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Experience: Model-Based, Feedback-Driven, Greybox Web Fuzzing with BackREST

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Fuzzing or fuzz testing is an automated software testing technique that involves providing invalid, unexpected, or random data as inputs to a computer program.

Wikipedia

Fuzzing Exercises Available Functionality

Fuzzers don't care about the ***intended*** functionality of a program.

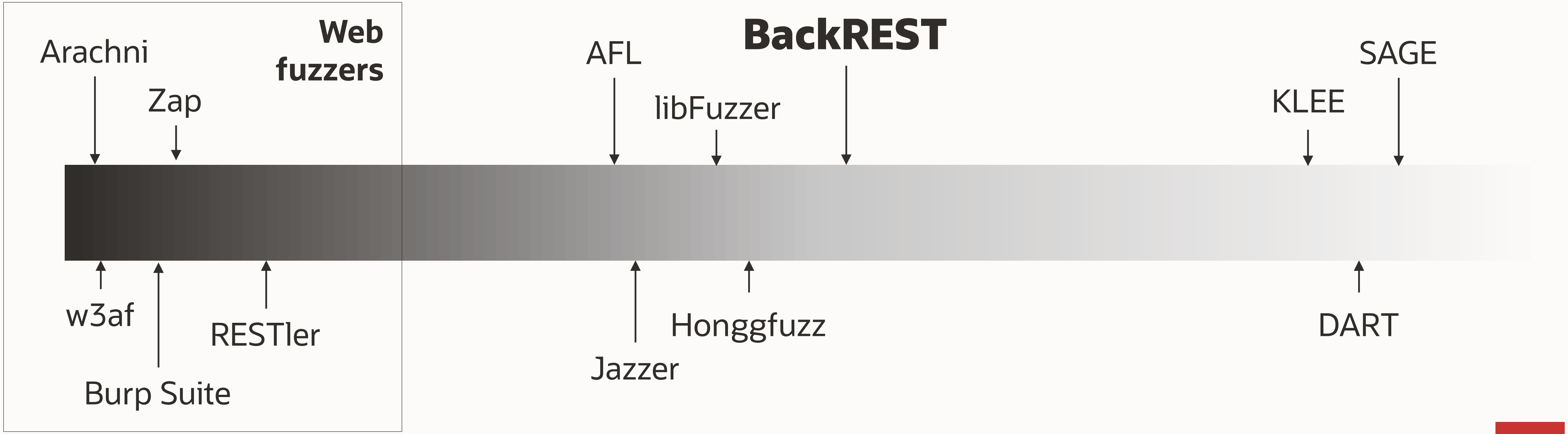
They find issues by exploring the space of ***available*** functionality.

Photo by Alexander Dummer: https://unsplash.com/photos/x4jRmkuDImo

Shades of Fuzzing

Fuzzers come in 3 shades: **black, grey,** and **white**

1. Blackbox fuzzers are completely program-agnostic.
2. Greybox fuzzers use limited program feedback (e.g. coverage, taint) to guide their search.
3. Whitebox fuzzers have complete access to the program's code.

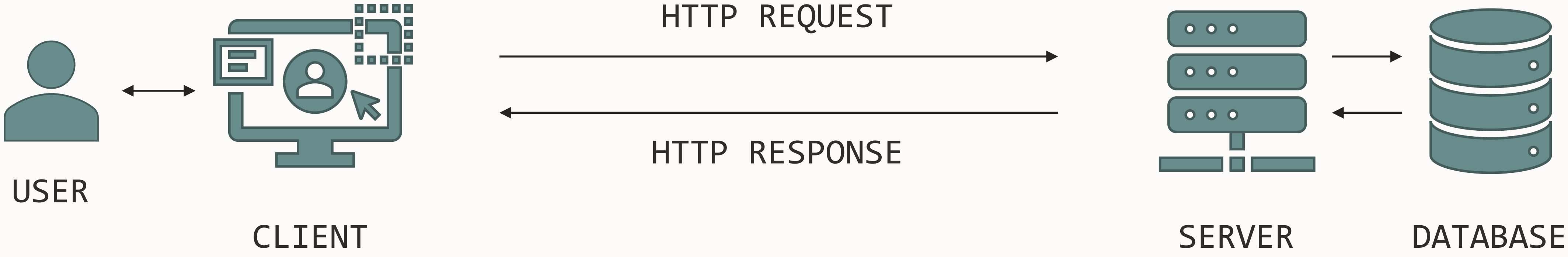


Model-Based Fuzzing

Model-Based Fuzzing of Web Applications

The client is the gateway to the server

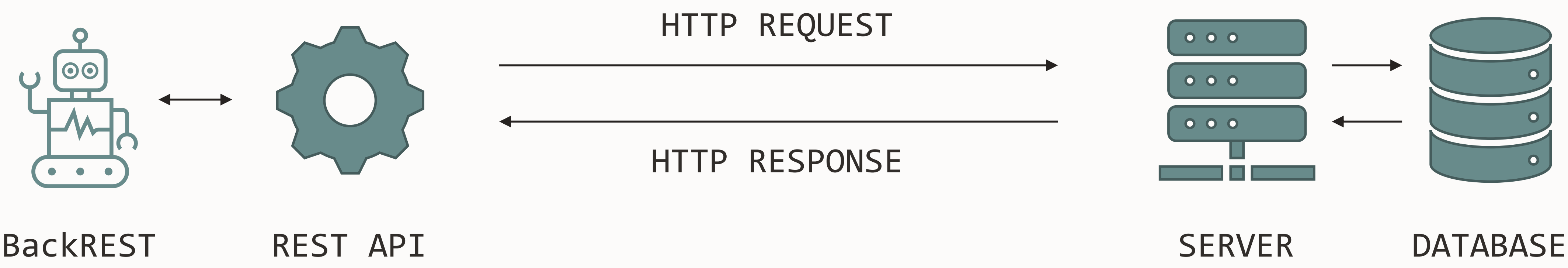
- The server is our fuzzing target because it is where critical operations are happening.
- Need to access the server *indirectly* through the client.
  - Random requests to the server will likely fail early sanity checks (e.g. parameters, types, headers, etc.)
  - Fuzzing the server through the client doesn’t scale.



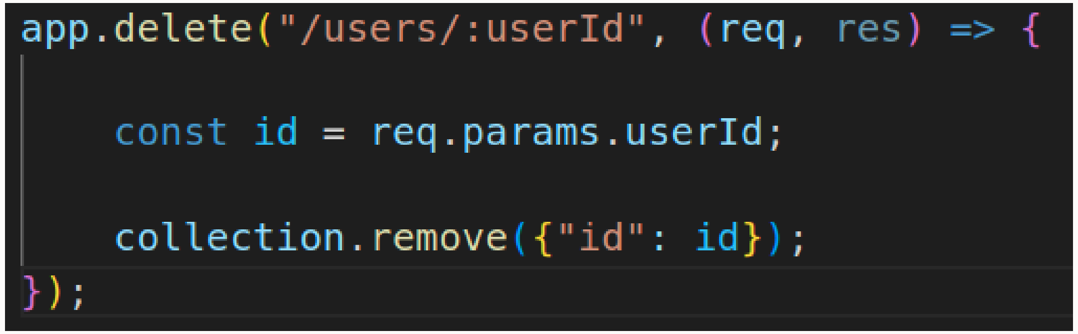
Model-Based Fuzzing of Web Applications

Abstracting away the client to fuzz the server

- Client-server interactions in modern applications typically adopt a REST-like format.
  - Interactions are defined and encapsulated unsing standard HTTP verbs, URLs, and request parameters.
- For fuzzing purposes, clients can be abstracted away as REST API models.



