

# *Kill All Mutants!*

(Intro to Mutation Testing)

by Dave Aronson

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CURRENT TOTAL TIME: ~48 mins. Slot is 60, so aim for 45-50.

NOTES TO SELF:

- add example like codemanship's one about needing to handle invalid instruction

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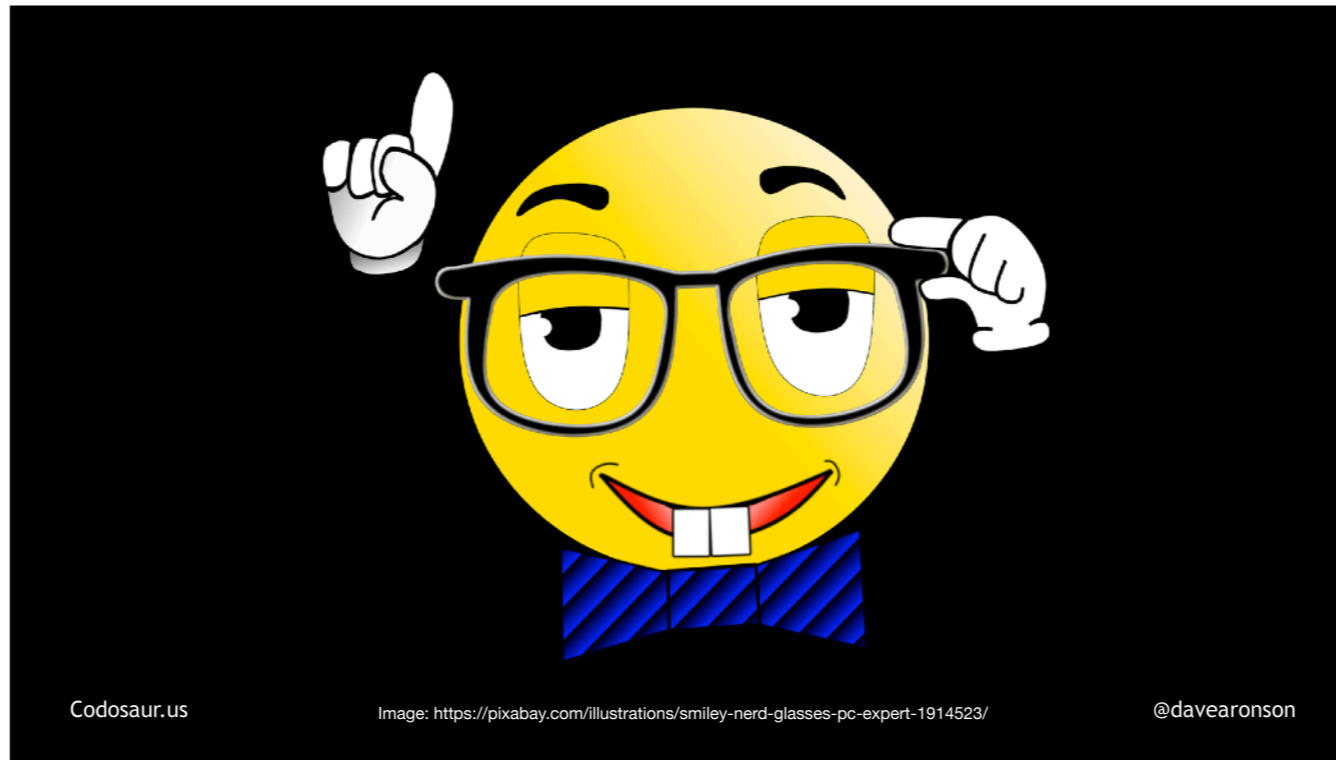
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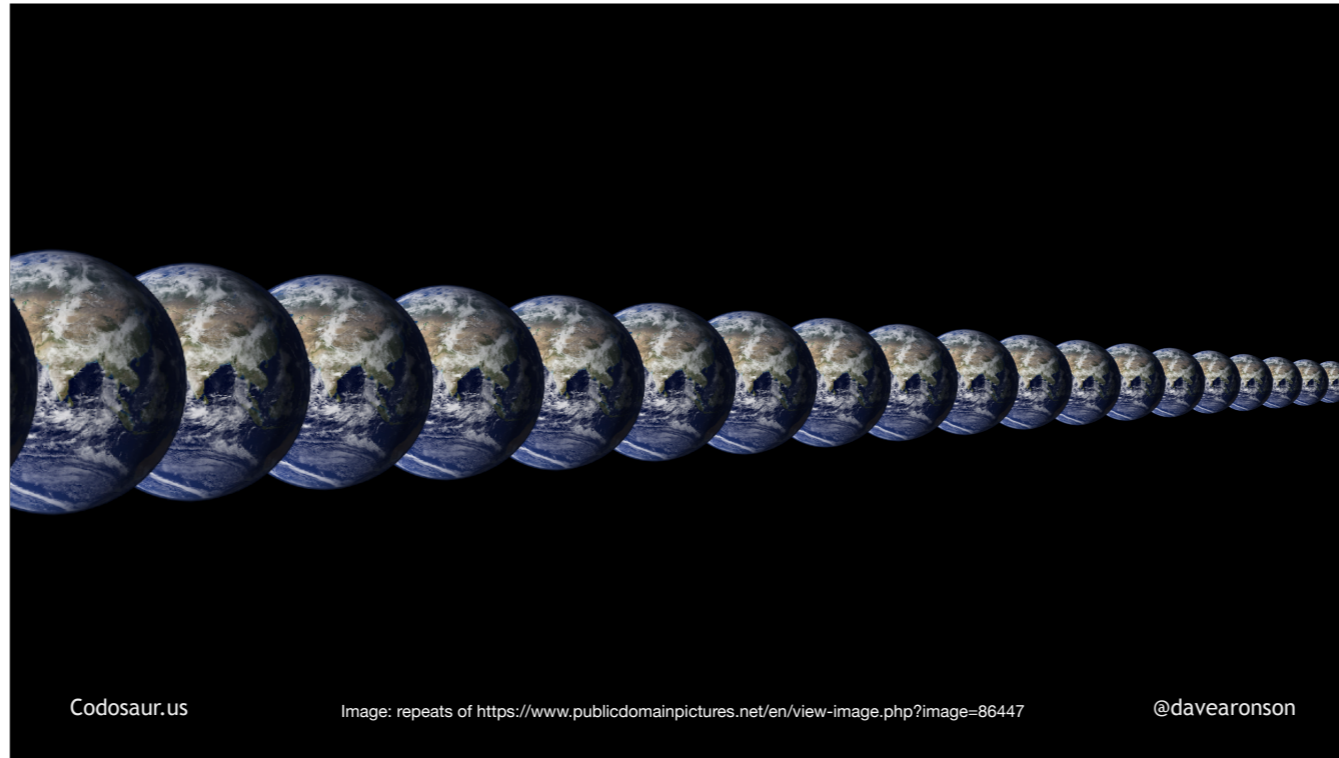
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G'day, Melbourne! I'm Dave Aronson, the T. Rex of Codosaurus, and I flew here all the way down here on my pet pterodactyl to teach you to *kill mutants!* (PAUSE!) But first, a disclaimer: I do not consider myself an . . .

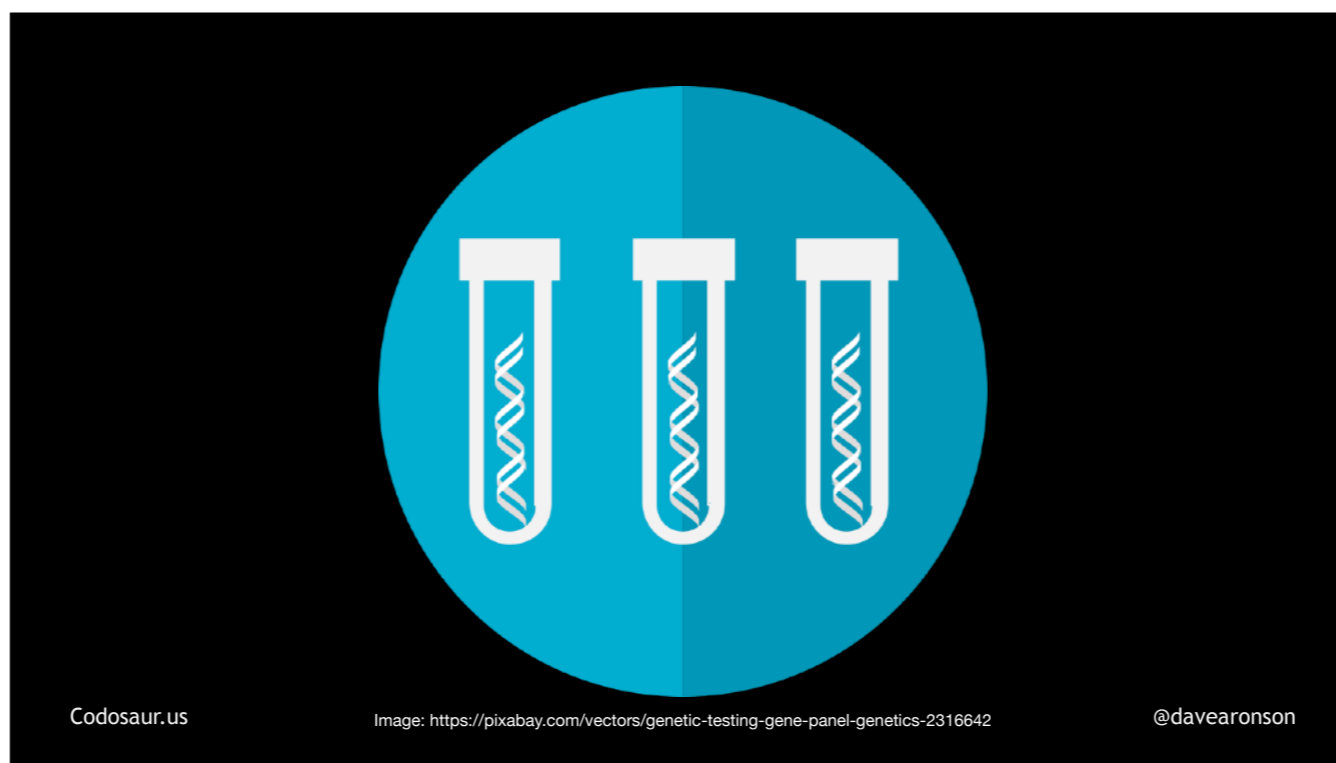


. . . expert on mutation testing. But one of the dirty little secrets of public speaking is that you don't *have* to be an expert on your topic! You just have to know a *little bit more* about it than the audience does, enough to make it worth their time to listen to you, and be able to *convey* it to them. And mutation testing is still rare enough, that most developers have never even *heard* of it!

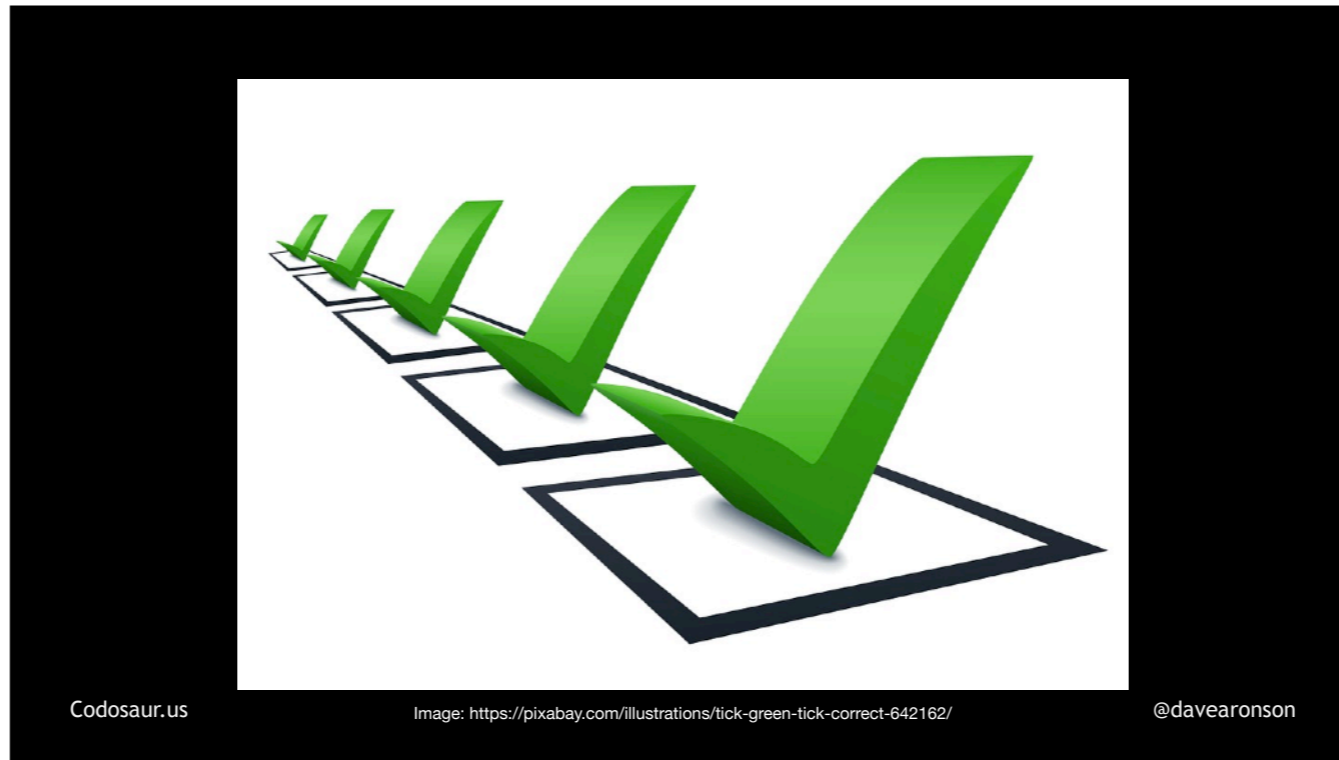
So let's start with the basics. What on . . .



