Zac Hatfield-Dodds Australian National University Canberra, Australia zac.hatfield.dodds@anu.edu.au

ABSTRACT

Fuzzing—whether generating or mutating inputs—has found many bugs and security vulnerabilities in a wide range of domains. Stateful and highly structured web APIs present significant challenges to traditional fuzzing techniques, as execution feedback is usually limited to a response code instead of code coverage and vulnerabilities of interest include silent information-disclosure in addition to explicit errors.

Our tool, Schemathesis, derives structure- and semantics-aware fuzzers from web API schemas in the OpenAPI or GraphQL formats, using property-based testing tools [23]. Derived fuzzers can be incorporated into unit-test suites or run directly, with or without end-user customisation of data generation and semantic checks.

We construct the most comprehensive evaluation of web API fuzzers to date, running eight fuzzers against sixteen real-world open source web services. OpenAPI schemas found in the wild have a long tail of rare features and complex structures. Of the tools we evaluated, Schemathesis was the only one to handle more than two-thirds of our target services without a fatal internal error. Schemathesis finds $1.4 \times$ to $4.5 \times$ more unique defects than the respectively second-best fuzzer for each target, and is the *only* fuzzer to find defects in four targets.

1 INTRODUCTION

Much modern software communicates over the internet, and each service therefore defines some kind of web API - often via a REST [9] or more recently GraphQL [10] architecture. Many services also provide machine-readable schemas or specifications which describe their input and output contracts and their semantics within the REST or GraphQL architecture.

Such API schemas can be used to derive a *service-specific* fuzzer that can use the known structure of valid inputs and sequences of actions to focus effort on interesting parts of an otherwise intractably large search space. Derived fuzzers can also check for otherwise silent semantic errors such as non-conforming responses, missing headers, or silent information-disclosure vulnerabilities, based on standard schema and HTTP semantics.

In practice OpenAPI [16] or GraphQL schemas are often *un-sound*, permitting inputs or actions not handled by the service. This may be due to errors in the schema or the service implementation, because working with sound schemas is uneconomical, or because of application-level constraints—such as database constraints, order of event timestamps, relations between endpoints, etc.—which cannot be expressed in the schema. We therefore see an ongoing role for human judgement in customising automatically derived fuzzers, analysing failures, detecting over-restrictive schemas, and hand-coding additional or more precise tests.

Dmitry Dygalo schemathesis.io Prague, Czech Republic dmitry@dygalo.dev

The main contributions of this paper are to:

- describe Schemathesis, a property-based testing library to automatically derive customisable web API fuzzers from OpenAPI or GraphQL schemas;
- demonstrate that Schemathesis discovers more defects and handles more real schemas than previous tools; and
- provide a large evaluation suite of real web services, schemas, and fuzzers as reusable containers for use in future research.

1.1 Property-based testing

Property-based testing (PBT) originated with the Haskell library QuickCheck [6], which emphasised testing algebraic properties of functions by generating many random inputs to a test function. PBT generally differs from fuzzing more in workflow and the affordances of tooling than fundamental concept (typically focussing on highly-structured and always-valid data, along with integrated shrinking). The definitive PBT library for Python is Hypothesis [23], with an estimated five hundred thousand users and dozens of third-party extensions. Hypothesis is explicitly designed as a library of tools to construct fuzzable tests—which can detect errors that direct fuzzing would not—and a non-user-visible bytestring-oriented fuzzing backend for them¹.

This abstraction has been very successful. The Hypothesis backend includes integrated shrinking and error-deduplication [24], targeted property-based testing [2, 21, 22], swarm testing [14], and optionally coverage-guided fuzzing. Structured inputs are defined using parser-combinators ('strategies'²); and only the primitives supplied by Hypothesis have any knowledge of the backend. Such separation of concerns has made it practical for third-party developers to write functions which take some formal description of a set of values—examples include type annotations, regular or contextfree grammars, validation callbacks, and JSONschema or GraphQL schemas—and return a strategy which generates examples.

Several projects have chosen to fuzz web APIs with Hypothesis because of the ease and effectiveness of sophisticated input generation, including swagger-fuzzer [8] swagger-conformance [28], Yelp's [3]-inspired fuzz-lightyear [20] for insecure direct object reference vulnerabilities, and finally Schemathesis itself.

1.2 Web API standards

The REST architecture was described in 2000 [9], with the Swagger/OpenAPI schema format subsequently invented in 2011. While OpenAPI is far from the *only* specification format for REST APIs, it is by far the most common. Thanks to the shared architecture

¹https://hypothesis.works/articles/what-is-property-based-testing/

²Most PBT libraries call their description of possible values "generators". Because generators are a builtin type in Python, Hypothesis instead names them "strategies".

and semantics, schemas in other formats³ can be quickly and often automatically translated into the OpenAPI format.

The GraphQL architecture and schema format were designed together at Facebook from 2012, and released in 2015 [10]. Motivated by performance considerations, GraphQL uses a fundamentally different data and request model to RESTful APIs, but the same property-based testing techniques are applicable to each.

While system state and highly structured inputs make fuzzing challenging, OpenAPI or GraphQL schemas make it practical to exploit this structure. Combined with HTTP's clear client/service interface and common properties arising from the standardised semantics, schema-based fuzzing has an enduring attraction.