Inferring REST API Models



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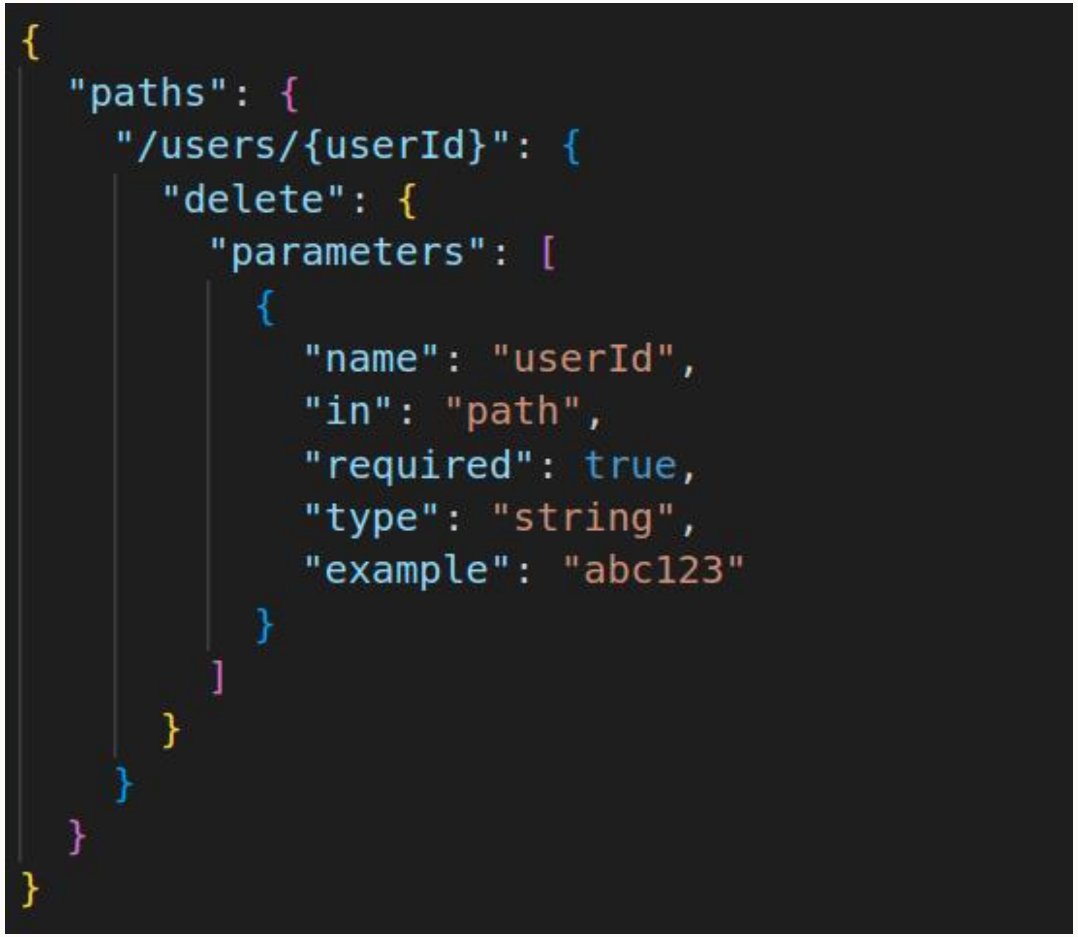

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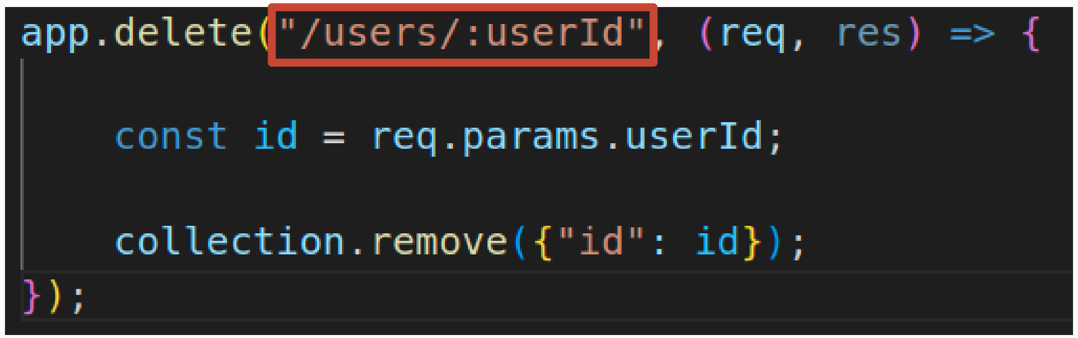

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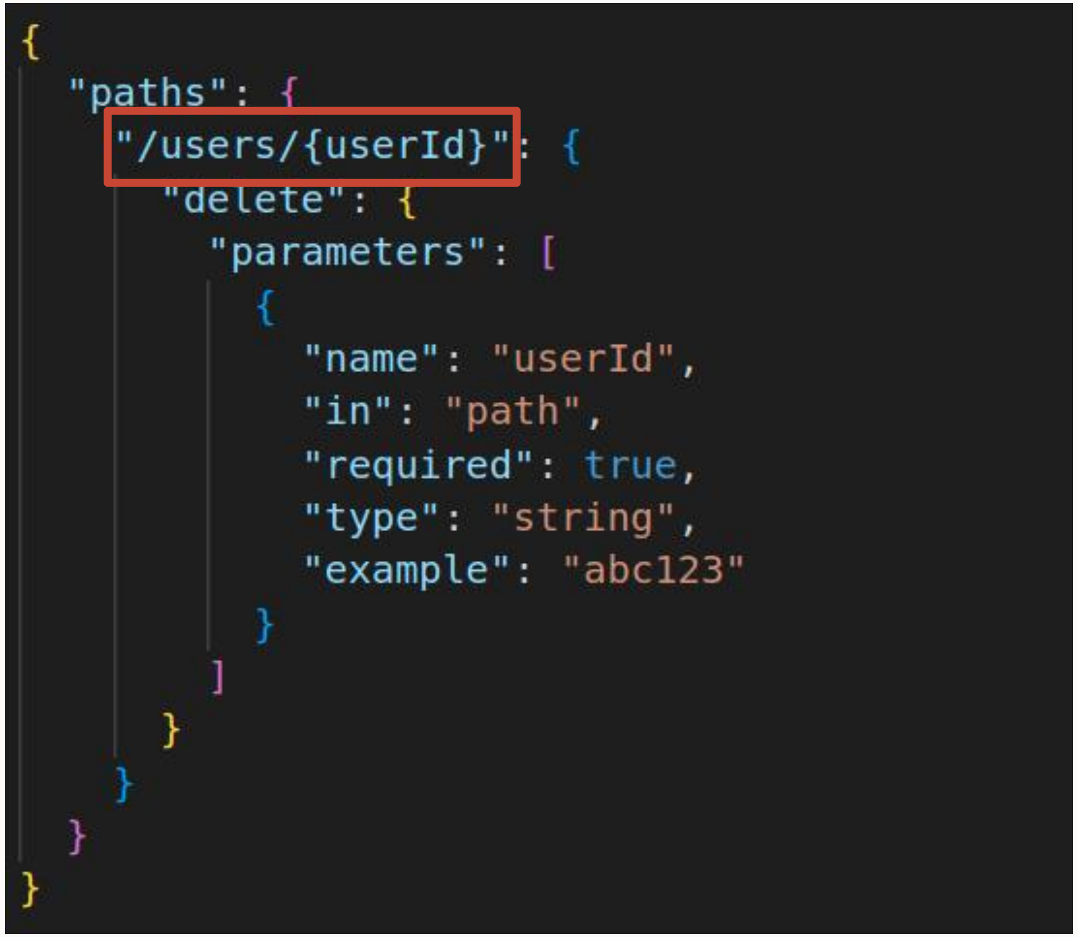

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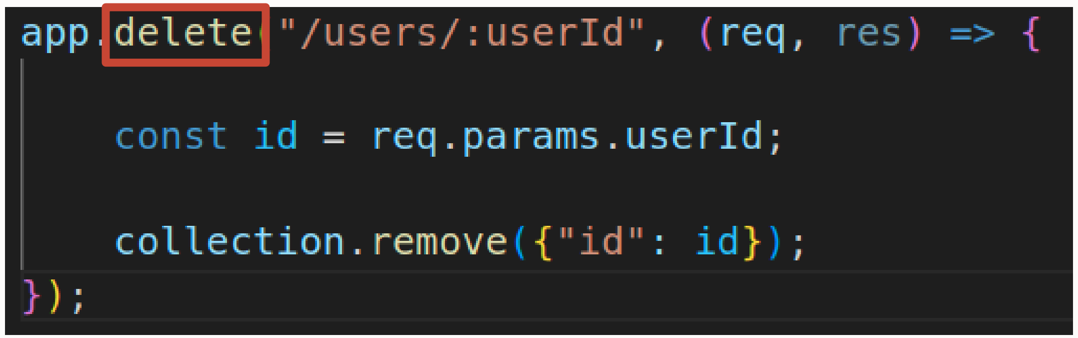

