QCon London 2017

Property-based testing in practice

Alex Chan
alexwlchan.net/qcon17
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$ whoami

- Alex Chan (@alexwlchan)
- Software developer at the Wellcome Trust
- OSS contributor:
    - python-hyper (HTTP/2)
    - PyOpenSSL
    - Hypothesis

Agenda

- The what & the why
- Choosing a library
- Practical testing patterns
- Advanced techniques

The what
&
the why

Anecdote-based testing

1) Write down some example inputs
2) Write down the expected outputs
3) Run the code – check they match

Property-based testing

1) Describe the input
2) Describe the *properties* of the output
3) Have the computer try lots of random examples – check they don’t fail

Property-based testing

```python
@given(lists(integers()))
def test_sorting_list_of_integers(xs):
    res = sorted(xs)
    assert isinstance(res, list)
    assert Counter(res) == Counter(xs)
    assert all(x <= y
               for x, y in zip(res, res[1:]))
```

Property-based testing

- The computer can try lots of examples – it’s much faster than you
- You’re more likely to catch edge cases
- You can find bugs you didn’t know about yet (exploratory testing)
- Really verify your assumptions
- (It’s fun!)

Choosing a library

- Ability to generate data
- Support for *shrinking*
- Memory of bad examples
- http://hypothesis.works/articles/quickcheck-in-every-language

Testing patterns

Fuzzing, part 1

- You know what inputs your code expects – does it handle them correctly?
- Easy way to get started
- Good for:
  - Any non-trivial function

Fuzzing, part 1

```
try:
    my_function(*args, **kwargs)
except KnownException:
    pass
```

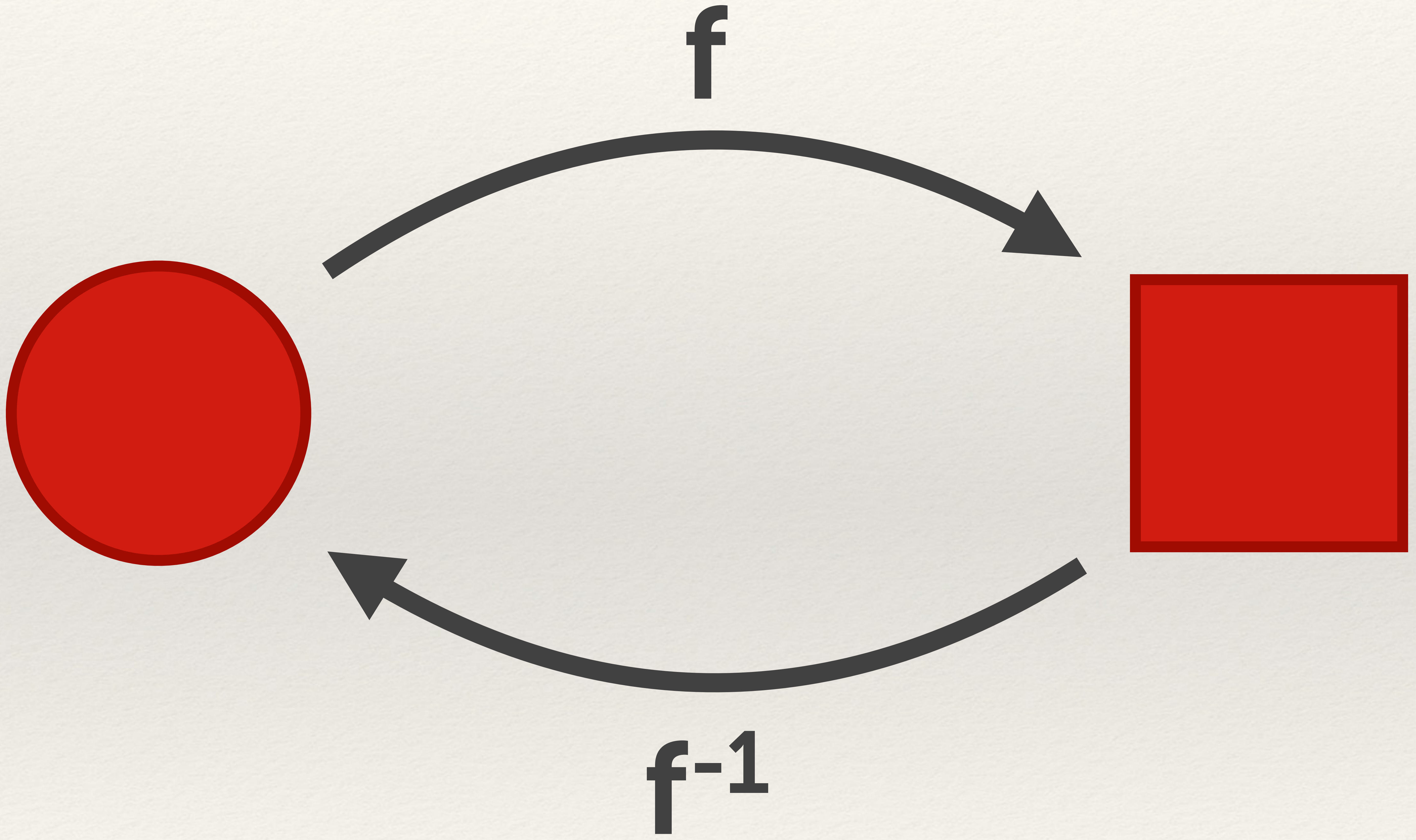
- Your function should never crash
- Your function should return the right type
- Your function should return a sensible value