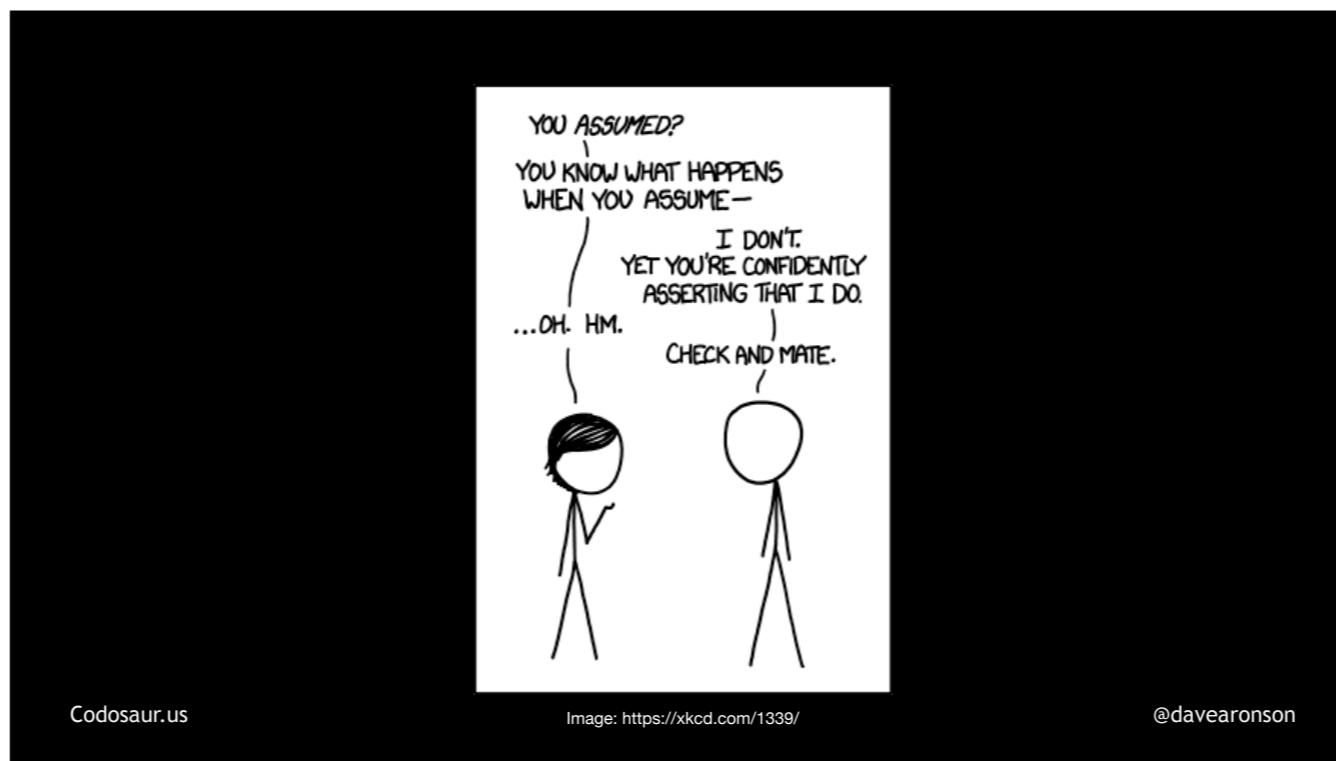
. . . Infinite Earths, is . . .



. . . mutation testing? In *our* universe, that of software development, not comic books, it's a software testing technique. (Surprise!) But why is *this* technique different from all *other* techniques? The big difference is that most of the others are about . . .



. . . checking whether our code is correct. Mutation testing . . .



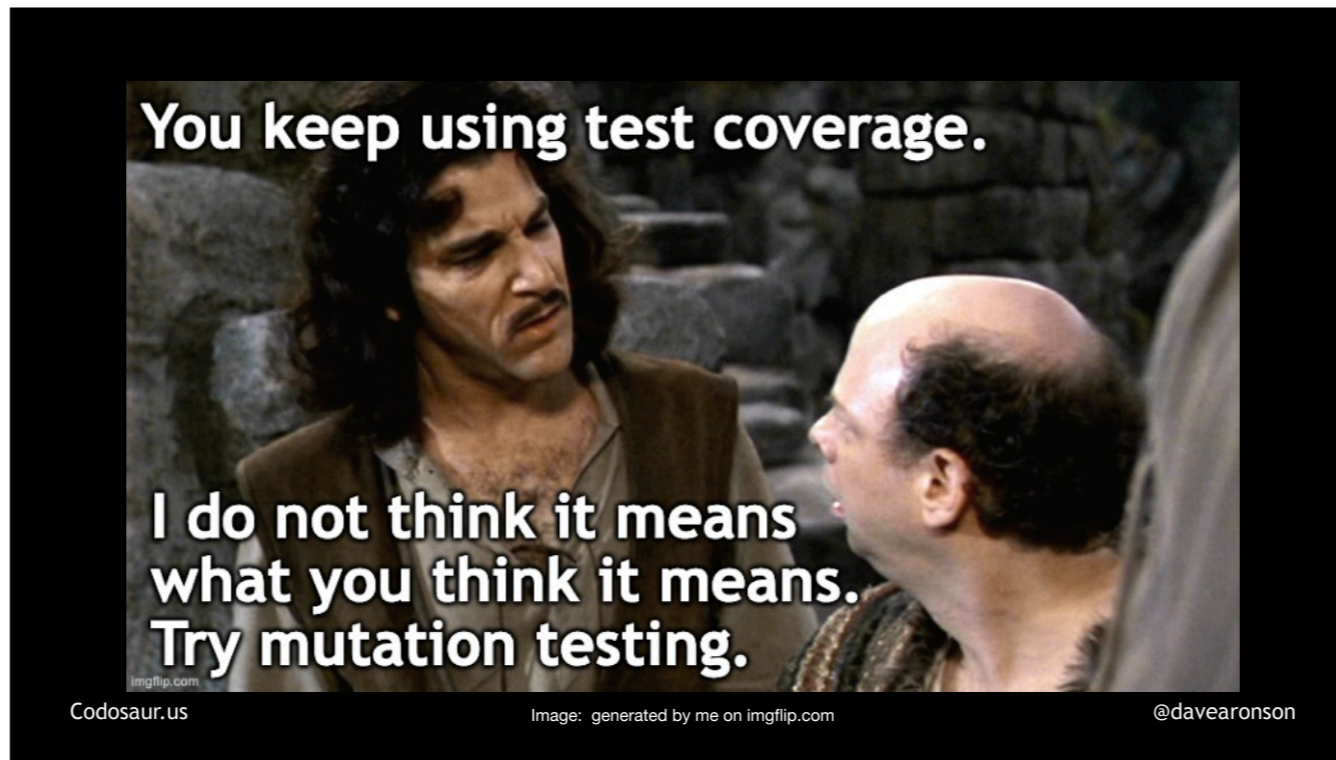
. . . *assumes* that our code is correct, at least in the sense of passing its tests. (And that means it assumes we *have* tests. More on that later.) Instead, mutation testing checks for not one but *two* other qualities. In my opinion, the more *important, interesting,* and usually *immediately useful* of these two qualities is that our test suite is . . .

```
"use strict";
```

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. . . *strict*. Now you may be thinking, “Isn’t that what test coverage is for? If we have 100% coverage, doesn’t that mean our code is fully tested?”



No. (PAUSE!) The *only* thing that test coverage tells us is that at least one test *executed* . . .

```
defmodule Conway do
  @alive "*"
  @dead " "

  def next_state(@alive, neighbors),
    do: if Enum.member?([3, 4], neighbors),
         do: @alive, else: @dead

  def next_state(@dead, neighbors),
    do: if neighbors == 3,
         do: @alive, else: @dead
end
```

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. . . the code it claims is “covered”. It tells us NOTHING about whether the *correctness* of that code *made any difference* to whether the test passed or failed.

By way of illustration, let’s look at . . .

```
test "live with 3 survives" do
  expected = @alive
  actual = next_state(@alive, 3)
  assert actual == expected
end
```

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... a test, and ...

```
test "live with 3 survives" do
  expected = @alive
  actual = next_state(@alive, 3)
  # assert actual == expected
end
```

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. . . comment out the assertion. Assertions might be commented out, removed, or not even written in the first place, for any number of reasons, usually not very good, but it's often done anyway. Our test still *runs* the function, so the lines *show as covered*, but we're not asserting anything, so the code is *obviously* not tested. This is just *one of many* ways that coverage can be misleading.

So how *can* we tell if the code's correctness made any difference to whether the test passes? That . . . is where mutation testing comes in.

To check that our test suite is *strict*, a mutation testing tool will . . .



. . . find the gaps in our test suite, that let our code get away with unwanted behavior. Once we find gaps, we can close them by either adding tests or improving existing tests. Lack of strictness comes mainly from *lack* of tests, poorly *written* tests, or poorly *maintained* tests, such as ones that didn't keep pace with changes in the code.

Speaking of which, the other thing mutation testing checks is that our code is what I call . . .





. . . puts these two together, by checking that every possible small change to the code does indeed make a noticeable change to its behavior, *and* that the test suite is indeed strict enough notice that change, and fail. Not all of the tests have to fail, but each change should make *at least one* test fail.

That's the positive side, but there are some drawbacks. As Fred Brooks told us back in 1986, there's no . . .



. . . silver bullet! Besides, those are for killing . . .



. . . werewolves, not mutants!

The first drawback is that it's rather . . .

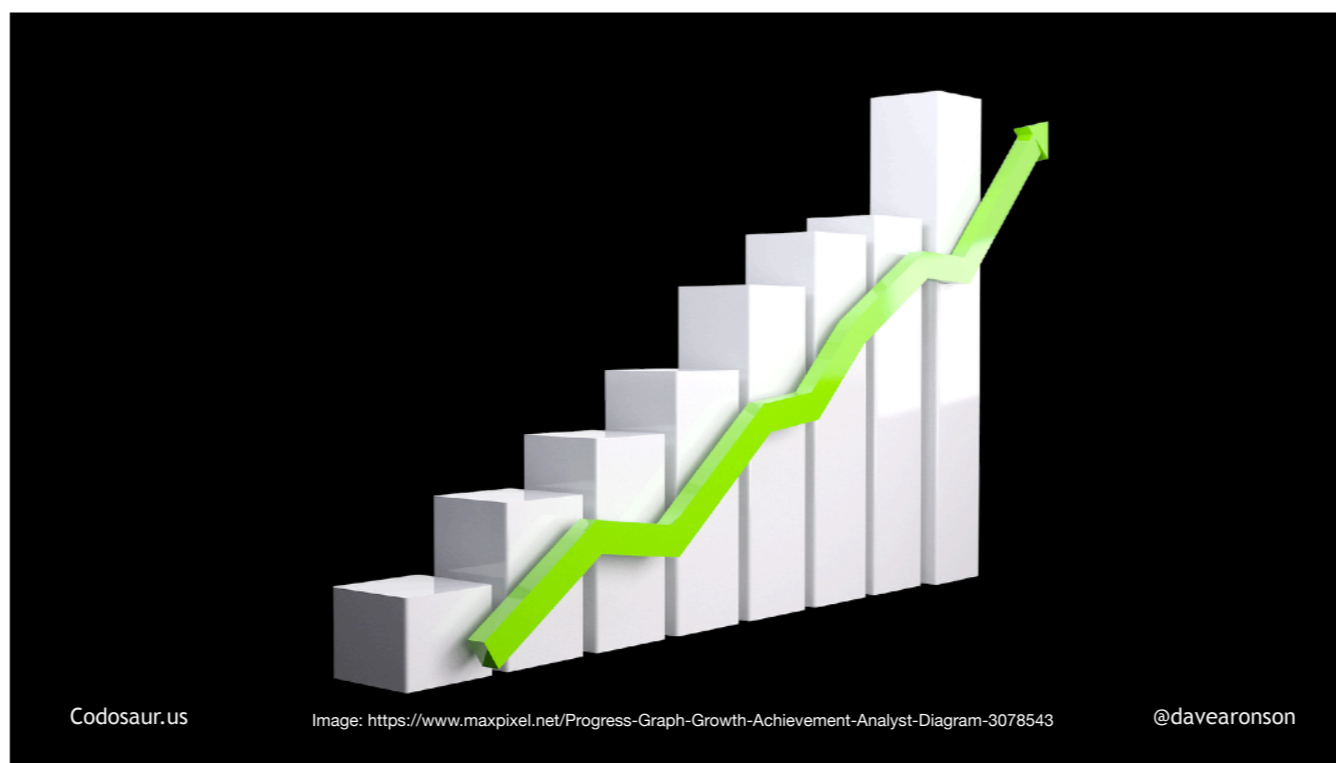


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Image: <https://www.jtfb.southcom.mil/Media/Photos/igphoto/2000888525/>

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. . . hard labor for the CPU, and therefore usually rather sloooow. We certainly won't want to mutation-test our whole codebase on every save! Maybe over a lunch break for a smallish system, or a weekend for a large one. Fortunately, most tools let us just check specific functions, files, and so on, plus they usually include some kind of . . .



. . . incremental mode, so that we can test only the changes since the last mutation test, or the last git commit, or the main branch, or some such difference. That, maybe we can do on each save, if we save often, use short-lived branches, and so on, like we know we're supposed to do but don't always.

Also, its CPU-intensive nature can really . . .



. . . run up our bills on cloud platforms such as AWS or Azure! (Or aZURE, however you PRONounce it.)

Another drawback is that mutation testing is . . .