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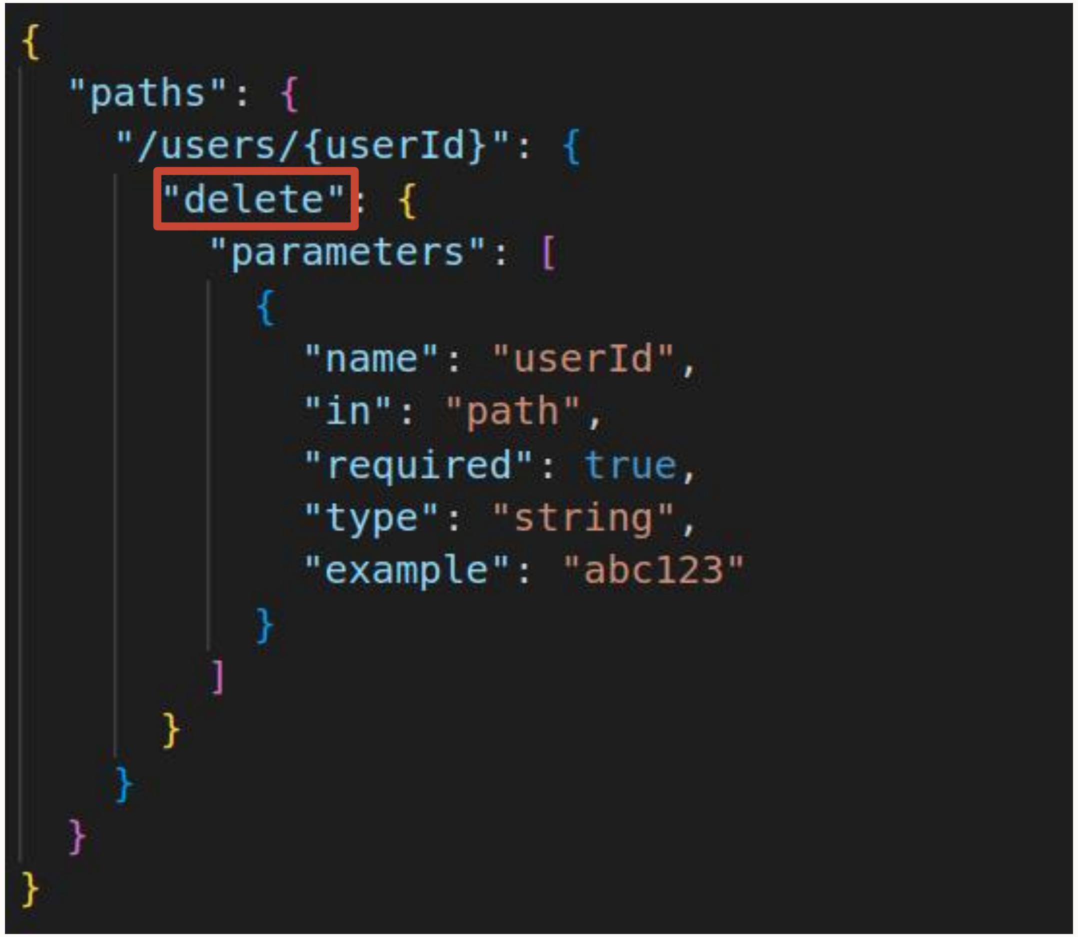

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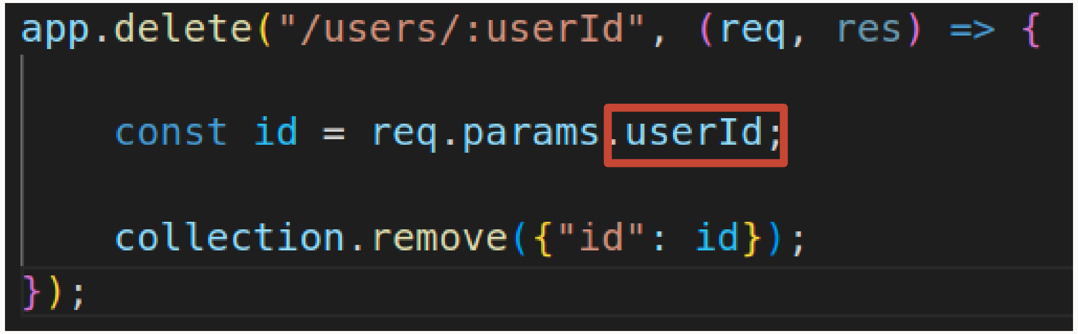

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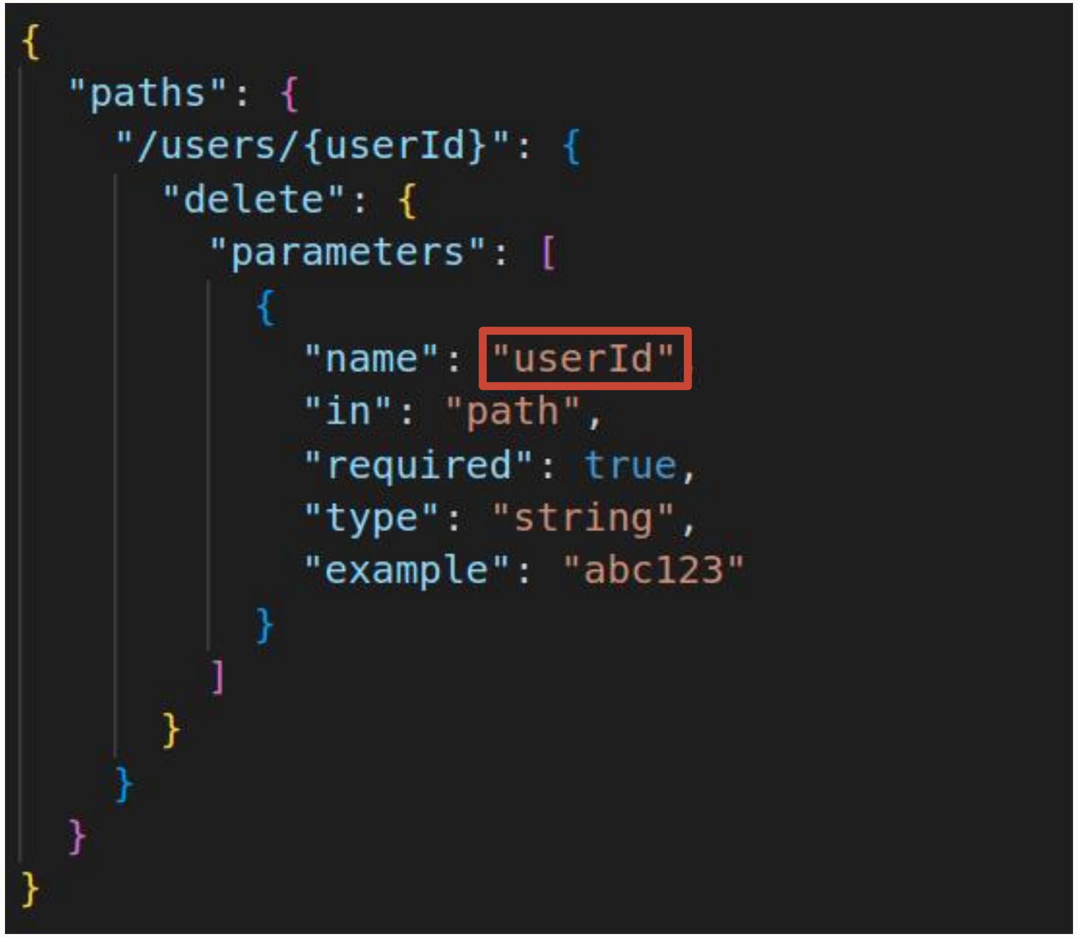

