Effective Software Testing with a String-Constraint Solver

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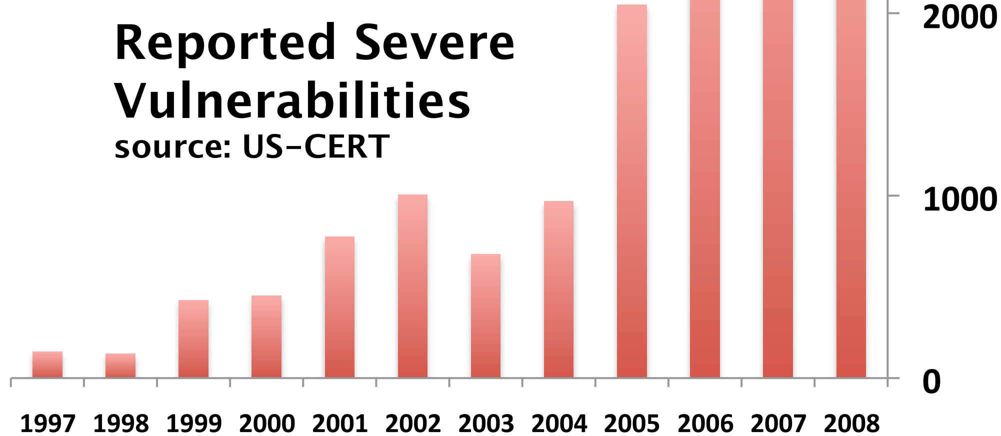
Software Testing Aims To Find Errors Before Users (Or Hackers) Do

Goals of software testing

- improve quality
- protect from adversaries



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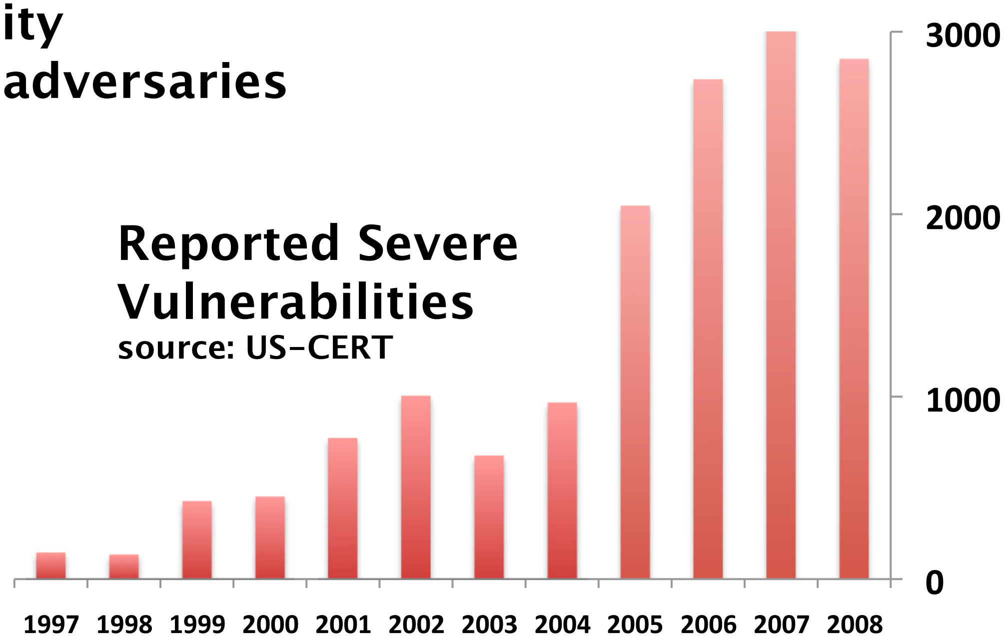


Research → Tech transfer → Hackers

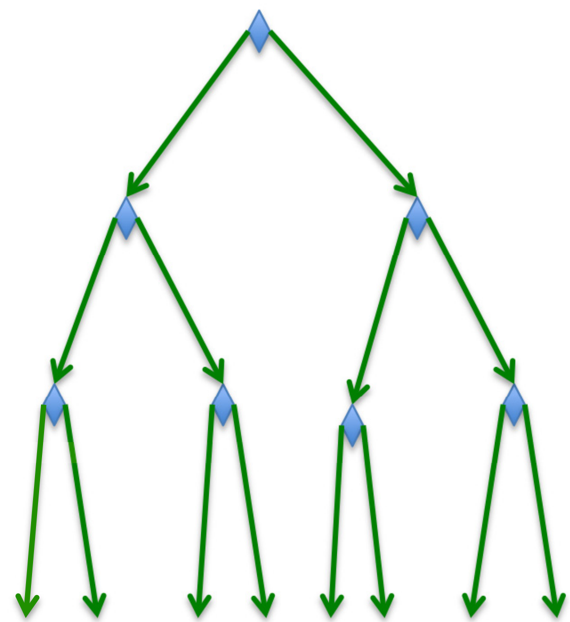
Goal: help find errors by improving testing tools

Concolic Testing Is An Effective Software Testing Methodology

Implementation-based: exploit knowledge of program code

Dynamic: observe running program using combined <u>conc</u>rete and symb<u>olic</u> execution

Constraint solver systematically enumerate execution paths



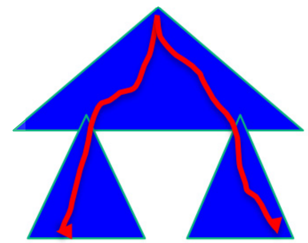
Tools: DART, CUTE, CREST, SAGE, EXE, Klee, Apollo, jFuzz

Key idea: improve effectiveness, applicability of concolic testing with a string-constraint solver

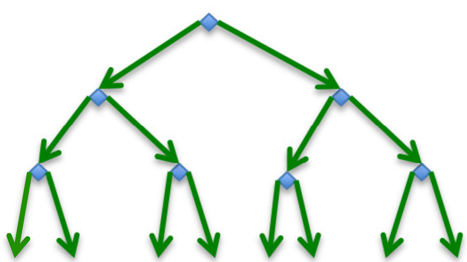
Effective Software Testing With A String-Constraint Solver

Concolic Security Testing
[ICSE'09]

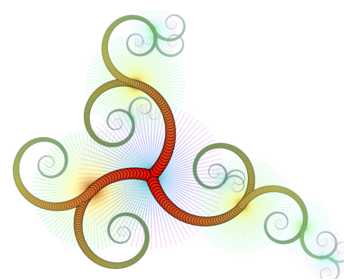
Grammar-based Concolic Testing
[PLDI'08]



Concolic Testing

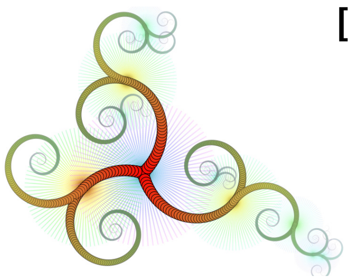


Hampi: String-Constraint Solver
[ISSTA'09]



Results Summary: String-Constraint Solver

Hampi: String-Constraint Solver [ISSTA'09]



- ✔ Novel solver for string constraints
- ✔ Supports context-free grammars, regular constraints
- ✔ Effective in concolic testing, program analysis
- ✔ Efficient: ~7x faster than a comparable solver

Results Summary: Concolic Security Testing

Concolic Security Testing [ICSE'09]

✔ Novel technique for creating SQL injection and XSS attacks on Web applications

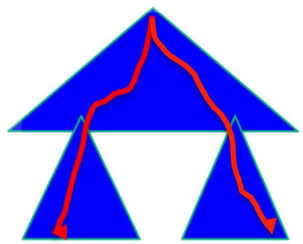
✔ Uses Hampi for grammar constraints to construct attack inputs

✔ First to create damaging second-order cross-site scripting (XSS) attacks

✔ 60 attacks (23 SQL injection, 37 XSS) on 5 PHP applications, 0 false positives

Results Summary: Grammar-based Concolic Testing

Grammar-based Concolic Testing [PLDI'08]



✔ Novel technique for testing programs with structured inputs

✔ Uses Hampi for input-format grammar constraints

✔ Improves coverage by 30-100%

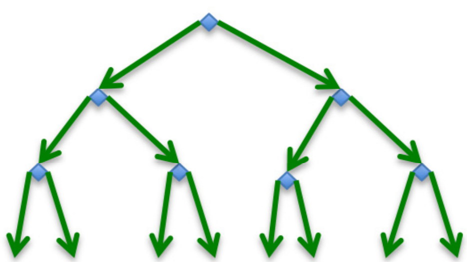
✔ 3 new infinite-loop errors

Effective Software Testing With A String-Constraint Solver

Concolic Security Testing
[ICSE'09]

Grammar-based Concolic Testing
[PLDI'08]

Concolic Testing



Hampi: String-Constraint Solver
[ISSTA'09]

Concolic Testing Combines Dynamic Symbolic Execution, Path Enumeration

```
void main(char[] in){
  int count=0;
  if (in[0] == 'b')
    count++;
  if (in[1] == 'a')
    count++;
  if (in[2] == 'd')
    count++;
  if (count == 3)
    ERROR;
}
```

xyz

Concolic Testing Combines Dynamic Symbolic Execution, Path Enumeration

```
void main(char[] in){
  int count=0;
  if (in[0] == 'b')
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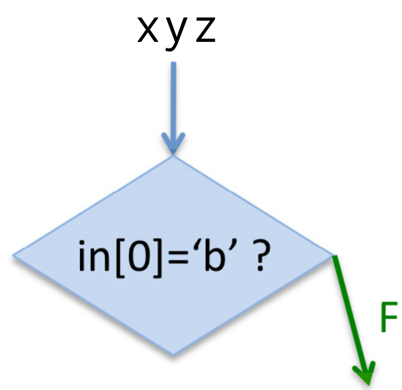

describes inputs that execute same path prefix

Path constraint: `(in[0]≠'b')`

Concolic Testing Combines Dynamic Symbolic Execution, Path Enumeration

```
void main(char[] in){
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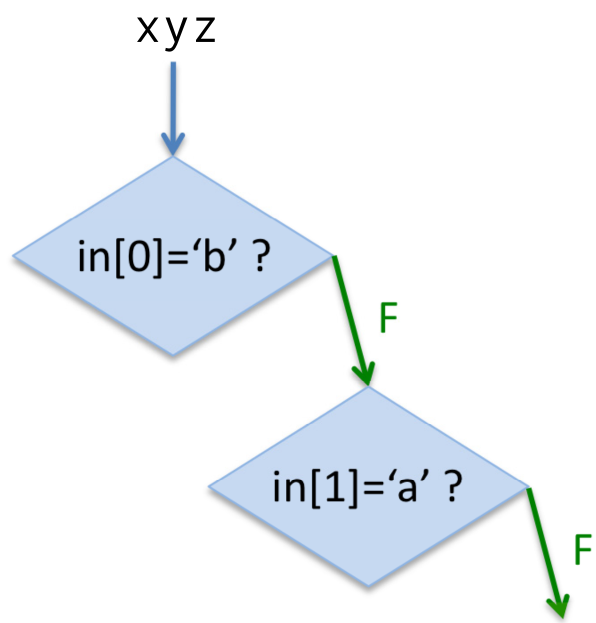

Path constraint: $(in[0] \neq 'b') \wedge (in[1] \neq 'a')$

Concolic Testing Combines Dynamic Symbolic Execution, Path Enumeration

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void main(char[] in){
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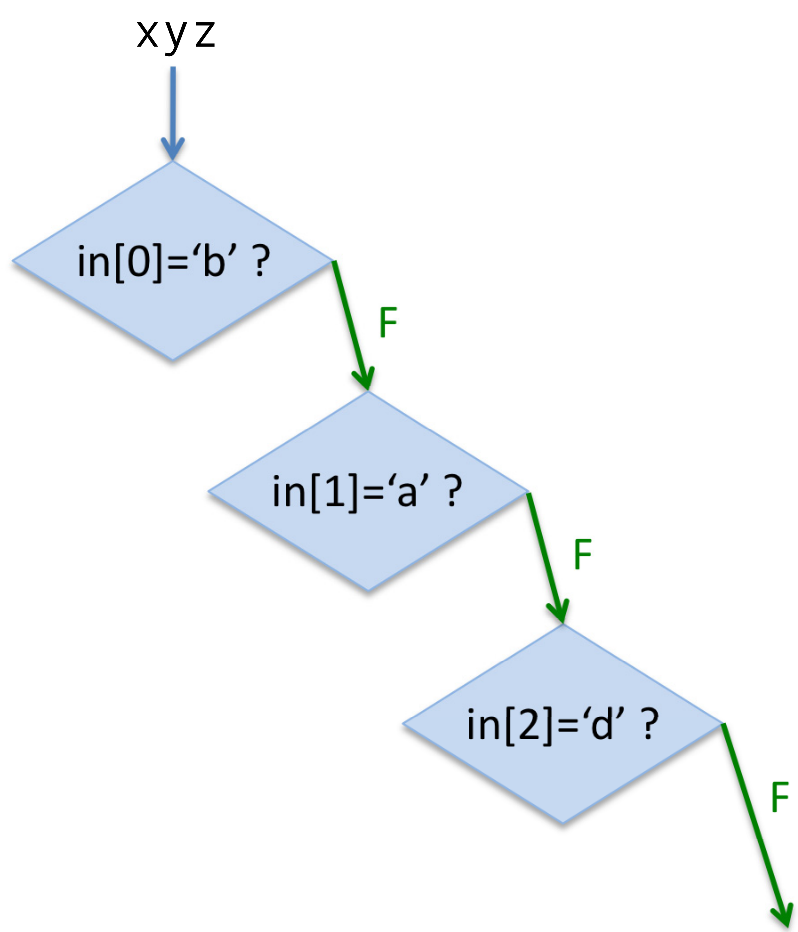

Path constraint: $(in[0] \neq 'b') \land (in[1] \neq 'a') \land (in[2] \neq 'd')$

Concolic Testing Combines Dynamic Symbolic Execution, Path Enumeration

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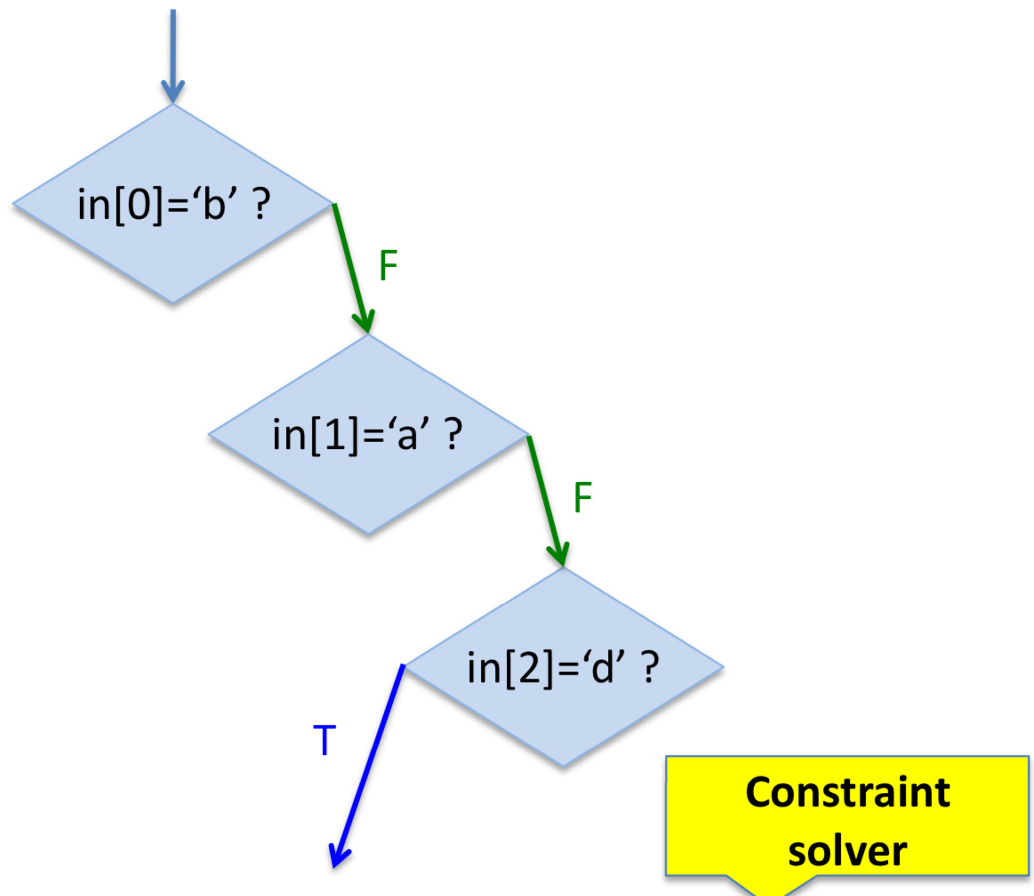