1.3 Standards imply semantic properties

In addition to input structure, schemas constrain application semantics. Wherever standards documents impose requirements on implementations, semantics-aware fuzzers can treat "requirements not violated" as a testable property—including RFC 7231's universal and relatively simple constraints on HTTP services, such as:

- 200 OK responses must have a non-empty body
- 204 No Content and 205 Reset Content responses must have an empty body
- 302 Found responses to a POST request must allow the subsequent response to use either POST or GET methods
- 405 Method Not Allowed responses must have an Allow header listing supported methods
- 500 Internal Server Error responses are always errors
- GET fails after successful DELETE (use-after-free rule) [4]
- GET fails after unsuccessful POST (resource-leak rule) [4]

In addition to input structure, API schemas document the expected content and structure of API responses and the relationship between endpoints. OpenAPI schemas extend HTTP semantics to include further schema-specific testable properties, including:

- Response has undeclared status code
- Response has undeclared content-type
- Response body matches the schema
- Response has wrong headers or missing required headers⁴
- Non-conforming requests are rejected (negative testing) [30]
- No information leaks from unauthorised requests [4, 20]

Information disclosure vulnerabilities such as insecure direct object references can be detected by making two sequences of requests. The "victim" sequence creates and then retrieves a private resource; then the "attacker" creates their own resource but attempts to retrieve the *victim* resource⁵. While in principle this could be done purely on the basis of OpenAPI's security and securitySchemes keywords, it is typically customised on a per-service basis.

Finally, we might wish to check for performance problems which could be exploited to mount a denial-of-service attack. These checks are typically disabled by default, because failure consists of exceeding a subjective and configurable threshold rather than a binary success/failure state:

- Slow responses, i.e. time to first (or last) byte of response
- Request amplification measured in number of requests, or total response size, or amplification ratio

Hypothesis' support for *targeted* property-based testing [21, 22] is particularly valuable for threshold tests [15], and targets may be reported either by Schemathesis derived fuzzers, or in user-supplied hooks. Anecdotally, we have found that multi-objective optimisation—e.g., targeting response size *and* amplification ratio—is remarkably effective.

1.4 Prior art in schema-based web API fuzzing

Property-based testing provides the most common framing for schema-based web API fuzzing, with early work such as [11, 13] focused on derived input generators (structure) and others [5, 19, 26], additionally deriving test oracles (semantics).

QuickREST [17] aims to free up human effort by automating API exploration with Clojure.spec. Their tool tests for response conformance and known HTTP status codes, with further properties specifiable by the user.

RESTTESTGEN [30] proposes heuristics to statically recover an 'operation dependency graph' which describes the relationship between response data and subsequent request to other endpoints and enables far more efficient testing with sequences of requests. They also comment on the importance of testing error handling, i.e. negative testing, using the property that nonconforming requests should receive HTTP 4xx instead of 2xx responses.

RESTler [3, 4] is a security testing tool in the tradition of greybox fuzzing, which infers dependencies between request types, generates sequences of requests satisfying those dependencies, and learns to predict sequence validity based on the responses to these test sequences. Their evaluation finds that all these features are required for effective testing of web APIs.

EvoMaster [1] frames the problem as one of Evosuite-style [12] *test-case generation*, using JVM instrumentation to evolve a high-coverage set of test cases. A blackbox mode supports non-JVM services, albeit with reduced performance. [7] also generates JUnit test suites, based on a model of schema and test semantics rather than execution feedback.

We are unaware of prior work on GraphQL schema-based testing beyond Karlsson et al [18], who demonstrate a proof-of-concept property-based testing tool and a method for evaluating the schema coverage achieved.

To summarise, an ideal feature set might include:

- Deriving input generators and test oracles from API schemas, for both valid and invalid actions and data
- Some kind of feedback to enable search-based testing, ideally available in the blackbox HTTP-only setting
- A way to make sequences of requests, and exploit the data in responses to make further semantically-meaningful requests
- A way to learn or discover relationships between endpoints for more efficient sequence-of-requests testing⁶

³such as RAML, WSDL, or API Blueprint

⁴Schemathesis seems to be the only fuzzer to check if required headers are missing.
⁵A property relating multiple input-output pairs is known as a *metamorphic relation*.

^[25] propose twenty-two such relations relevant to web application security, which are often easier to check than one-shot properties. See also §2.1.

⁶e.g. [30]'s operation dependency graph. Schemathesis relies on OpenAPI 3.0 "links" for this purpose, which are often omitted from schemas despite their value to tools.

2 SCHEMATHESIS

Schemathesis is a tool for automated blackbox or whitebox randomised testing of web APIs, deriving structure- and semanticsaware fuzzers from OpenAPI or GraphQL schemas.

Derived fuzzers use Hypothesis' [23] mature and sophisticated toolkit for creating test inputs—including hybrid random generation, feedback-guided structured mutation, and explicit examples plus a variety of test functions and oracles for both individual endpoints and sequences of requests to multiple endpoints. Both data-generation and test oracles can easily be customised by the end user.

Schemathesis can be used via a command-line interface or a Python API, in either case to fuzz services written in any language via HTTP. If the service under test is *also* written in Python, Schemathesis can communicate in-process using the WSGI and ASGI⁷ conventions rather than over the network. This is often considerably faster, and supports coverage-guided fuzzing with tools such as HypoFuzz⁸, or Atheris⁹ via Hypothesis' fuzz_one_input interface.

With thousands of downloads every week, Schemathesis is a thriving open-source project. It has already been widely adopted, integrated into Microsoft's REST API Fuzz Testing project¹⁰, training from Red Hat¹¹, and is the basis for the IBM Service Validator [29].