Fuzzing, part 1

```
GET https://api.example.net/items?id={id}
```

- Expected HTTP return codes: 200, 4xx
- Response should be valid JSON
- Response should have the right schema

Round-trip/inverses



Round-trip/inverses

- Look for functions which are mutual inverses
- Applying both functions should be a no-op
- Good for:
  - Serialisation/deserialisation
  - Parsing/unparsing
  - Read/write

Round-trip/inverses

```python
from mercurial.encoding import *

@given(binary())
def test_decode_inverts_encode(s):
    assert fromutf8b(toutf8b(s)) == s
```

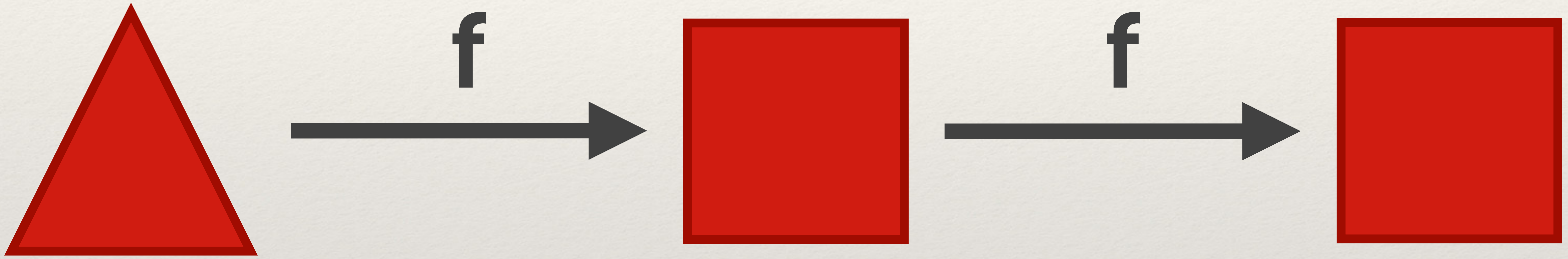
```
Falsifying example: s = '\xc2\xc2\x80'
```

Round-trip/inverses

```python
from dateutil.parser import parse

@given(datetimes())
def test_parsing_iso8601_dates(d):
    assert parse(str(d)) == d
```

```
Falsifying example:
d = datetime.datetime(4, 4, 1, 0, 0)
```

Idempotent functions



Idempotent functions

- Look for functions which are *idempotent*
- Applying the function to its output should be a no-op
- Good for:
    - Cleaning/fixing data
    - Normalisation
    - Escaping

Idempotent functions

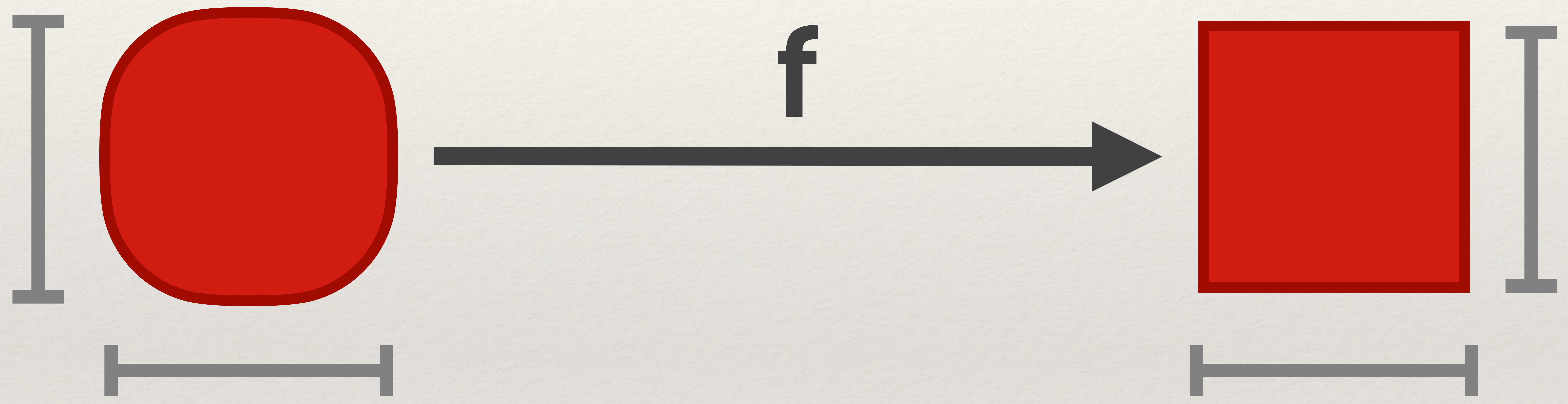
```python
from unicodedata import normalize

@given(text())
def test_normalizing_is_idempotent(string):
    result = normalize('NFC', string)
    assert result == normalize('NFC', result)
```

