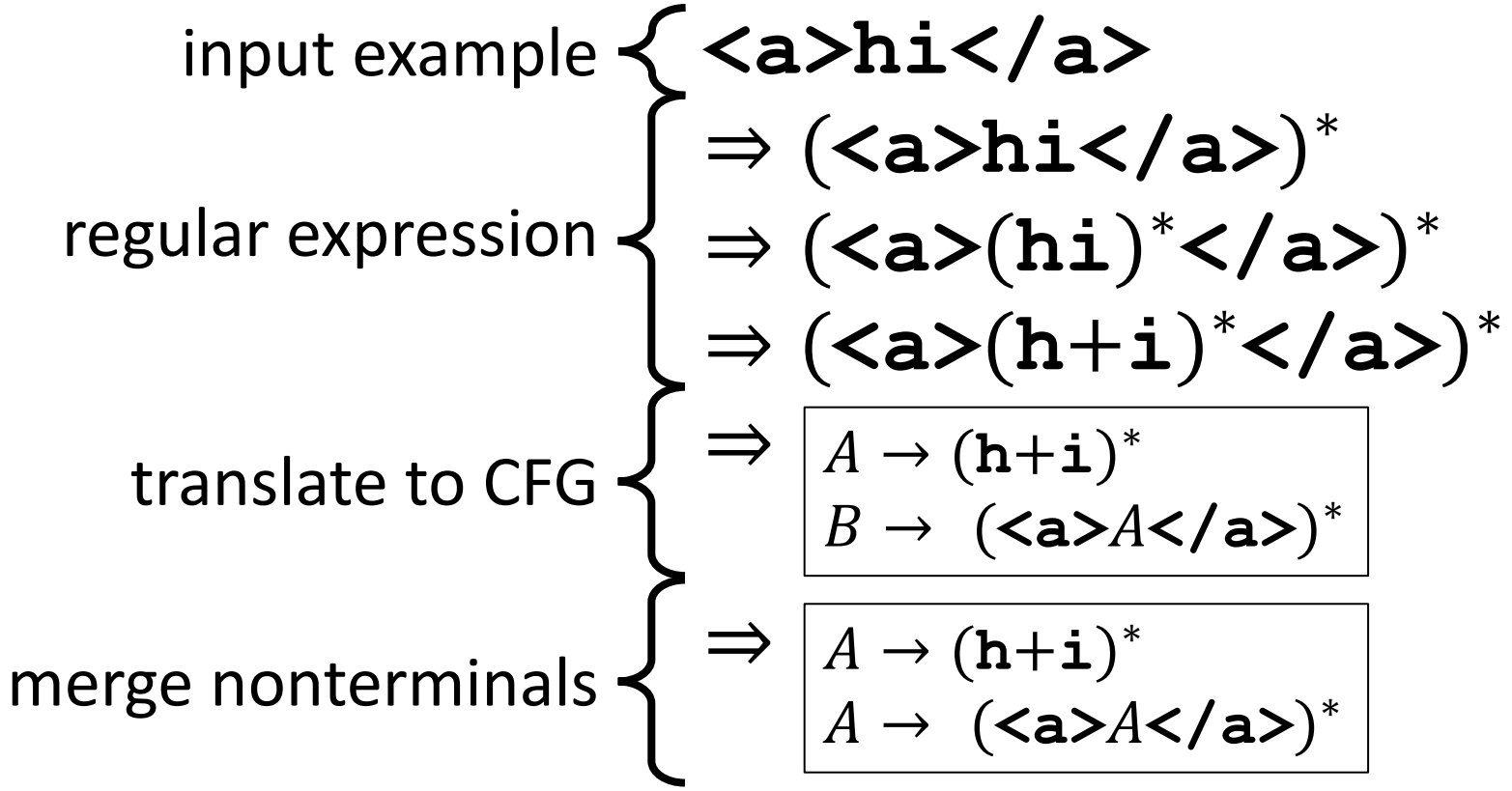
$\Rightarrow$ $(\texttt{<a>}(\texttt{h}+\texttt{i})^*\texttt{})^*$

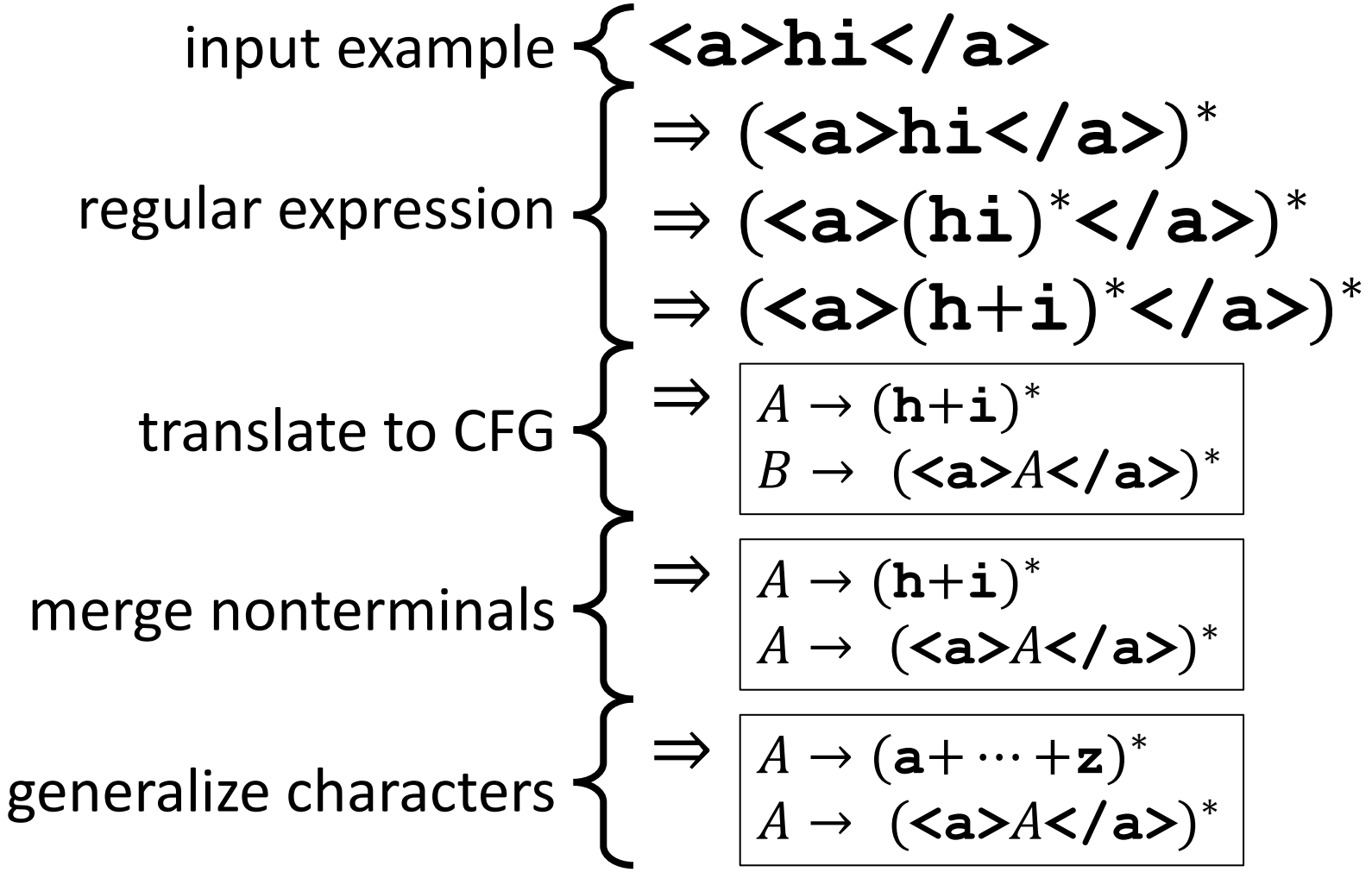
translate to CFG

$\Rightarrow$

$A \rightarrow (\texttt{h}+\texttt{i})^*$

$B \rightarrow (\texttt{<a>}A\texttt{})^*$


input example
regular expression
translate to CFG
merge nonterminals
<a>hi
⇒ (<a>hi)*
⇒ (<a>(hi)*)*
⇒ (<a>(h+i)*)*
⇒
A → (h+i)*
B → (<a>A)*
⇒
A → (h+i)*
A → (<a>A)*


input example
<a>hi
regular expression
⇒ (<a>hi)*
⇒ (<a>(hi)*)*
⇒ (<a>(h+i)*)*
translate to CFG
⇒
A → (h+i)*
B → (<a>A)*
merge nonterminals
⇒
A → (h+i)*
A → (<a>A)*
generalize characters
⇒
A → (a+ ⋯ +z)*
A → (<a>A)*

Multiple Input Examples

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Input examples: $\alpha_1, \ldots, \alpha_k$

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Merging nonterminals:	C
Generalize constants:	C'

Evaluation

Evaluation

Grammar learning: Compare to language learners

Evaluation

Grammar learning: Compare to language learners

Fuzz testing: Compare to fuzzers

Evaluation: Grammar Learning

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Baselines: L-Star, RPNI

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Grammars: URL, Grep, LISP, XML

Evaluation: Grammar Learning

Baselines: L-Star, RPNI

Grammars: URL, Grep, LISP, XML

Inputs: membership oracle $\mathcal{O}$
50 random strings $E_{\text{in}} \subseteq L_*$
5 minutes

