

Introduction to Property-Based Testing

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1 Introduction

Software testing plays an important role to ensure the software works as expected [2]. It usually needs a lot of human effort. To make testing efficient, test automation was introduced [6]. Developing and designing automated tests is expensive, but it would be cheaper than traditional test as time goes by [6]. Property-based testing is one of the ways to make tests automated.

Property-based testing should be noticed by DevOps developers. The basic idea behind DevOps is to increase the efficiency of software planning, integration, deployment, testing, feedback and monitoring [11, 1]. Property-based testing could contribute to DevOps culture, since it allows to write better tests with less effort in coding in a long term [8].

This essay introduces what is property-based testing, what are differences compared with traditional tests, how to do property-based testing, and tries to give suggestions through discussion and evaluation about when to apply property-based testing.

2 What is property-based testing?

Property-based testing is to generate tests based on property requirements and features [7]. It can detect bugs in many categories. There was an example that nearly 60,000 lines of code were tested by around 500 lines of code using a tool of property-based testing [8]. The bugs came from:

- Issues of software performance: timing, handling faults, race condition, and system restrictions [8]
- Issues of coding: usage of API, programming logic, typing [8]
- Other issues: documentation and hardware [8]

In this section, an example is used to introduce what is the idea of property-based testing. Then, two features: generator and shrinking are introduced.

2.1 Basic idea of Property-based testing

Figure 1 shows a function which needs to be tested. This function multiplies two input values.

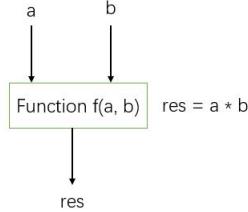


Figure 1: Multiplication function

To test this function, instead of thinking about concrete test cases, the most critical thing is to find the properties of the function. As known to all, pure multiplication has two important properties:

- Associative property: $(a * b) * c = a * (b * c)$
- Commutative property: $a * b = b * a$

According to these properties, the tests could be:

- Associative property: verify $f(f(a, b), c) = f(a, f(b, c))$
- Commutative property: verify $f(a, b) = f(b, a)$

The data of a , b and c should be automatically generated by property-based testing tools. In this way, testing data are automatically created to verify property rules. To improve the tests, property-based testing provides generators to generate better test cases, and it owns the feature of shrinking to reproduce the error.

2.2 Generator

Generators are responsible for creating input data randomly [3], which is a critical element of property-based testing. High randomness in test cases implies high coverage, which indicates that the tests are highly reliable [8].

The property-based testing tools provides default predefined generators for basic data types [3]. For example, PropEr, which is a property-based testing tool for Erlang has an generator *rangeMin*, *Max* [8]. This generator can offer an integer in the range of *Min* and *Max*, including the value of *Min* and *Max* [8]. Programmers can also utilize the combination of predefined generators for data with higher complexity [3].

Sometimes, even the combination of the basic generators can not meet the needs. For data which are not in basic data types and more complicated demands, property-based testing allows custom generators [8]. Custom generators can do many things. It can collect the statistical analysis of the test, such as giving a report of distribution of generated input [8]. It is also possible to clarify the size of the generator, use a self-written function as a generator, reformat the generated data, limit the generated data by demand, and enable the probabilistic distribution of complex data types [8]. In addition, generators in a recursive manner are also supported by some tools, for suitable situations, such as counting the words [8]. Property-based testing also provides symbolic calls as a notation to make data structures more explicit and understandable [8]. Custom generators enable more possibilities for developers to create better tests.

Developers should use default generators and customize specific generators according to demands and situations. Different property-based tools might have variation in generators, which should be paid attention by developers.

2.3 Shrinking

Shrinking is an important feature of property-based testing. It can narrow down and regenerate where the error happens, which helps the developers to figure out where the problem is [12].

Here is an example which is adapted from a paper from Fang-Yi Lo et al.. Figure 2 shows a function which removes the elements in a list, and the removed elements should be equal to the first input parameter [12].

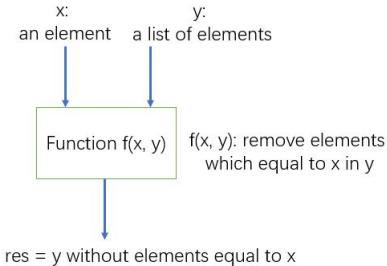


Figure 2: Remove function

Property-based testing could provide a result that [3, 4, 7, 10, 4, 16, 5, 9] is not able to pass the test [12]. Based on that, shrinking could reduce the size of this counterexample to [4, 4] [12]. From this reduced result, developers can guess that the possible mistake in the function [12]. In this example, the fault in implementation of the function only deletes the first equivalent element in the list [12].

Shrinking can narrow the counterexample, which helps developers to find where the mistake is. This is one of the best features of property-based testing.