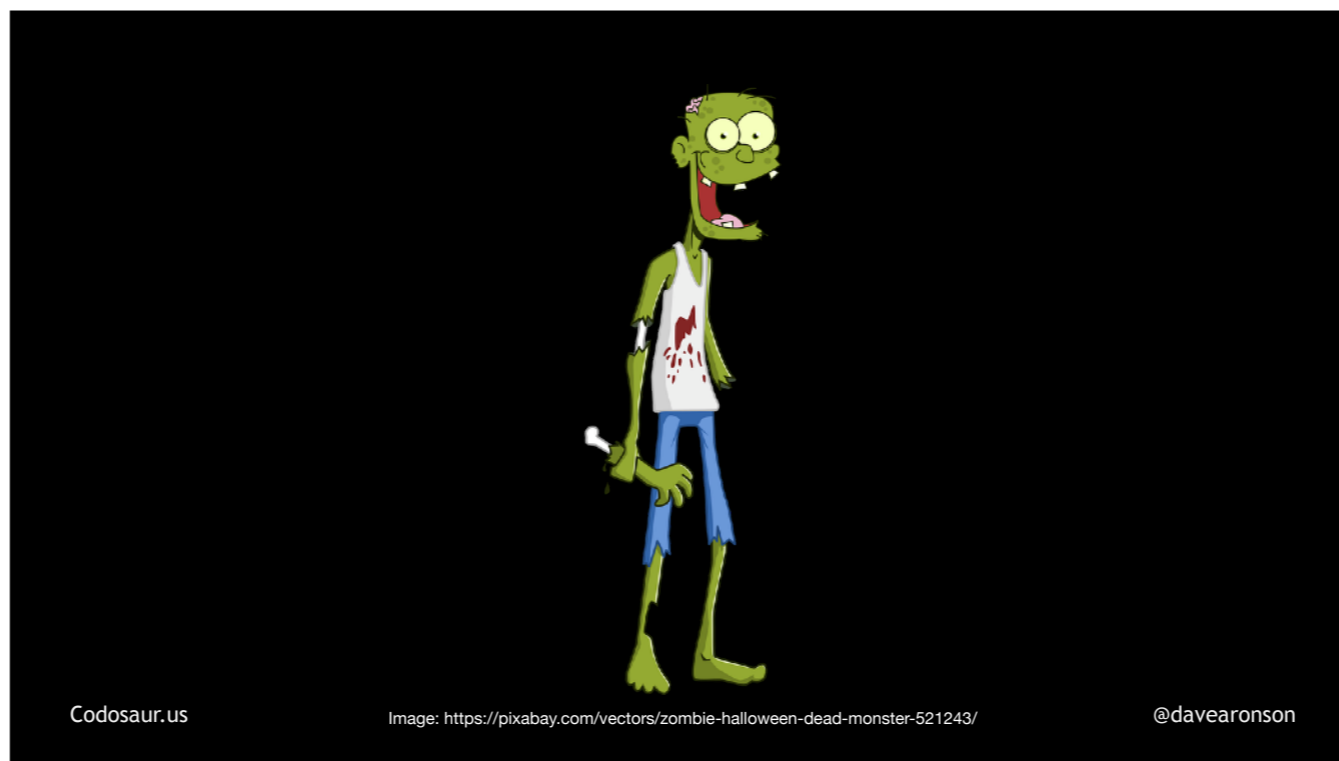


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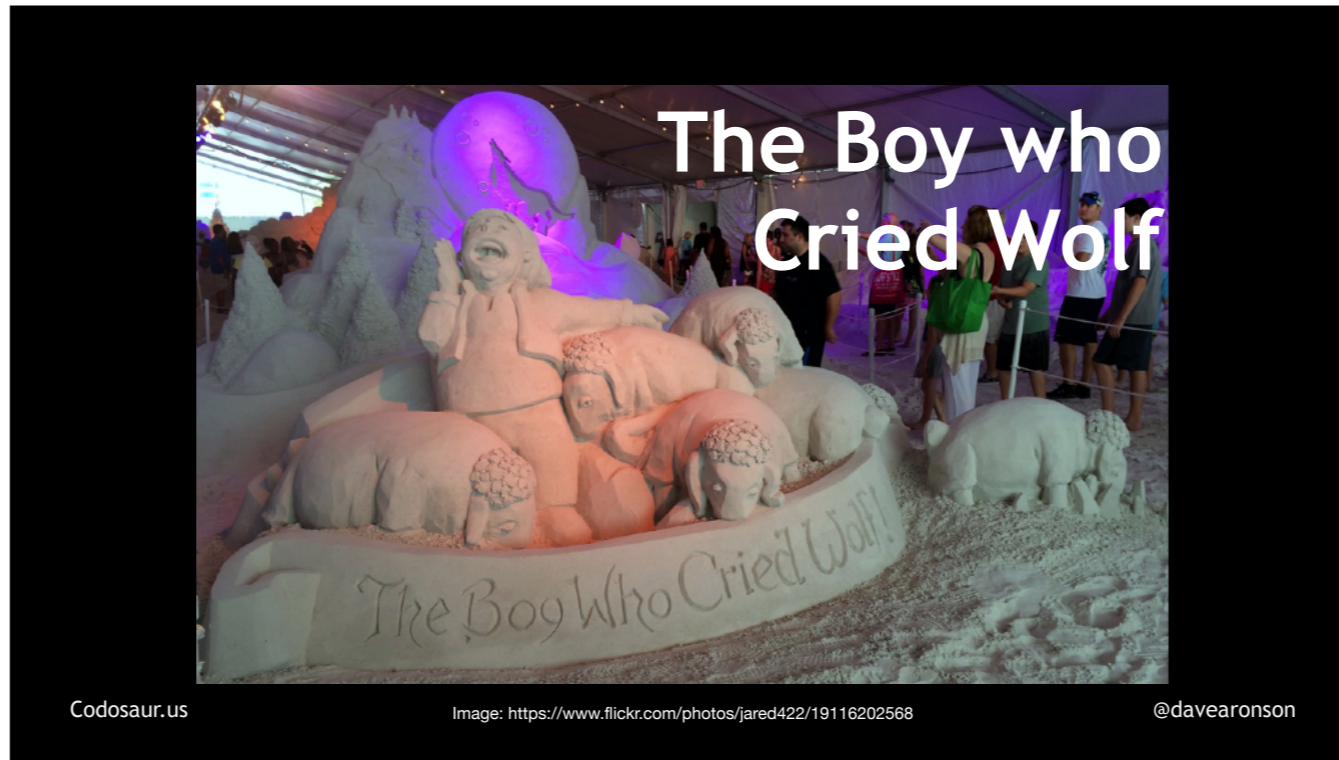
Image: <https://www.flickr.com/photos/ell-r-brown/5866767106>

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. . . not at all a beginner-friendly technique! It tells us that some particular change to the code made no difference to the test results, but what does *that* even mean? It takes a lot of interpretation to figure out what a mutant is trying to tell us. Their accent is verrah straynge, and they're almost as incoherent as . . .



. . . zombies, but with a much bigger vocabulary, so they're not always on about braaaaaains. They're *usually* trying to tell us that our code is meaningless, or our tests are lax, or both, but it can be very hard to figure out exactly *how!* Even worse, sometimes it's a . . .



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Image: <https://www.flickr.com/photos/jared422/19116202568>

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. . . false alarm, because the mutation didn't make a test fail, but it didn't make any real difference in the first place. It can still take quite a lot of time and effort to figure *that* out.

Even if a mutation *does* make a difference, there is normally quite a lot of code that we . . .



. . . *shouldn't bother* to test. For instance, if we have a debugging log message that says "The value of X is" and then the value of X, that constant part will get mutated, but we don't really care! Fortunately, most tools have ways to say "don't bother mutating this line", or even this whole function, maybe this module, or file . . . but that's usually with comments, which can clutter up the code, and make it less readable.

Now that we've seen the pros and cons, how does mutation testing work, unlike the bloke on this sign? It . . .

### Point Mutations

**DNA** ——— **mRNA**

**Normal**  
DNA: GUUCGAUUGA / CAAGCTAACT  
mRNA: GUUCGAUUGA

**Missense**  
DNA: GUUCGUUGA / CAAGCAACT  
mRNA: GUUCGUUGA

**Frameshift insertion**  
DNA: GUUCGAUUGA / CAAGCTAACT  
mRNA: GUUCGAUUGA

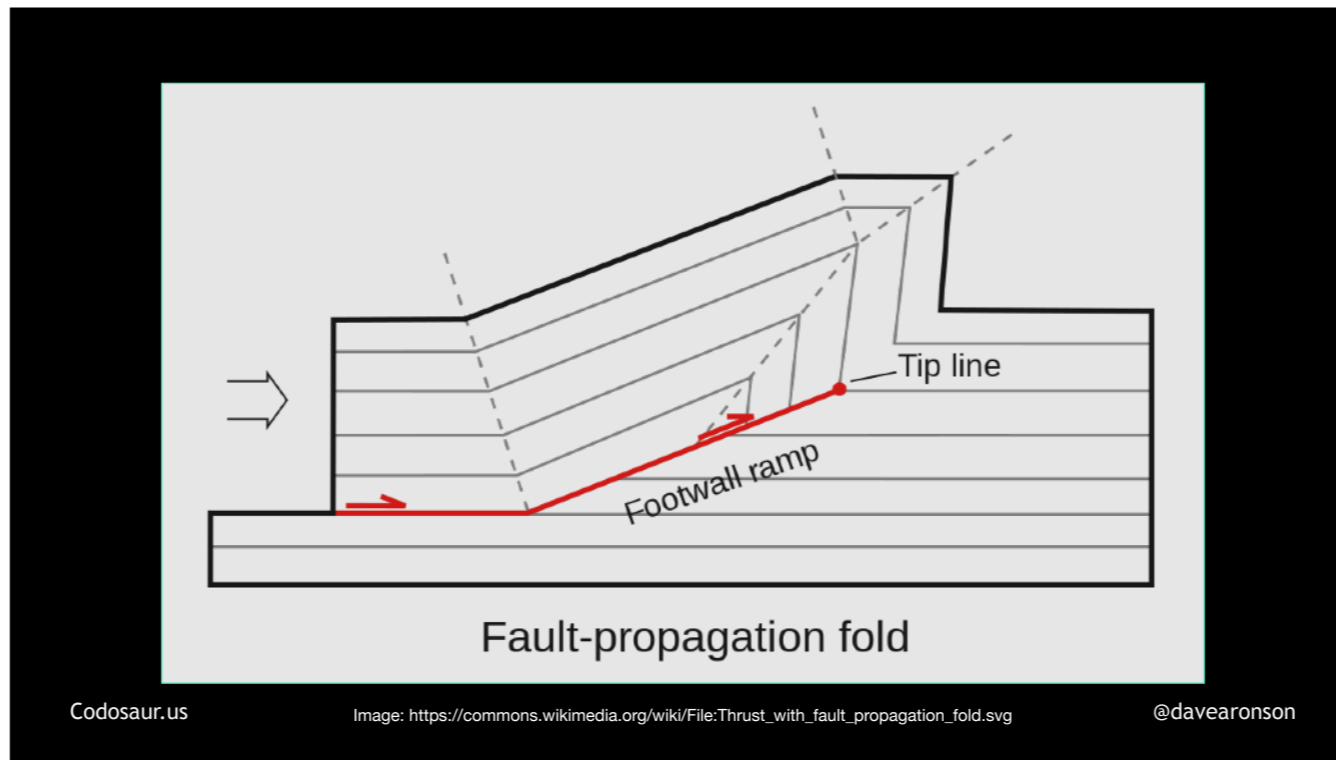
**Frameshift deletion**  
DNA: GUUCUUGA / CAAGAACT  
mRNA: GUUCUUGA

**Nonsense**  
DNA: GUUUGG / CAATCC  
mRNA: GUUUGG (STOP)

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. . . *mutates* copies of our code, hence the name. It does this to create test failures, also known as . . .



. . . faults. So, mutation testing can be categorized as a *fault-based* testing technique. This means it is related to something you might already be familiar with:



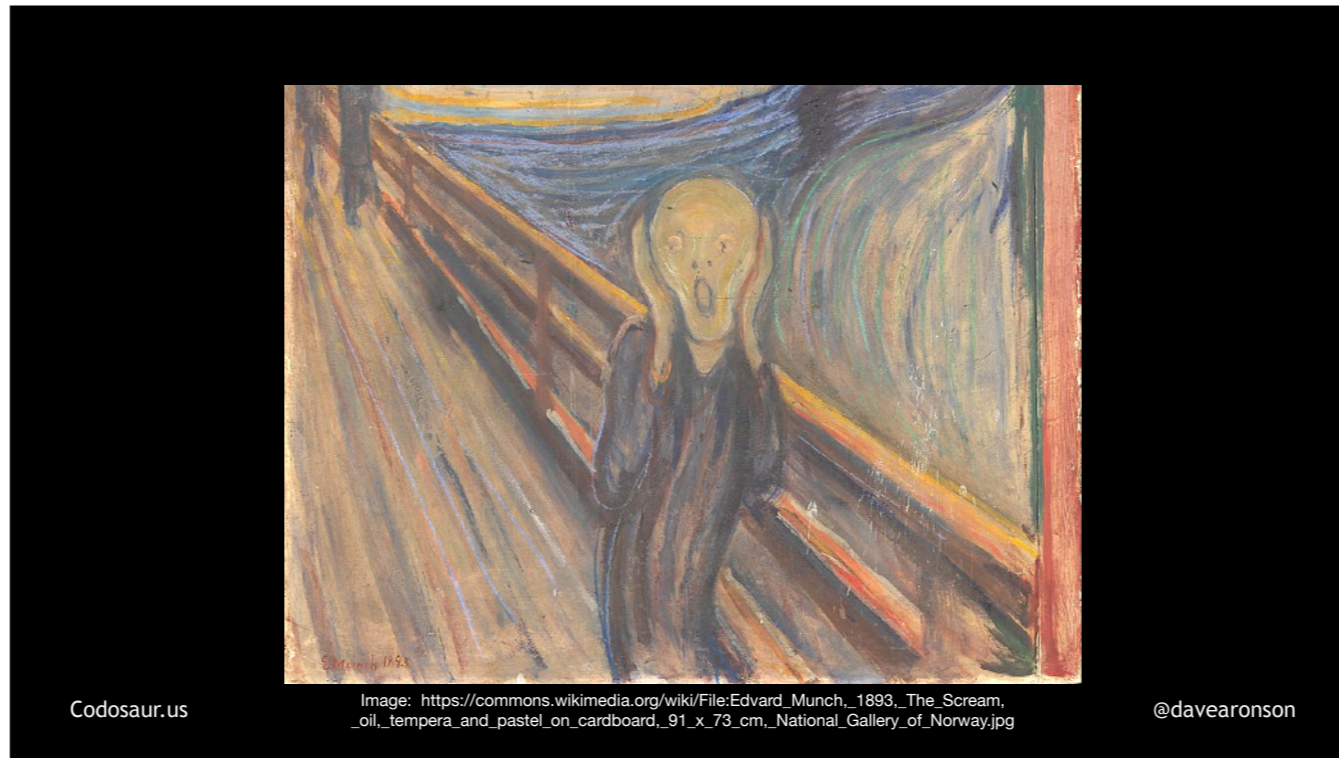
. . . Chaos Monkey, from Netflix. Just like Chaos Monkey helps Netflix discover flaws in their error recovery, mutation testing helps us discover flaws in our tests and our code. But the way mutation testing does it, is sort of . . .



. . . upside down from what Chaos Monkey does. Chaos Monkey is best known for . . .



. . . injecting faults, such as dropped connections, into Netflix's . . .