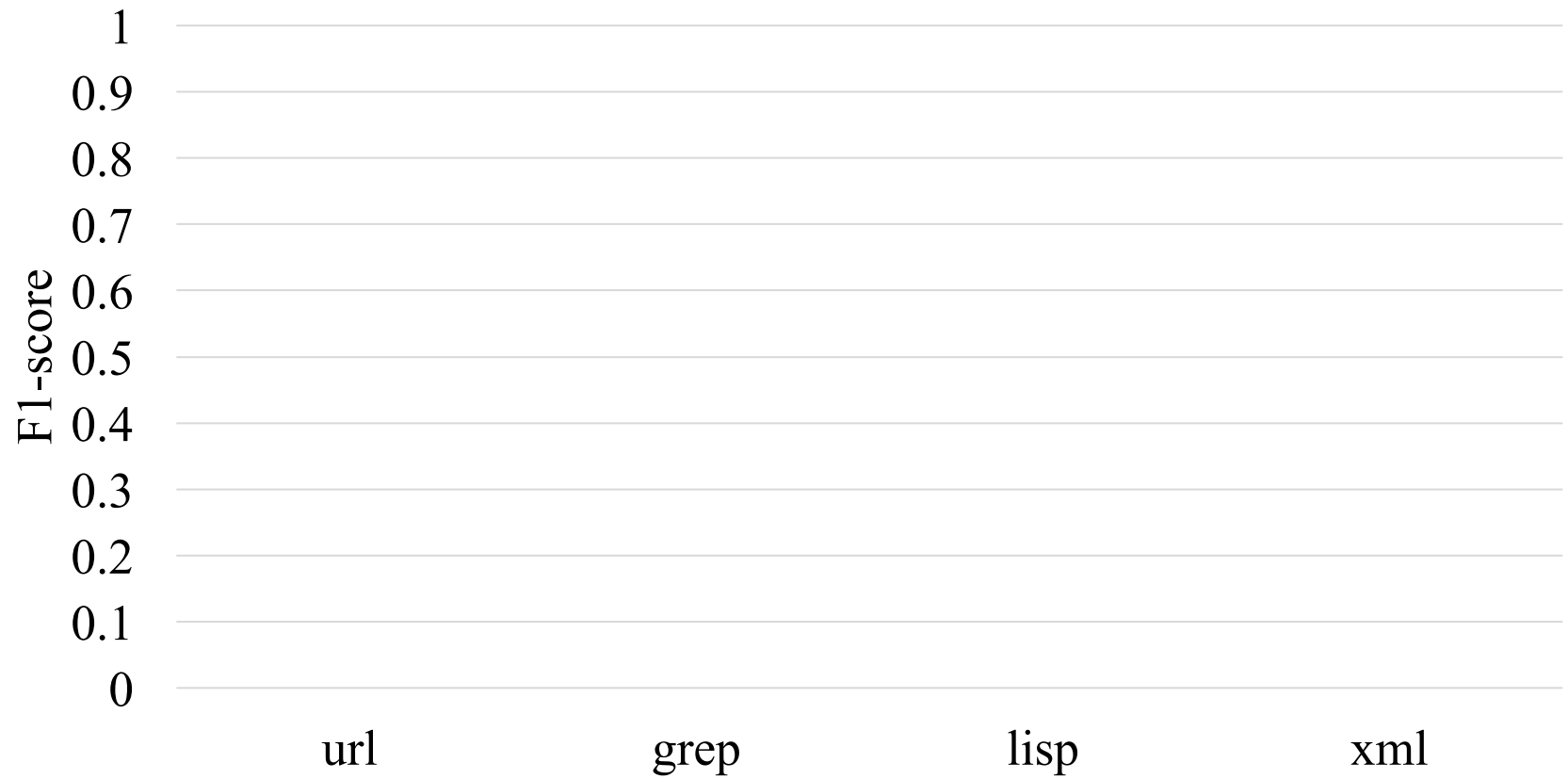
Evaluation: Grammar Learning

Precision: $$\frac{\#\text{ valid sampled inputs}}{\#\text{ sampled inputs}}$$

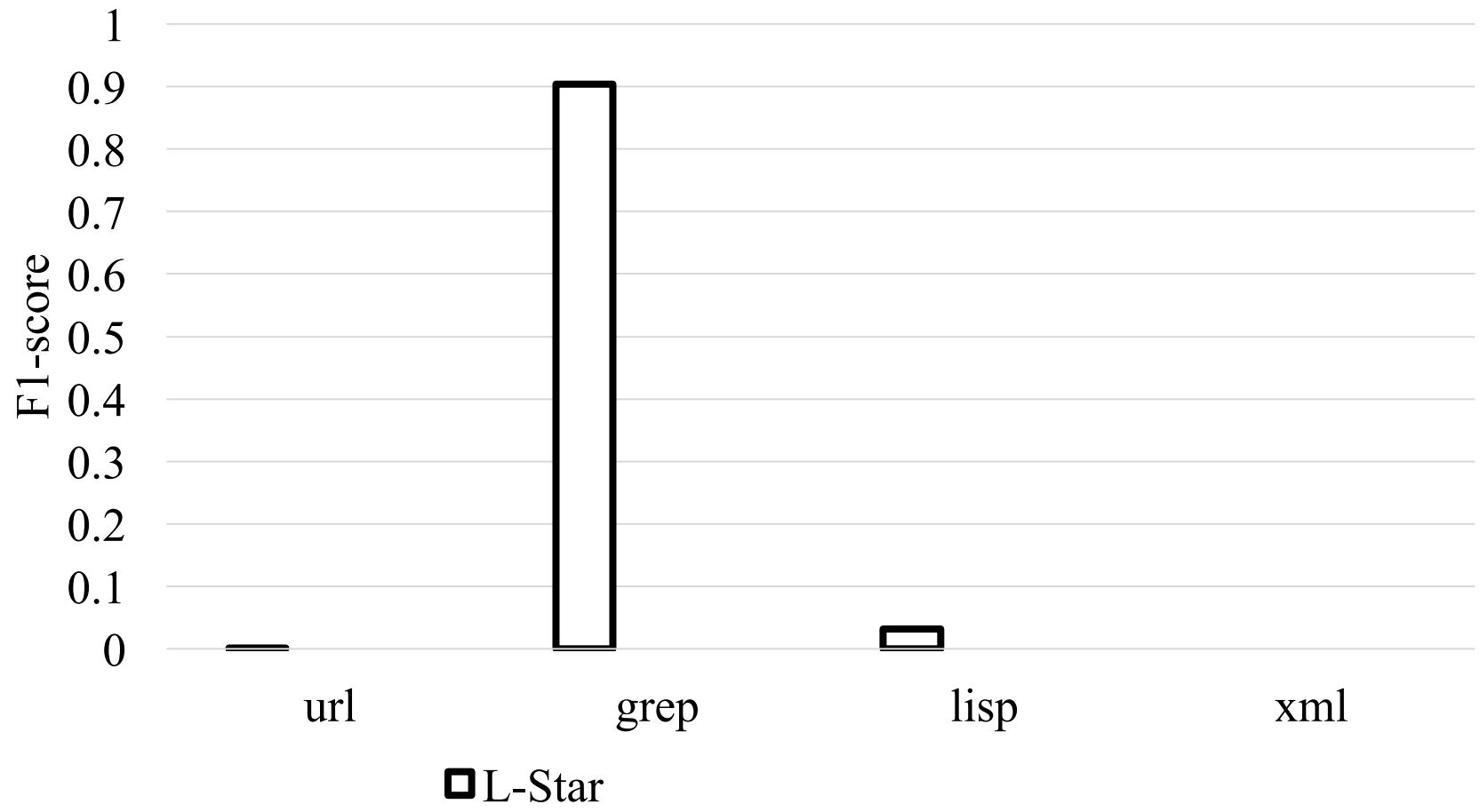
Recall: $$\frac{\#\text{ true inputs that might be sampled}}{\#\text{ true inputs}}$$

F_1-Score: $$\frac{2 \cdot \text{precision} \cdot \text{recall}}{\text{precision} + \text{recall}}$$

Evaluation: Grammar Learning



Evaluation: Grammar Learning



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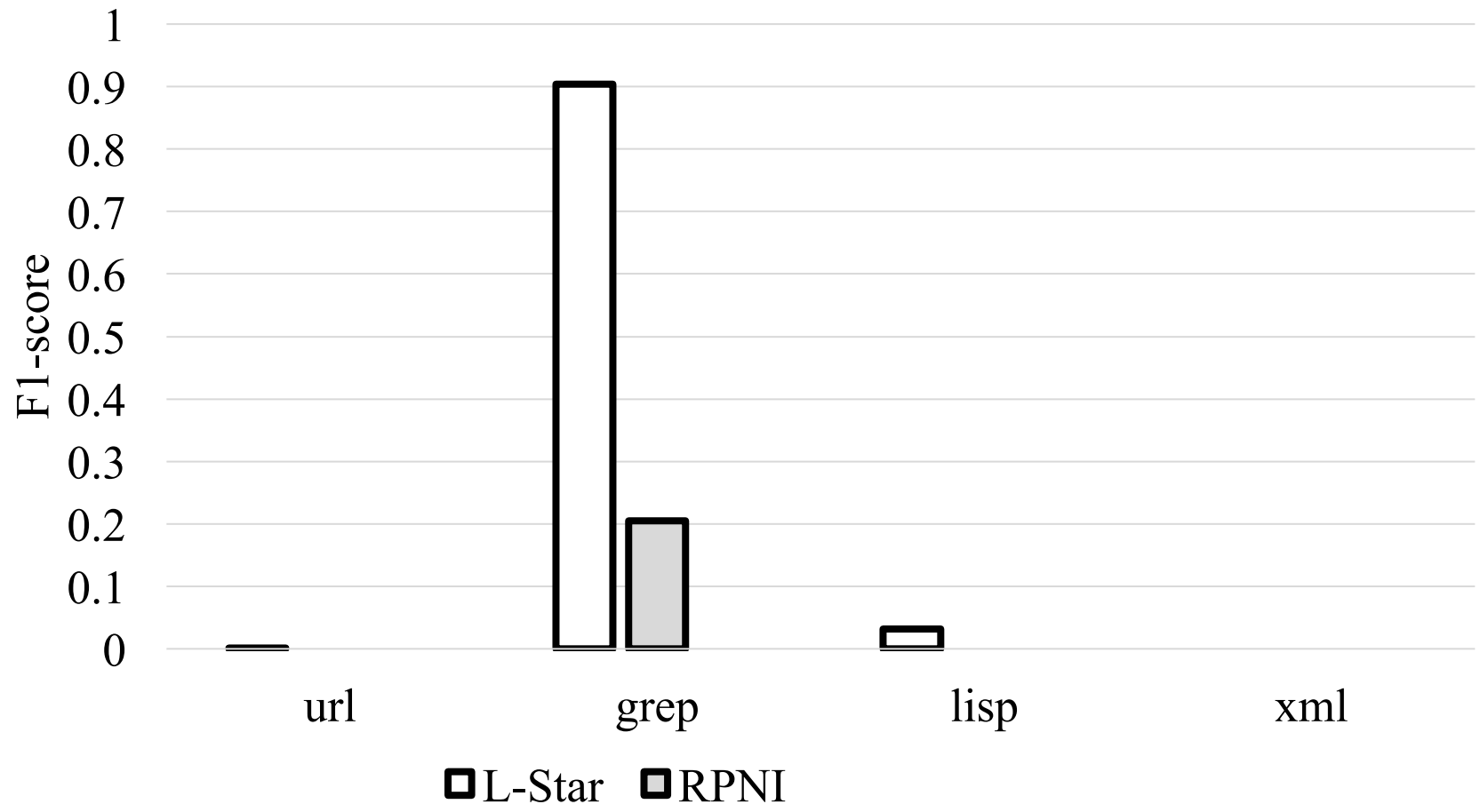

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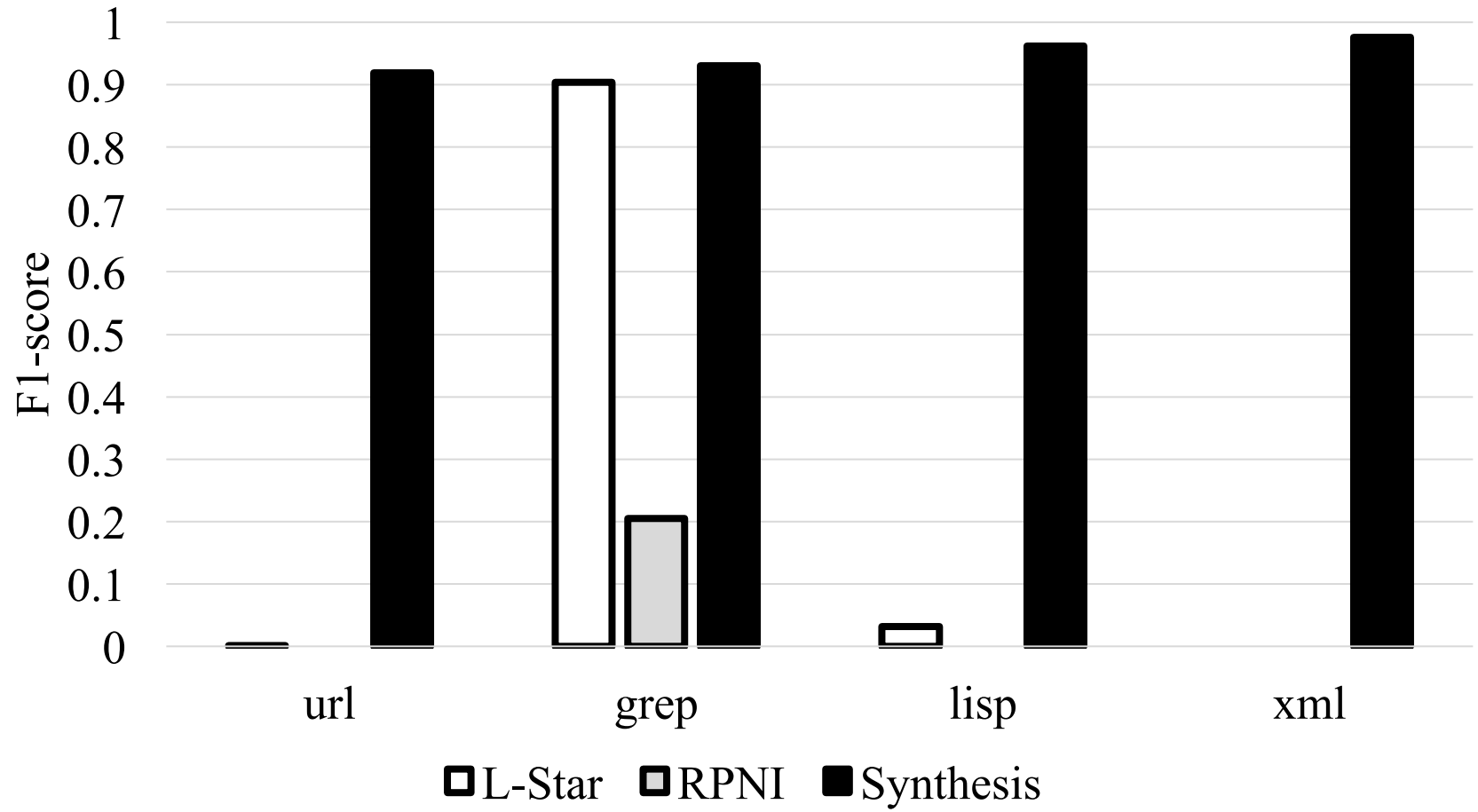

