Escape from auto-manual testing with Hypothesis!

Zac Hatfield-Dodds

THE AIATSIS MAP OF INDIGENOUS AUSTRALIA
INDIAN OCEAN
TIMOR SEA
ARAFURA SEA
TORRES STRAIT
CORAL SEA
SOUTH PACIFIC OCEAN
GULF OF CARPENTARIA
INDIAN OCEAN
GREAT AUSTRALIAN BIGHT
SOUTHERN OCEAN
SOUTH PACIFIC OCEAN
TASMAN SEA

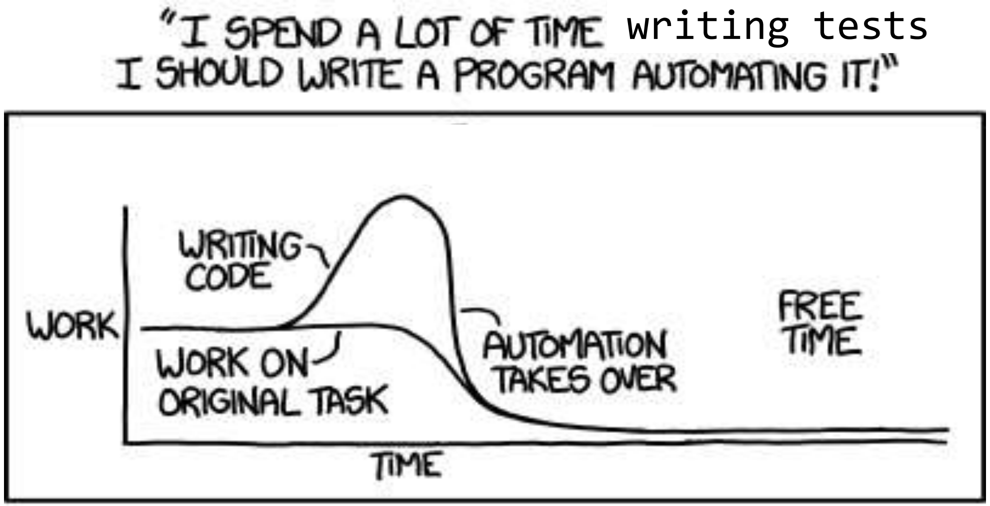
Goals for today

- Understand where property-based testing fits in a test taxonomy
- Understand key concepts in property-based testing and generative testing
- Be familiar with most of the Hypothesis library
- Ready to test your projects with Hypothesis, whether proprietary or open source

Running plan

- Alternate short talks with hands-on exercises
- Four blocks:
  - Intro to property-based testing
  - Hypothesis "strategies" and testing "tactics"
  - ~~Metamorphic relations and hyperproperties~~ Testing complex functions or whole programs
  - Performance, config, and community

- Open for questions *at any time*


"I SPEND A LOT OF TIME writing tests
I SHOULD WRITE A PROGRAM AUTOMATING IT!"
WRITING CODE
WORK
WORK ON ORIGINAL TASK
AUTOMATION TAKES OVER
FREE TIME
TIME

PROPERTY-BASED TESTING 101

A quick overview of software testing

ACTUALLY, LET’S START ELSEWHERE

______-driven-development

Not applicable today.

I’m talking about what tests we write,
not when we write them

Design for testability

- Immutable data
- Canonical formats
- Well-defined interfaces
- Separate IO and computation logic
- Explicit arguments for all dependencies
- Deterministic behaviour
- Lots of assertions

What’s a assertion?

“an expression in a program
which is **always true**
unless there is a bug.”

http://wiki.c2.com/?WhatAreAssertions

Where do tests come from?

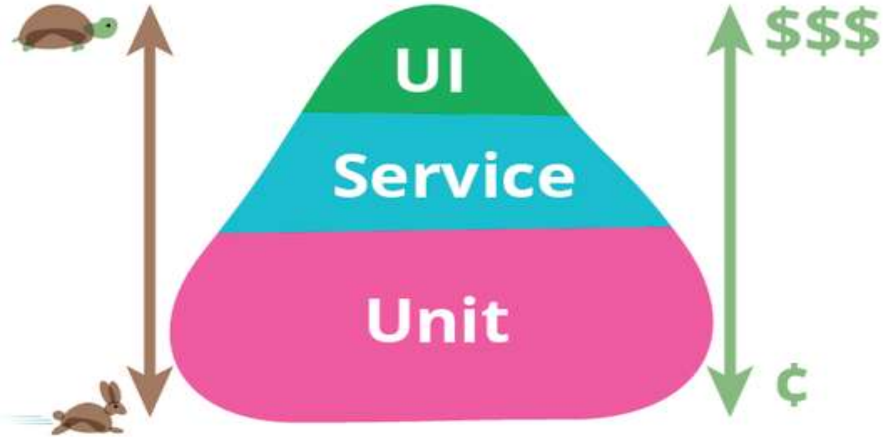
- Specifying behaviour in advance
- Checking new features
- Defending against possible bugs
  – Stopping old bugs from coming back

What should a test do?