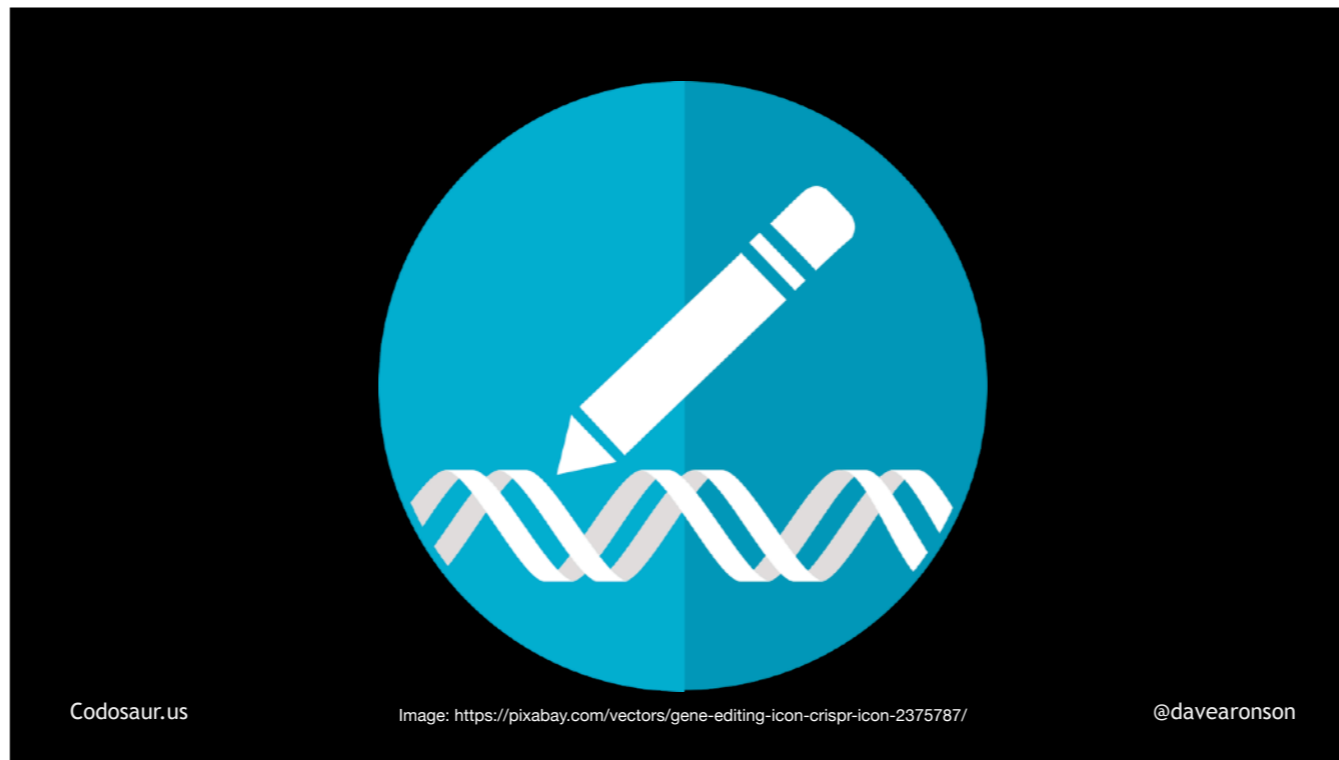


. . . production network.

If all still goes well, in the sense that Netflix's customers don't notice, and their metrics are still good, then Netflix knows that their error recovery is working fine. Mutation testing, however, injects semantic . . .



. . . *changes*, not necessarily *problems*. It doesn't usually *know* whether these semantic changes will create *faults* or not. We certainly hope they all will, but that depends on the test suite. It injects them *into* . . .



. . . copies of our code, not our actual network. It does its work in our . . .



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Image: <https://sservi.nasa.gov/articles/ladee-vibration-testing-complete/>

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. . . *test* environment, not production. (Whew!) And if everything still goes well, *in the sense that* . . .



```
$ mutation_tester
.....
.....
.....
.....
.....
.....
.....
280 tests, 0 assertions, 0 mutants,
0 failures, 0 errors, 0 excluded
```



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... there *is* a problem! Remember, each change to our code should make *at least* one test *fail*.

Mutation testing has also been compared to ...



. . . fuzzing, a security penetration technique involving throwing random data at an application. Mutation testing is somewhat like fuzzing our *code* rather than fuzzing the *data*, but it's . . .



. . . not random. These tools have a set of mutations they know how to do. The smarter ones can use the results of simpler mutations, to know they don't need to bother with more complex ones, so it's not doing everything it knows how to do, but it's still not random.

But enough about differences. What exactly does mutation testing *do*, and how? Let's start with a high-level view. First, our chosen tool . . .

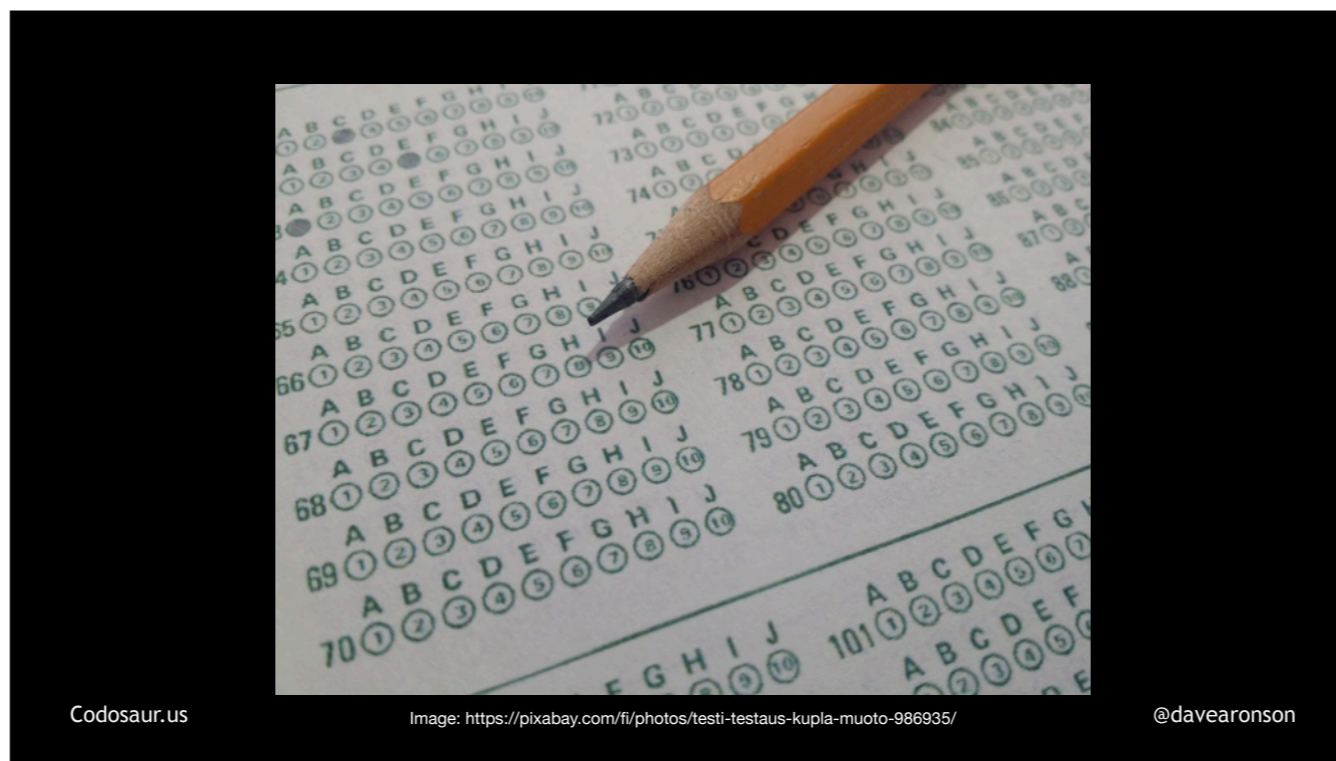


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Image: <https://commons.wikimedia.org/wiki/File:Disassembled-rubix-1.jpg>

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. . . breaks our code apart into pieces to test. Usually, these are our functions -- or methods if we're using an object-oriented language, but I'm just going to say functions. Then, for each function, it tries to find . . .



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Image: <https://pixabay.com/fi/photos/testi-testaus-kupla-muoto-986935/>

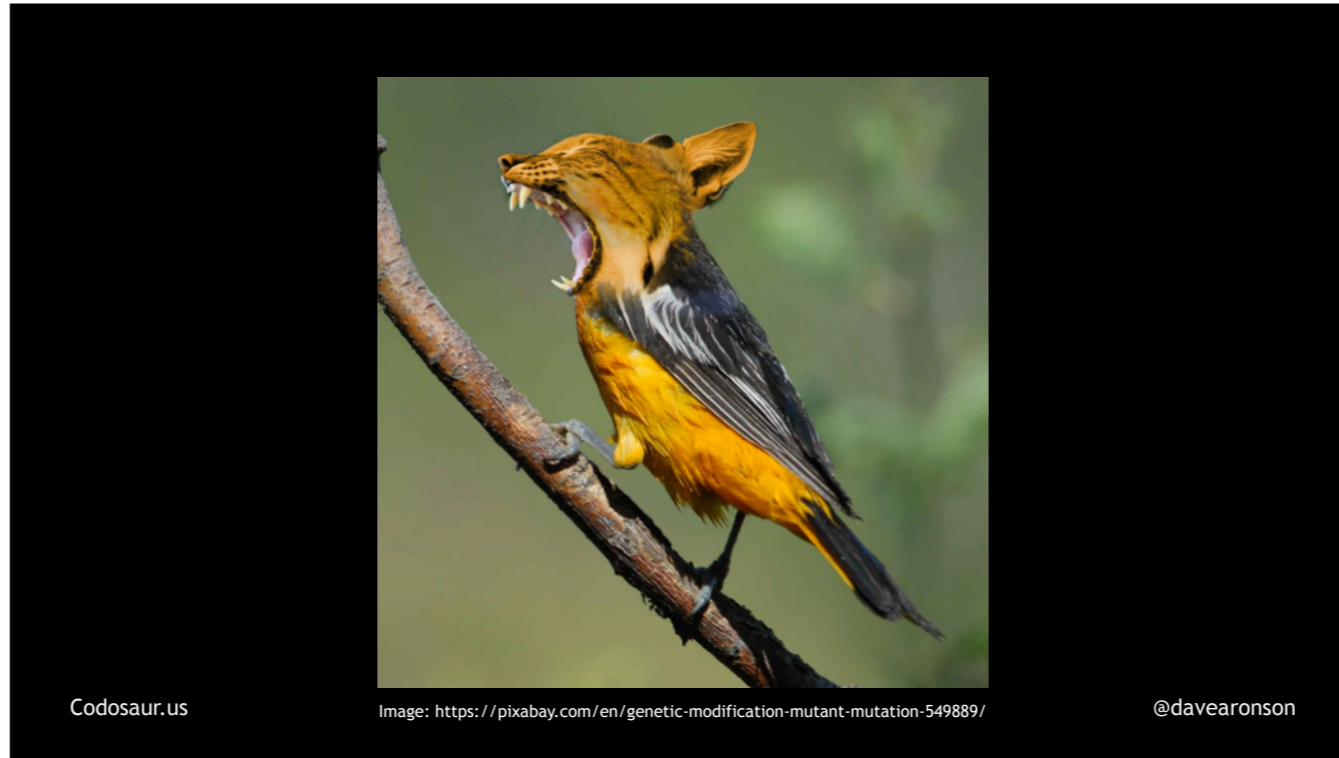
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. . . the *tests* that cover that function. If the tool can't find any applicable tests, most will simply skip this function. Better yet, those will usually warn us, so we know we need to add or annotate some tests. (More on that later.) Some, though, will use the whole test suite, which is horribly inefficient, because it's running a lot of tests that are not relevant to this function.

Assuming we aren't skipping this function, next the tool . . .



. . . makes the mutants. To do that, it looks closely at this function to see how it can be changed. For each tiny little way the tool sees to change this function, the tool makes . . .



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Image: <https://pixabay.com/en/genetic-modification-mutant-mutation-549889/>

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. . . one mutant, with *that one tiny little change*.

Once our tool is done creating all the mutants it can for a given function, it iterates over . . .



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Image: <https://www.flickr.com/photos/39160147@N03/15074089655>

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. . . that list. And now we get to the heart of the concept.

Mutating function whatever, at something.ex:42											
Test #	1	2	3	4	5	6	7	8	9	10	Result
Mutant #											
1	✓	✓	✓	✓	🕒						In Progress
2											To Do
3											To Do
4											To Do
5											To Do

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This chart represent the progress of our tool. The tools generally don't give us quite all this information, let alone so well organized, but it's a conceptual model I use to illustrate the point.

For each . . .

Mutating function whatever, at something.ex:42

Test #	1	2	3	4	5	6	7	8	9	10	Result
Mutant #											
1	✓	✓	✓	✓	🕒						In Progress
2											To Do
3											To Do
4											To Do
5											To Do

. . . mutant, derived from . . .

Mutating function whatever, at something.ex:42

Test #	1	2	3	4	5	6	7	8	9	10	Result	
Mutant #												
1	✓	✓	✓	✓	🕒						In Progress	
2											To Do	
3											To Do	
4											To Do	
5											To Do	

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... a given function, the tool runs the function's ...

Mutating function whatever, at something.ex:42

Test #	1	2	3	4	5	6	7	8	9	10	Result	
Mutant #												
1	✓	✓	✓	✓	🕒						In Progress	
2											To Do	
3											To Do	
4											To Do	
5											To Do	

. . . tests, but it runs them . . .

Mutating function whatever, at something.ex:42

Test #	1	2	3	4	5	6	7	8	9	10	Result	
Mutant #												
1	✓	✓	✓	✓	🕒						In Progress	
2											To Do	
3											To Do	
4											To Do	
5											To Do	

... using the *current mutant* in place of the original function.

(PAUSE) If any test ...

Mutating function whatever, at something.ex:42

Test #	1	2	3	4	5	6	7	8	9	10	Result
Mutant #											
1	✓	✓	✓	✓	✗						In Progress
2											To Do
3											To Do
4											To Do
5											To Do

... *fails*, this is called ...