2.1 Single requests or sequences?

Internally, Schemathesis distinguishes single-request tests from those which make a sequence of requests to multiple endpoints, using the data from past responses. In 2020, we converted the latter from special-purpose logic to a thin wrapper around Hypothesis' RuleBasedStateMachine, a generic system defined in terms of transition rules between states¹². Comparing these implementations gives us some basis to discuss the advantages of property-based testing.

The new state-machine tests tend to report *fewer* bugs per run, because they test the whole system rather than individual endpoints, but are correspondingly faster to run. The difference is fundamentally a property-based testing vs. a fuzzing workflow: the new style is designed for interactive use in a run-fix-rerun cycle, rather than long-running testing campaigns.

We believe that the heuristics built into Hypothesis, including swarm testing [14], make a substantial contribution to Schemathesis' performance. While such techniques can be added to standalone tools, our experience is that the implementation effort is best shared and tuned in dedicated property-based testing libraries which benefit from synergies between techniques. ¹³

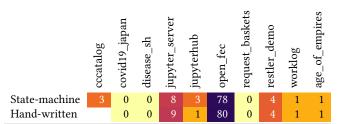


Table 1: Switching to Hypothesis' state-machines made Schemathesis considerably faster and improved the quality of reported failures. In this evaluation on schemas we augumented with OpenAPI 'links', state-machine tests detected a similar number of defects the old hand-written approach. See Section 3.2 for details.

2.2 Hypothesis-Jsonschema

Schemathesis converts schemas into data generators using the hypothesis-jsonschema¹⁴ library, whose from_schema() function takes an arbitrary JSON Schema¹⁵ and returns a Hypothesis strategy to generate valid instances. JSONschema is something of a *lingua franca* for web related schemas; Swagger and OpenAPI use it directly, while others are easy to convert into JSONschemas. Simple schemas admit simple translations:

```
{"type": "integer", "minimum": 0, "maximum": 10}
-> st.integers(min_value=0, max_value=10)
```

while others, especially if they involve the oneOf or allOf¹⁶ combinators, defy easy or efficient translation. We therefore 'canonicalise' schemas by defining a suite of rewrite rules which preserve schema semantics while reducing the need for rejection sampling, and iterate them to a fixpoint. Consider for example:

```
{"type": "object", "allOf": [
    {"additionalProperties": false},
    {"properties": {"a": {"type": "string"}}},
]}
```

containing intersecting constraints - the value must be an object, must not contain any items if it is an object, and if the value is an object with key "a", the corresponding value must be a string. Our rewrite rules combine these constraints into a single schema:

{"additionalProperties": False,
 "properties": {"a": False},
 "type": "object",
 "maxProperties": 1}

and further simplify that schema into a minimal form:

{'type': 'object', 'maxProperties': 0}

Such nonlocal constraints are common in real-world schemas even before accounting for widespread use of the *ref* keyword. We therefore inline non-recursive references, merge overlapping subschemas, and canonicalise the results before converting the schema

⁷Web Server Gateway Interface and Asynchronous Server Gateway Interface ⁸https://hypofuzz.com/

⁹https://github.com/google/atheris

¹⁰https://github.com/microsoft/rest-api-fuzz-testing

¹¹https://appdev.consulting.redhat.com/tracks/contract-first/

¹²Similar to [5]'s use of QuiviQ state machines

 $^{^{13}}$ For example, Hypothesis is to our knowledge the only tool to support both swarm

testing and targeted property-based testing [14, 21, 22].

¹⁴https://pypi.org/project/hypothesis-jsonschema/

¹⁵https://json-schema.org/

¹⁶anyOf is trivially satisfied by taking the union of the generators for sub-schemas. oneOf admits a quadratically-large translation to allOf, not, and anyOf-e.g. oneOf: [a, b, ...] → anyOf: [{a, {not: {anyOf: [b, ...]}}}, ...]but linear-size rewrites and rejection sampling are usually much faster in practice.

Zac Hatfield-Dodds and Dmitry Dygalo

to a Hypothesis strategy, which makes hypothesis-jsonschema considerably faster than naïve translators such as Jsongen [13] with an otherwise similar design.

As well as generating valid inputs with no relation to ordinary production traffic, this logic gives us an elegant way to synthesise *subtly invalid examples* for 'negative testing' to check that nonconforming requests are rejected by the API: create a set of variant schemas, e.g. "an invalid instance of a valid type", and then use each of the variants to generate input:

```
schema = ...
gen_invalid = from_schema(
    {"type": schema["type"], "not": schema}
)
```

This generator will be as efficient as anything we could write by hand¹⁷, guaranteeing that instances are invalid with a minimum of rejection sampling. By contrast, RESTTESTGEN [30] generates data for negative testing by applying relatively crude mutations to valid instances.

2.3 Customising Schemathesis

One of Schemathesis' strengths is ease of customisation via our command-line interface or from Python. The four main ways to customise tests for a specific API are *hooks*, *checks*, *serialisers*, and *format strategies*.

Hooks. call user-defined functions to customise Schemathesis' behaviour at different steps of the testing process:

- Hooks such as before_process_path allow you change the API schema for certain endpoints, working around incompatibilities or changing the data that will be generated
- Hooks like before_generate_query allow you to replace Hypothesis strategies that are inferred from API schemas, for example by adding a filter to reject undesired test cases
- Network request hooks allow you to send additional custom test cases, or to adjust generated data before sending it to the application under test
- Custom targets, for e.g. performance tests as in §1.3

Checks. are custom test oracles, which allow verification of userdefined properties of responses received from the application under test. Because checks are decoupled from data generation, they can be run for both known-valid and known-invalid test cases.

