Beyond Deductive Inference in Program Analysis

Osbert Bastani

Stanford University

Thesis Defense

October 2017

80 KLOC

10 MLOC

Linux

20.2 MLOC

Google

2 BLOC

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100 LOC

1 bug

Program analysis tools help developers write correct software coverity®

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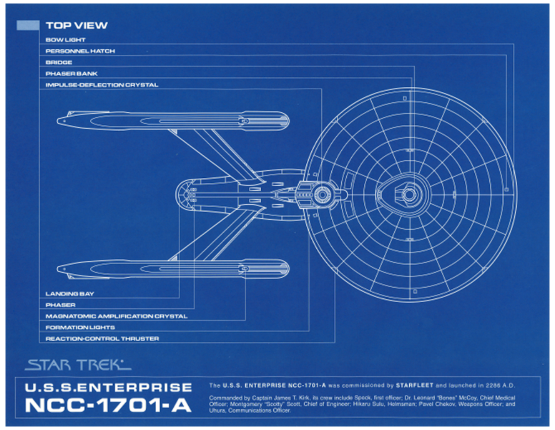
```
int main(int argc, char **argv) {
  char *keys;
  size_t keycc, oldcc, keyalloc;
  bool with_filenames;
  size_t cc;
  int opt, prepended;
  int prev_optind, last_recursive;
  int fread_errno;
  intmax_t default_context;
  FILE *fp;
  exit_failure = EXIT_TROUBLE;
  initialize_main (&argc, &argv);
  set_program_name (argv[0]);
  program_name = argv[0];
  // ...
}
```



TOP VIEW
BOW LIGHT
PERSONNEL HATCH
BRIDGE
PHASER BANK
IMPULSE-DEFLECTION CRYSTAL
LANDING BAY
PHASER
MAGNATOMIC AMPLIFICATION CRYSTAL
FORMATION LIGHTS
REACTION-CONTROL THRUSTER
STAR TREK
U.S.S.ENTERPRISE
NCC-1701-A
The U.S.S. ENTERPRISE NCC-1701-A was commissioned by STARFLEET and launched in 2286 A.D. Commanded by Captain James T. Kirk, its crew include Spock, first officer; Dr. Leonard "Bones" McCoy, Chief Medical Officer; Montgomery "Scotty" Scott, Chief of Engineer; Hikaru Sulu, Helmsman; Pavel Chekov, Weapons Officer; and Uhura, Communications Officer.

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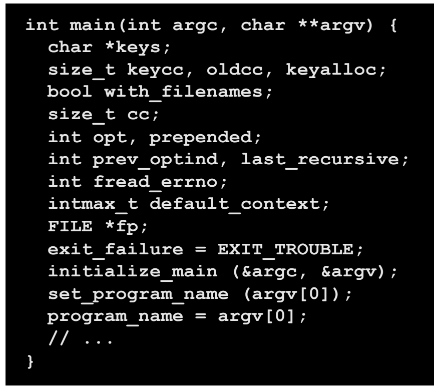

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```

- No memory bugs
- Not malicious

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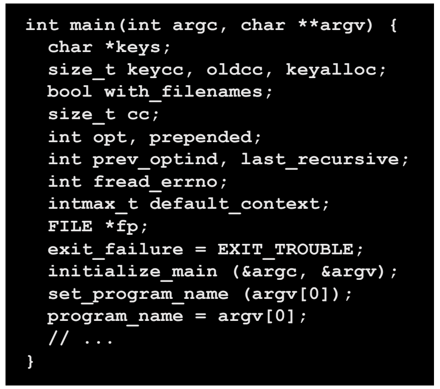
Static

- Analyze

Dynamic:

- Execute



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```

- No memory bugs
- Not malicious

Static

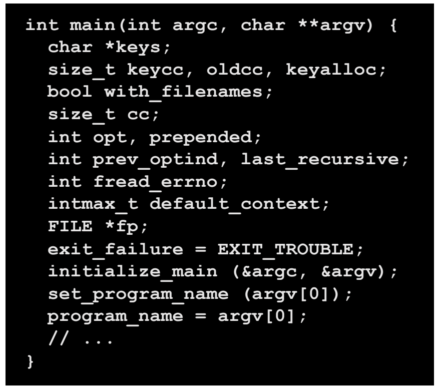
- Analyze

Dynamic:

- Execute

- Correctness proof
- Bugs

Problem: Missing information about inputs



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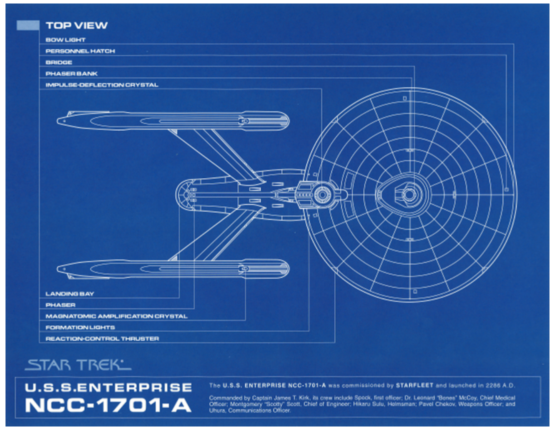
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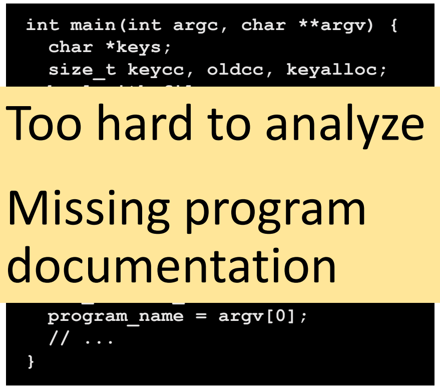

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  // ...
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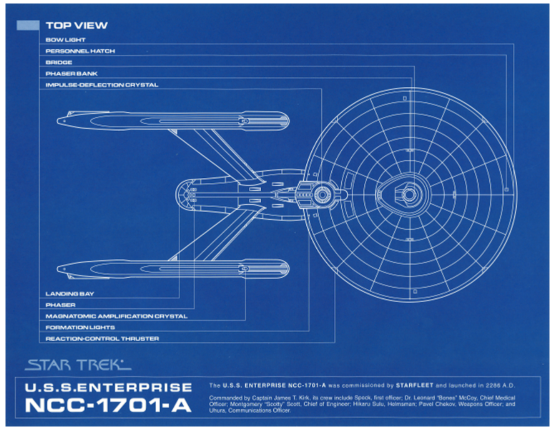
```

- Too hard to analyze
- Missing program documentation



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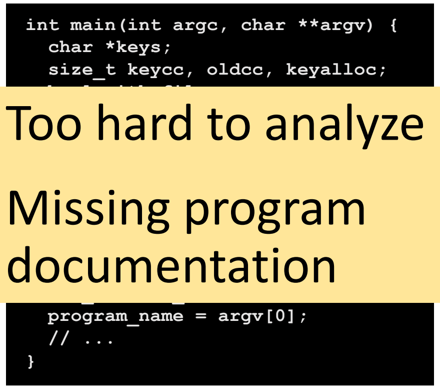

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  ...
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}
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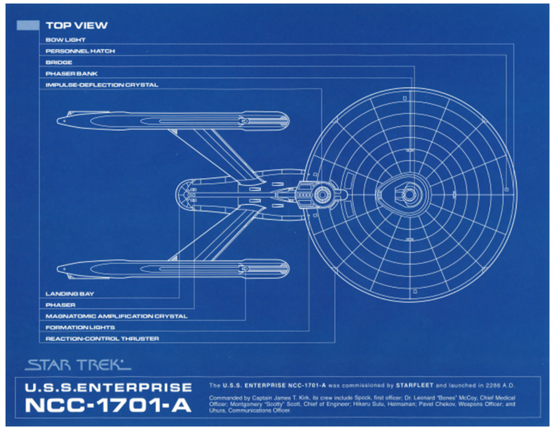

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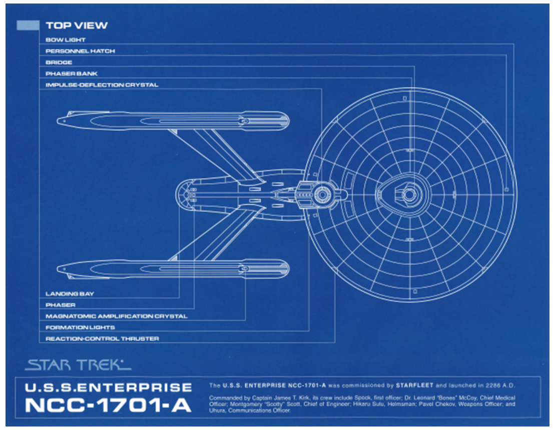

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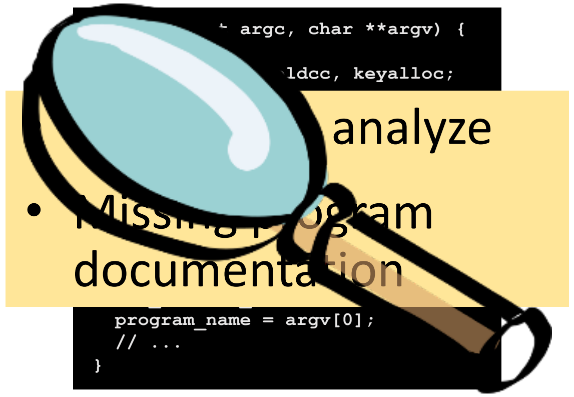
Solution: Infer missing information

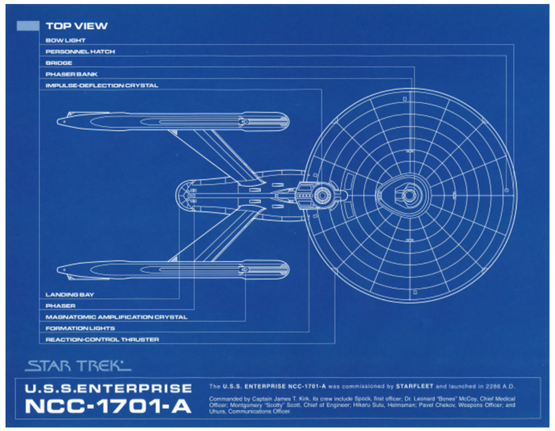


```
    argc, char **argv) {
    ldcc, keyalloc;
```

analyze

- Missing program documentation

```
  program_name = argv[0];
  // ...
}
```



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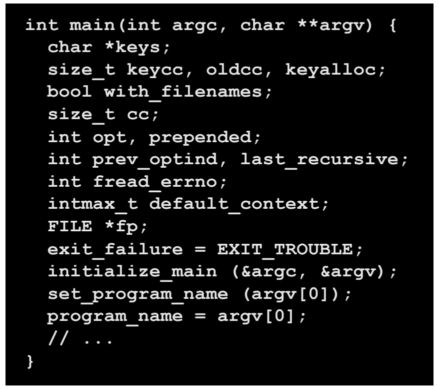
Problem: Missing code needs **summaries**
Solution: Interactively infer summaries

Problem: Fuzzer aided by **input language**
Solution: Automatically infer input language

Inferring Summaries of Missing Code

Osbert Bastani, Saswat Anand, and Alex Aiken

POPL 2015



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  bool with_filenames;
  size_t cc;
  int opt, prepended;
  int prev_optind, last_recursive;
  int fread_errno;
  intmax_t default_context;
  FILE *fp;
  exit_failure = EXIT_TROUBLE;
  initialize_main (&argc, &argv);
  set_program_name (argv[0]);
  program_name = argv[0];
  // ...
}
```

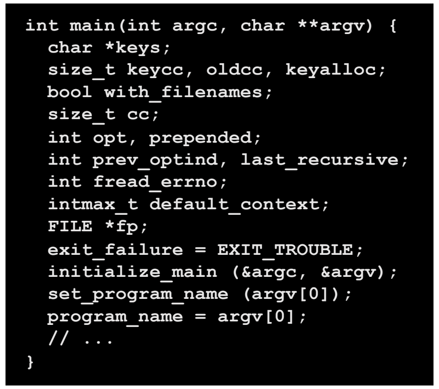
Android app

security analyst

malware?

Find **malicious behaviors** using source to sink **taint flows**

Information leak:	location	flows to	Internet
SMS Fraud:	phone #	used in	SMS send
Ransomware:	network packets	encrypt	files



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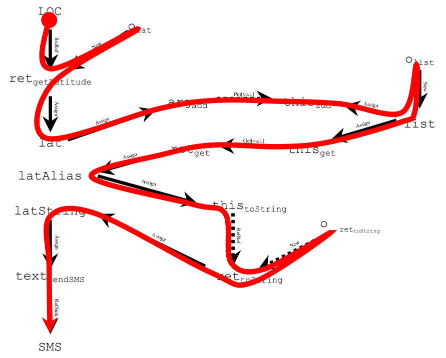
  // ...
}
```

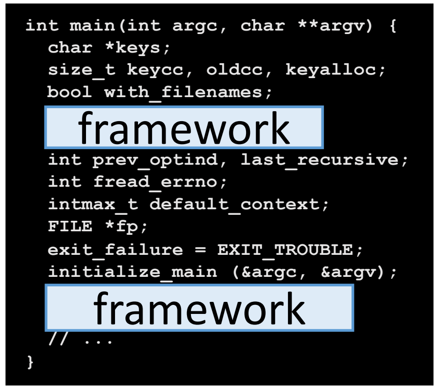
Android app



taint analysis

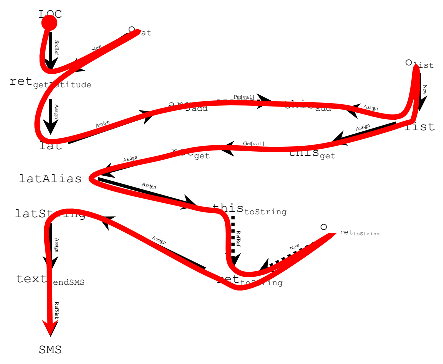
location → Internet
SMS → Internet

malicious behaviors



```
int main(int argc, char **argv) {
  char *keys;
  size_t keycc, oldcc, keyalloc;
  bool with_filenames;
  framework
  int prev_optind, last_recursive;
  int fread_errno;
  intmax_t default_context;
  FILE *fp;
  exit_failure = EXIT_TROUBLE;
  initialize_main (&argc, &argv);
  framework
  // ...
}
```

Android app



taint analysis

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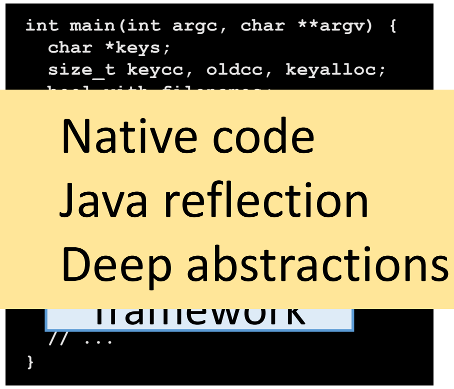
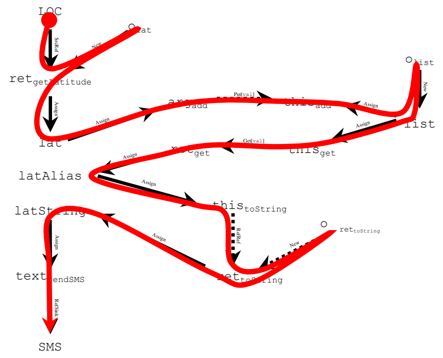


```
int main(int argc, char **argv) {
  char *keys;
  size_t keycc, oldcc, keyalloc;
  // ...
}
```

- Native code
- Java reflection
- Deep abstractions

Android app



taint analysis

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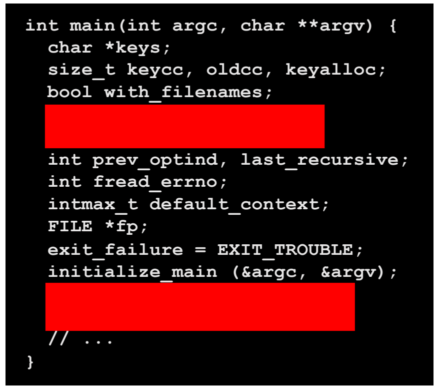

```
int main(int argc, char **argv) {
  char *keys;
  size_t keycc, oldcc, keyalloc;
  bool with_filenames;
  [redacted]
  int prev_optind, last_recursive;
  int fread_errno;
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  // ...
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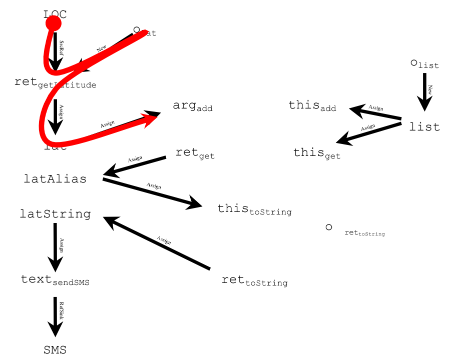
```

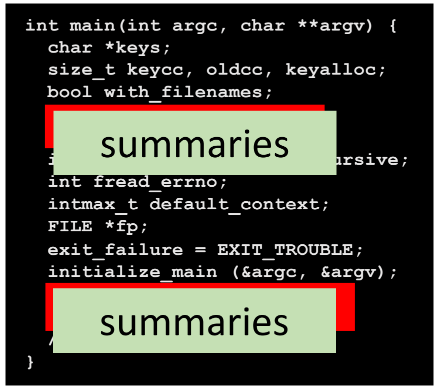
Android app



taint analysis

?

malicious behaviors



```
int main(int argc, char **argv) {
  char *keys;
  size_t keycc, oldcc, keyalloc;
  bool with_filenames;
      summaries
  i                            ursive;
  int fread_errno;
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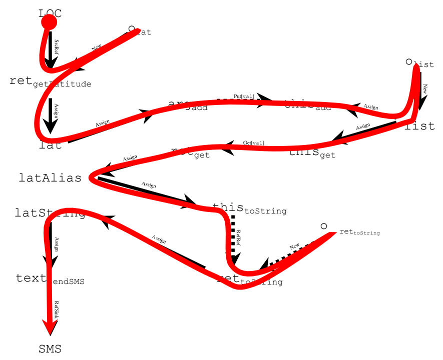
```

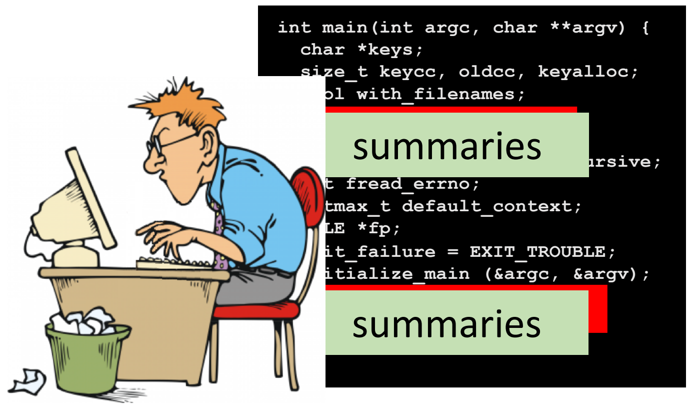
Android app



taint analysis

location → Internet
SMS → Internet

malicious behaviors



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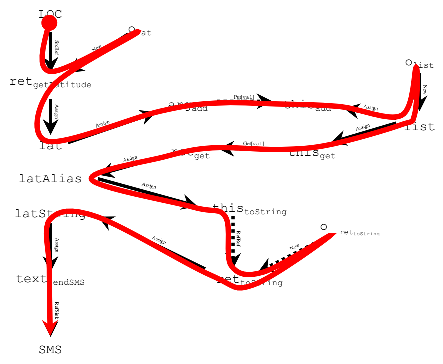
Android app



taint analysis

location → Internet
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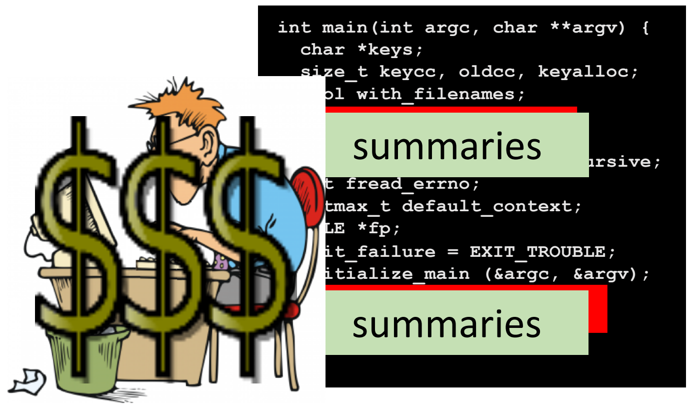

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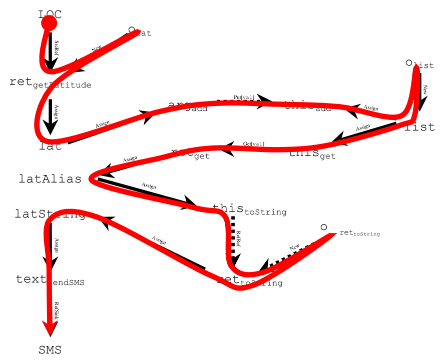

taint analysis

location → Internet
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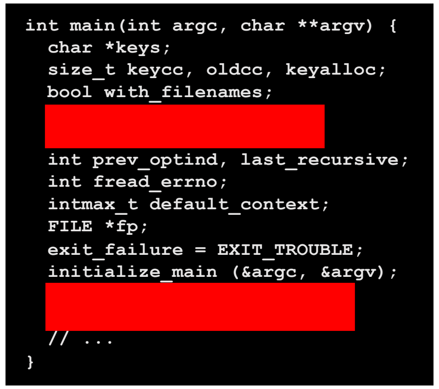

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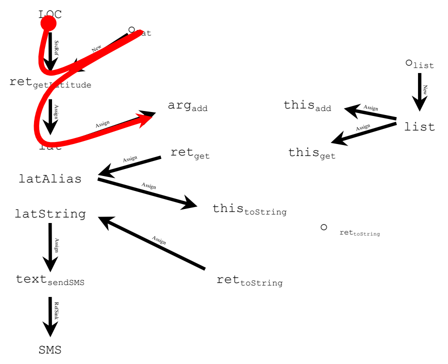
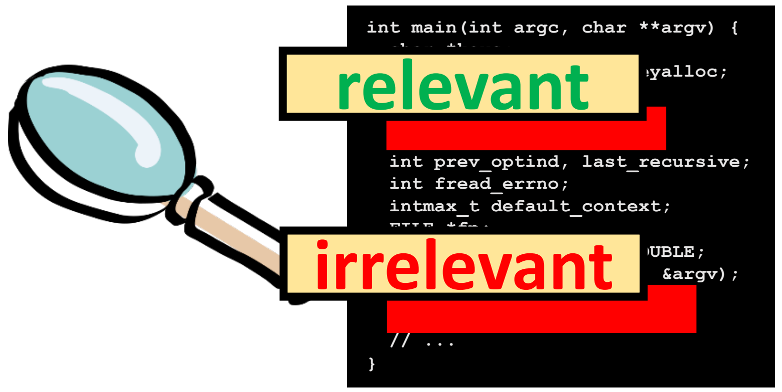
Android app



taint analysis

?

malicious behaviors



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                                  yalloc;

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  int fread_errno;
  intmax_t default_context;

                                  UBLE;
                                  &argv);

  // ...
}
```
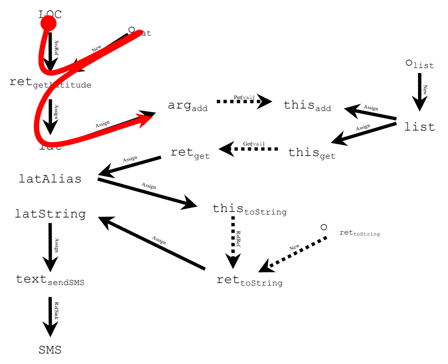

Android app



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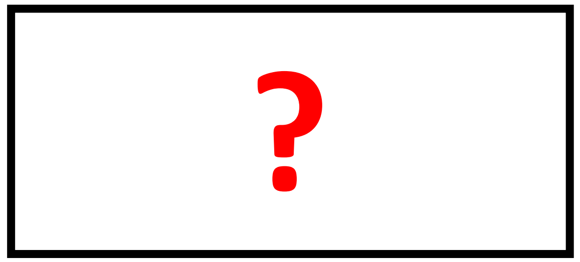
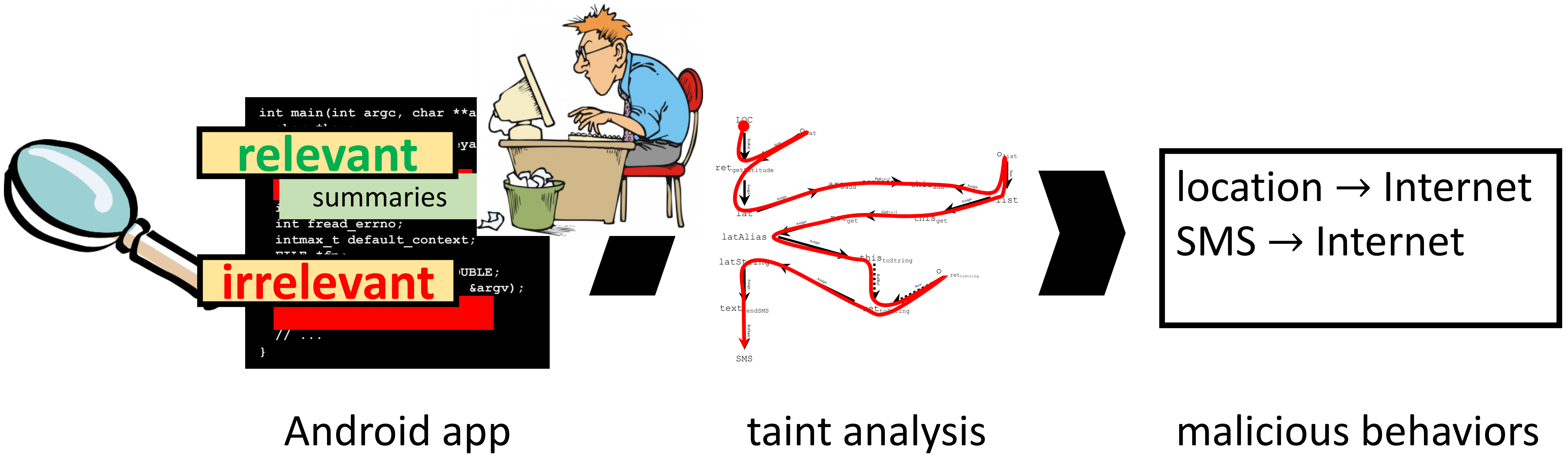


malicious behaviors


relevant
summaries
irrelevant
int main(int argc, char **a
int fread_errno;
intmax_t default_context;
UBLE;
&argv);
// ...
}
LOC
latAlias
SMS
location → Internet
SMS → Internet
Android app
taint analysis
malicious behaviors

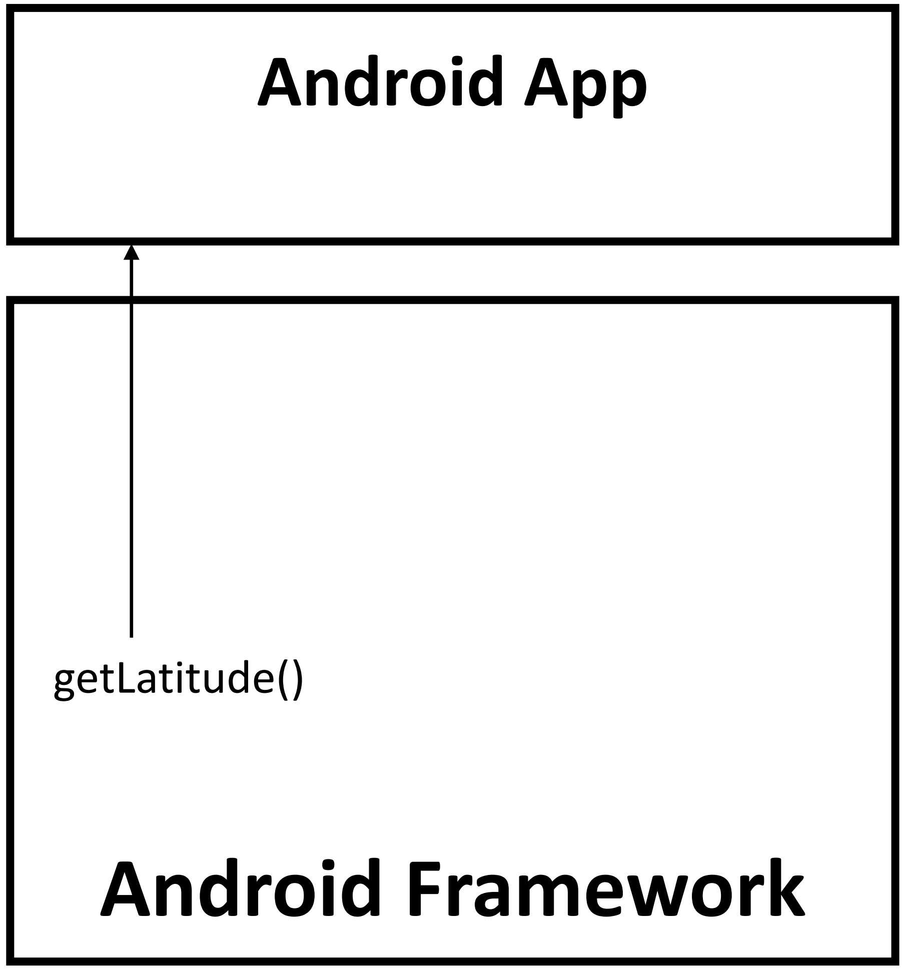
Taint Analysis

```
Double lat = getLatitude();
List list = new List();
list.add(lat);
Double latAlias = list.get(0);
String latStr = latAlias.toString();
sendHttp(latStr);
```

Android App
Android Framework

Taint Analysis

```
1. Double lat = getLatitude();
2. List list = new List();
3. list.add(lat);
4. Double latAlias = list.get(0);
5. String latStr = latAlias.toString();
6. sendHttp(latStr);
```



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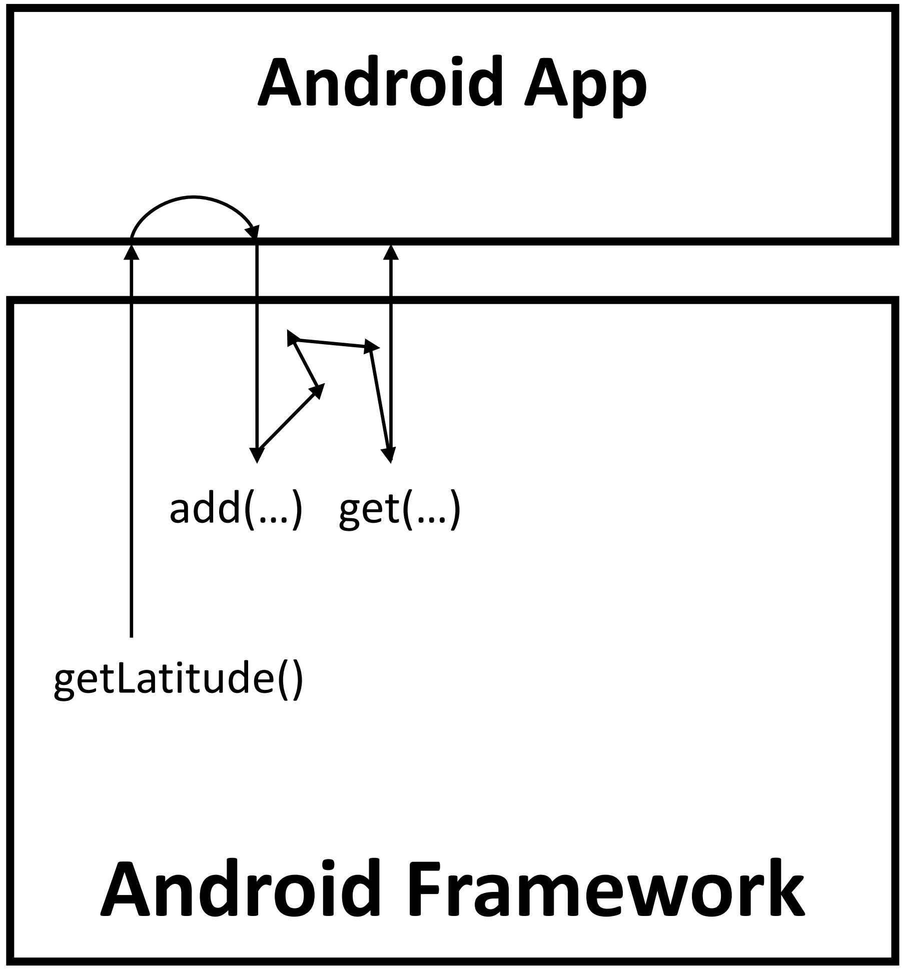

Taint Analysis

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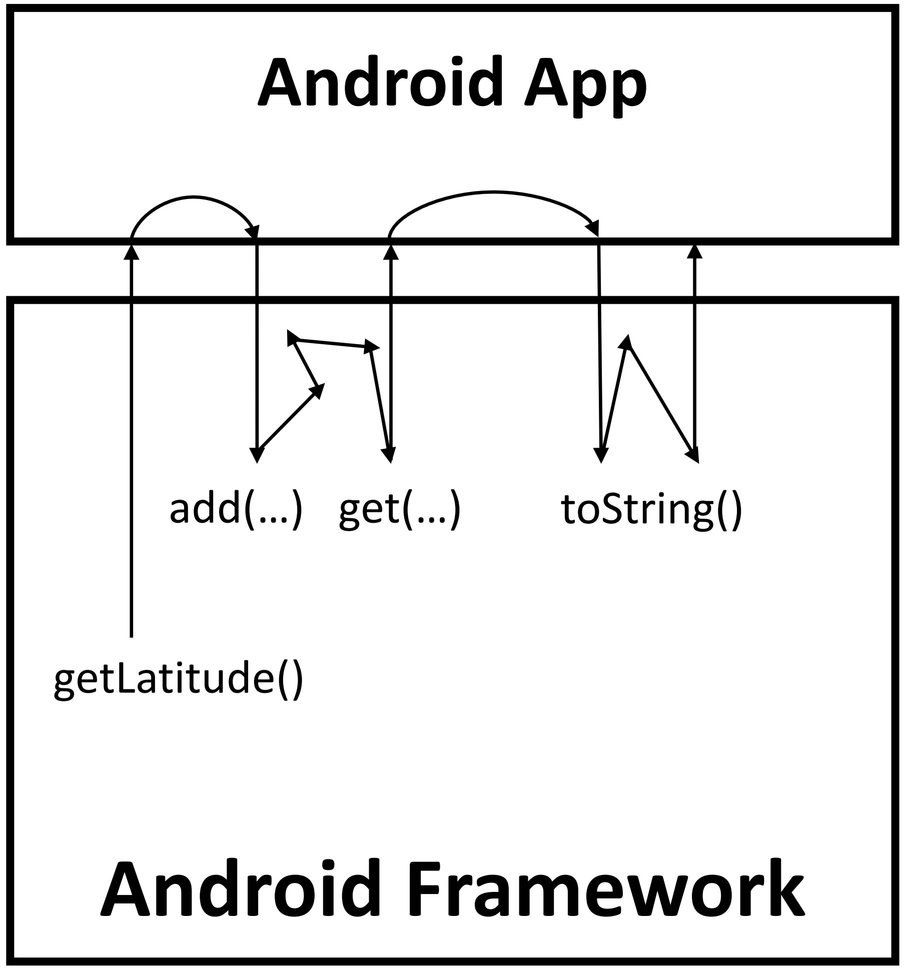

