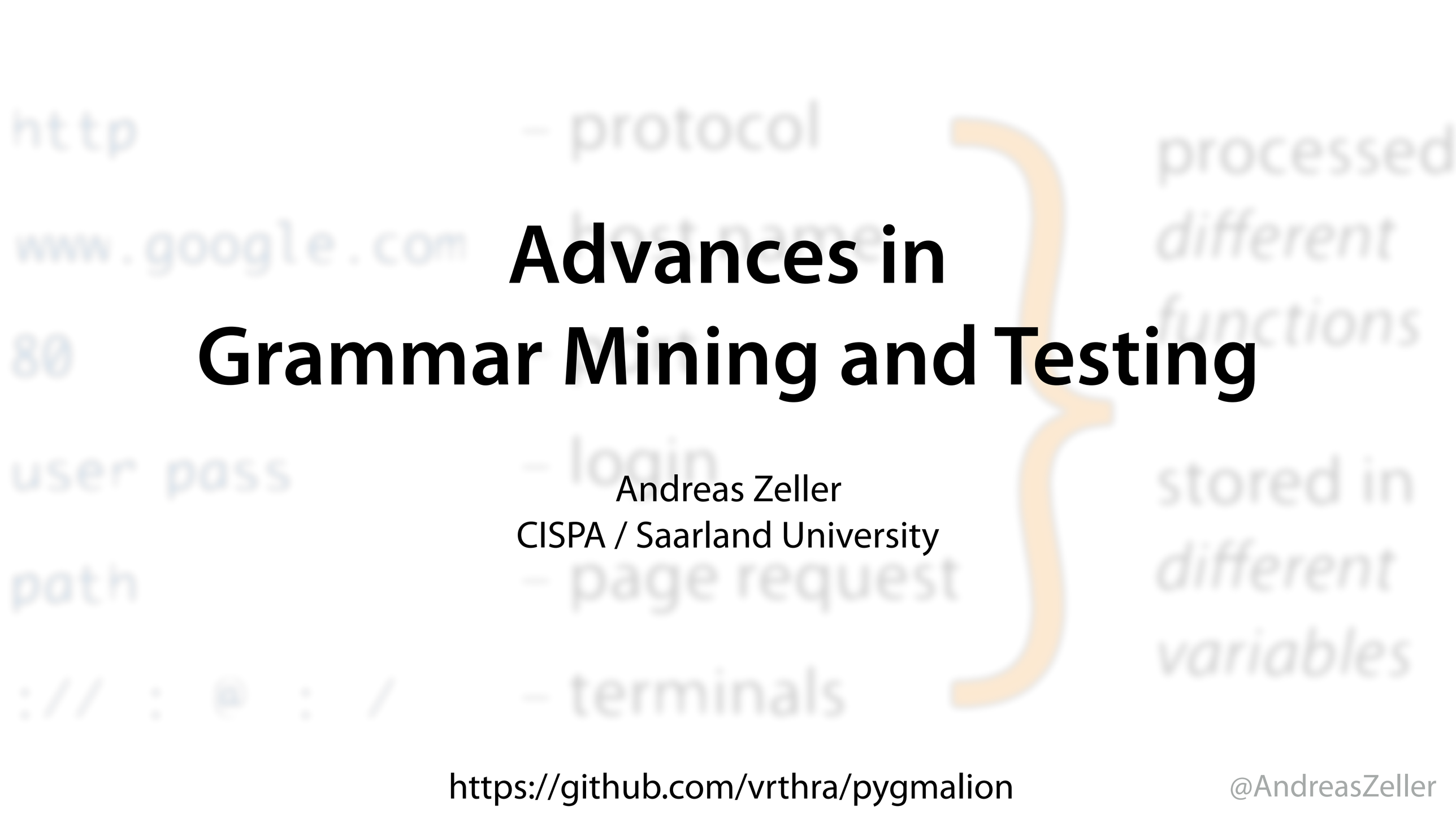

Advances in Grammar Mining and Testing

Andreas Zeller
CISPA / Saarland University

https://github.com/vrthra/pygmalion

@AndreasZeller


Saarbrücken


CISPA
HELMHOLTZ-ZENTRUM i. G.
GEFÖRDERT VOM
Bundesministerium
für Bildung
und Forschung
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Scientific excellence in fundamental research
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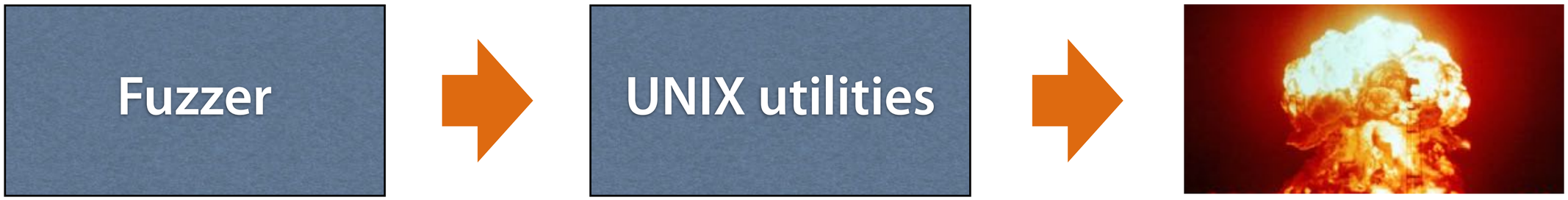
Fuzzing

Random Testing at the System Level

```
[;x1-GPZ+wcckc];,N9J+?#6^6\e?]9lu2_%'4GX"0VUB[E/r
~fApu6b8<{%siq8Zh.6{V,hr?;{Ti.r3PIxMMMv6{xS^+'Hq!AxB"YXRS@!
Kd6;wtAMefFWM(`|J_<1~o}z3K(CCzRH JIIvHz>_*.\>JrlU32~eGP?
lR=bF3+;y$3lodQ<B89!5"W2fK*vE7v{')KC-i,c{<[~m!]o;{.'}Gj\(X}
EtYetrpbY@aGZ1{P!AZU7x#4(Rtn!q4nCwqol^y6}0|
Ko=*JK~;zMKV=9Nai:wxu{J&UV#HaU)*BiC<),`+t*gka<W=Z.
%T5WGHZpI30D<Pq>&]BS6R&j?#tP7iaV}-}`\?[_[Z^LBMPG-
FKj'\xwuZ1=Q`^`5,$N$Q@[!CuRzJ2D|vBy!^zkhdf3C5PAkR?V hn|
3='i2Qx]D$qs4O`1@fevnG'2\11Vf3piU37@55ap\zIyl"'f,
$ee,J4Gw:cgNKLie3nx9(`efSlg6#[K"@WjhZ}r[Scun&sBCS,T[/
vY'pduwgzDlVNy7'rnzxNwI)(ynBa>%|b`;`9fG]P_0hdG~$@6
3]KAeEnQ7lU)3Pn,0)G/6N-wyzj/MTd#A;r
```

Fuzzing

Random Testing at the System Level



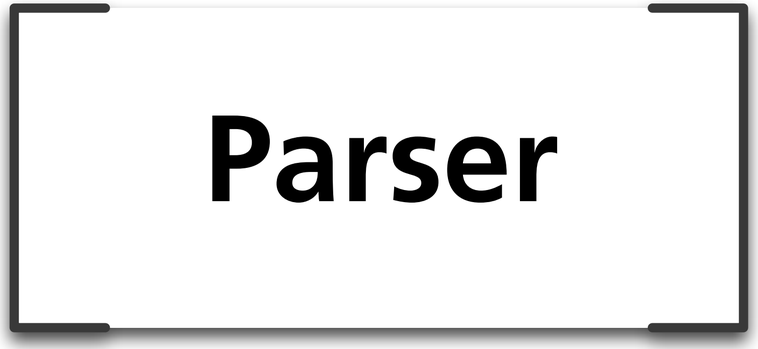
“ab’d&gfdfggg”

grep • sh • sed …

25%–33%

Grammar Fuzzing

- Suppose you want to test a *parser* –
  to compile and execute a program
- To get deep into the program, you need
  syntactically correct inputs



LangFuzz (2012)