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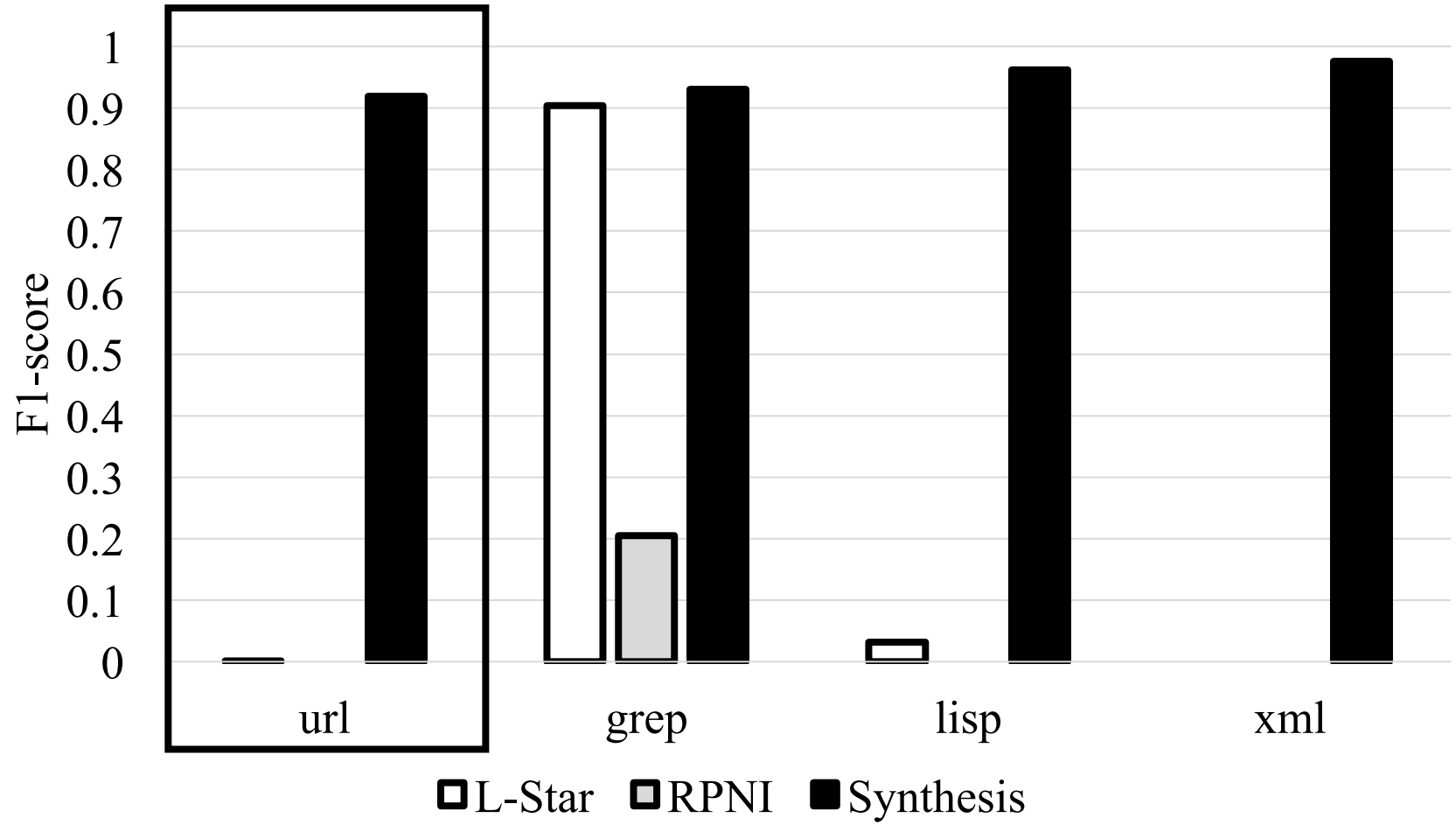

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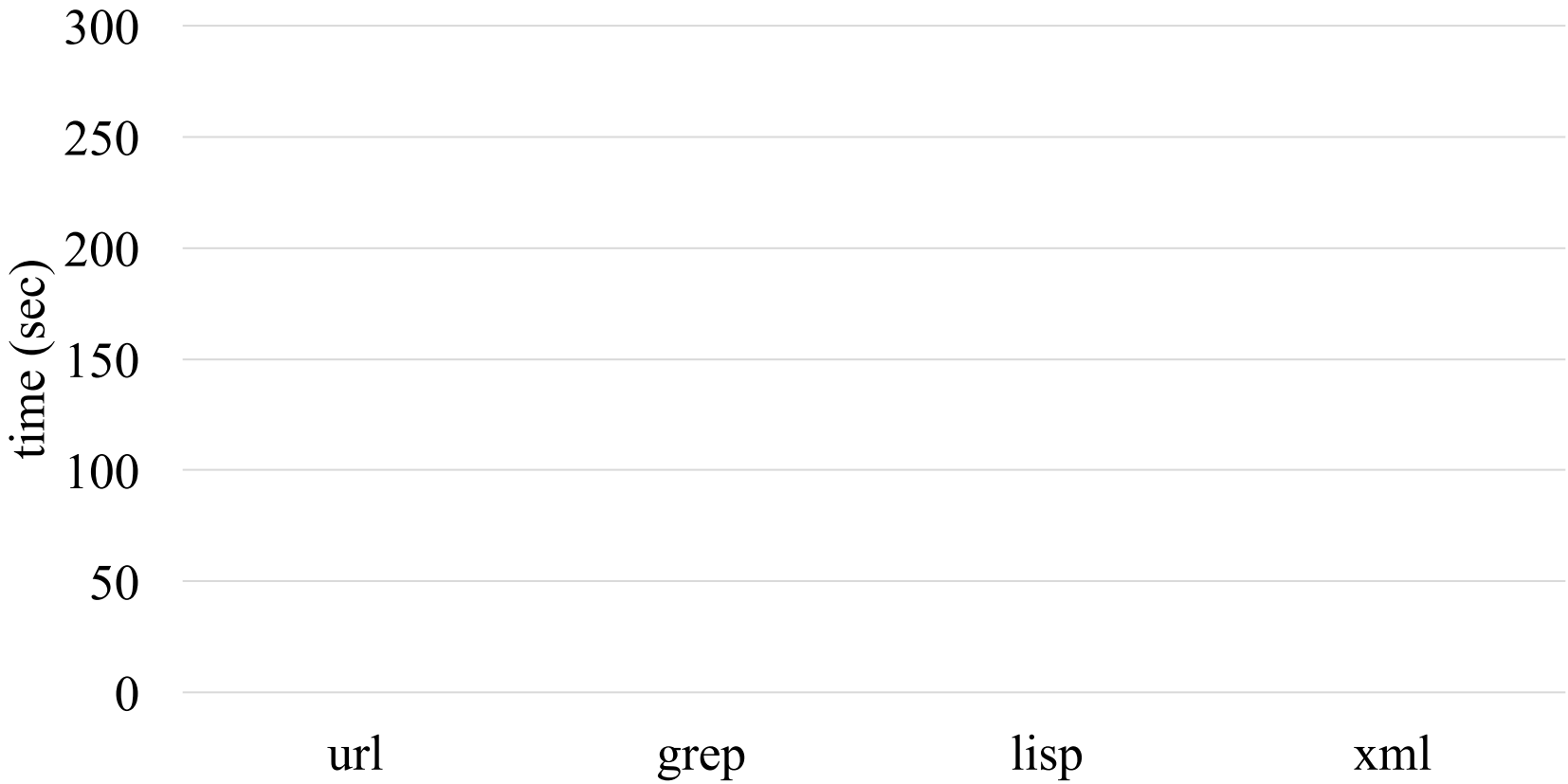

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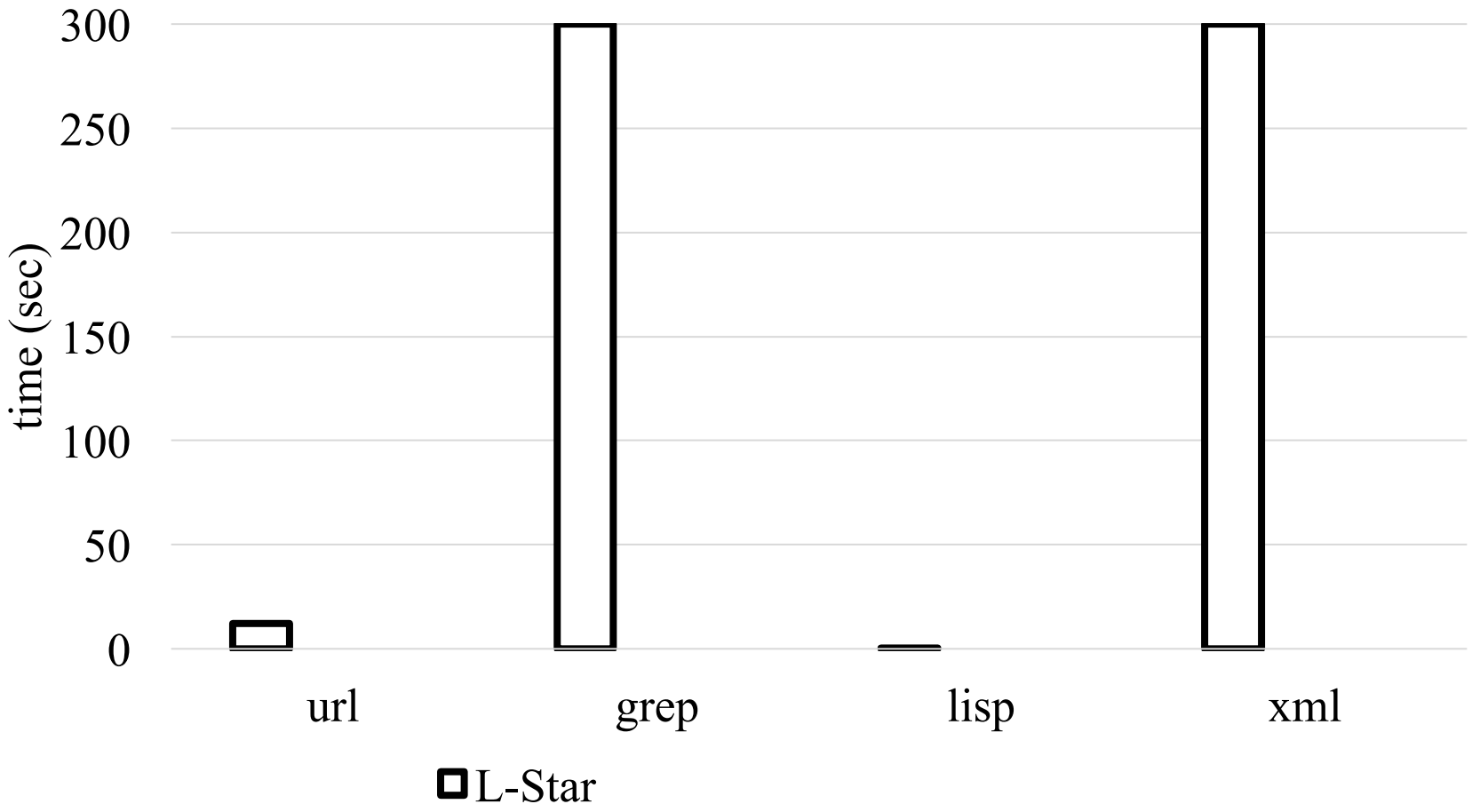