Path constraint: (in[0]≠'b')∧(in[1]≠'a')∧(in[2]='d')➔xyd

Concolic Testing Combines Dynamic Symbolic Execution, Path Enumeration

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void main(char[] in){
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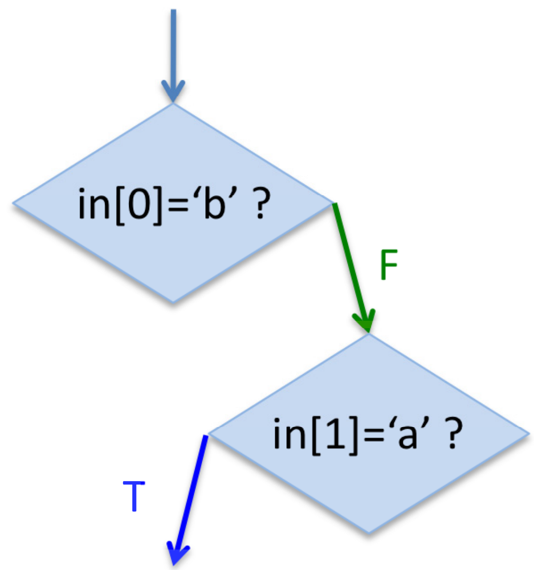

Path constraint: $(in[0] \neq 'b') \wedge (in[1] = 'a') \rightarrow$ xaz

Concolic Testing Combines Dynamic Symbolic Execution, Path Enumeration

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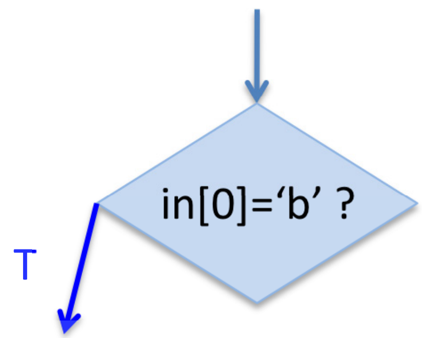

Path constraint: `(in[0]='b')`➔`byz`

Concolic Testing Systematically Enumerates All Paths In The Program

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void main(char[] in){
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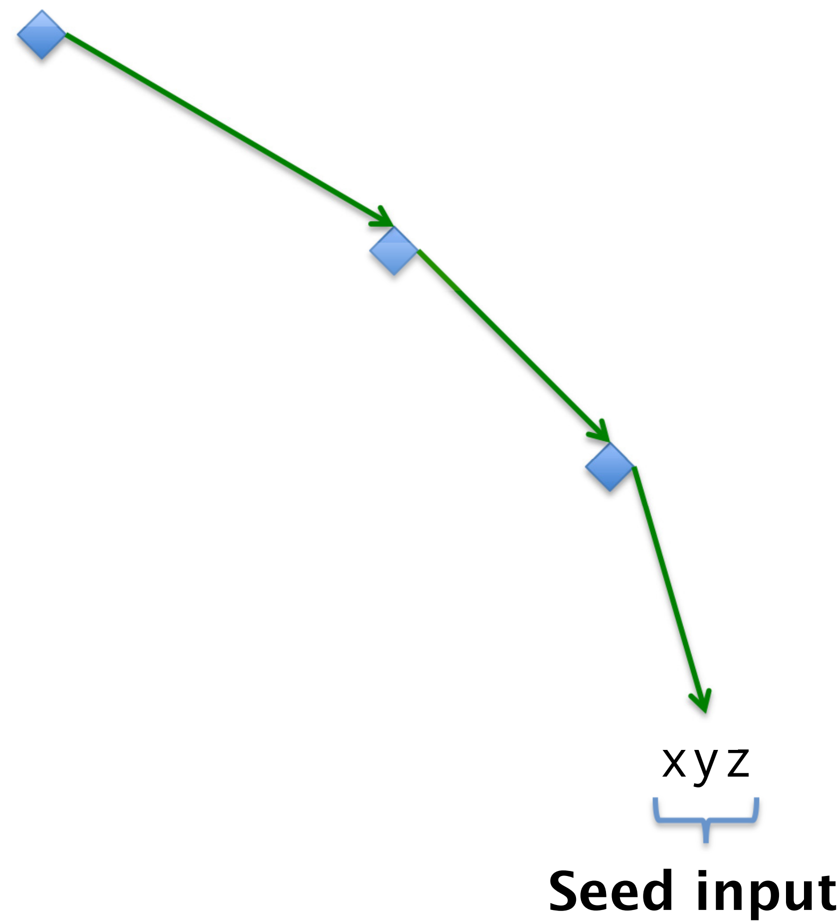

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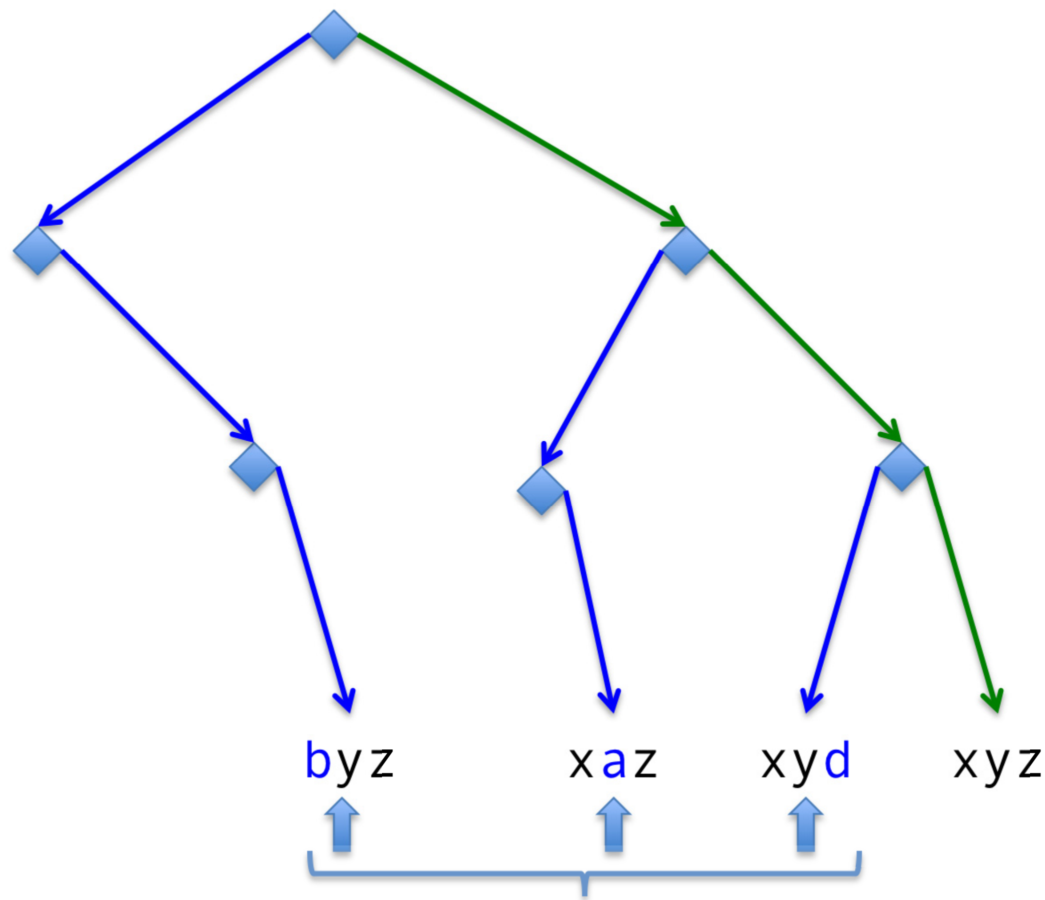

Generated inputs
(each covers a new path)

Concolic Testing Systematically Enumerates All Paths In The Program

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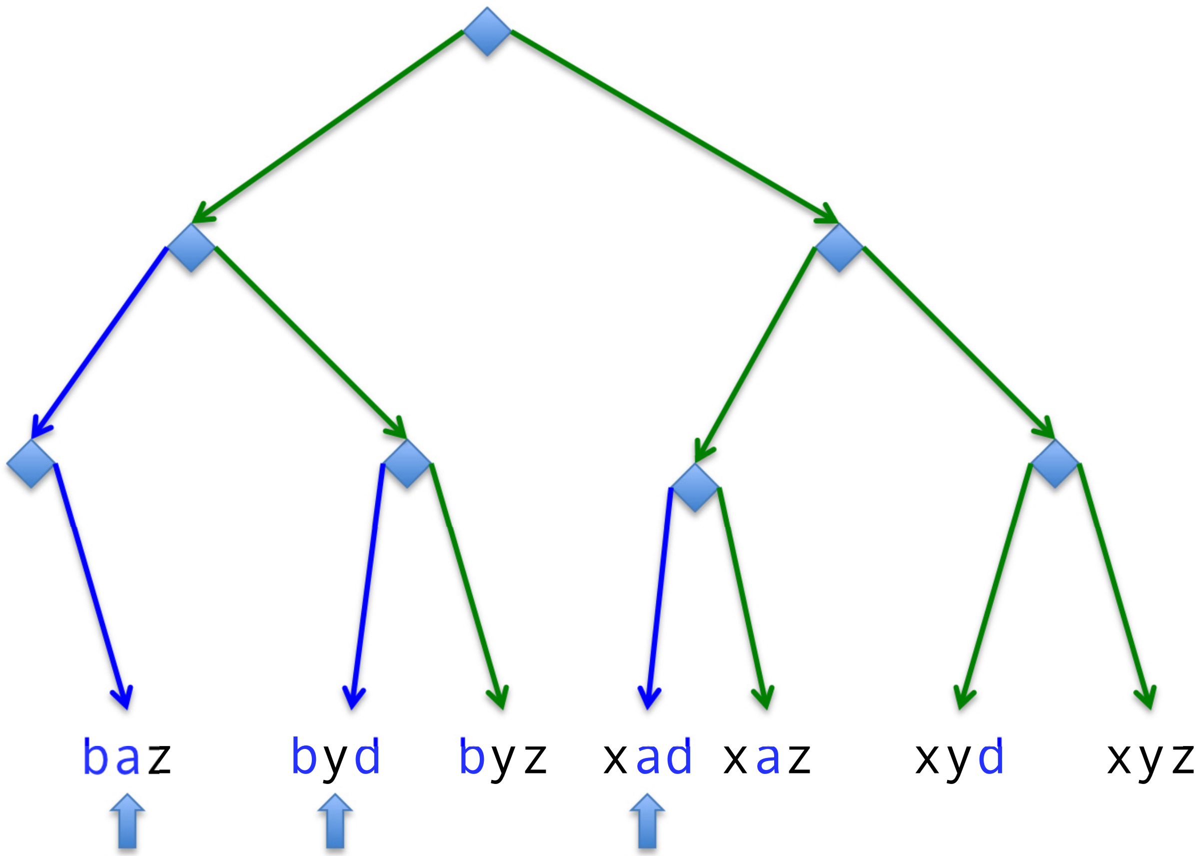

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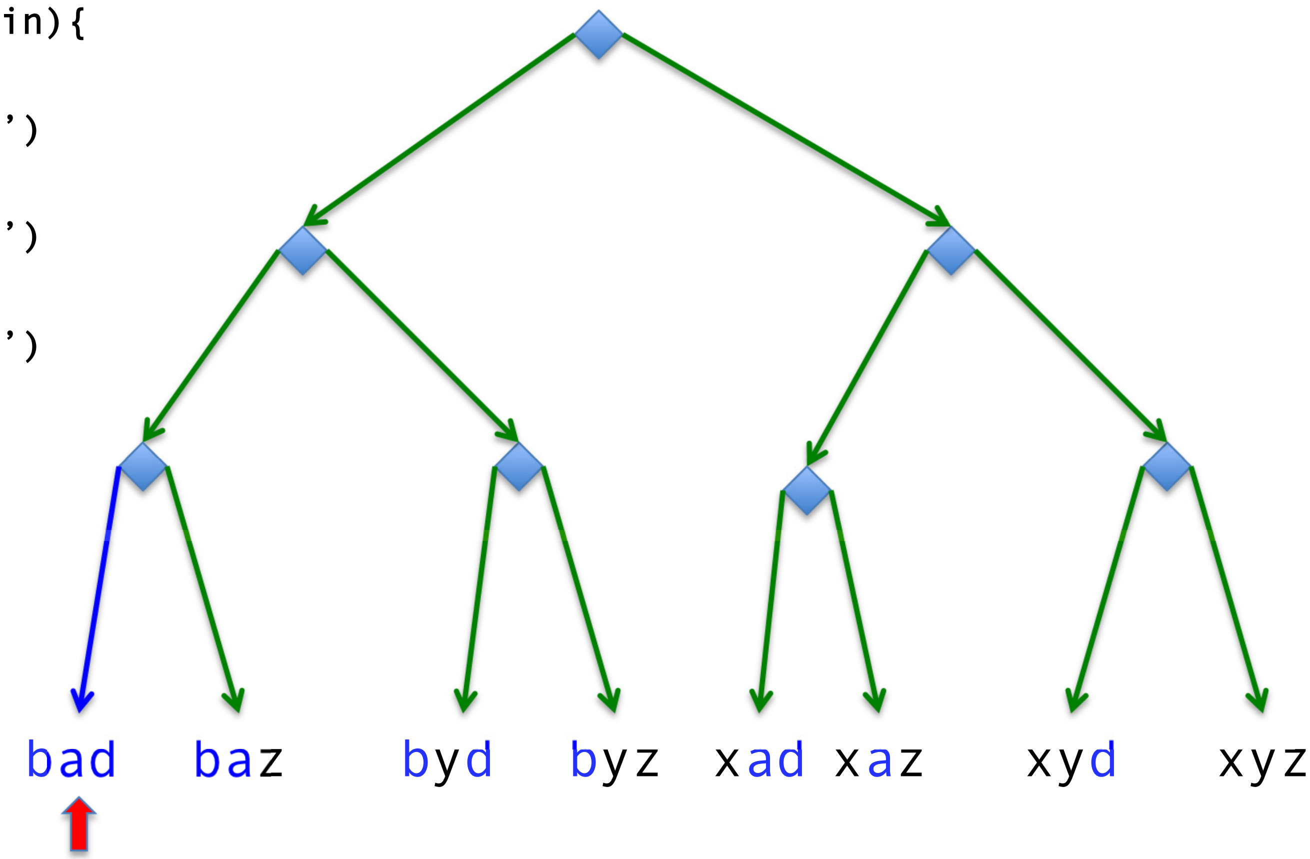

Concolic testing creates inputs for all program paths.