- Fuzz tester for JavaScript and other languages
- Uses a full-fledged *grammar* to generate inputs
- Uses grammar to *parse existing inputs*

JavaScript Grammar

If Statement

IfStatement[full] ⇒
  `if` *ParenthesizedExpression* *Statement*[full]
| **`if`** *ParenthesizedExpression* *Statement*[noShortIf] **`else`** *Statement*[full]
IfStatement[noShortIf] ⇒ **`if`** *ParenthesizedExpression* *Statement*[noShortIf] **`else`** *Statement*[noShortIf]

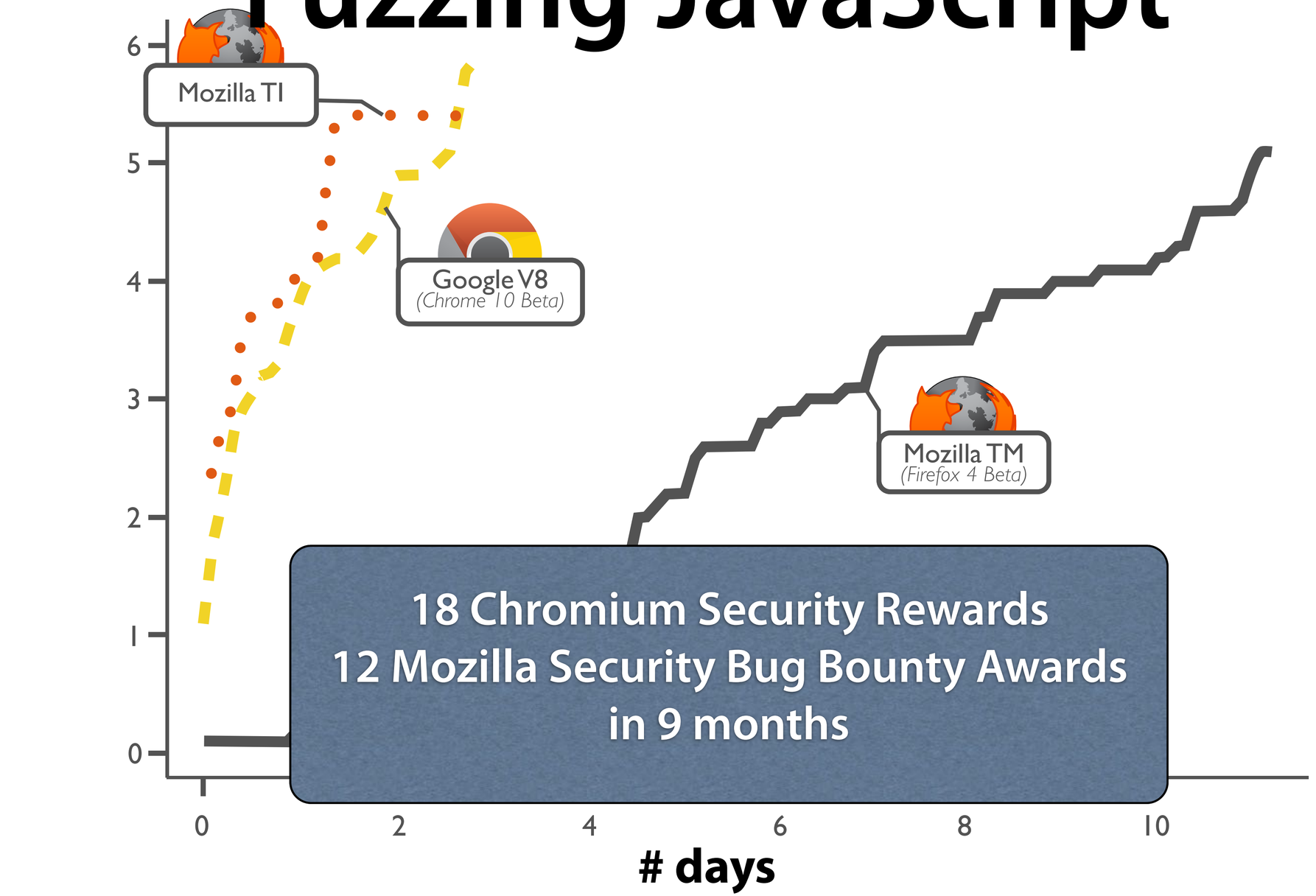
Switch Statement

SwitchStatement ⇒
  `switch` *ParenthesizedExpression* **`{ }`**
| **`switch`** *ParenthesizedExpression* **`{`** *CaseGroups* *LastCaseGroup* **`}`**
CaseGroups ⇒
  «empty»
| *CaseGroups* *CaseGroup*
CaseGroup ⇒ *CaseGuards* *BlockStatementsPrefix*

A Generated Input

```
1 var haystack = "foo";
2 var re_text  = "^foo";
3 haystack += "x";
4 re_text  += "(x)";
5 var re = new RegExp(re_text);
6 re.test(haystack);
7 RegExp.input = Number();
8 print(RegExp.$1);
```

Fuzzing JavaScript



Learning Grammars

If Statement

IfStatement[full] ⇒
  if *ParenthesizedExpress*
| **if** *ParenthesizedExpress*
IfStatement[noShortIf] ⇒ **if** *Pa*

f **else** *Statement*[noShortIf]

Switch Statement

SwitchStatement ⇒
  switch *ParenthesizedEx*
| **switch** *ParenthesizedEx*

p **}**

CaseGroups ⇒
  «empty»
| *CaseGroups CaseGroup*
CaseGroup ⇒ *CaseGuards BlockStatementsPrefix*

Learning Grammars

- Let us characterize program behavior
  via its **input/output language**
- Assume I/O is a stream of characters (symbols)
- Assume we can characterize this stream
  via a **formal language** – regular expressions, grammars
- We want to **learn** such a language from the program

Learning Grammars

```
http://user:pass@www.google.com:80/path
```

Program

Learning Grammars

```
http://user:pass@www.google.com:80/path
```

`http` – protocol

Learning Grammars

```
http://user:pass@www.google.com:80/path
```

`http` – protocol

`www.google.com` – host name

Learning Grammars

```
http://user:pass@www.google.com:80/path
```

`http`	– protocol
`www.google.com`	– host name
`80`	– port

Learning Grammars

```
http://user:pass@www.google.com:80/path
```

`http`	– protocol
`www.google.com`	– host name
`80`	– port
`user pass`	– login

Learning Grammars

```
http://user:pass@www.google.com:80/path
```

`http`	– protocol
`www.google.com`	– host name
`80`	– port
`user pass`	– login
`path`	– page request

Learning Grammars

```
http://user:pass@www.google.com:80/path
```

`http`	– protocol
`www.google.com`	– host name
`80`	– port
`user pass`	– login
`path`	– page request
`:// : @ : /`	– terminals

Learning Grammars

```
http://user:pass@www.google.com:80/path
```

`http`	– protocol
`www.google.com`	– host name
`80`	– port
`user pass`	– login
`path`	– page request
`:// : @ : /`	– terminals

processed in *different functions*

stored in *different variables*

Tracking Input

We *track input characters* throughout program execution:

1. *Dynamic tainting* labels all characters read (and derived values) with their origin
2. *Recognizing inputs* checks string variables whether they hold input fragments (simpler)

Grammar Inference

- Start with grammar $START ::= *input*

```
$START ::= http://user:pass@www.google.com:80/path#ref
```

Grammar Inference

- For each (*var*, *value*) we find during execution, where *value* is a substring of *input*:
  1. Replace all occurrences of *value* by $*VAR*
  2. Add a new rule $VAR ::= *value*

```
$START ::= http://user:pass@www.google.com:80/path#ref


fragment = 'ref'
url = '/path'
path = '/path'
scheme = 'http'
netloc = 'user:pass@www.google.com:80'
```

Grammar Inference

- For each (*var*, *value*) we find during execution, where *value* is a substring of *input*:
  1. Replace all occurrences of *value* by $*VAR*
  2. Add a new rule $VAR ::= *value*

```
$START ::= http://$NETLOC/path#ref
$NETLOC ::= user:pass@www.google.com:80


fragment = 'ref'
url = '/path'
path = '/path'
scheme = 'http'
```