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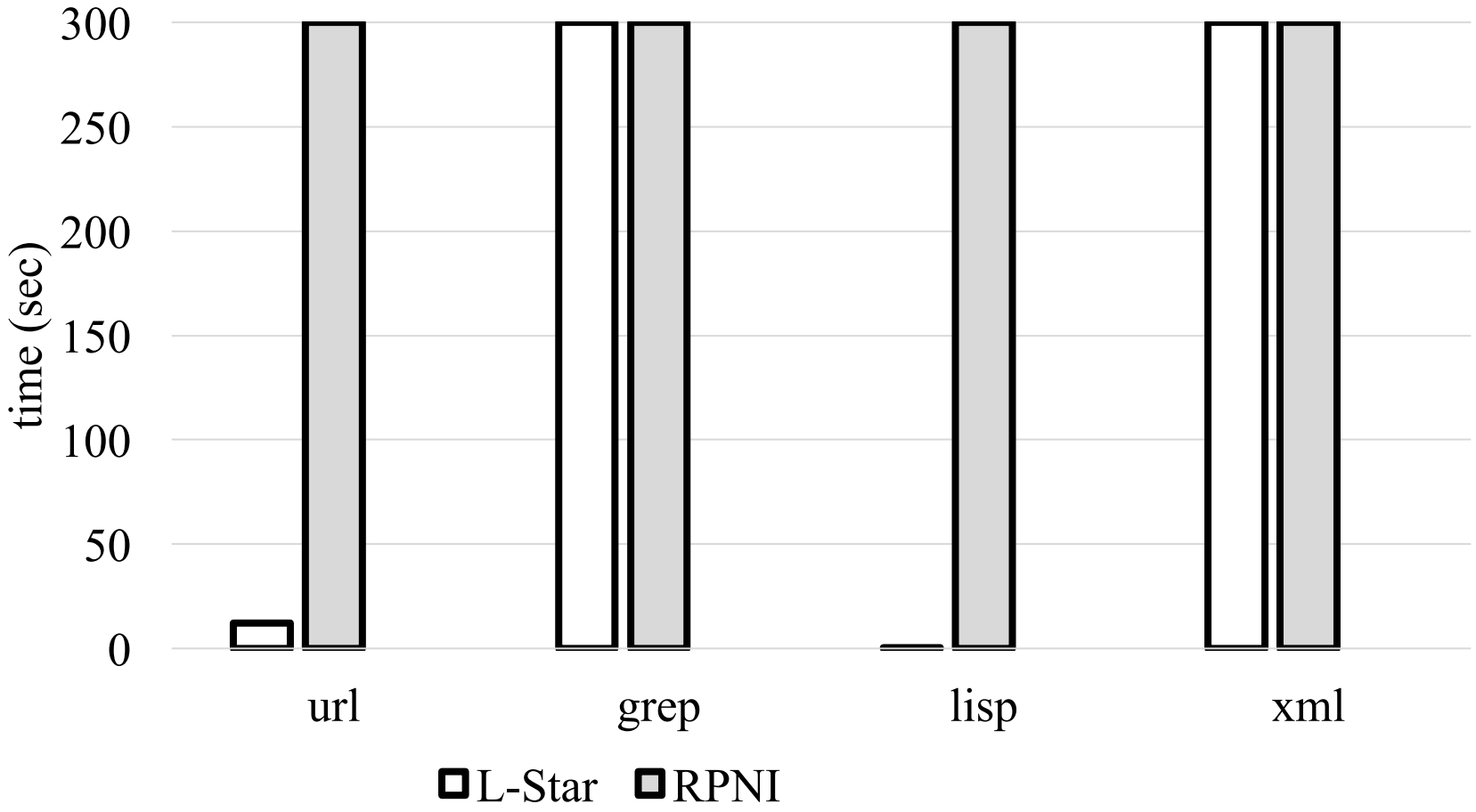

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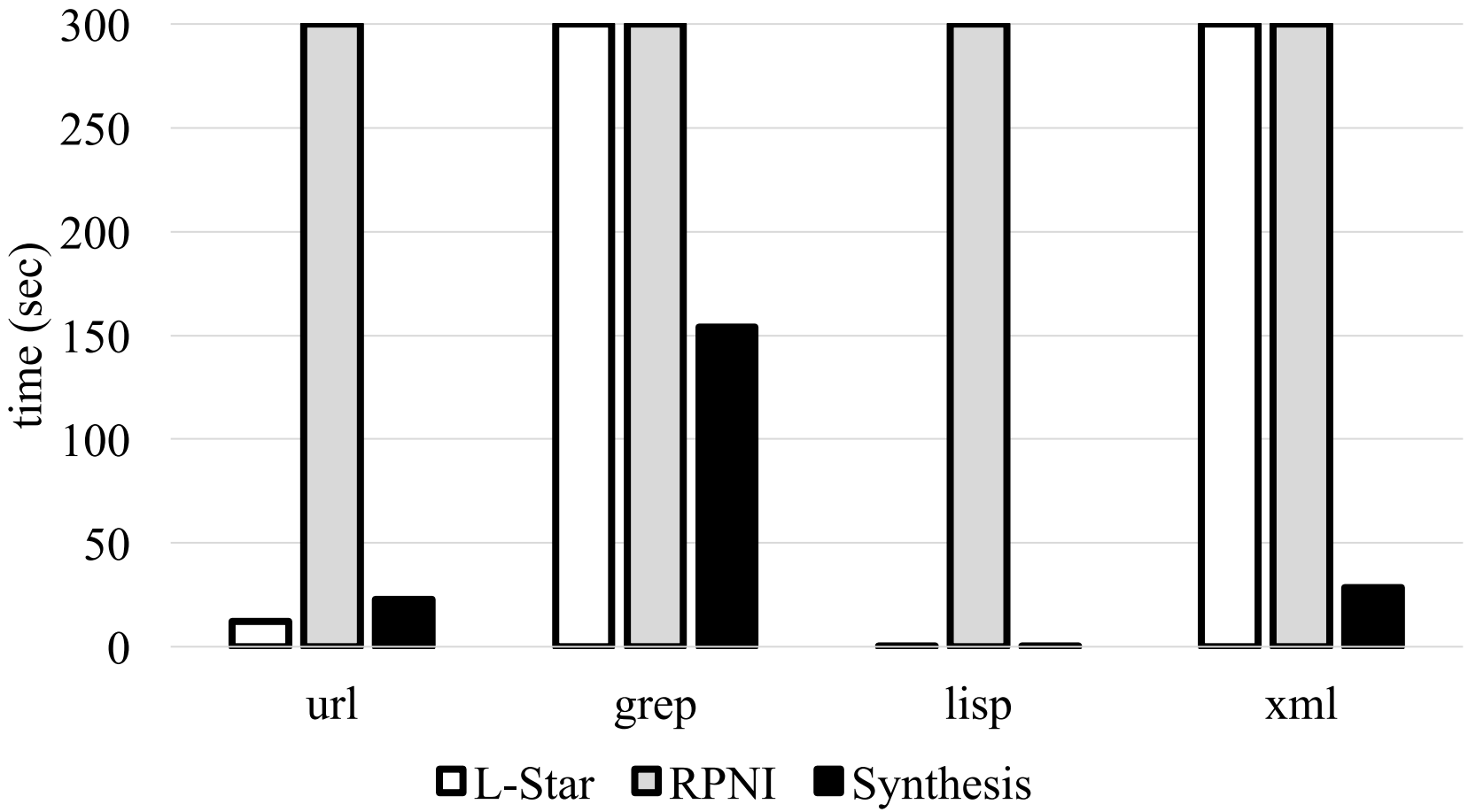

Evaluation: Fuzz Testing

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Fuzzer: synthesize grammar,
randomly resample subtrees of parse tree

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Baselines: naïve (random insertions/deletions)
afl-fuzz (production fuzzer)

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Baselines: naïve (random insertions/deletions)
afl-fuzz (production fuzzer)

Programs: Grep, Sed, Flex, Bison, XML Parser
Python, Ruby, SpiderMonkey (parser only)

Evaluation: Fuzz Testing

Fuzzer:	synthesize grammar, randomly resample subtrees of parse tree
Baselines:	naïve (random insertions/deletions) afl-fuzz (production fuzzer)
Programs:	Grep, Sed, Flex, Bison, XML Parser Python, Ruby, SpiderMonkey (parser only)
Inputs:	50,000 samples

Evaluation: Fuzz Testing

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Valid coverage: $\mathrm{Cov}(E) = \#(\text{lines covered by } E \cap L_*)$