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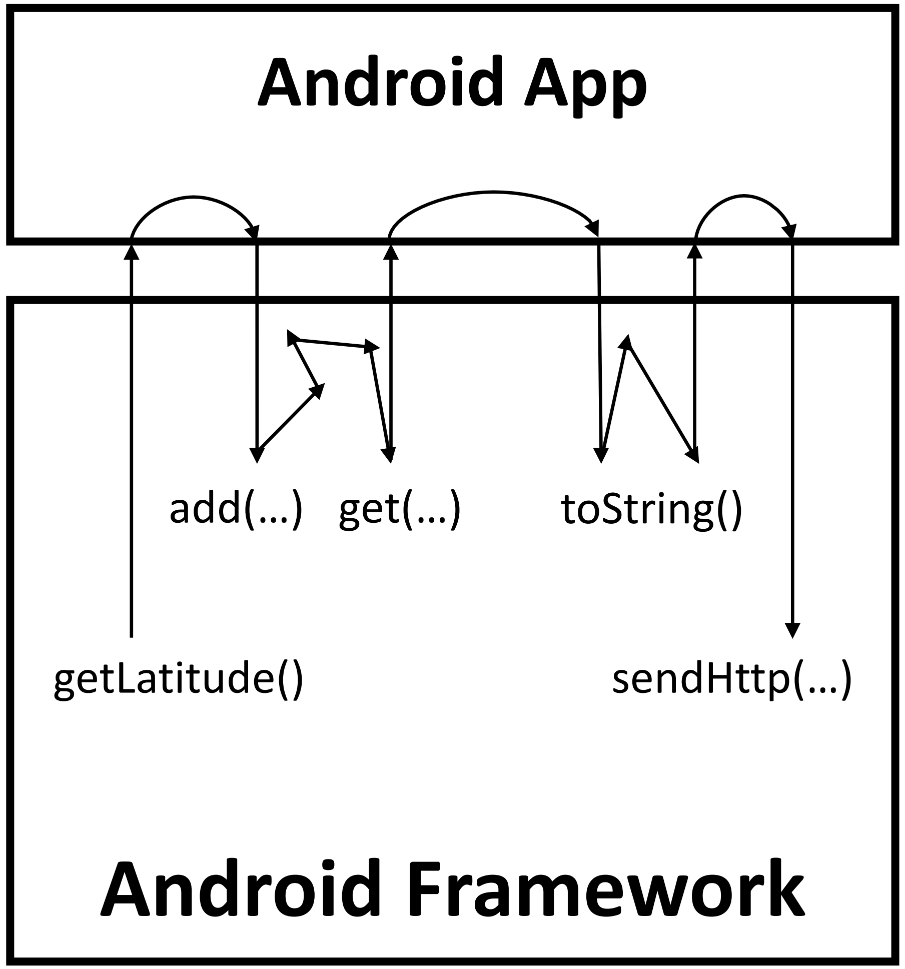

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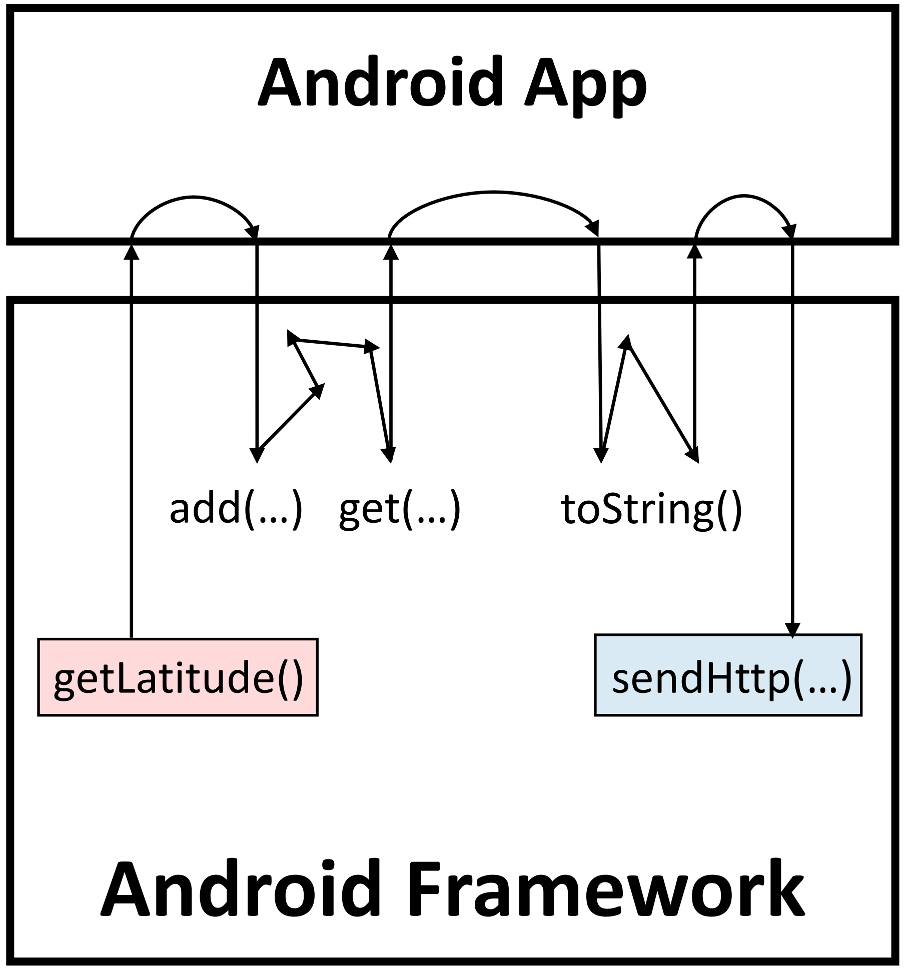
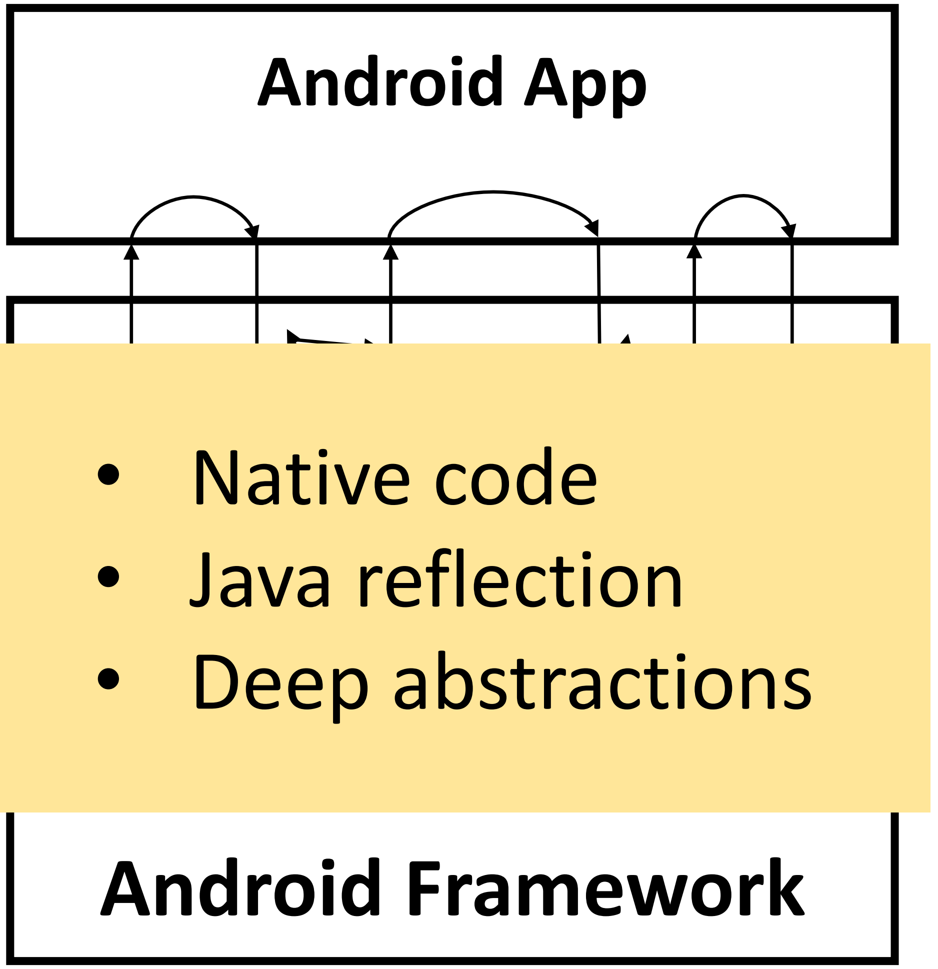
5. **String** latStr = latAlias.toString();
6. sendHttp(latStr);



Taint Analysis

```
Double lat = getLatitude();
List list = new List();
list.add(lat);
Double latAlias = list.get(0);
String latStr = latAlias.toString();
sendHttp(latStr);
```



- Native code
- Java reflection
- Deep abstractions

Flow summary

- Describes taint transfer
- **@flow**(x, y) means "x tainted ⇒ y tainted"

```
class Double:
    @flow(this, return)
    String toString() {}
```

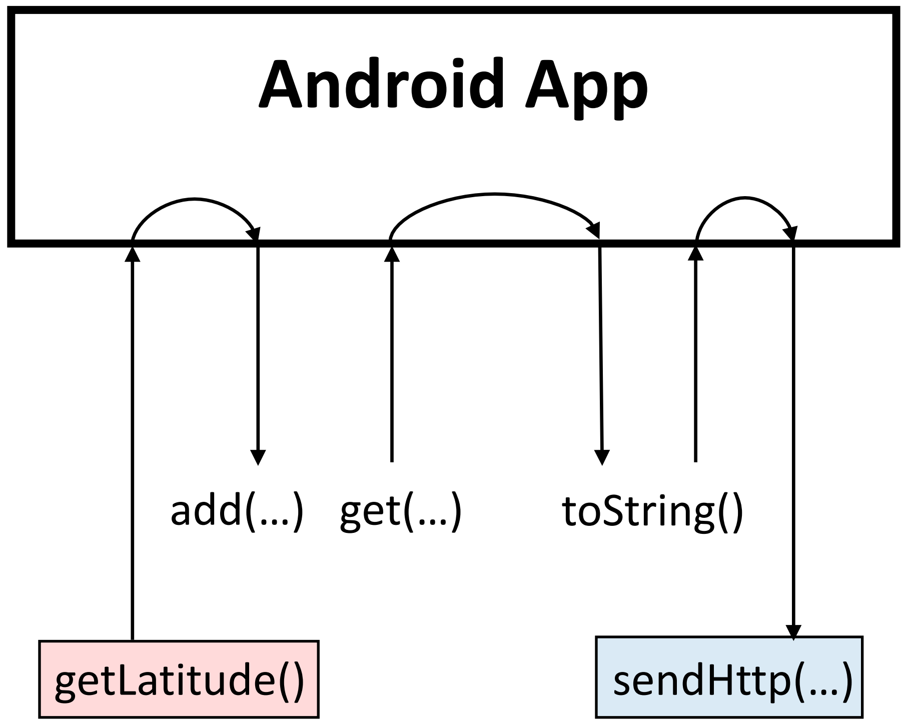
Alias summary

- Describes aliasing
- **@alias**(x, y) means "x may alias y"

```
class List:
    @alias(arg, this.val)
    void add(Object arg) {}

    @alias(this.val, return)
    Object get(Integer index) {}
```

Taint Analysis

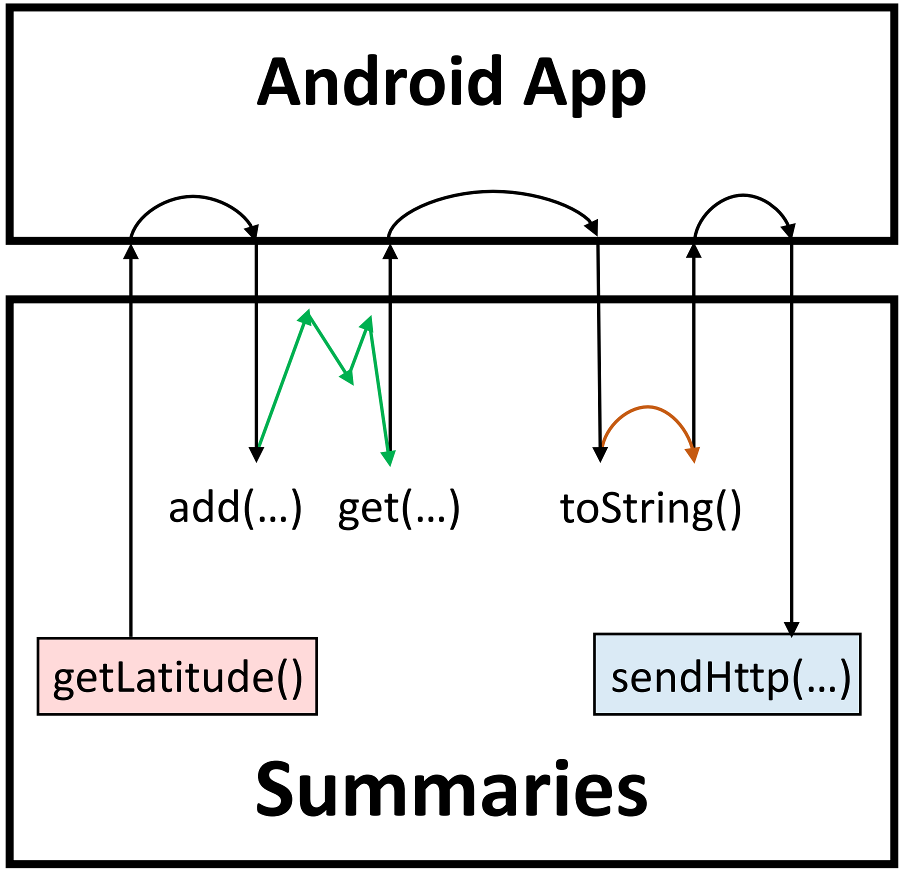


Taint Analysis

```
class List:
    @alias(arg, this.val)
    void add(Object arg) {}

    @alias(this.val, return)
    Object get(Integer index) {}

class Double:
    @flow(this, return)
    String toString() {}
```



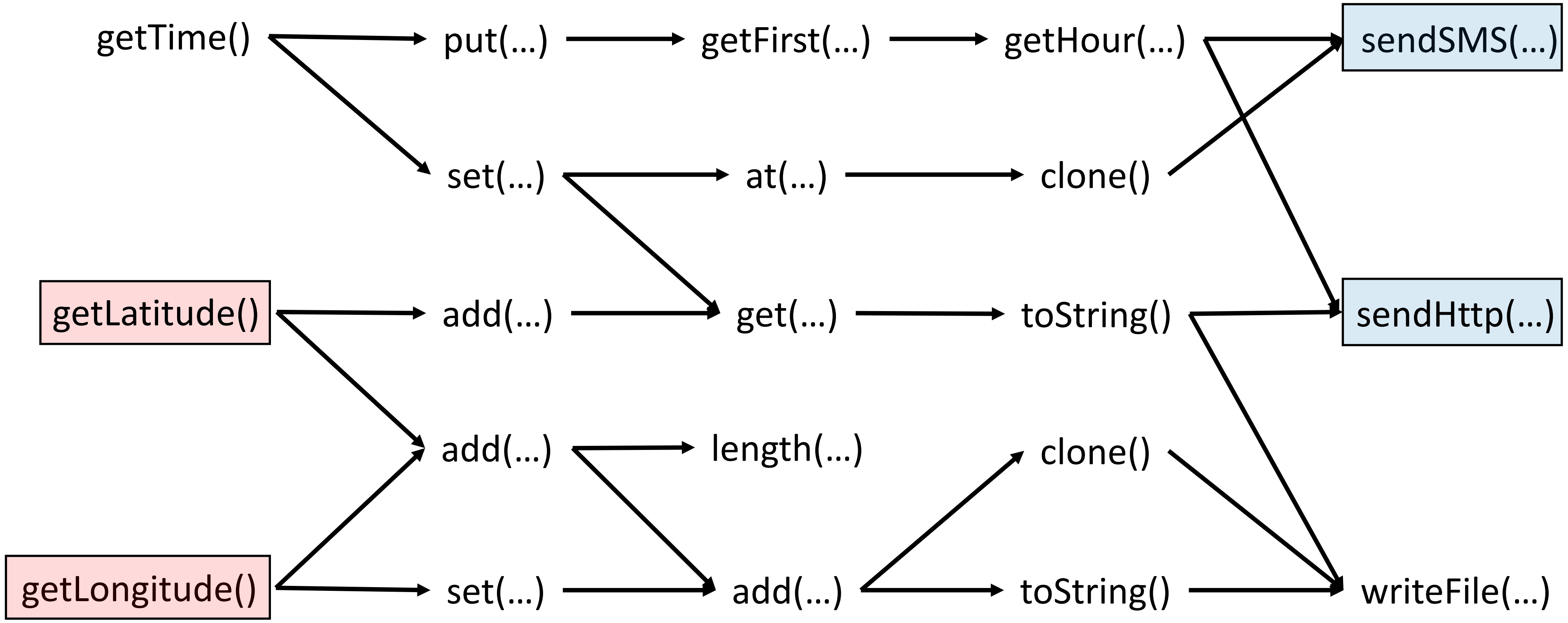
Writing summaries is time consuming:

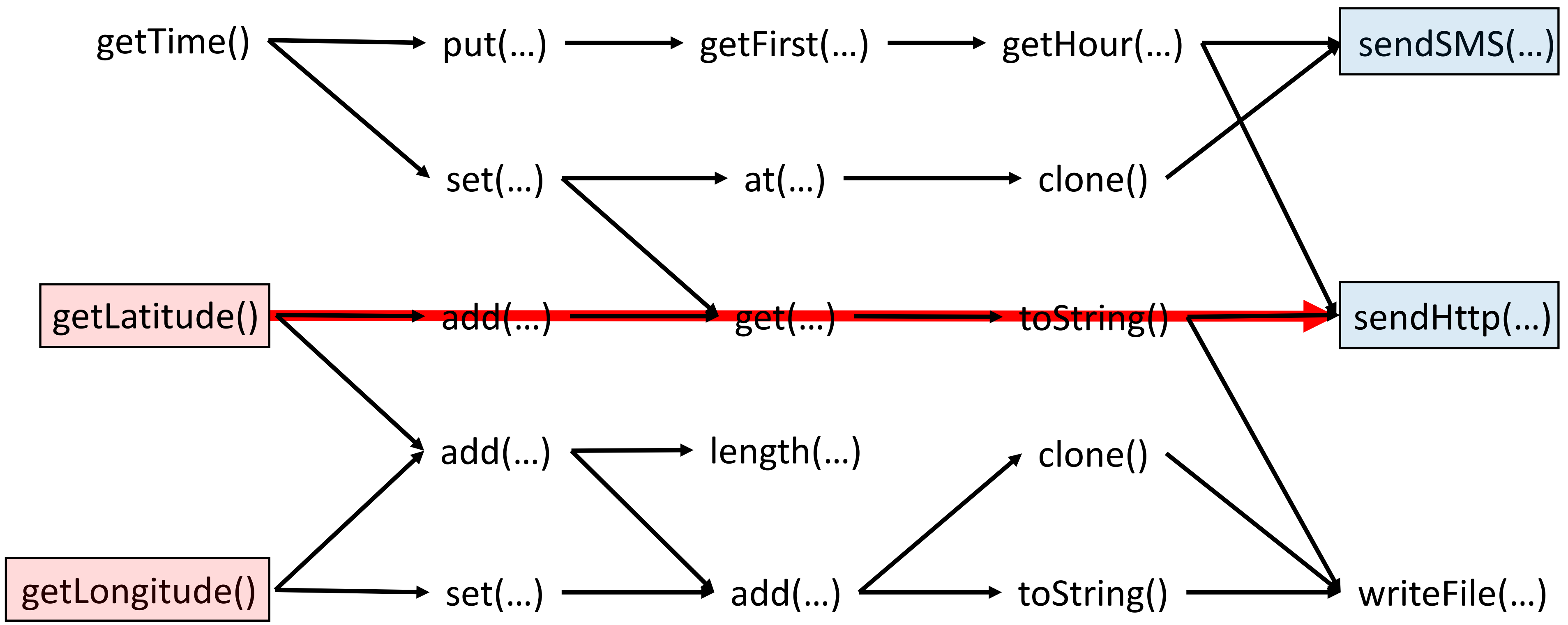
- $\approx 30{,}000$ framework methods
- $\approx 10{,}000$ needed for a typical app
- Maintenance

Insight: Only some methods are relevant

- > 200 apps
- About $1{,}600$ summaries

write summaries **as needed**


getTime()
put(…)
getFirst(…)
getHour(…)
sendSMS(…)
set(…)
at(…)
clone()
getLatitude()
add(…)
get(…)
toString()
sendHttp(…)
add(…)
length(…)
clone()
getLongitude()
set(…)
add(…)
toString()
writeFile(…)


getTime()
put(...)
getFirst(...)
getHour(...)
sendSMS(...)
set(...)
at(...)
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toString()
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length(...)
clone()
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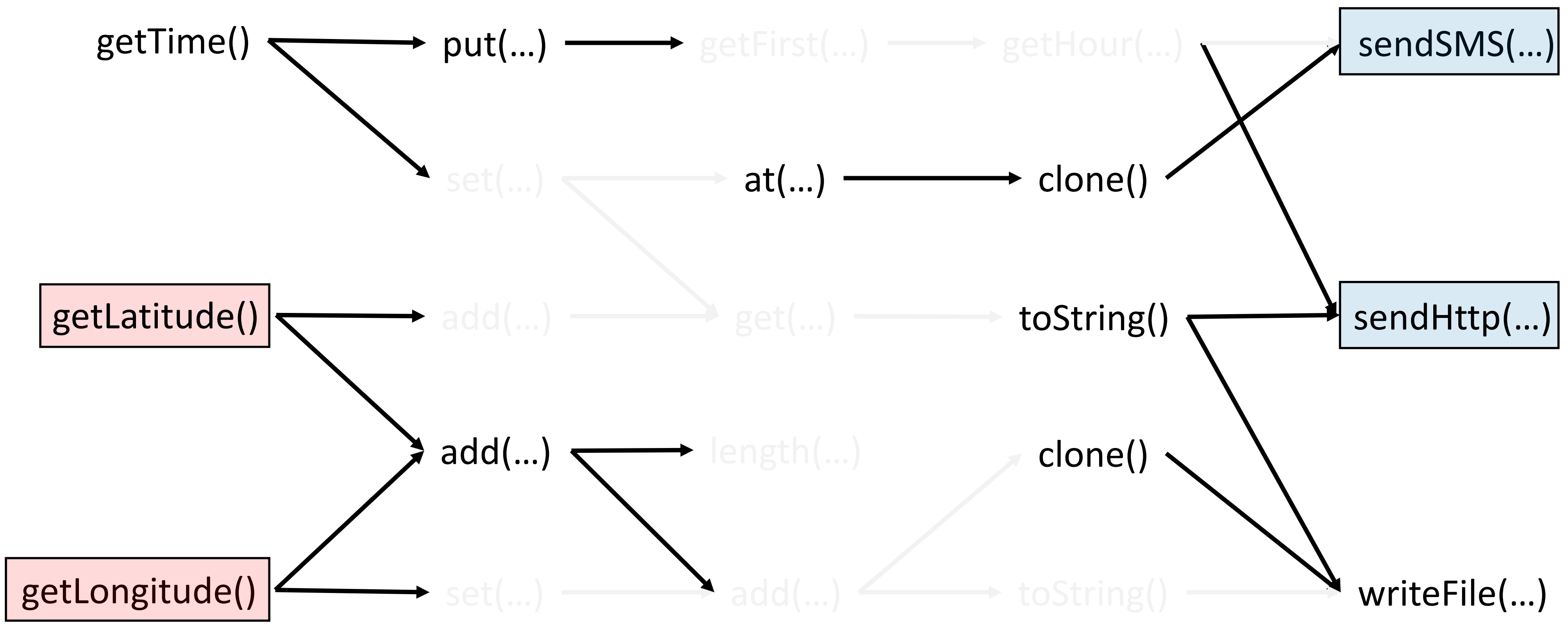
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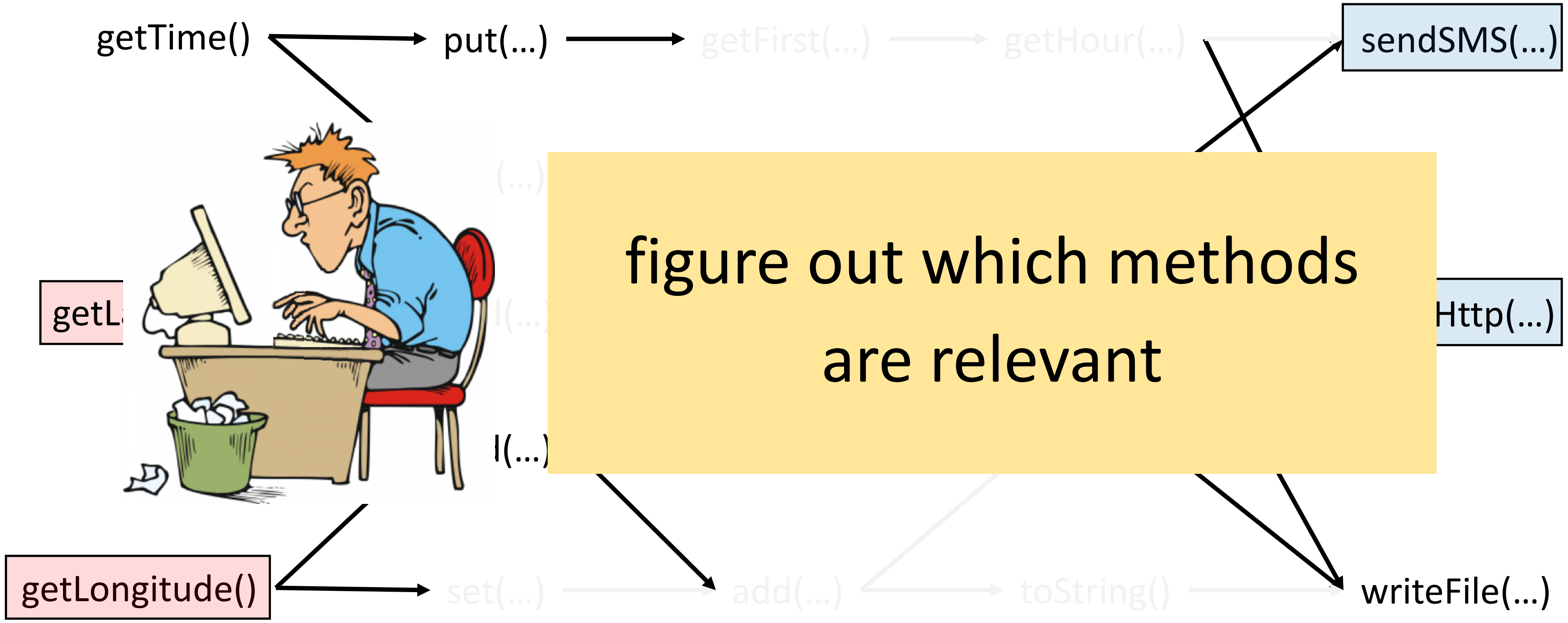
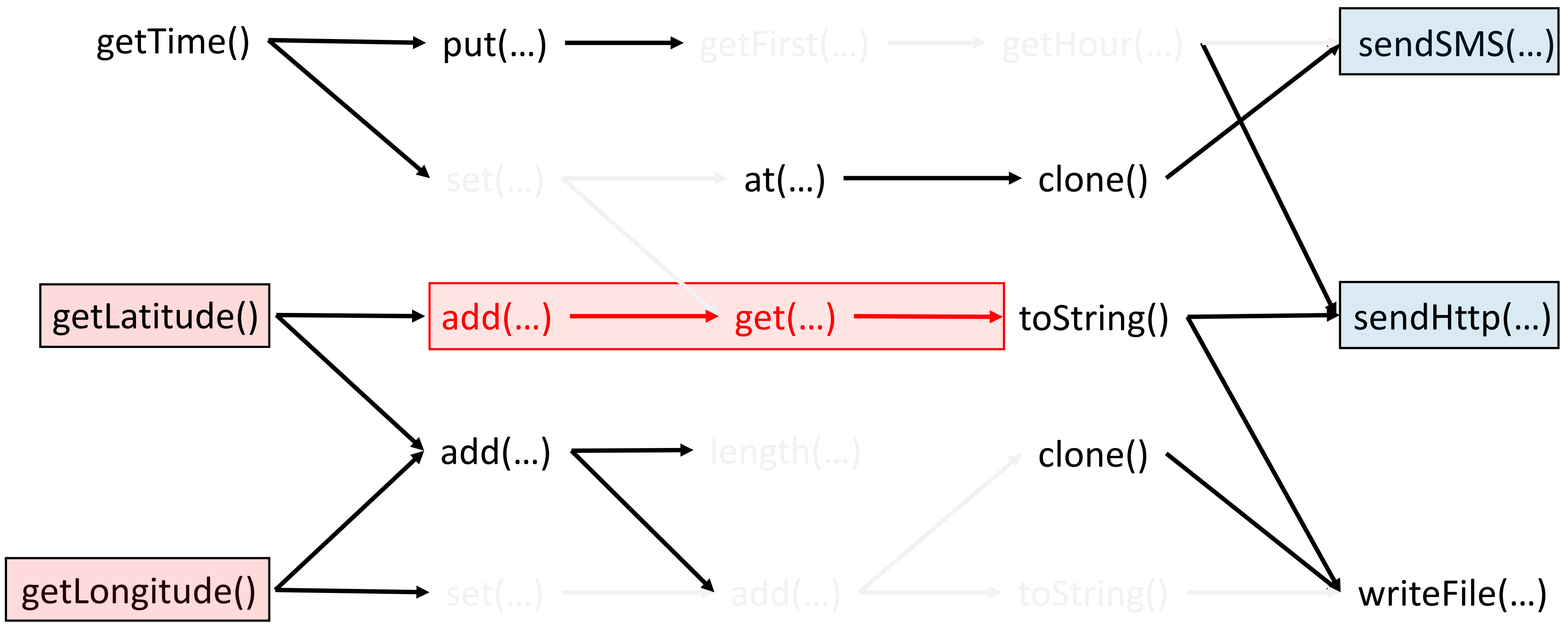


figure out which methods are relevant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Step 1: Worst-case analysis

location → Internet
SMS → Internet
device ID → SMS
…

Step 2: Infer summaries

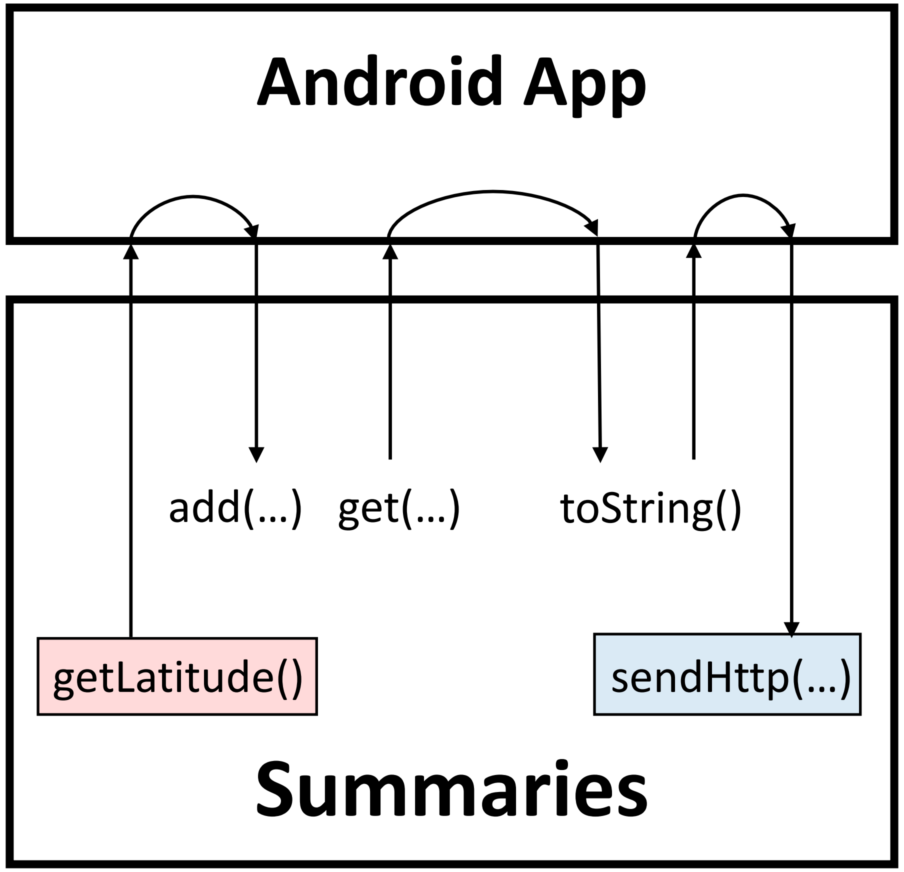
Step 3: Analyst corrections

Step 1: Worst-case Analysis

```
class List:
    @alias(arg, this.val)
    void add(Object arg) {}

    @alias(this.val, return)
    Object get(Integer index) {}

class Double:
    @flow(this, return)
    String toString() {}
```



Step 1: Worst-case Analysis

```
class List:
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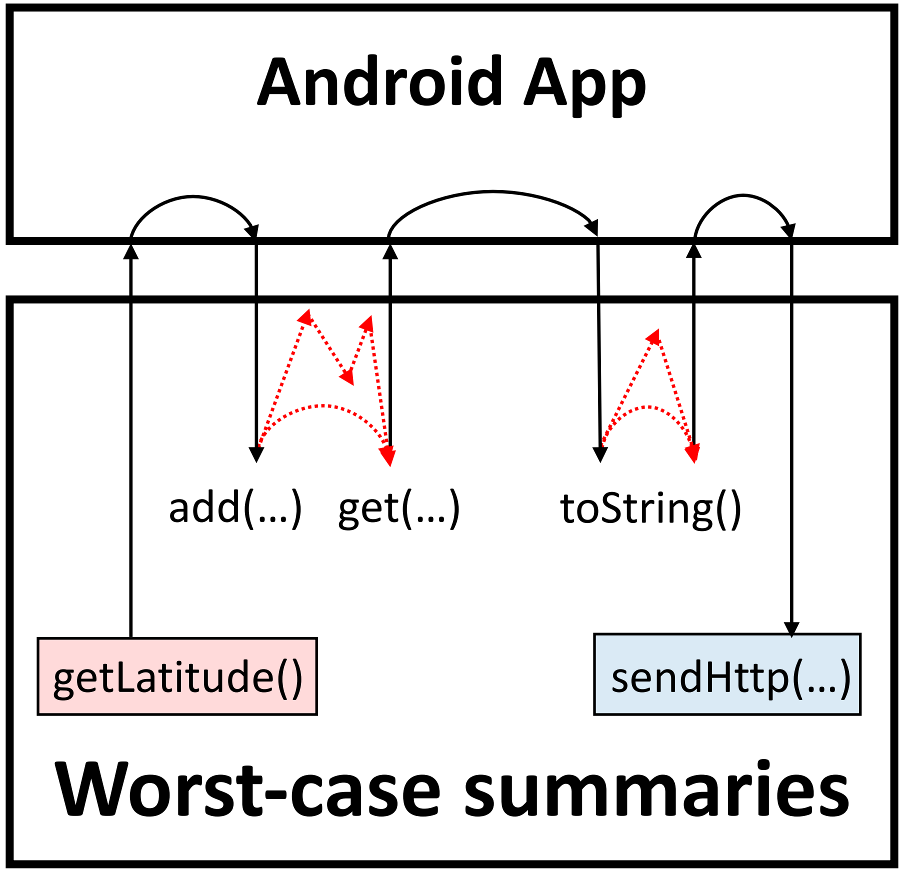

location → Internet
device ID → SMS
…

Step 2: Summary Inference