Grammar Inference

- For each (*var*, *value*) we find during execution, where *value* is a substring of *input*:
  1. Replace all occurrences of *value* by $*VAR*
  2. Add a new rule $VAR ::= *value*

```
$START ::= $SCHEME://$NETLOC/path#ref
$NETLOC ::= user:pass@www.google.com:80
$SCHEME ::= http


fragment = 'ref'
url = '/path'
path = '/path'
```

Grammar Inference

- For each (*var*, *value*) we find during execution, where *value* is a substring of *input*:
  1. Replace all occurrences of *value* by $*VAR*
  2. Add a new rule $VAR ::= *value*

```
$START ::= $SCHEME://$NETLOC$PATH#ref
$NETLOC ::= user:pass@www.google.com:80
$SCHEME ::= http
$PATH ::= /path


fragment = 'ref'
url = '/path'
```

Grammar Inference

- For each (*var*, *value*) we find during execution, where *value* is a substring of *input*:
  1. Replace all occurrences of *value* by $*VAR*
  2. Add a new rule $VAR ::= *value*

```
$START ::= $SCHEME://$NETLOC$PATH#$FRAGMENT
$NETLOC ::= user:pass@www.google.com:80
$SCHEME ::= http
$PATH ::= /path
$FRAGMENT ::= ref


url = '/path'
```

Grammar Inference

- For each (*var*, *value*) we find during execution, where *value* is a substring of *input*:
  1. Replace all occurrences of *value* by $*VAR*
  2. Add a new rule $VAR ::= *value*

```
$START ::= $SCHEME://$NETLOC$PATH#$FRAGMENT
$NETLOC ::= user:pass@www.google.com:80
$SCHEME ::= http
$PATH ::= $URL
$FRAGMENT ::= ref
$URL ::= /path
```

Demo

AUTOGRAM

AUTOGRAM: a grammar miner for Java programs

Uses *active learning* to infer

- repetitions
- optional parts
- common elements (numbers, identifiers…)

Höschele, Zeller: "Mining Input Grammars from Dynamic Taints", ASE 2016

URLs

```
http://user:password@www.google.com:80/command?foo=bar&lorem=ipsum#fragment
http://www.guardian.co.uk/sports/worldcup#results
ftp://bob:12345@ftp.example.com/oss/debian7.iso
```

```
URL ::= PROTOCOL '://' AUTHORITY PATH ['?' QUERY] ['#' REF]
AUTHORITY ::= [USERINFO '@'] HOST [':' PORT]
PROTOCOL ::= 'http' | 'ftp'
USERINFO ::= /[a-z]+:[a-z]+/
HOST ::= /[a-z.]+/
PORT ::= '80'
PATH ::= /\/[a-z0-9.\/]*/
QUERY ::= 'foo=bar&lorem=ipsum'
REF ::= /[a-z]+/
```

INI Files

```
[Application]
Version = 0.5
WorkingDir = /tmp/mydir/
[User]
User = Bob
Password = 12345
```

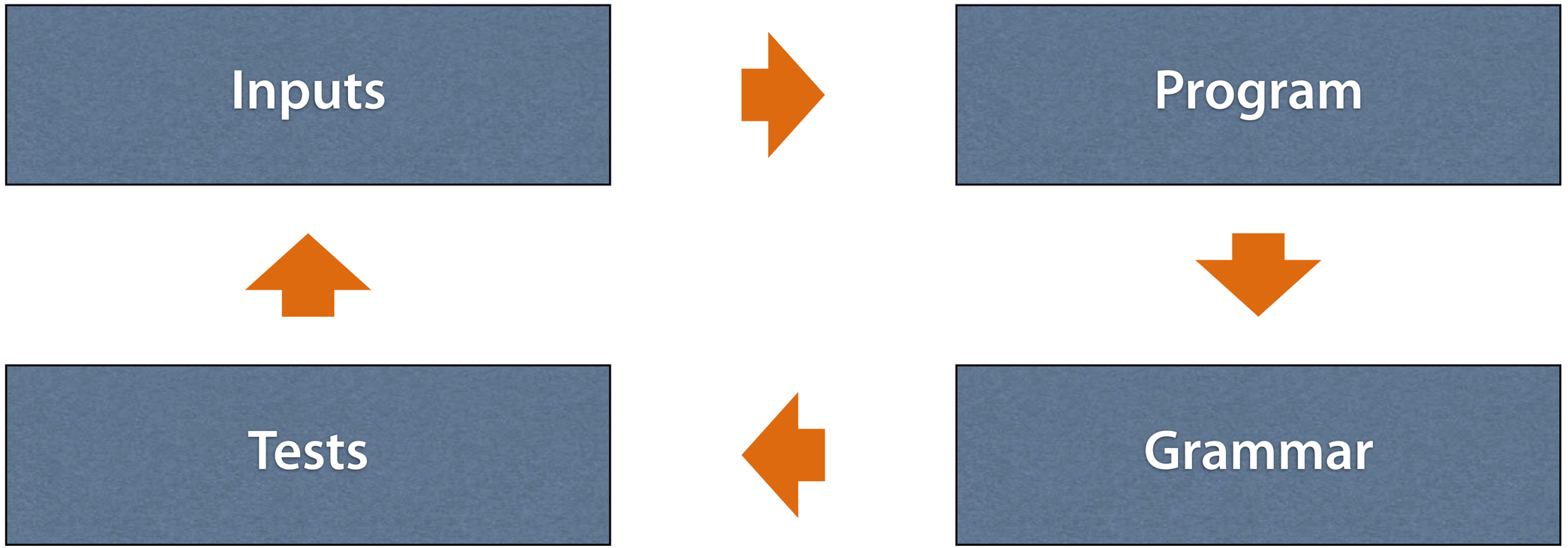
```
INI ::= LINE+
LINE ::= SECTION_LINE '\r'
       | OPTION_LINE  ['\r']
SECTION_LINE ::= '[' KEY ']'
OPTION_LINE ::= KEY ' = ' VALUE
KEY ::= /[a-zA-Z]*/
VALUE ::= /[a-zA-Z0-9\/]/
```

JSON Input

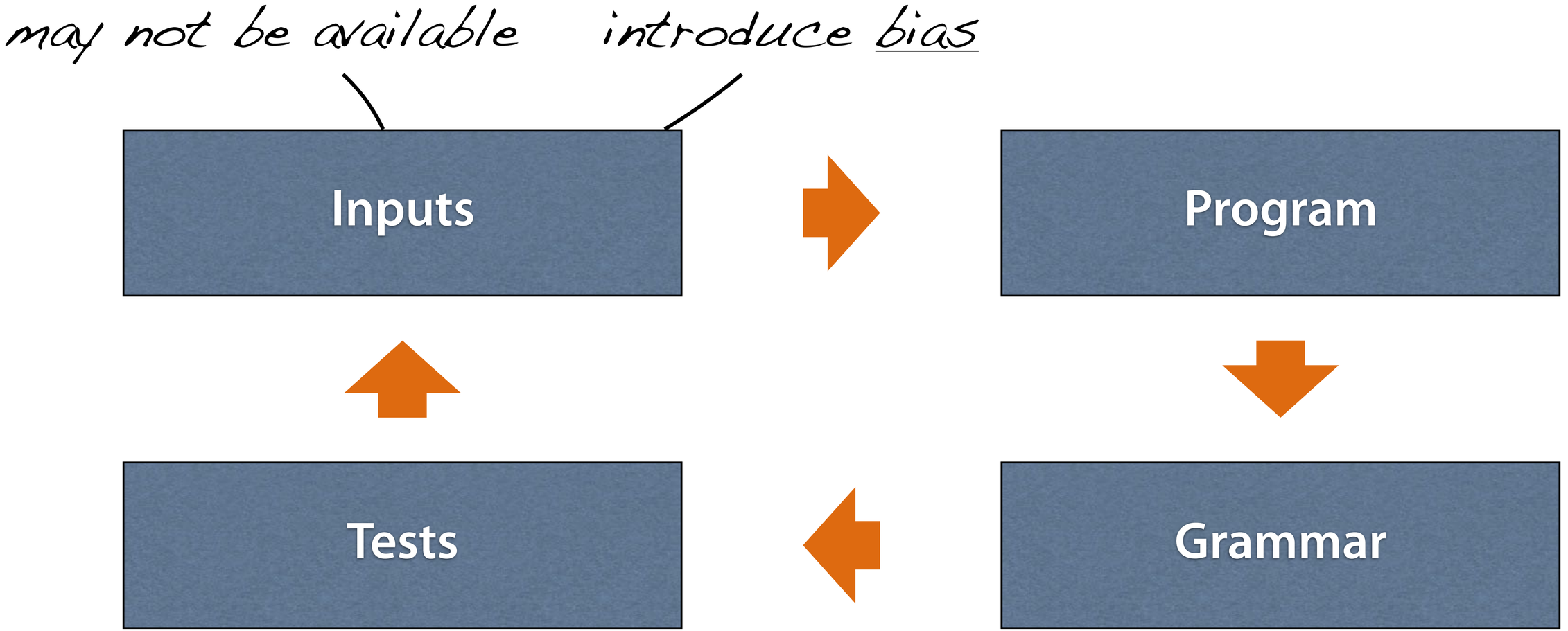
```
{
 "v": true,
 "x": 25,
 "y": -36,
 …
}
```

```
JSON ::= VALUE
VALUE ::= JSONOBJECT | ARRAY | STRINGVALUE |
          TRUE | FALSE | NULL | NUMBER
TRUE ::= 'true'
FALSE ::= 'false'
NULL ::= 'null'
NUMBER ::= ['-'] /[0-9]+/
STRINGVALUE ::= '"' INTERNALSTRING '"'
INTERNALSTRING ::= /[a-zA-Z0-9 ]+/
ARRAY ::= '['
 [VALUE [',' VALUE]+]
']'
JSONOBJECT ::= '{'
 [STRINGVALUE ':' VALUE
  [',' STRINGVALUE ':' VALUE]
  +]
'}'
```