Idempotent functions

```
PUT https://api.example.net/items
{item_data}

GET https://api.example.net/items/count
```

- PUT’ing an item increments the item count
- PUT’ing the same item twice doesn’t

Invariant properties



Invariant properties

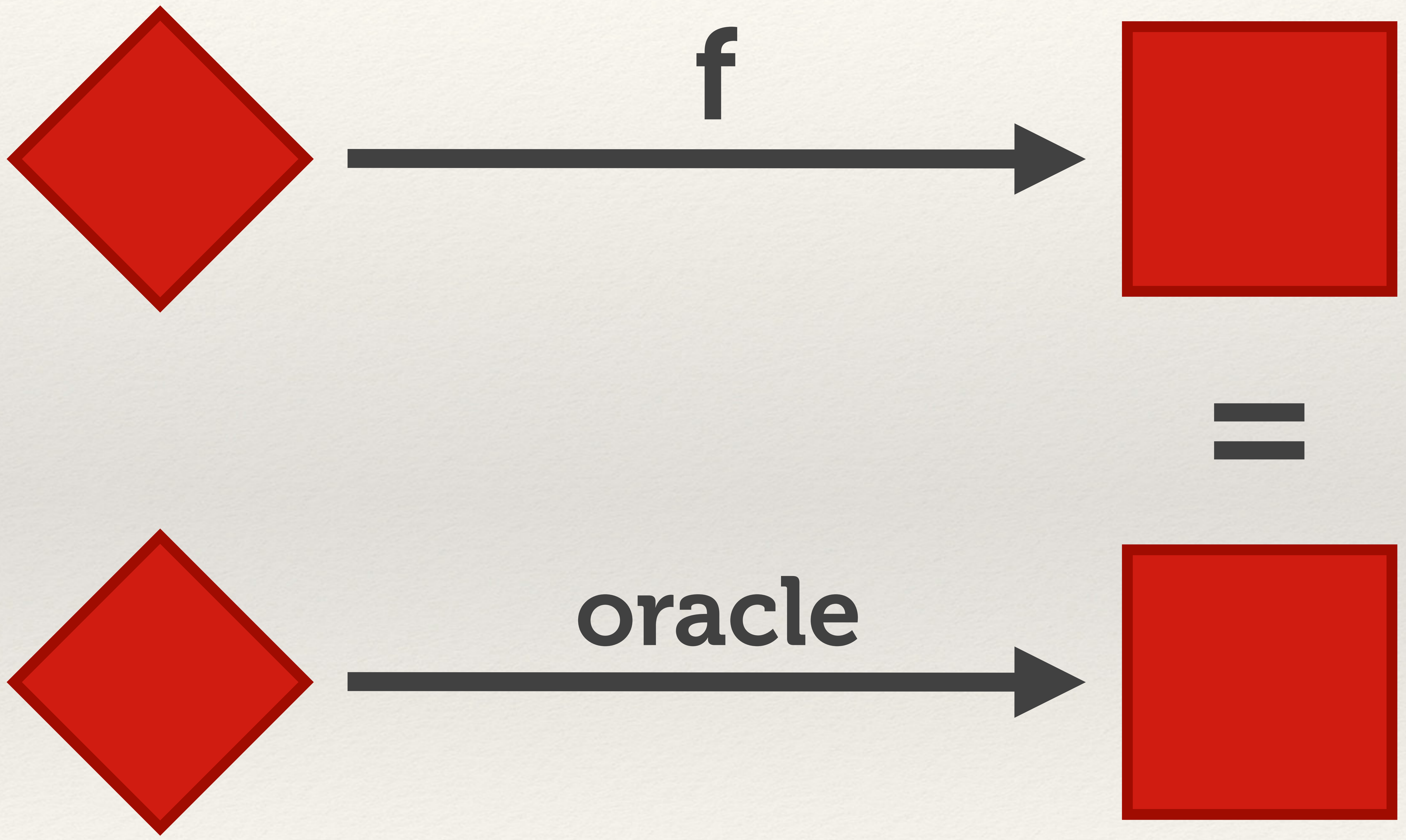
- Look for properties that don’t change when you run your code
- Measuring them before and after should give the same result
- Good for:
  - Transformations
  - Anything where the result is reflected back

Invariant properties

```python
@given(text())
def test_lowercasing_preserves_cases(xs):
    assert len(xs.lower()) == len(xs)
```

```
Falsifying example:
xs = 'İ'
```