Serialisers. Generated data must be serialised before transmission to to the application under test. Schemathesis supplies default serialisers for common media types such as application/json, multipart/form-data, and text/plain. Custom serialisers can overide these defaults, or add support for less common media types expected by the application.

Format strategies. Many Open API schemas use custom format keywords to describe the input data. For example, if the API under test consumes data that is expected to contain a payment card number, this might be expressed as:

```
{"type": "string", "format": "payment_card"}
```

```
<sup>17</sup>we designed comprehensive rewrite rules based on our knowledge of the spec, and
update or expand them when inefficiencies are reported, e.g. by Reviewer #2 (really!)
```

Category	Number	Should work?
Total OpenAPI directory endpoints	66,925	_
Schemathesis correctly handles	65,195	_
With unhandled recursive refs	1,254	yes
With Python-incompatible regex	170	opt
With too complex schemas	26	yes
With un-inlined remote refs	8	yes
With YAML parsing issues	168	no
With invalid enums	45	no
With path parameters including /	33	no
With logically unsatisfiable schemas	26	no

Table 2: OpenAPI Directory endpoints, with detailed breakdown of those Schemathesis does not handle.

The JSONschema specification requires implementations to ignore unknown format keys, so Schemathesis allows the user to supply a strategy that will be used to generate values for this format:

```
def luhn_ok(card_number: str) -> bool:
    """Validate check digit for the card number."""
schemathesis.register_string_format(
    "payment_card",
    st.from_regex(r"^4[0-9]{15}$").filter(luhn_ok)
)
```

2.4 The limits of specification support

hypothesis-jsonschema correctly, and almost always efficiently, handles every construct from draft-04 to draft-07 of the JSONschema specification except for recursive references. It's tested against every schema in the official JSONschema compatibility test suite, the hundreds of real-world schemas from schemastore.org, and fuzzed with a custom schema generator—to the point of finding bugs in Python's jsonschema validator library and omissions from the standard-compliance test suite.¹⁸

Schemathesis supports almost everything in the OpenAPI spec, covering the subset in common use and including user-defined extensions. Of the more than three thousand schemas in the OpenAPI directory, we successfully parse a higher proportion than are actually valid—and can generate data for some endpoints of many invalid schemas. Table 2 shows a detailed breakdown of the endpoints we do *not* support; aside from (some) recursive references, more endpoints are *invalid* than *unsupported*.

Schemathesis currently handles recursive references by unrolling and inlining the schema up to a reasonable depth. This is sufficient for more than 98% of endpoints in the OpenAPI directory; but also the most common reason we fail to generate data. We'd prefer to leverage property-based testing by expressing recursive schemas directly with Hypothesis' deferred() generator, but modifying hypothesis-jsonschema's rewrite rules to be reference-aware is a tricky engineering challenge—and unrolling works well enough that to date other features have always taken priority.

¹⁸See Julian/jsonschema/issues?q=author%3AZac-HD+label%3ABug and json-schema-org/JSON-Schema-Test-Suite/pulls?q=author%3AZac-HD

Issue	Description
django-rest-framework#7134 and #7448	Crash on SQLite integer overflow due to validator order
django-rest-framework-jwt#70	Internal server error when token is invalid unicode
tfranzel/drf-spectacular#186	Generated schema is too permissive
satellite-passes-api#2 and #4	Internal server errors on missing attribute, missing cache key
tournesol-backend#17	Checking HTTP status codes found "a lot of bugs"
OfficiumDivinum#4	Eleven failing tests with Schemathesis
python-restx/flask-restx#303	Non-matching X- fields filter out all results instead of no results
http-rs/async-h1#144	Numerous client-side failures, causes unclear
tiangolo/fastapi#240	Invalid schema (following wrong version of specification)
tiangolo/fastapi#3790	Nonconforming response when reporting validation errors
goadesign/goa#2840	Schema is missing known HTTP status codes
optimade-python-tools#763	Schema is missing known HTTP status codes
marshmallow-code/apispec#614	Invalid schema attempting to bound datetime strings
django-action-framework#14	Internal server error on unexpected URL fragment
jupyter-server#518	Schemathesis motivates and rewards comprehensive schemas

Table 3: A sample of GitHub issues reporting independent use of Schemathesis.

We hypothesize that OpenAPI schemas found in the wild have a long tail of rare features and complex structures, such that most non-trivial schemas include at least one which breaks naïve fuzzers.

3 EVALUATION

We experimentally evaluate Schemathesis'—and previous web API fuzzers—defect detection, runtime, and consistency of reporting. These experiments are restricted to containerised open-source services, ensuring that they are representative, reproducible, and do not attack live systems.

Since Schemathesis was open-sourced in August 2019, a range of bug reports on GitHub have been attributed to Schemathesis. A representative sample is shown in Table 3 to contextualize our experiments.

Users evidently value detection of server errors (caused by conforming inputs or not), as well as reporting of invalid, incomplete, or overly-permissive schemas. Almost all of these results require the fuzzer to understand schema semantics, in addition to the structure of inputs and possible actions, to a higher degree than "HTTP 500 means failure".

3.1 Experiment design

We run three configurations of Schemathesis, and seven other fuzzing tools in their default configurations ¹⁹ (Table 4), on sixteen open-source web APIs (Table 5), for thirty runs each.