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Image: <https://pixabay.com/id/illustrations/tengkorak-dan-tulang-bersilang-mawar-693484/>

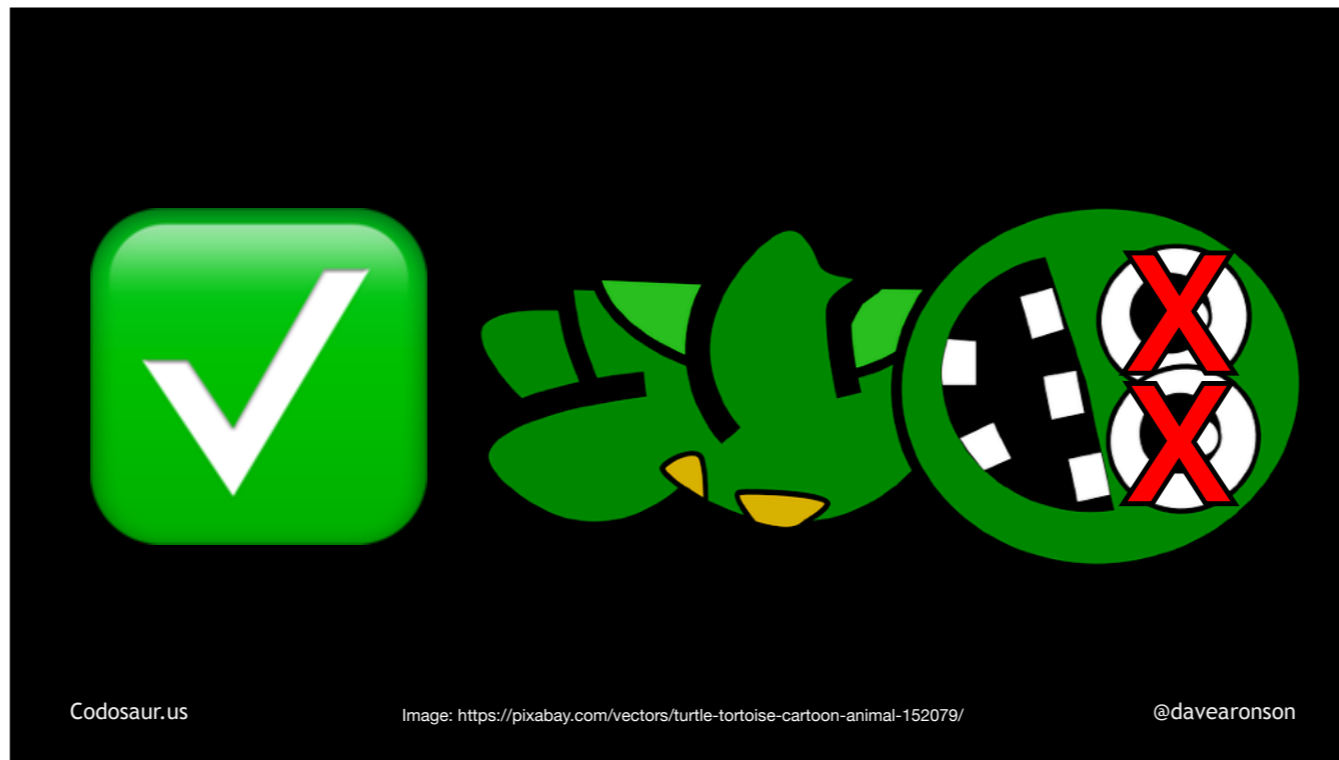
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. . . “killing the mutant”. And now for a brief detour. Some people . . .



. . . object to this “violent communication”, especially since, in the comic books, mutants are often metaphors for marginalized groups of people, and the tech industry is *finally* starting to become more sensitive to such issues. I’ve been trying to come up with something nicer, but the terminology is pretty well established, so it’s hard to change, so for this presentation, I’m going to stick to the standard term of “killing” the mutant.

Anyway, whatever we *call* it, it’s a . . .



... *good* thing. It means that our code is *meaningful* enough that the tiny change that the tool made, to *create* this mutant, actually made a noticeable difference in the function's behavior, *and* that our *test* suite is *strict* enough that at least one test actually *noticed* that difference, and failed. Then, the tool will ...

Mutating function whatever, at something.ex:42

Test #	1	2	3	4	5	6	7	8	9	10	Result
Mutant #											
1	✓	✓	✓	✓	✗						Killed
2											To Do
3											To Do
4											To Do
5											To Do

. . . mark that mutant killed, . . .

Mutating function whatever, at something.ex:42

Test #	1	2	3	4	5	6	7	8	9	10	Result
Mutant #											
1	✓	✓	✓	✓	✗						Killed
2											To Do
3											To Do
4											To Do
5											To Do

. . . stop running any more tests against it, and . . .

Mutating function whatever, at something.ex:42											
Test #	1	2	3	4	5	6	7	8	9	10	Result
Mutant #											
1	✓	✓	✓	✓	✗						Killed
2	🕒										In Progress
3											To Do
4											To Do
5											To Do

. . . move on to the next one. Once a mutant has made *one* test fail, we don't care how many more it *could* make fail, like perhaps some of . . .

Mutating function whatever, at something.ex:42											
Test #	1	2	3	4	5	6	7	8	9	10	Result
Mutant #											
1	✓	✓	✓	✓	✗						Killed
2	🕒										In Progress
3											To Do
4											To Do
5											To Do

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. . . tests six through ten for Mutant #1. Like so much in computers, we only care about ones and zeroes.

On the other claw, if a mutant . . .

Mutating function whatever, at something.ex:42											
Test #	1	2	3	4	5	6	7	8	9	10	Result
Mutant #											
1	✓	✓	✓	✓	✗						Killed
2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	In Progress
3											To Do
4											To Do
5											To Do

... lets all the tests pass, then the mutant is said to have ...

Mutating function whatever, at something.ex:42											
Test #	1	2	3	4	5	6	7	8	9	10	Result
Mutant #											
1	✓	✓	✓	✓	✗						Killed
2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Survived!
3											To Do
4											To Do
5											To Do

... *survived*. That means that the mutant has the ...



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Image: [https://nl.wikipedia.org/wiki/Bestand:Mimic\\_Octopus2.jpg](https://nl.wikipedia.org/wiki/Bestand:Mimic_Octopus2.jpg)

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. . . superpower of mimicry, skilled enough to *fool our tests!* This usually means that our code is meaningless, or our tests are lax, or both — and now it's up to us to figure out how.

Now let's peel back one . . .



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Image: <https://pixabay.com/fi/photos/avaruusolento-marsin-vihreä-hirviö-722415/>

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. . . layer of the onion, and look at some *technical details* of how this works. First, our tool parses . . .

```
defmodule Conway do
  @alive "*"
  @dead  " "

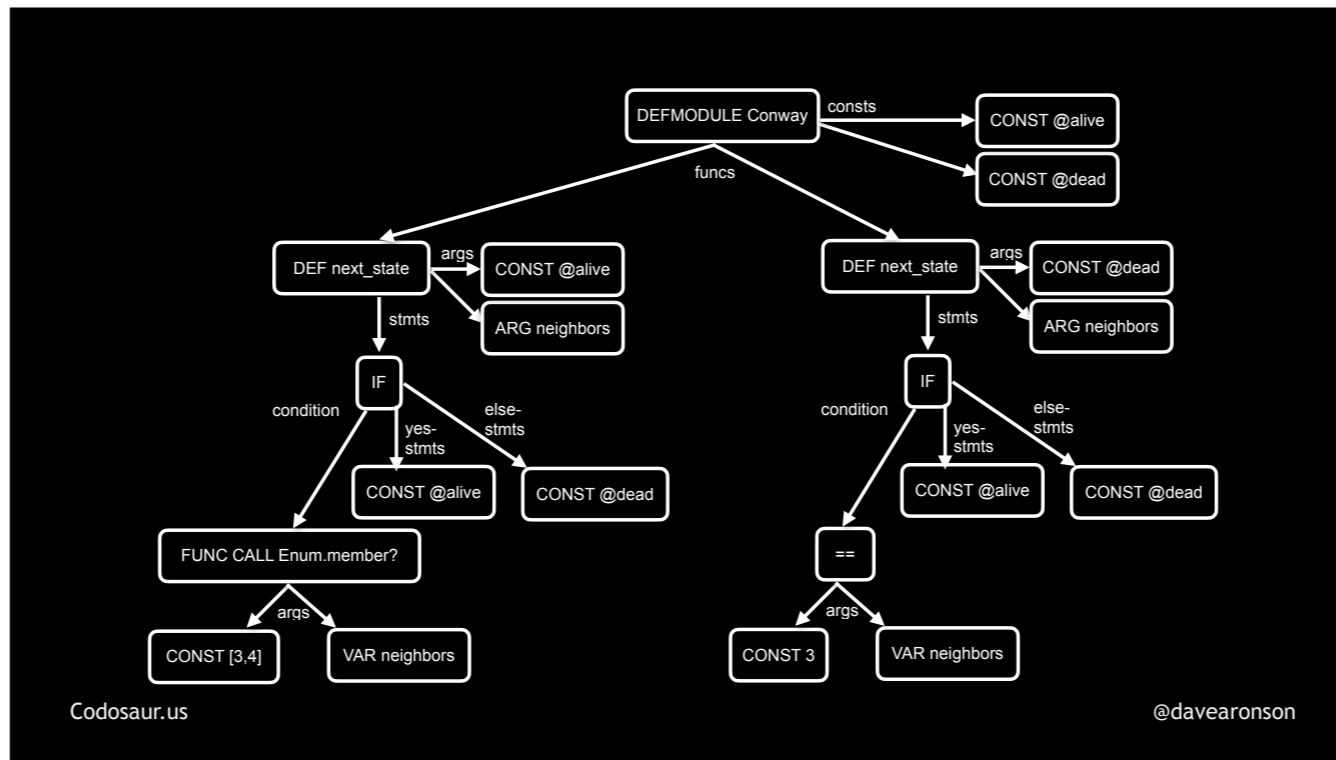
  def next_state(@alive, neighbors),
    do: if Enum.member?([3, 4], neighbors),
         do: @alive, else: @dead

  def next_state(@dead, neighbors),
    do: if neighbors == 3,
         do: @alive, else: @dead
end
```

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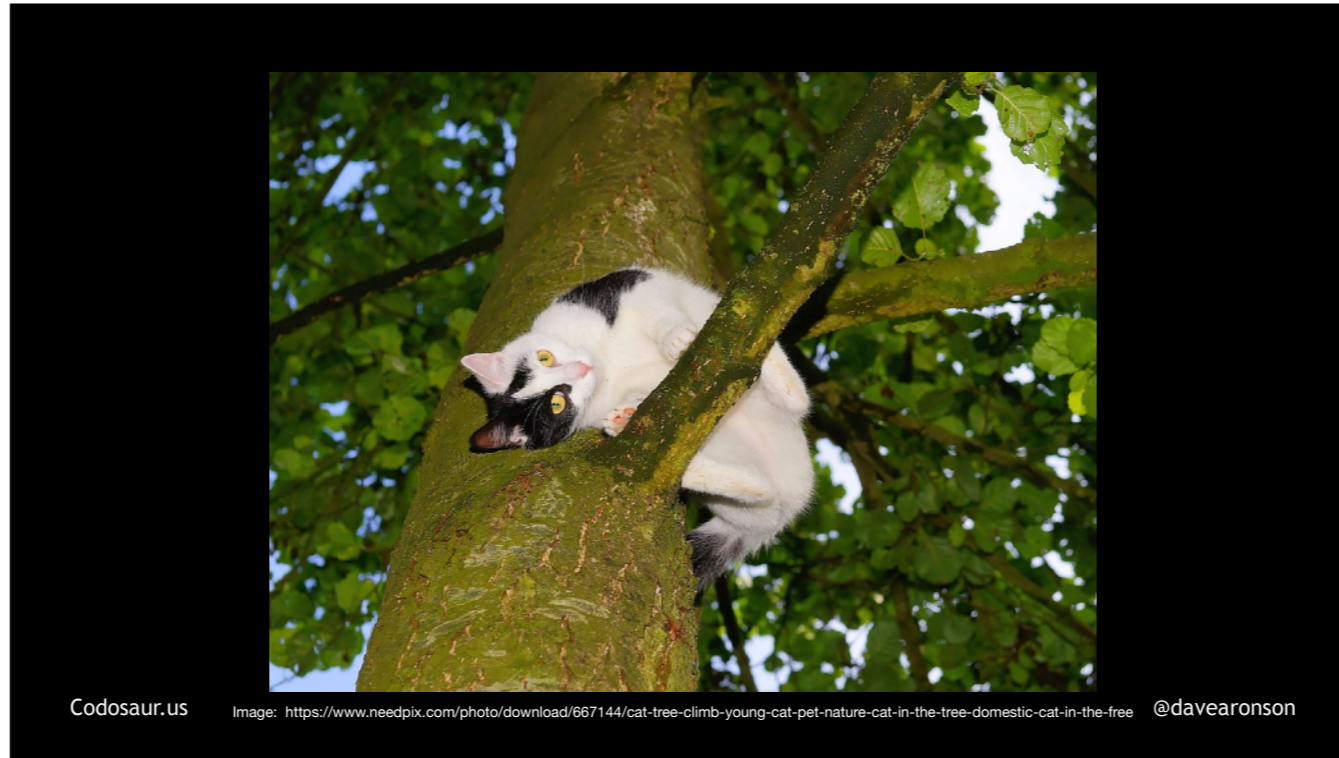
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. . . our code, usually into an Abstract Syntax Tree, so that this code becomes . . .



. . . this AST. I'm going to assume that you're familiar with the concept of an AST, but don't worry about understanding this one in detail, just notice that there are two subtrees in there that represent functions, the ones rooted at DEF nodes. They have the same name, but that's okay in some languages.

Anyway, after the tool creates an AST out of our code, then it . . .



. . . traverses the tree, looking for sub-trees, or branches if you will, that represent each function. After finding *them*, it handles each one as I described before, starting with looking for each one's *tests* . . . but how does it do *that*? That usually relies mainly on us developers, either . . .

```
@mumu tests-for foo  
test "#foo turns 3 into 6" do  
  foo(3).must_equal 6  
end  
  
test "#foo turns 4 into 10" do  
  foo(4).must_equal 10  
end
```

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... annotating our tests, as I hinted at earlier, or following some kind of ...

```
test "#foo turns 3 into 6" do
  foo(3).must_equal 6
end
```

```
test "#foo turns 4 into 10" do
  foo(4).must_equal 10
end
```

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. . . convention in naming the tests, the files, or perhaps both. These manual techniques are often supplemented and sometimes even replaced by . . .