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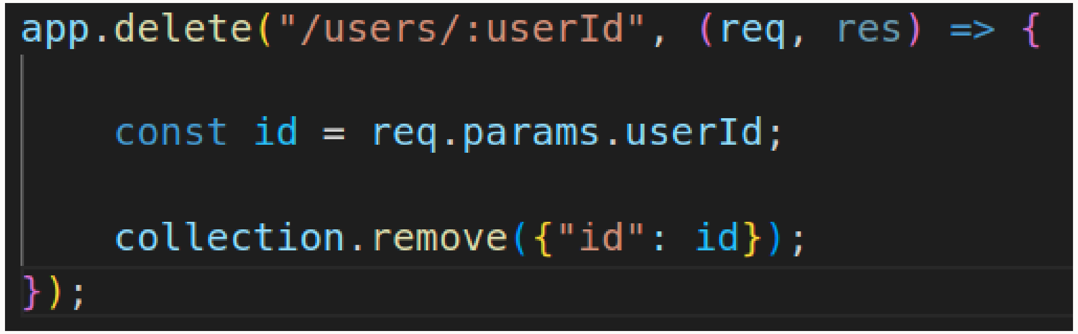

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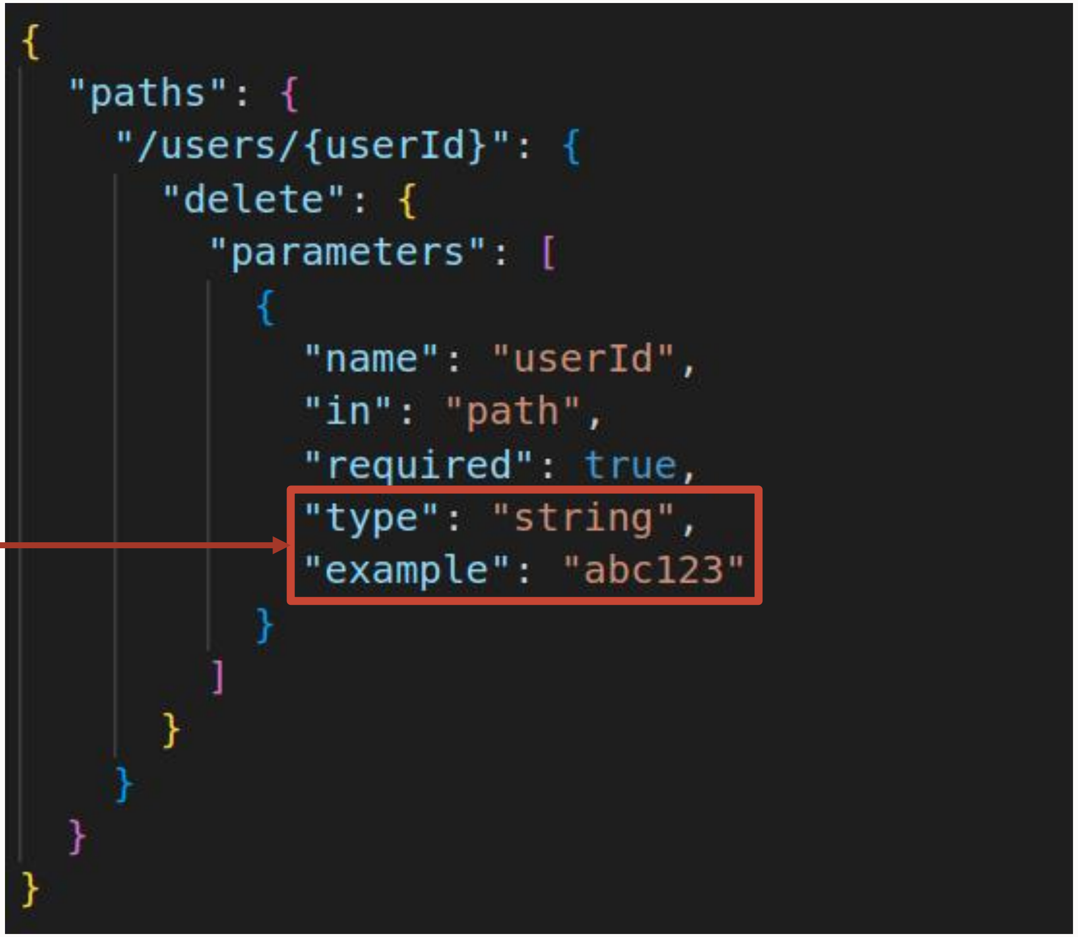
Inferred through:

1. State-aware crawling
2. Static type inference



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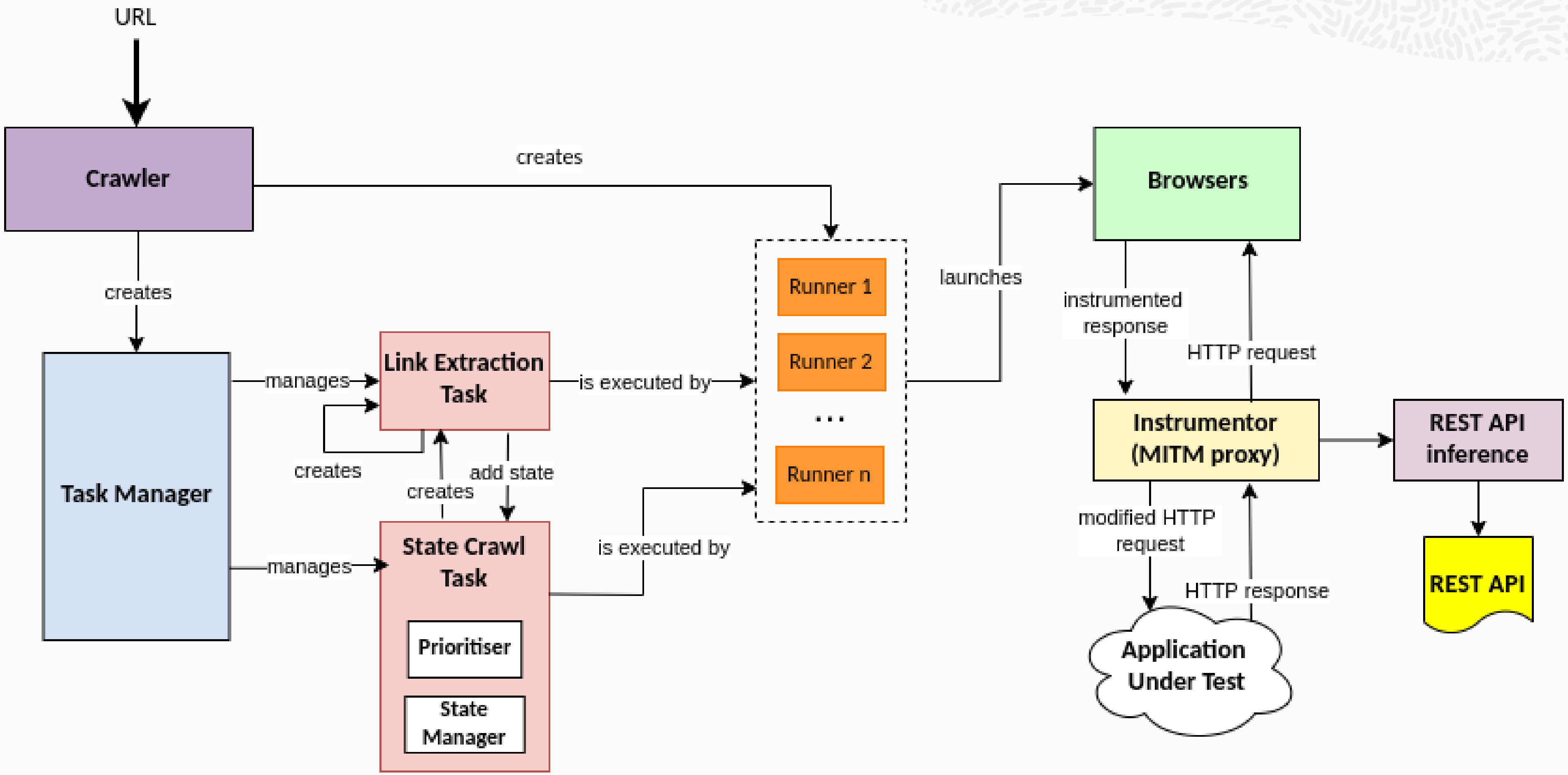
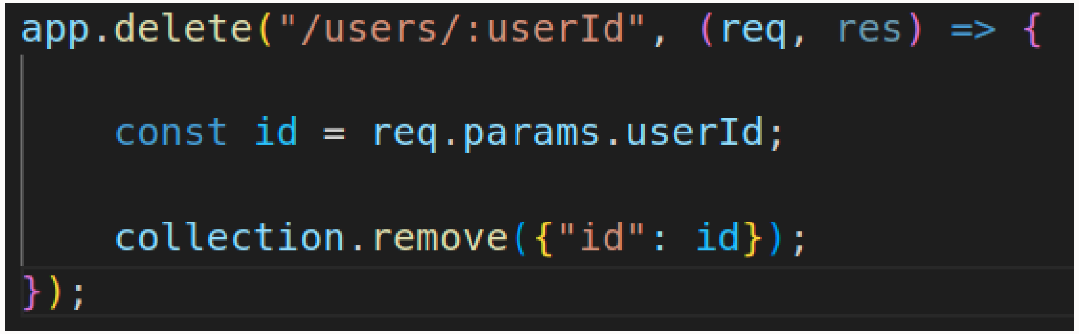
Inferring REST APIs With Prioritised State-Aware Crawling