```
class List:
    @alias(arg, this.val)
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    @alias(this.val, return)
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class Double:
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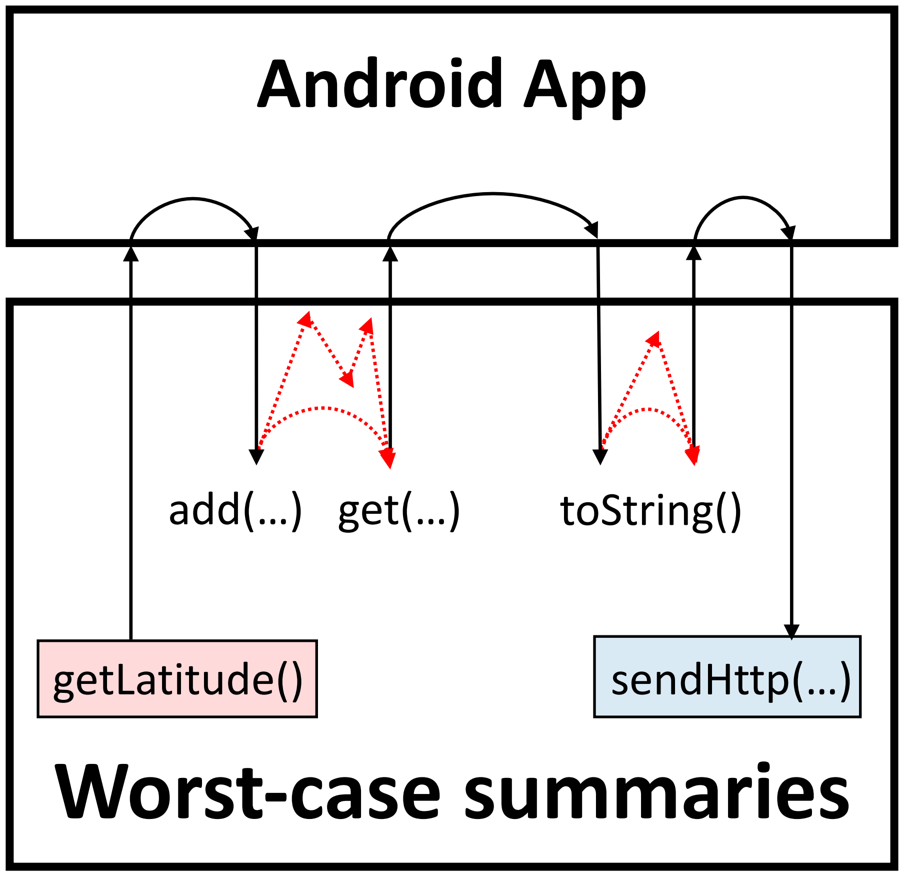
    String toString() {}
```



location → Internet
device ID → SMS
…

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```
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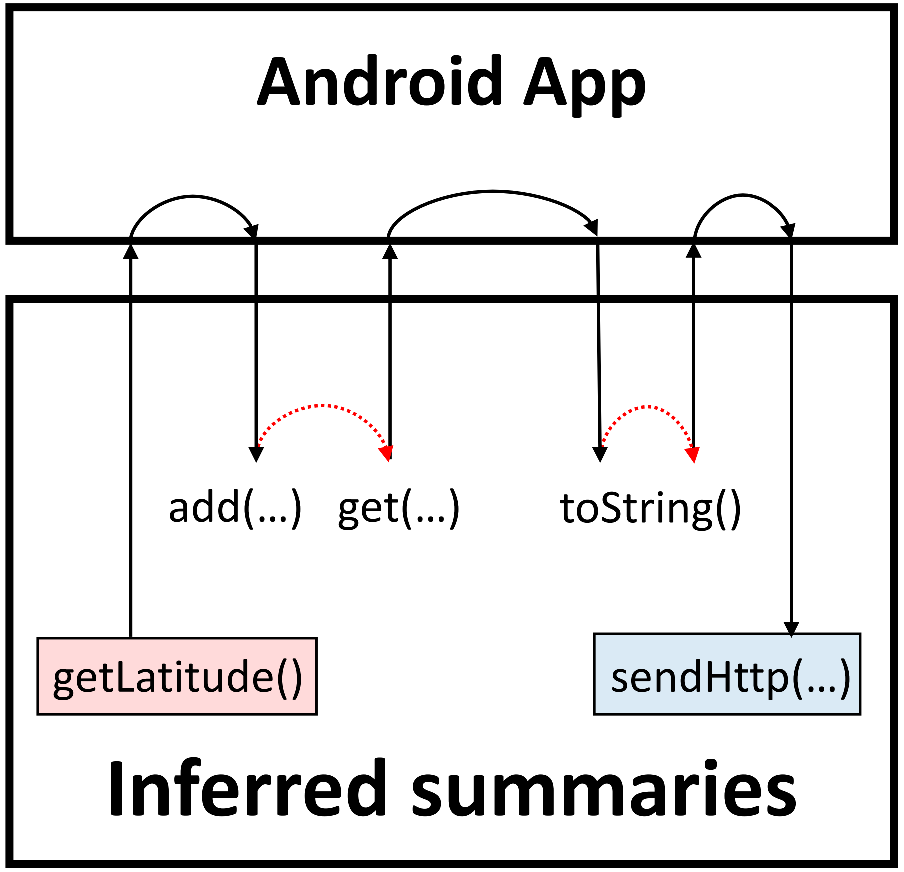

location → Internet
device ID → SMS
…

Step 3: Analyst corrections

```
class List:
    @alias(arg, this.val)
    void add(Object arg) {}

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    Object get(Integer index) {}

class Double:
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```

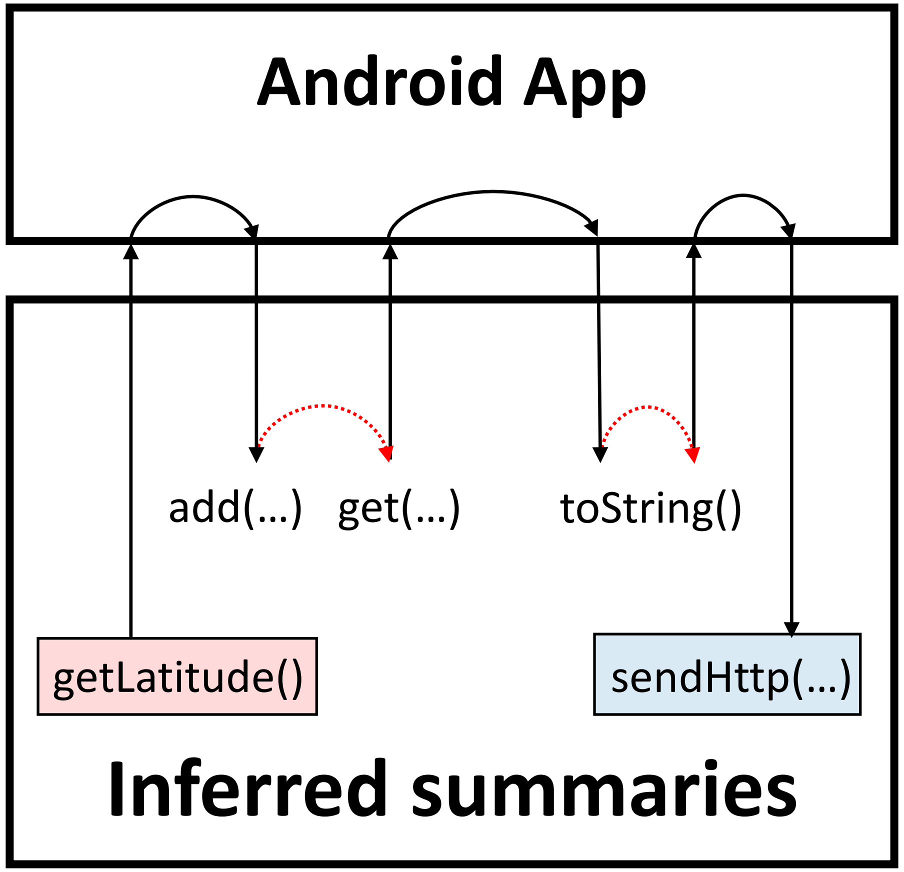

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device ID → SMS
…

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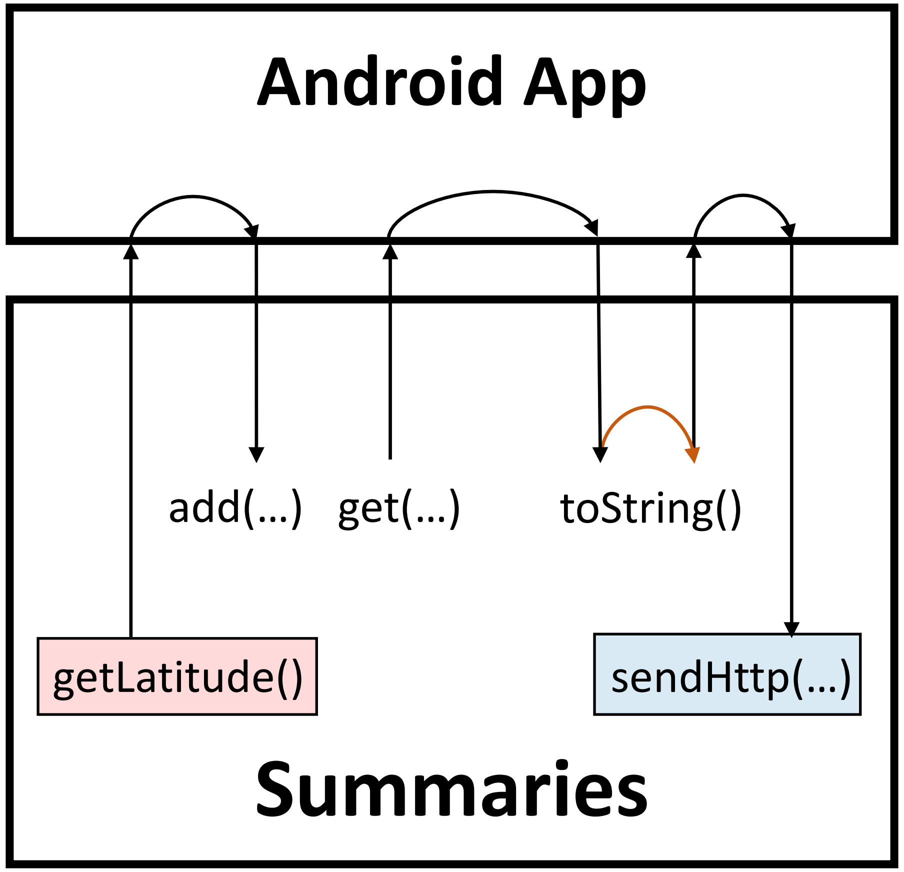

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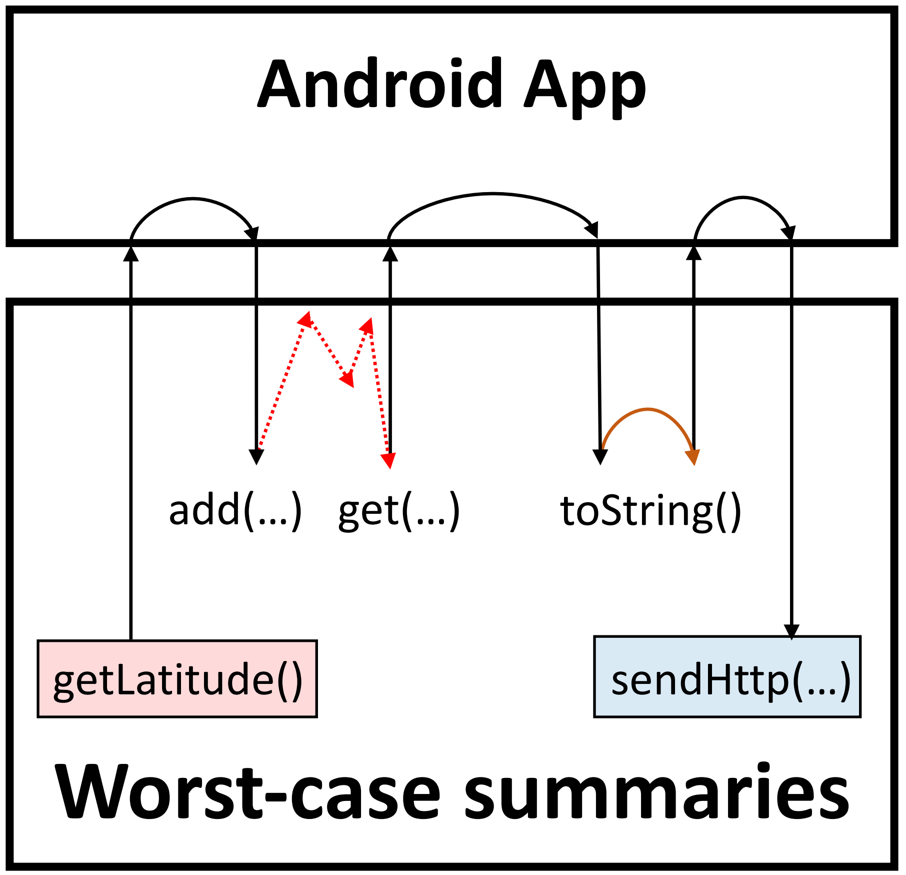

location → Internet

Step 2: Summary inference

```
class List:
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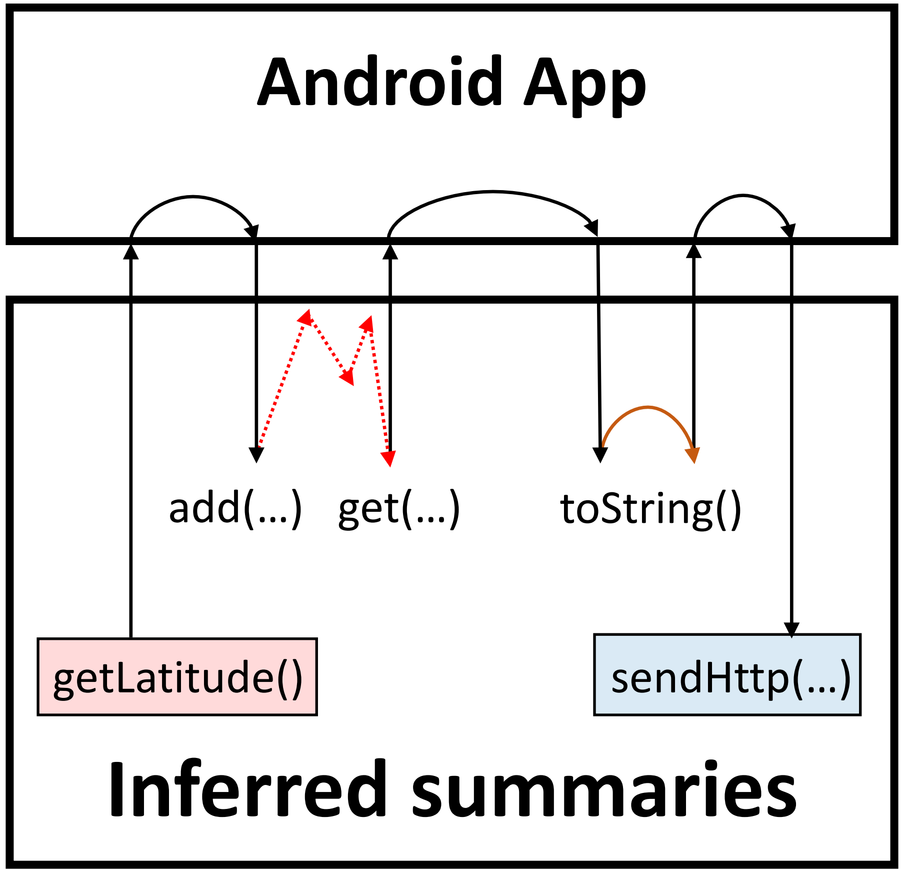

location → Internet

Step 3: Analyst corrections

```
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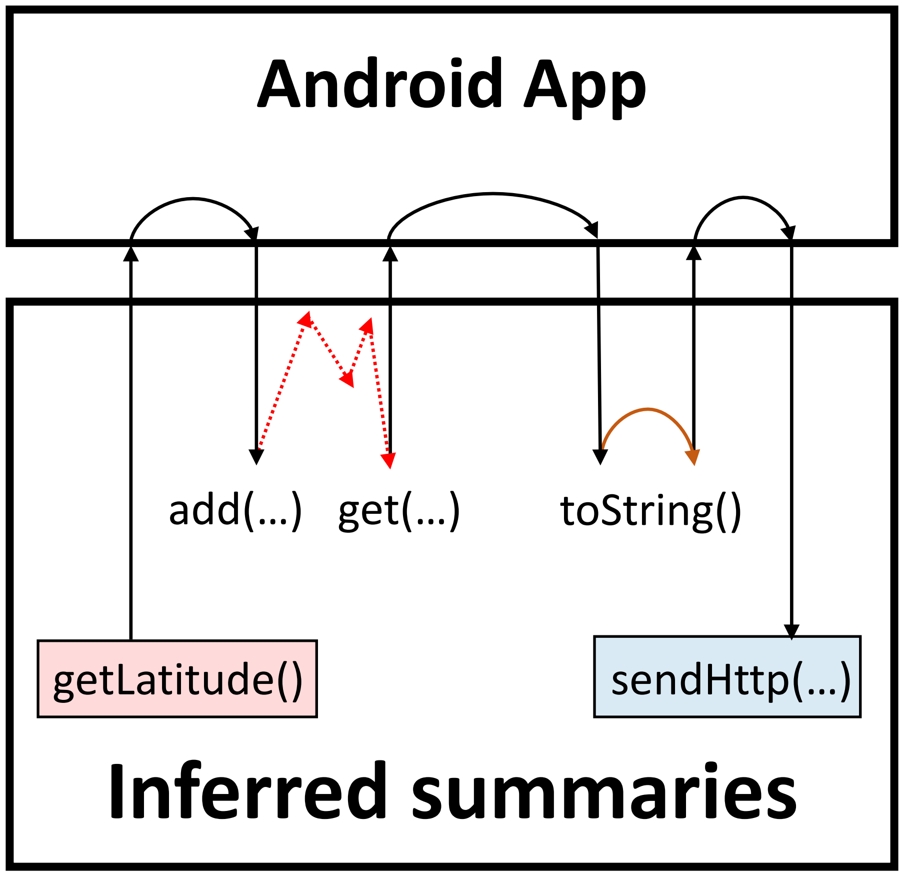

location → Internet

Step 3: Analyst corrections

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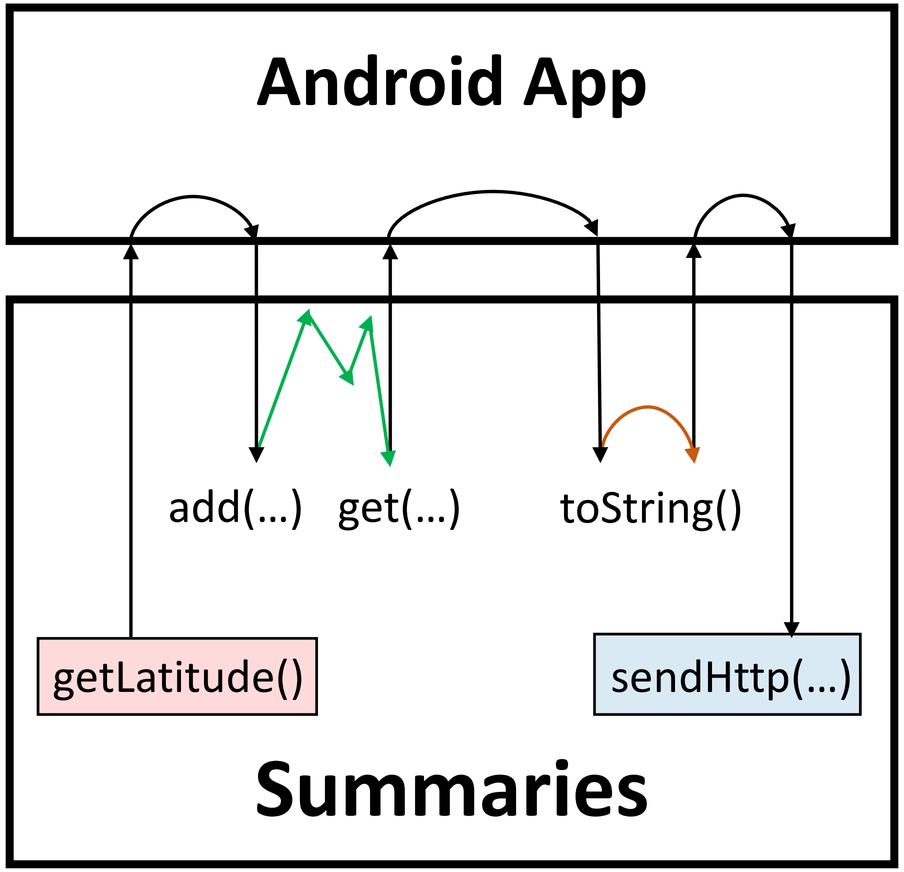


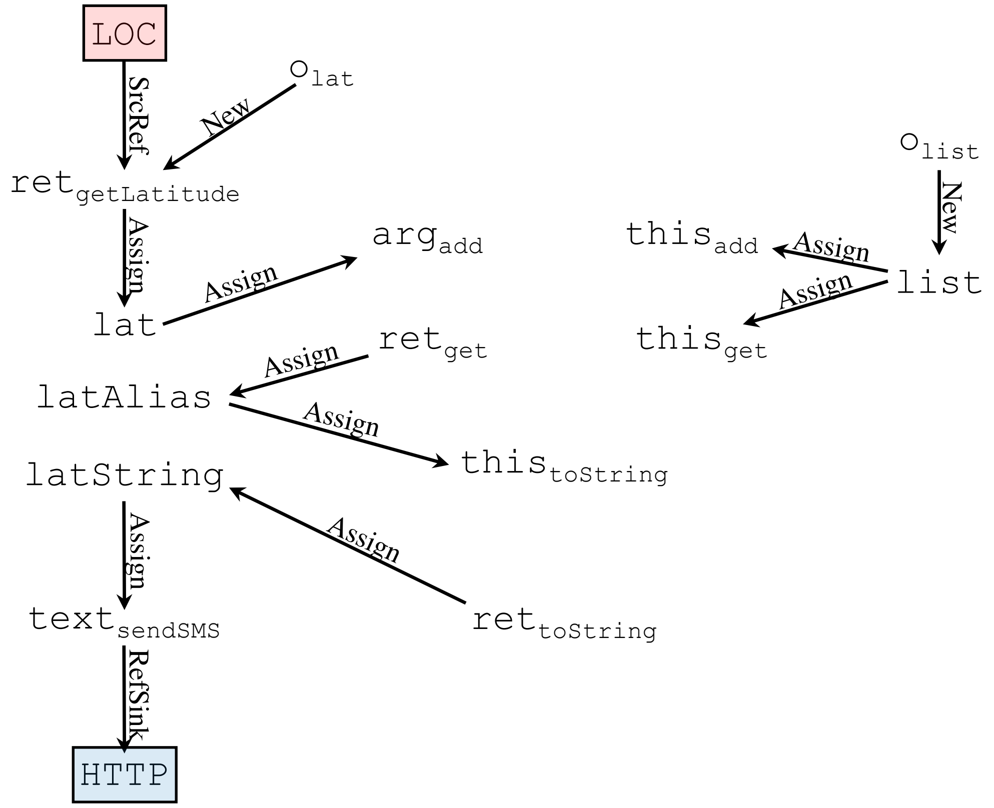
location → Internet

Assume:	The analyst answers correctly
Guarantee:	Results are as if we know all summaries

CFL Reachability

CFL Reachability: Phase 1

1. **Double** lat = getLatitude();
2. **List** list = **new** List();
3. list.add(lat);
4. **Double** latAlias = list.get(0);
5. **String** latStr = latAlias.toString();
6. sendHttp(latStr);



CFL Reachability: Phase 1

```
class List:
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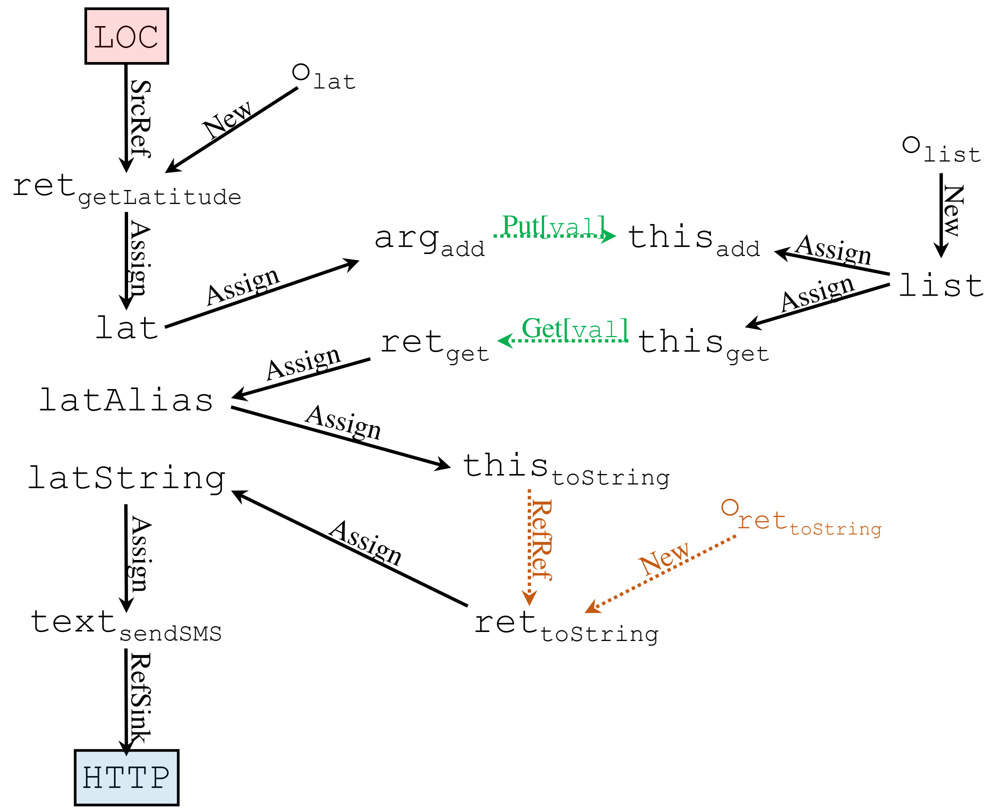
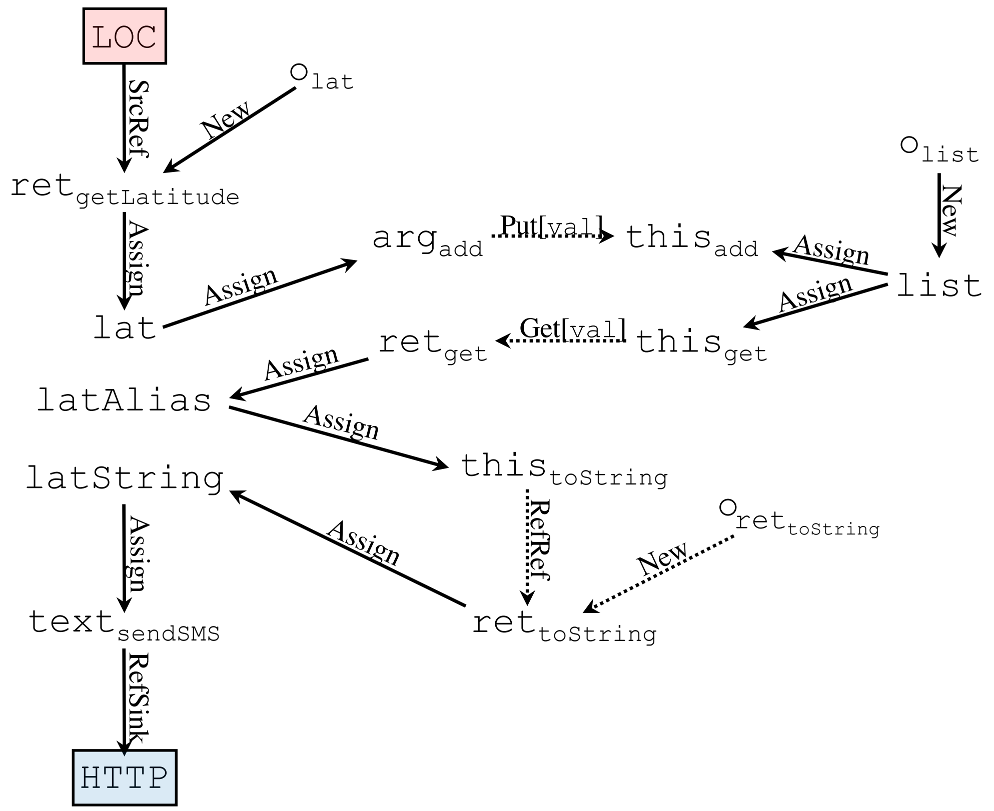
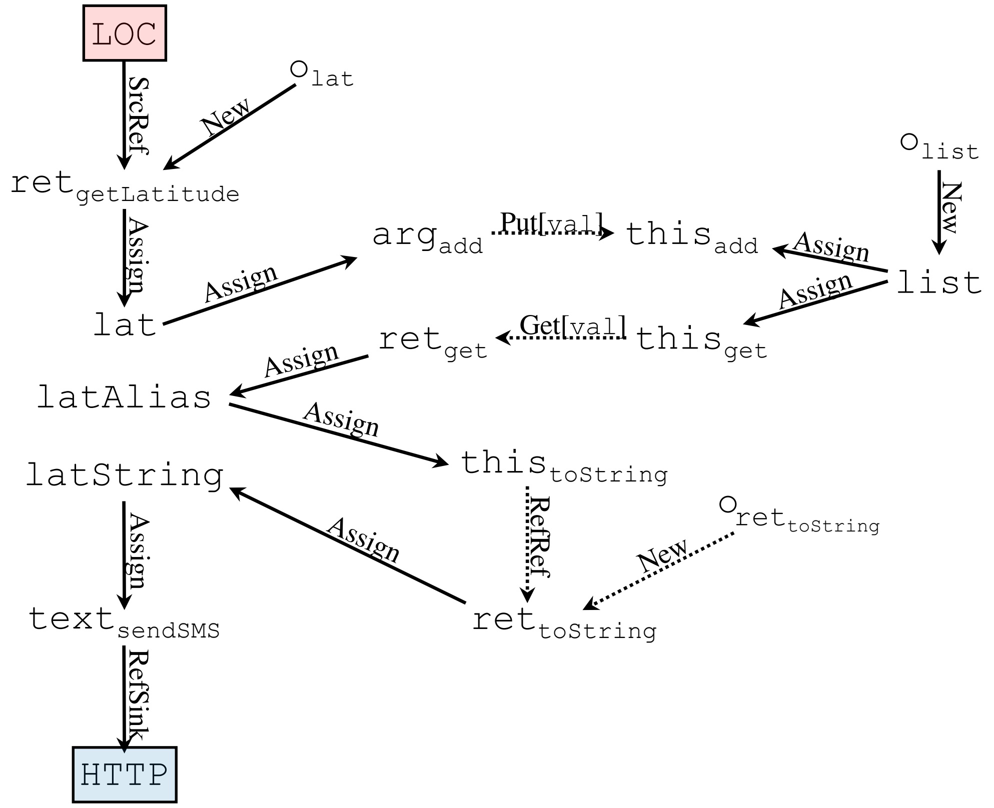


CFL Reachability: Phase 2



CFL Reachability: Phase 2

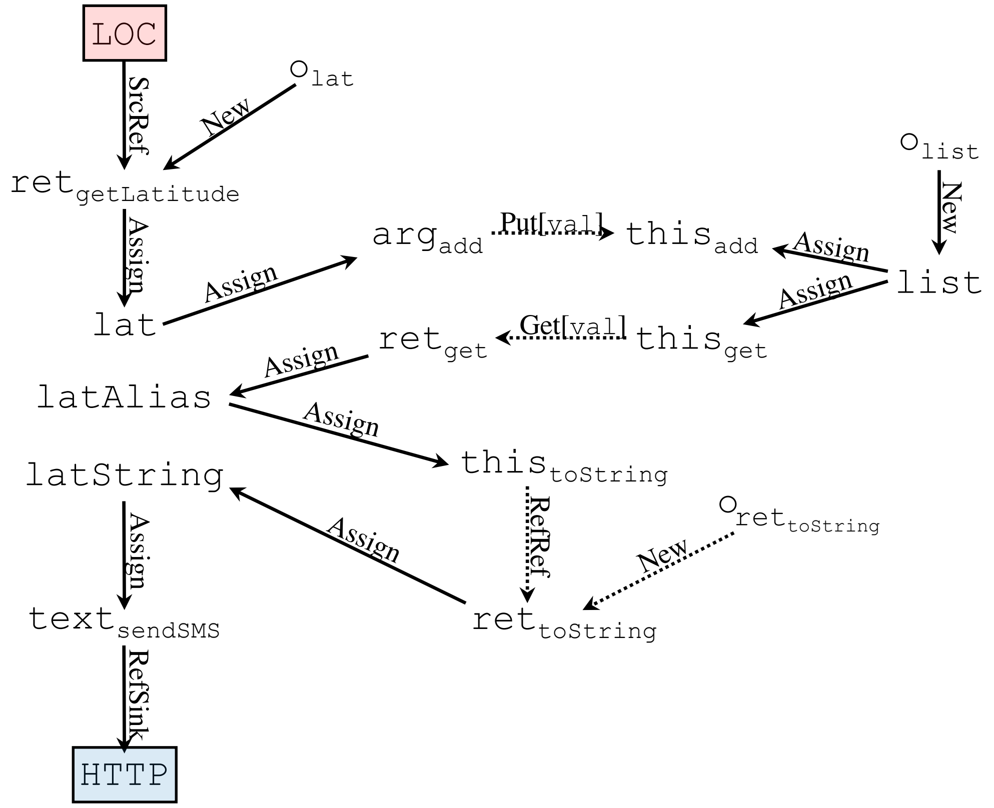
- Source sink paths



CFL Reachability: Phase 2

- Source sink paths
- Labels along path satisfy:

$$\ell_1 \dots \ell_n \in L_{\text{flow}}$$



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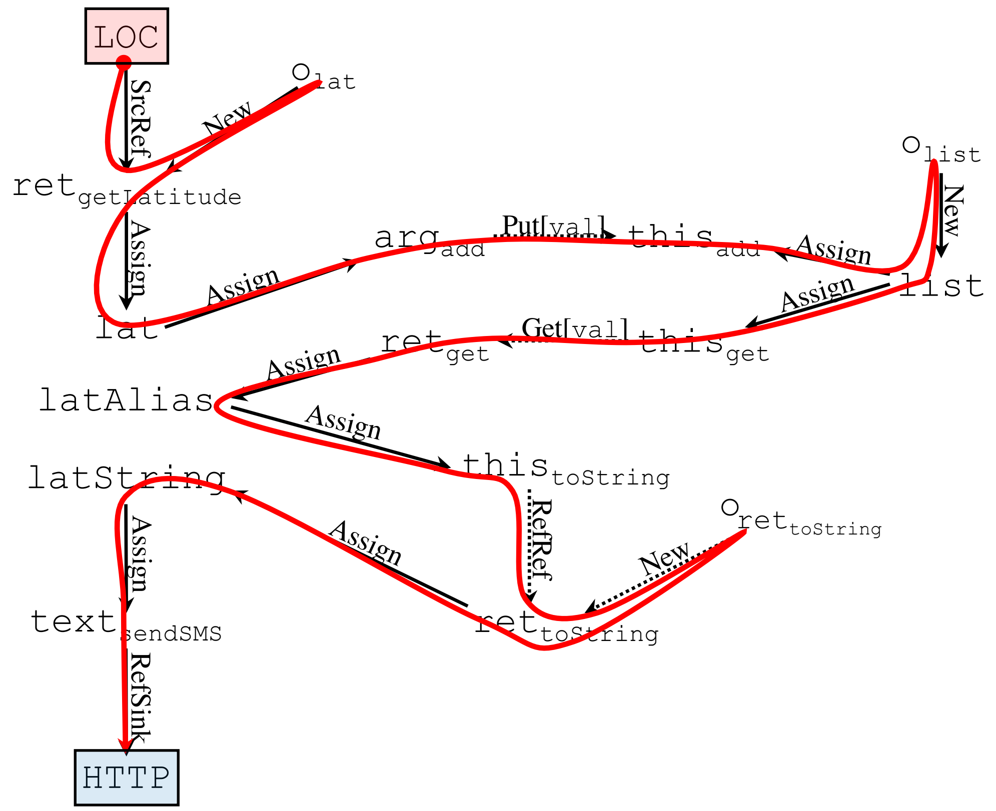

CFL Reachability: Phase 2

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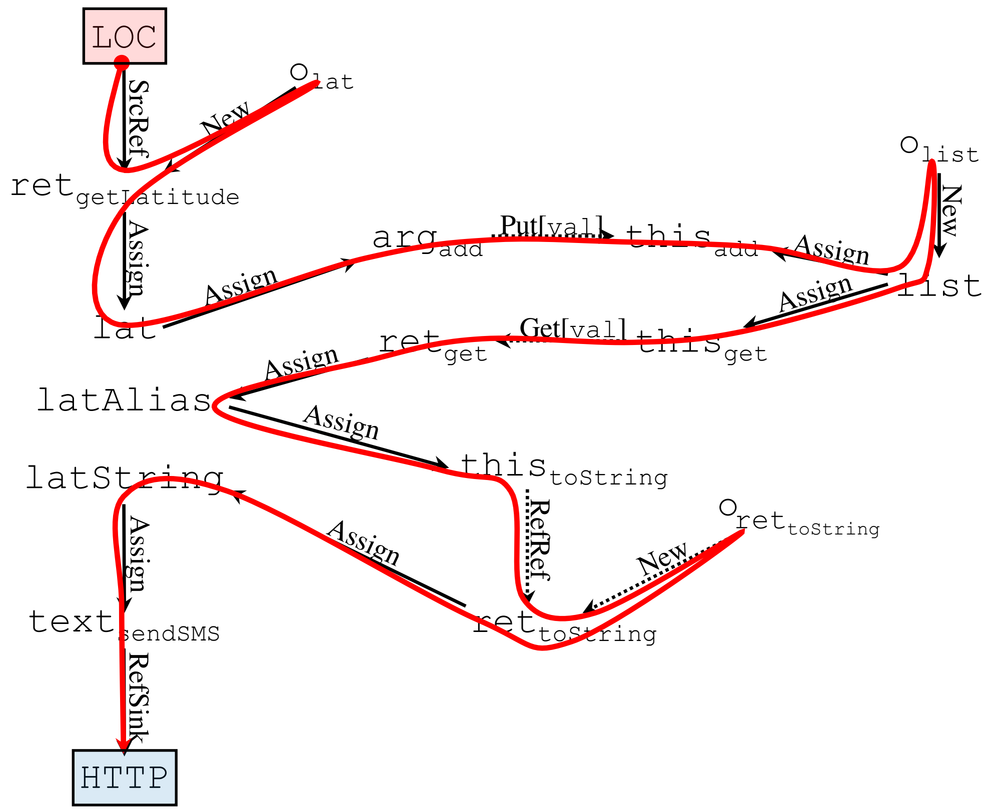
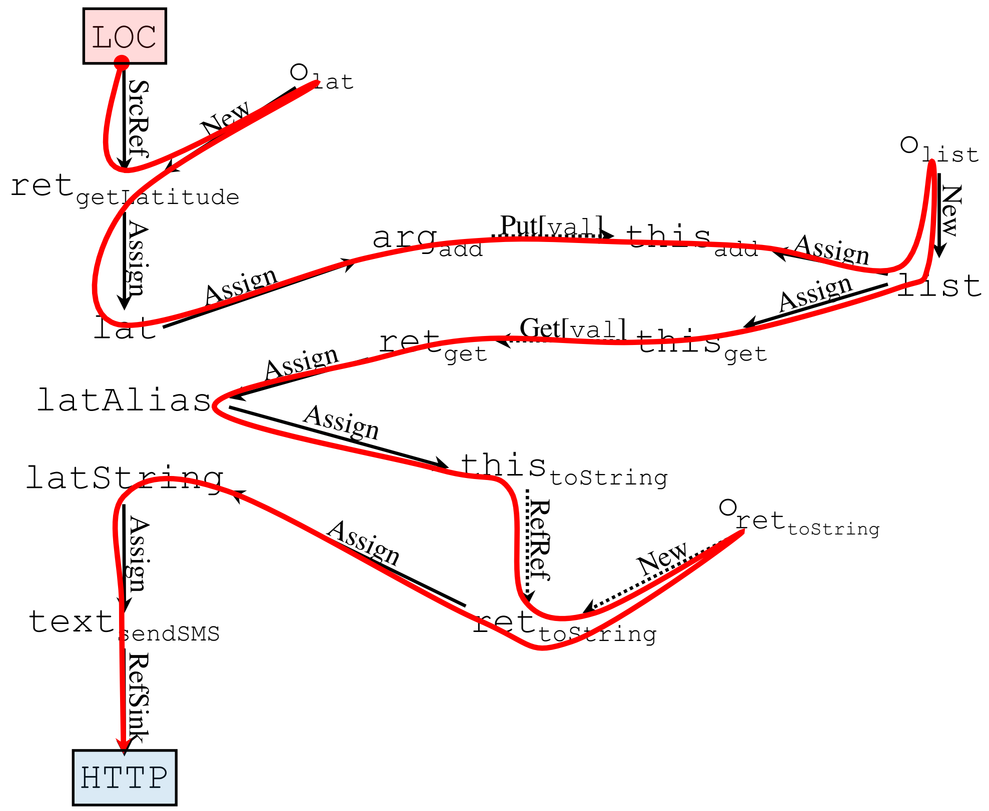


$$\text{SrcRef}\ \overline{\text{New}}\ \text{New Assign Assign Put[val] Assign}\ \overline{\text{New}}\ \text{New Assign Get[Val] Assign Assign RefRef}\ \overline{\text{New}}\ \text{New Assign Assign RefSink} \in L_{\text{flow}}$$

Missing Summaries



Missing Summaries