Effective Software Testing With A String-Constraint Solver

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Concolic Testing

Hampi: String-Constraint Solver
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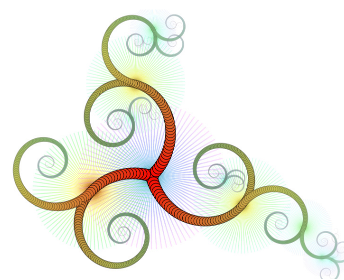
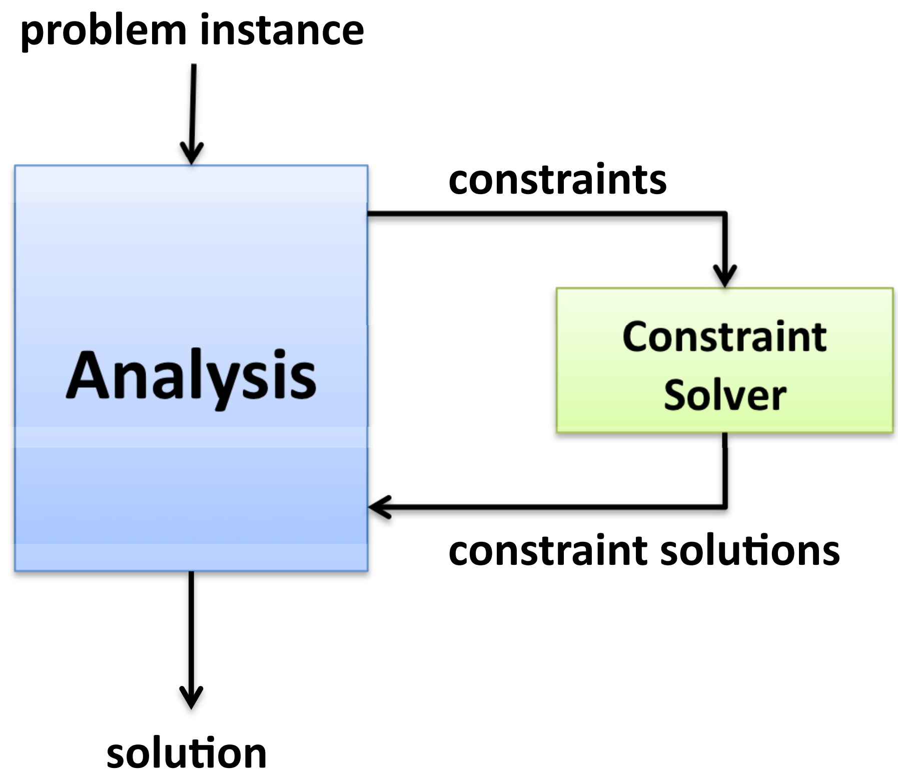


Many Program Analyses Reduce To Constraint Generation And Solving



Benefits

+ declarative formulation
+ better modularity
+ efficiency improvements

Downsides

– limited by solver's theory

Hampi: constraint solver for a theory of strings

String-Constraint Solver Finds Assignments For String Variables

Finite alphabet Σ (e.g., ASCII characters)

String variables over Σ*

```
var v
```

String constraints – language membership:

```
assert v ∈ L
```

Context-free, regular, etc.

String operations

```
concat("foo", v, "bar")
```

Hampi Uses Length Bounding To Support Context-Free Constraints

more expressive

context-free	$L_1 \cap \ldots \cap L_N$	**Undecidable**

more tractable

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bound(any language) → bounded regular

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more tractable

bound(any language) ➔ bounded regular

Key Hampi idea: bound length of strings for high expressiveness, efficiency

Hampi Can Solve Context-Free and Regular Constraints

"Find a 4-character string `v`, such that:

- `(v)` has balanced parentheses, and
- `(v)` contains substring `()()`"

Hampi Can Solve Context-Free and Regular Constraints

String variable →

```
var v:4;

cfg E := "()" | E E | "(" E ")";

reg Ebounded := bound(E, 6);

val q := concat( ”(" , v , “)" );

assert q in Ebounded;
assert q contains “()()";
```

“Find a 4-character string v, such that:

- **(v) has balanced parentheses, and**
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Hampi Can Solve Context-Free and Regular Constraints

Context-free grammar

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```

Regular lang. declaration (arrow to the `reg` line)

“Find a 4-character string v, such that:

- **(v) has balanced parentheses, and**
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Hampi Can Solve Context-Free and Regular Constraints

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var v:4;

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```

Declaration of (v)

“Find a 4-character string v, such that:

- **(v) has balanced parentheses, and**
- **(v) contains substring ()()”**

Hampi Can Solve Context-Free and Regular Constraints

```
var v:4;

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assert q contains “()()";
```

Constraints →

“Find a 4-character string v, such that:
- **(v) has balanced parentheses, and**
- **(v) contains substring ()()”**

Hampi finds satisfying assignment v =)()(

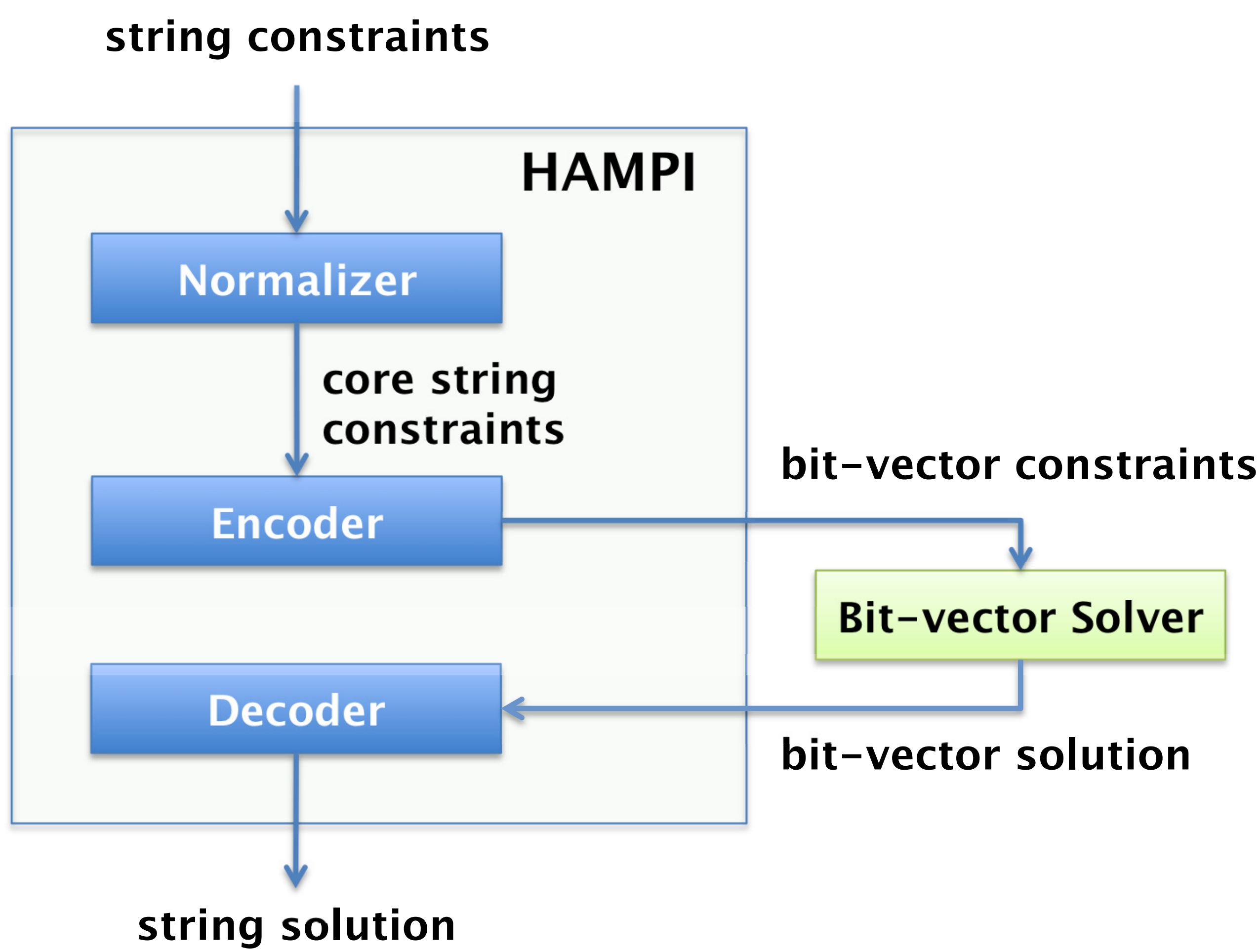
Hampi Supports Rich String Constraints

● full support

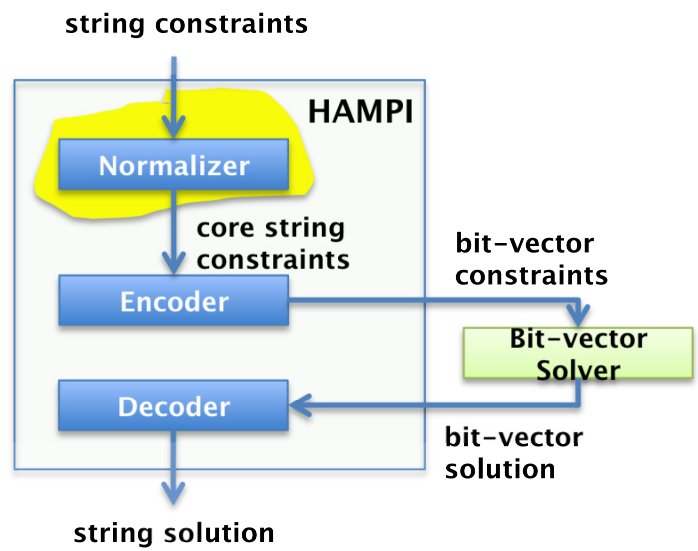
◒ partial support

	Hampi	CFGAnalyzer	Wassermann	Bjorner	Hooijmeier	Emmi	MONA	Caballero
context-free grammars	●	●	◒					
regular expressions	●	●	◒		●	●	◒	
string concatenation	●			●	●		●	●
stand-alone tool	●	●					●	
unbounded length			●		●	●	●	

Hampi Encodes String Constraints In Bit-Vector Logic



Hampi Normalizer Converts String Constraints To Core Form



Core string constraint have only regular expressions

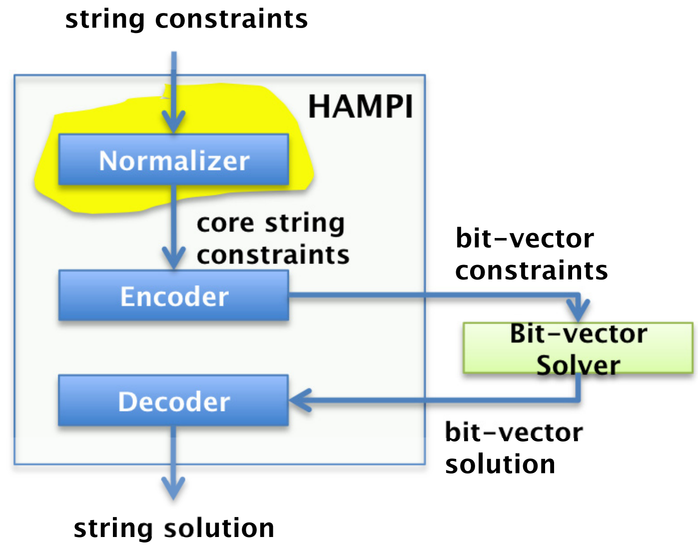
Expand grammars to regexps

- **expand nonterminals**
- **eliminate inconsistencies**
- **enumerate choices exhaustively**

`cfg` *E* `:= "(" ` *E* ` ")" | ` *E E* ` | "()";`

➡ `bound(`*E*`, 6)`

Hampi Normalizer Converts String Constraints To Core Form



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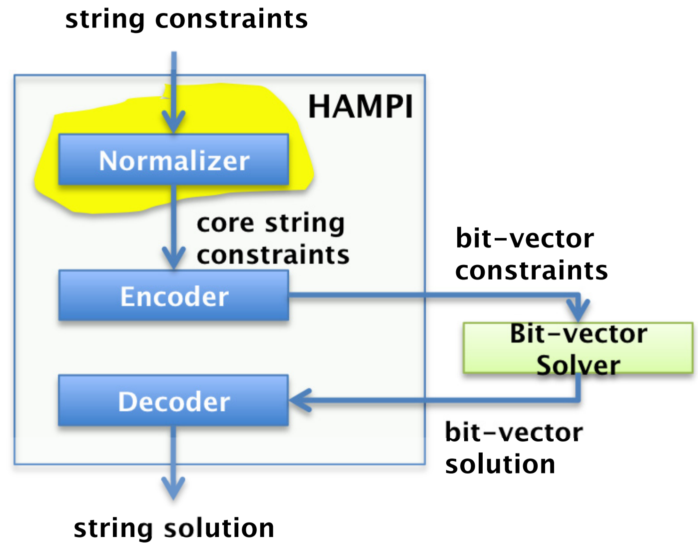
```
cfg E := "(" E ")” | E E | "()”;
```

$$\overbrace{E}^{6}$$

Hampi Normalizer Converts String Constraints To Core Form



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```
cfg E := "(" E ")" | E E | "()";
```

$$\overbrace{(\ E\ )}^{6} + \overbrace{E\ E}^{6} + \overbrace{(\,)}^{6}$$

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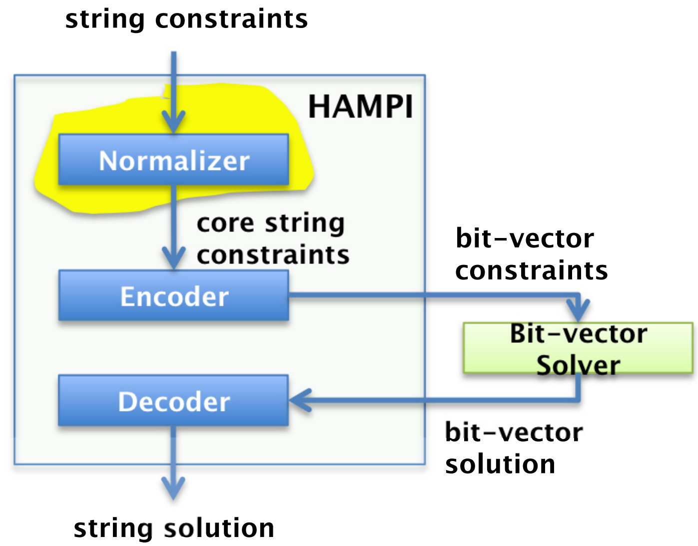
Core string constraint have only regular expressions



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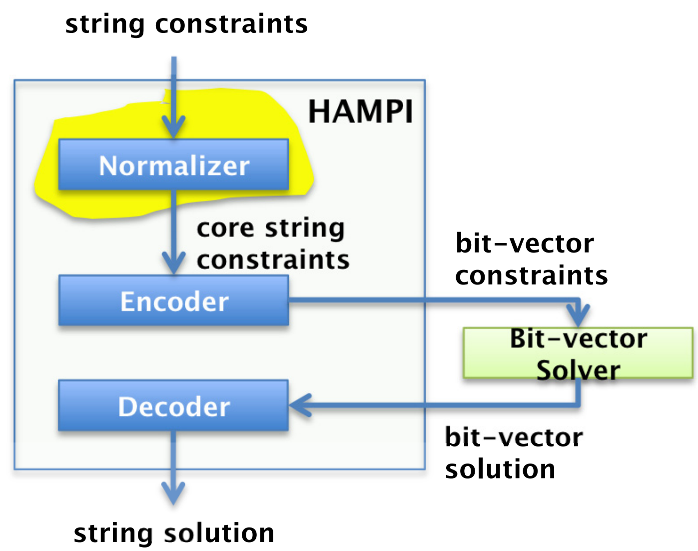


Core string constraint have only regular expressions

Expand grammars to regexps

- **expand nonterminals**
- **eliminate inconsistencies**

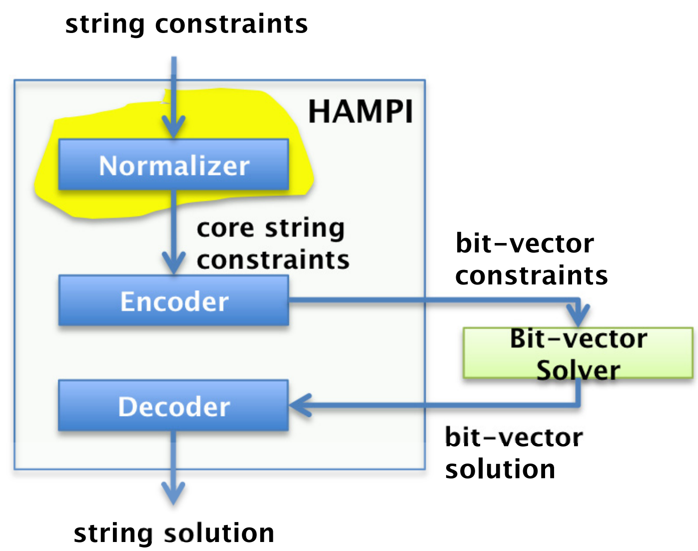
➡ **enumerate choices exhaustively**