Gelato: Feedback-driven and Guided Security Analysis of Client-side Web Applications, Behnaz Hassanshahi, Hyunjun Lee, Padmanabhan Krishnan, SANER 2022 (to appear)

Augmenting Crawled APIs With Static Type Inference



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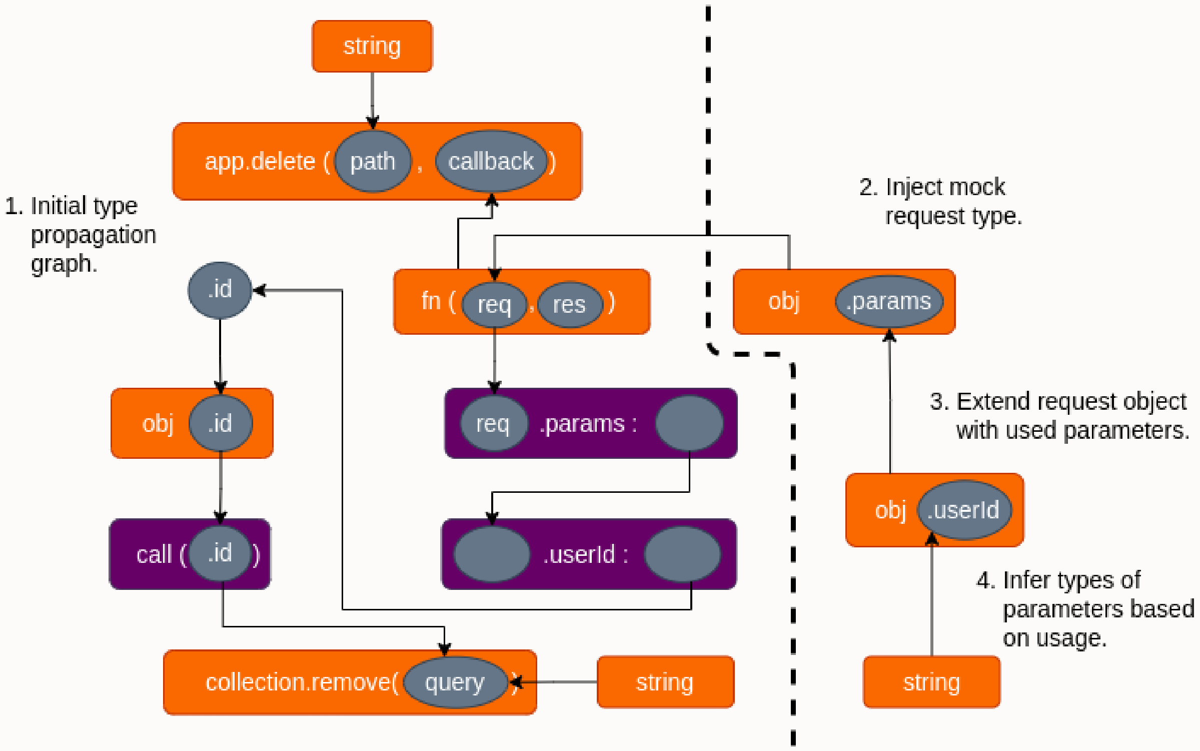


1. Initial type propagation graph.

2. Inject mock request type.

3. Extend request object with used parameters.

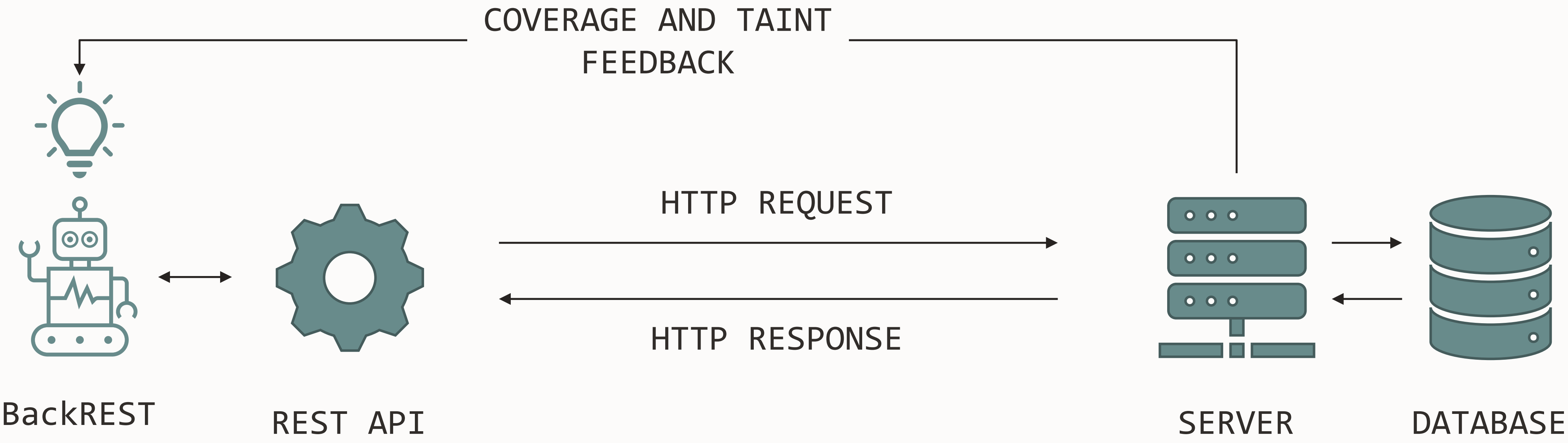
4. Infer types of parameters based on usage.

Feedback-Driven Fuzzing

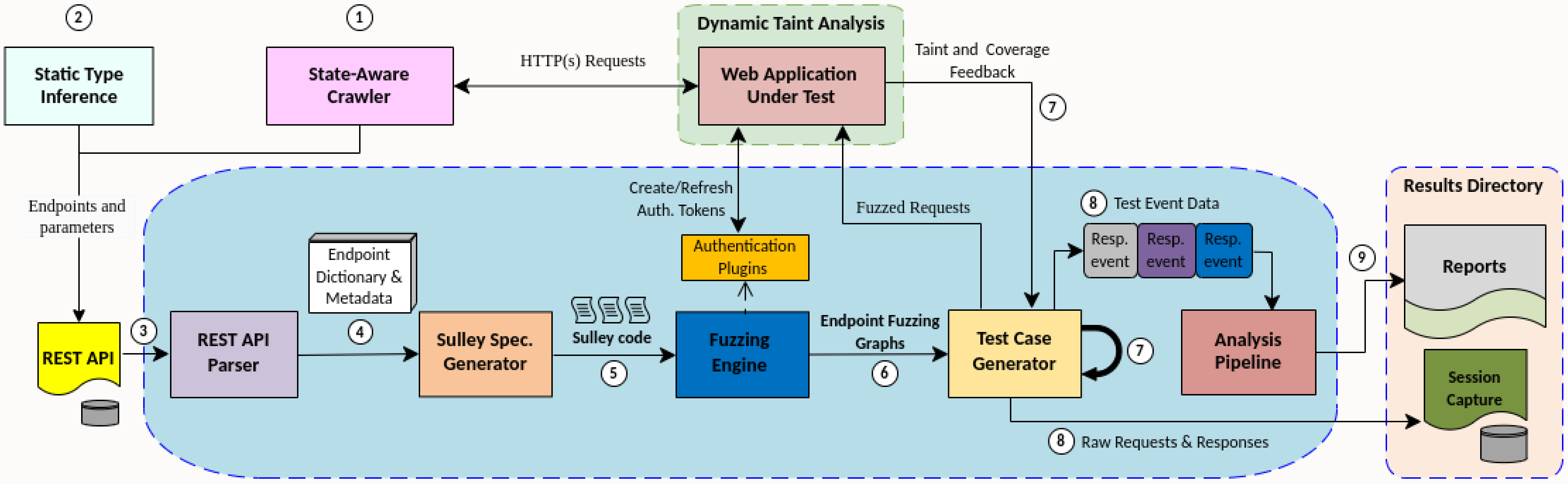
Feedback-Driven Fuzzing of Web Applications