To our knowledge, this is the most comprehensive evaluation of web API fuzzers to date. Our scripts make it easy to add further fuzzing tools or targets in Docker containers, and will be maintained as a standard benchmark suite for the community.

The full set of containers to reproduce our work, or use it in evaluating future fuzzers, is available from github.com/schemathesis/webapi-fuzzing-project, along with both raw and processed data.

Name	Version	Language	Supported schemas
Schemathesis	3.9.0	Python	Open API, GraphQL
Restler	7.1.0	Python, F#	Open API 2 / 3
Cats	5.2.3	Java	Open API 2 / 3
TnT-Fuzzer	2.3.1	Python	Open API 2
Got-Swag	1.3.0	JavaScript	Open API 2
APIFuzzer	b786c1b	Python	Open API 2
Fuzz-lightyear	0.0.9	Python	Open API 2
Swagger-conform	0.2.5	Python	Open API 2
Fuzzy Swagger	0.1.11	Python	Open API 2
Swagger fuzzer	0.1.0	Python	Open API 2

Table 4: Evaluated schema-based web API fuzzers.

For ease of analysis, we parse the 250GB of raw logs into a JSON summary, and further reduce this dataset to report the duration, number of events, and per-run reports of each unique defect.

Manual defect triage and deduplication is impractical for such a large and extensible evaluation. Instead, where possible we monitor the fuzzing process using Sentry²⁰, a widely-used platform for error tracking and performance monitoring. This gives us a cross-language notion of unique defects, i.e. internal server errors deduplicated by code location—regardless of triggering endpoint or what the fuzzer was attempting to check at the time.

We add semantic errors²¹ to our defect count by counting each kind of bug report parsed from saved logs only once per endpoint, regardless of variations or how many times it was observed. This matches our experience of users' tend to group reports which are consistently either fixed or ignored.

This typically works well, with the notable exception of TnT-Fuzzer—which reports more than a thousand 404 Not Found responses *for randomly-generated paths*:

20 https://sentry.io/

¹⁹mostly - following [27], we avoided fuzzing e.g. Jupyter's /shutdown endpoint

²¹unexpected status code, schema non-conformance, information disclosure, etc.

Zac Hatfield-Dodds and Dmitry Dygalo

Service	Language	Framework	Endpoints	Schema type	Schema source
aalises/age-of-empires-II-api	Python	Flask 1.1.2	8	Open API 3.0.0	Static
creativecommons/cccatalog-api	Python	Django 2.2.13	8	Swagger 2.0	Dynamic, drf-yasg 1.17.1
ryo-ma/covid19-japan-web-api	Python	Flask 1.1.2	4	Swagger 2.0	Dynamic, flasgger 0.9.4
disease-sh/api	JavaScript	Express 4.17.1	34	Swagger 2.0	Static
postmanlabs/httpbin	Python	Flask 1.0.2	73	Swagger 2.0	Dynamic, flasgger 0.9.0
jupyter-server/jupyter_server	Python	Tornado 6.1.0	29	Swagger 2.0	Static
jupyterhub/jupyterhub	Python	Tornado 6.1.0	35	Swagger 2.0	Static
mailhog/MailHog	Go	Net/HTTP	2	Swagger 2.0	Static
fecgov/openFEC	Python	Flask 1.1.1	85	Swagger 2.0	Dynamic, flask-apispec 0.7.0
ajnisbet/opentopodata/	Python	Flask 1.1.2	2	Open API 3.0.2	Static
rtyler/otto	Rust	Tide 0.14.0	2	Open API 3.0.3	Static
fossasia/pslab-webapp	Python	Flask 1.1.2	3	Swagger 2.0	Dynamic, flasgger 0.9.5
pulp/pulpcore	Python	Django 2.2.17	67	Open API 3.0.3	Dynamic, drf-spectacular 0.11.0
darklynx/request-baskets	Go	Net/HTTP	20	Swagger 2.0	Static
microsoft/restler-fuzzer	Python	Flask 1.1.2	6	Swagger 2.0	Static
IBM/worklog	Python	Flask 1.0.2	9	Swagger 2.0	Dynamic, flasgger 0.9.1

Table 5: Tested web services, chosen to represent a variety of programming languages, schema formats (OpenAPI and GraphQL), and sources (generated or hand-written) across a realistic range of sizes, structures, and API complexity.

We therefore count any number of "unexpected 404" reports as a single unique defect per target, ignoring the path.

3.2 Defect-detection experiment

In all-checks mode, Schemathesis reports a total of 755 bugs across fourteen out of our sixteen targets, including 111 HTTP 500 responses, 436 unexpected status codes, 52 non-schema-conforming responses, and 152 responses with a wrong or missing content type. Schemathesis finds $1.4\times$ to $4.5\times$ more defects than the respectively second-best fuzzer for each target, and is the *only* fuzzer to find defects in four targets.

Schemathesis was the only one of the tools we evaluated to handle all-or more than two-thirds of-our targets without a fatal internal error. Surprisingly, this appears unrelated to our pairing of OpenAPI 3 targets with fuzzers which do not claim to support OpenAPI 3.

Table 6 shows a summary of identified defects by fuzzer and target, some of which might be resolved by making the schema more permissive, particularly the unexpected status codes. We argue that such mismatches between specified and actual behaviour are still reasonably described as bugs - the schema being no less important than the implementation of the service. The issues listed in Table 3 indicates that at least some of our users agree.