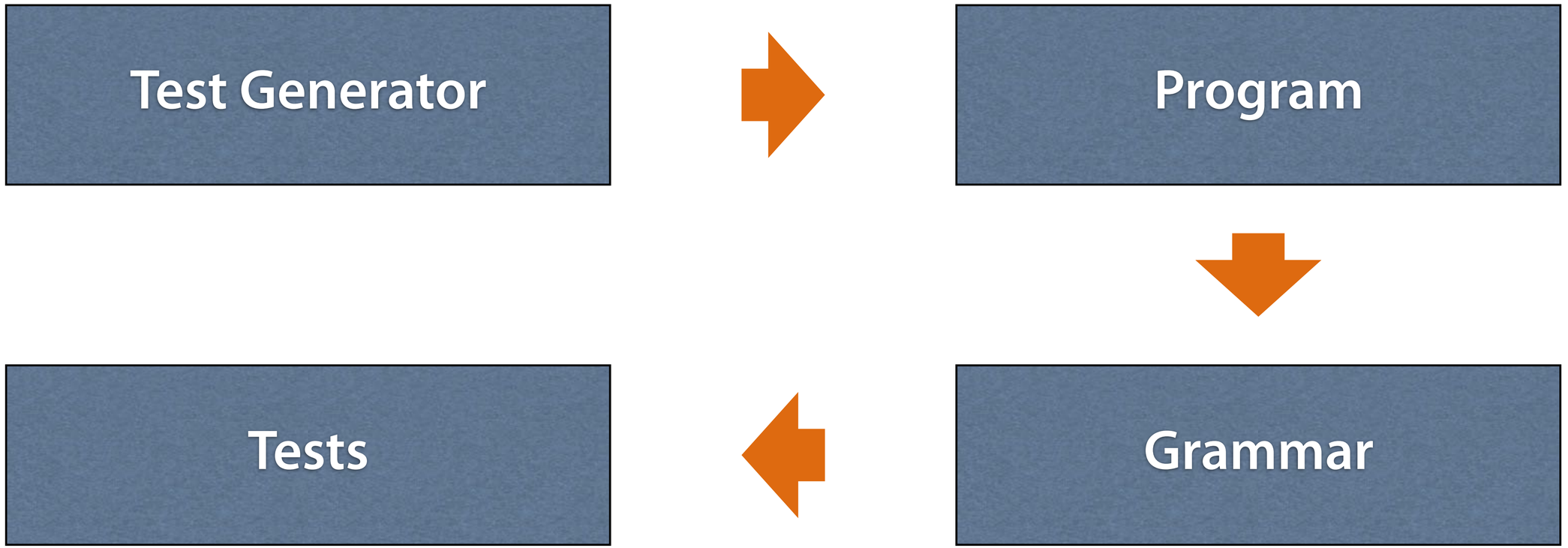
Testing with Mined Grammars



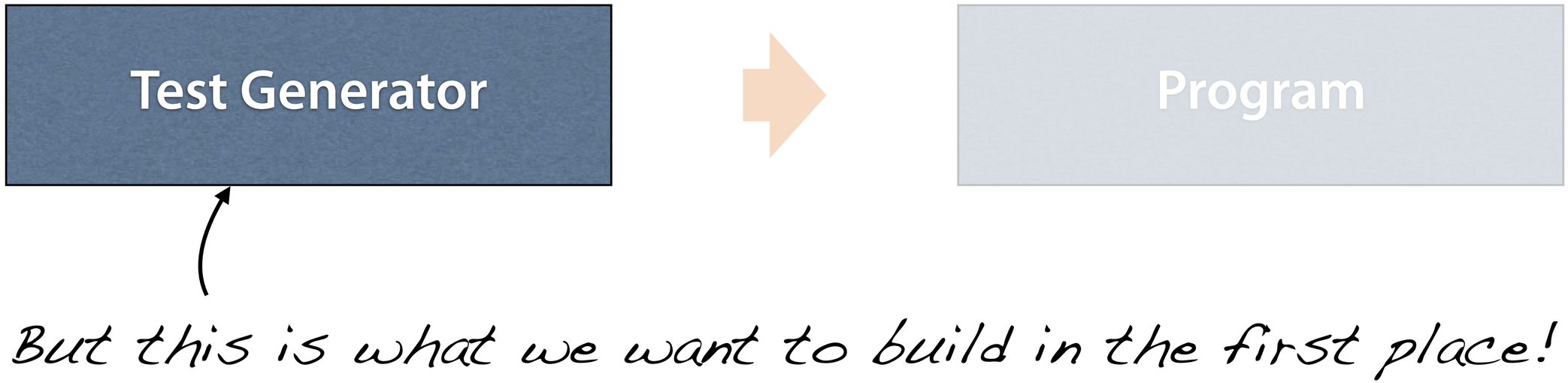
Testing with Mined Grammars



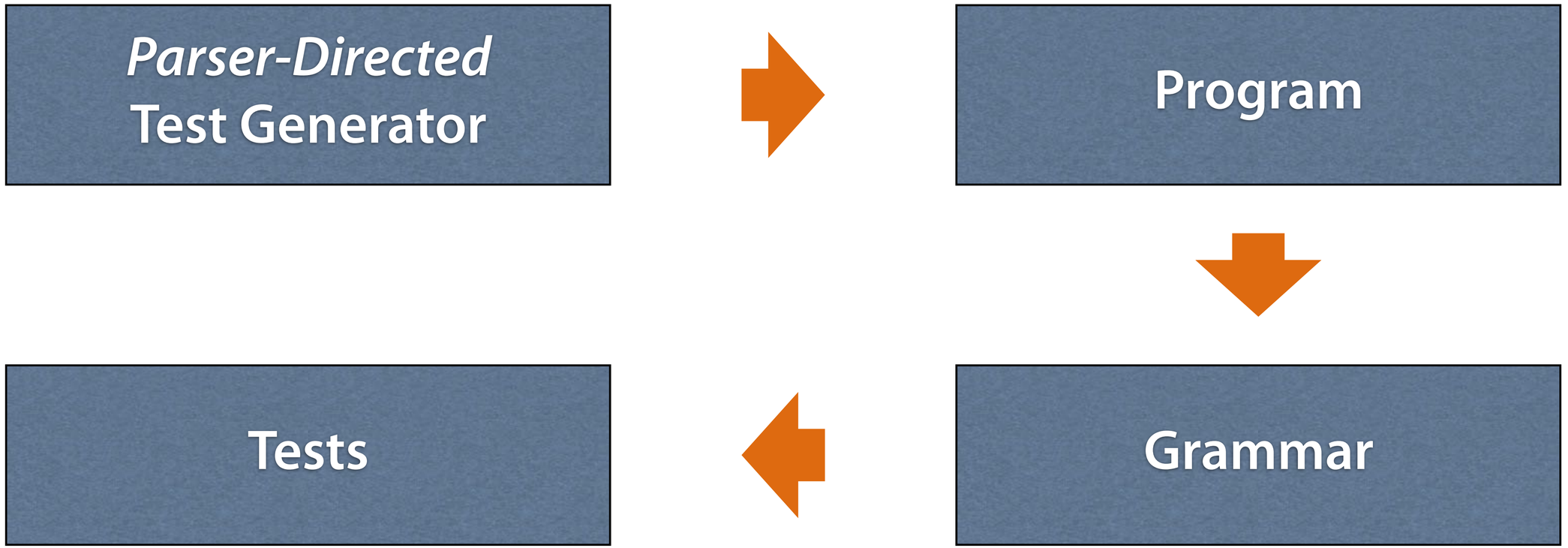
Sample-Free Grammar Learning



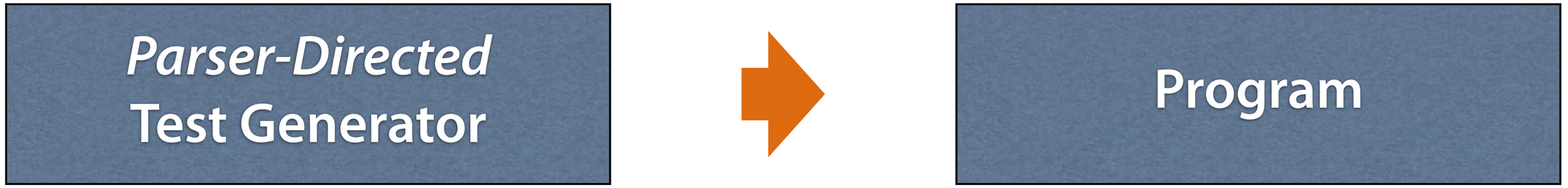
Sample-Free Grammar Learning



Sample-Free Grammar Learning



Dynamic Checks

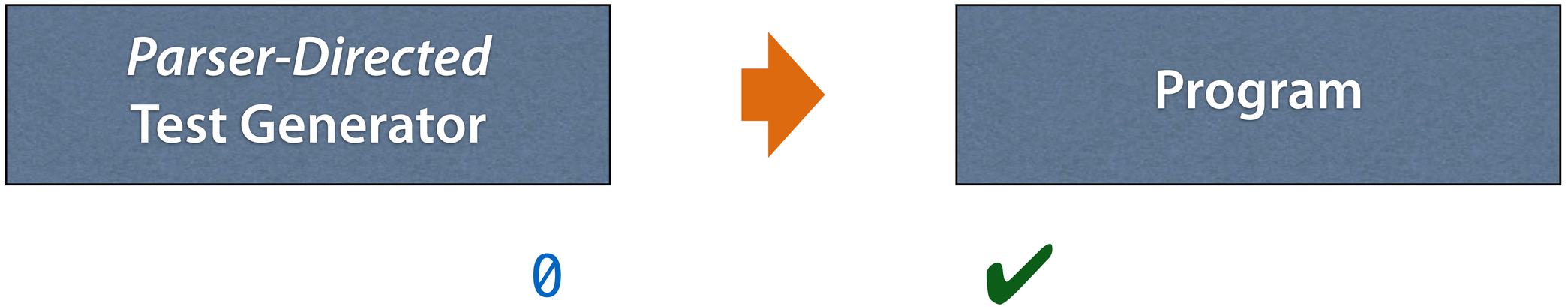


xyzzy

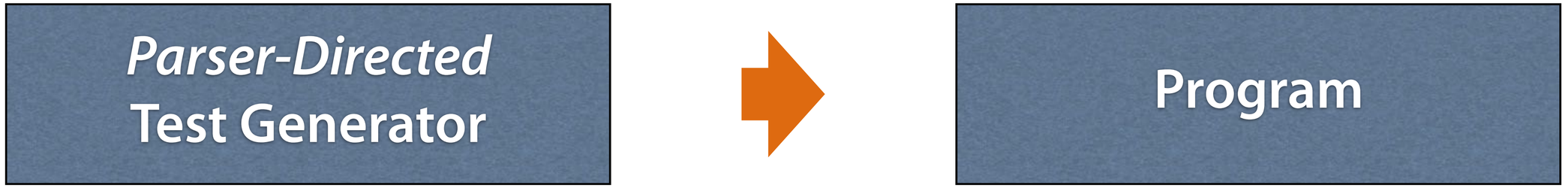
✗

- checks for digit
- checks for "true"/"false"
- checks for ""
- checks for '['
- checks for '{'

Dynamic Checks