Test oracle



Test oracle

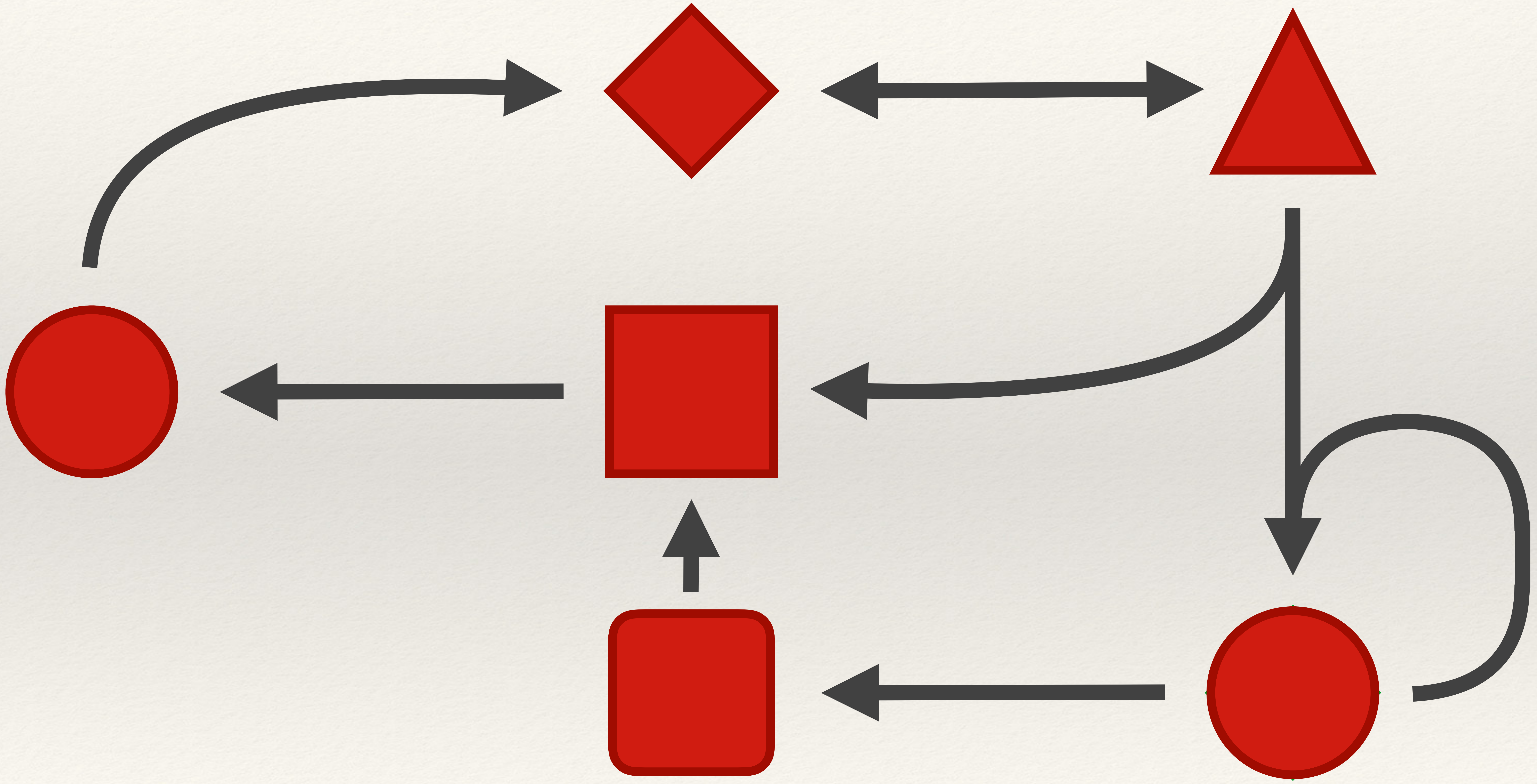
- Look for an alternative implementation (your oracle)
- Your code should always match the oracle
- Good for:
  - Refactoring legacy code
  - Mocking/emulating
  - Complicated code with a simple alternative

Testing patterns

- Fuzzing (part 1)
- Round trip/inverse
- Idempotent functions
- Invariant properties
- Test oracles

Advanced techniques

Stateful testing



Stateful testing

1) Describe the possible states
2) Describe what actions can take place in each state
3) Describe how to tell if the state is correct
4) Have the computer try lots of random actions – look for a breaking combination

Stateful testing

- Testing a priority queue/binary heap
    - Create a new heap
    - Check if the heap is empty
    - Push a value/pop the first value
    - Merge two heaps together
- http://hypothesis.works/articles/rule-based-stateful-testing/

```python
def heap_new():
    return []

def is_heap_empty(heap):
    return not heap

def heap_push(heap, value):
    heap.append(value)
    idx = len(heap) - 1
    while idx > 0:
        parent = (idx - 1) // 2
        if heap[parent] > heap[idx]:
            heap[parent], heap[idx] = heap[idx], heap[parent]
            idx = parent
        else:
            break

def heap_pop(heap):
    return heap.pop(0)
```

```python
from hypothesis.stateful import *

class HeapMachine(RuleBasedStateMachine):

    def __init__(self):
        super(HeapMachine, self).__init__()
        self.heap = heap_new()

    @rule(value=integers())
    def push(self, value):
        heap_push(self.heap, value)

    @rule()
    @precondition(lambda self: self.heap)
    def pop(self):
        correct = min(self.heap)
        result = heap_pop(self.heap)
        assert correct == result
```