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Evaluation: Fuzz Testing

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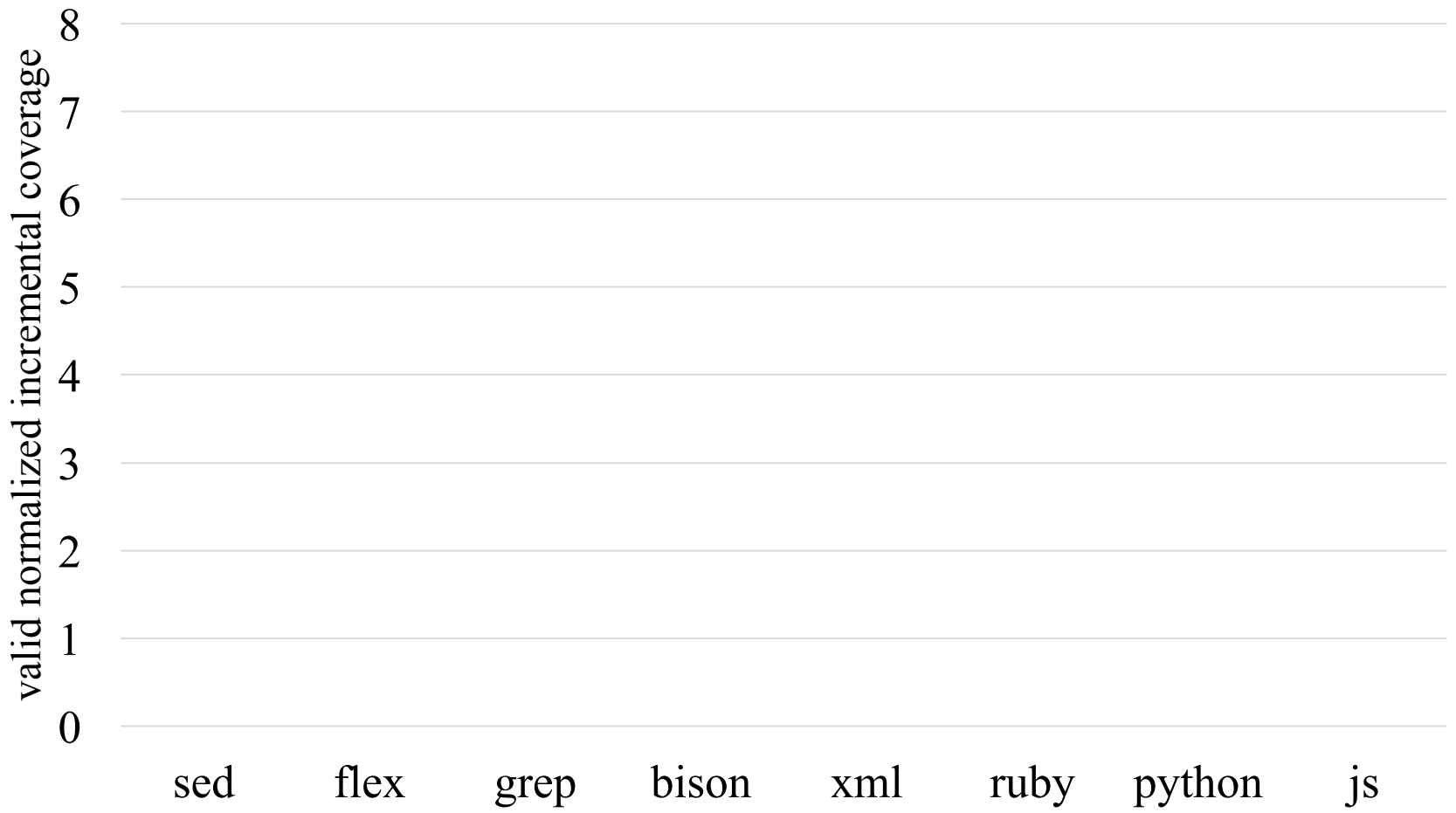
Incremental coverage: $\mathrm{IncCov}(E) = \mathrm{Cov}(E) - \mathrm{Cov}(\alpha_{\mathrm{in}})$

Normalized: $\mathrm{NormIncCov}(E) = \dfrac{\mathrm{IncCov}(E)}{\mathrm{IncCov}(E_{\mathrm{naïve}})}$

Evaluation: Fuzz Testing



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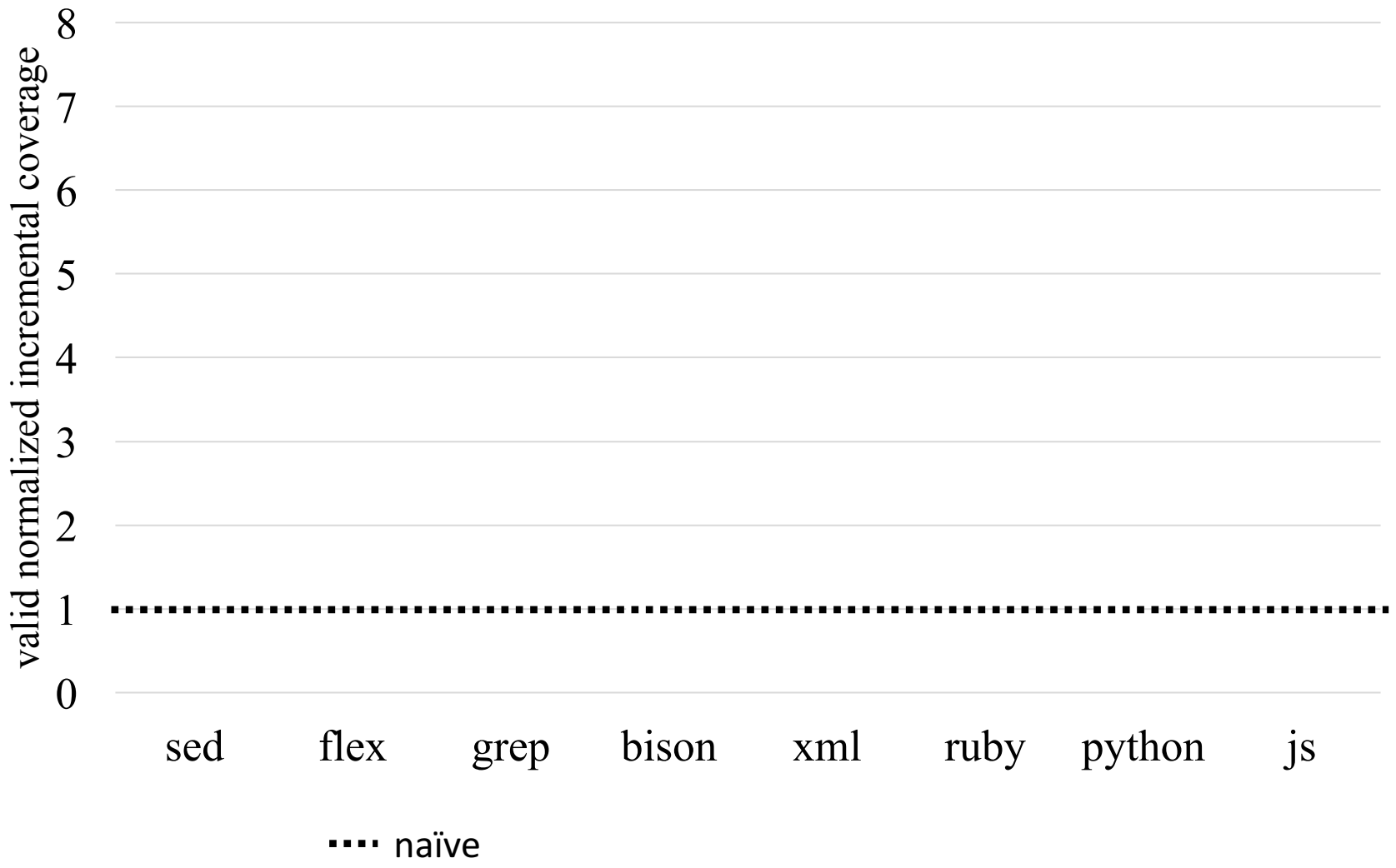

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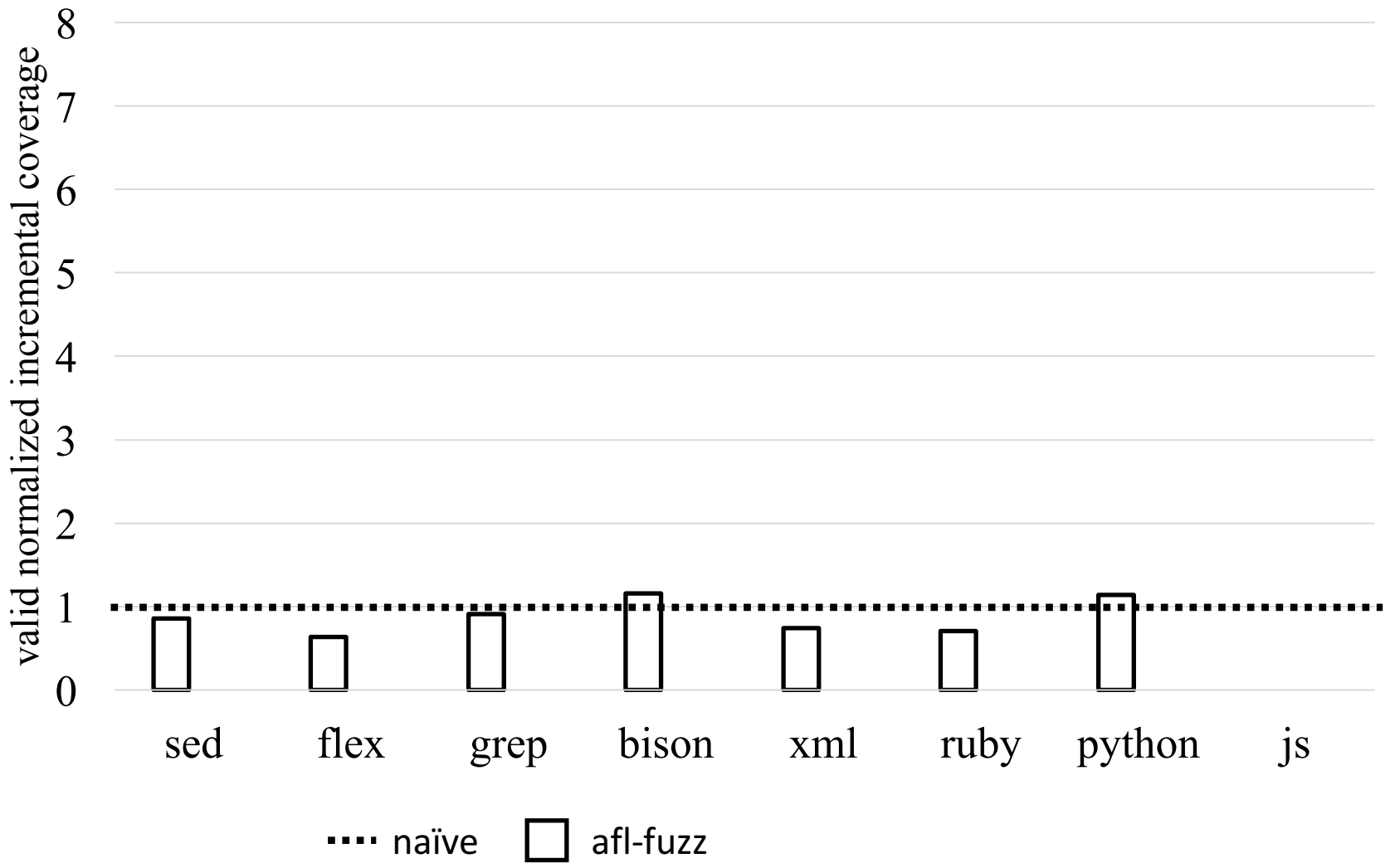