To support clear comparisons to fuzzers which check fewer semantic properties, Table 7 shows only HTTP 500 internal server errors. We see a rich understanding of application semantics, including over request sequences, as a key contribution of our research. Nonetheless, Schemathesis detected more unique errors than the respectively second-best fuzzer for each target.

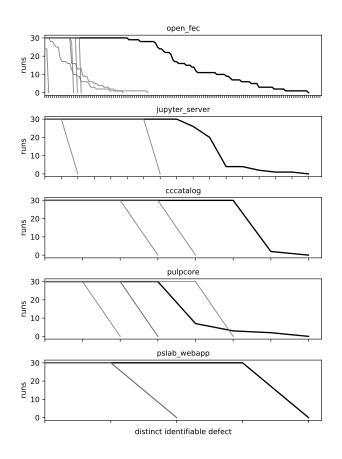


Figure 1: Sorting unique defects by the number of runs detecting them, we see that Schemathesis (black) is less consistent but discovers more than other fuzzers. Defect IDs are consistent between runs but not between fuzzers.

	cccatalog	covid19_japan	disease_sh	httpbin	jupyter_server	jupyterhub	mailhog	open_fec	pslab_webapp	request_baskets	restler_demo	worklog	age_of_empires	opentopodata	otto_parser	pulpcore
OpenAPI version	2	2	2	2	2	2	2	2	2	2	2	2	3	3	3	3
Endpoints	8	4	34	73	29	35	2	85	3	20	6	9	8	2	2	67
api_fuzzer		0	0	36			0	17	2	16		6	4	0		11
cats		0	0		5		0	10	2	0				0		6
fuzz_lightyear								2	0							
got_swag								32			0		0			13
restler	2	0			1		0	3	2	0	0	0	0	0		
schemathesis:AllChecks	13	0	11	316	32	12	1	184		39	14	3	7	1	0	24
schemathesis:Default		0	0	66	10	1	0	80	2	0		1	1	0	0	5
schemathesis:Negative		0	0	13	8	40	0	73	2	0	1		1	0	0	9
swagger_fuzzer tnt_fuzzer								16								10

Table 6: Total number of unique defects across all 30 runs, regardless of triggering endpoint, using Sentry to determine 'ground truth' for internal server errors and custom log parsing to group property violations.

api_fuzzer		0	0	13			0	17	2	0		1	0	0		0
cats		0	0		2		0	10	2	0				0		2
fuzz_lightyear								1	0							
got_swag	2							5			0		0			0
restler	2	0			1		0		2	0	0	0	0	0		
schemathesis:AllChecks	6	0	0	15	15	2	0	78	4	0	6	2	0	0	0	8
schemathesis:Default		0	0	10		1	0	80	2	0	4	1	0	0	0	5
schemathesis:Negative		0	0	11		6	0	73	2	0	1	3	0	0	0	9
swagger_fuzzer								0								
tnt_fuzzer																0

 Table 7: Total unique HTTP 500 server errors, for comparison between tools which check different semantic properties.

api_fuzzer		3	23:32	13:25			2	11:01	23	12		31	3	4		15:56
cats		5	6:45		11		4	1:42	8	5				4		1:42
fuzz_lightyear								11	1							
got_swag	1							16			1		1			1
restler	5	3			5		3	4:28:06	3	10	4	17	3	3		
schemathesis:AllChecks	12	2	2:49	25:51	16	20	2	10:32	4	7	9	37	6	5:48	2	4:16
schemathesis:Default	29	2	9:41	42:29	28	1:06	3	8:18	2	37	49	35	5	3	2	8:52
schemathesis:Negative	53	16	4:36	11:38	50	1:40:50	15	6:48:18	3	3:12	33	41	8	15	6	42:32
swagger_fuzzer								6								
tnt_fuzzer																3

Table 8: Mean runtime, showing a clear but noisy correlation to number of endpoints and detected defects.

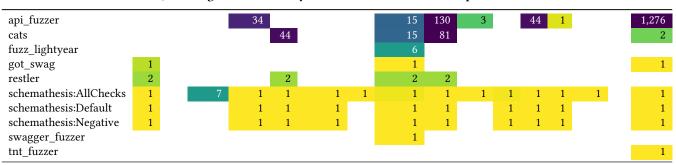


Table 9: Mean number of reports per unique defect, of those reported in a given run. Hypothesis' shrinking allows Schemathesis to report a single easy-to-understand example for each defect, easing triage.

Property-based testing workflows also outperform fuzzing when it comes to actionable reporting. Table 9 shows the mean number of reports per unique defect, averaged over each independent run. Schemathesis reports a single minimal triggering input or actionsequence for each, with the exception of a few cases where our evaluation harness uses additional information from server logs to deduplicate internal errors.

Figure 1 shows the consistency of defect-detection between runs. For most tools, detection is binary: if they do not discover a defect on the first run, they are unlikely to ever do so. APIFuzzer, Cats, and Schemathesis are less consistent for all but the easiest defects.

In Schemathesis, we attribute this effect to the property-based testing workflow! Because the user is expected to fix each failing test by changing either the service or the test harness, Hypothesis stops looking shortly after finding the first failing input. When there are multiple defects which may be discovered in different orders, this early stopping also reduces consistency compared to long-running fuzzing workflows (Table 8).

If inconsistency is driven by low detection probabilities instead of early stopping, this is also good news for users: they can simply run these fuzzers for longer and discover more defects—and in the absence of a run reporting *zero* defects, they are likely to do so.