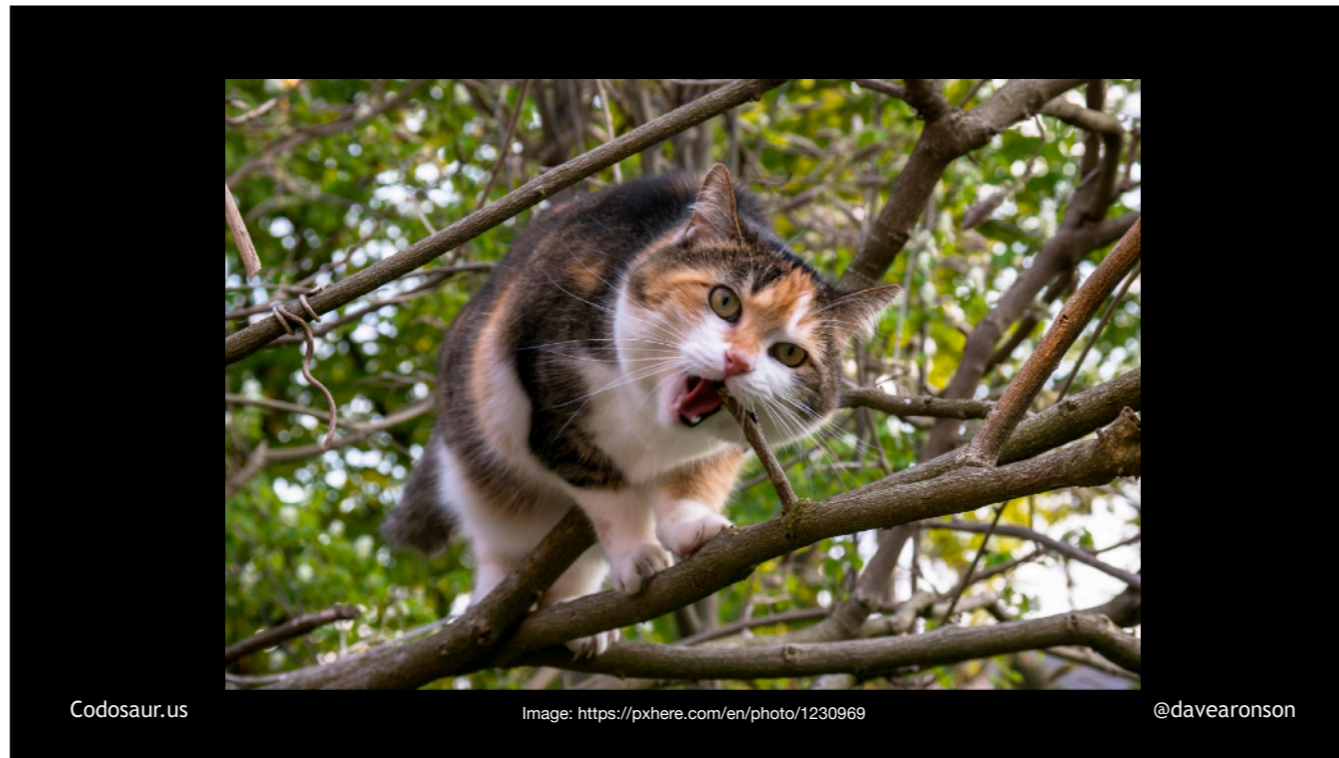
```
test "#foo turns 3 into 6" do
  foo(3).must_equal 6
end
```

```
test "#foo turns 4 into 10" do
  foo(4).must_equal 10
end
```

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. . . the tool looking at what tests call what functions, though that can get tricky and unreliable. After the tool has found the function's tests, then, assuming it won't skip this function because it *didn't* find any tests, it makes the mutants. To make mutants *from* an AST subtree, it . . .

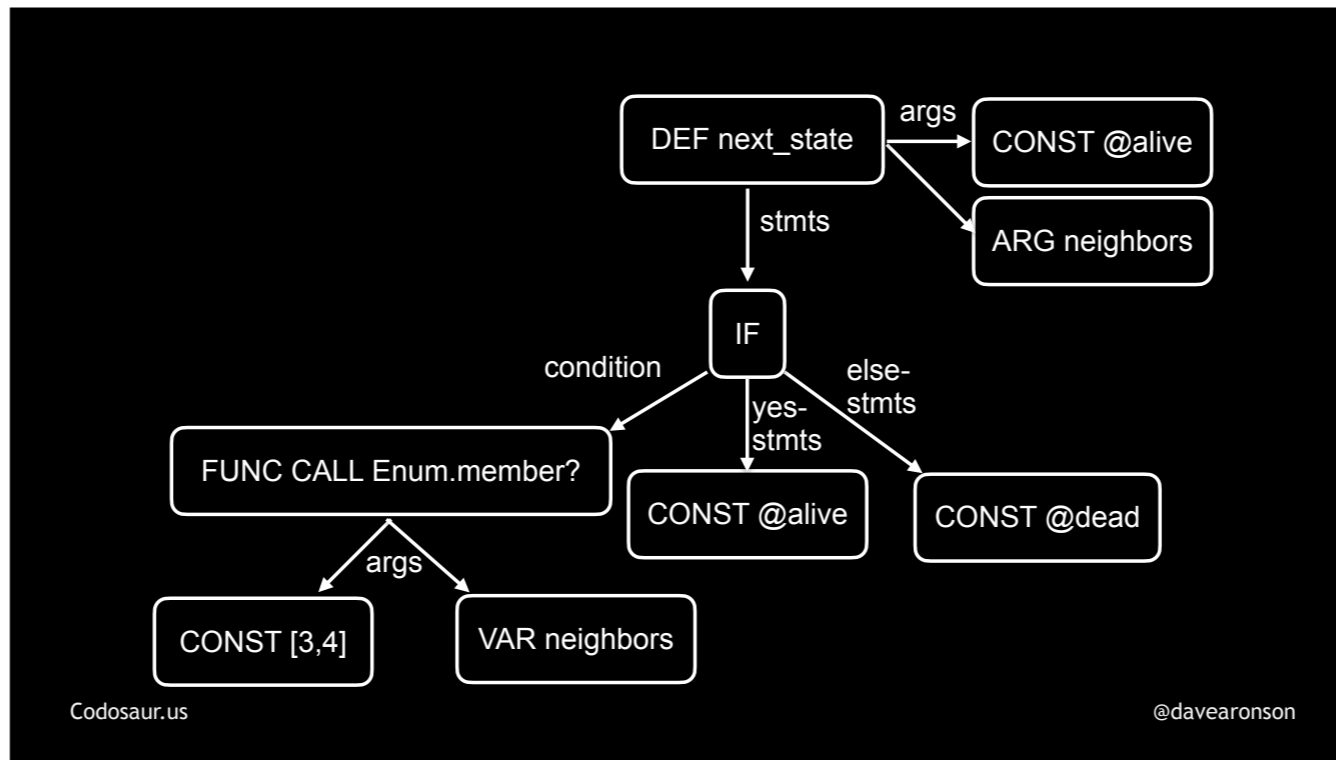


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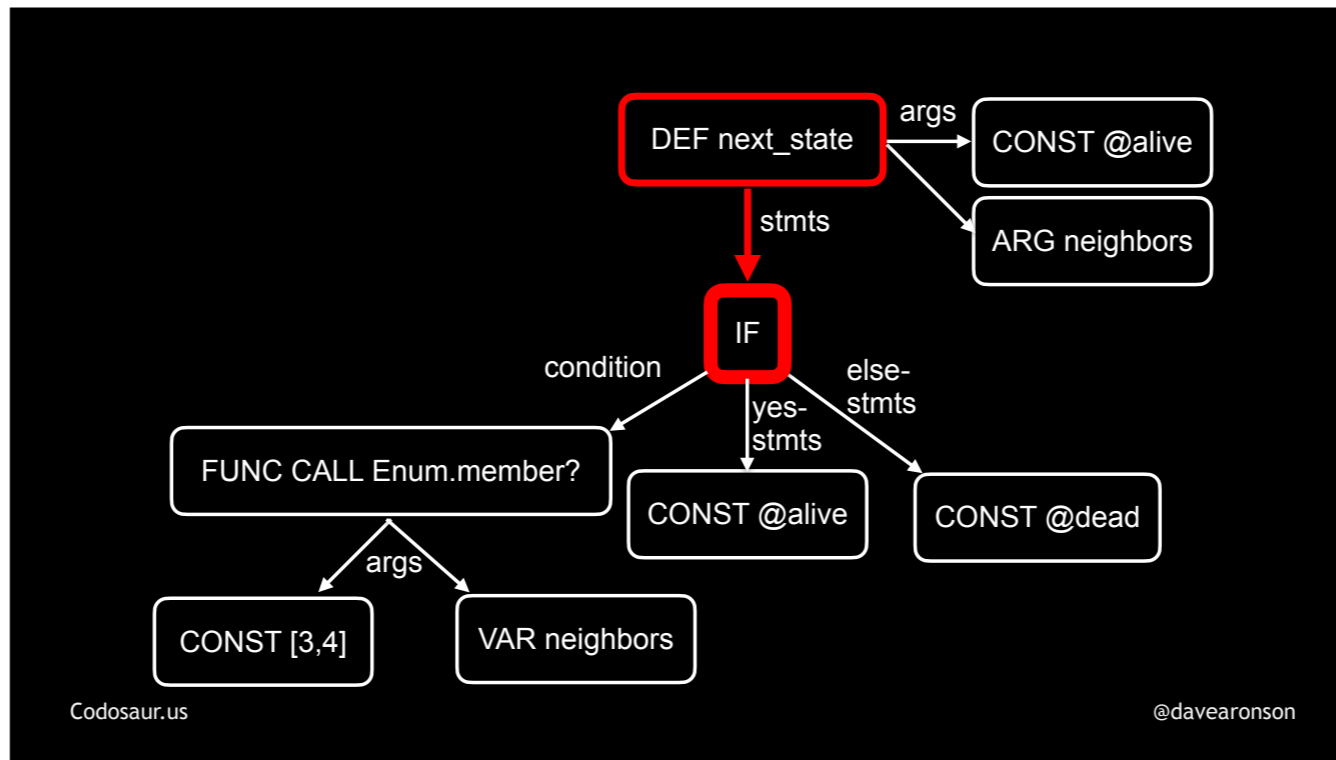
Image: <https://pxhere.com/en/photo/1230969>

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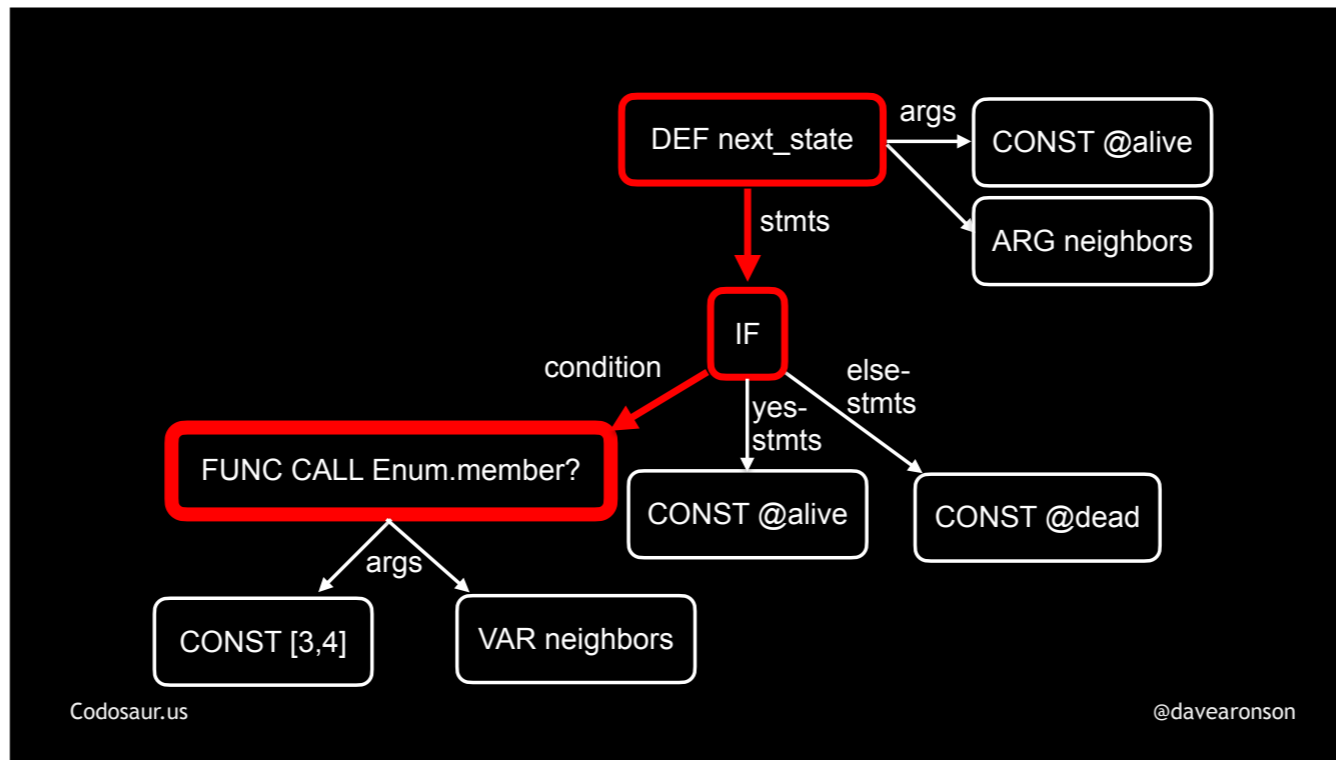
. . . traverses that subtree, just like it did to the whole thing. However, now, instead of looking for even *smaller* subtrees it can *extract*, like twigs or something, it looks for *nodes* where it can *change* something. Each time it finds one, then for each way it can change that node, it makes one copy of the function's AST subtree, with that one node changed, in that one way. For instance, suppose our tool has started traversing . . .