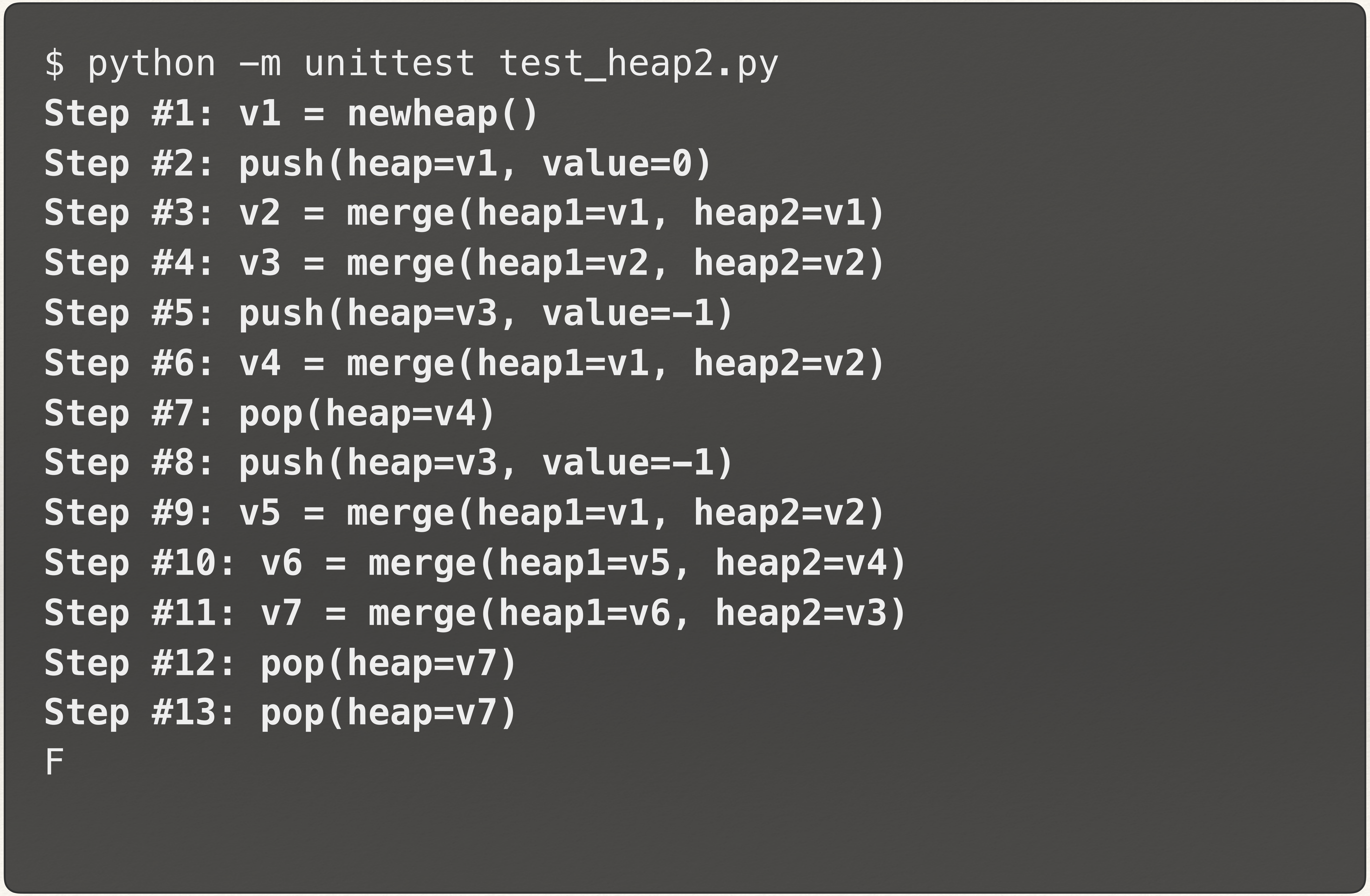
```
$ python -m unittest test_heap1.py
Step #1: push(value=0)
Step #2: push(value=1)
Step #3: push(value=0)
Step #4: pop()
Step #5: pop()
F
===========================================================
FAIL: runTest (hypothesis.stateful.HeapMachine.TestCase)
-----------------------------------------------------------
```

```python
def heap_merge(heap1, heap2):
    heap1, heap2 = sorted((heap1, heap2))
    return heap1 + heap2
```

```python
class HeapMachine(RuleBasedStateMachine):
    Heaps = Bundle('heaps')

    @rule(target=Heaps)
    def new_heap(self):
        return heap_new()

    @rule(heap=Heaps, value=integers())
    def push(self, heap, value):
        heap_push(heap, value)

    @rule(heap=Heaps.filter(bool))
    def pop(self, heap):
        correct = min(heap)
        result = heap_pop(heap)
        assert correct == result

    @rule(target=Heaps, heap1=Heaps, heap2=Heaps)
    def merge(self, heap1, heap2):
        return heap_merge(heap1, heap2)
```

```
$ python -m unittest test_heap2.py
Step #1: v1 = newheap()
Step #2: push(heap=v1, value=0)
Step #3: push(heap=v1, value=1)
Step #4: push(heap=v1, value=1)
Step #5: v2 = merge(heap2=v1, heap1=v1)
Step #6: pop(heap=v2)
Step #7: pop(heap=v2)
F
===========================================================
FAIL: runTest (hypothesis.stateful.HeapMachine.TestCase)
-----------------------------------------------------------
```