4 DIRECTIONS FOR FUTURE RESEARCH

Expand and share benchmark suite. Our evaluation suite is designed to be reused, and will be maintained as an open source project by the Schemathesis developers. Adding and updating REST and GraphQL fuzzers ²² and targets, improving our understanding of the 'ground truth' by manually identifying defects or better automated tools for triage, and collaboration among fuzzer developers would all be valuable contributions.

Build defect analysis into fuzzers. A single HTTP 500 internal error should be reported once, not once-per-triggering-endpoint and automatic defect analysis works well enough in our evaluation that we think this is within reach, at least when running in-process or with an existing monitoring solution²³.

Support the long tail of schema features. Schemathesis has gone further down this path than previous fuzzers, and outperforms accordingly. What further gains are locked behind support for rare features such as ECMA-specific regex syntax, non-unrollable recursive references, or niche content-types?

Investigate code-coverage-guided fuzzing for web APIs. While coverage-guided fuzzing has been highly successful for native code, to date it has been impractical to evaluate the value of coverage feedback for web API fuzzing. Schemathesis' support for ASGI/WSGI in-process fuzzing, and EvoMaster's JVM instrumentation, allow measuring the value of coverage feedback²⁴ in present systems.

Improved request-sequence testing without "links". Schemathesis is often limited by the absence of OpenAPI "links" describing how

data from one response can be used to make further requests. Investigating [3, 30]-style heuristics or ways to learn links from traffic records could substantially improve performance.

Recommend schema improvements. Tools could suggest improvements to API schemas, whether to resolve basic type confusions or refine their semantics. This would be particularly valuable in combination with learned links between endpoints.

Embed property checks into web frameworks. Web frameworks which dynamically generate the application schema from code could also check conformance with the schema at runtime. Even if limited to a debug mode for performance, such automatic test oracles could improve the effectiveness of property-naïve fuzzers and other forms of testing

5 CONCLUSION

Building on mature and versatile property-based testing tools makes Schemathesis easily adaptable to specific services or workflows and remarkably effective. Working with Hypothesis offers a integrated and growing suite of useful techniques which we would not otherwise have implemented.

Schemathesis is the only fuzzer in our comprehensive evaluation to handle every real-world schema and web service, and consistently reports more defects than the previous state-of-the-art.

We hope that future work on web API fuzzing will reuse—and perhaps extend—our summary of testable properties and our evaluation corpus of tools and services.

REFERENCES

- Andrea Arcuri. 2018. EvoMaster: Evolutionary Multi-context Automated System Test Generation. In 2018 IEEE 11th International Conference on Software Testing, Verification and Validation (ICST). 394–397. https://doi.org/10.1109/ICST.2018. 00046
- [2] Cornelius Aschermann, Sergej Schumilo, Ali Abbasi, and Thorsten Holz. 2020. IJON: Exploring Deep State Spaces via Fuzzing. In 2020 IEEE Symposium on Security and Privacy (SP). 1597–1612. https://doi.org/10.1109/SP40000.2020.00117
- [3] Vaggelis Atlidakis, Patrice Godefroid, and Marina Polishchuk. 2019. REST-ler: Automatic Intelligent REST API Fuzzing. In Proceedings of the 41st International Conference on Software Engineering. IEEE Press. https://www.microsoft.com/enus/research/uploads/prod/2018/04/restler.pdf
- [4] Vaggelis Atlidakis, Patrice Godefroid, and Marina Polishchuk. 2020. Checking Security Properties of Cloud Service REST APIs. In 2020 IEEE 13th International Conference on Software Testing, Validation and Verification (ICST). IEEE. https: //doi.org/10.1109/icst46399.2020.00046
- [5] Clara Benac Earle, Lars-Åke Fredlund, Ångel Herranz, and Julio Mariño. 2014. Jsongen: A Quickcheck Based Library for Testing JSON Web Services. In Proceedings of the Thirteenth ACM SIGPLAN Workshop on Erlang (Gothenburg, Sweden) (Erlang '14). Association for Computing Machinery, New York, NY, USA, 33–41. https://doi.org/10.1145/2633448.2633454
- [6] Koen Claessen and John Hughes. 2000. QuickCheck: A Lightweight Tool for Random Testing of Haskell Programs. Proceedings of the Fifth ACM SIGPLAN International Conference on Functional Programming (2000). https://doi.org/10. 1145/357766.351266
- [7] Hamza Ed-douibi, Javier Luis Cánovas Izquierdo, and Jordi Cabot. 2018. Automatic Generation of Test Cases for REST APIs: A Specification-Based Approach. In 2018 IEEE 22nd International Enterprise Distributed Object Computing Conference (EDOC). 181–190. https://doi.org/10.1109/EDOC.2018.00031
- [8] Boris Feld. 2016. Swagger Fuzzer. https://github.com/Lothiraldan/swagger-fuzzer
- [9] Roy Thomas Fielding. 2000. REST: Architectural Styles and the Design of Networkbased Software Architectures. Doctoral dissertation. University of California, Irvine. http://www.ics.uci.edu/-fielding/pubs/dissertation/top.htm
- [10] The GraphQL Foundation. 2021. GraphQL. https://graphql.org/
- [11] Miguel A. Francisco, Macías López, Henrique Ferreiro, and Laura M. Castro. 2013. Turning Web Services Descriptions into Quickcheck Models for Automatic Testing. In Proceedings of the Twelfth ACM SIGPLAN Workshop on Erlang (Boston, Massachusetts, USA) (Erlang '13). Association for Computing Machinery, New York, NY, USA, 79–86. https://doi.org/10.1145/2505305.2505306

 $^{^{22}\}mathrm{e.g.}$ RESTest [26], EvoMaster [1], and Karlsson et al [18]

²³respectively e.g. Schemathesis ASGI/WSGI support, or Sentry

²⁴ as distinct from the client-observable notions of behavioural coverage that can be explored using e.g. Schemathesis targets.