Dynamic Checks



`0` ✔

- checks for digit
- checks for "true"/"false"
- checks for ""
- checks for '['
- checks for '{'

Learning Behavior

Parser-Directed Test Generator

Program

`0`

✔

- checks for digit
- checks for "true"/"false"
- checks for ""
- checks for '['
- checks for '{'

Dynamic Checks

Parser-Directed
Test Generator

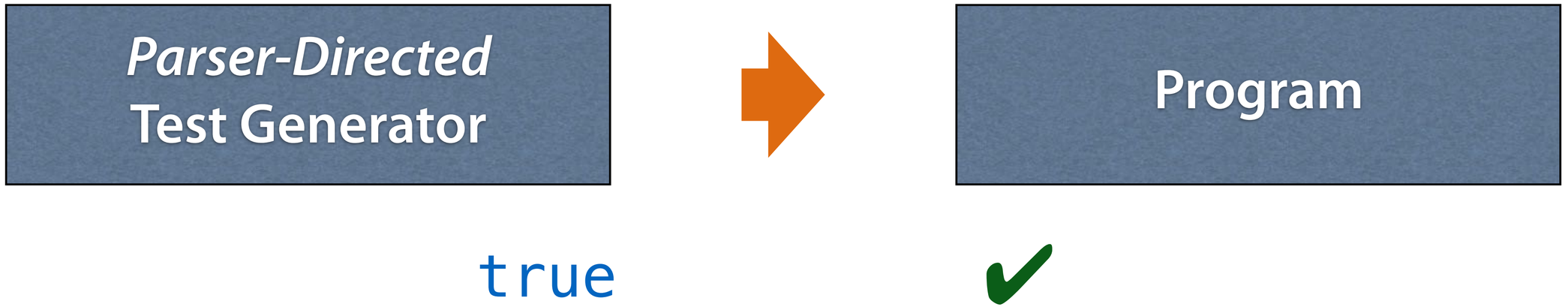
Program

`0`

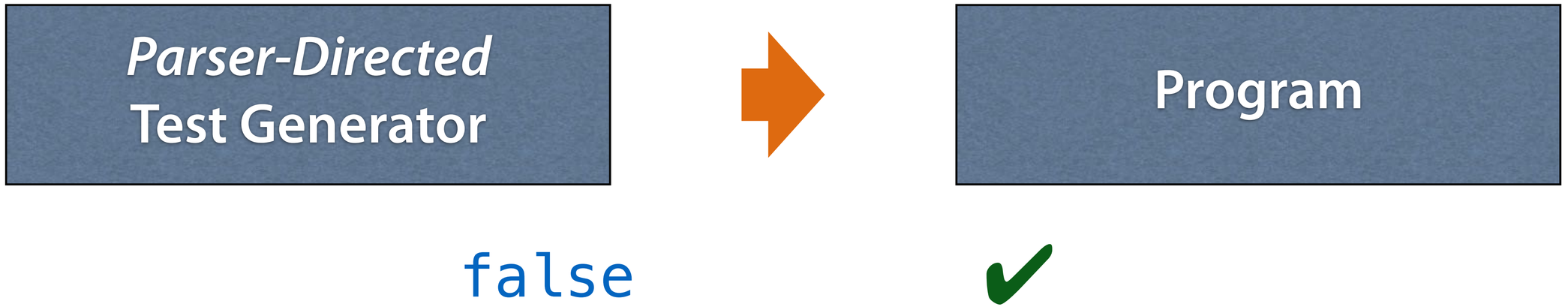
✔

- checks for digit
- checks for "true"/"false"
- checks for ""
- checks for '['
- checks for '{'