```
class List:
    @alias(arg, this.val)
    void add(Object arg) {}

    @alias(this.val, return)
    Object get(Integer index) {}

class Double:
    @flow(this, return)
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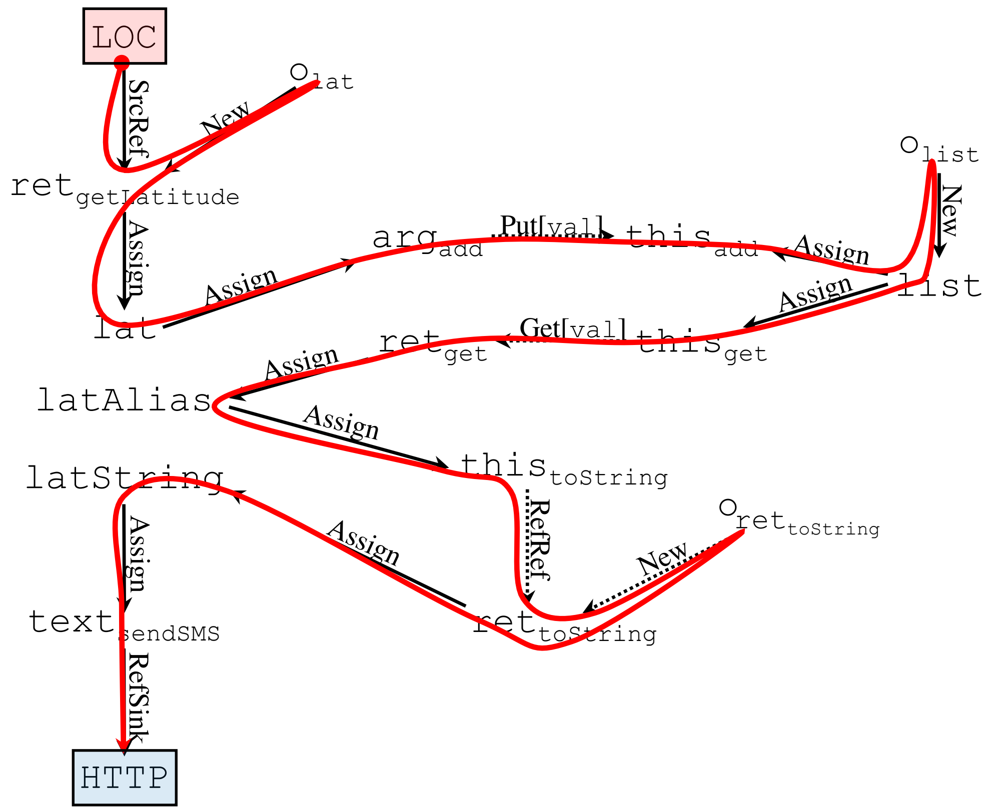
```



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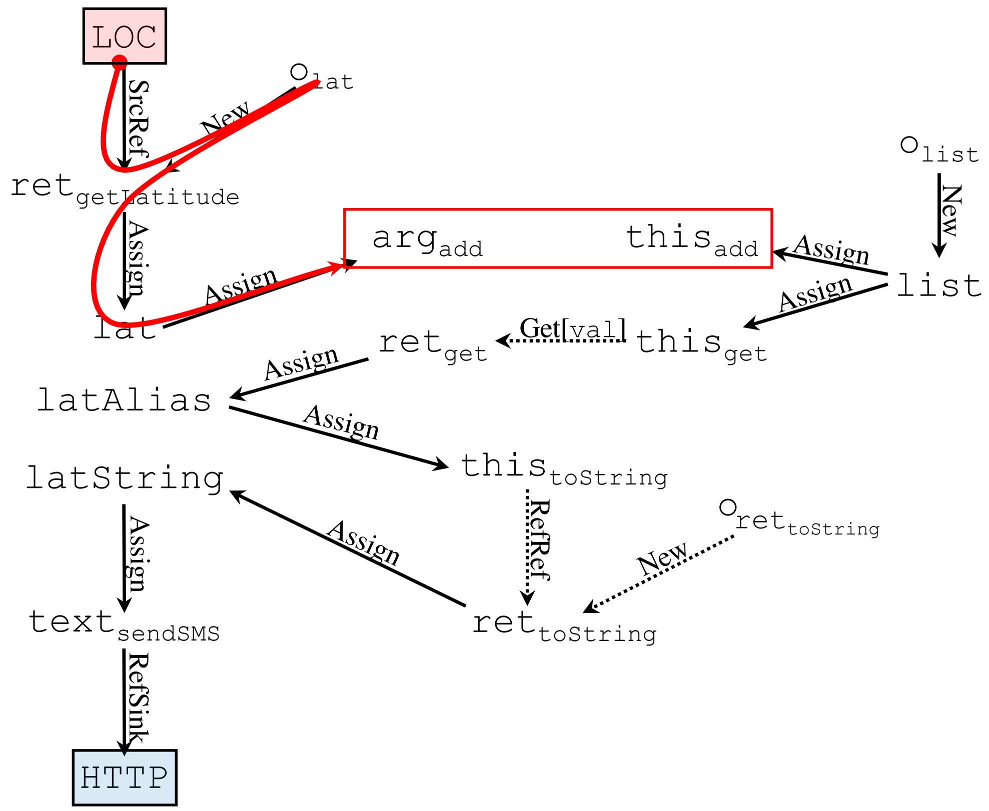

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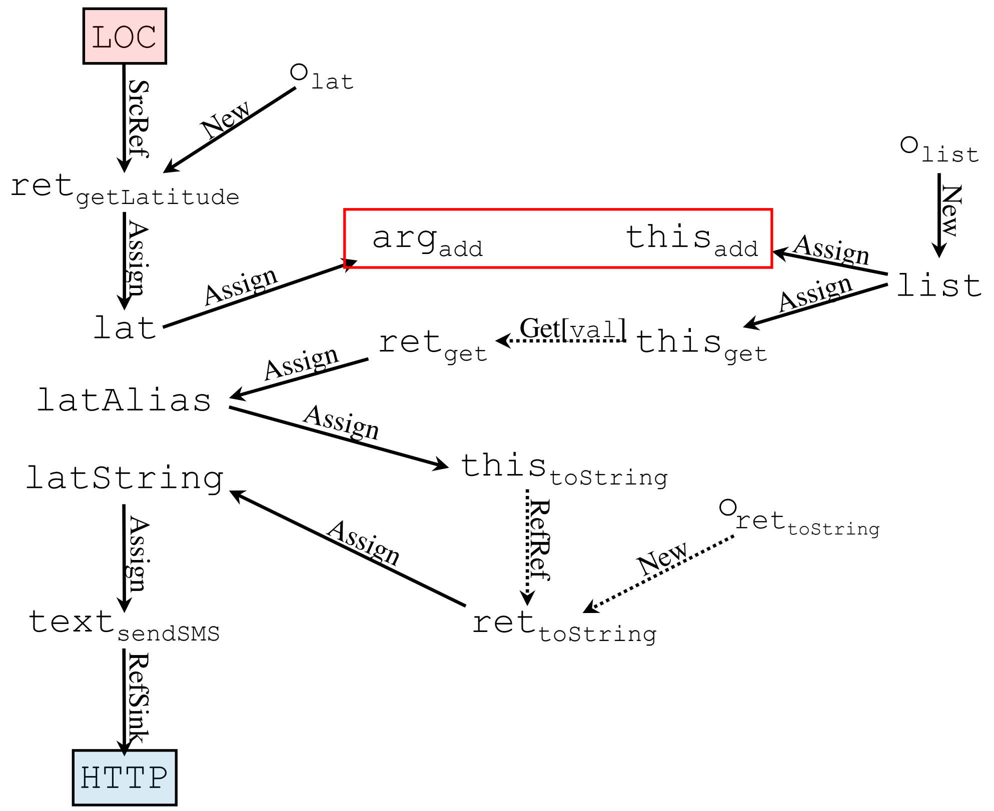

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class List:
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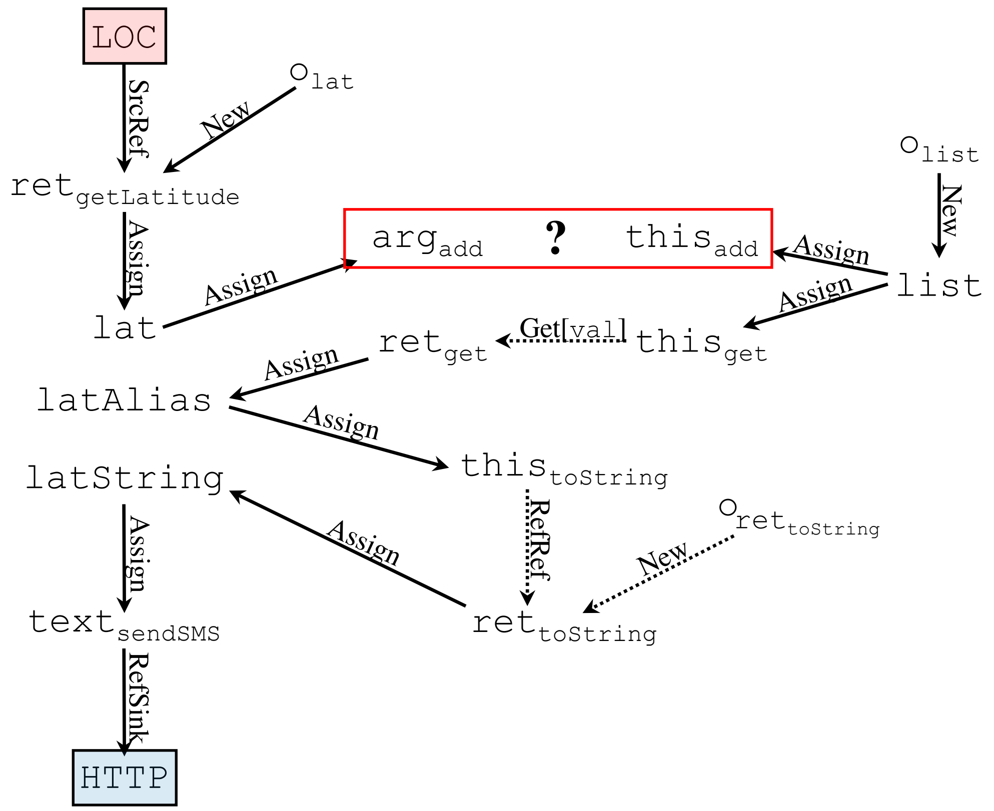

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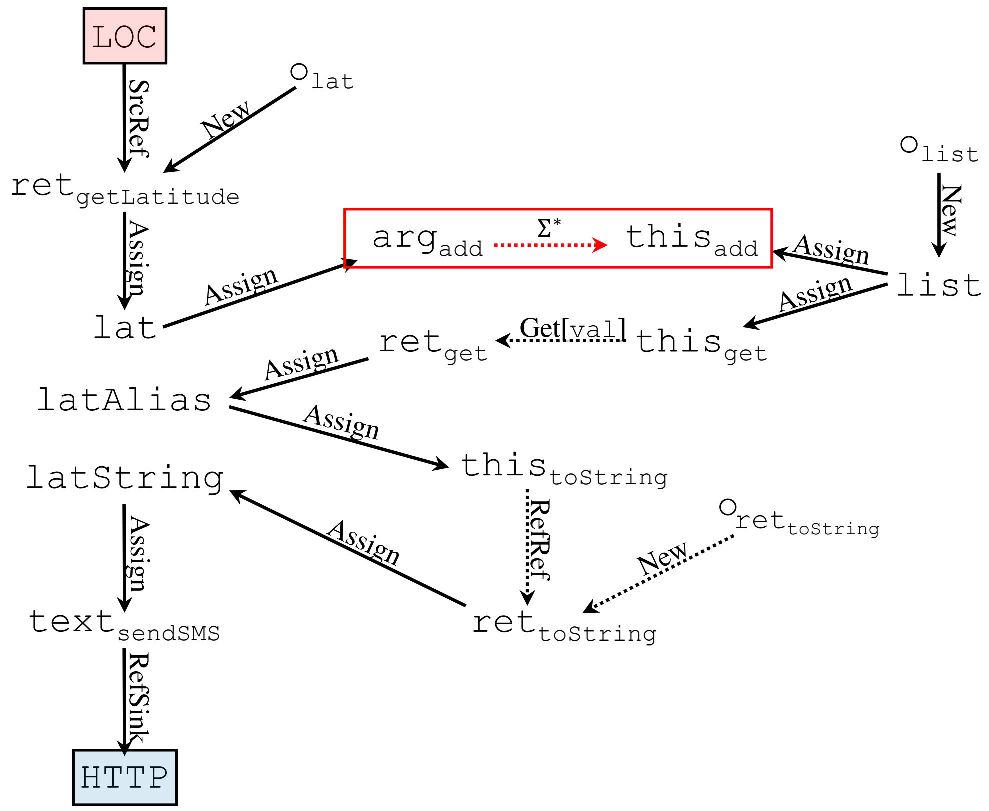

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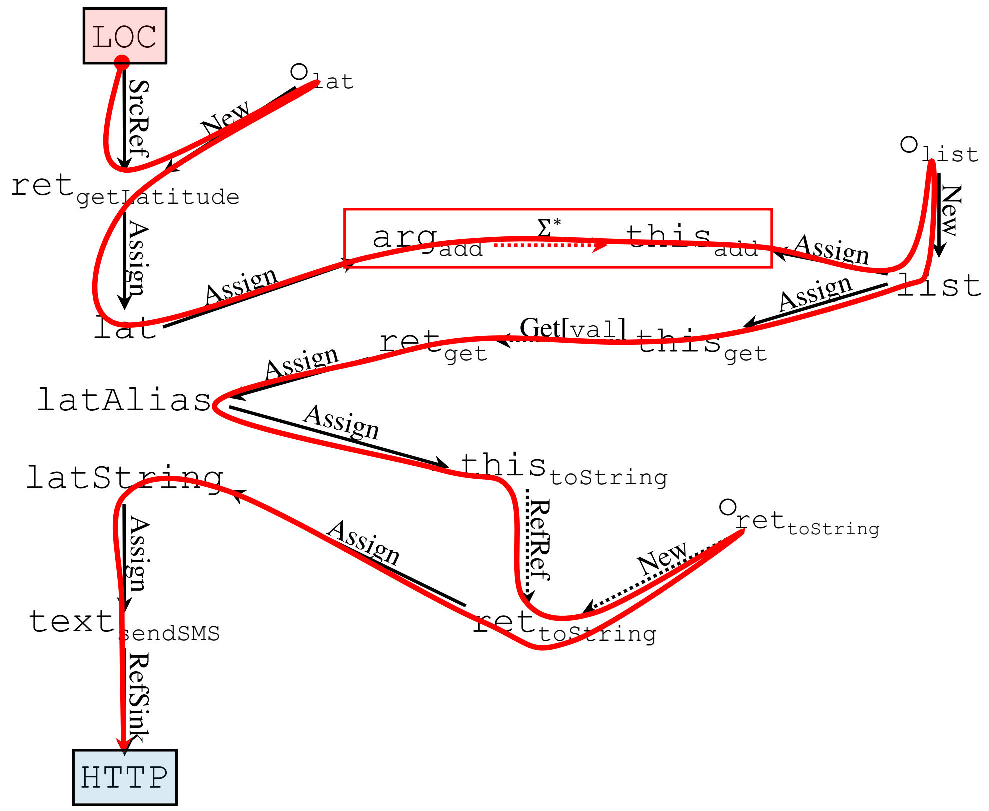

SrcRef $\overline{\text{New}}$ New Assign Assign (Put[val] $\in \Sigma^*$) Assign $\overline{\text{New}}$ New Assign Get[Val] Assign Assign RefRef $\overline{\text{New}}$ New Assign Assign RefSink $\in L(C_{\text{flow}})$

Key idea: Worst-case Subgraph

Key idea: Worst-case Subgraph

$$\xrightarrow{\Sigma^*}$$

Key idea: Worst-case Subgraph

$$\begin{tikzcd} {} \arrow[r, "\Sigma^*"] & {} \arrow[r, phantom, "="] & {} \arrow[r, "\epsilon"] & t \arrow[r, "\epsilon"] \arrow[loop, out=240, in=260, "\sigma_1"'] \arrow[loop, out=280, in=300, "\sigma_n"] & {} \\ & & & \cdots & \end{tikzcd}$$

Step 1: Worst-case Analysis

```
class List:
    @alias(arg, this.val)
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    @alias(this.val, return)
    Object get(Integer index) {}

class Double:
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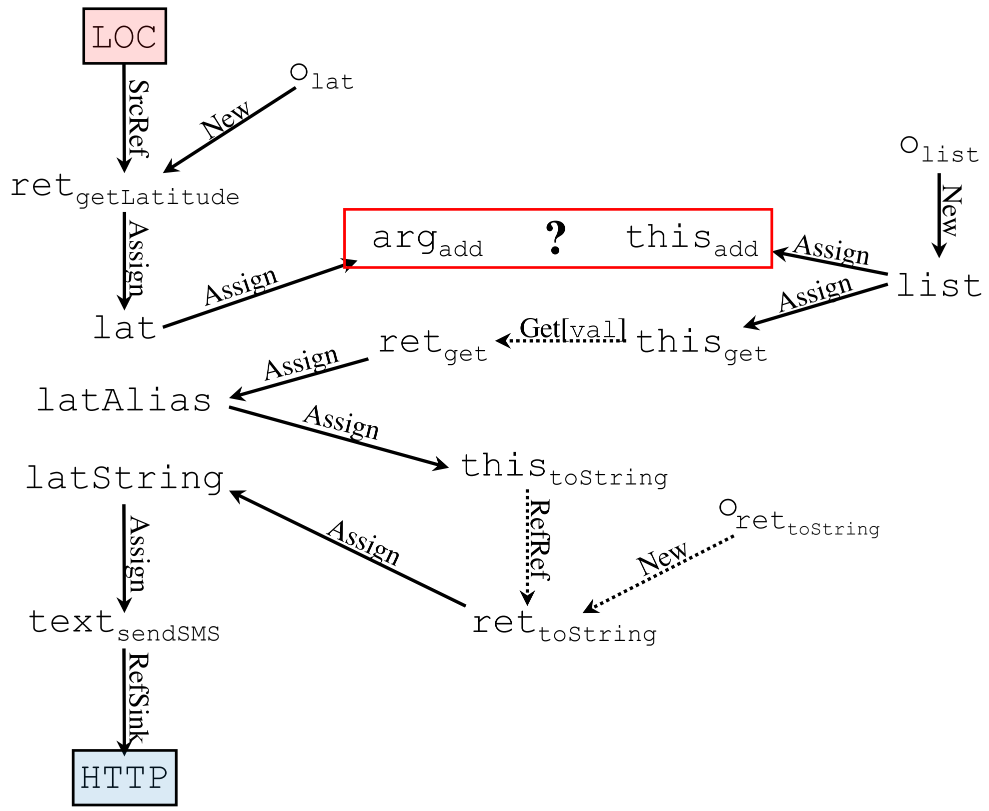
    String toString() {}
```



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```
class List:
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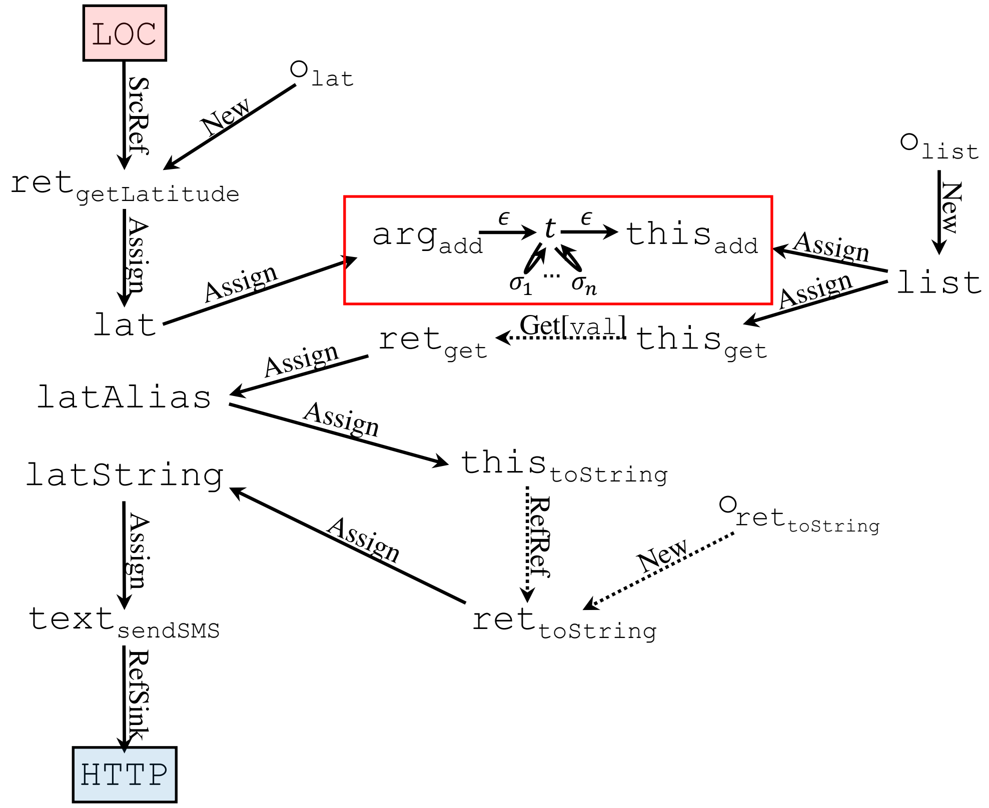
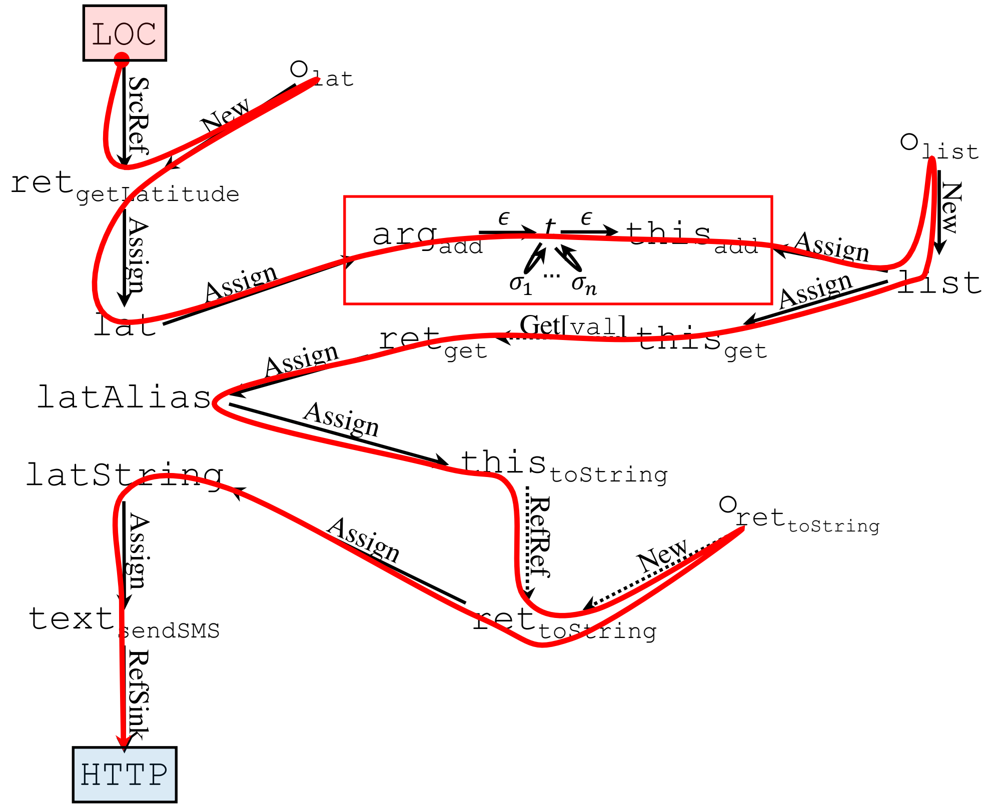
```



Step 1: Worst-case Analysis

```
1.  class List:
2.      @alias(arg, this.val)
3.      void add(Object arg) {}
4.
5.      @alias(this.val, return)
6.      Object get(Integer index) {}
7.
8.  class Double:
9.      @flow(this, return)
10.     String toString() {}
```



SrcRef $\overline{\text{New}}$ New Assign Assign ϵ Put[val] ϵ Assign $\overline{\text{New}}$ New Assign Get[Val] Assign Assign RefRef $\overline{\text{New}}$ New Assign Assign RefSink $\in L(C_{\text{flow}})$

Step 2: Summary Inference

```
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    @alias(this.val, return)
    Object get(Integer index) {}

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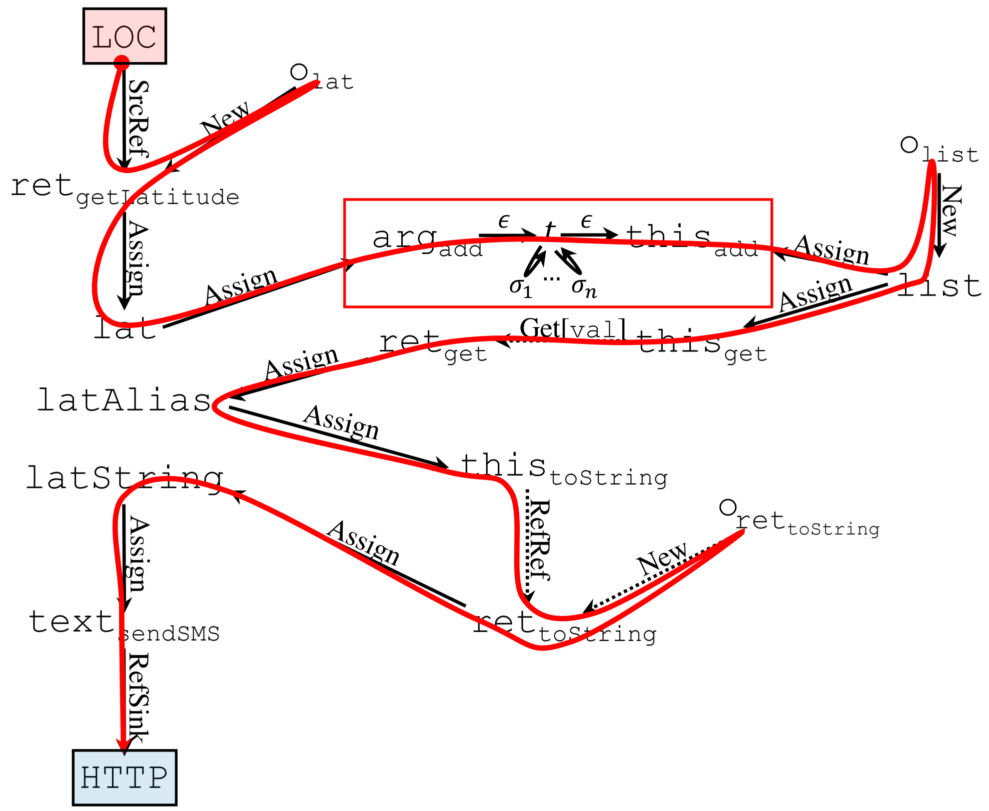

Key Idea: Shortest Path

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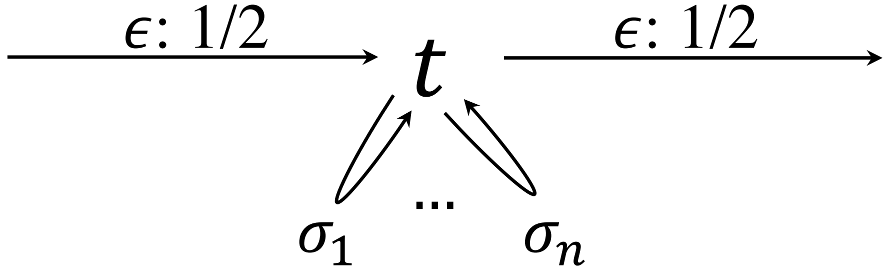

(Other edges have weight 0)

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```
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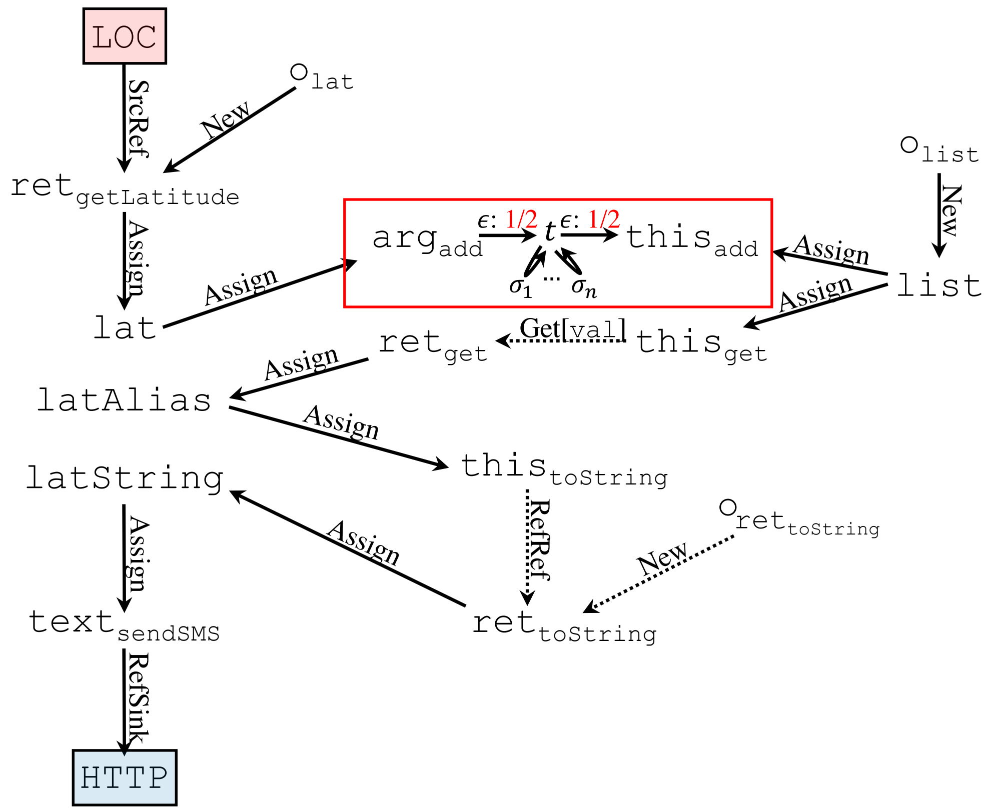

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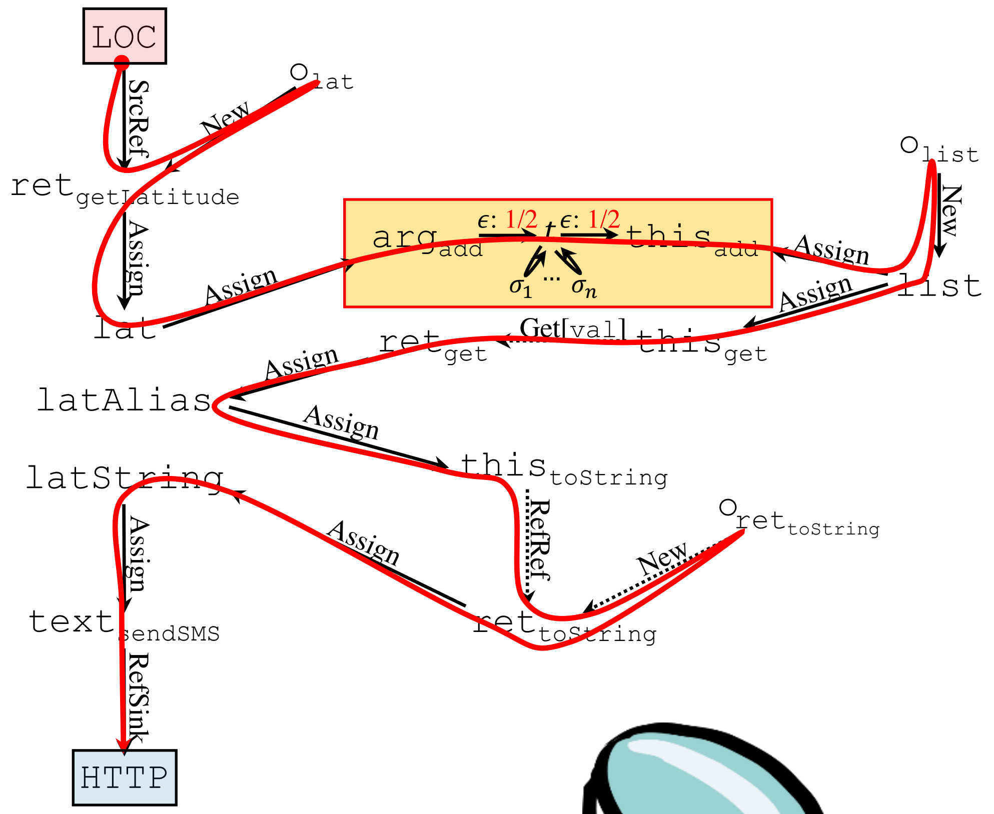

Step 3: Analyst Corrections