```
cfg E := "(" E ")” | E E | "()”;
```

$$(\overbrace{E}^{4}) + \overbrace{E \ E}^{6}$$

Hampi Normalizer Converts String Constraints To Core Form

Core string constraint have only regular expressions



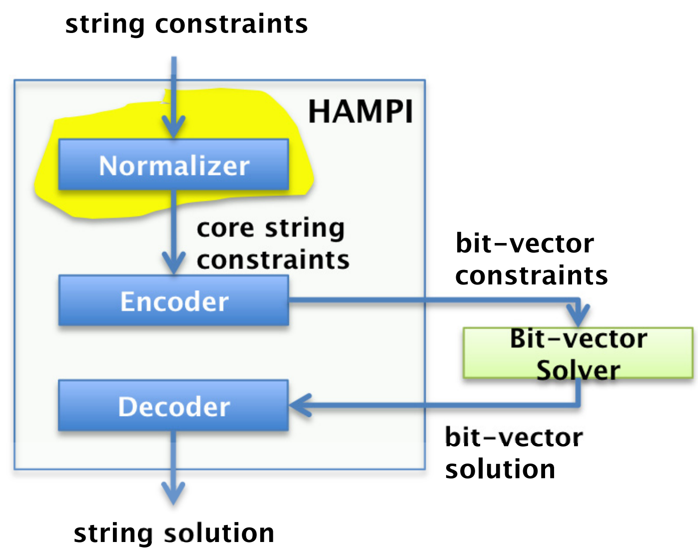
Expand grammars to regexps

- expand nonterminals
- ➡ eliminate inconsistencies
- enumerate choices exhaustively

cfg E := "(" E ")” | E E | "()”;

$$(\overbrace{E}^{4}) + \overbrace{E}^{0}\,\overbrace{E}^{6} + \overbrace{E}^{1}\,\overbrace{E}^{5} + \overbrace{E}^{2}\,\overbrace{E}^{4} + \overbrace{E}^{3}\,\overbrace{E}^{3} + \overbrace{E}^{4}\,\overbrace{E}^{2} + \overbrace{E}^{5}\,\overbrace{E}^{1} + \overbrace{E}^{6}\,\overbrace{E}^{0}$$

Hampi Normalizer Converts String Constraints To Core Form



Core string constraint have only regular expressions

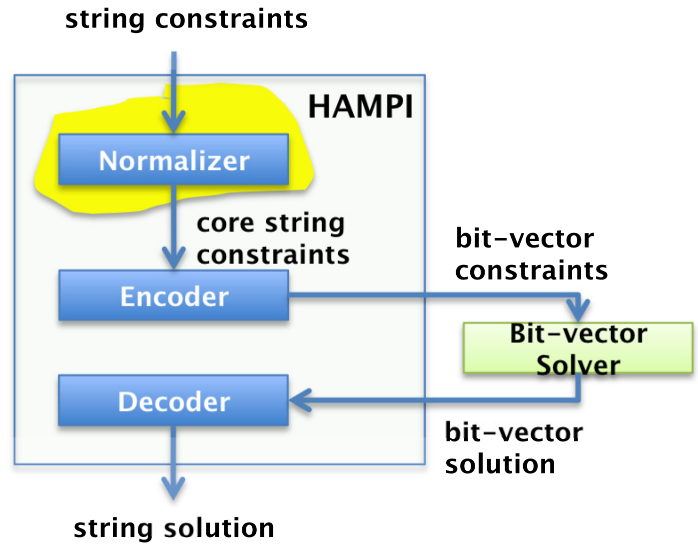
Expand grammars to regexps

- **expand nonterminals**
- ➡ **eliminate inconsistencies**
- **enumerate choices exhaustively**

```
cfg E := "(" E ")" | E E | "()";
```

$$(\overset{4}{E}) + \overset{0}{E}\ \overset{6}{E} + \overset{1}{E}\ \overset{5}{E} + \overset{2}{E}\ \overset{4}{E} + \overset{3}{E}\ \overset{3}{E} + \overset{4}{E}\ \overset{2}{E} + \overset{5}{E}\ \overset{1}{E} + \overset{6}{E}\ \overset{0}{E}$$

Hampi Normalizer Converts String Constraints To Core Form



Core string constraint have only regular expressions

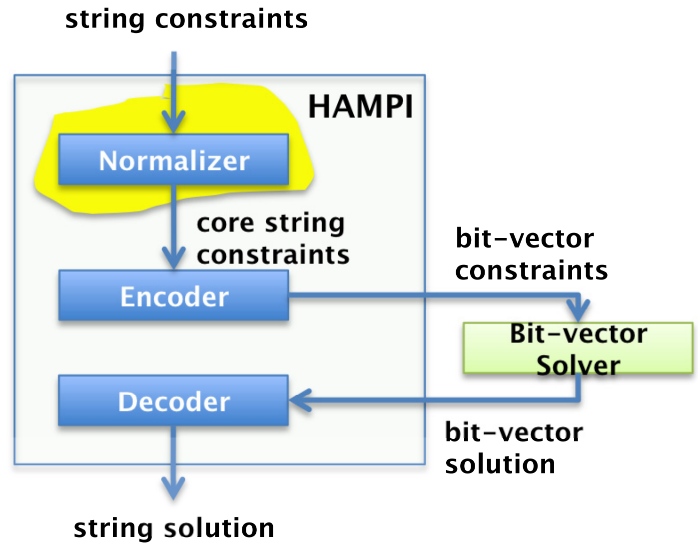
Expand grammars to regexps

- **expand nonterminals**
- **eliminate inconsistencies**
- **enumerate choices exhaustively**