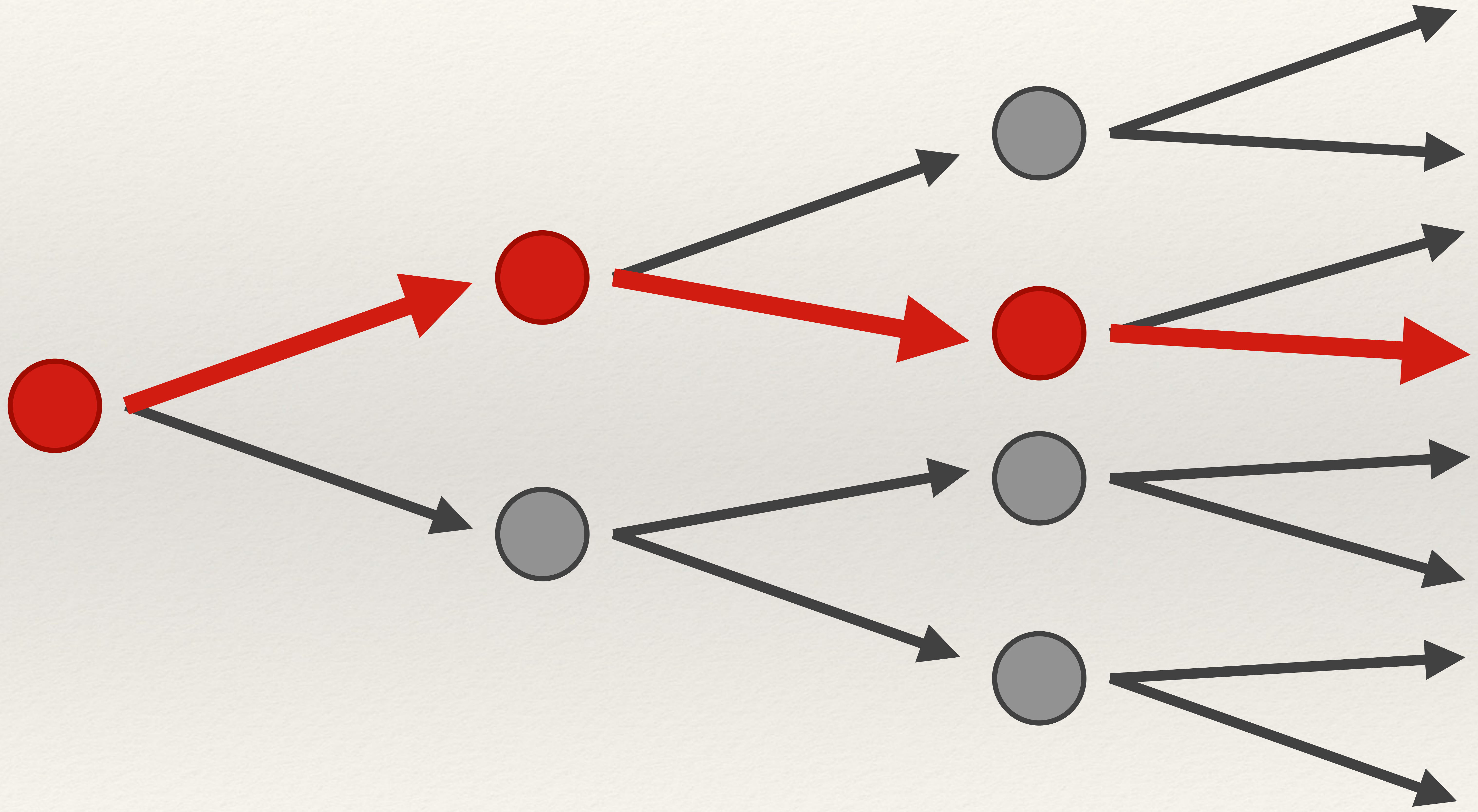
```python
def heap_merge(x, y):
    result = []
    i = 0
    j = 0
    while i < len(x) and j < len(y):
        if x[i] <= y[j]:
            result.append(x[i])
            i += 1
        else:
            result.append(y[j])
            j += 1
    result.extend(x[i:])
    result.extend(y[j:])
    return result
```


```
$ python -m unittest test_heap2.py
Step #1: v1 = newheap()
Step #2: push(heap=v1, value=0)
Step #3: v2 = merge(heap1=v1, heap2=v1)
Step #4: v3 = merge(heap1=v2, heap2=v2)
Step #5: push(heap=v3, value=-1)
Step #6: v4 = merge(heap1=v1, heap2=v2)
Step #7: pop(heap=v4)
Step #8: push(heap=v3, value=-1)
Step #9: v5 = merge(heap1=v1, heap2=v2)
Step #10: v6 = merge(heap1=v5, heap2=v4)
Step #11: v7 = merge(heap1=v6, heap2=v3)
Step #12: pop(heap=v7)
Step #13: pop(heap=v7)
F
```

Stateful testing in practice

- Hypothesis itself – the examples database
- State of a Mercurial repo
- An HTTP/2 Priority tree
- Interacting HTTP/2 stacks