```
class List:
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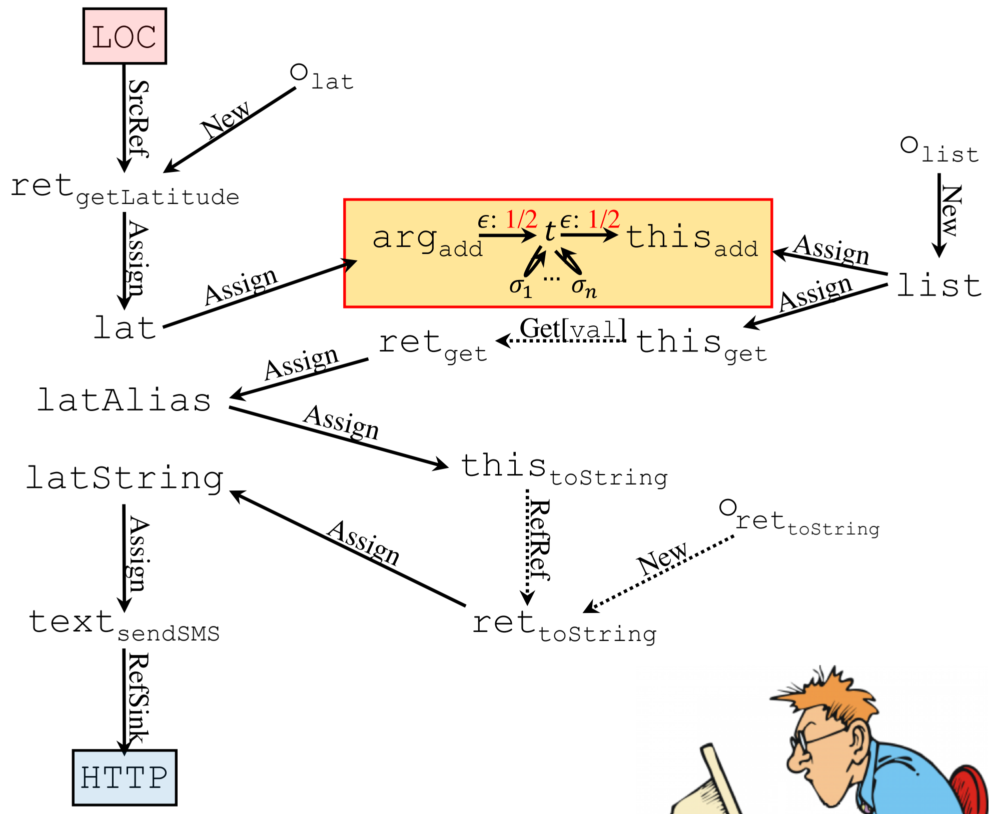

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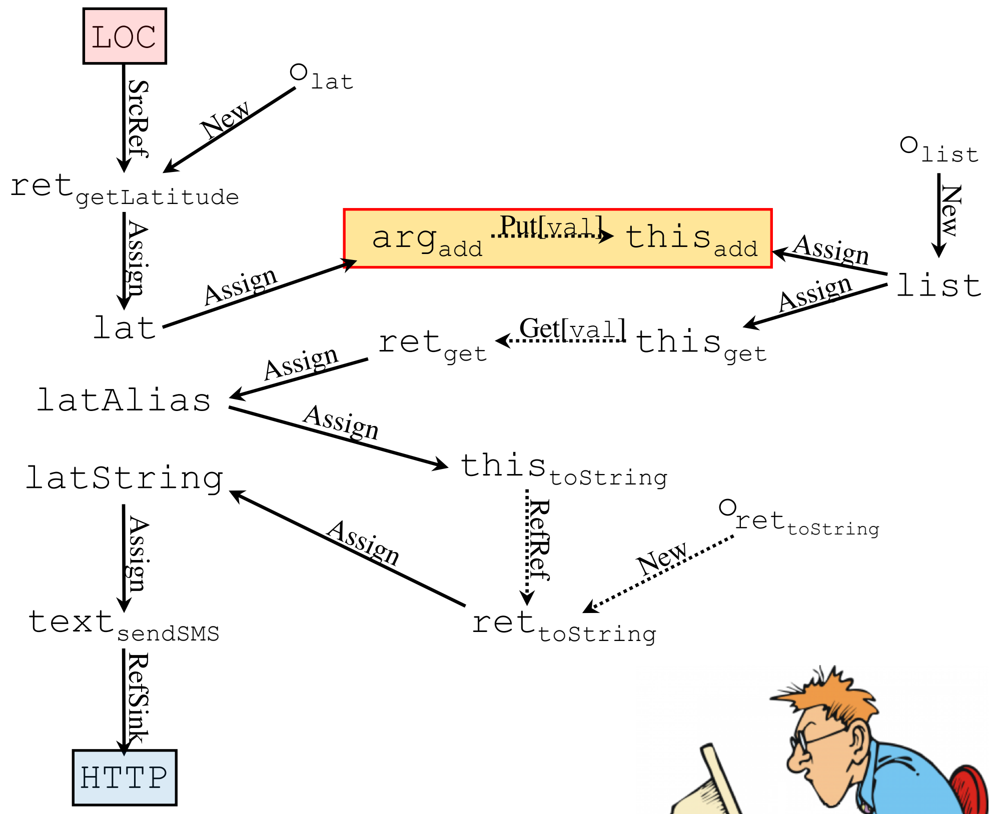
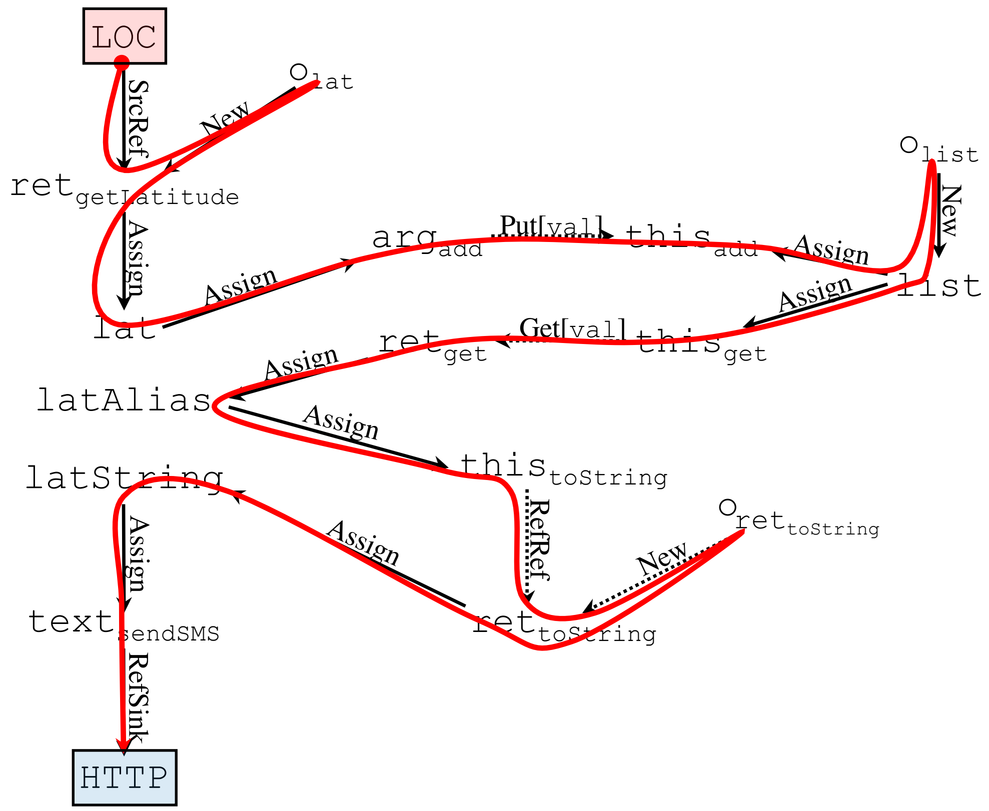
    String toString() {}
```



```
class List:
    @alias(arg, this.val)
    void add(Object arg) {}

    @alias(this.val, return)
    Object get(Integer index) {}

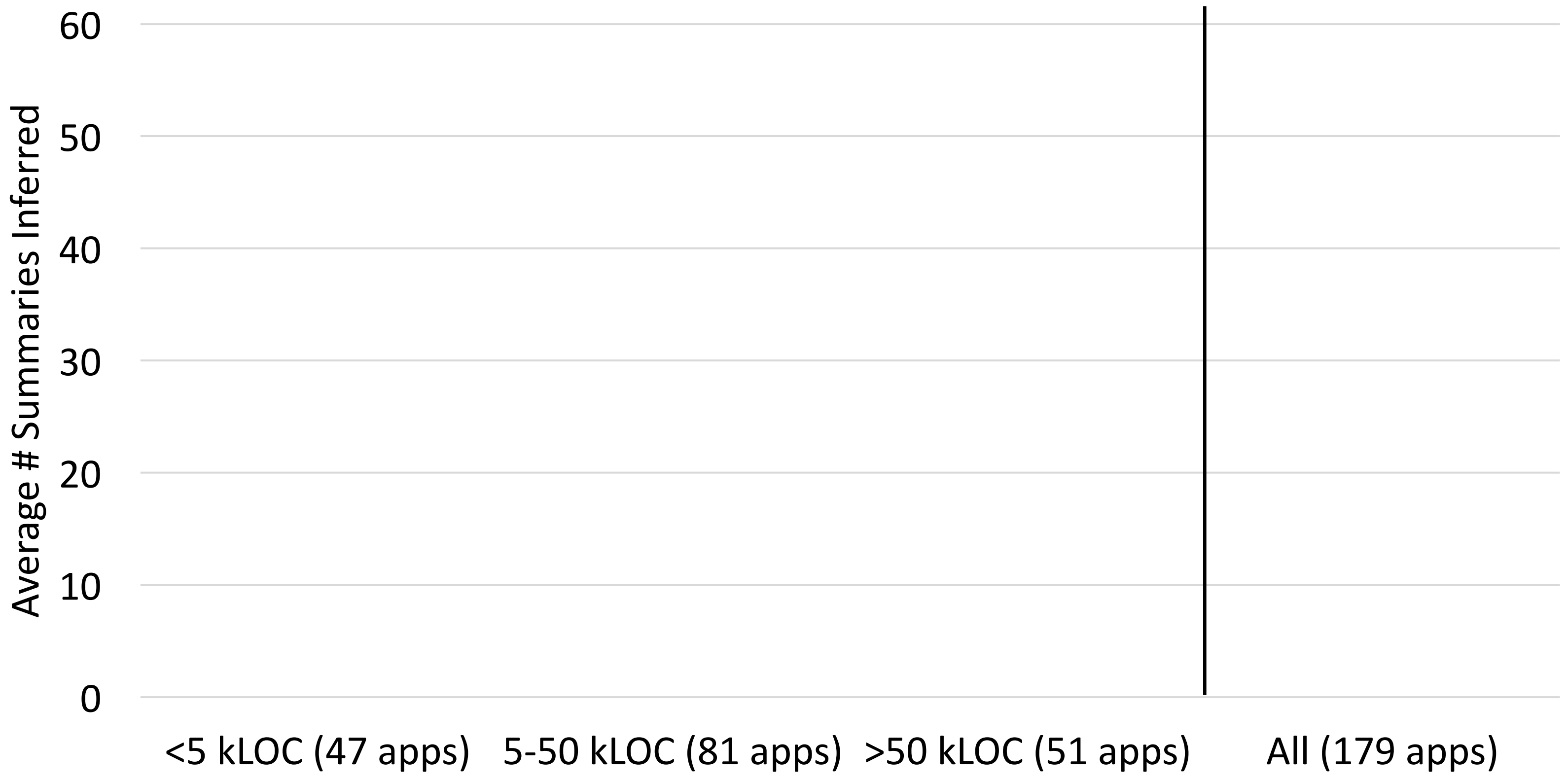
class Double:
    @flow(this, return)
    String toString() {}
```



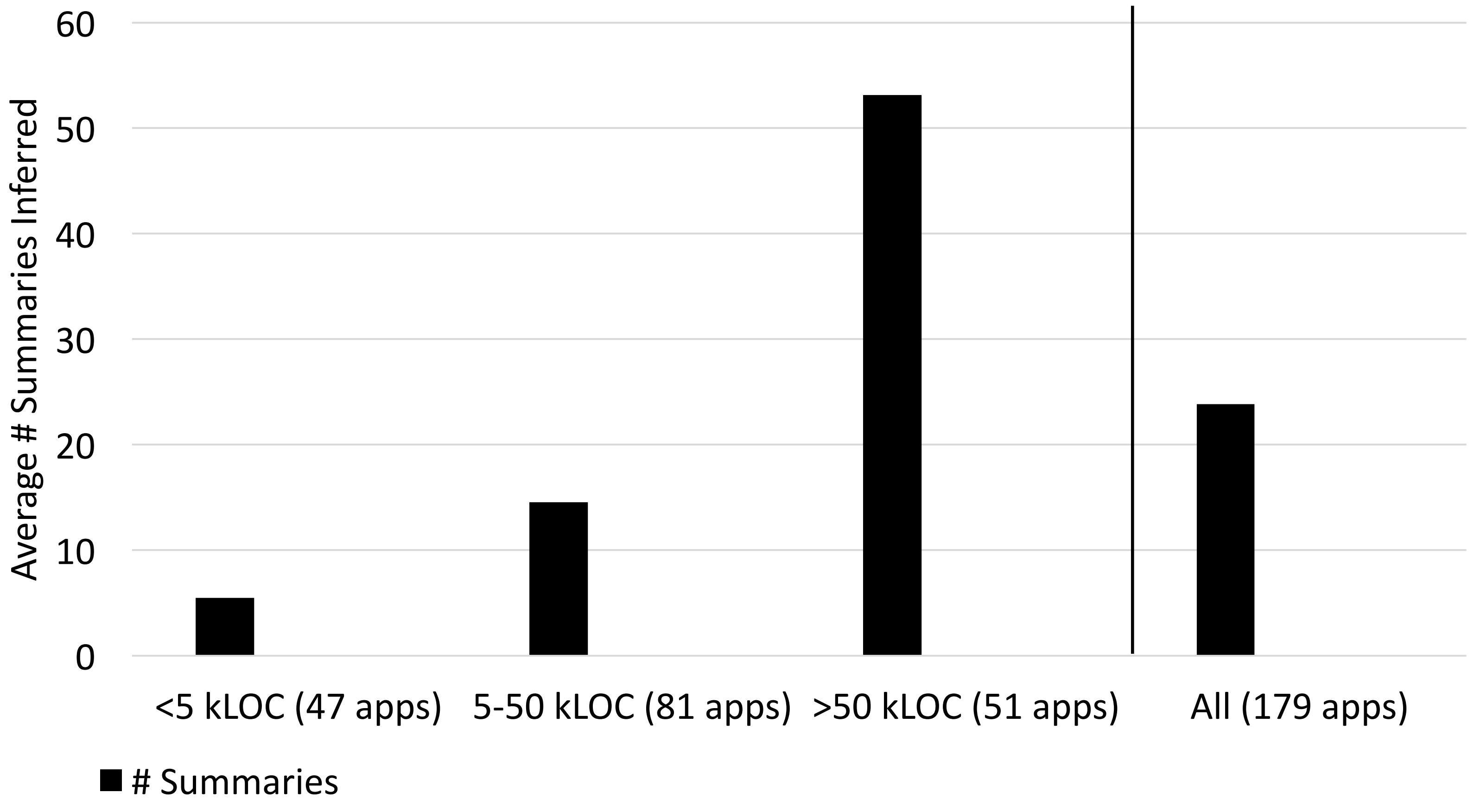
Evaluation

- **Total:** 179 apps (Symantec/Google Play/Darpa)
- **Flow:** 179 apps
- **Alias:** 156 apps

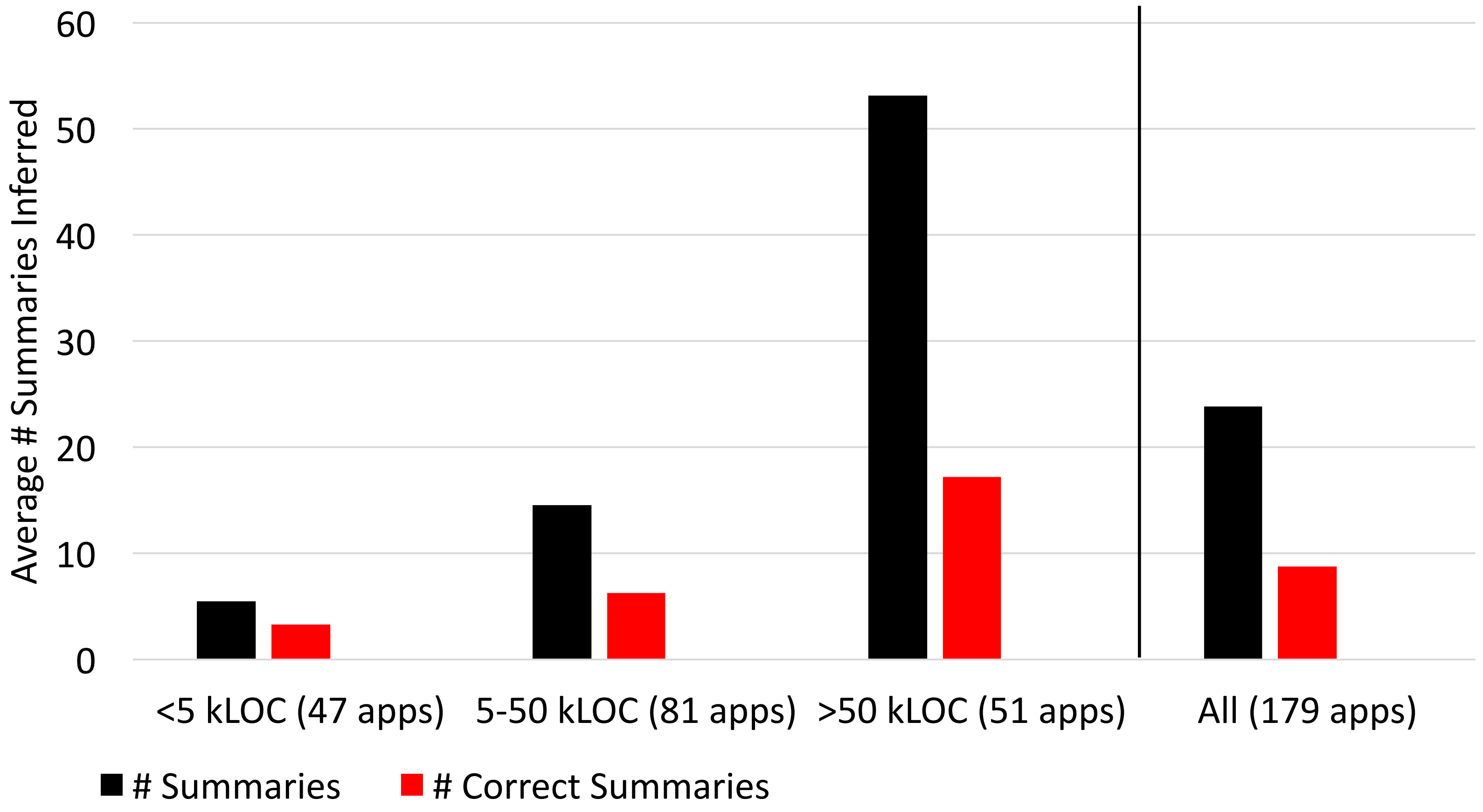
Evaluation: Flow Summaries



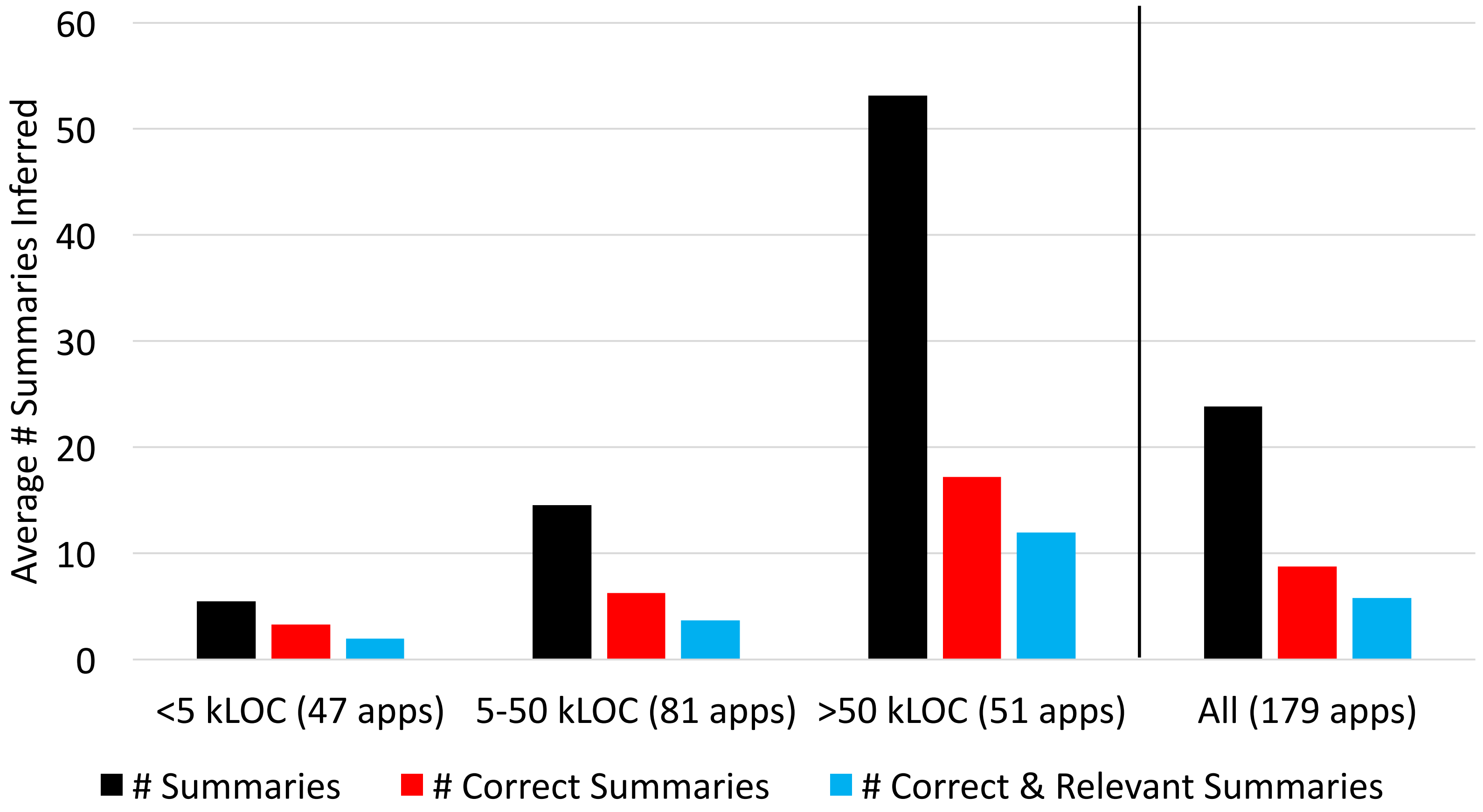
Evaluation: Flow Summaries



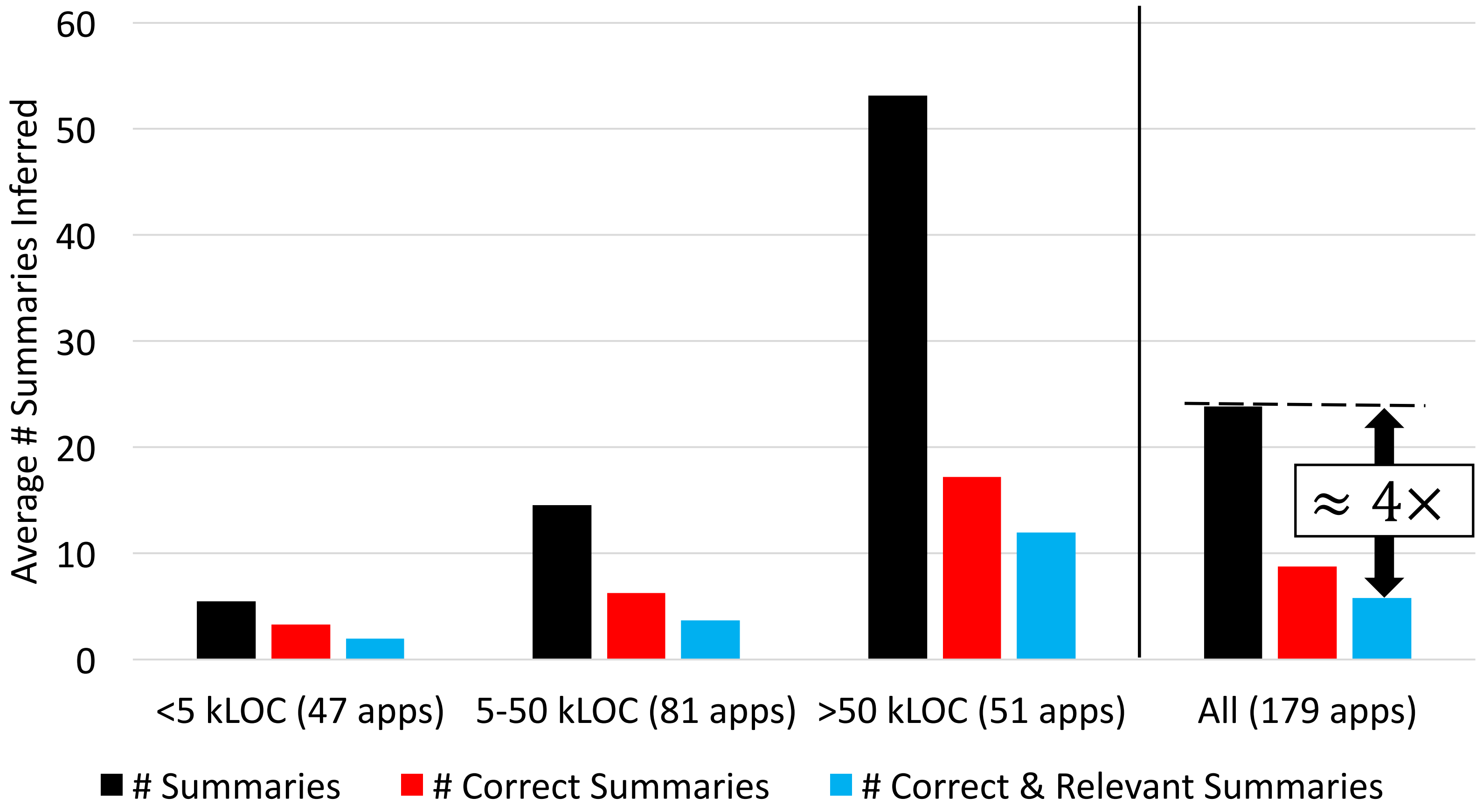
Evaluation: Flow Summaries



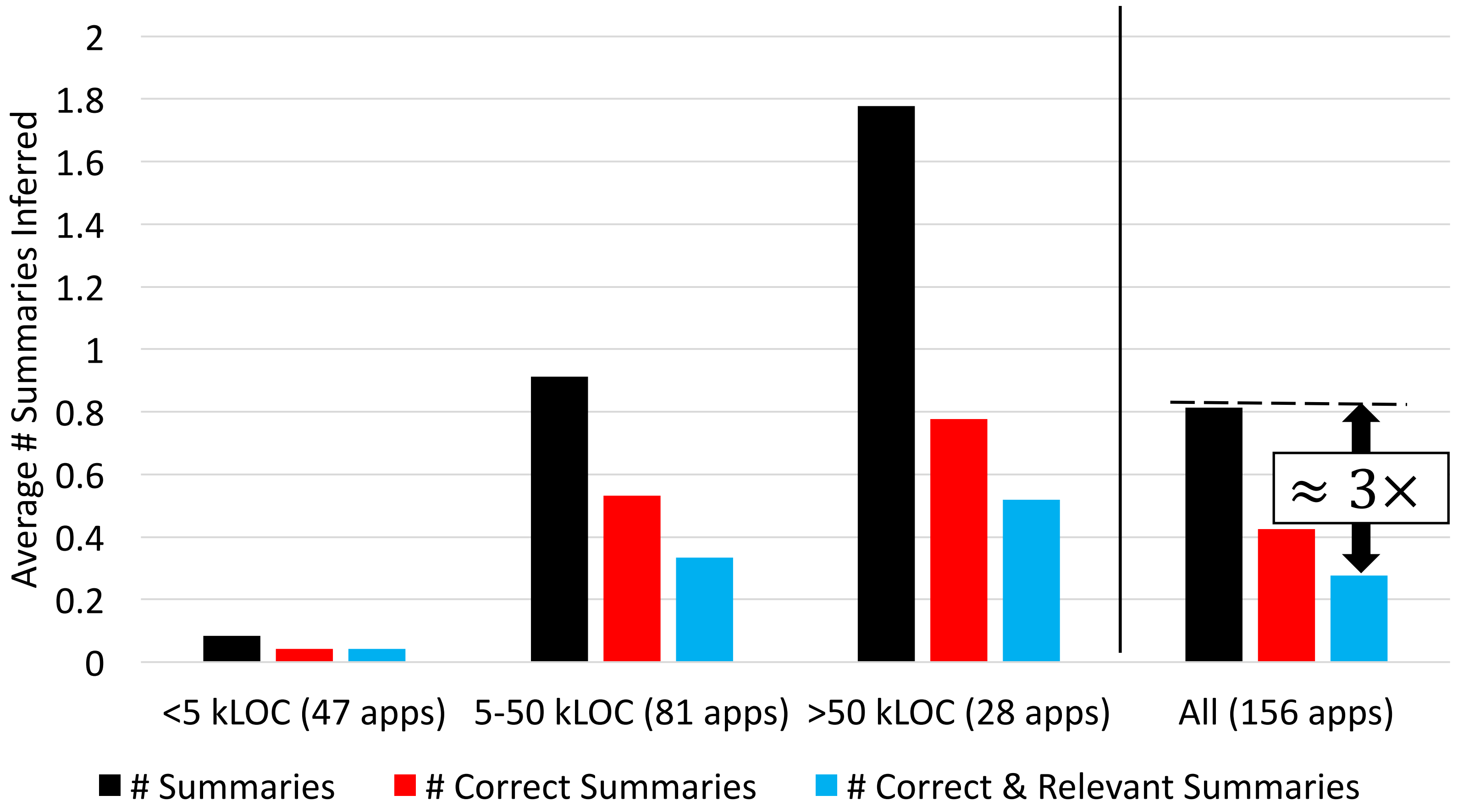
Evaluation: Flow Summaries



Evaluation: Flow Summaries



Evaluation: Alias Summaries



Human users hold valuable knowledge

- A little interaction goes a long way

Related Work

- Interactively inferring program invariants (Dillig 2012)
- Interactively inferring library specifications (Zhu 2013)

Follow-Up Work

Follow-Up Work

Untrusted Responses (OOPSLA 2015)

- Instrumentation to enforce responses

Follow-Up Work

Untrusted Responses (OOPSLA 2015)

- Instrumentation to enforce responses

“Interact” with Executions

- **Step 3:** ~~Analyst corrections~~ → Monitor executions

Follow-Up Work

Untrusted Responses (OOPSLA 2015)

- Instrumentation to enforce responses

“Interact” with Executions

- **Step 3:** ~~Analyst corrections~~ $\rightarrow$ Monitor executions

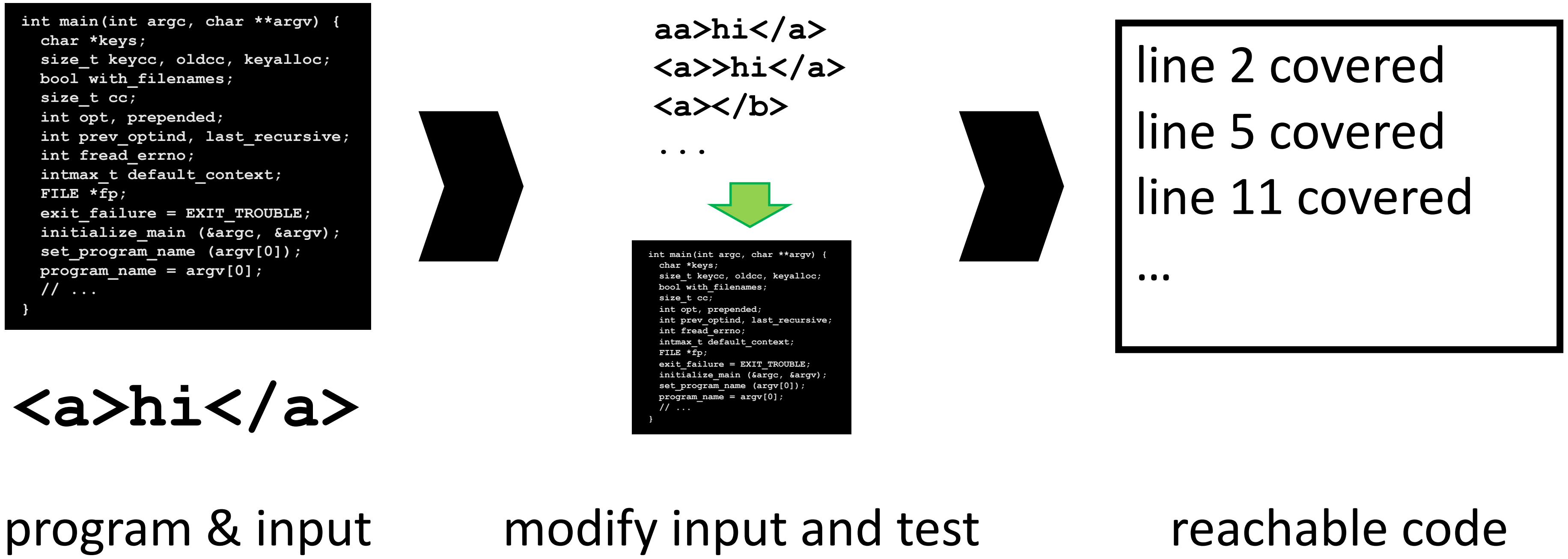
Automatic Test Generation

- **Input:** ~~Android app~~ $\rightarrow$ Synthesized test cases

Inferring Grammars for Fuzz Testing

Osbert Bastani, Rahul Sharma, Alex Aiken, and Percy Liang

PLDI 2017



```
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;
  FILE *fp;
  exit_failure = EXIT_TROUBLE;
  initialize_main (&argc, &argv);
  set_program_name (argv[0]);
  program_name = argv[0];
  // ...
}
```

```
<a>hi</a>
```

```
aa>hi</a>
<a>>hi</a>
<a></b>
...
```

```
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;
  FILE *fp;
  exit_failure = EXIT_TROUBLE;
  initialize_main (&argc, &argv);
  set_program_name (argv[0]);
  program_name = argv[0];
  // ...
}
```

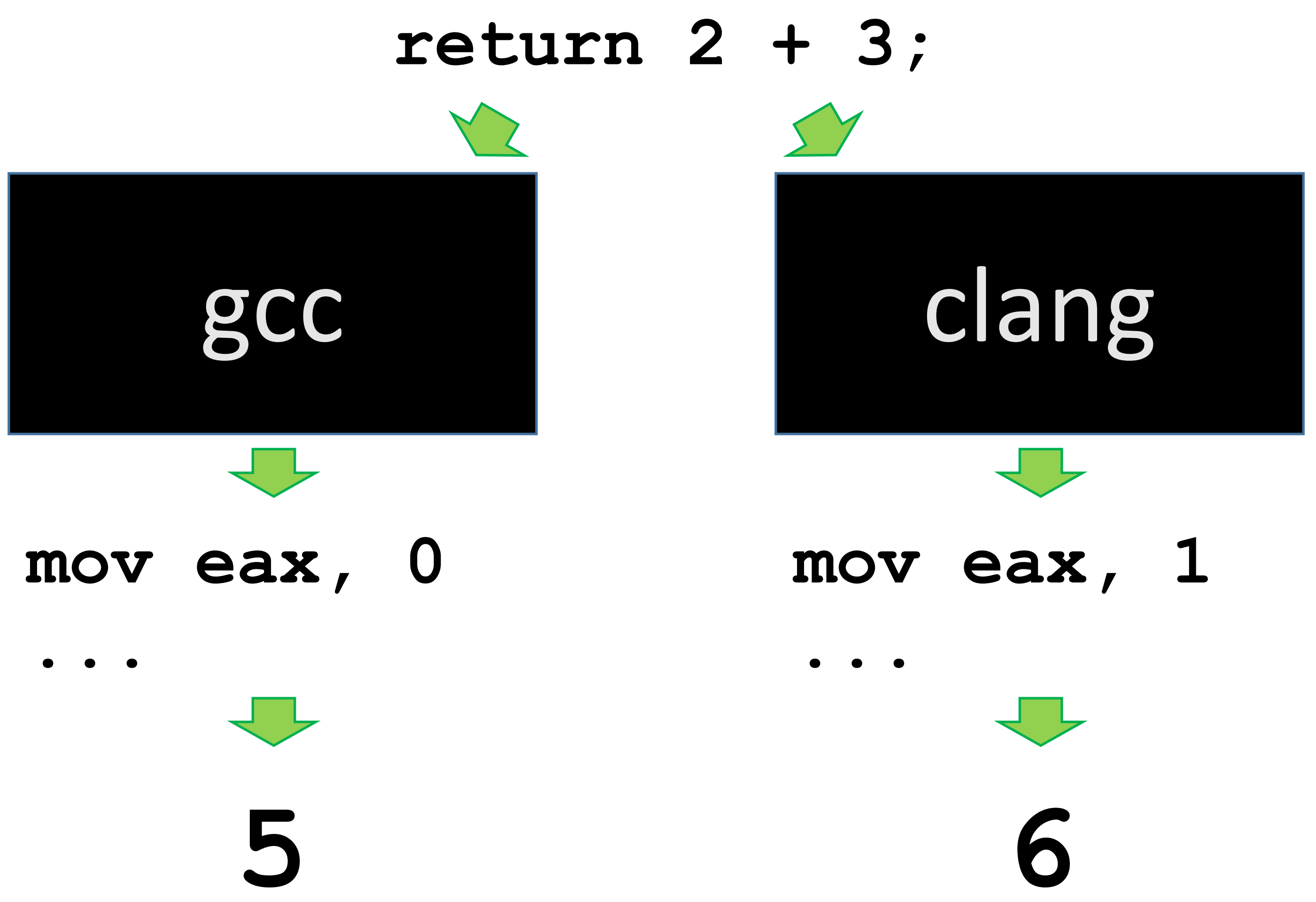
line 2 covered
line 5 covered
line 11 covered
...

Security Vulnerabilities (Miller 1990, …)