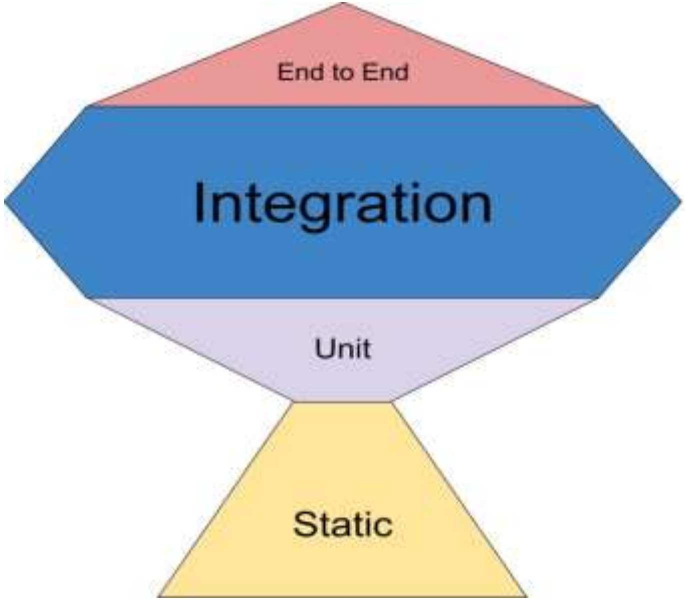
- “arrange, act, assert”
- “given, when, then”

- Execute the “system under test”
- Fail if and only if a bug is introduced

How big should a test be?



Martin Fowler



Kent C. Dodds

Ok, but what are we testing?

- Anything we can observe from code
  - Input and output data
  - Actions after a command
  - Performance (tricky)

…usually by turning it into input/output data

- User-relevant behaviour, so that our code reliably does what it needs to.

“Auto-manual tests”

- Humans
  - Decide the input
  - Write the test function
  - Determine and check expected results

- Doing it in code is *repeatable*, not *automated*

Other kinds of tests

- Diff tests
  - Does new version reproduce known output?
- Mutation tests
  - Add bugs to check they're detected by tests
- Doctests
  - Check that examples in docs still work
- Coverage tests
  - Find unexecuted (i.e. untested) parts of your code
  - Please never use percent coverage!

"I SPEND A LOT OF TIME writing tests
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For real, this time.

PROPERTY-BASED TESTING 101

Property-based testing

- User:
  - Describes valid inputs
  - Writes a test that passes for any valid input
- Engine:
  - Generates many *test cases*
  - Runs your test for each input
  - Reports minimal failing inputs (usually)

```python
from hypothesis import given, strategies as st

@given(
    st.lists(st.integers(), min_size=1)
)
def test_a_sort_function(ls):

    # we can compare to a trusted implementation,
    assert dubious_sort(ls) == sorted(ls)

    # or check the properties we need directly.
    assert Counter(out) == Counter(ls)
    assert all(a<=b for a, b in zip(out, out[1:]))
```

Exercise #1

- Clone repo: tiny.cc/zhd-workshop
  github.com/Zac-HD/escape-from-automanual-testing

- `pip install pytest hypothesis`
  - In your preferred environment, py2 or py3

- `pytest pbt-101.py`

- Open file, edit per comments, re-run tests

STRATEGIES AND TACTICS

`hypothesis.strategies`

- Describes inputs for `@given` to generate

- Only construct strategies via the public API
  - SearchStrategy type is only public for type hints
  - Composing factories is nicer anyway!