```
cfg E := "(" E ")" | E E | "()";
```

$$\Rightarrow \; (\overbrace{E}^{4}) + \overbrace{E}^{2}\overbrace{E}^{4} + \overbrace{E}^{4}\overbrace{E}^{2}$$

Hampi Normalizer Converts String Constraints To Core Form



Core string constraint have only regular expressions

Expand grammars to regexps
- expand nonterminals
- eliminate inconsistencies
- enumerate choices exhaustively

cfg *E* := "(" *E* ")" | *E* *E* | "()";

([()() + (())]) +

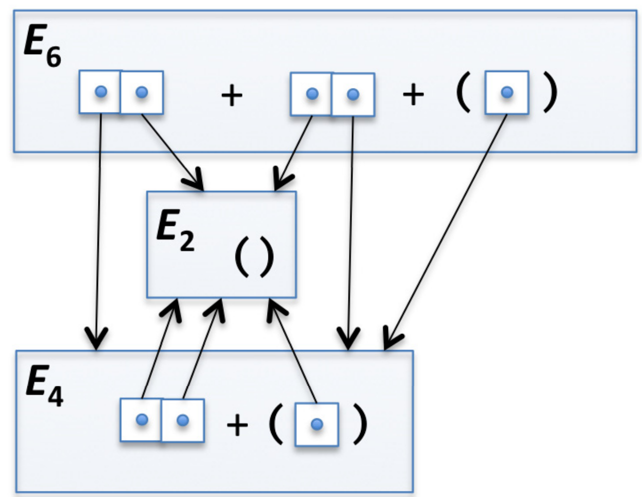
bound(*E*, 6) → () [()() + (())] +

[()() + (())] ()

Hampi Normalizer Uses Compact Representations Of Expressions

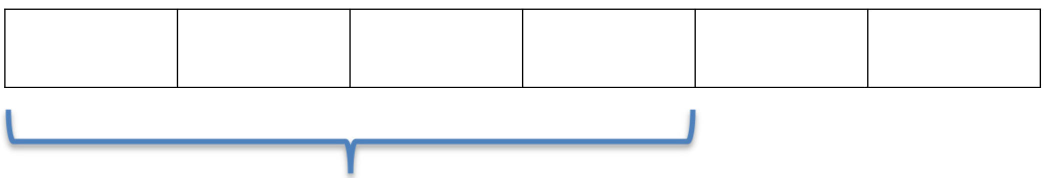
$$\left.\begin{array}{l} \overbrace{(\,)}^{E_2}\,\overbrace{[\,(\,)(\,) + ((\,))\,]}^{E_4} \;+ \\ \;[\,(\,)(\,) + ((\,))\,](\,) \;+ \\ (\,[\,(\,)(\,) + ((\,))\,]\,) \end{array}\right\} E_6$$

shared graph nodes for common subexpressions



Bit Vectors Are Ordered, Fixed-Size, Sets Of Bits

Bit vector B (length 6 bits)



$$(B[0:4] = B[2:4]) \land (B[1:3] = 101)$$

offset:length

Bit Vectors Are Ordered, Fixed-Size, Sets Of Bits

Bit vector B (length 6 bits)

0	1	0	1	0	1

$$(B[0:4] = B[2:4]) \wedge (B[1:3] = 101)$$

offset:length

Bit-vector solver finds the solution B = 010101

Hampi Encodes Core Constraints As Bit-Vector Constraints

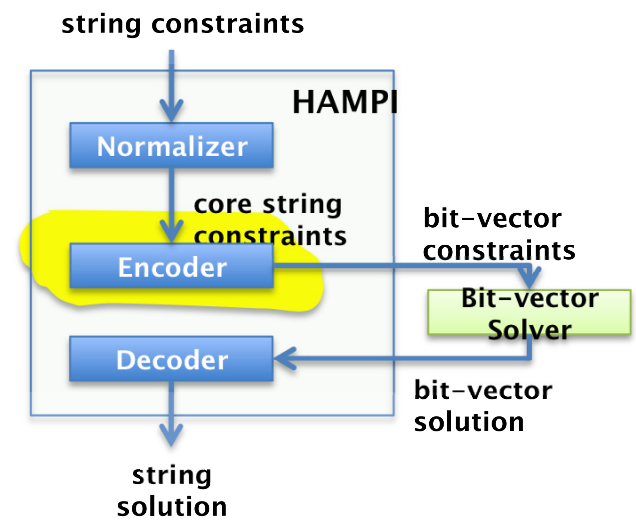
Map alphabet Σ to bit-vector constants:

(→ 0

) → 1

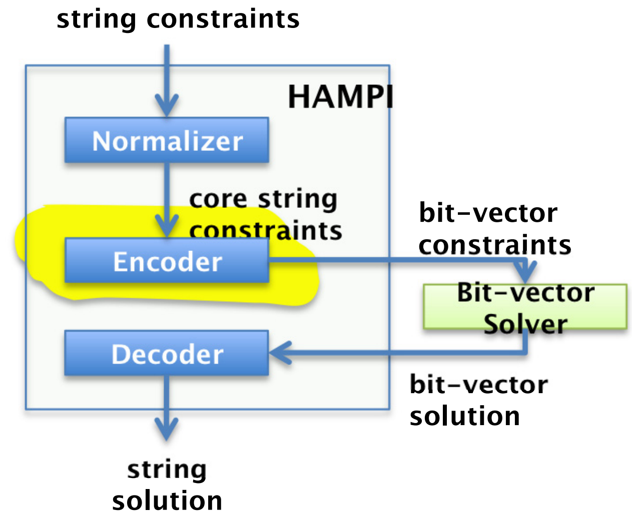
Compute size of bit-vector B:

(1+4+1) * 1 bit = 6 bits



(v) ∈ ()[()() + (())] + [()() + (())]() + ([()() + (())])

Hampi Encodes Regular Expressions Recursively



Encode regular expressions recursively

- union + → disjunction $\vee$
- concatenation → conjunction $\wedge$
- Kleene star * → conjunction $\wedge$
- constant → bit-vector constant

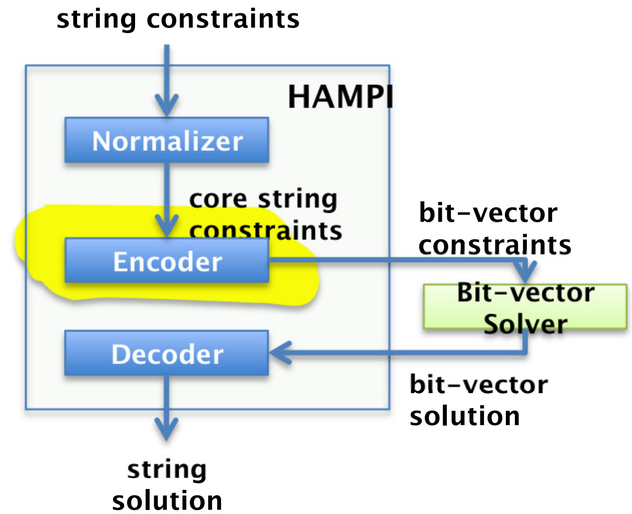
$$(v) \in ()[()() + (())] + [()() + (())]() + ([()() + (())])$$

$$\text{Formula } \Phi_1 \quad \vee \quad \text{Formula } \Phi_2 \quad \vee \quad \text{Formula } \Phi_3$$

Hampi Encoder Exploits Shift-Symmetry In Constraints

Shift-symmetric constraints = identical modulo offset in bit vector

Hampi reuses encoding templates for symmetric constraints



(v) ∈ () [()() + (())] + [()() + (())] () + ([()() + (())])

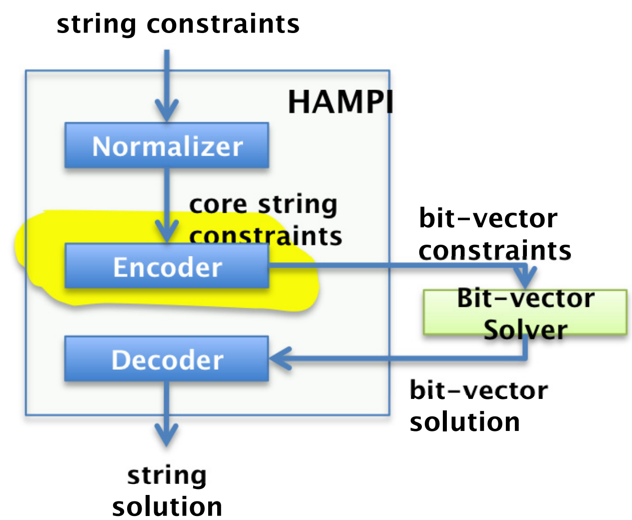
B[0:2] = 01

B[5:2] = 01

Shift-symmetric constraints

Hampi Encoder Exploits Shift-Symmetry In Constraints

Shift-symmetric constraints =
identical modulo offset in bit vector



Hampi reuses encoding templates for symmetric constraints

(v) ∈ () [()() + (())] + [()() + (())] () + ([()() + (())])

ϕ at offset 2 | ϕ at offset 0 | ϕ at offset 1

Shift-symmetric constraints

Hampi Uses Bit-Vector Solver And Decodes Solution

bit-vector constraints

Bit-vector Solver STP

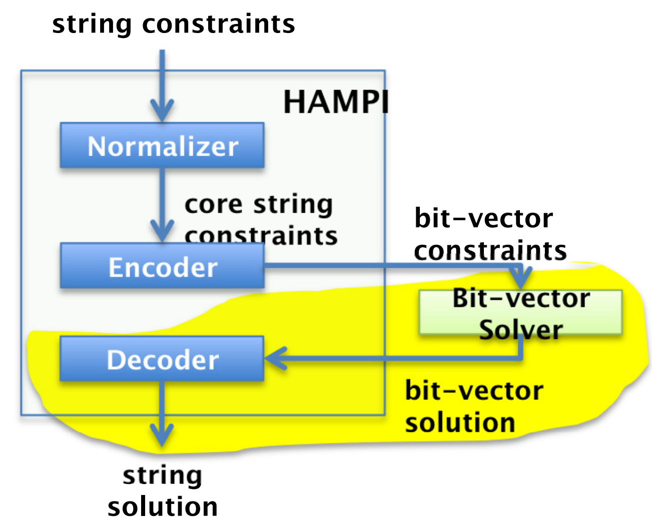
`B = 010101`

Decoder

Maps bits back to alphabet Σ

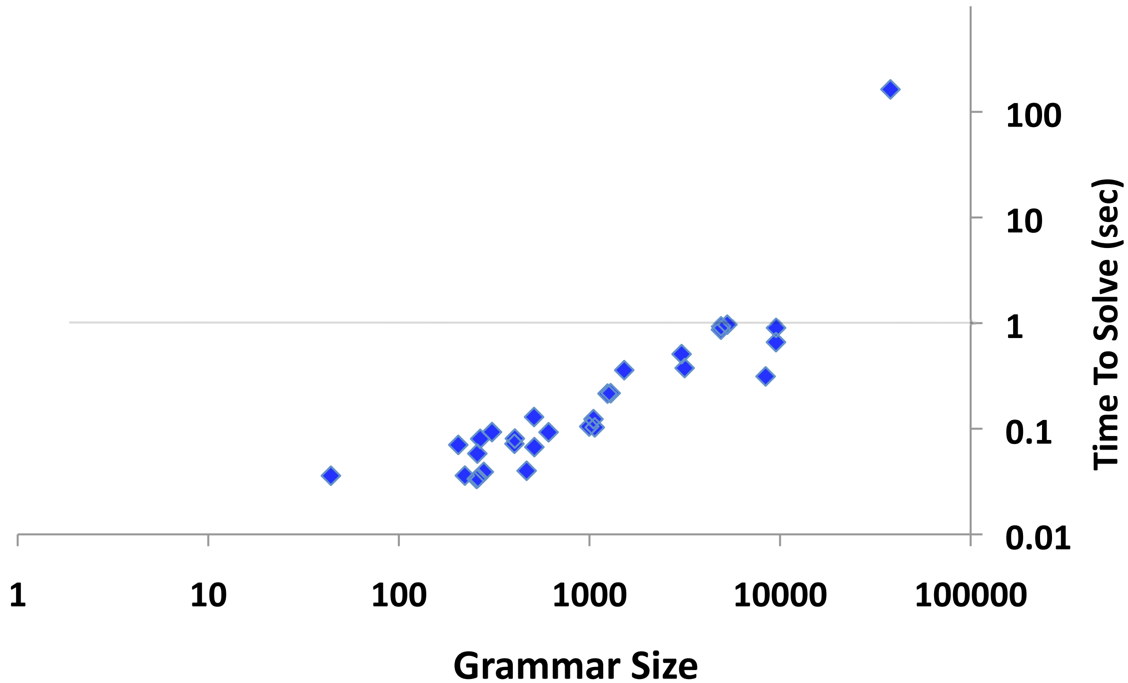
`B = ()()()`

`v =  )()(`



Result 1: Hampi Is Effective In Static SQL Injection Analysis

1367 string constraints from [Wassermann PLDI'07]



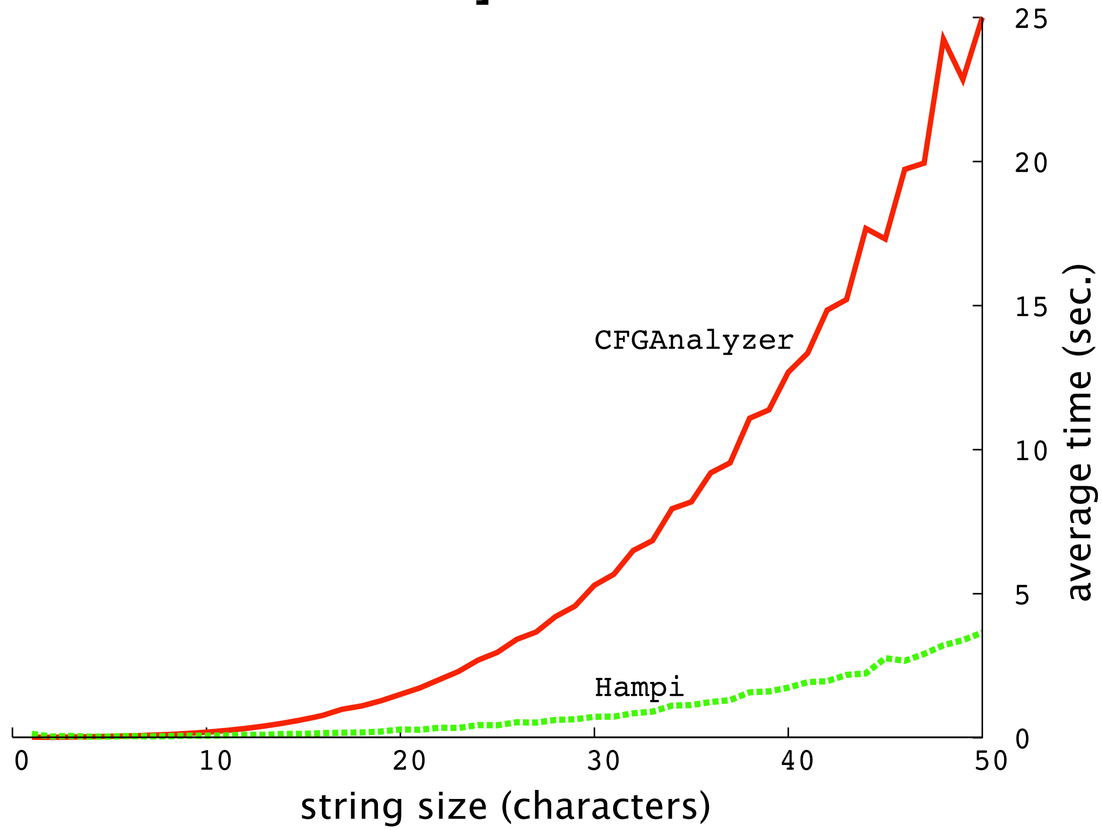
Hampi scales to large grammars

Hampi solved 99.7% of constraints in < 1 sec per constraint

All solvable constraints had short solutions $N \leq 4$

Result 2: Hampi Is Faster Than The CFGAnalyzer Solver

CFGAnalyzer encodes bounded grammar problems in SAT [Axelsson et al ICALP'08]



For size 50, Hampi is 6.8x faster on average (up to 3000x faster)

Effective Software Testing With A String-Constraint Solver

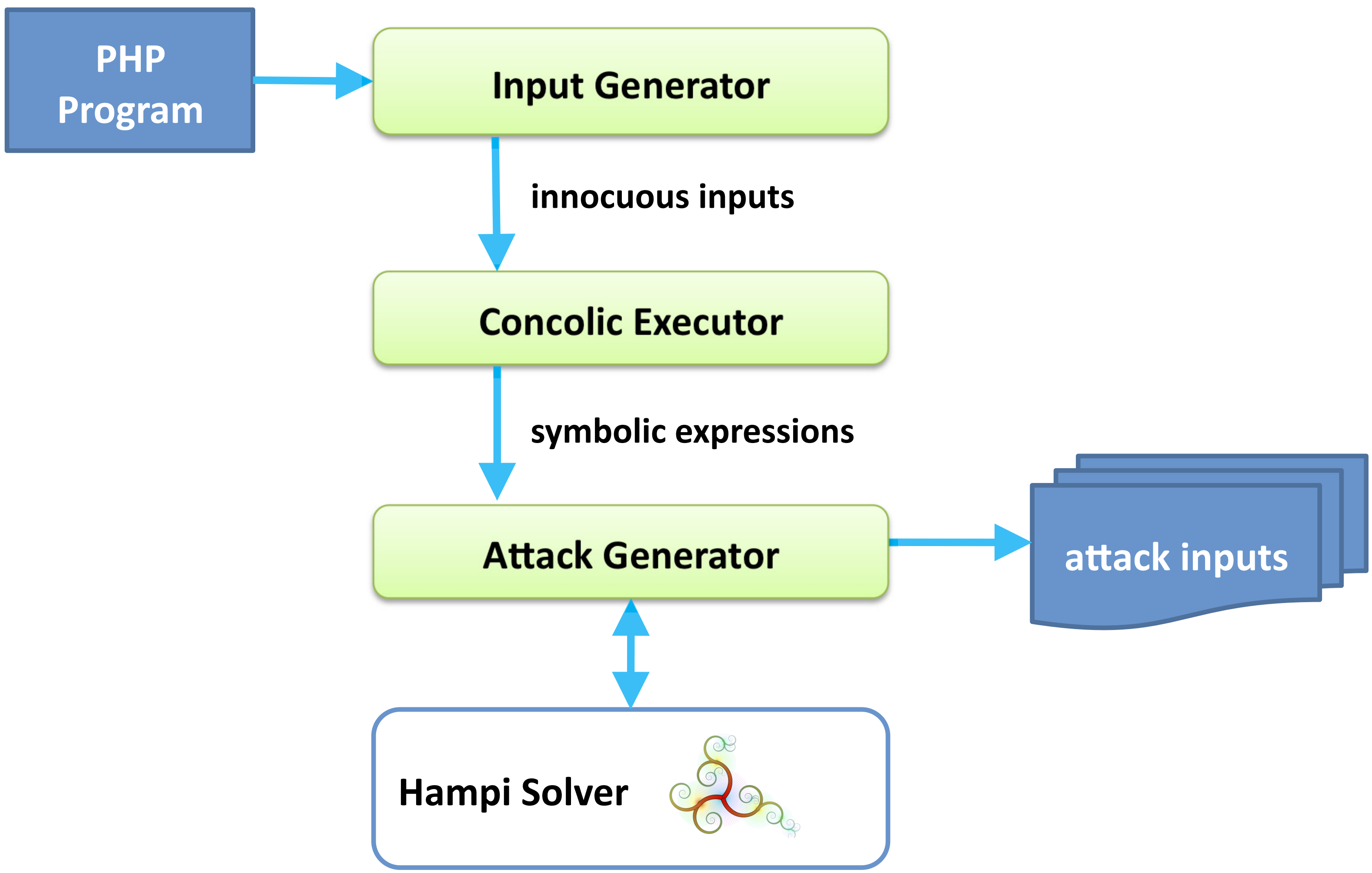
Concolic Security Testing
[ICSE'09]

Grammar-based Concolic Testing
[PLDI'08]

Concolic Testing

Hampi: String-Constraint Solver
[ISSTA'09]

Ardilla Mutates Generated Inputs To Construct Attacks



SQL Injection Attacks Modify Structure Of Database Queries

Innocuous input:
v → 1

```
SELECT msg FROM messages WHERE topicid='1'
```

SQL Injection Attacks Modify Structure Of Database Queries

Innocuous input:
v → 1

```
SELECT msg FROM messages WHERE topicid=‘1’
```

user input

Symbolic expression for SQL query

```
concat(SELECT msg FROM messages WHERE topicid=‘ v ’)
```

SQL Injection Attacks Modify Structure Of Database Queries

Innocuous input:
v → 1

```
SELECT msg FROM messages WHERE topicid=‘1’
```

user input

Symbolic expression for SQL query

```
concat(SELECT msg FROM messages WHERE topicid=‘ v ’)
```

Attack input:
v → 1’ OR ‘0’=‘0

attack tautology

```
SELECT msg FROM messages WHERE topicid=‘1’ OR ‘0’=‘0’
```

Attacker gets access to all messages

Example: Hampi Constraints That Create SQL Injection Attacks

user input string

```
var v : 12;
```

SQL grammar

```
cfg SqlSmall := "SELECT ” [a-z]+ " FROM ” [a-z]+ " WHERE " Cond;
cfg Cond := Val "=" Val | Cond " OR " Cond;
cfg Val := [a-z]+ | "'” [a-z0-9]* "'" | [0-9]+;
```

bounded SQL grammar

```
reg SqlSmallBounded := bound(SqlSmall, 53);
```

SQL query

```
val q := concat("SELECT msg FROM messages WHERE topicid='", v, "'");
```

SQLI attack conditions

```
assert q in SqlSmallBounded;
assert q contains "OR ‘0'=‘0'";
```

“q is a valid SQL query”

“q contains an attack tautology”

Example: Hampi Constraints That Create SQL Injection Attacks

user input string

```
var v : 12;
```

SQL grammar

```
cfg SqlSmall := "SELECT ” [a-z]+ " FROM ” [a-z]+ " WHERE " Cond;
cfg Cond := Val "=" Val | Cond " OR " Cond;
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```

bounded SQL grammar

```
reg SqlSmallBounded := bound(SqlSmall, 53);
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SQL query

```
val q := concat("SELECT msg FROM messages WHERE topicid='", v, "'");
```

SQLI attack conditions