```
<<a>ai</a>
```

```
int main(int argc, char **argv) {
  char *keys;
  size_t keycc, oldcc, keyalloc;
  bool with_filenames;
  size_t cc;
  int op                  ;
  int                              ive;
  int
  int
  FIL
  exit                           E;
  init                          rgv);
  set_program_name (argv[0]);
  program_name = argv[0];
  // ...
}
```

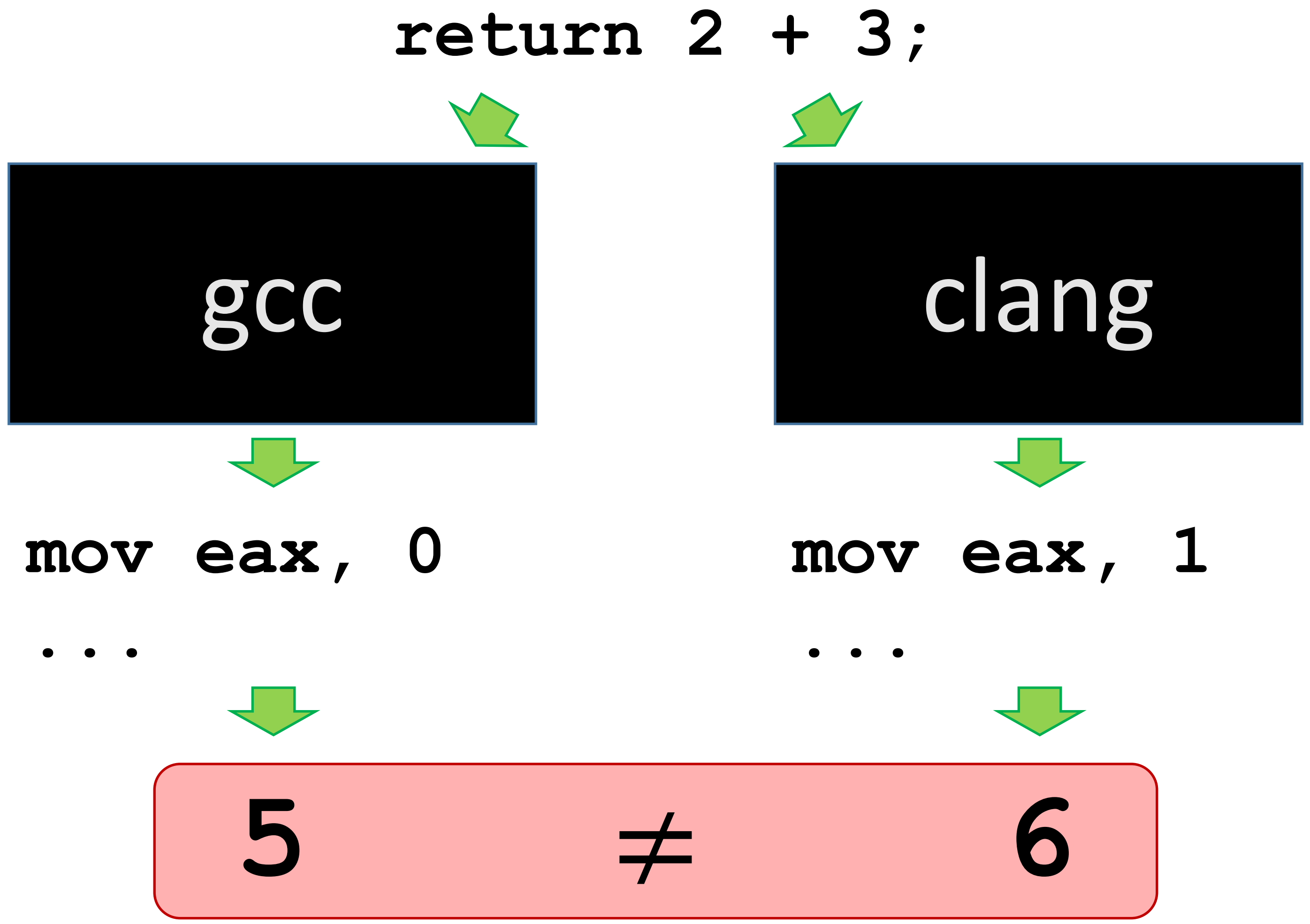
Compiler Bugs (Yang 2011, …)

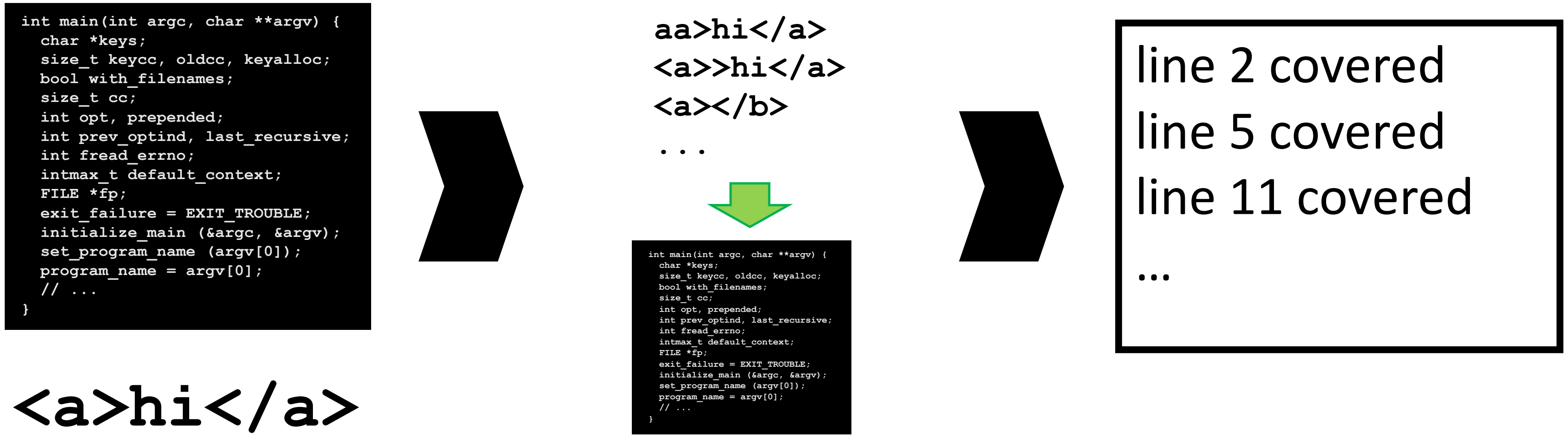

```
return 2 + 3;
```

```
mov eax, 0
...
```

```
mov eax, 1
...
```

Compiler Bugs (Yang 2011, …)





```
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;
  FILE *fp;
  exit_failure = EXIT_TROUBLE;
  initialize_main (&argc, &argv);
  set_program_name (argv[0]);
  program_name = argv[0];
  // ...
}
```

```
<a>hi</a>
```

```
aa>hi</a>
<a>>hi</a>
<a></b>
...
```

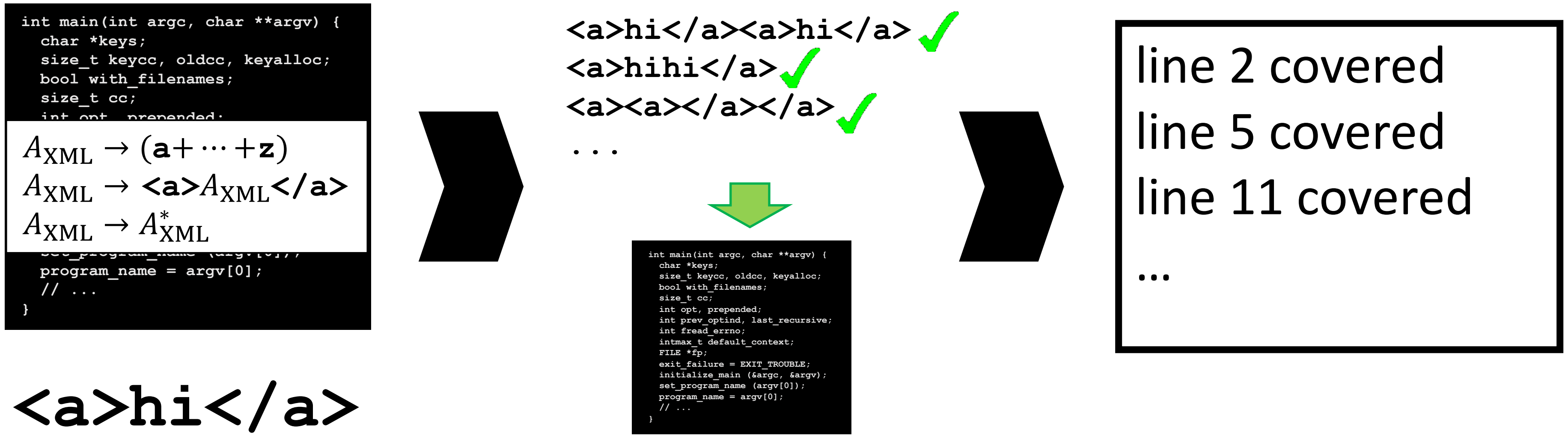
```
int main(int argc, char **argv) {
  char *keys;
  size_t keycc, oldcc, keyalloc;
  bool with_filenames;
  size_t cc;
  int opt, prepended;
  int prev_optind, last_recursive;
  int fread_errno;
  intmax_t default_context;
  FILE *fp;
  exit_failure = EXIT_TROUBLE;
  initialize_main (&argc, &argv);
  set_program_name (argv[0]);
  program_name = argv[0];
  // ...
}
```

```
line 2 covered
line 5 covered
line 11 covered
...
```

program & input

modify input and test

reachable code



```
int main(int argc, char **argv) {
  char *keys;
  size_t keycc, oldcc, keyalloc;
  bool with_filenames;
  size_t cc;
  int opt, prepended;
```

$$A_{\text{XML}} \rightarrow (\mathbf{a}+\cdots+\mathbf{z})$$
$$A_{\text{XML}} \rightarrow \texttt{<a>}A_{\text{XML}}\texttt{</a>}$$
$$A_{\text{XML}} \rightarrow A_{\text{XML}}^{*}$$

```
  set_program_name (argv[0]);
  program_name = argv[0];
  // ...
}
```

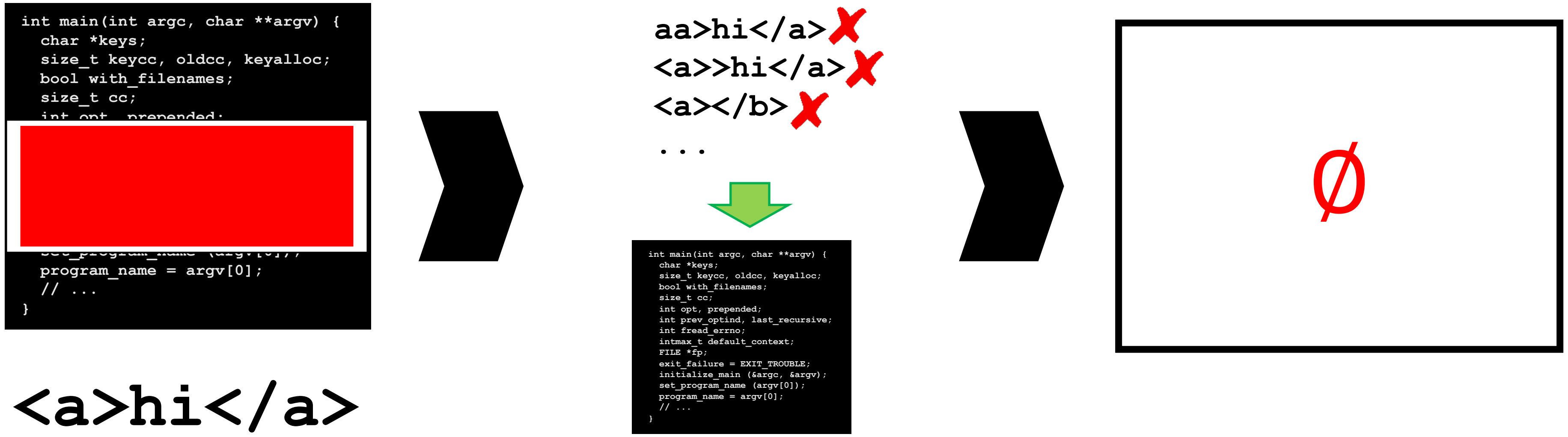
`<a>hi</a>`

```
<a>hi</a><a>hi</a> ✓
<a>hihi</a> ✓
<a><a></a></a> ✓
...
```

```
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;
  FILE *fp;
  exit_failure = EXIT_TROUBLE;
  initialize_main (&argc, &argv);
  set_program_name (argv[0]);
  program_name = argv[0];
  // ...
}
```

line 2 covered
line 5 covered
line 11 covered
...

program & input   modify input and test   reachable code



```
int main(int argc, char **argv) {
  char *keys;
  size_t keycc, oldcc, keyalloc;
  bool with_filenames;
  size_t cc;
  int opt, prepended;
[redacted]
  program_name = argv[0];
  // ...
}
```

`<a>hi</a>`

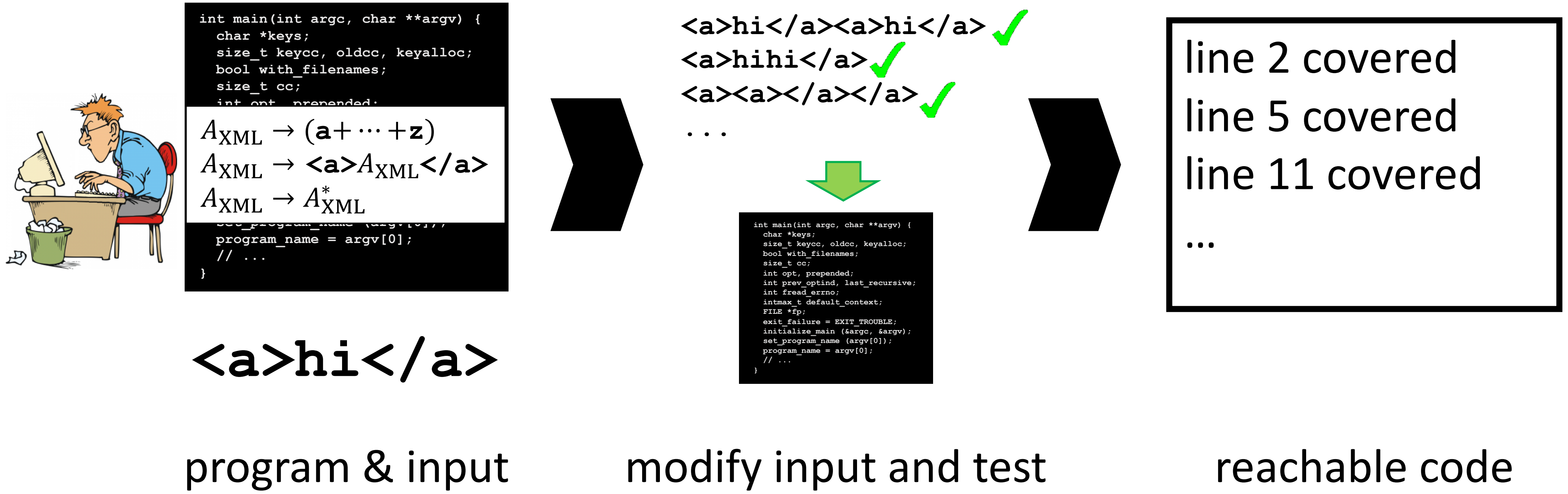
```
aa>hi</a> ✗
<a>>hi</a> ✗
<a></b> ✗
...
```

```
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;
  FILE *fp;
  exit_failure = EXIT_TROUBLE;
  initialize_main (&argc, &argv);
  set_program_name (argv[0]);
  program_name = argv[0];
  // ...
}
```

program & input

modify input and test

reachable code



```
int main(int argc, char **argv) {
  char *keys;
  size_t keycc, oldcc, keyalloc;
  bool with_filenames;
  size_t cc;
  int opt, prepended;
  set_program_name (argv[0]);
  program_name = argv[0];
  // ...
}
```

$A_{\text{XML}} \rightarrow (\mathtt{a} + \cdots + \mathtt{z})$

$A_{\text{XML}} \rightarrow \mathtt{<a>}A_{\text{XML}}\mathtt{</a>}$

$A_{\text{XML}} \rightarrow A_{\text{XML}}^{*}$

`<a>hi</a>`

program & input

```
<a>hi</a><a>hi</a> ✓
<a>hihi</a> ✓
<a><a></a></a> ✓
. . .
```

```
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;
  FILE *fp;
  exit_failure = EXIT_TROUBLE;
  initialize_main (&argc, &argv);
  set_program_name (argv[0]);
  program_name = argv[0];
  // ...
}
```

modify input and test

```
line 2 covered
line 5 covered
line 11 covered
...
```

reachable code

```
int main(int argc, char **argv) {
  char *keys;
  size_t keycc, oldcc, keyalloc;
  bool with_filenames;
  size_t cc;
  int opt, prepended;
```

$A_{\mathrm{XML}} \rightarrow (\mathtt{a} + \cdots + \mathtt{z})$

$A_{\mathrm{XML}} \rightarrow \mathtt{<a>}A_{\mathrm{XML}}\mathtt{</a>}$

$A_{\mathrm{XML}} \rightarrow A_{\mathrm{XML}}^{*}$

```
  program_name = argv[0];
  // ...
}
```

`<a>hi</a>`

program & input

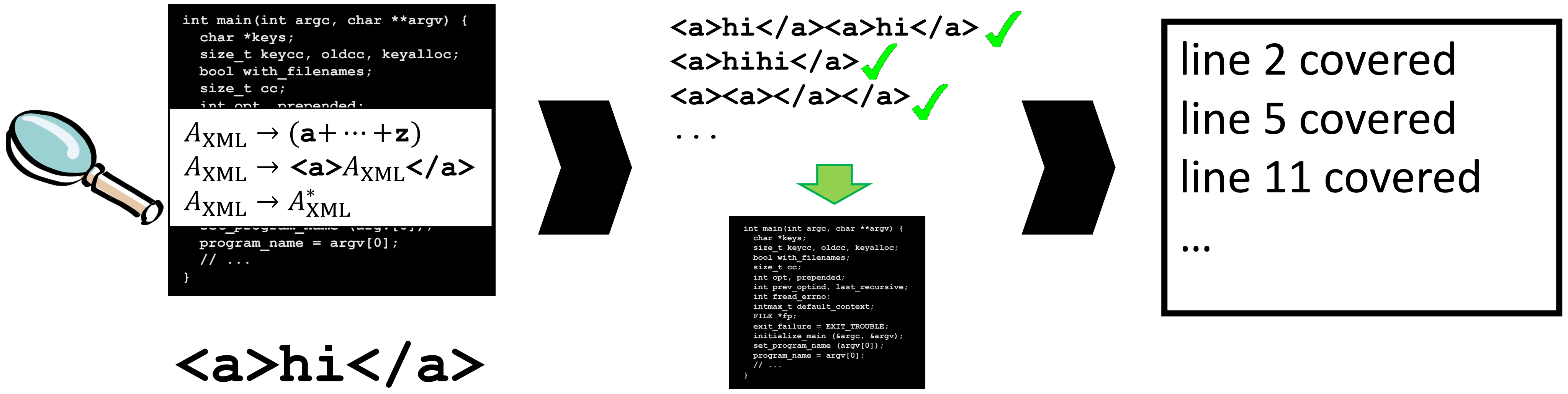
```
<a>hi</a><a>hi</a> ✓
<a>hihi</a> ✓
<a><a></a></a> ✓
. . .
```

```
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;
  FILE *fp;
  exit_failure = EXIT_TROUBLE;
  initialize_main (&argc, &argv);
  set_program_name (argv[0]);
  program_name = argv[0];
  // ...
}
```

modify input and test

line 2 covered
line 5 covered
line 11 covered
...

reachable code



```
int main(int argc, char **argv) {
  char *keys;
  size_t keycc, oldcc, keyalloc;
  bool with_filenames;
  size_t cc;
  int opt, prepended;
```

$A_{\mathrm{XML}} \to (\mathtt{a}+\cdots+\mathtt{z})$

$A_{\mathrm{XML}} \to \mathtt{<a>}A_{\mathrm{XML}}\mathtt{</a>}$

$A_{\mathrm{XML}} \to A_{\mathrm{XML}}^{*}$

```
  set_program_name (argv[0]);
  program_name = argv[0];
  // ...
}
```

`<a>hi</a>`

```
<a>hi</a><a>hi</a> ✓
<a>hihi</a> ✓
<a><a></a></a> ✓
. . .
```

```
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;
  FILE *fp;
  exit_failure = EXIT_TROUBLE;
  initialize_main (&argc, &argv);
  set_program_name (argv[0]);
  program_name = argv[0];
  // ...
}
```

line 2 covered
line 5 covered
line 11 covered
...

program & input

modify input and test

reachable code

Grammar Synthesis Algorithm

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

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

input example & membership oracle

$A_{\text{XML}} \to (\texttt{a}+\cdots+\texttt{z})$
$A_{\text{XML}} \to \texttt{<a>}A_{\text{XML}}\texttt{</a>}$
$A_{\text{XML}} \to A_{\text{XML}}^*$

grammar approximating **target language** L_{XML}

Idea: Construct a series of increasingly general languages

Idea: Construct a series of increasingly general languages

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

Idea: Construct a series of increasingly general languages

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

Idea: Construct a series of increasingly general languages

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

Idea: Construct a series of increasingly general languages

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

Idea: Construct a series of increasingly general languages

$$\begin{tikzcd}
 & & \text{generalization steps} \arrow[dl] \arrow[dr] \arrow[drrr] & & & & \\
\alpha_{\text{in}} = \texttt{<a>hi</a>} & \subseteq & (\texttt{<a>hi</a>})^* & \subseteq & (\texttt{<a>}(\texttt{hi})^*\texttt{</a>})^* & \subseteq & \ldots
\end{tikzcd}$$

Idea: Construct a series of increasingly general languages

generalization steps

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

Idea: Construct a series of increasingly general languages

generalization steps

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

current language L_i

Idea: Construct a series of increasingly general languages

generalization steps

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

current language L_i

generalized language L_{i+1}

Idea: Construct a series of increasingly general languages

generalization steps

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

current language L_i generalized language L_{i+1}

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

Idea: Construct a series of increasingly general languages

generalization steps

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

current language L_i generalized language L_{i+1}

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

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

Idea: Construct a series of increasingly general languages

generalization steps

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

current language L_i generalized language L_{i+1}

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

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

Generalization Step

Generalization Step

```
<a>hi</a>
```

current
language

Generalization Step

`<a>hi</a>`

$\rightarrow$

$($**`<a>hi</a>`**$)^*$

$\vdots$

$($**`<`**$)^*$**`a>hi</a>`**

$\vdots$

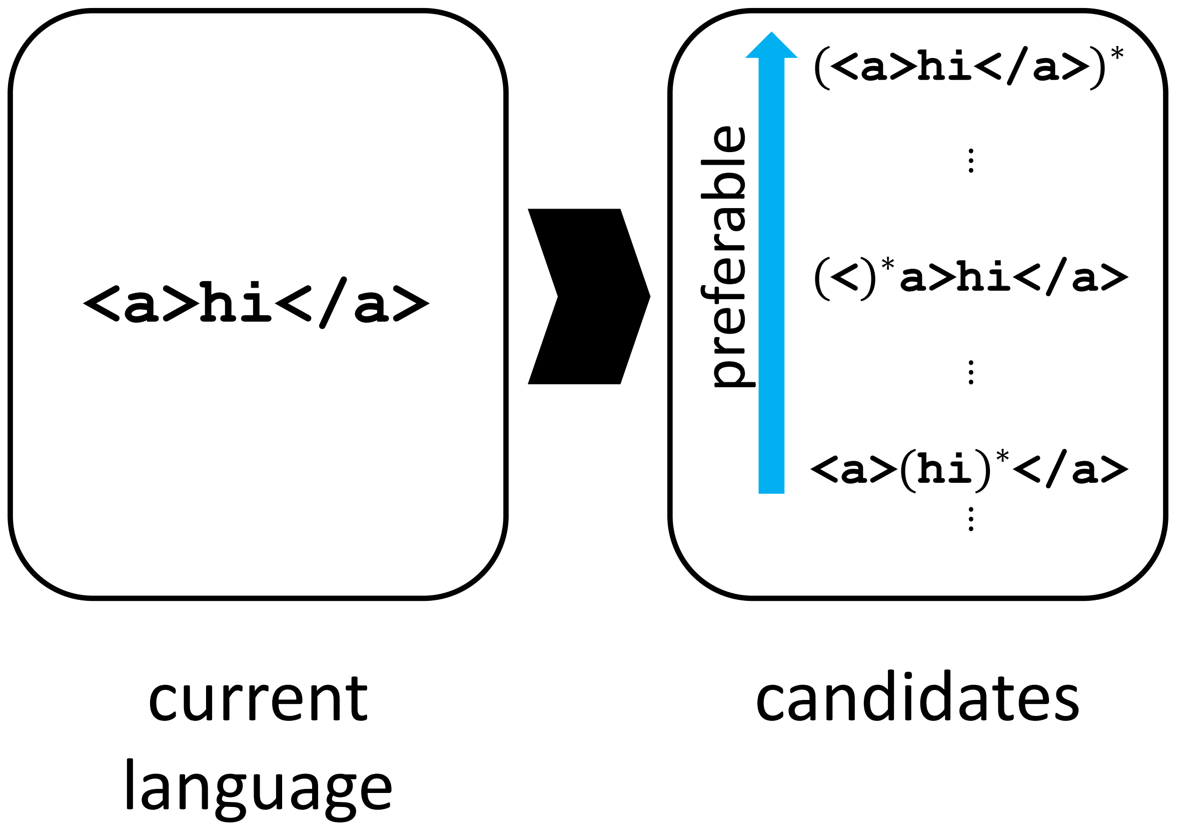
`<a>`$($**`hi`**$)^*$**`</a>`**

$\vdots$

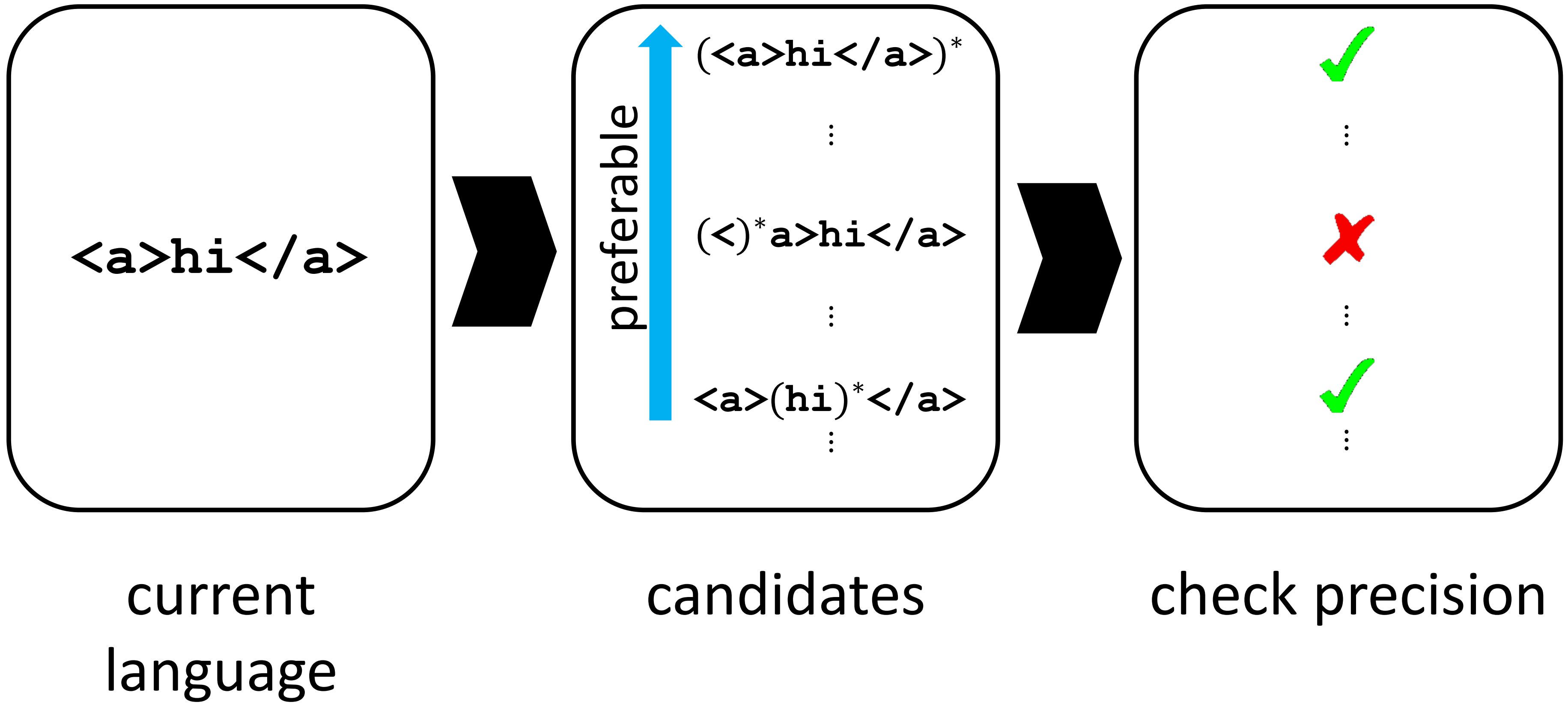
current language

candidates

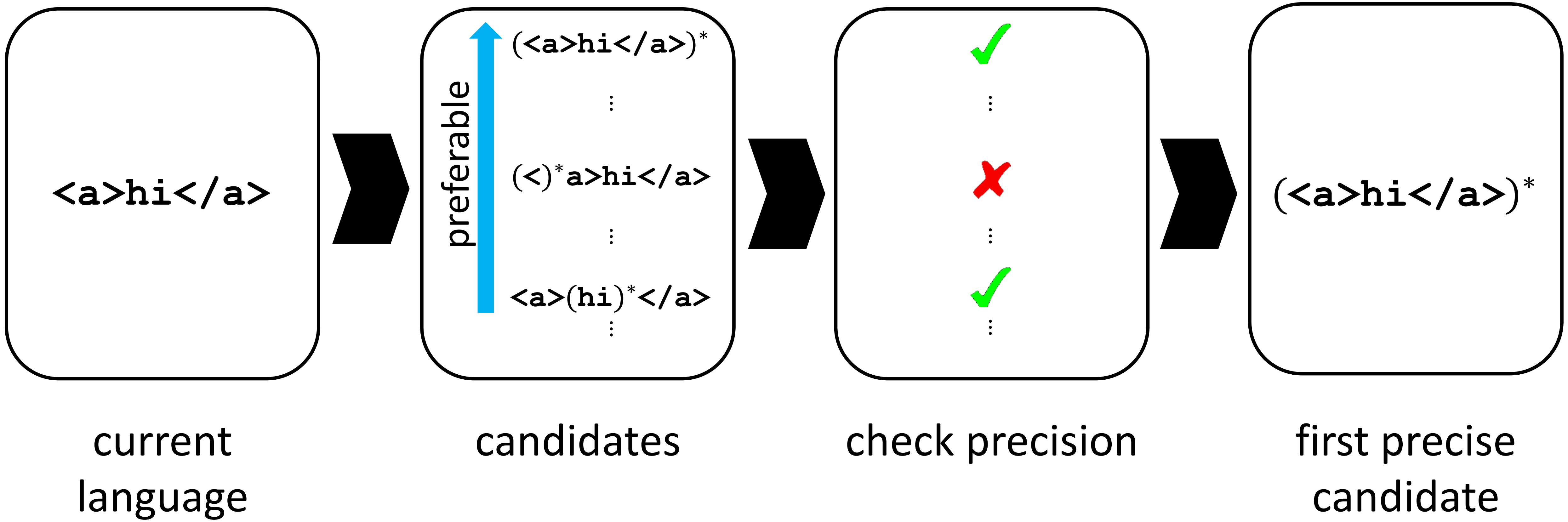
Generalization Step



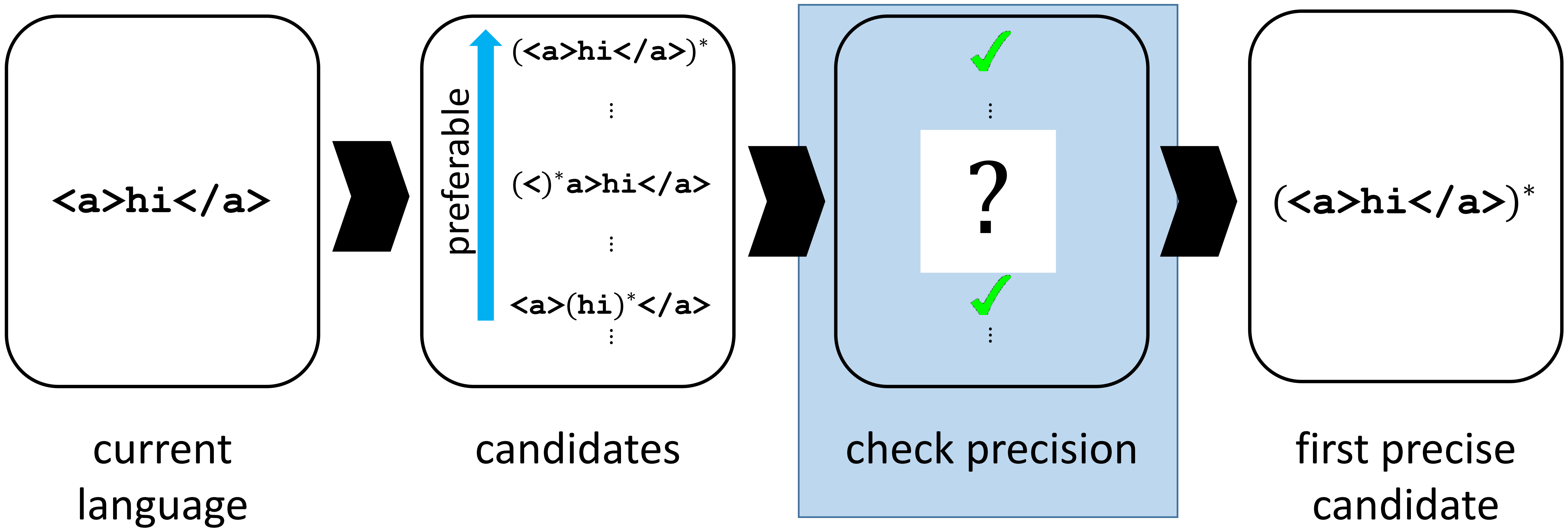
Generalization Step



Generalization Step



Generalization Step



Check Precision

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

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

Check Precision

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

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

Check Precision

infinite!

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

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

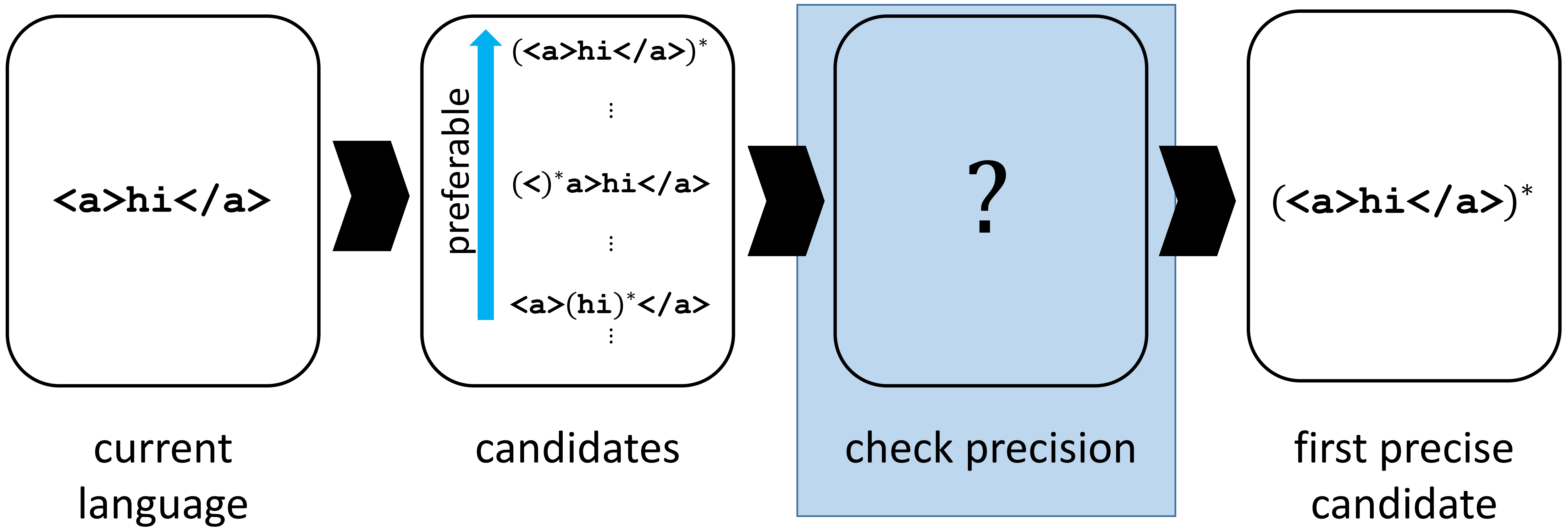
Check Potential Precision

finite subset of **checks**

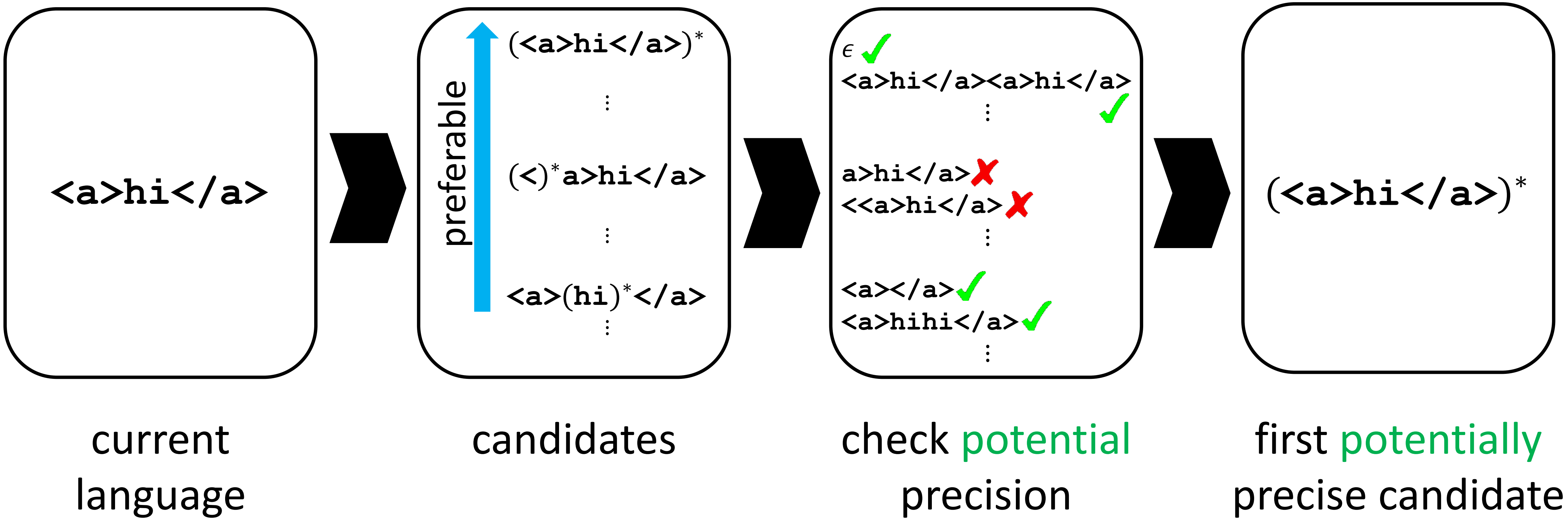
For every $\alpha \in \boldsymbol{S} \subseteq (\texttt{<a>hi</a>})^* \setminus \texttt{<a>hi</a>}$:

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

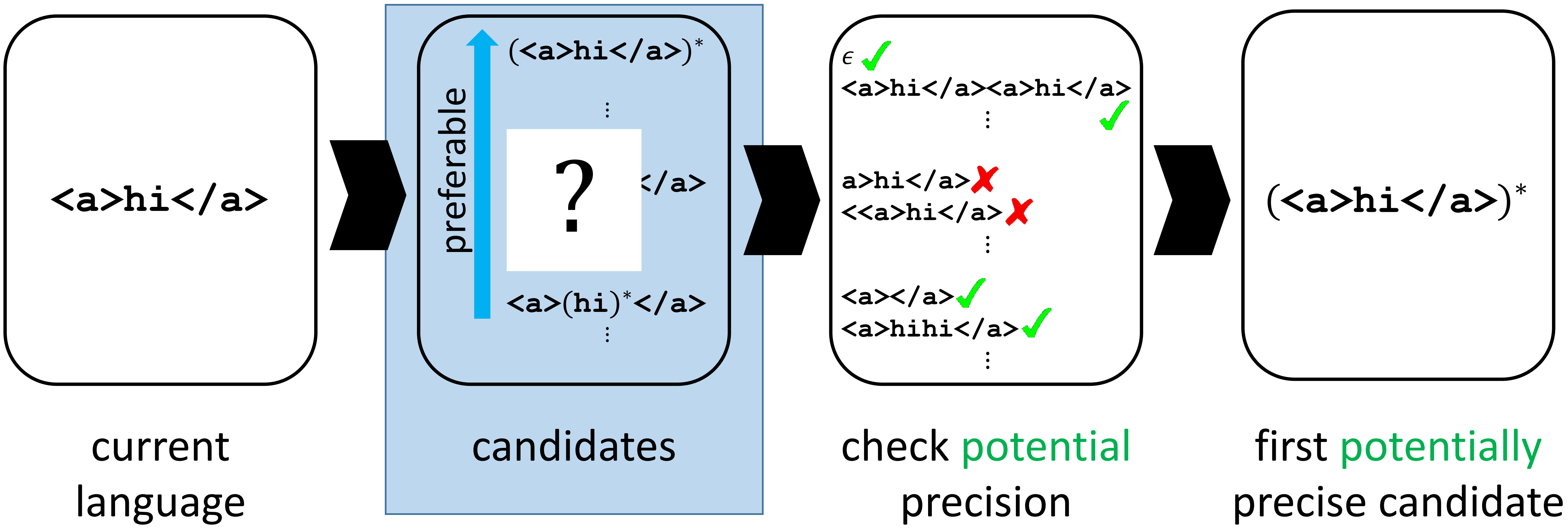
Generalization Step



Generalization Step



Generalization Step