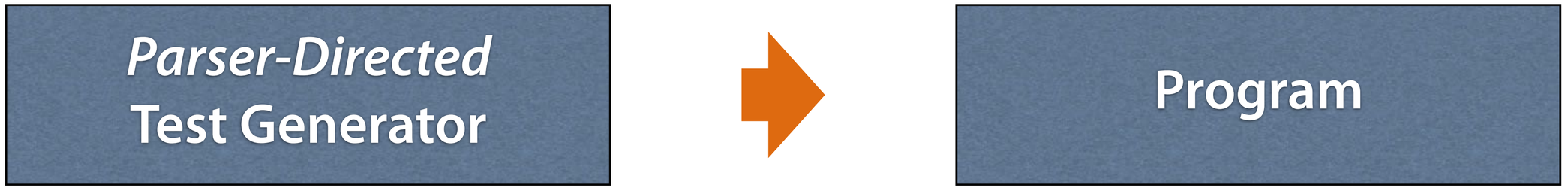
Dynamic Checks



Dynamic Checks



Dynamic Checks

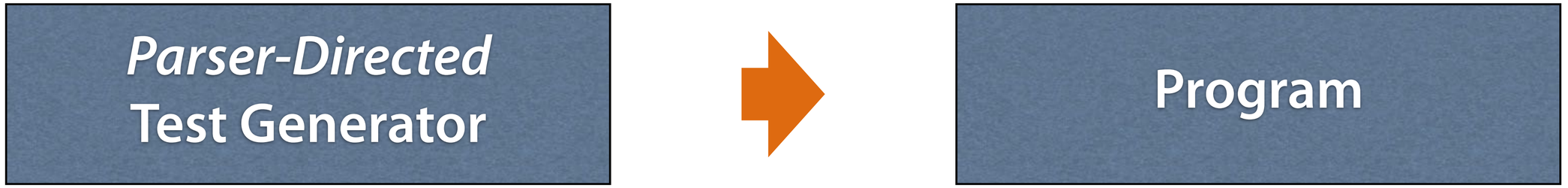


`false`

✔

- checks for digit
- checks for "true"/"false"
- checks for ""
- checks for '['
- checks for '{'

Dynamic Checks



`false`

✔

- checks for digit
- checks for "true"/"false"
- checks for ""
- checks for '['
- checks for '{'

Dynamic Checks

Parser-Directed Test Generator

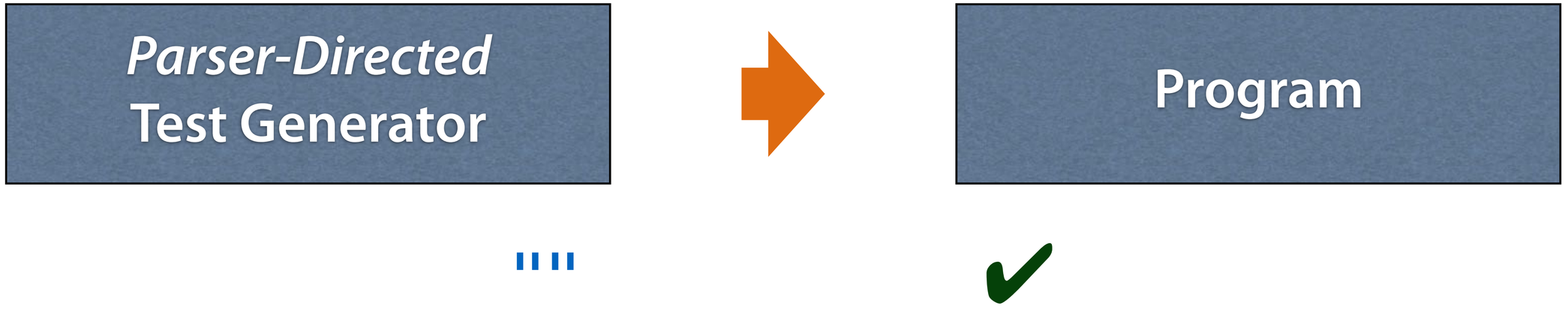
Program

"

✗

- checks for ""
- checks for '\'
- checks for character

Dynamic Checks



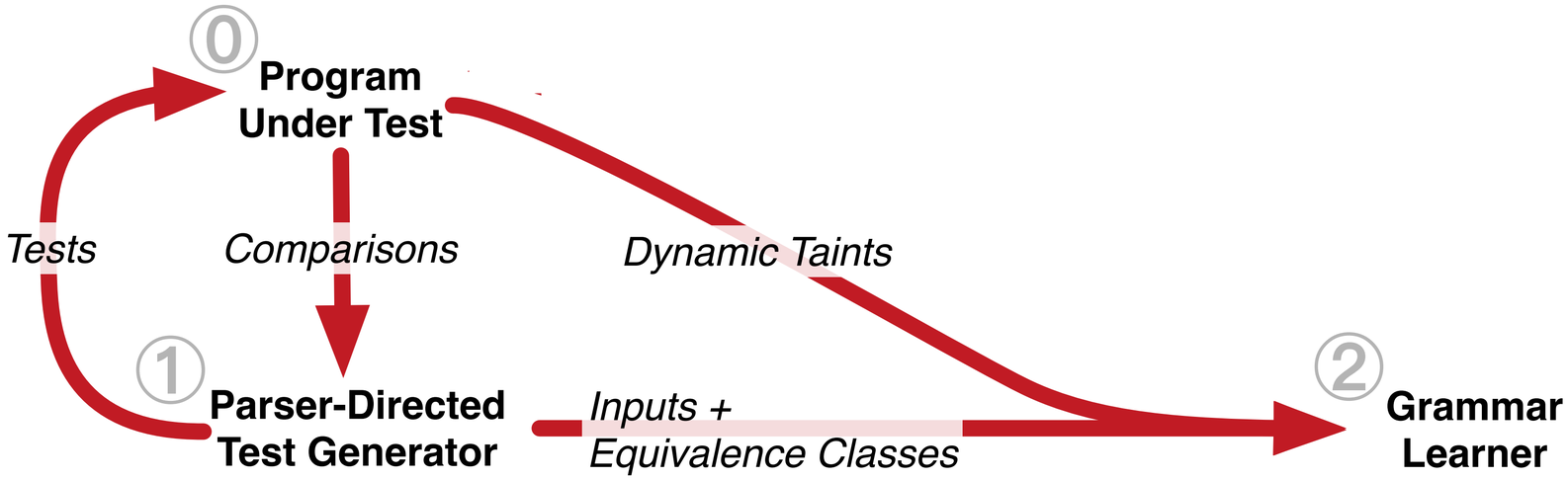
Learning JSON

Parser-Directed
Test Generator

```
JSON ::= VALUE
VALUE ::= JSONOBJECT | ARRAY | STRINGVALUE |
          TRUE | FALSE | NULL | NUMBER
TRUE ::= 'true'
FALSE ::= 'false'
NULL ::= 'null'
NUMBER ::= ['-'] /[0-9]+/
STRINGVALUE ::= '"' INTERNALSTRING '"'
INTERNALSTRING ::= /[a-zA-Z0-9 ]+/
ARRAY ::= '['
 [VALUE [',' VALUE]+]
']'
JSONOBJECT ::= '{'
 [STRINGVALUE ':' VALUE
  [',' STRINGVALUE ':' VALUE]
  +]
'}'
```