Values

- Simplest strategies are for values
  - None, bools, numbers, Unicode or binary strings…
- Finer-grained than types
  - Optional bounds for value or length
  - Arguments like `allow_nan` or `timezones`

Collections

- Lists, sets, dicts, iterables, etc.
  - Take a strategy for `elements` (or keys/values)
  - Optional min_size and max_size

Map and Filter methods

`s.map(f)`

- applies function *f* to example
- shrinks *before* mapping

`s.filter(f)`

- retry unless *f(ex)*
- mostly for edge cases

```
s = integers()
s.map(str) # strings of digits

# even integers
s.map(lambda x: x * 2)
# odd ints, slowly
s.filter(lambda x: x % 2)

# Lists with some unique numbers
lists(s, 2).filter(
  lambda x: len(set(x)) >=2
)
```

Complicated data

- Got a list of values?
  - `sampled_from` or `permutations` can help
- Recursive strategies just work
  - At least three ways to define them
- Combine strategies:
  - `integers() | text()`
  - Can’t take intersection though.
- Call anything with `builds()`

Inferring strategies

A schema is a machine-readable description:

- Used for validating input
- Can generate input instead!

This tests both validation and logic.

regex, array dtype, django model, attrs classes, type hints, database…

```
>>> from_regex(r'^[A-Z]\w+$')
'Fgjdfas'
'D榙譞Ć斊\n'
```

```
>>> from_dtype('f4,f4,f4')
(-9.00713e+15, 1.19209e-07, nan)
(0.5, 0.0, -1.9)
```

```
>>> def f(a: int): return str(a)
>>> builds(f)
'20091'
'-507'
```

Beyond the standard library

- hypothesis.extra
  - Django, Numpy, Pandas, Lark, pytz, dateutil…
- Also many third-party extensions, e.g.
  - Geojson, SQLAlchemy, networkx, jsonschema, Lollipop, Mongoengine, protobuf…

Data dependencies

Custom strategies

- Similar to interactive data in tests

```
@composite
def str_and_index(draw, min_size):
    s = draw(text(min_size=min_size))
    i = draw(integers(0, len(s) - 1))
    return (s, i)

str_and_index().example()
```

Interactive data

- Run part of a test, then get more input
- Useful with complex dataflow

```
@given(data())
def test_something(data):
    i = data.draw(integers(...))
```

Minimal examples

- Strategies shrink
  - From the inside out
    - i.e. before map or filter are applied
  - Towards the smallest and shortest example
  - Based on the strategy definition
- Multiple errors possible per test!

Inline st.data()

- Draw more data *within* the test function
  - Great for complex or stateful systems
  - Use `@composite` instead if you can

```python
@given(st.data())
def a_test(data):
    x = data.draw(integers(0, 100), label="First number")
    y = data.draw(integers(x, 100), label="Second number")
    # Do something with `x` and `y`
```

STRATEGIES AND TACTICS

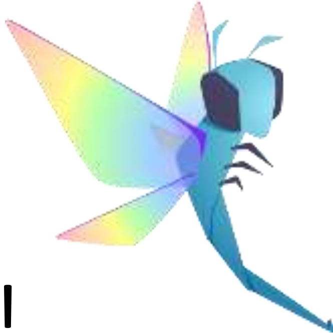
Tactics: what do we test?

- “Auto-manual” testing
  - output == expected
- Oracle tests (full specification)
  - Does a magic “oracle” function say output is OK?
- Partial specification
  - Can identify some but not all failures
- Metamorphic testing
- Hyper-properties

Oracles

- Fantastic for refactoring or testing performance optimisations
- “reverse oracles”
  - Generate an answer, ask the oracle for a matching question, test that code gets the answer
- You may need to test the Oracle too

Partial specification



- We don’t need an exact answer for tests!
  - min(xs) <= mean(xs) <= max(xs)

- Lots of serialisation specs are like this
  - In fact almost all specs are partial

Special-case oracles

- If your oracle only works for some valid inputs, that's still useful to test those inputs
- Or a more precise test for a subset of inputs
  - – Monotonic functions, positive numbers, etc.
  - – Varying just one parameter to simplify results

Common properties

- Shared by lots of code
  - Often good API design generally
  - Or worth it just for testability

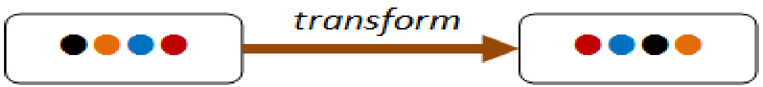
“Does not crash”

- Just call your function with valid input:

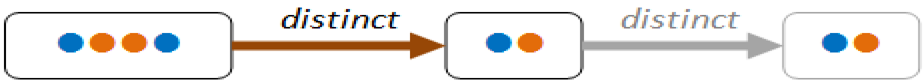
```python
@given(lists(integers()))
def test_fuzz_max(xs):
    max(xs) # no assertions in the test!
```

- This is embarrassingly effective.