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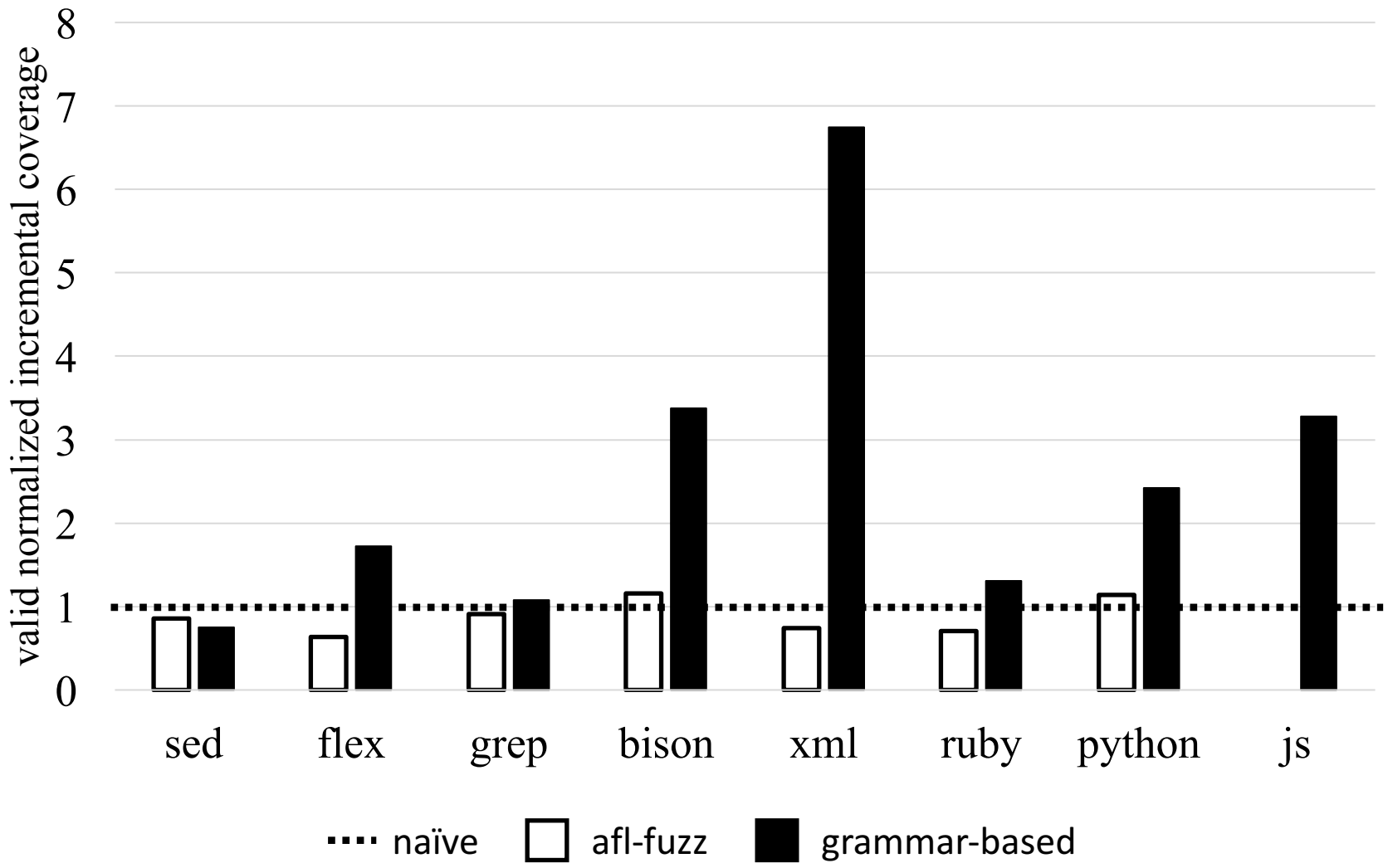

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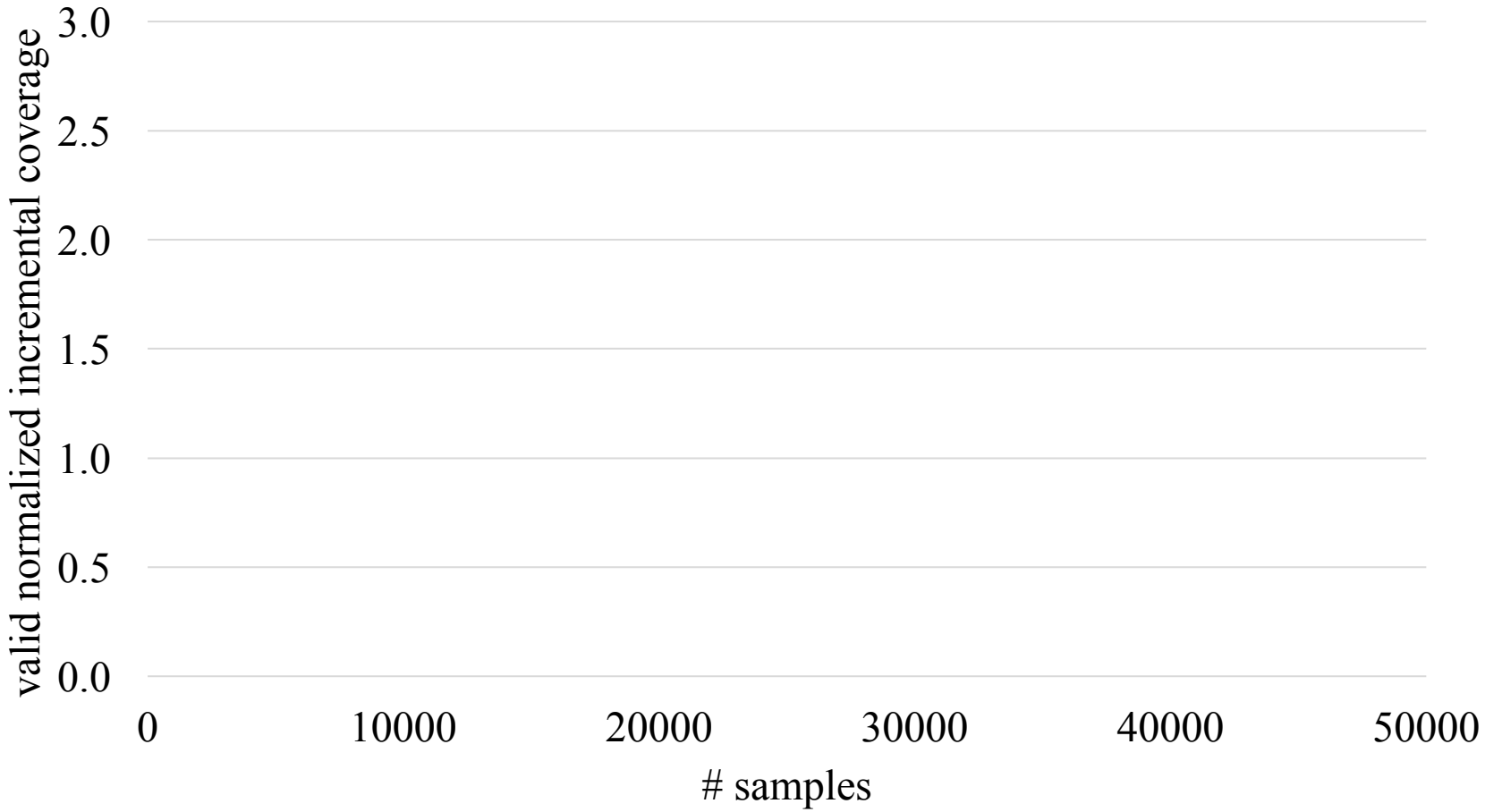

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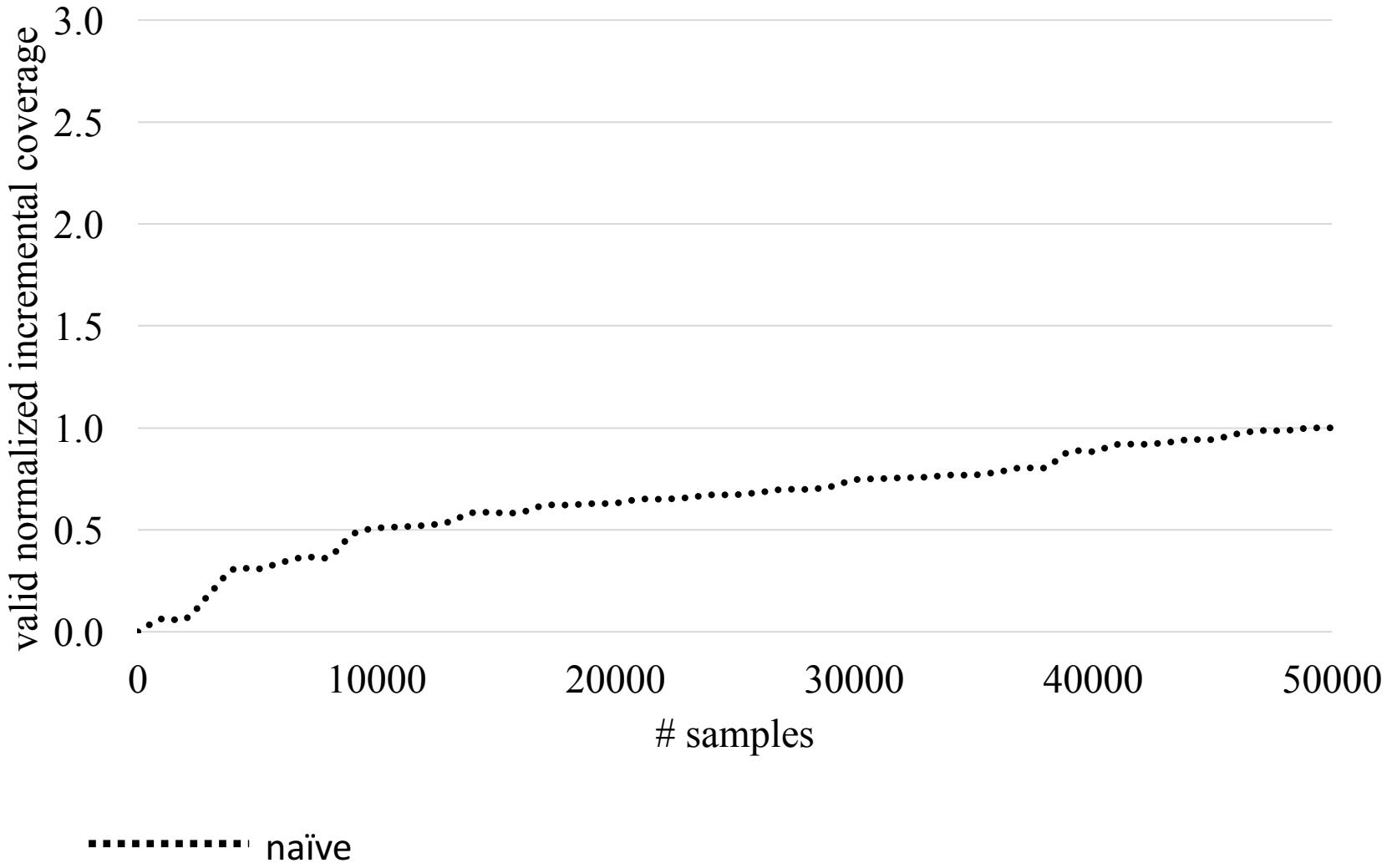