Fuzzing, part 2



Fuzzing, part 2

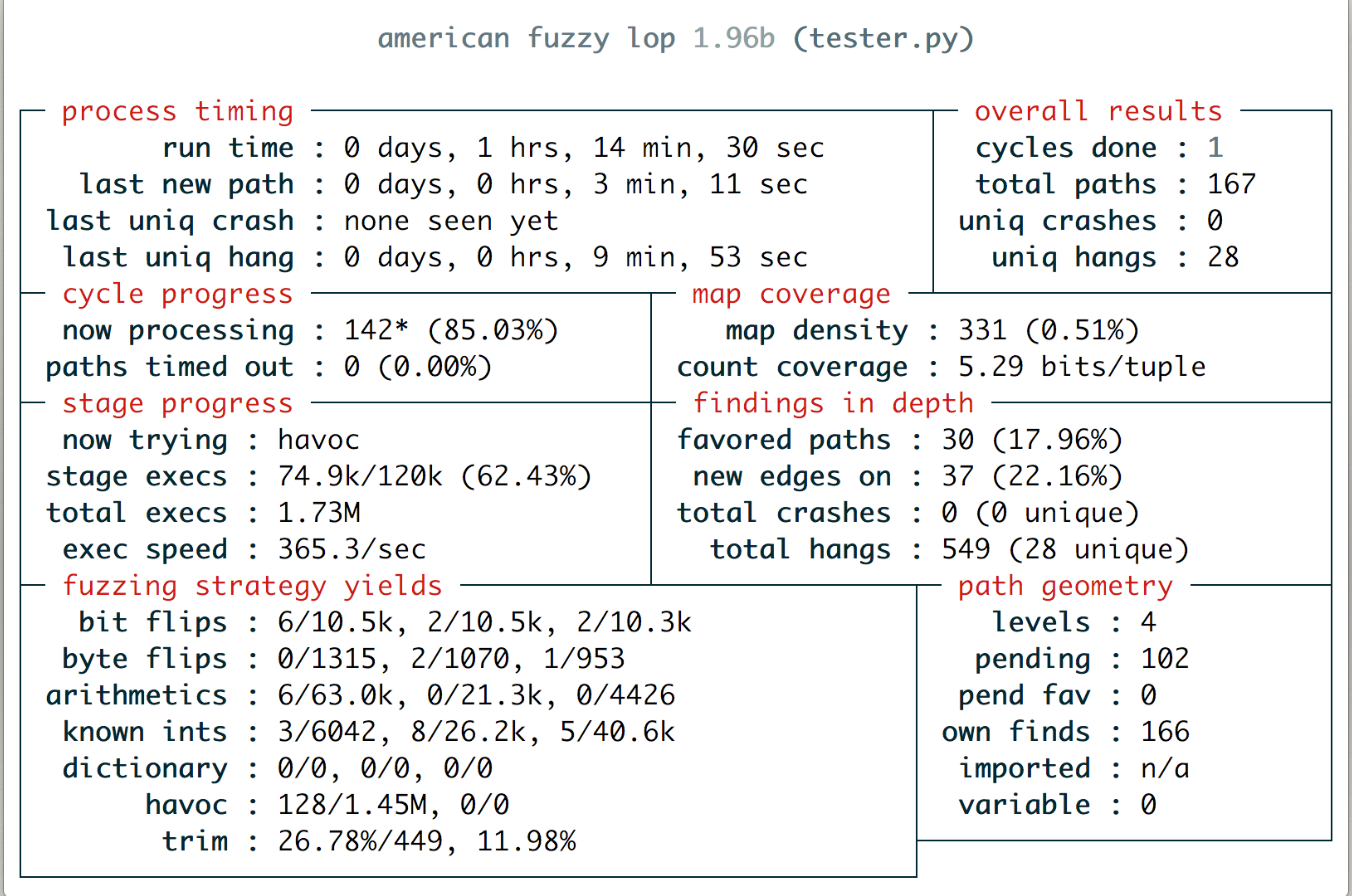
- Random fuzzing only scratches the surface – what if we want to go deeper?
- We need to get smarter!

Enter AFL

- AFL uses tracing to see different paths through our code. It can “learn” the data under test.
- Good for:
  - File formats
  - Parsers
  - Anywhere with untrusted input