Invariants



```
Counter(ls) == Counter(sorted(ls))
```

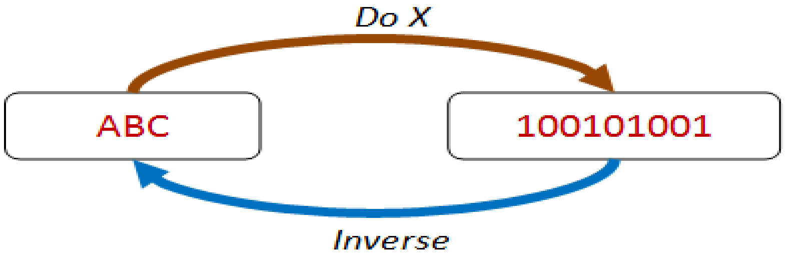


```
ls != set(ls) == set(set(ls))
```

Round-trips

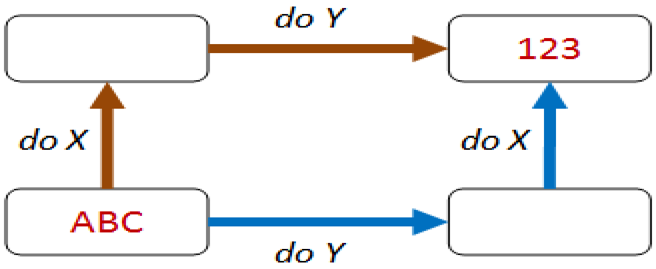
“inverse functions”

- `add          / subtract`
- `json.dumps   / json.loads`



or just related:

- `factorize   / multiply`
- `set_x       / get_x`
- `list.append / list.index`



Testing unknown answers

- A really powerful technique:
  - when we don’t know what the answer should be, we might still know how it relates to input

- For example,
  - Shuffle input -> same output
  - Add number above mean -> mean increases
  - Change gender field -> same hiring decision

Exercise #2

- Same plan as last time:
  - `pytest strategies-and-tactics.py`
  - Open, edit, re-test

Go get snacks, water, visit a restroom, etc.

Back here in ten minutes for next section!

BIO-BREAK

TESTING THE UNTESTABLE

Untestable or annoying?

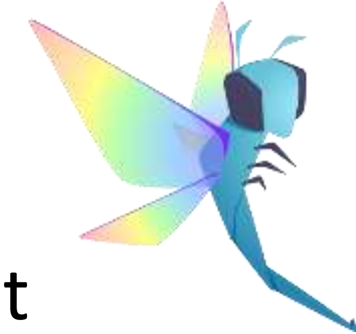
- No other way to get the answer
  - Black boxes
  - Simulations of complicated systems
  - Machine learning

- Code with lots of state
  - i.e. not a function with input and output
  - Includes networking, databases, etc.

Scary jargon for “a complicated but really useful property”

METAMORPHIC RELATIONS

Metamor-whatsit?



- We don’t know how input relates to output
- BUT
  - Given an input and corresponding output
  - Make a known change to the input
  - We might know how the output should change (or not change)