```
assert q in SqlSmallBounded;
assert q contains "OR ‘0'=‘0'";
```

“q is a valid SQL query”

“q contains an attack tautology”

Hampi finds an attack input: v → 1’ OR ‘0’=‘0

Result: Ardilla Finds New Attacks

60 attacks on 5 PHP applications

23 SQL injection

4 cases of data corruption
19 cases of information leak

29 XSS first order

8 XSS second order

0 false positives

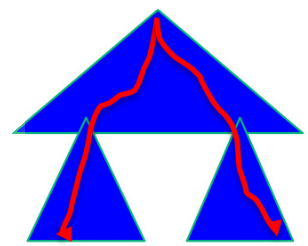
216 Hampi constraints solved

- 46% of constraints in < 1 second per constraint
- 100% of constraints in < 10 seconds per constraint

Effective Software Testing With A String-Constraint Solver

Concolic Security Testing
[ICSE'09]

Grammar-based Concolic Testing
[PLDI'08]



Concolic Testing

Hampi: String-Constraint Solver
[ISSTA'09]

Sometimes Concolic Testing Is Not Much Better Than Random Fuzzing

Randomly mutates bytes seed inputs

Random Fuzz Testing

50 well-formed seed inputs

Concolic Testing

50 well-formed seed inputs

Program under test: JavaScript interpreter

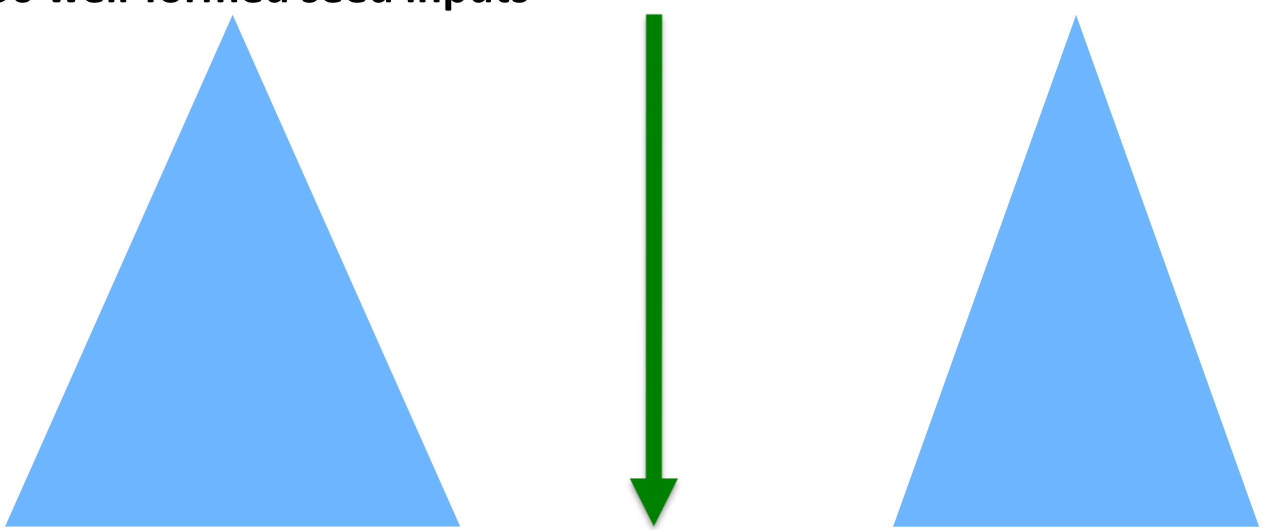
Sometimes Concolic Testing Is Not Much Better Than Random Fuzzing

Random Fuzz Testing

50 well-formed seed inputs

Concolic Testing

50 well-formed seed inputs



8658 inputs

2 hours