- [12] Gordon Fraser and Andrea Arcuri. 2011. EvoSuite: Automatic Test Suite Generation for Object-Oriented Software. In Proceedings of the 19th ACM SIGSOFT Symposium and the 13th European Conference on Foundations of Software Engineering (Szeged, Hungary) (ESEC/FSE '11). Association for Computing Machinery, New York, NY, USA, 416-419. https://doi.org/10.1145/2025113.2025179
- [13] Lars Ake Fredlund, Clara Benac Earle, Angel Herranz, and Julio Marino. 2014. Property-Based Testing of JSON Based Web Services. In 2014 IEEE International Conference on Web Services. IEEE. https://doi.org/10.1109/icws.2014.110
- [14] Alex Groce, Chaoqiang Zhang, Eric Eide, Yang Chen, and John Regehr. 2012. Swarm Testing. In Proceedings of the 2012 International Symposium on Software Testing and Analysis (ISSTA 2012). Association for Computing Machinery, New York, NY, USA, 78–88. https://doi.org/10.1145/2338965.2336763
- [15] Zac Hatfield-Dodds. 2020. Falsify your Software: validating scientific code with property-based testing. In Proceedings of the 19th Python in Science Conference. https://doi.org/10.25080/majora-37cdd580-016
- [16] The OpenAPI Initiative. 2021. OpenAPI. https://www.openapis.org/
- [17] Stefan Karlsson, Adnan Causevic, and Daniel Sundmark. 2019. Quick-REST: Property-based Test Generation of OpenAPI-Described RESTful APIs. arXiv:1912.09686 [cs.SE]
- [18] Stefan Karlsson, Adnan Čaušević, and Daniel Sundmark. 2020. Automatic Property-based Testing of GraphQL APIs. arXiv:2012.07380 [cs.SE]
- [19] Leonidas Lampropoulos and Konstantinos Sagonas. 2012. Automatic WSDLguided Test Case Generation for PropEr Testing of Web Services. *Electronic Proceedings in Theoretical Computer Science* 98 (Oct 2012), 3–16. https://doi.org/ 10.4204/eptcs.98.3
- [20] Aaron Loo, Joey Lee, and Victor Zhou. 2020. Automated IDOR Discovery through Stateful Swagger Fuzzing. https://engineeringblog.yelp.com/2020/01/automatedidor-discovery-through-stateful-swagger-fuzzing.html
- [21] Andreas Löscher and Konstantinos Sagonas. 2017. Targeted Property-Based Testing. In Proceedings of the 26th ACM SIGSOFT International Symposium on Software Testing and Analysis (Santa Barbara, CA, USA) (ISSTA 2017). Association for Computing Machinery, New York, NY, USA, 46–56. https://doi.org/10.1145/

3092703.3092711

- [22] Andreas Löscher and Konstantinos Sagonas. 2018. Automating Targeted Property-Based Testing. In 2018 IEEE 11th International Conference on Software Testing, Verification and Validation (ICST). 70–80. https://doi.org/10.1109/ICST.2018.00017
- [23] David MacIver, Zac Hatfield-Dodds, and Many Contributors. 2019. Hypothesis: A new approach to property-based testing. *Journal of Open Source Software* 4, 43 (2019), 1891. https://doi.org/10.21105/joss.01891
- [24] David R. MacIver and Alastair F. Donaldson. 2020. Test-Case Reduction via Test-Case Generation: Insights from the Hypothesis Reducer (Tool Insights Paper). In 34th European Conference on Object-Oriented Programming (ECOOP 2020) (Leibniz International Proceedings in Informatics (LIPIcs), Vol. 166). 13:1–13:27. https://doi.org/10.4230/LIPIcs.ECOOP.2020.13
- [25] Phu X. Mai, Fabrizio Pastore, Arda Goknil, and Lionel Briand. 2020. Metamorphic Security Testing for Web Systems. In 2020 IEEE 13th International Conference on Software Testing, Validation and Verification (ICST). 186–197. https://doi.org/10. 1109/ICST46399.2020.00028
- [26] Alberto Martin-Lopez, Sergio Segura, and Antonio Ruiz-Cortés. 2021. RESTest: Automated Black-Box Testing of RESTful Web APIs. In Proceedings of the 30th ACM SIGSOFT International Symposium on Software Testing and Analysis. Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/ 3460319.3469082
- [27] Barton P. Miller, Mengxiao Zhang, and Elisa R. Heymann. 2020. The Relevance of Classic Fuzz Testing: Have We Solved This One? arXiv:2008.06537 [cs.SE]
- [28] Oli Pratt. 2017. Swagger-conformance. https://pypi.org/project/swaggerconformance/
- [29] Barrett Schonefeld. 2020. IBM-service-validator. https://pypi.org/project/ibmservice-validator/
- [30] Emanuele Viglianisi, Michael Dallago, and Mariano Ceccato. 2020. RESTTEST-GEN: Automated Black-Box Testing of RESTful APIs. In 2020 IEEE 13th International Conference on Software Testing, Validation and Verification (ICST). 142–152. https://doi.org/10.1109/ICST46399.2020.00024