Adding coverage and taint feedback

- A REST API model allows for efficient **blackbox** fuzzing.
- Adding coverage and taint feedback brings BackREST into **greybox** fuzzing territory.



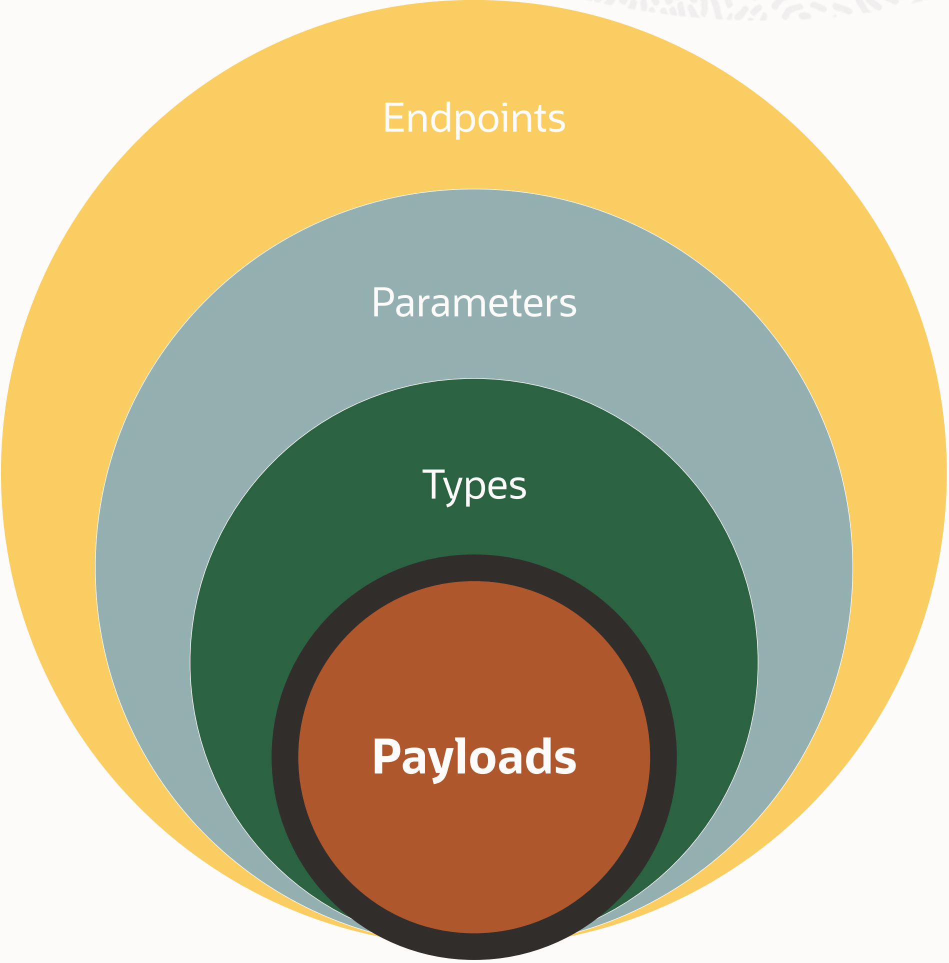
BackREST Architecture



Coverage Feedback To Filter Payloads

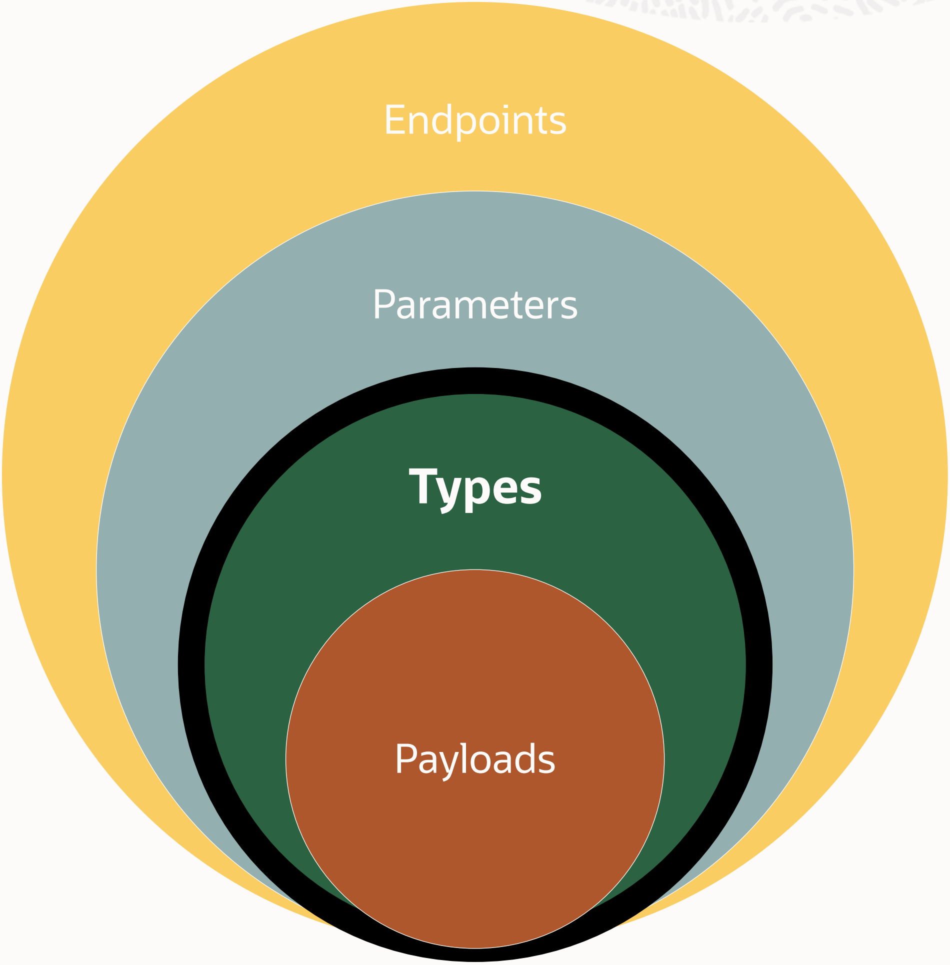
- Coverage feedback helps identify code that has not been thoroughly exercised and more likely to contain bugs.

- BackREST uses coverage to *skip* inputs from its payload dictionary.
  - After *T* payloads of a given type (e.g. SQL, JWT, string, numeric) that did not increase coverage, skip to next type.



Taint Feedback To Filter Types

- Taint feedback helps identify input values reaching key program locations
- BackREST uses taint inference[1] to identify the *type* of payload that will most likely trigger vulnerabilities.
  - E.g. inputs reaching an SQL operation should be sent malformed or malicious SQL fragments.