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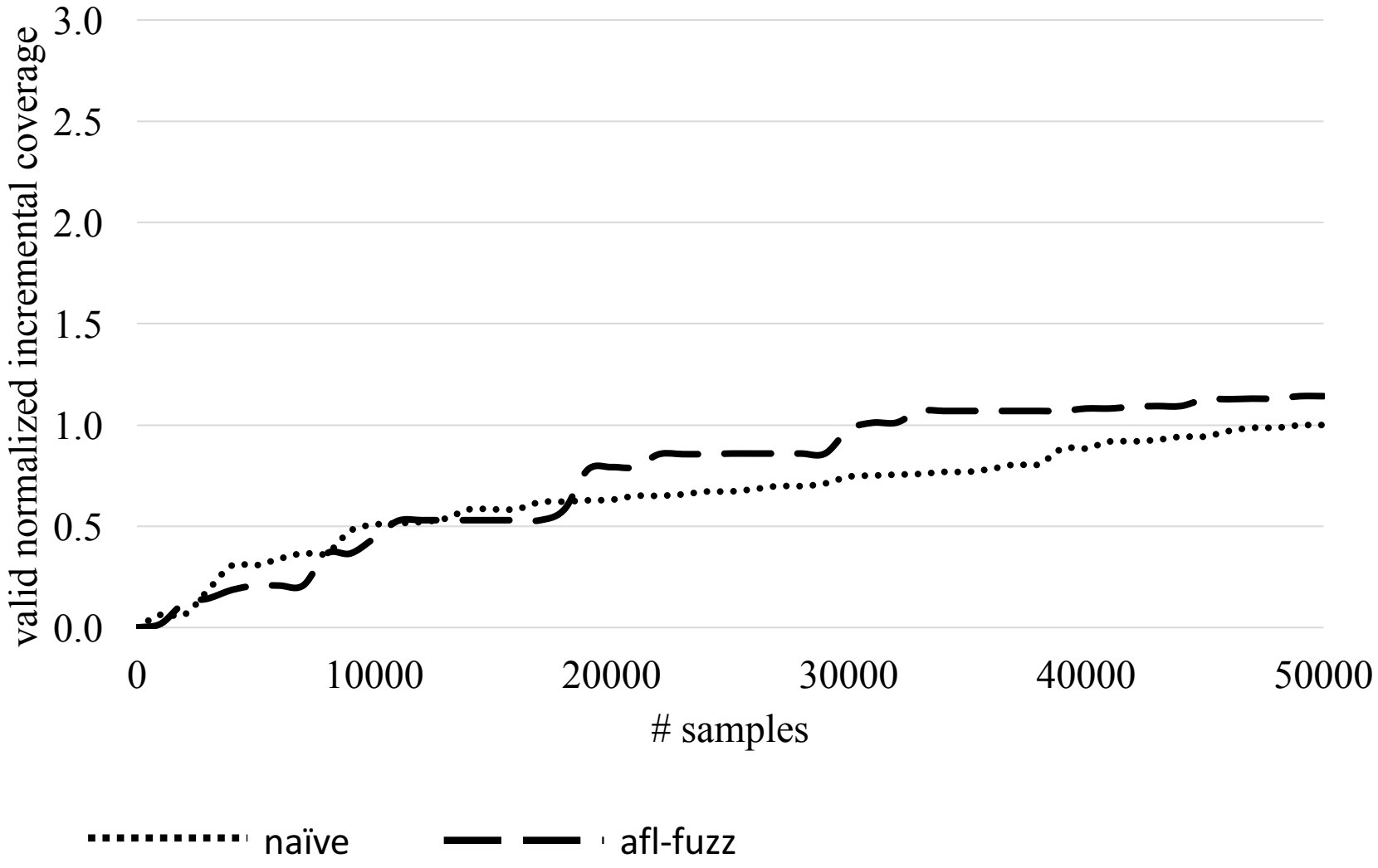

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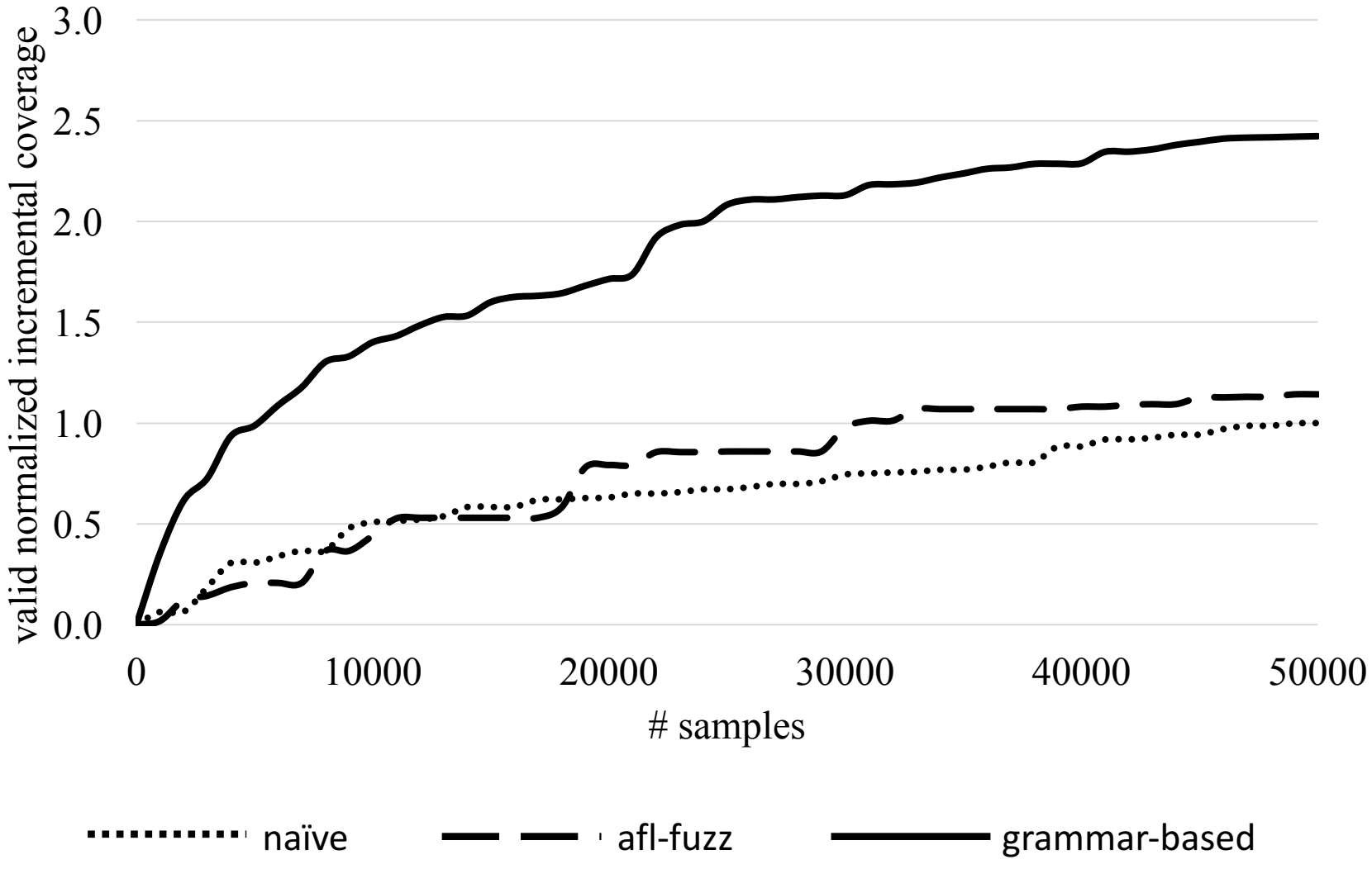

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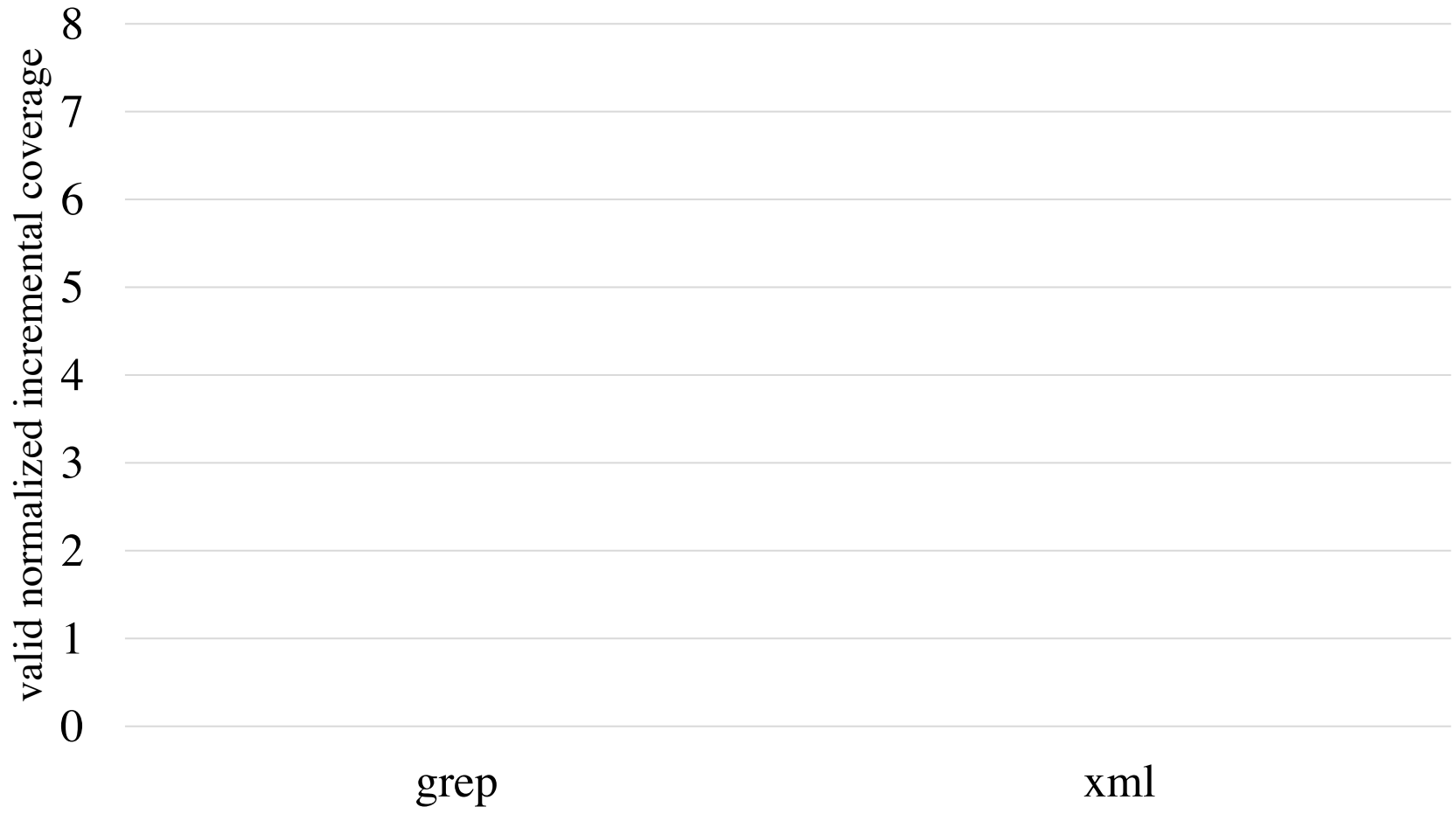

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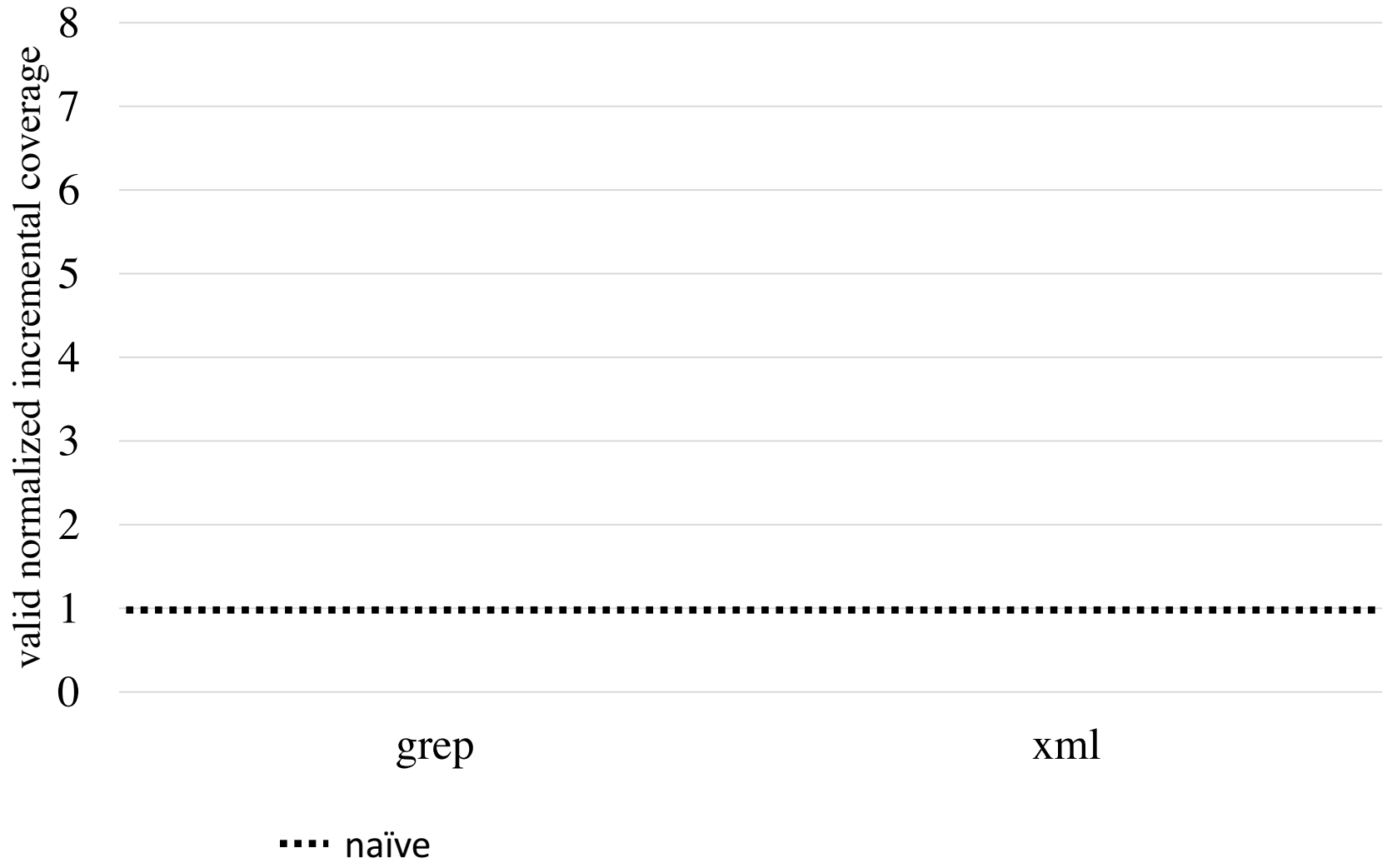