3 Comparison with traditional tests

Fred Hebert gave an intuitive example in the first section of his book [8]. In this example, the tested function merges many sorted function to one single sorted function [8]. Figure 3 presents the traditional way of testing, which is written in Erlang. As presented, the developers need to generate test cases to cover all possible situations, which is a very annoying process. In addition, there are still more possible test cases besides the ones in figure 3, which means that it is always hard for developers to write a comprehensive test [8].

```
merge_test() ->
    [] = merge([]),
    [] = merge([[[]]]),
    [] = merge([[],[]]),
    [] = merge([[],[],[]]),
    [1] = merge([[1]]),
    [1,1,2,2] = merge([[1,2],[1,2]]),
    [1] = merge([[1],[1,[]]]),
    [1] = merge([[],[1],[1]]),
    [1] = merge([[],[],[1]]),
    [1,2] = merge([[1],[2],[[]]]),
    [1,2] = merge([[1],[1],[2]]),
    [1,2] = merge([[1],[1,1],[2]]),
    [1,2,3,4,5,6] = merge([[1,2],[[],[5,6],[],[3,4],[]]]),
    [1,2,3,4] = merge([[4],[3],[2],[1]]),
    [1,2,3,4,5] = merge([[1],[2],[3],[4],[5]]),
    [1,2,3,4,5,6] = merge([[1],[2],[3],[4],[5],[6]]),
    [1,2,3,4,5,6,7,8,9] = merge([[1],[2],[3],[4],[5],[6],[7],[8],[9]]),
    Seq = seq(1,100),
    true = Seq == merge(map(fun(E) -> [E] end, Seq)),
    ok.
```

Figure 3: Traditional way of testing [8]

Figure 4 presents how the function can be tested with the help of PropEr, which is a property-based testing tool for Erlang. It basically generates many sorted list with different length and elements as inputs. After that, it verifies the result of the function with these inputs equals to applying *append* and *sort* function.

```
sorted_list(N) -> ?LET(L, list(N), sort(L)).
prop_merge() ->
    ?FORALL(List, list(sorted_list(pos_integer())),
        merge(List) == sort	append(List))).
```

Figure 4: Property-based way of testing [8]

These code have fewer lines than traditional code and they need less effort from test developers [8]. Test developers only need to find out the property

to verify, and to code the generator, which would be not as boring as thinking about all possible test cases.

In addition, this example tells that there is difference between traditional testing and property-based testing in the aspect of coverage metric. Since it is not feasible to test all possible inputs, coverage metric is important, because it evaluates how much the test cases cover the possibilities [4]. Coverage metric can indicate if the more test cases are needed, or the test cases are enough to have valuable conclusion [4]. Property-based testing allows powerful coverage metric because of the automatically generated inputs [7]. As in the example, the code in figure 4 covers far more possibilities than the traditional way of testing in figure 3 [8].

Moreover, property-based testing provides many useful features, such as shrinking and generators, which helps test developers to locate the errors and create tests in a convenient way, as the previous sections introduce.

To summarize, property-based testing performs distinctly compared with traditional testing, in the aspect of coverage and decreasing human effort to find all possible test cases. It also offers developers convenient features to develop property-based tests.

4 Ways to property-based testing

In this section, some tools for property-based testing are introduced.

One of the most popular tool is QuickCheck, which was created for Haskell by Koen Claessen and John Hughes in 1999 [9]. It can generate a large amount of test inputs according to the specified specifications [5]. Then, the authors of the QuickCheck build QuviQ, a company to supply the services of QuickCheck for business customers, and they build QuickCheck for Erlang to gain a larger market. Later, based on this tool, the Erlang community released two other open source derivatives, PropEr and Triq. [8]

After the release of QuickCheck, it becomes the most widely-used tools for property-based testing at a time [10]. Then, lots of programming language communities released re-implementations in other languages. For example, ScalaCheck for Scala, FSCheck for F, quick.Check for Go [10], CppQuickCheck for C++, QuickTheories for Java, Hypothesis for Python and so on.

Compared with QuickCheck, the later tools have various changes in functionalities. Take Hypothesis as an example, Hypothesis provides stronger way to reduce test-cases automatically, and it offers targeted property-based testing [14].

Developers should choose tools for property-based testing based on their own situation and developing languages. For instance, Erlang developers might have to choose between QuickCheck and PropEr. For the developers who prefer free tools, PropEr could be a better choice. But for developers who place emphasis on finding concurrency bugs, QuickCheck could be worthy.

5 Evaluation and discussion

Property-based testing would be useful in some situations. Property-based tests are often suitable for the kinds of situations where the input cannot be identified, especially if the objects to test are associated with real-world situations. If there are a lot of possible combinations of inputs which might cause problem in the program, it would be hard for developers cover all in traditional unit testing.

However, property-based testing is not irreplaceable in all situations. The cost of setting up a property-based test would be higher than setting up a traditional test. The biggest difference with unit testing is that the property-based testing are generalized but unit tests can only be used for one possible scenario. Due to this, property-based testing is often much slower than unit testing. This is taken for granted, according to the design of property-based testing, each test is performed multiple times for a particular property, not just a particular case. In addition, developing tests to be generic rather than specific is not a simple task [8]. Finding good properties would be relatively more difficult than finding specific test cases in traditional tests.

Thus, property-based testing is not yet a complete replacement for traditional testing, such as unit testing, especially in the early days of Test Driven Development (TDD), where sample-based testing will perform better. Developer teams need to decide whether to apply property-based testing based on cost, plan and other factors carefully.

6 Conclusion

To summarize, property-based testing is to test by automatically generated test cases based on given properties, instead of testing by specified inputs from developers. It provides powerful features, such as shrinking and custom generators. There are many tools for property-based testing available such as QuickCheck, PropEr and Hypothesis. Developers could decide whether to apply property-based testing based on cost and concrete conditions.

For future research, there are many sub-fields of property-based testing which can be investigated. Targeted property-based testing is to create inputs by certain strategy instead of randomly generation [13]. There are also studies on how to test stateful properties. In addition, improving the coverage of property-based test could be a topic.

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