[1] **Affogato: Runtime Detection of Injection Attacks for Node.js**, François Gauthier, Behnaz Hassanshahi, and Alexander Jordan, SOAP 2018

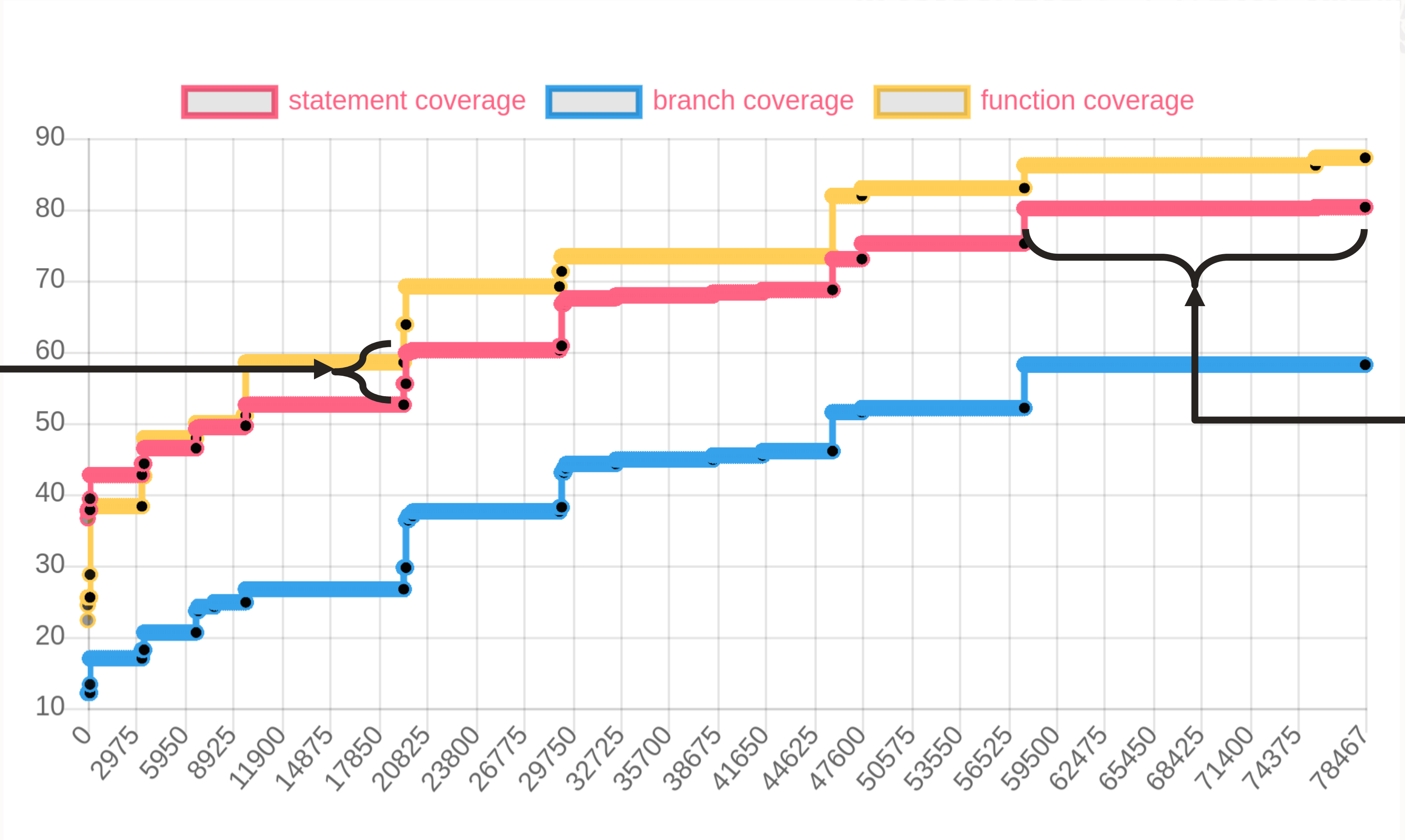
Results

Benchmark Applications and Inferred APIs

Application	Description	Version	SLOC	Files	Entry points*	Request parameters*
Nodegoat	Educational	1.3.0	970 450	12 180	19 (0)	28 (0)
Keystone	CMS	4.0.0	1 393 144	13 891	20 (0)	69 (46)
Apostrophe	CMS	2.0.0	774 203	5 701	184 (0)	633 (531)
Juice-shop	Educational	8.3.0	725 101	7 449	69 (0)	71 (64)
Mongo-express	DB manager	0.51.0	646 403	7 378	29 (0)	96 (49)

* Number of statically inferred values in parenthesis

Coverage Increases When BackREST Switches Endpoints



Fuzzing a new endpoint

Cycling through payloads

Impact of Coverage and Taint Feedback Loops on Total Coverage and Runtime

Application	Coverage (%)			Time (hh:mm:ss)		
	Baseline	Coverage	Cov. & Taint	Baseline	Coverage	Cov. & Taint
Nodegoat	**80.31**	78.54	75.59	0:42:39	0:06:07	**0:05:44**
Keystone	**48.31**	48.05	45.43	5:46:29	0:49:25	**0:13:23**
Apostrophe	–	**48.40**	45.52	–	11:11:42	**6:17:34**
Juice-shop	74.73	**76.34**	75.85	12:48:15	1:10:31	**1:08:26**
Mongo-express	**69.62**	69.57	66.59	2:21:49	0:16:07	**0:11:07**

Impact of Coverage and Taint Feedback on Vulnerability Reports

Baseline (B), Coverage feedback (C), Coverage & Taint feedback (CT)

Application	(No)SQLi			Cmd injection			XSS			DoS		
	B	C	CT	B	C	CT	B	C	CT	B	C	CT
Nodegoat	0	0	**3**	0	0	**3**	**5**	5	5	**0**	0	0
Keystone	0	0	**0**	0	0	**0**	**1**	1	0	**0**	0	0
Apostrophe	0	0	**0**	0	0	**0**	**1**	1	1	**2**	1	1
Juice-shop	1	1	**2**	0	0	**1**	**4**	1	1	**1**	0	0
Mongo-express	0	0	**5**	0	0	**2**	**0**	0	0	**3**	3	3
Total	1	1	**10**	0	0	**6**	**11**	8	7	**6**	4	4