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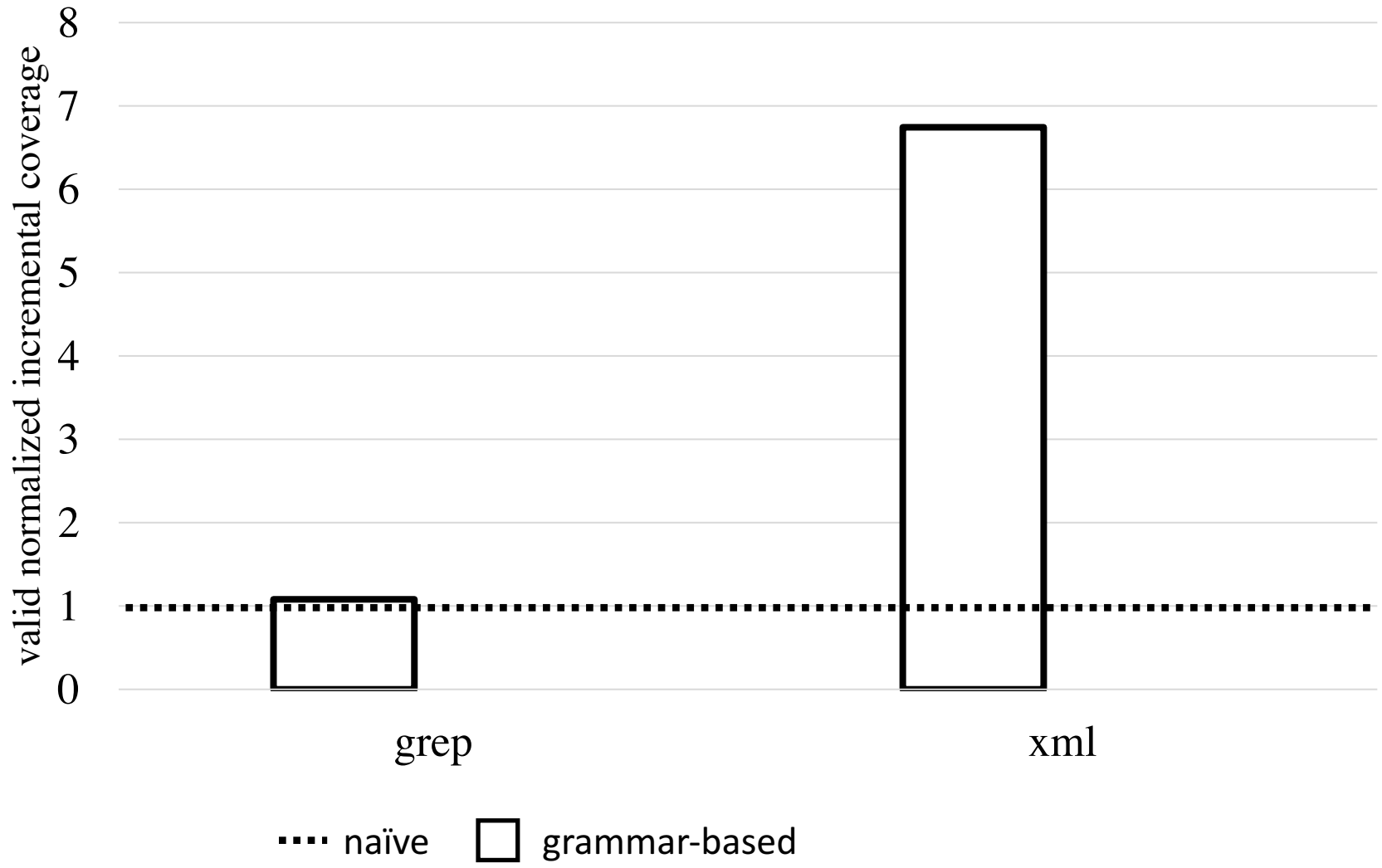

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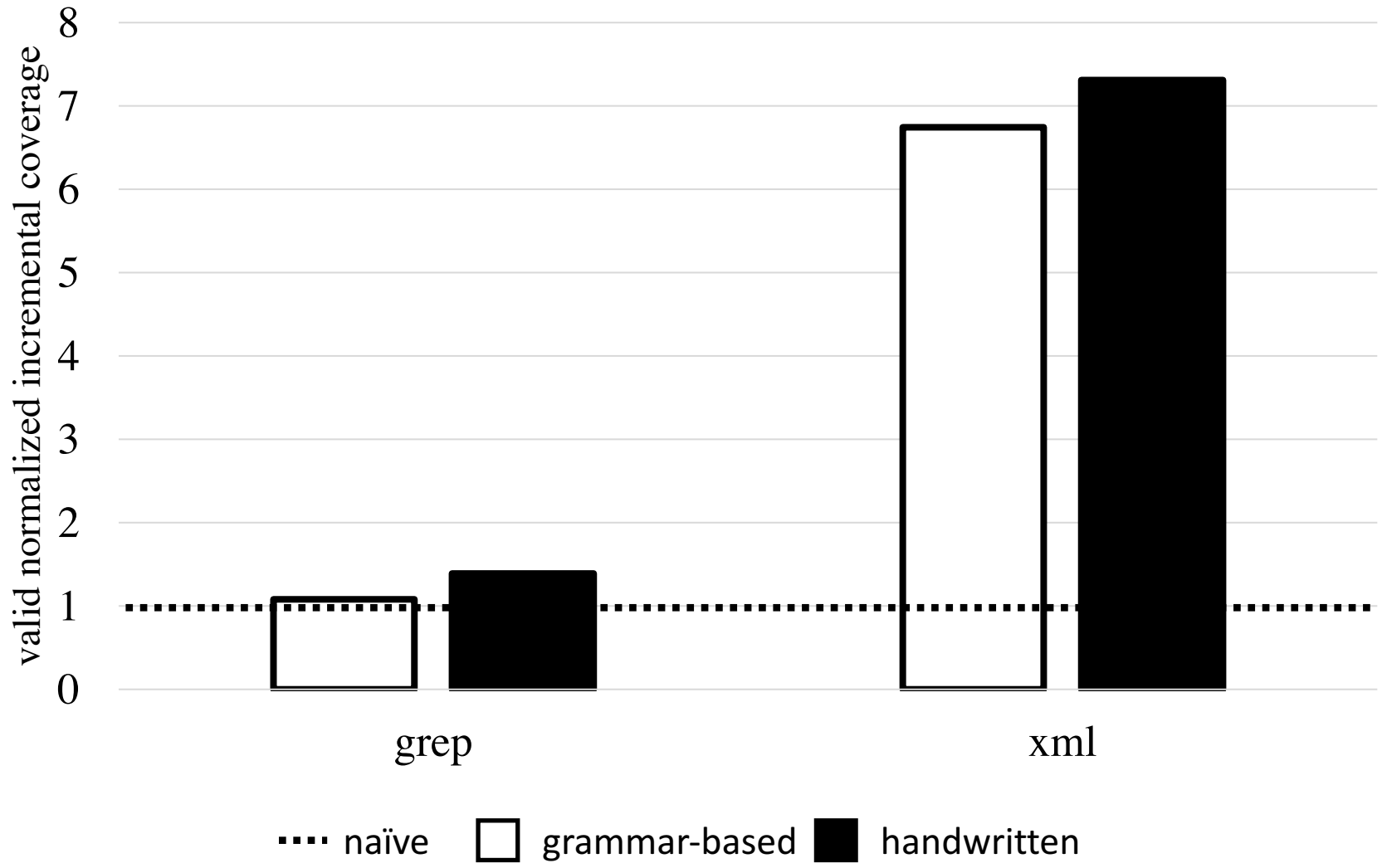

Learn program properties from input-output examples

- “Extreme” form of active learning

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Questions?

Backup Slides

Phase One: Regular Expressions

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Repetitions: $S\alpha T$

Phase One: Regular Expressions

Repetitions: $S\alpha T \Rightarrow S\alpha^{*}T$

Phase One: Regular Expressions

Repetitions: $S\alpha T \Rightarrow S\alpha^{*}T$

Alternations: $S\alpha\beta T$

Phase One: Regular Expressions

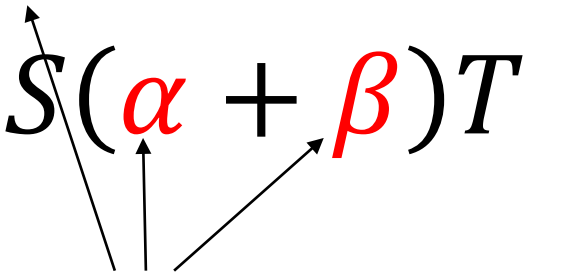
Repetitions: $S\alpha T \Rightarrow S\alpha^* T$

Alternations: $S\alpha\beta T \Rightarrow S(\alpha + \beta)T$

Phase One: Regular Expressions

Repetitions: $S\alpha T \Rightarrow S\alpha^* T$

Alternations: $S\alpha\beta T \Rightarrow S(\alpha + \beta)T$



recursively generalize

Phase Two: Merging CFG Nonterminals

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$$A \rightarrow \ldots A \ldots B \ldots$$
$$B \rightarrow \ldots A \ldots C \ldots$$

Phase Two: Merging CFG Nonterminals

$$\boxed{\begin{array}{l} A \rightarrow \ \ldots A \ldots B \ldots \\ B \rightarrow \ \ldots A \ldots C \ldots \end{array}} \Rightarrow \boxed{\begin{array}{l} A \rightarrow \ \ldots A \ldots A \ldots \\ A \rightarrow \ \ldots A \ldots C \ldots \end{array}}$$

Guarantees

Guarantees

Theorem 1: The search space includes all regular languages

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Theorem 2: The search space includes all "generalized matching parentheses" languages

Generalized Matching Parentheses

$$T \to R(T_1 + \cdots + T_k)^* R'$$

Guarantees

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Need to use the “right” candidate ordering

Guarantees

Need to use the “right” candidate ordering
We use an intuitive heuristic that works empirically