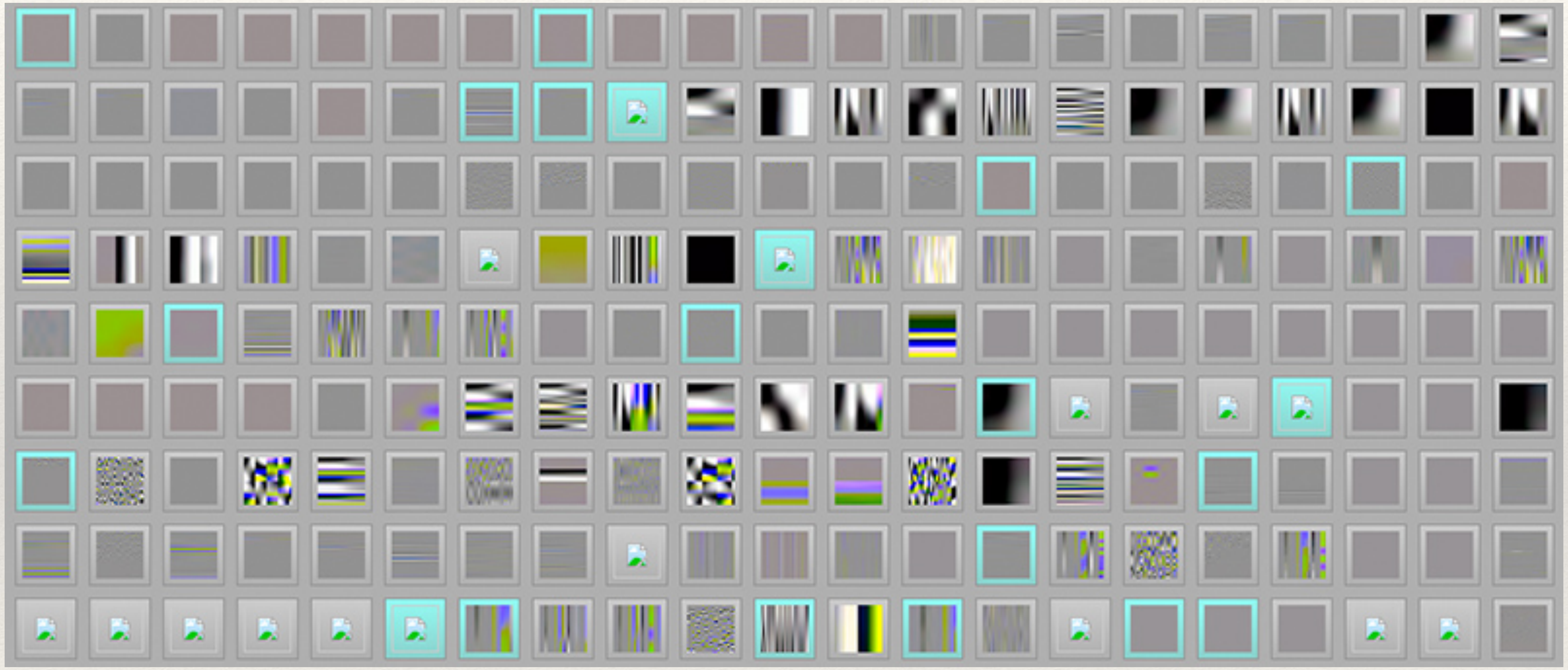
Enter AFL

```
import afl, hpack, sys

afl.init()

d = hpack.Decoder()
try:
    d.decode(sys.stdin.buffer.read())
except hpack.HPACKError:
    pass
```



```
                    american fuzzy lop 1.96b (tester.py)

┌─ process timing ─────────────────────────────────────┬─ overall results ─────┐
│        run time : 0 days, 1 hrs, 14 min, 30 sec      │  cycles done : 1      │
│   last new path : 0 days, 0 hrs, 3 min, 11 sec       │  total paths : 167    │
│ last uniq crash : none seen yet                      │ uniq crashes : 0      │
│  last uniq hang : 0 days, 0 hrs, 9 min, 53 sec       │   uniq hangs : 28     │
├─ cycle progress ────────────────────┬─ map coverage ─┴───────────────────────┤
│  now processing : 142* (85.03%)     │    map density : 331 (0.51%)           │
│ paths timed out : 0 (0.00%)         │ count coverage : 5.29 bits/tuple      │
├─ stage progress ────────────────────┼─ findings in depth ────────────────────┤
│  now trying : havoc                 │ favored paths : 30 (17.96%)            │
│ stage execs : 74.9k/120k (62.43%)   │  new edges on : 37 (22.16%)            │
│ total execs : 1.73M                 │ total crashes : 0 (0 unique)           │
│  exec speed : 365.3/sec             │   total hangs : 549 (28 unique)        │
├─ fuzzing strategy yields ───────────┴─────────────┬─ path geometry ──────────┤
│   bit flips : 6/10.5k, 2/10.5k, 2/10.3k           │    levels : 4            │
│  byte flips : 0/1315, 2/1070, 1/953               │   pending : 102          │
│ arithmetics : 6/63.0k, 0/21.3k, 0/4426            │  pend fav : 0            │
│  known ints : 3/6042, 8/26.2k, 5/40.6k            │ own finds : 166          │
│  dictionary : 0/0, 0/0, 0/0                       │  imported : n/a          │
│       havoc : 128/1.45M, 0/0                      │  variable : 0            │
│        trim : 26.78%/449, 11.98%                  ├──────────────────────────┘
└───────────────────────────────────────────────────┘
```

Enter AFL



Pulling JPEGs out of thin air, Michael Zalweski

Property-based testing in practice

- Property-based testing is a powerful way to write more tests, find more bugs, get more confidence in your code
- Practical testing patterns like round-trip, idempotent functions and test oracle
- Advanced techniques like stageful testing with Hypothesis, fuzzing with AFL

Property-based testing in practice

Slides and links

https://alexwlchan.net/qcon17/

Hypothesis

https://hypothesis.works/

AFL

http://lcamtuf.coredump.cx/afl/

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