- That’s it – but this is really, really powerful

Compilers

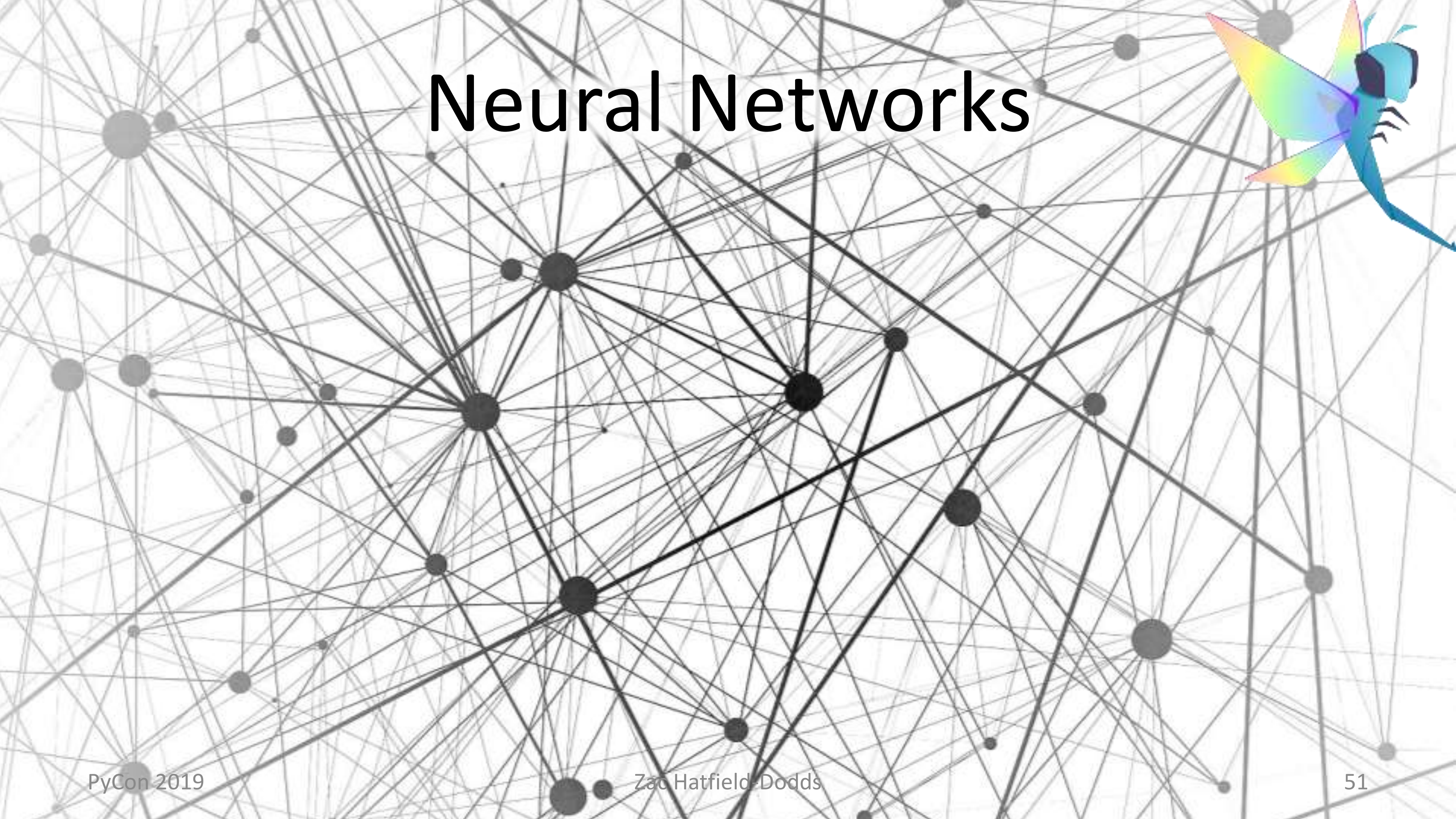
- Very popular technique for compilers!
  - Generate valid program
  - Use many different compilers and settings
  - Run and compare results
  - Any difference == there’s a bug somewhere

- A kind of differential testing

RESTful APIs

- Who knows what a query should return?
  - – Adding a search term should give fewer results
  - – The number of results should not change depending on pagination: spotify/web-api#225
  - – Plus standard properties from before
    - update then get, delete then can’t get, etc.

Neural Networks



Neural Networks

- State of the art of NN testing is *terrible*
  - Embed lots of assertions
  - Use simple properties across single steps

- Testing things like…
  - Training steps change neuron weights
  - Bounds on inputs and outputs
  - Converges when expected to

Computer vision

- Cars should not confidently choose a different action if the camera feed has
  - slight changes in contrast or brightness or scale
  - a small skew or offset or blur added
  - light rain or fog added

- https://deeplearningtest.github.io/deepTest/
  - Luckily there aren’t many on the road (yet)

aka ‘model checking’

STATEFUL TESTING

Most software has state

- [citation needed]
  - FP is the study of getting around this problem
  - Networks are stateful. Databases are stateful.
  - The world has state, so your code needs it too

- Is this a problem for generative testing?
  - Nope!
  - We just need to represent things properly…

(non)deterministic finite automata

- A nice formalism
  - The automata has some internal state
  - Which actions are valid depends on the state
  - There’s a special starting state
- Sound familiar?
  - Regular expressions are all DFAs*
  - We can model finite automata as classes

RuleBasedStateMachine

```python
from hypothesis.stateful import RuleBasedStateMachine, rule, precondition

class NumberModifier(RuleBasedStateMachine):
    num = 0

    @rule(n=integers())
    def add_n(self, n):
        self.num += n

    @precondition(lambda self: self.num != 0)
    @rule()
    def divide_with_one(self):
        self.num = 1 / self.num
```