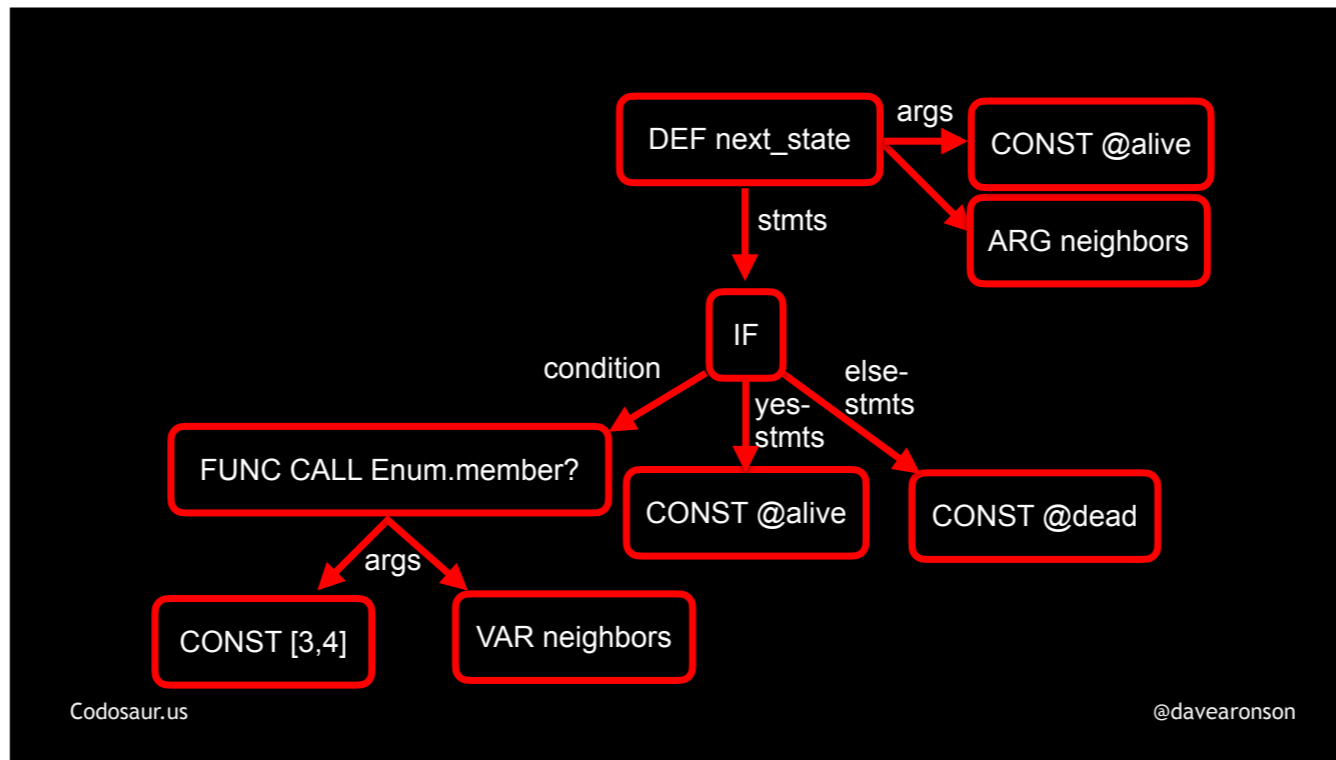
. . . one of the function subtrees from the AST I showed earlier, and has only gotten down to . . .



. . . this if statement. For each way the tool could change that node, it would make a fresh copy, of this whole subtree, with only that one node changed, in that one way. After it's done making as many mutants as it can from *that* node, it would continue traversing the subtree, to . . .



... another node. Again, for each way it could change *that* node, it would make a copy of this whole subtree, with only that mutation. And so on, until it has .  
..



. . . traversed the entire subtree.

Now, I've been talking a lot about changing things, so what kind of changes are we talking about? There are quite a lot!

`x + y` could become: `x - y`  
`x * y`  
`x / y`  
`x ** y`

`x || y` could become: `x && y`  
`x ^ y`

`x | y` could become: `x & y`  
`x ^ y`

Maybe even swap *between sets!*

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It could change a mathematical, logical, or bitwise operator from one to another.

In languages and situations where we can do so, it could even substitute an operator from a different category. For instance, in many languages, we can treat *anything* as *booleans*, so *x times y* could become, for instance, *x and y*, or *x bitwise-exclusive-or y*.

`x - y` could also become `y - x`

`x / y` could also become `y / x`

`x ** y` could also become `y ** x`

`"x" <> "y"` could also become `"y" <> "x"`

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When the *order* of operands matters, such as in subtraction, division, exponentiation, or string concatenation, it could *swap* them.

`x < y`

could become:

`x <= y`

`x == y`

`x != y`

`x >= y`

`x > y`

It could change a *comparison* from one to another.

$x$

could become:

$-x$

$!x$

$\sim x$

. . . or vice-versa!

It could insert *or remove* a mathematical, logical, or bitwise *negation*.

```
a = foo(x)  
b = bar(y)
```

could become:

```
a = foo(x)
```

or

```
b = bar(y)
```

It can remove an entire *statement*.

```
if x == y, do: foo(z)
```

could become:

```
foo(z)
```

It can remove an if-condition, so that something that might be skipped or done, is always done.

```
while x == y, do: foo(z)
```

could become:

```
foo(z)
```

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It can remove a looping condition, so that something that might be skipped, done once, or done *multiple* times, is always done once.

```
def f(x, y), do: x * y
could become:
def f(x, y), do: 0
def f(x, y), do: :math.max_int
def f(x, y), do: "a string"
def f(x, y), do: nil
def f(x, y), do: x
def f(x, y), do: fail("boom")
def f(x, y), do: # nothing
etc.
```

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It could replace a function's *entire contents* with returning a constant, or any of the arguments, or raising an error, or nothing at all, if the language permits, as many do.

```
42      43      "42"      :math.min_int
could   41      [42]      :math.max_int
become: -42     {42}      :math.min_float
        1       []       :math.max_float
        0       {}       :math.infinity
        -1      %{}      :math.epsilon
        42.1    nil      etc.
        41.9
```

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It could change a value item to some other value, such as changing 42 to any of these, and many more but I had to stop somewhere. It could even change it to something of a different and possibly incompatible type, such as changing a number into a, if I may quote . . .



. . . Smeagol, “string, or nothing!”

There are *many* many more types of changes, but I trust you get the idea!

From here on, there are no more low-level details I want to add, so let’s peel back one last layer, and look at . . .

```
for function in find_functions(Application)
  tests = find_tests(function)
  if none?(tests)
    warn_about_no_tests(function)
    next function
  end
  for mutant in make_mutants(function)
    for test in tests
      if (fails(test, with_code: mutant))
        next mutant
      end
    end
    end
    report_as_surviving(mutant)
  end
end
```

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. . . some pseudocode illustrating how it works. I'll wait a bit so you have some time to take pictures.  
(TODO: INSERT SOME TALKING HERE!)

Everybody done taking pictures?

Now let's *finally* walk through some *examples!* We'll start with an easy one. Suppose we have a function . . .

```
def power(x, y) do
  x ** y
end
```

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. . . like so. Never mind *why*, it makes a good simple example, so let's just roll with it.

Think about what a mutant made from this might *return*, since that's what our tests would probably be looking at. It sure doesn't look like it has side effects.

Mainly it could return results such as . . .

```
x + y      :math.min_int
x - y      :math.max_int
x * y      :math.max_float
x / y      :math.min_float
y ** x     :math.infinity
x          :math.epsilon
y         raise(DeliberateError)
0         "some random string"
1         []
-1        {}
0.1       %{}
-0.1      nil
```

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. . . any of *these* expressions or constants, and, again, many more but I had to stop somewhere.

Now suppose we had only one test . . .

```
assert power(2, 2) == 4
```

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. . . like so. This is a rather poor test, and I think why is immediately obvious to most of us, but even so, *most* of those mutants on the previous slide *would get killed* by this test, the ones shown . . .

<code>x + y</code>	<code>:math.min_int</code>
<del><code>x - y</code></del>	<del><code>:math.max_int</code></del>
<code>x * y</code>	<code>:math.max_float</code>
<del><code>x / y</code></del>	<del><code>:math.min_float</code></del>
<code>y ** x</code>	<code>:math.infinity</code>
<del><code>x</code></del>	<del><code>:math.epsilon</code></del>
<del><code>y</code></del>	<del><code>raise(DeliberateError)</code></del>
<del><code>0</code></del>	<del><code>"some-random-string"</code></del>
<del><code>1</code></del>	<del><code>{}</code></del>
<del><code>-1</code></del>	<del><code>{}</code></del>
<del><code>0.1</code></del>	<del><code>%{}</code></del>
<del><code>-0.1</code></del>	<del><code>nil</code></del>

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. . . here in crossed-out green. The ones returning constants, are very unlikely to match. There's no particular reason a tool would put a 4 there, as opposed to zero, 1, -1, infinity, minus infinity, and other such significant numbers. Subtracting gets us zero, dividing gets us one, returning either argument alone gets us two, and the mismatched types and deliberate errors will at *least* make the test not pass. But . . .

```
x + y
x - y
x * y
x / y
y ** x
y
0
1
-1
0.1
-0.1

:math.min_int
:math.max_int
:math.max_float
:math.min_float
:math.infinity
:math.epsilon
raise(DeliberateError)
"some-random-string"
[]
{}
%{}
nil
```

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. . . addition, multiplication, and exponentiation in the reverse order, all get us the correct answer. Mutants based on *these* mutations will therefore "survive" this test.

So how do we see that happening? When we run our tool, it gives us a report, that looks roughly like . . .

```
function "power" (demo.ex:42)
has 4 surviving mutants:
```

```
42 - def power(x, y) do
42 + def power(y, x) do
```

```
43 -   x ** y
43 +   x + y
```

```
43 -   x ** y
43 +   x * y
```

```
43 -   x ** y
43 +   y ** x
```

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. . . this. The exact words, format, amount of context, etc., will depend on exactly which tool we use, but the information should be pretty much the same.

To fully unpack this, it's saying that if we changed . . .

```
function "power" (demo.ex:42)  
has 4 surviving mutants:
```

```
42 - def power(x, y) do  
42 + def power(y, x) do
```

```
43 -   x ** y  
43 +   x + y
```

```
43 -   x ** y  
43 +   x * y
```

```
43 -   x ** y  
43 +   y ** x
```

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. . . the function called power, which is in . . .

```
function "power" (demo.ex:42)  
has 4 surviving mutants:
```

```
42 - def power(x, y) do  
42 + def power(y, x) do
```

```
43 -   x ** y  
43 +   x + y
```

```
43 -   x ** y  
43 +   x * y
```

```
43 -   x ** y  
43 +   y ** x
```

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. . . file demo.ex, and starts at line 42 . . .

```
function power (demo ex:42)  
has 4 surviving mutants:
```

```
42 - def power(x, y) do  
42 + def power(y, x) do
```

```
43 -   x ** y  
43 +   x + y
```

```
43 -   x ** y  
43 +   x * y
```

```
43 -   x ** y  
43 +   y ** x
```

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. . . in any of four different ways, then all its tests would still pass.

It then goes on to tell us that those four ways are: . . .

```
function "power" (demo.ex:42)  
has 4 surviving mutants:
```

```
42 - def power(x, y) do  
42 + def power(y, x) do
```

```
43 -   x ** y  
43 +   x + y
```

```
43 -   x ** y  
43 +   x * y
```

```
43 -   x ** y  
43 +   y ** x
```

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. . . to change line 42 to swap the arguments, or . . .

```
function "power" (demo.ex:42)
has 4 surviving mutants:
```

```
42 - def power(x, y) do
42 + def power(y, x) do
```

```
43 - x ** y
43 + x + y
```

```
43 - x ** y
43 + x * y
```

```
43 - x ** y
43 + y ** x
```

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. . . change line 43 to change the exponentiation into addition or multiplication, or . . .

```
function "power" (demo.ex:42)
has 4 surviving mutants:
```

```
42 - def power(x, y) do
42 + def power(y, x) do
```

```
43 -   x ** y
43 +   x + y
```

```
43 -   x ** y
43 +   x * y
```

```
43 -   x ** y
43 +   y ** x
```

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... to change line 43 to to swap the operands.

So what is ...

```
function "power" (demo.ex:42)
has 4 surviving mutants:
```

```
42 - def power(x, y) do
42 + def power(y, x) do
```

```
43 -   x ** y
43 +   x + y
```

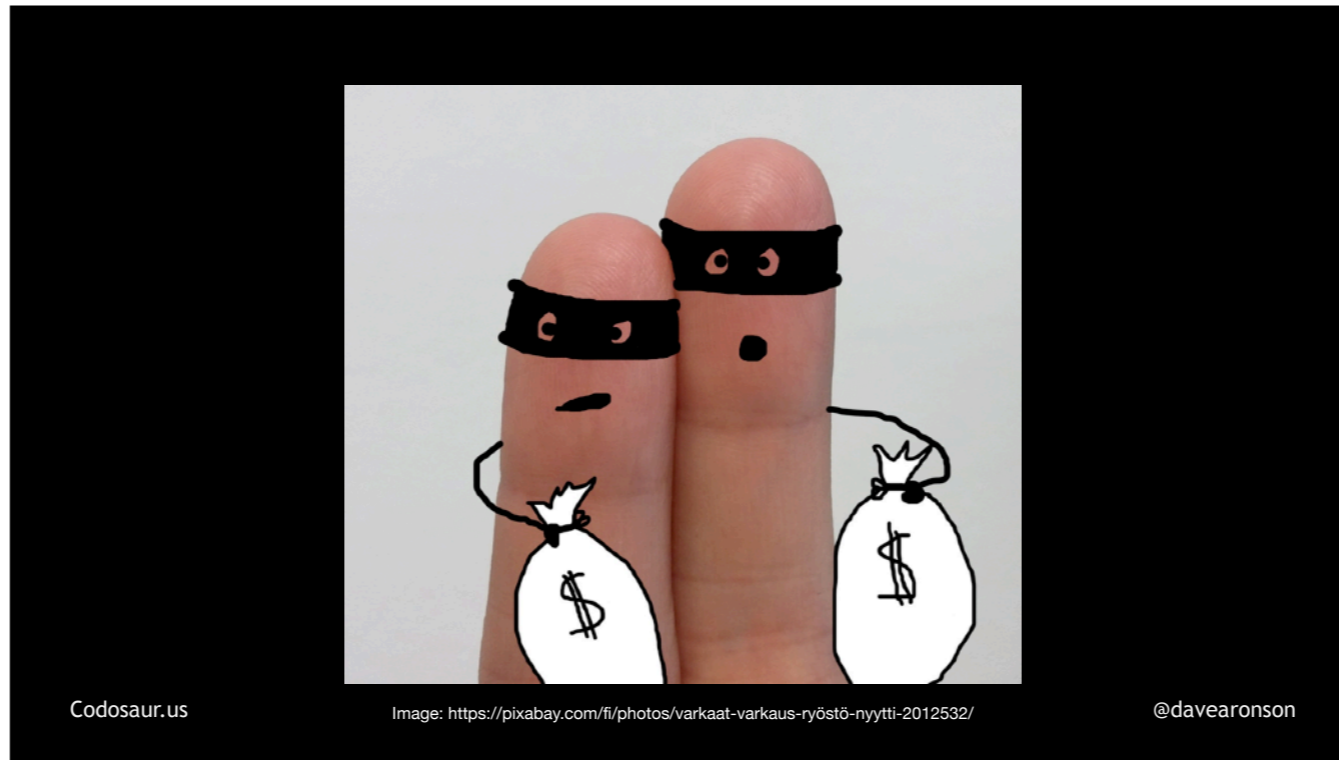
```
43 -   x ** y
43 +   x * y
```

```
43 -   x ** y
43 +   y ** x
```

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. . . this set of surviving mutants trying to tell us? The very high level message is that our test suite is not sufficient, either because there aren't enough tests, or the ones we have just aren't very good, or both. But we knew that! The question boils down to, how are these mutants surviving? Are they . . .