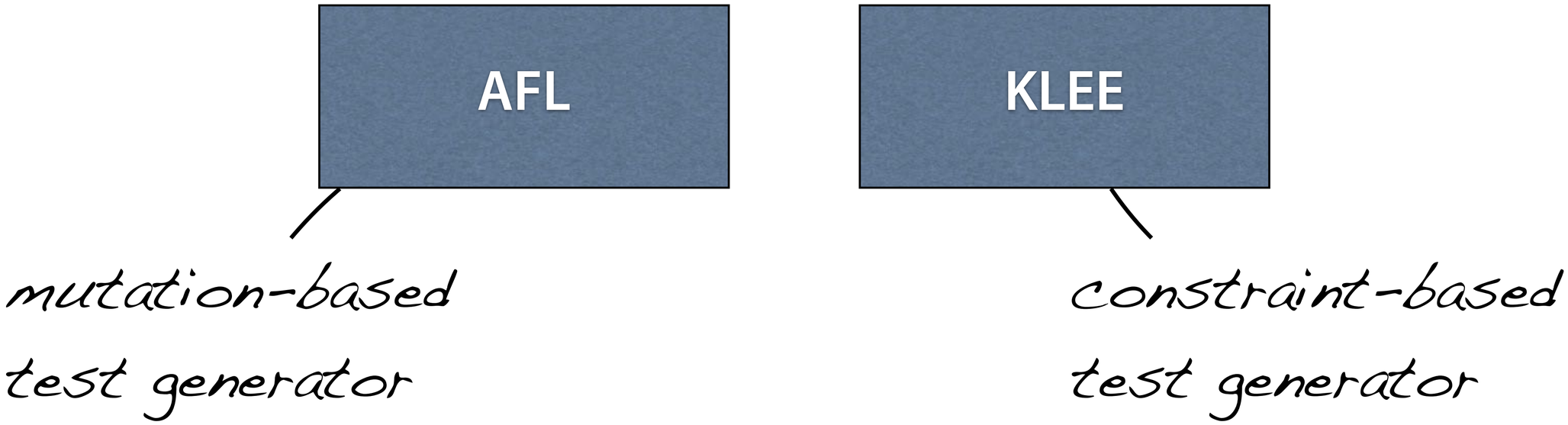
All in One

PYGMALION prototype for Python programs

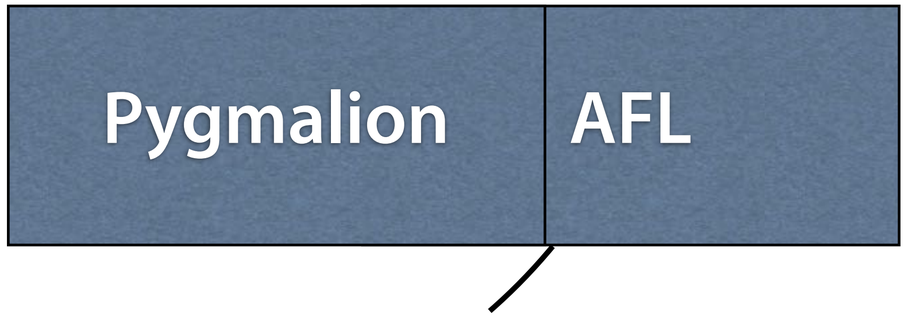


Gopinath, Mathis, Höschele, Kampmann, Zeller: "Sample-Free Learning of Input Grammars"

Initial Evaluation



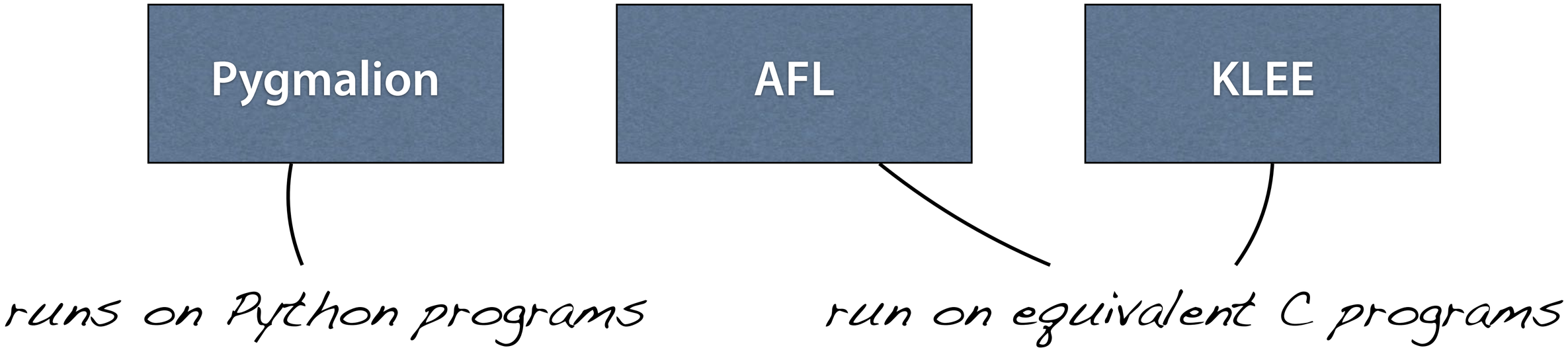
Initial Evaluation



mutation-based test generator

constraint-based test generator

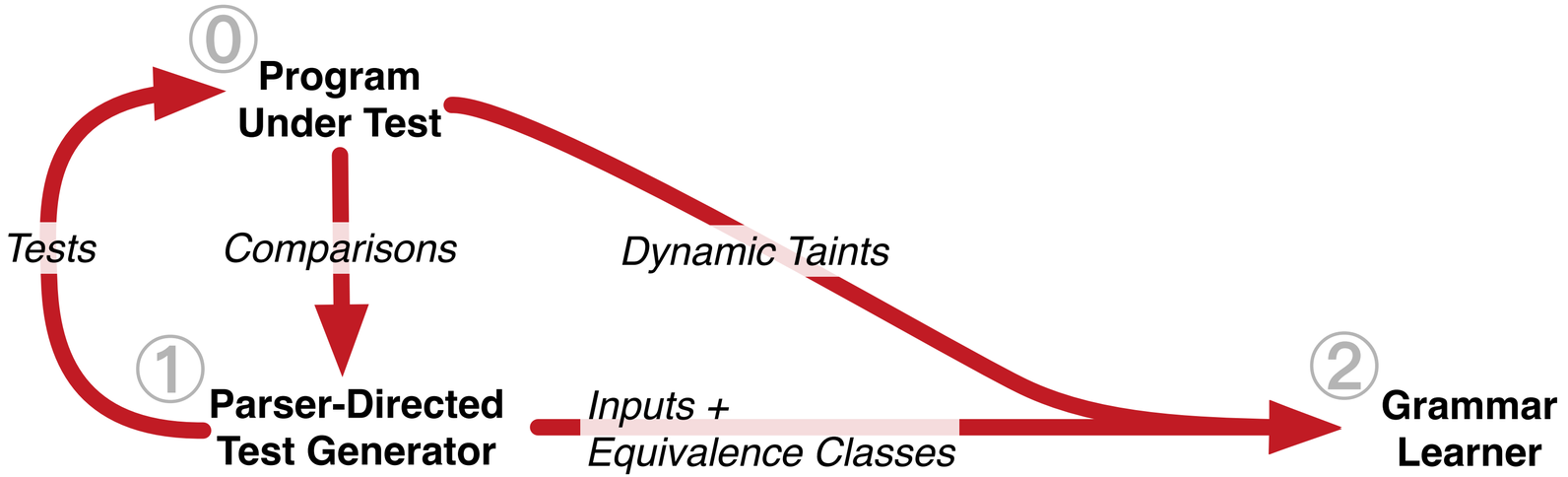
Initial Evaluation



No seed inputs for any tool

Testing with Inferred Grammars

PYGMALION prototype for Python programs



Perfect coverage, much faster than AFL, much better structure than KLEE

Gopinath, Mathis, Höschele, Kampmann, Zeller: "Sample-Free Learning of Input Grammars"

Test Generation Compared

AFL

```
..............................
```

Low coverage, few valid inputs

KLEE

```
nullÿÿÿÿÿÿÿÿÿÿÿÿÿÿÿÿÿÿÿÿÿÿÿÿÿÿÿÿÿÿÿÿÿÿ
```

Top coverage, but flat inputs

Pygmalion

```
[false ,[{ "o":{ , "$dYPrlj@?BR":
397  [+ ]"Sl+l4GzCW(C":-94}} ],
[false,null]]
```