Other ways to do it

- GenericStateMachine is deprecated

- `st.data(...)` within a test function
  - Way, way overpowered – and very little structure
  - I mean, it really does work
  - But might not shrink well – this is subtle magic

Exercise #3

- Same plan as last time, again:

  -
    ```
    pytest test-the-untestable.py
    ```
  - Open, edit, re-test

In which we discuss all the other things that you might want to know.

PERFORMANCE, CONFIGURATION, AND COMMUNITY

Observability

`--hypothesis-show-statistics`

- Shows timing stats, perf breakdown, exit reasons
- Add custom entries by calling `event()` in a test

- Use `note()` if you like print-debugging
  - Only prints for minimal failing example
  - Details controlled by `verbosity` setting

Performance (generation)

- All pretty obvious in generation phase:
  - Calling slow things or many things is slow
  - Generating larger data takes longer
  - Filter more, and getting output takes longer

- Otherwise Hypothesis is pretty fast!

Performance (shrinking)

- Composition of shrinking
  - If any part shrinks, the whole should shrink
  - Order of recursive terms is important!
- Keep things local
  - Put filters (or assume) as far in as possible
  - Avoid drawing a size, then that many things

- Don’t waste more tuning than you save!

Configuration

- `hypothesis.settings`
- Per-test decorator or whole-suite profiles
- Lots of options
  - deadline, max_examples, report_multiple_bugs, database, etc.

Reproducing failures

- Hypothesis tests should **never** be flaky.
  - We detect most user-caused flakiness too
- Failures cached and retried until fixed
  - for local dev, reproducibility is automatic
- Printed seed to re-run failures from CI
- Explicit decorator for really tough cases

Update early & often!

- Hypothesis releases every pull request.
  - All bug fixes are available in ~30 minutes
  - As are features, performance improvements, …
  - We use strict semver and code review
  - (and have a fantastic test suite ☺)

- So stay up to date – for your own sake!

Who uses Hypothesis?

- 4% of all Pythonistas (PSF survey)
- Many companies
- ~2000 open source projects (github stats)
- Blockchain! (sigh)

Consulting Services

- Want exciting new features?
- Want Hypothesis training for your team?
- Want your tests (and code) reviewed?

- Zac Hatfield-Dodds and David MacIver
  - Say hi via hello@hypothesis.works

About the project

- MPL-2.0 license
- New contributors welcome!
  - most remaining issues are non-trivial
  - using or extending Hypothesis is valued too

- Tries to be *legible*
  - we design APIs and errors to teach users
  - does what you expect; or explains why not

When I don’t use Hypothesis

- Checking that invalid things are invalid
- When I have a comprehensive corpus
  - Though I might use Hypothesis too…
- For very slow tests
- Checking rare edge cases
  - But consider @example to share test function

WRAPPING UP

Hypothesis @ PyCon 2019

- This tutorial (Thursday)
- Maintainers summit (lightning talk, Saturday)
- A lovely poster – get a copy!
- *Escape from Auto-manual Testing* (Sunday)
  - You can skip the talk, but send your friends!
- We’ll be at the sprints (Mon – Thurs)
  - Working on Hypothesis itself
  - Helping other projects use Hypothesis

How Hypothesis works on the inside, or, computer science is !!fun!!

BONUS: SCARY INTERNAL DETAILS

You **DO NOT** need to know any of this to use Hypothesis

An imperative view

- Everything can be described in bits [citation needed]
  - So we can generate values with random bits, choose branches with random bits, etc.
  - Random generation is really easy!

- Therefore, every example has a byte-string
  - Replay examples by using it instead of random
  - Save and restore arbitrary test cases
  - Get a total ordering (shortlex) for any strategy

Imperative shrinking

- Goal: shorter (or lexically better) buffer
- Try lots of passes:
  - Delete runs of bytes
  - Reduce byte values
  - Tuned combinations of the above
  - (in the literature “hierarchal delta debugging”)
- Update the “current buffer” each time we see the same test failure

A functional view

- `bytes -> object` ? That’s a parser!
  - The strategies API is “parser combinators”
  - We can discard unused buffer post-fixes
  - Extract test structure from calls
    (a strategy + test is an unrestricted grammar)

- *Super* useful when shrinking!

Functional shrinking

- Structured transformations:
  - Delete collection elements
  - Simultaneously reduce integers
  - Replace sub-examples with minimal form
  - Reorder like values
  - Subtree substitution

- (often) more efficient than byte-level shrinks

The rest is ‘just’…

- Engineering details
- Designing for understanding
- Documentation & outreach
- Project management
- etc.