```
<a>hi</a>
```

$\texttt{<a>hi</a>}$

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

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

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

$$\texttt{<a>hi</a>}$$
$$\Rightarrow (\texttt{<a>hi</a>})^*$$
$$\Rightarrow (\texttt{<a>}(\texttt{hi})^*\texttt{</a>})^*$$
$$\Rightarrow (\texttt{<a>}(\texttt{h}+\texttt{i})^*\texttt{</a>})^*$$
$$\Rightarrow \boxed{\begin{array}{l} A \to (\texttt{h}+\texttt{i})^* \\ B \to (\texttt{<a>}A\texttt{</a>})^* \end{array}}$$

$\texttt{<a>hi</a>}$

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

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

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

$$\Rightarrow \boxed{\begin{array}{l} A \to (\texttt{h}+\texttt{i})^* \\ B \to (\texttt{<a>}A\texttt{</a>})^* \end{array}}$$

$$\Rightarrow \boxed{\begin{array}{l} A \to (\texttt{h}+\texttt{i})^* \\ A \to (\texttt{<a>}A\texttt{</a>})^* \end{array}}$$

$\texttt{<a>hi</a>}$

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

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

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

$\Rightarrow \boxed{\begin{array}{l} A \rightarrow (\texttt{h}+\texttt{i})^* \\ B \rightarrow (\texttt{<a>}A\texttt{</a>})^* \end{array}}$

$\Rightarrow \boxed{\begin{array}{l} A \rightarrow (\texttt{h}+\texttt{i})^* \\ A \rightarrow (\texttt{<a>}A\texttt{</a>})^* \end{array}}$

$\Rightarrow \boxed{\begin{array}{l} A \rightarrow (\texttt{a}+\cdots+\texttt{z})^* \\ A \rightarrow (\texttt{<a>}A\texttt{</a>})^* \end{array}}$

Evaluation

Grammar learning:	Compare to existing algorithms
Fuzz testing:	Compare to existing fuzzers

Evaluation: Grammar Learning

Baselines:	L-Star, RPNI
Grammars:	URL, Grep, LISP, XML
Inputs:	membership oracle $\mathcal{O}$ 50 random strings $E_{\mathrm{in}} \subseteq L_*$

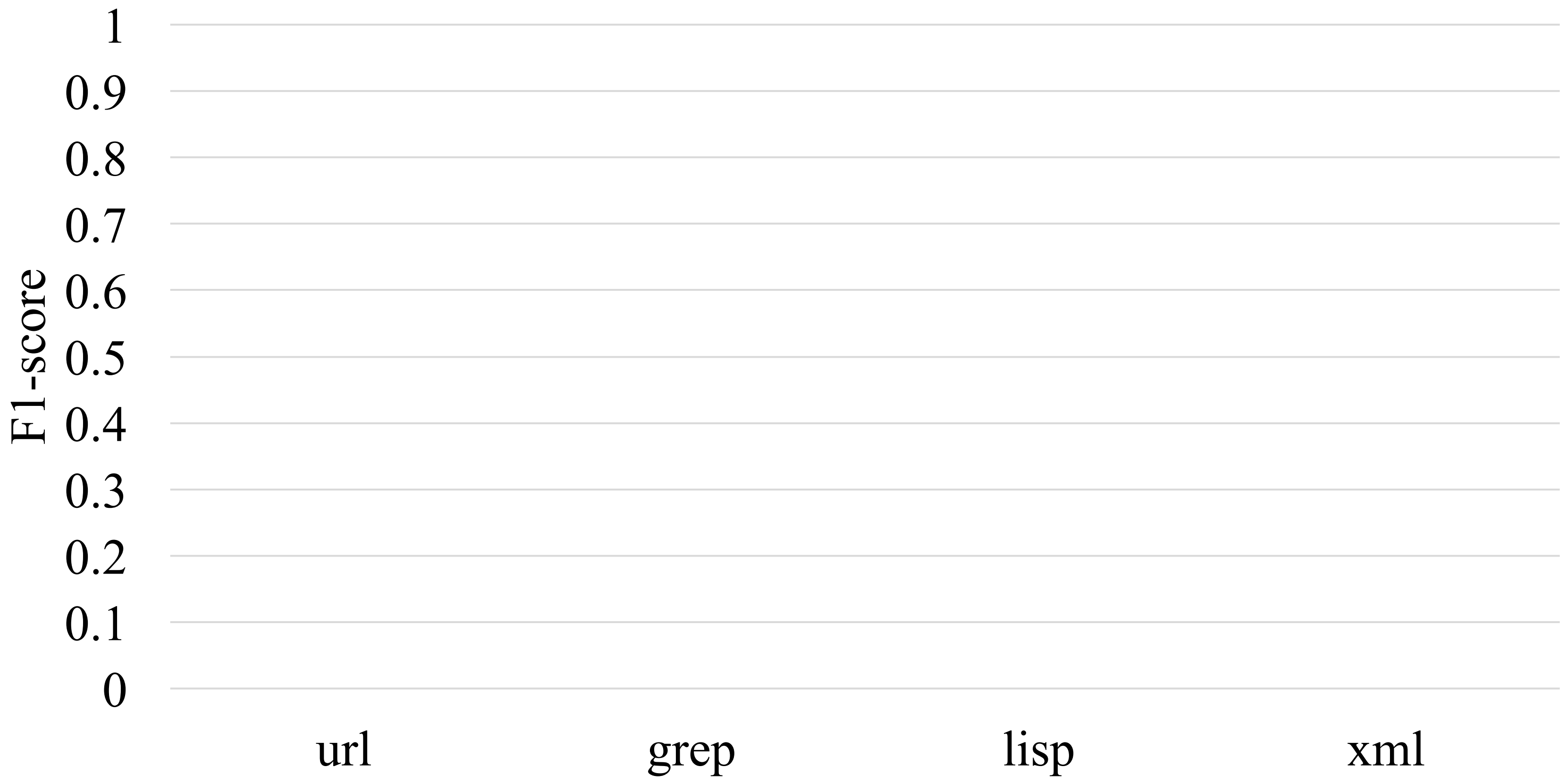
Evaluation: Grammar Learning

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

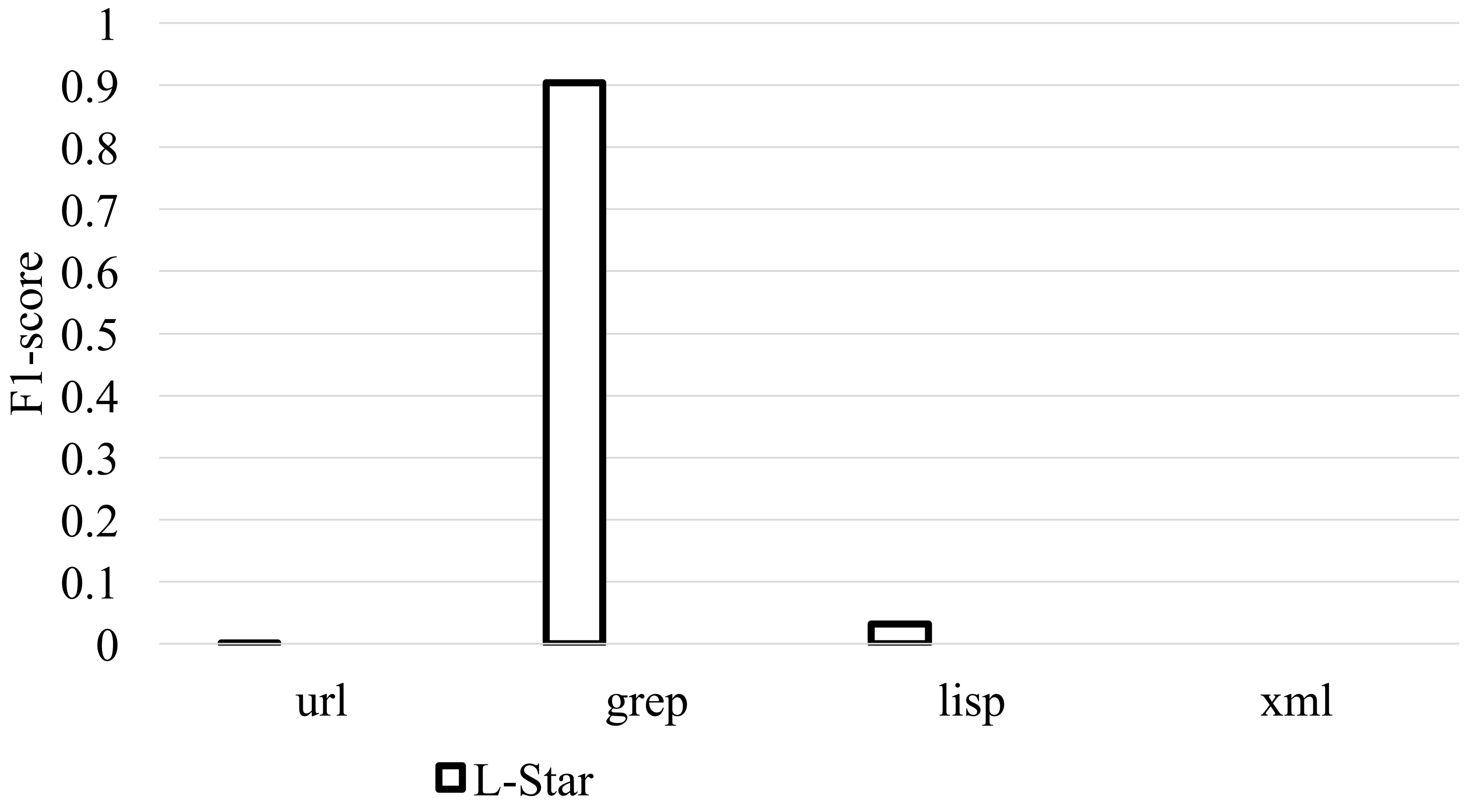
Recall: $$\frac{\#\text{ true inputs that might be sampled}}{\#\text{ true inputs}}$$

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

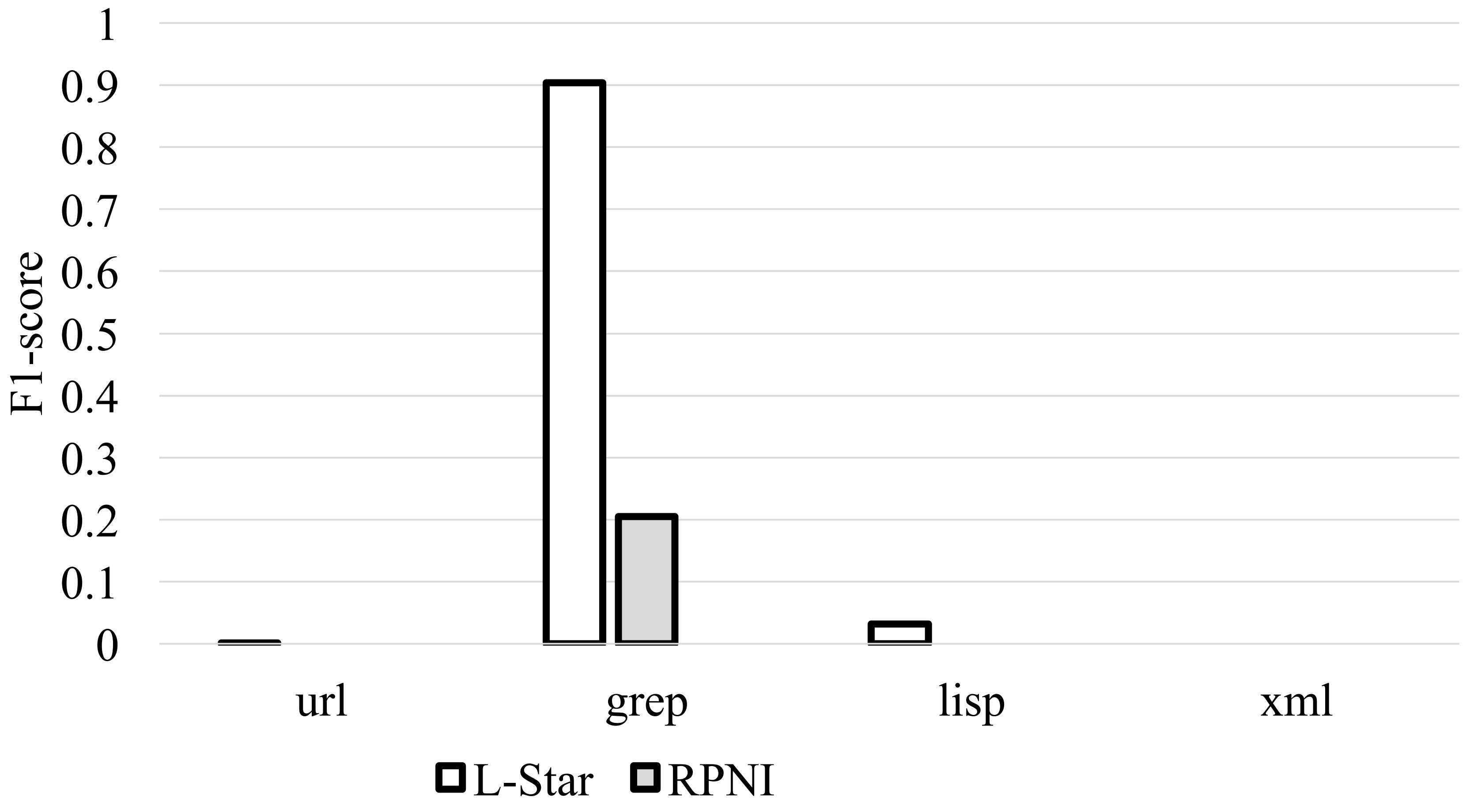
Evaluation: Grammar Learning



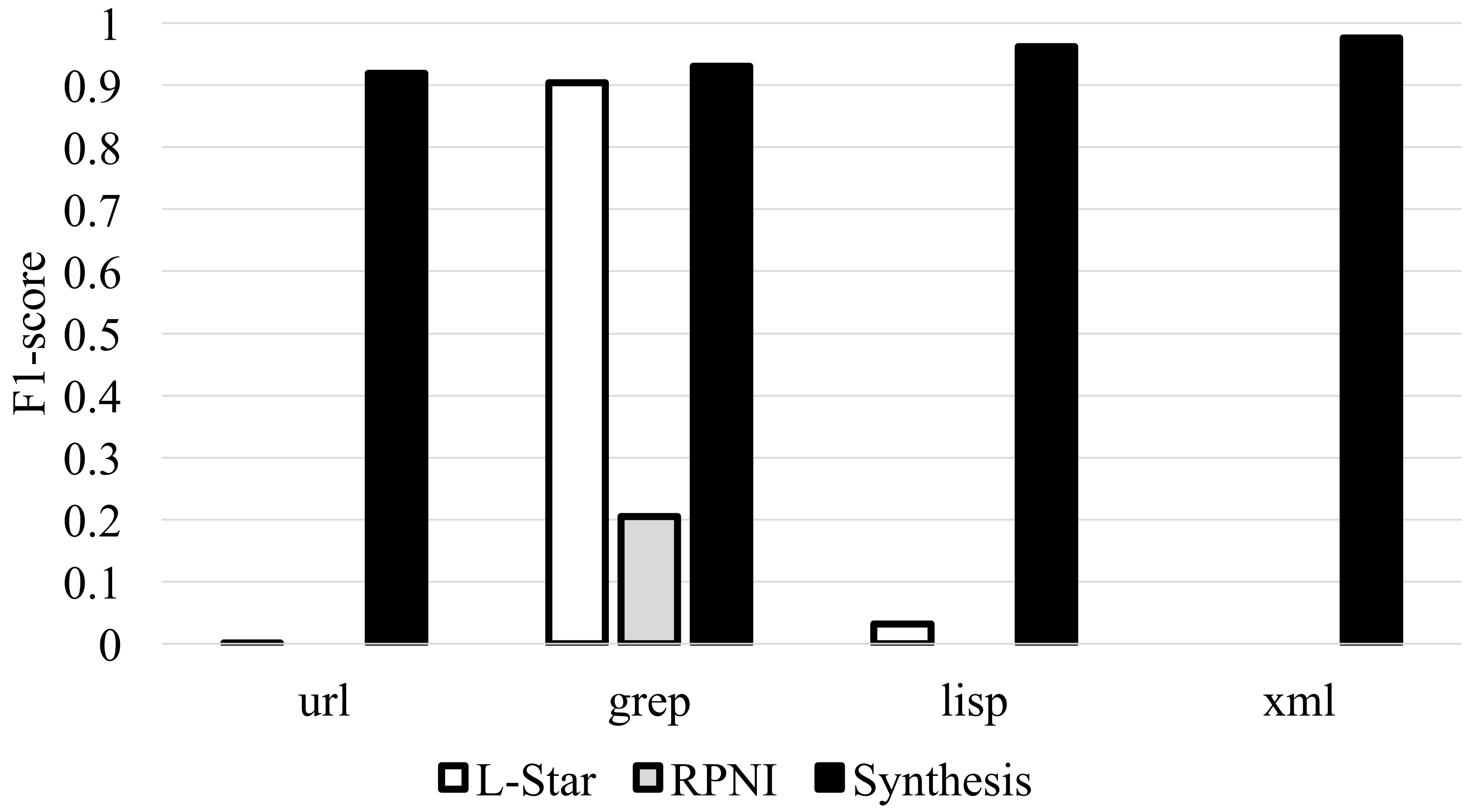
Evaluation: Grammar Learning



Evaluation: Grammar Learning



Evaluation: Grammar Learning



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)

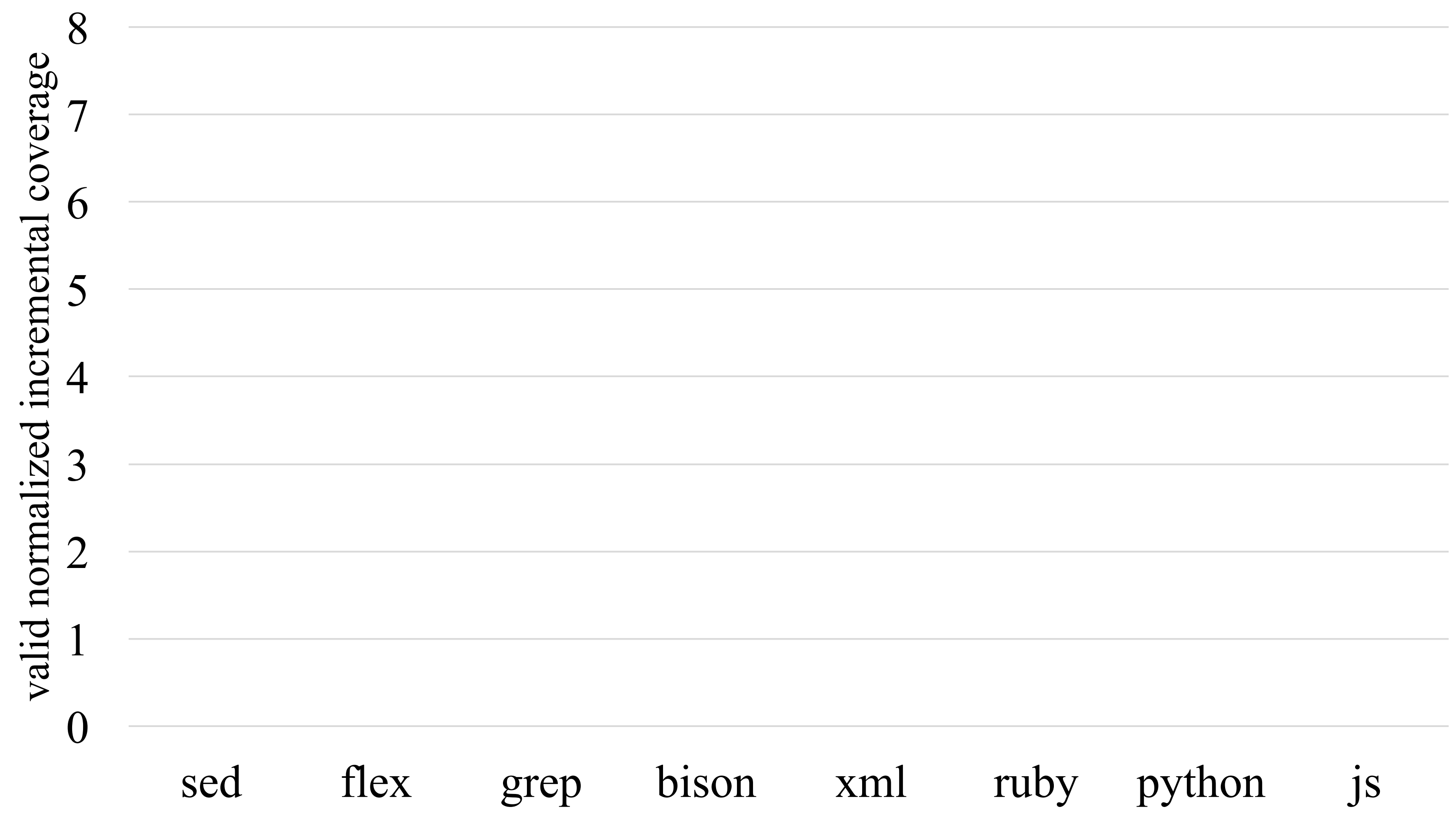
Evaluation: Fuzz Testing

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

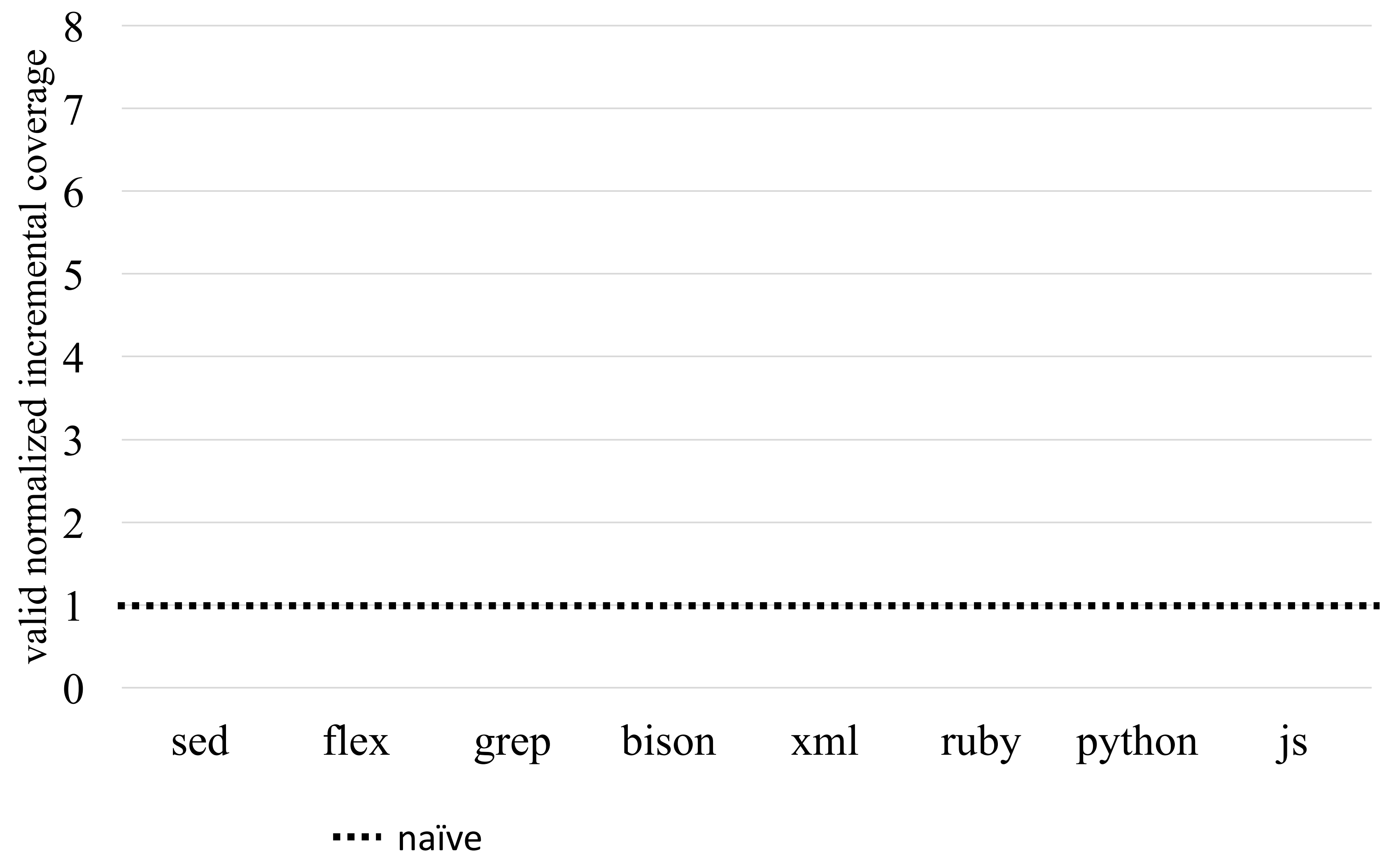
Incremental coverage: $\mathrm{IncCov}(E) = \mathrm{Cov}(E) - \mathrm{Cov}(\alpha_{\mathrm{in}})$

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

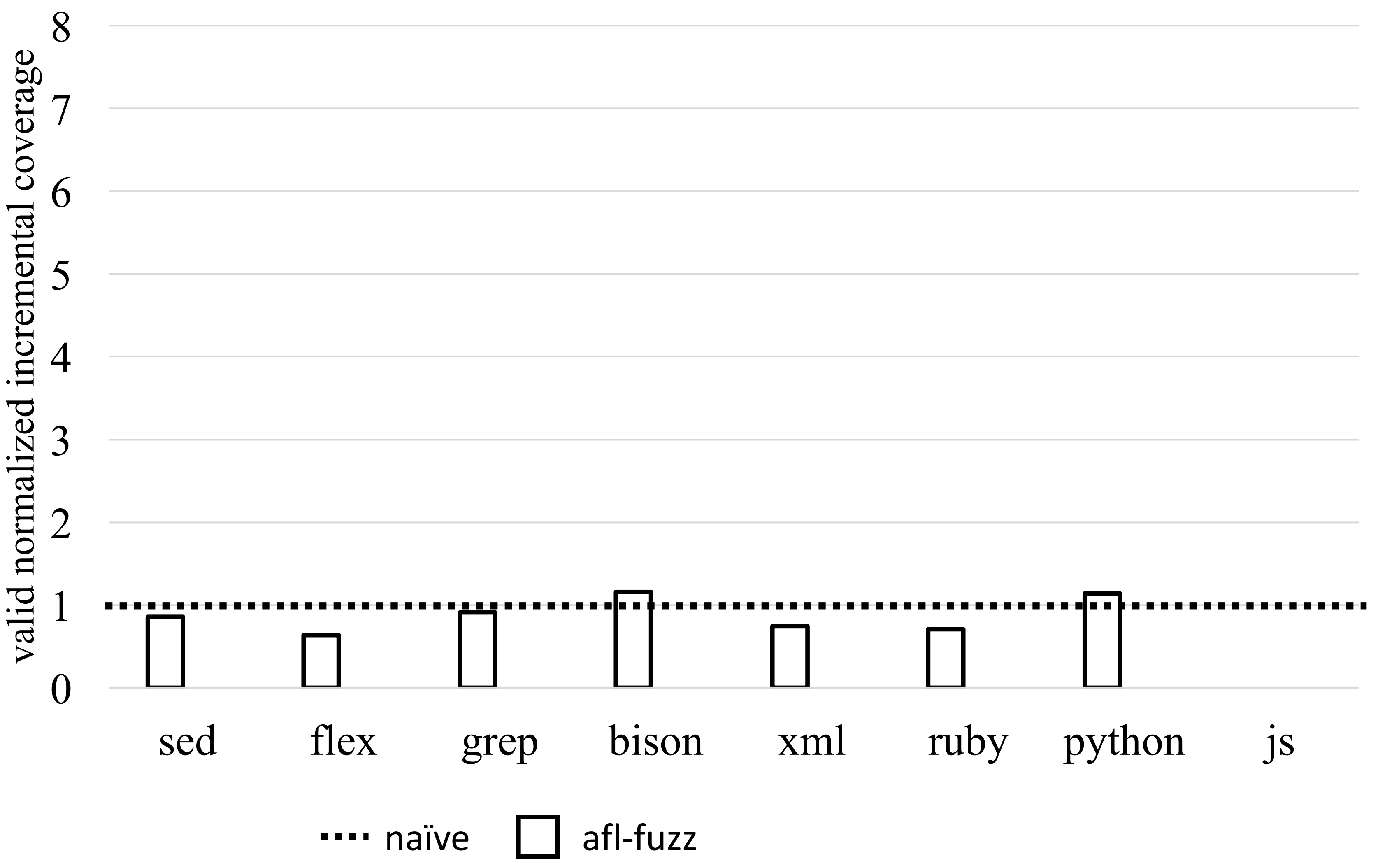
Evaluation: Fuzz Testing



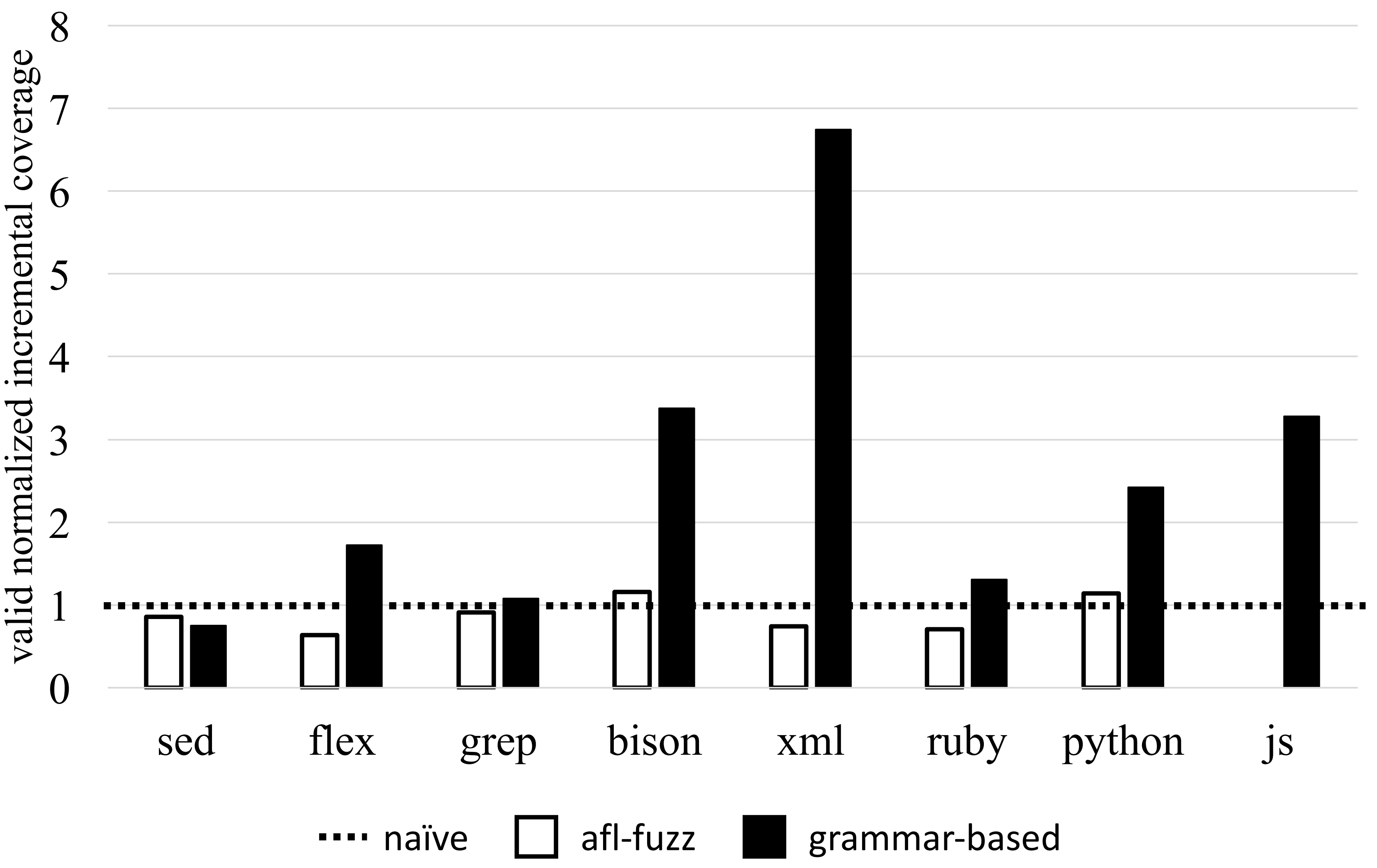
Evaluation: Fuzz Testing



Evaluation: Fuzz Testing



Evaluation: Fuzz Testing



median 2× improvement in incremental coverage

Learn program properties from input-output examples

- “Extreme” form of active learning

Related Work

- Infer program invariants from executions (Ernst 2007)
- Infer program input grammar using dynamic taint analysis (Höschele 2016)

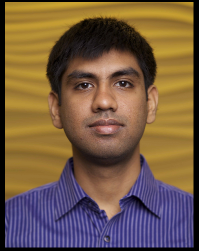
Conclusions & Related Work

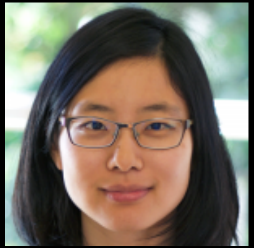
Infer…

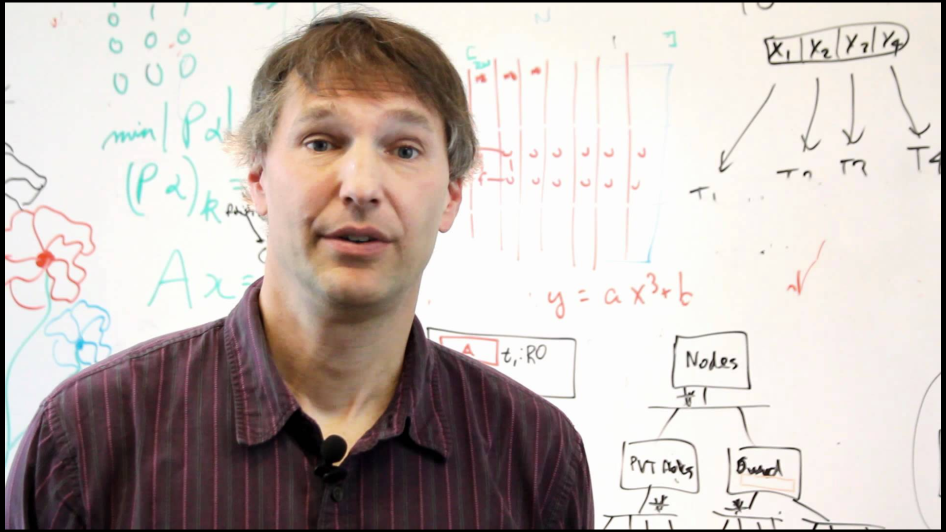
- Flow summaries (Zhu 2013)
- Input formats (Höschele 2016)
- Sources/sinks (Livshits 2009)
- Typestate specifications (Beckman 2011)
- Program invariants (Ernst 2007, Dillig 2012)
- …

Conclusions & Related Work

Inference can substantially improve
the cost-effectiveness of program analysis tools





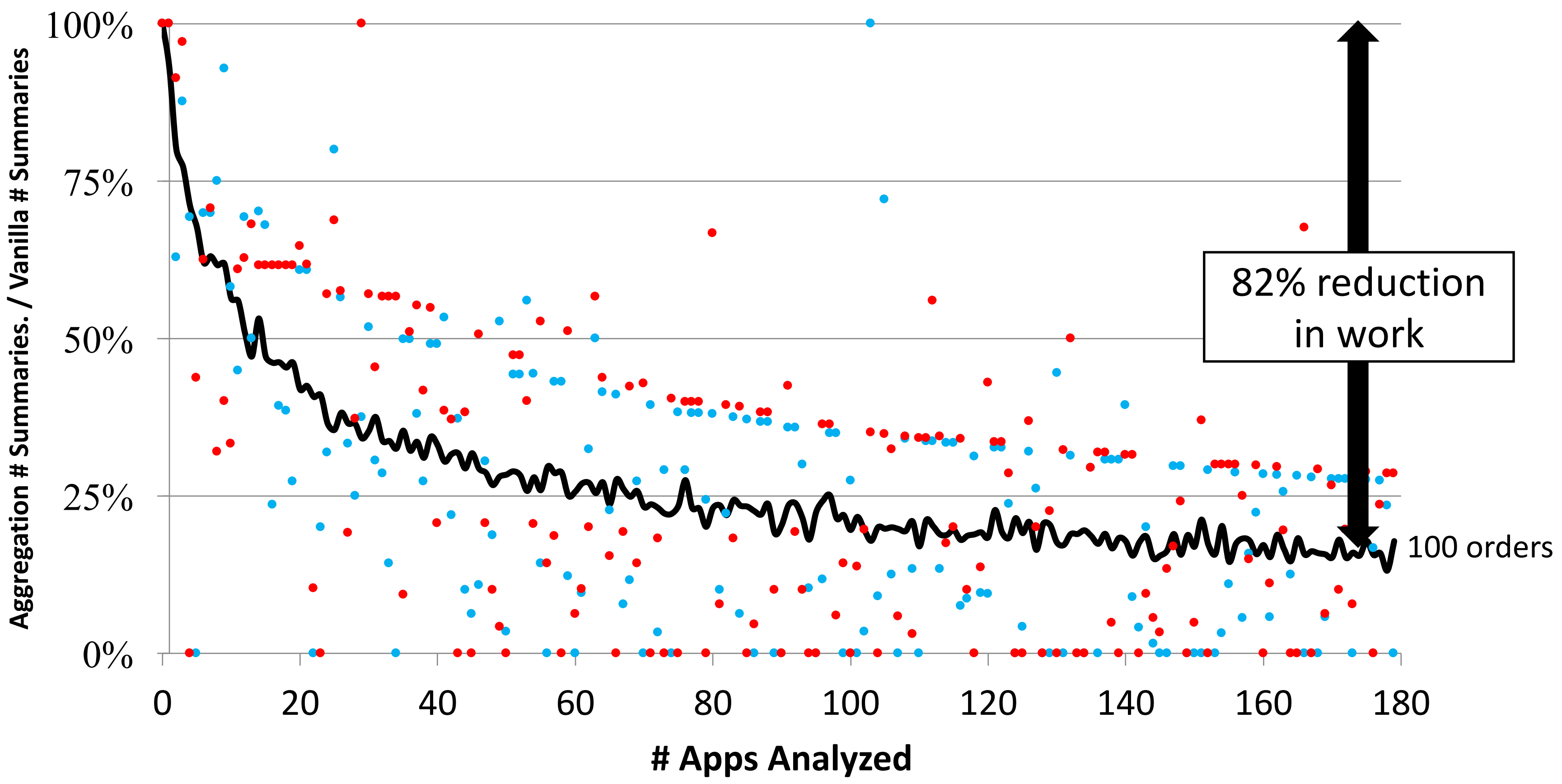

Nodes
$y = ax^3+b$

Questions?

Backup Slides

$$
\begin{array}{lcl}
\text{SrcSink} & \rightarrow & \text{SrcObj FlowsTo RefSink} \\
\text{SrcObj} & \rightarrow & \text{SrcObj FlowsTo RefRef } \overline{\text{FlowsTo}} \\
\text{SrcObj} & \rightarrow & \text{SrcRef } \overline{\text{FlowsTo}} \\
\text{FlowsTo} & \rightarrow & \text{New} \\
\text{FlowsTo} & \rightarrow & \text{FlowsTo Assign} \\
\text{FlowsTo} & \rightarrow & \text{FlowsTo Put[f] FlowsTo } \overline{\text{FlowsTo}} \text{ Get[f]}
\end{array}
$$

Aggregating Summaries over Time



Untrusted Responses (OOPSLA 2015)

Untrusted Responses (OOPSLA 2015)

Step 1: Worst-case analysis

location → Internet
SMS → Internet
device ID → SMS
…

Step 2: Infer summaries

Step 3: Analyst corrections

specification inference

Untrusted Responses (OOPSLA 2015)

Step 1: Worst-case analysis

location → Internet
SMS → Internet
device ID → SMS
...

Step 2: Infer summaries

Step 3: Analyst corrections

specification inference