6883 inputs

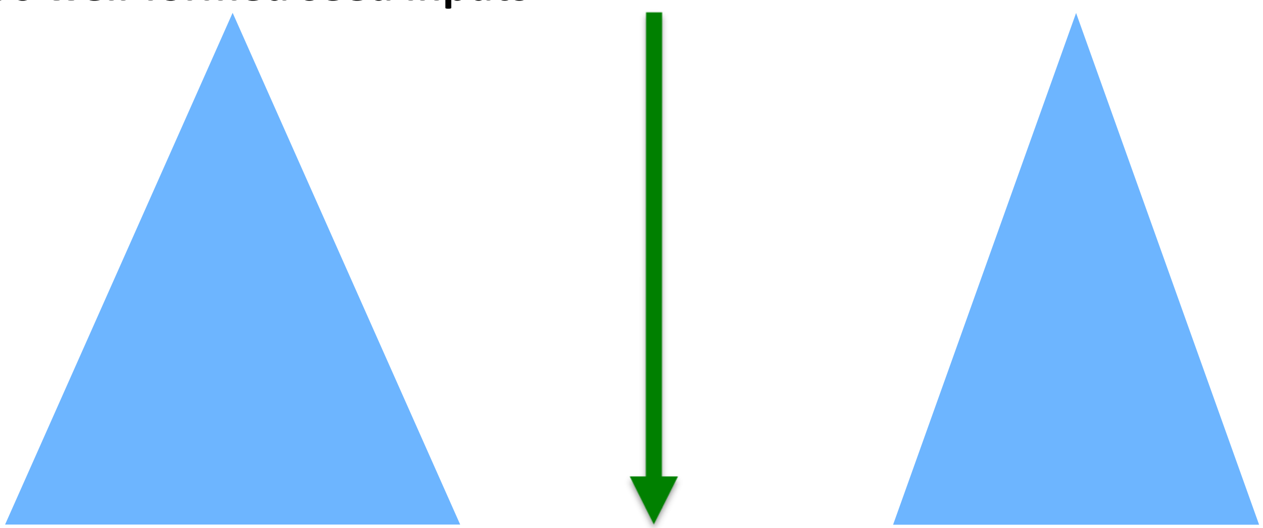
Sometimes Concolic Testing Is Not Much Better Than Random Fuzzing

Random Fuzz Testing

50 well-formed seed inputs

Concolic Testing

50 well-formed seed inputs



8658 inputs

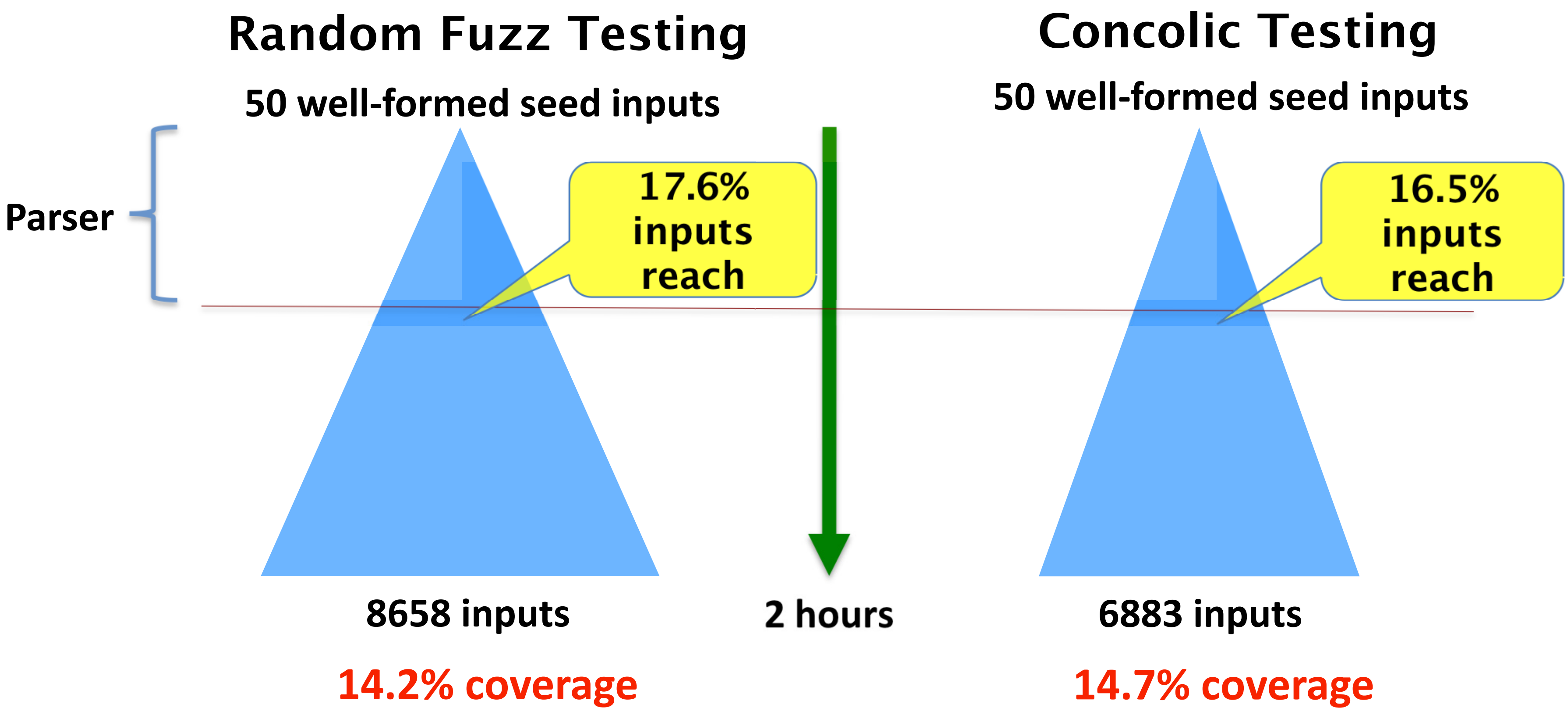
14.2% coverage

2 hours

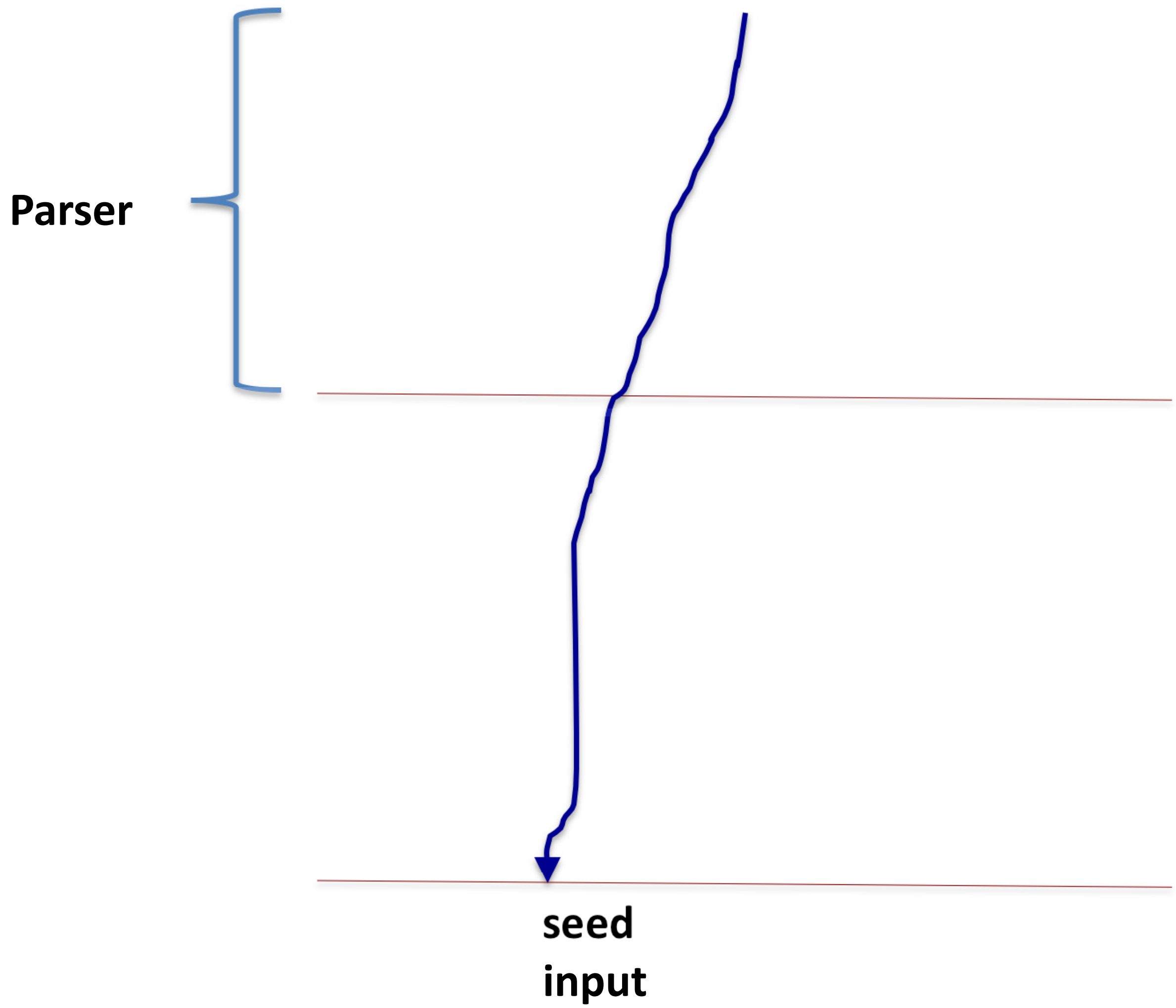
6883 inputs

14.7% coverage

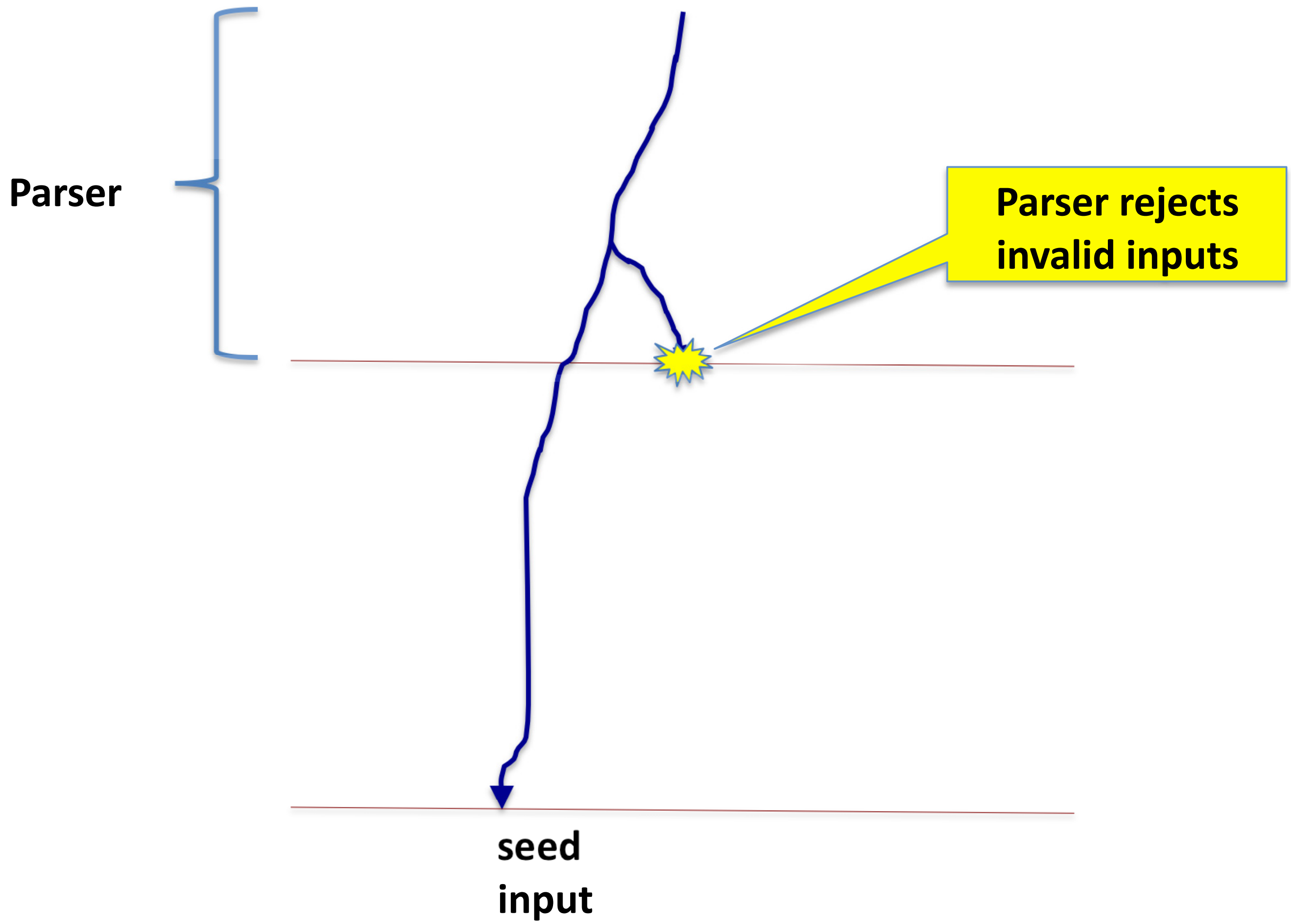
Sometimes Concolic Testing Is Not Much Better Than Random Fuzzing



Most Generated Inputs Get Rejected Quickly



Most Generated Inputs Get Rejected Quickly



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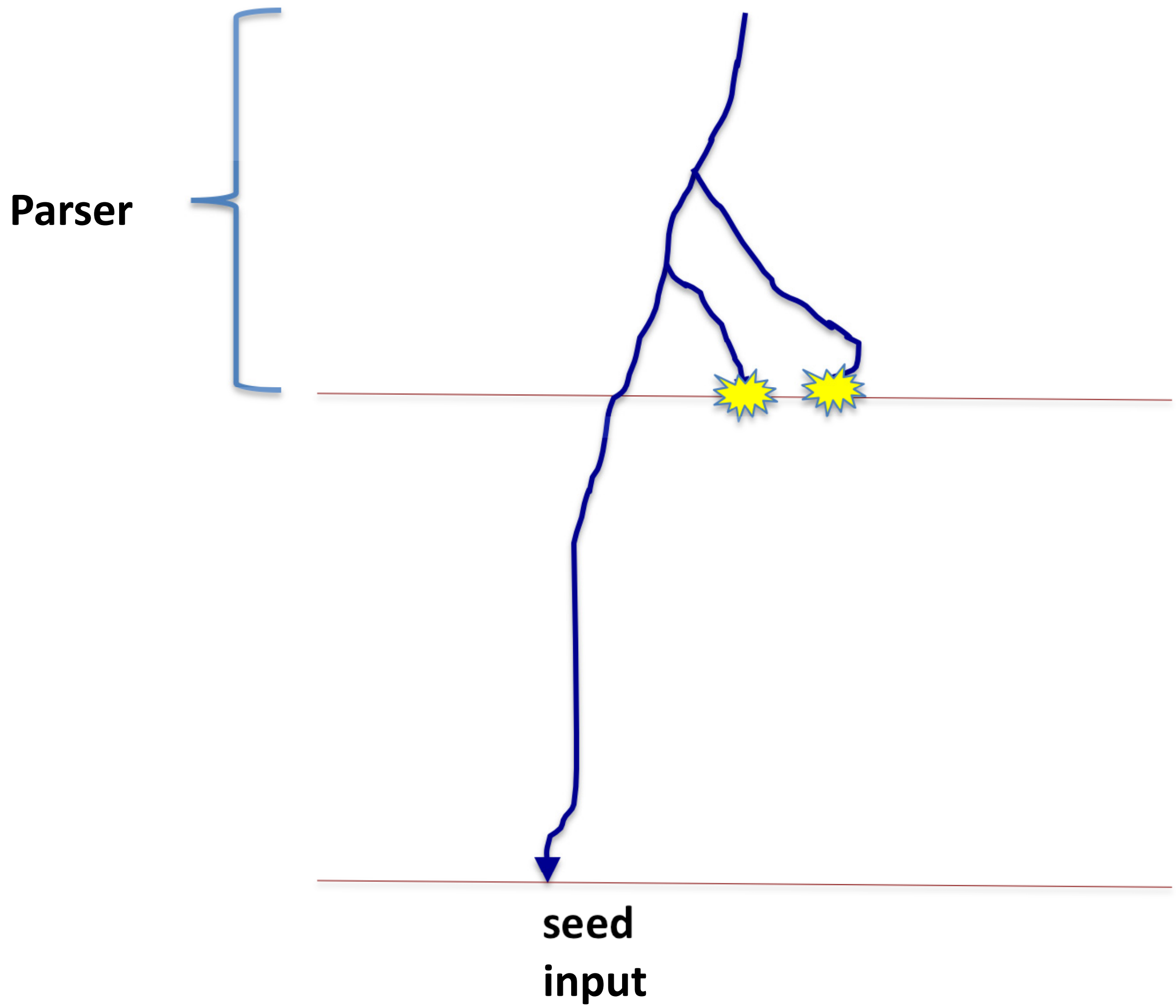

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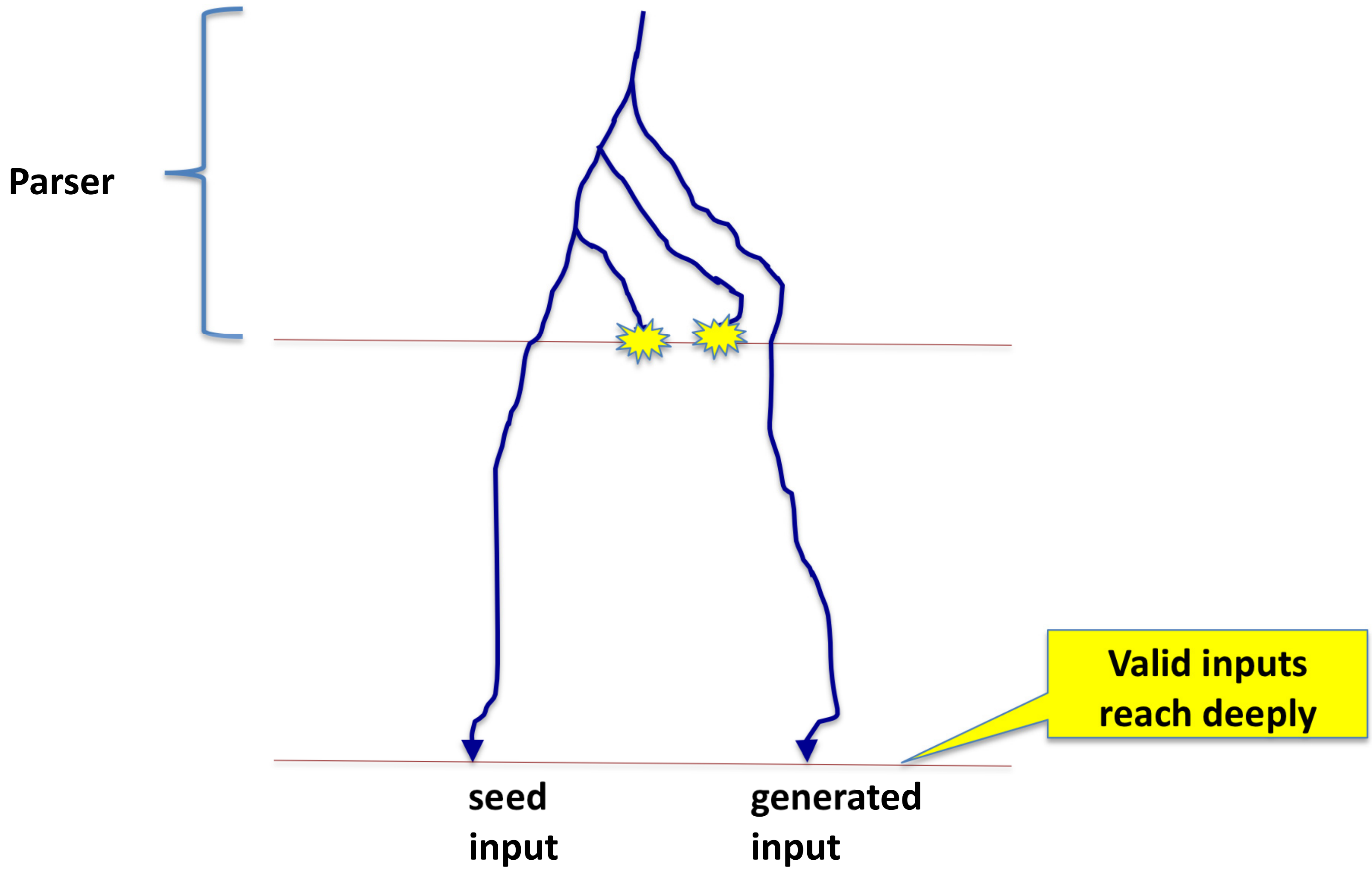
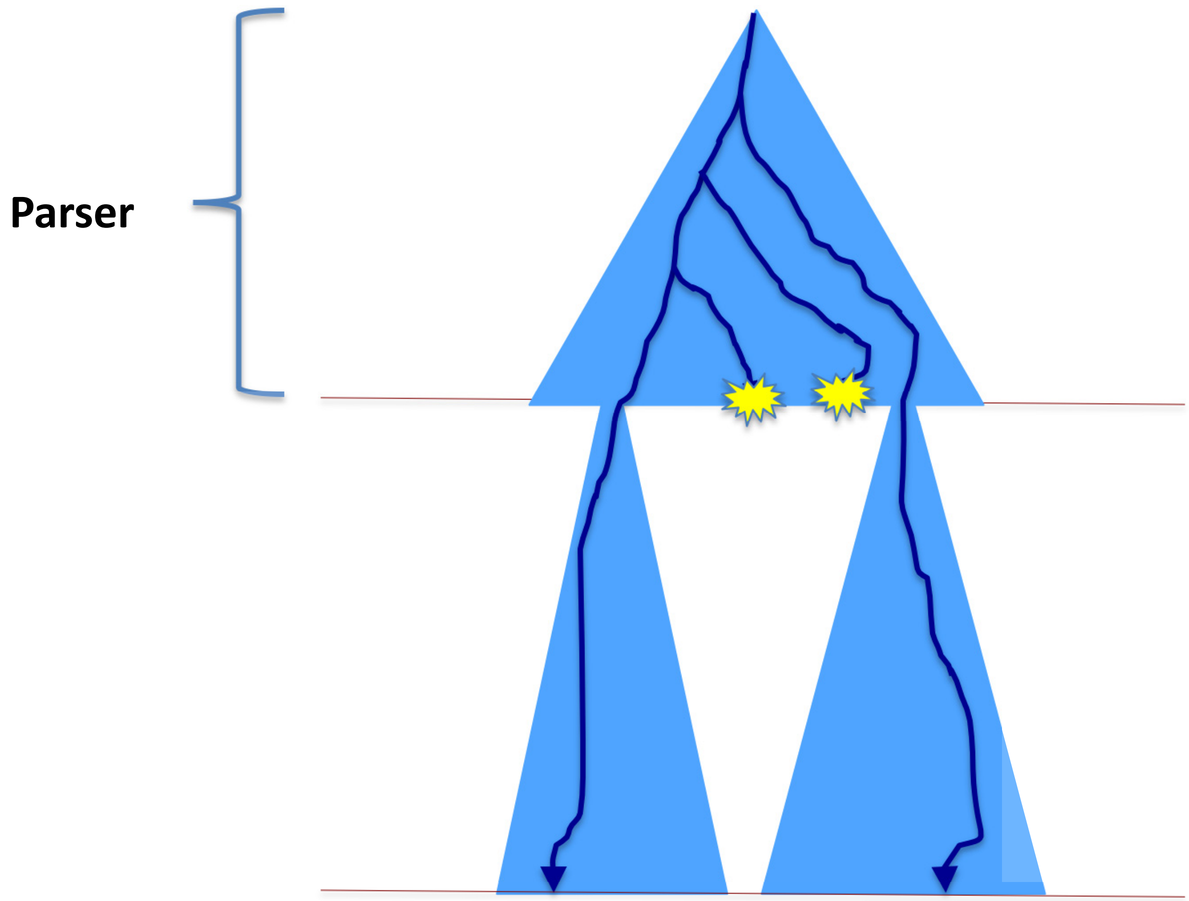
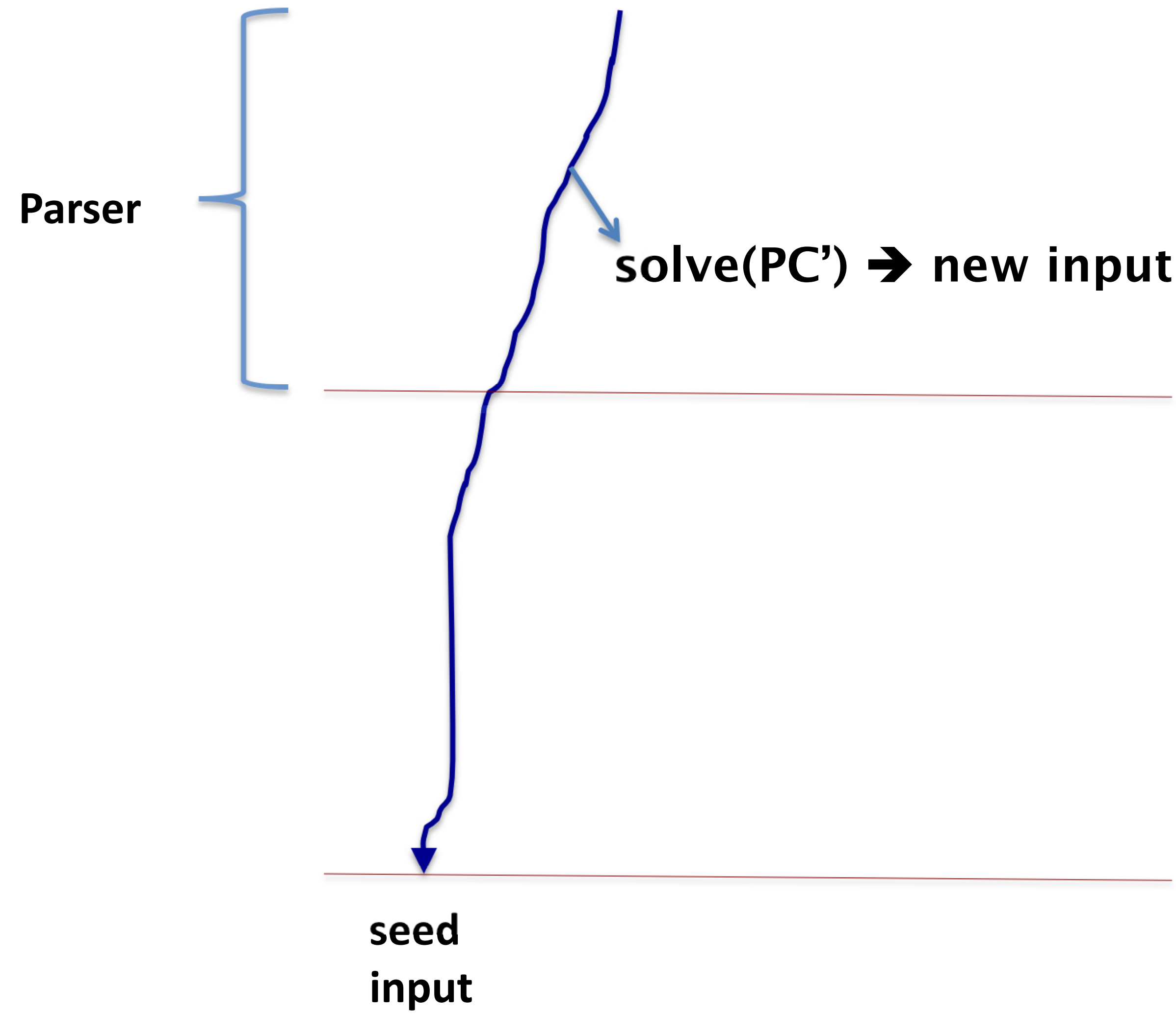


Most Generated Inputs Get Rejected Quickly

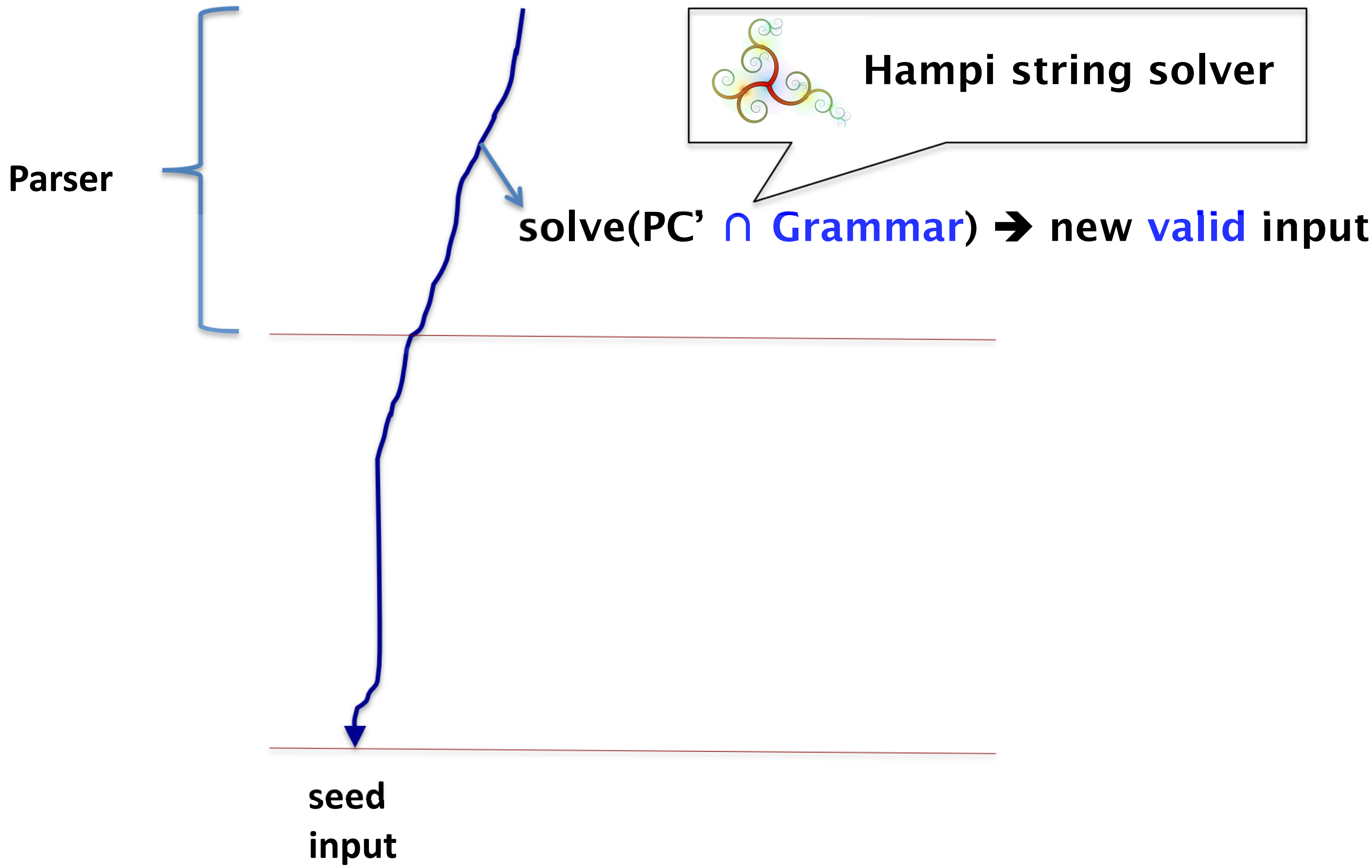


Key idea: generate only valid inputs

Input-Format Grammar Guides Creation Of Effective Inputs



Input-Format Grammar Guides Creation Of Effective Inputs



String-Constraint Solver Helps Create Valid Inputs

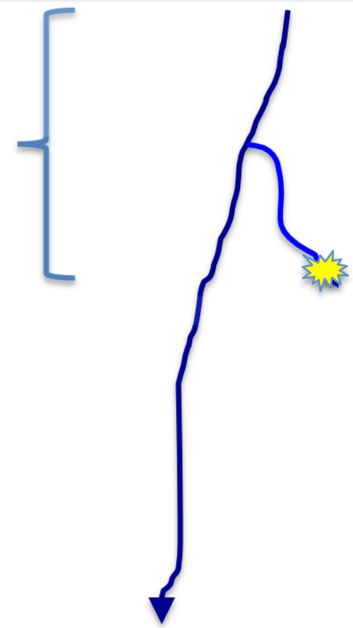
Seed input (for JavaScript interpreter):