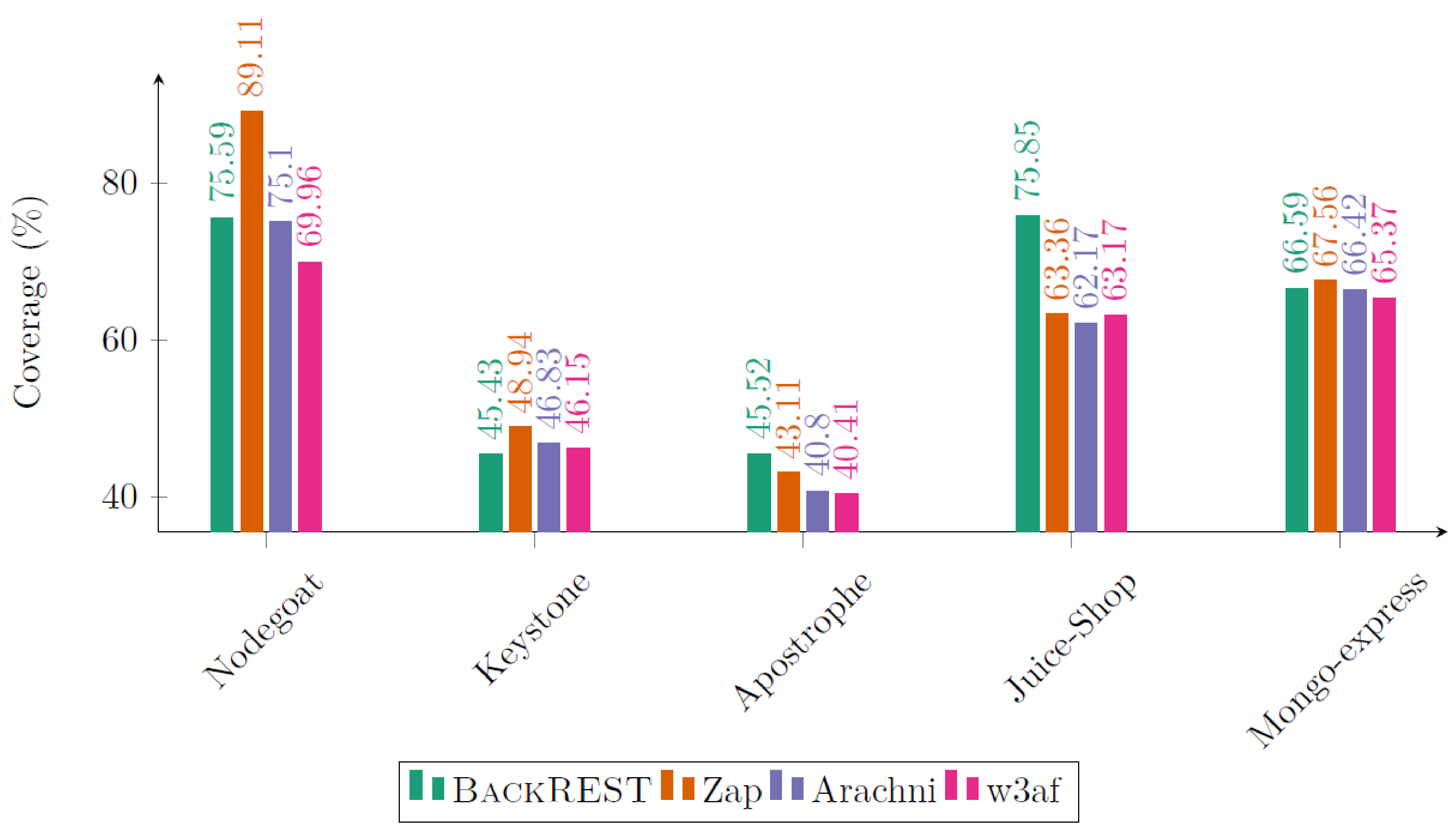
A Note On Server-Side State Modelling

- RESTler[1] is the first study to investigate stateful server-side fuzzing of web services.
  - Authors have found a positive correlation between stateful fuzzing and increases in coverage.
  - We have not observed a similar effect on our benchmark applications.

- We also attempted to model server-side state by inferring dependencies between endpoints.
  - This did not improve coverage for all but the Mongo-express application.
  - In this case, the dependencies were intuitive (e.g. insert a document before deleting it) and easily configured manually.

[1] **RESTler: Stateful REST API Fuzzing**, Atlidakis, Vaggelis, Patrice Godefroid, and Marina Polishchuk. ICSE 2019.

BackREST Coverage vs. State-Of-The-Art



BackREST 0-days vs. State-Of-The-Art

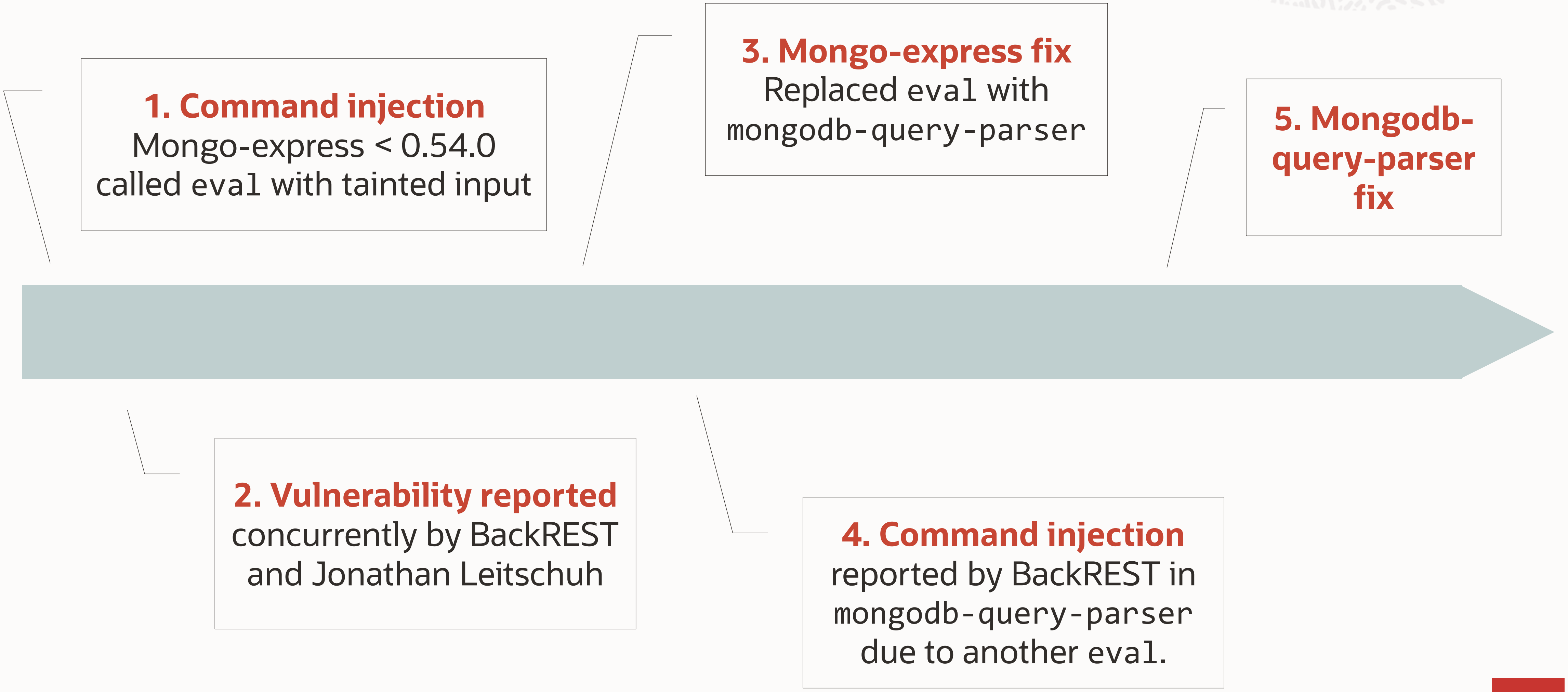
Codebase	Vulnerability	Found by	Taint only	Severity
MarsDB	Command injection	BackREST	✓	Critical
Sequelize	Denial-of-Service	BackREST		Moderate
Apostrophe	Denial-of-Service	BackREST		–
Apostrophe	Denial-of-Service	BackREST		Low
Mongo-express	Command injection	BackREST	✓	Critical
Mongo-express	Denial-of-Service	BackREST, Zap, Arachni, w3af		Medium
Mongodb-query-parser	Command injection	BackREST	✓	Critical
MongoDB	Denial-of-Service	BackREST, Zap		High

MongoDB: **1 671 653** weekly downloads

Sequelize: **648 745** weekly downloads

Case Study: Mongo-express and Mongodb-query-parser

Taint feedback detected two command injections



1. Command injection
Mongo-express < 0.54.0
called `eval` with tainted input

2. Vulnerability reported
concurrently by BackREST
and Jonathan Leitschuh

3. Mongo-express fix
Replaced `eval` with
`mongodb-query-parser`

4. Command injection
reported by BackREST in
`mongodb-query-parser`
due to another `eval`.

5. Mongodb-query-parser fix

Conclusions

Why Does BackREST Detect More 0-Days?

- Total coverage does not significantly differ between BackREST and state-of-the-art ✗
- State-modelling hasn’t made a significant impact on our benchmarks ✗
- Taint feedback is unique to BackREST and allows to
  - Select the payloads that will most likely trigger vulnerabilities ✓
  - Detect vulnerabilities that are *invisible* to blackbox fuzzers ✓
- Payload dictionaries encapsulate expert knowledge about web vulnerabilities ✓
- Uncovering more complete API models through state-aware crawling helps trigger more vulnerabilities ✓

Conclusion

- BackREST is a model-based, coverage- and taint-driven greybox fuzzer that:
  - Guides a state-aware crawler to infer REST-like APIs
  - Uses coverage feedback to improve performance.
  - Uses taint feedback to detect vulnerabilities and guide payload selection.

- BackREST:
  - Achieved speedups ranging from 7.4× to 25.9×.
  - Consistently detected more (No)SQLi, command injection, and XSS vulnerabilities than three state-of-the-art web fuzzers.
  - Detected six 0-days that were missed by all other fuzzers.

Our feedback loops are simple enough to be applied to existing black-box web application fuzzers.

Thank you

François Gauthier

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