```
int main(int argc, char **argv) {
  char *keys;
  size_t key      olde    eyalloc;
  bool with     ilenames;
  size_t c
  int opt,     epended;
  int prev              ecursive;
  int frea
  intmax_
  FILE *
  exit_f                 E;
  initi                  rgv);
  set_pr                 ;
  progra
  // ...
}
```

deploy app with instrumentation

Untrusted Responses (OOPSLA 2015)

Step 1: Worst-case analysis

location → Internet
SMS → Internet
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…

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  int opt,    epended;
  int prev  ot       st    ecursive;
  int frea
  intmax_
  FILE *
  exit_                      E;
  initi                     rgv);
  set_pr                     ;
  progra
  // ...
}
```

deploy app with instrumentation

inferred (reachability) summaries eliminated 92% of false positives compared to using worst-case summaries

“Interact” with Executions

“Interact” with Executions

Step 1: Worst-case analysis

location → Internet
SMS → Internet
device ID → SMS
…

Step 2: Infer summaries

Step 3: Monitor executions

“Interact” with Executions

Step 1: Worst-case analysis

location → Internet
SMS → Internet
device ID → SMS
…

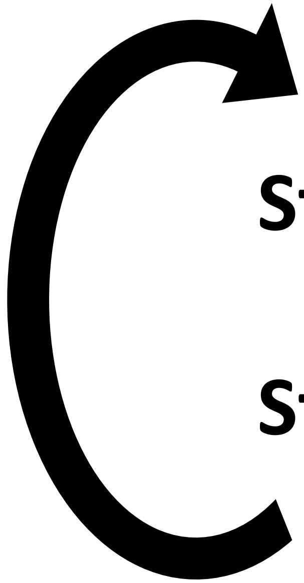
Step 2: Infer summaries

Step 3: Monitor executions

inferred 432 true positives (with 48 false positives)

Automatic Test Generation

Automatic Test Generation



Step 1: Synthesize tests

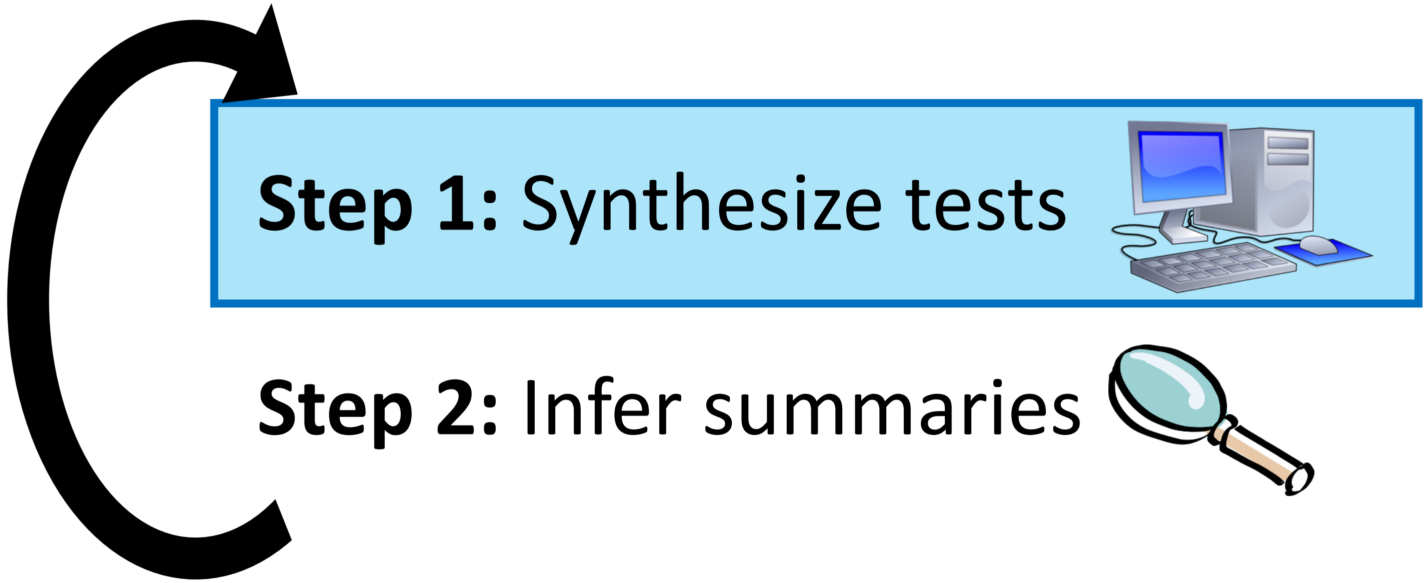
Step 2: Infer summaries

Automatic Test Generation

Step 1: Synthesize tests

Step 2: Infer summaries

Automatic Test Generation



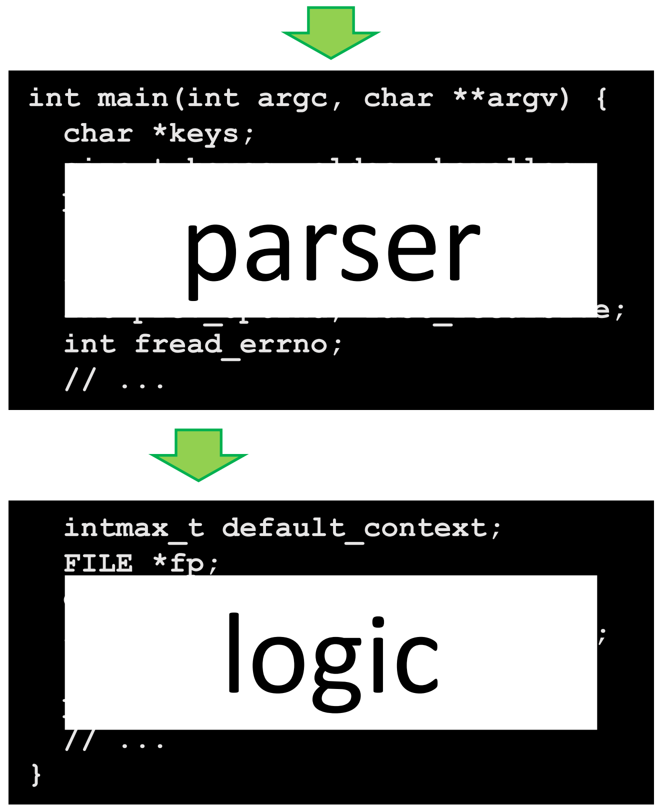
Step 1: Synthesize tests

Step 2: Infer summaries

Java Collections API summaries: 733 inferred versus 58 existing

$$A_{\text{XML}} \to (\mathtt{a} + \cdots + \mathtt{z})$$
$$A_{\text{XML}} \to \mathtt{<a>} A_{\text{XML}} \mathtt{</a>}$$
$$A_{\text{XML}} \to A_{\text{XML}}^{*}$$

`<a>hi</a>`



```
int main(int argc, char **argv) {
  char *keys;
  int fread_errno;
  // ...
```

```
  intmax_t default_context;
  FILE *fp;
  // ...
}
```

aa>hi</a>

$$A_{\text{XML}} \to (\mathtt{a}+\cdots+\mathtt{z})$$
$$A_{\text{XML}} \to \mathtt{<a>}A_{\text{XML}}\mathtt{</a>}$$
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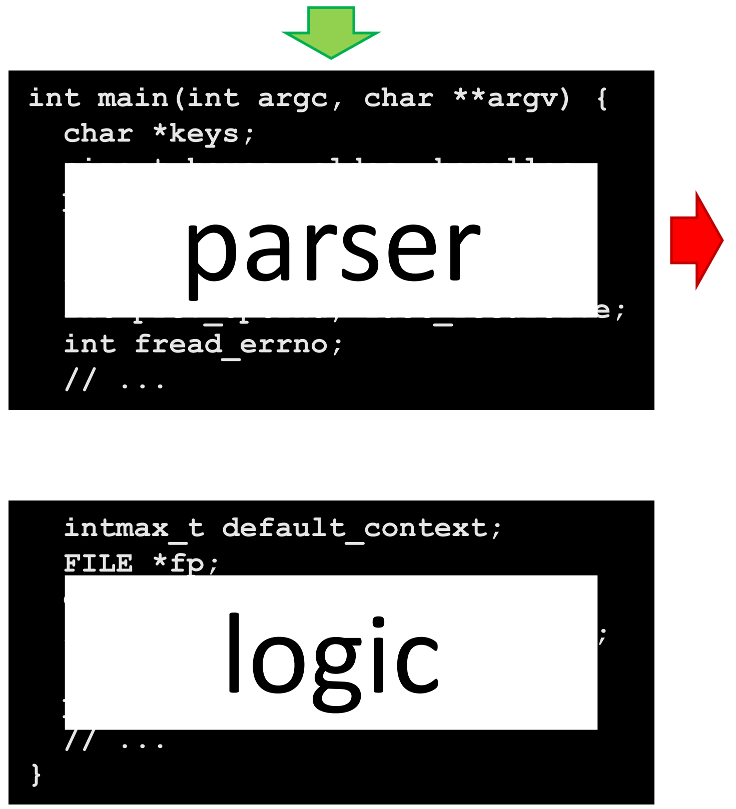
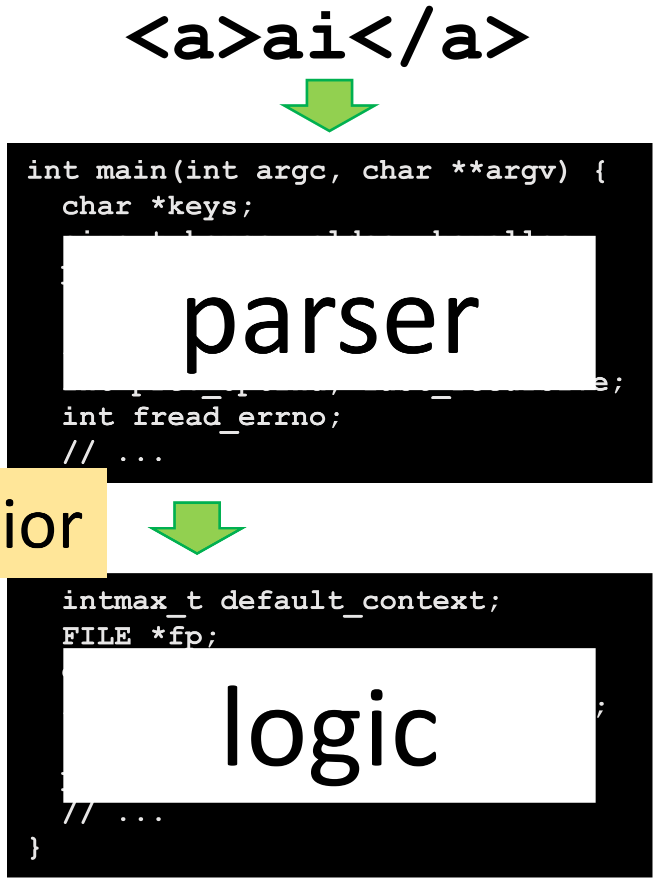


```
int main(int argc, char **argv) {
  char *keys;

  int fread_errno;
  // ...
```

```
  intmax_t default_context;
  FILE *fp;

  // ...
}
```

unmatched '>'!

$$
\begin{aligned}
A_{\mathrm{XML}} &\rightarrow (\mathtt{a}+\cdots+\mathtt{z}) \\
A_{\mathrm{XML}} &\rightarrow \mathtt{<a>}A_{\mathrm{XML}}\mathtt{</a>} \\
A_{\mathrm{XML}} &\rightarrow A_{\mathrm{XML}}^{*}
\end{aligned}
$$



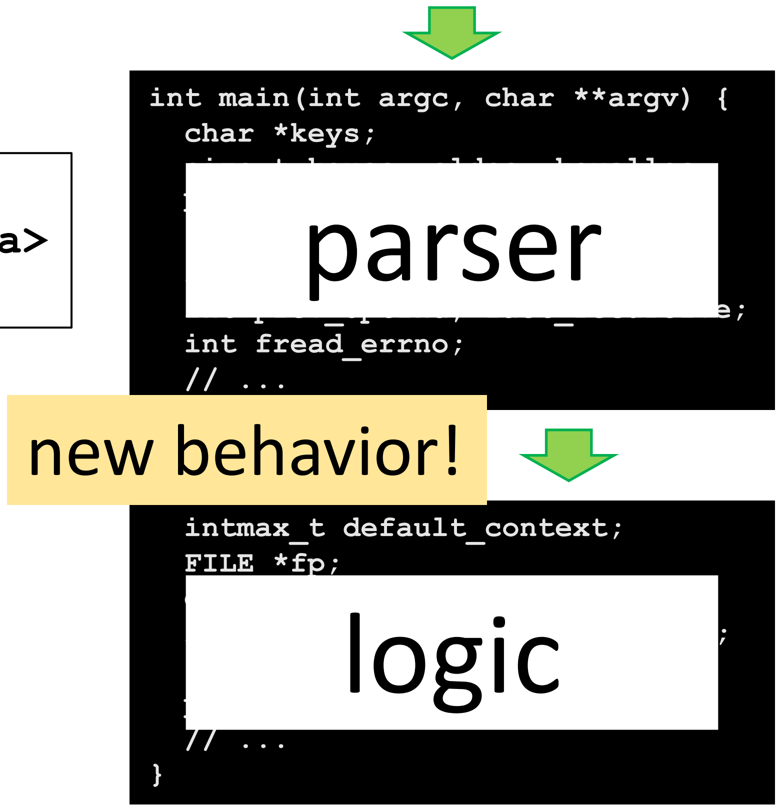
```
int main(int argc, char **argv) {
  char *keys;
  int fread_errno;
  // ...
```

```
  intmax_t default_context;
  FILE *fp;
  // ...
}
```

same behavior

`<a><a>hi</a></a>`

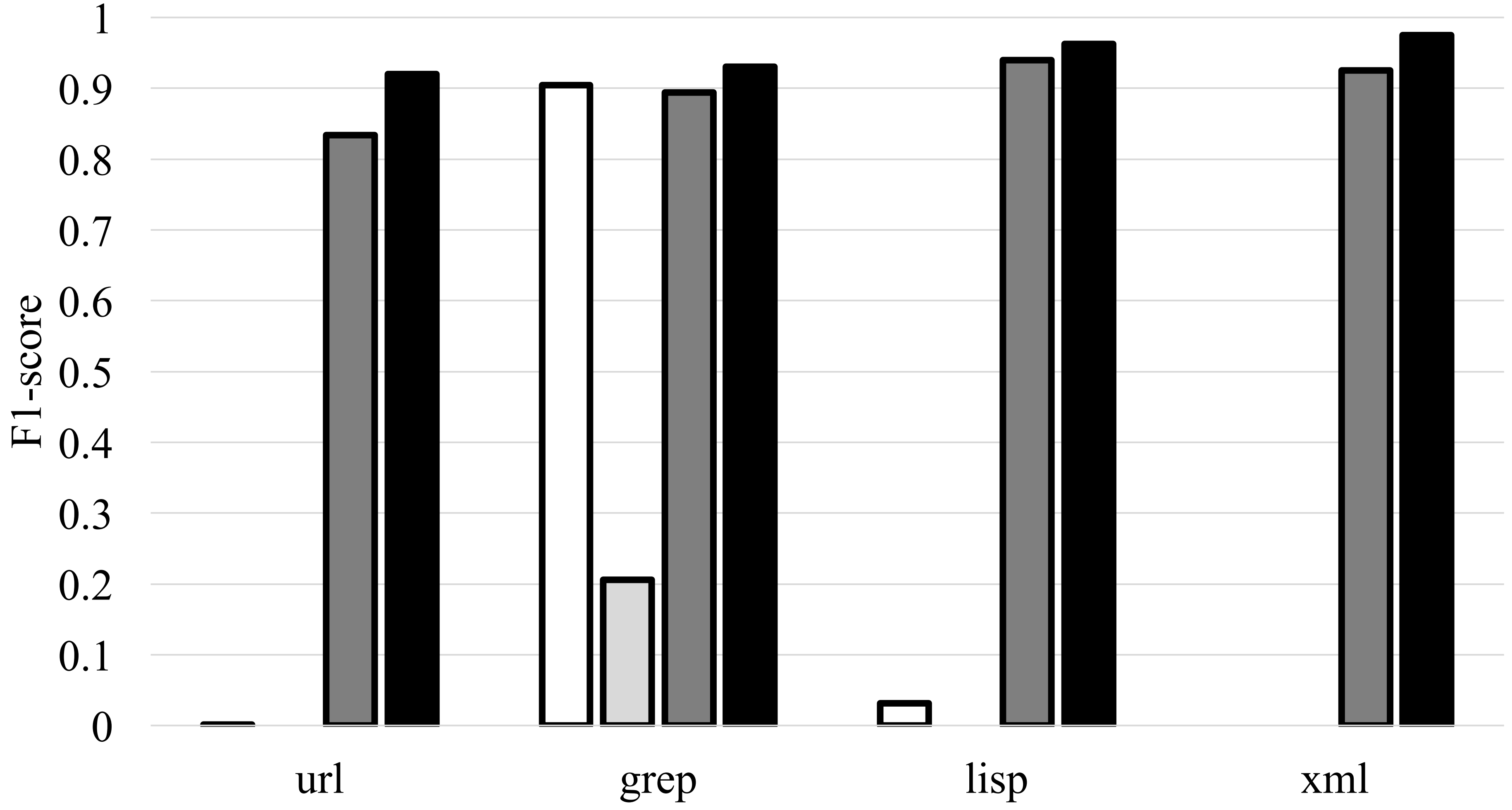
$$A_{\text{XML}} \to (\mathtt{a}+\cdots+\mathtt{z})$$
$$A_{\text{XML}} \to \mathtt{<a>}A_{\text{XML}}\mathtt{</a>}$$
$$A_{\text{XML}} \to A_{\text{XML}}^{*}$$



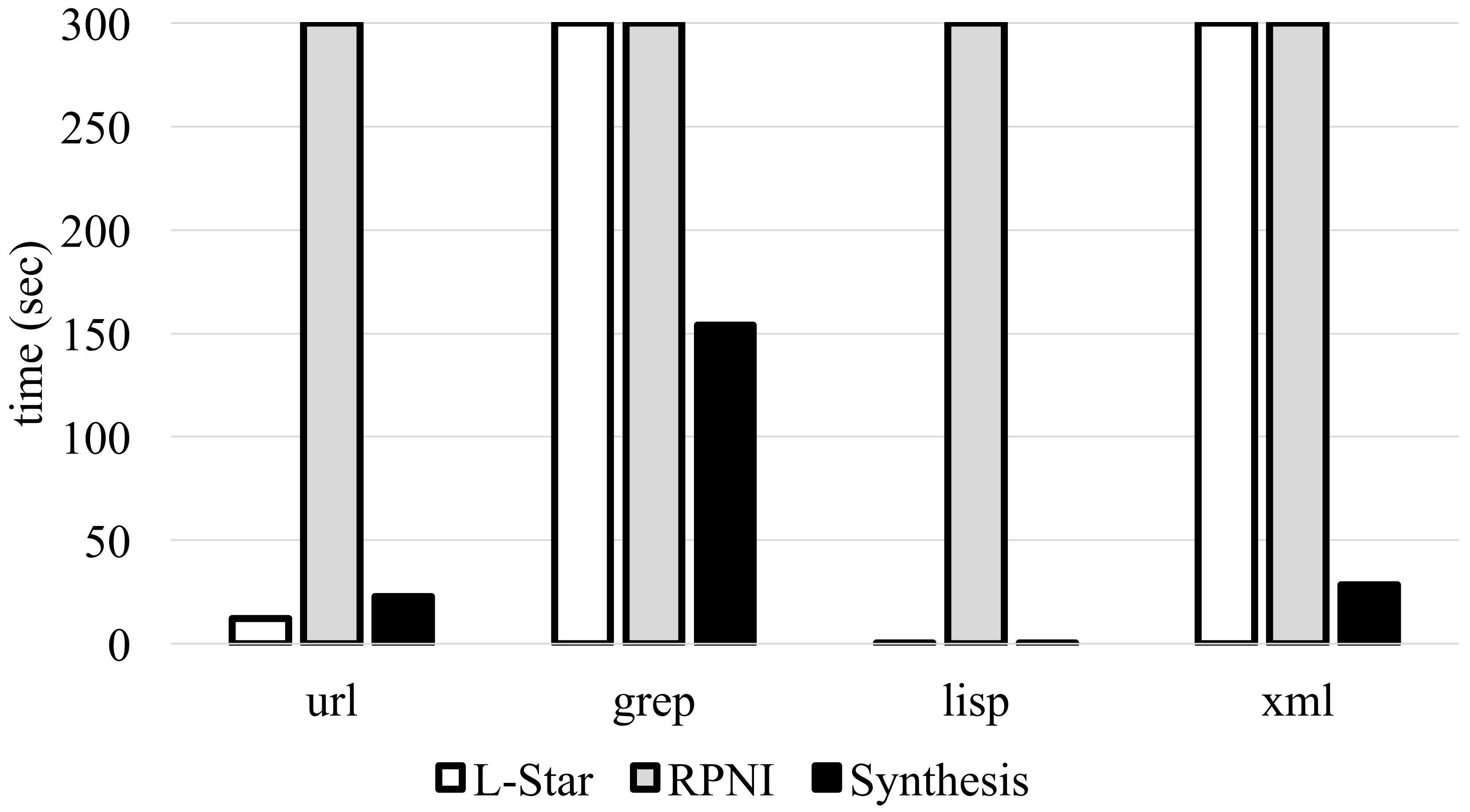
```
int main(int argc, char **argv) {
  char *keys;
  int fread_errno;
  // ...
```

```
  intmax_t default_context;
  FILE *fp;
  // ...
}
```

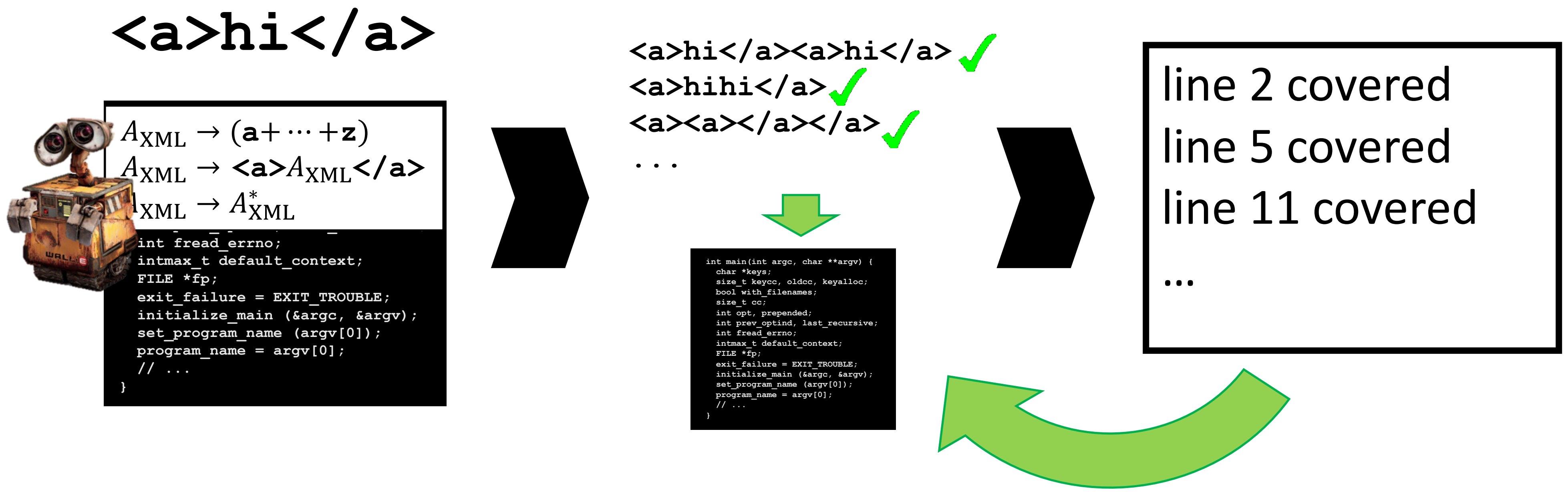
F_1 Score



Running Time



Coverage-Guided Fuzz Testing



`<a>hi</a>`

$A_{\text{XML}} \to (\texttt{a}+\cdots+\texttt{z})$
$A_{\text{XML}} \to \texttt{<a>}A_{\text{XML}}\texttt{</a>}$
$A_{\text{XML}} \to A^{*}_{\text{XML}}$

```
  int fread_errno;
  intmax_t default_context;
  FILE *fp;
  exit_failure = EXIT_TROUBLE;
  initialize_main (&argc, &argv);
  set_program_name (argv[0]);
  program_name = argv[0];
  // ...
}
```

```
<a>hi</a><a>hi</a> ✓
<a>hihi</a> ✓
<a><a></a></a> ✓
...
```

```
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;
  FILE *fp;
  exit_failure = EXIT_TROUBLE;
  initialize_main (&argc, &argv);
  set_program_name (argv[0]);
  program_name = argv[0];
  // ...
}
```

line 2 covered
line 5 covered
line 11 covered
...

40% improvement in incremental coverage on XML (preliminary)

Lexer Synthesis

`<a>hi</a>`

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

oracle & input

$$\texttt{<a>}[\texttt{a}-\texttt{z}]^{*}\texttt{</a>}$$

lexer

$$A_{\text{XML}} \rightarrow (\texttt{a} + \cdots + \texttt{z})$$
$$A_{\text{XML}} \rightarrow \texttt{<a>} A_{\text{XML}} \texttt{</a>}$$
$$A_{\text{XML}} \rightarrow A_{\text{XML}}^{*}$$

grammar

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