Top coverage, deep structure, control

Findings

- AFL is great for covering error-handling code
- Pygmalion and KLEE both achieve top coverage
- ~75% of inputs generated by Pygmalion are valid
- Pygmalion exercises far more input combinations
- Grammars give you control over what you want to test

Challenges

- **Implicit information flow**
  Generated scanners and parsers
- **Context-sensitive features**
  Binary formats, identifiers
- **Scale and applicability**
  Port Pygmalion to C (2019)
- **Teach this!**
  Book "Generating Software Tests"


R. Gopinath


M. Höschele

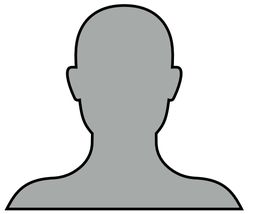

B. Mathis

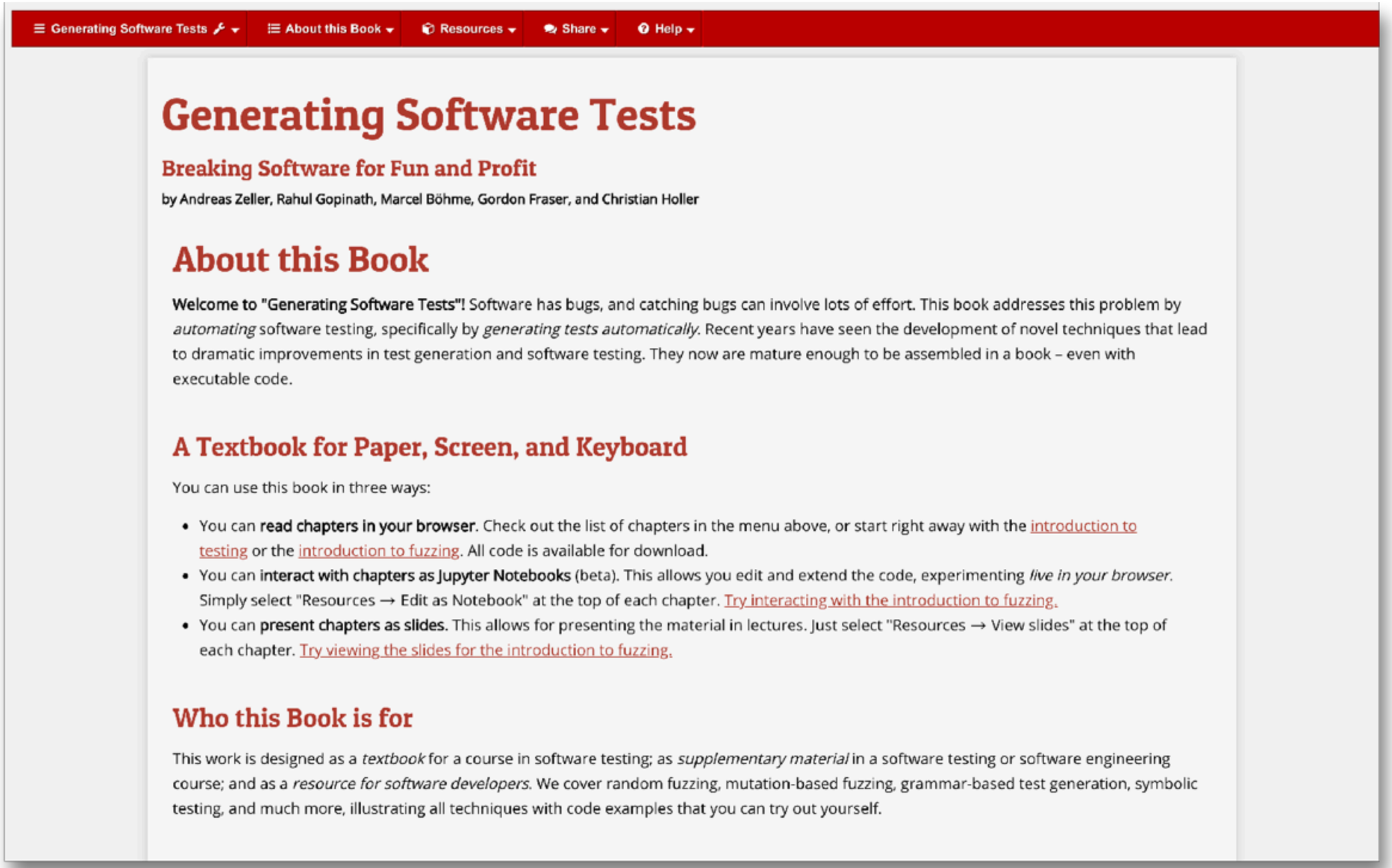

N. Havrikov


A. Kampmann


E. Soremekun

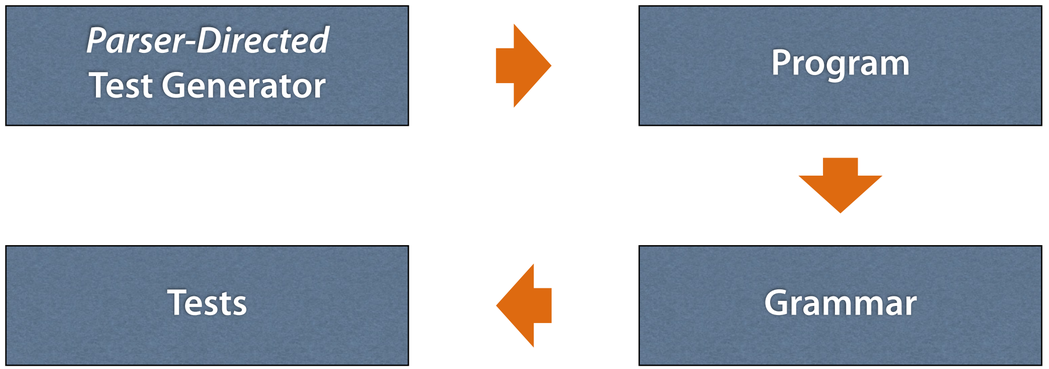

K. Jamrozik


M. Mera



Demo

Parser-Directed Testing



@AndreasZeller

Learning Grammars

```
http://user:password@www.google.com:80/command?foo=bar&lorem=ipsum#fragment
http://www.guardian.co.uk/sports/worldcup#results
ftp://bob:12345@ftp.example.com/oss/debian7.iso
```

```
URL ::= PROTOCOL '://' AUTHORITY PATH ['?' QUERY] ['#' REF]
AUTHORITY ::= [USERINFO '@'] HOST [':' PORT]
PROTOCOL ::= 'http' | 'ftp'
USERINFO ::= /[a-z]+:[a-z]+/
HOST ::= /[a-z.]+/
PORT ::= '80'
PATH ::= /\/[a-z0-9.\/]*/
QUERY ::= 'foo=bar&lorem=ipsum'
REF ::= /[a-z]+/
```

Höschele, Zeller: "Mining Input Grammars from Dynamic Taints", ASE 2016

@AndreasZeller

Test Generation Compared

AFL `.....`

Low coverage, few valid inputs

KLEE `nullÿÿÿÿÿÿÿÿÿÿÿÿÿÿÿÿÿÿÿÿÿÿÿÿÿÿÿÿÿÿ`

Top coverage, but flat inputs

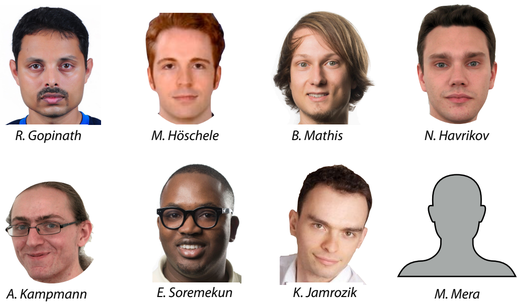
Pygmalion

```
[false ,[{ "o":{ , "$dYPrlj@?BR":
397  [+ ]"S|+|4GzCW(C":-94}} ],
[false,null]]
```

Top coverage, deep structure, control

Challenges

- **Implicit information flow**
  generated scanners and parsers
- **Context-sensitive features**
  binary formats, identifiers
- **Scale and Applicability**
  port Pygmalion to C (this Fall)



https://github.com/vrthra/pygmalion

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