```
function f(){ var v = 3; }
```

Constraints on tokens (created during execution)

token$_0$ = function
token$_1$ = id
token$_2$ = (
token$_3$ =)
token$_4$ = {
token$_5$ = var
…

String-Constraint Solver Helps Create Valid Inputs



Seed input (for JavaScript interpreter):

```
function f(){ var v = 3; }
```

Constraints on tokens
(created during execution)

$\texttt{token}_0 = \texttt{function}$
$\texttt{token}_1 = \texttt{id}$
$\texttt{token}_2 = \texttt{(}$
$\texttt{token}_3 = \texttt{)}$
$\texttt{token}_4 = \texttt{\{}$
$\texttt{token}_5 \neq \texttt{var}$

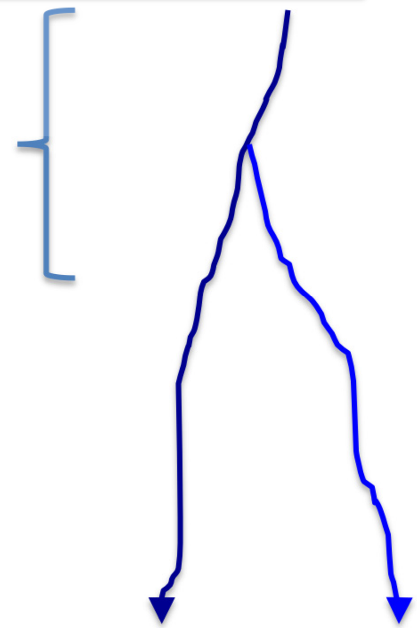
Normal solver → nonparsable input

```
function f(){ try v = 3; }
```

String-Constraint Solver Helps Create Valid Inputs

Seed input (for JavaScript interpreter):

```
function f(){ var v = 3; }
```



Constraints on tokens
(created during execution)

token$_0$ = function
token$_1$ = id
token$_2$ = (
token$_3$ =)
token$_4$ = {
token$_5$ ≠ var

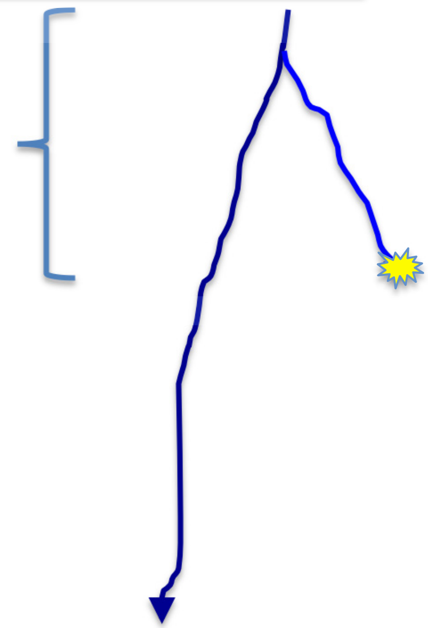
Normal solver → nonparsable input

```
function f(){ try v = 3; }
```

Hampi solver → complete parsable input

```
function f(){ try { } catch ( id ) { } finally { }; }
```

String-Constraint Solver Helps Avoid Dead-End Inputs



Seed input (for JavaScript interpreter):

```
function f(){ var v = 3; }
```

Constraints on tokens (created during execution)

$token_0$ = function

$token_1$ = id

$token_2$ = (

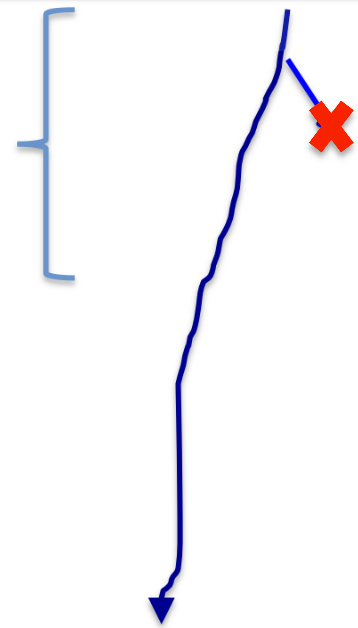
$token_3$ =)

$token_4 \neq$ {

Normal solver → nonparsable input

```
function f() var var v = 3; }
```

String-Constraint Solver Helps Avoid Dead-End Inputs



Seed input (for JavaScript interpreter):

```
function f(){ var v = 3; }
```

Constraints on tokens (created during execution)

$token_0$ = function

$token_1$ = id

$token_2$ = (

$token_3$ =)

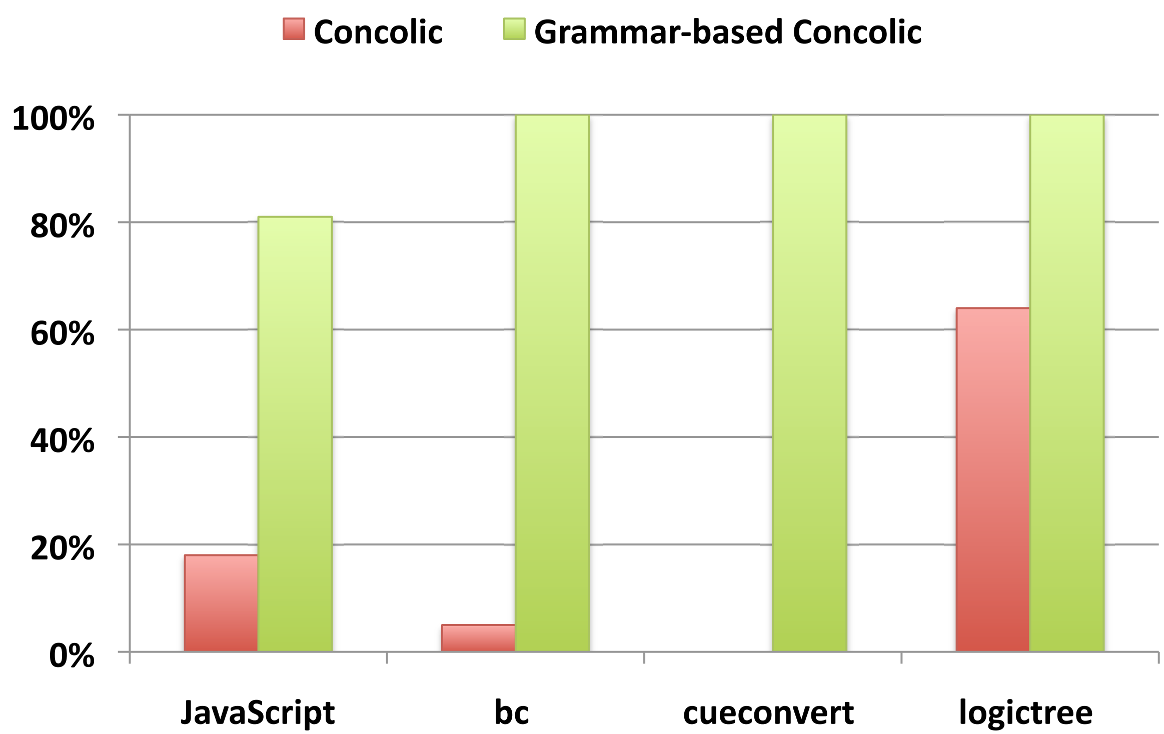
$token_4 \neq$ {

Normal solver → nonparsable input

```
function f() var var v = 3; }
```

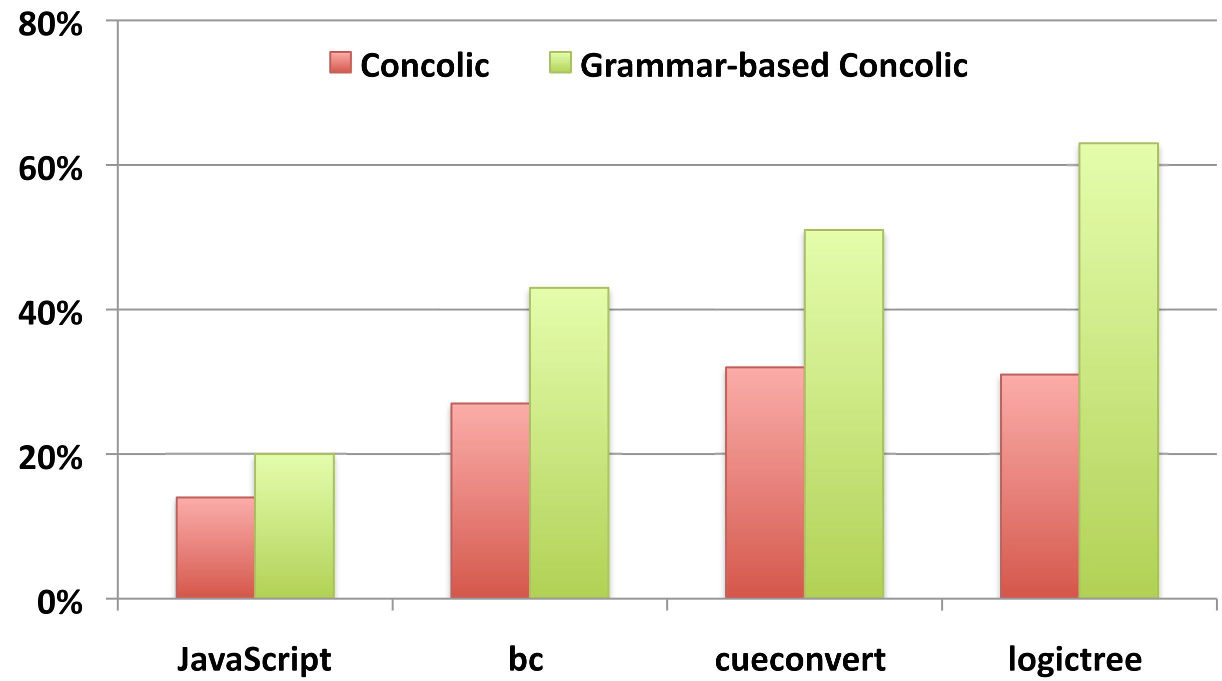
Hampi solver → no input tested, search tree pruned

Results: Grammar-Based Concolic Testing Improves Deep Reachability



Up to 20x deep reachability improvement: more generated inputs reach beyond the parser

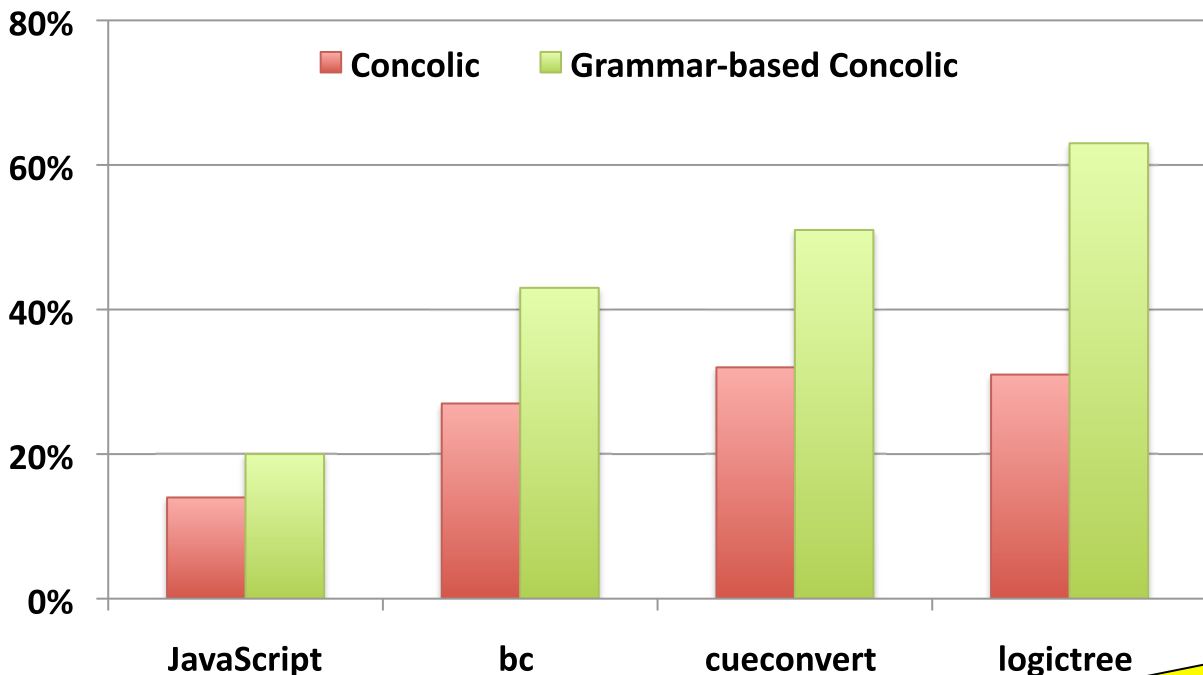
Results: Grammar-Based Concolic Testing Improves Coverage



Up to 2x coverage improvement

Results: Grammar-Based Concolic Testing Improves Coverage

and finds new bugs

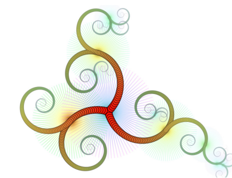


3 infinite-loop bugs

Up to 2x coverage improvement

Summary: Effective Software Testing With A String-Constraint Solver

Hampi String-Constraint Solver

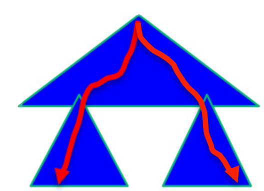


- expressive: supports context-free grammars
- efficient: solver real-world constraint quickly

Concolic Security Testing

- creates attacks on Web applications by input generation and mutation with Hampi string-constraint solver

Grammar-Based Concolic Testing



- effectively tests programs with structured inputs by using Hampi string-constraint solver and input grammars