. . . pulling heists? Are they getting free room and board at the . . .



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Image: <https://pixabay.com/fi/photos/varkaat-varkaus-ryöstö-nyytti-2012532/>

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. . . Xavier Institute? Or what?

The usual answer is that . . .

```
original_power(x, y)
==
mutant_power(y, x)
```

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. . . they return the same result as the original function. Or they have the same side effect — whatever our tests are looking at. To determine how *that* happens, we can take a closer look, at one mutant, and a test it passes. Let's start with . . .

the change:

```
43 - x ** y
```

```
43 + x + y
```

our test:

```
assert power(2, 2) == 4
```

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... the "plus" mutant. Looking at the change, together with our test, makes it much clearer that this one survives because ...



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Image: meme going around, original source unfindable, sorry

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. . . two *plus* two equals two *to* the second power. (And so does two *times* two, but he's in the background, so we'll save him for later.)

So how can we *kill* . . .

the change:

```
43 - x ** y  
43 + x + y
```

our test:

```
assert power(2, 2) == 4
```

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. . . this mutant, in other words, make at least one test fail when run against it? It's quite simple in this case. We need to make at least one test use inputs such that *x to the y* is different from *x plus y*. For instance, we could add a test or change our test to . . .

```
assert power(2, 4) == 16
```

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. . . something like this, asserting that two to the *fourth* power is *sixteen*. All the mutants that our original test killed, *this would still kill*. Two *plus* four is six, not *sixteen*, so this should kill the plus mutant just fine. For that matter, two *times* four is eight, which is *also* not sixteen, so this would kill the "times" mutant as well. You'll often find that killing one mutant, kills others as well.

However, . . .



. . . the (ahem) pair of argument-swapping mutants survive! That's okay, we can . . .



. . . attack them separately, no need to kill all the mutants at once and be some kind of superhero about it. To kill *them*, again, we can either add a test, or adjust an existing test, to . . .

```
assert power(2, 3) == 8
```

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. . . assert that two to the *third* power is *eight*. Three squared is nine, not eight, so this kills the argument-swapping mutants. Better yet, two *plus* three is five, two *times* three is six, and both of those are, guess what, not eight, so the "plus" and "times" mutants *stay* dead, and we don't get any . . .



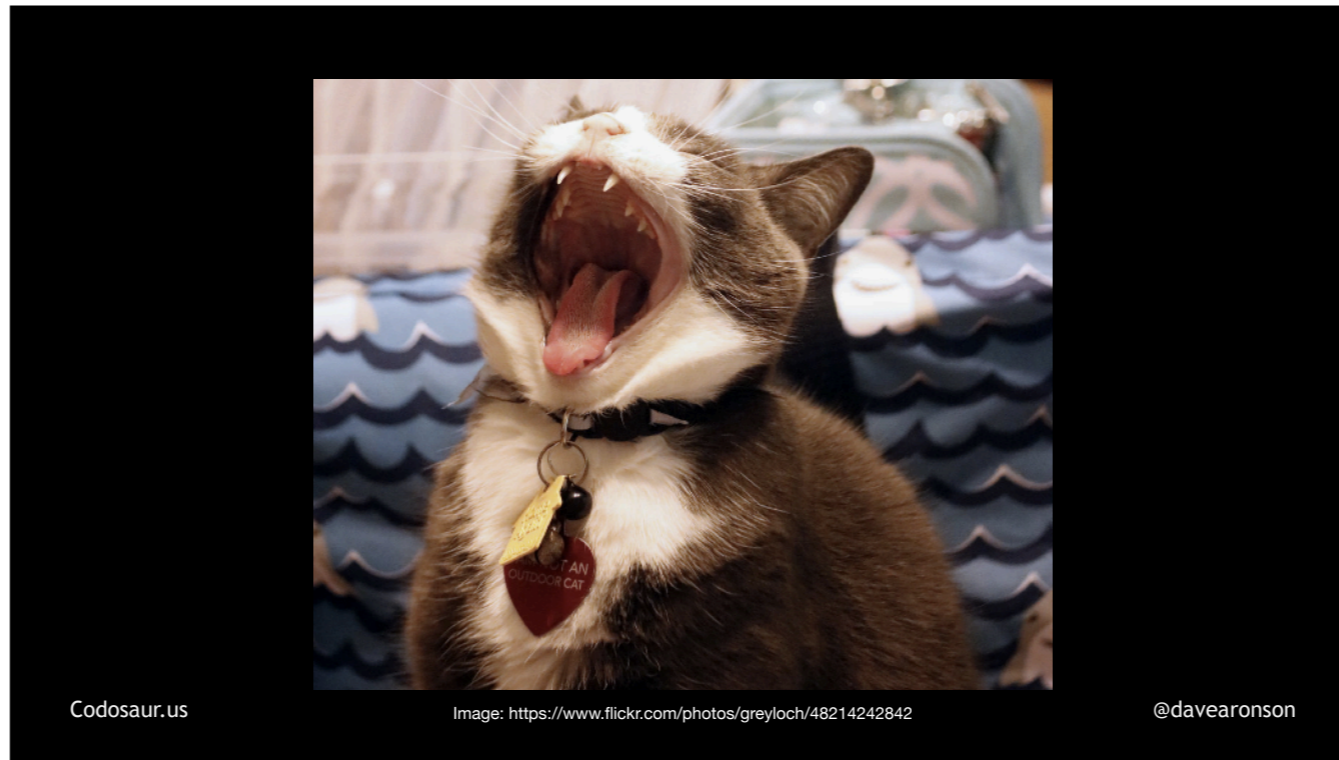
. . . zombie mutants wandering around, even if . . .

```
assert power(2, 3) == 8
```

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. . . this were still our one and only test. (PAUSE!) With these inputs, the correct operation is the only simple common one that yields the correct answer. This isn't the *only* solution, though; we could have used two to the *fifth*, *three* squared, three to the fifth, vice-versa, and infinitely more. Even if we stuck to single digits, there are *lots* of ways to skin . . .



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Image: <https://www.flickr.com/photos/greyloch/48214242842>

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. . . *that* flerken!

This may make mutation testing sound . . .



. . . simple, but this is a downright trivial example, so we could easily think up arguments to make *all* mutants, within reason, behave differently from the original code.

So let's look at a more *complex* example!

Suppose we have a function to send a message, . . .

```
def send_message(buf, len)
  sent = 0
  while sent < len
    sent_now = send_bytes(buf + sent,
                          len - sent)

    sent += sent_now
  end
  sent
end
```

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. . . like so. This function, `send_message`, sends as much data as `send_bytes` can handle in one chunk, looping to pick up where it left off, until the message is all sent. This is a very common pattern in communication software.

A mutation testing tool could make lots of mutants from this, but one of particular interest, would be . . .

```
def send_message(buf, len)
  sent = 0
-  while sent < len
    sent_now = send_bytes(buf + sent,
                          len - sent)

    sent += sent_now
-  end
  sent
end
```

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. . . this, removing those lines with the minus signs, an example of removing a looping conditional.

That would make the code read effectively like . . .

```
def send_message(buf, len)
  sent = 0

  sent_now = send_bytes(buf + sent,
                        len - sent)

  sent += sent_now

  sent
end
```

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... this.

Now suppose that this mutant does indeed survive our test suite, which consists mainly of ...

```
assert send_message(msg, size) == size
```

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. . . *this*. (PAUSE!) There's a bit more that I'm not going to show you *quite* yet, dealing with setting the size and creating the message. Even without seeing that test code though, what does the survival of that non-looping mutant tell us? (PAUSE!)

If a mutant that only goes through . . .

```
def send_message(buf, len)
  sent = 0
  while sent < len
    sent_now = send_bytes(buf + sent,
                          len - sent)

    sent += sent_now
  end
  sent
end
```

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. . . that loop once, acts the same as our normal code, as far as our tests can tell, that means that our *tests* are only making our code go through that loop once. So what does that mean? (PAUSE!) By the way, you'll find that interpreting mutants involves a lot of asking "*so what does that mean*", often deeply recursively!

In this case, it means that we're not testing sending a message larger than `send_bytes` can handle in one chunk! There are many ways that can happen, but the most *likely* is that we simply didn't test with a big enough message. For instance, . . .

```
in module Network:
```

```
max_chunk_size = 10_000
```

```
in test_send_message:
```

```
msg = "foo"
```

```
size = length(msg)
```

```
# other setup, like stubbing send_bytes
```

```
assert send_message(msg, size) == size
```

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. . . suppose our maximum chunk size, what `send_bytes` can handle in one chunk, is 10,000 bytes. However, for whatever reason, . . .

```
in module Network:
    max_chunk_size = 10_000

in test_send_message:
    msg = "foo"
    size = length(msg)
    # other setup, like stubbing send_bytes
    assert send_message(msg, size) == size
```

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. . . we're only testing with a tiny little *three* byte message. Or maybe four if we have a null terminator, maybe a bit more depending just how it's serialized, but almost certainly nowhere near 10\_000. (PAUSE!)

The obvious fix is to use a message larger than our maximum chunk size. We can easily construct one, as shown . . .

```
in module Network:
```

```
max_chunk_size = 10_000
```

```
in test_send_message:
```

```
size = Network::max_chunk_size + 1
```

```
msg = "x" * size
```

```
# other setup, like stubbing send_bytes
```

```
assert send_message(msg, size) == size
```

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... here. (PAUSE!) We just take the maximum size, add some, we could add 1, double it, whatever, and construct that big a message.

But perhaps, to paraphrase Shakespeare, the fault, dear Melbourne, is not in our tests, but in our code, that these mutants are survivors. Maybe we *did* test with the *largest* permissible message, out of a set of predefined messages, or at least message *sizes*. For instance, ...

```
in module Message:
```

```
SmallMsgSize = 1_000
```

```
LargeMsgSize = 5_000
```

```
in test_send_message:
```

```
size = Message::LargeMsgSize
```

```
msg = Message.make_msg("a" * size)
```

```
# other setup, like stubbing send_bytes
```

```
assert send_message(msg, size) == size
```

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. . . here we have Small and Large message sizes, we test with a Large, and yet, this mutant survives! In other words, we're still sending the whole message in one chunk. What could possibly be wrong with that? What is this mutant trying to tell us in this case? (PAUSE!)

In *this* scenario, it's trying to tell us that a version of `send_message` with the looping removed will do the job just fine. If we remove the looping, we wind up with . . .

```
def send_message(buf, len)
  sent = 0

  sent_now = send_bytes(buf + sent,
                        len - sent)

  sent += sent_now

  sent
end
```

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. . . this code I showed you earlier. If we run our mutation testing tool on *this*, it will show a lot of other stuff as now being redundant, because we only needed it to support the looping. If we *also* remove all of that, then it boils down to . . .

```
def send_message(buf, len)
  send_bytes(buf, len)
end
```

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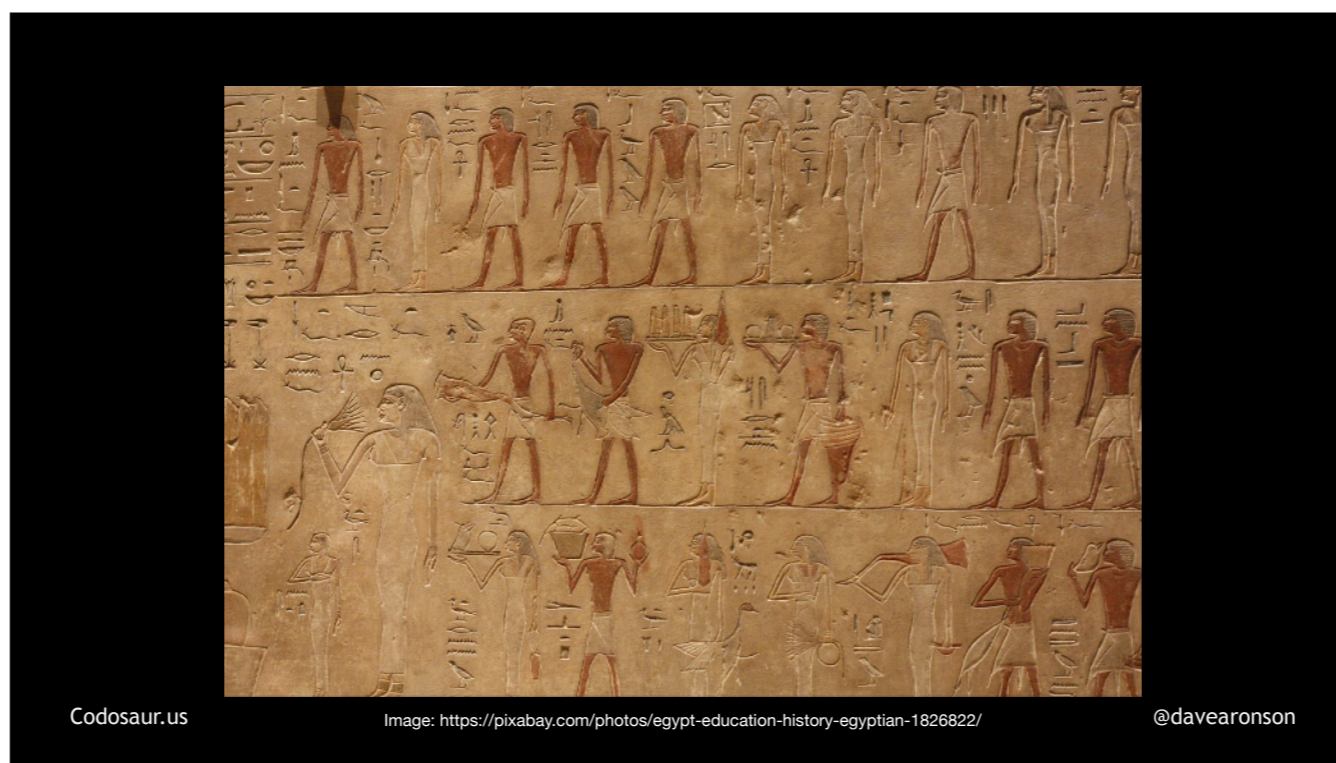
@davearonson

. . . this. (PAUSE!) Now it's pretty clear: the *entire* `send_message` function may well be *redundant*, so we can just use `send_bytes` directly! It might not be, though, because, in real-world code, there may be some logging, error handling, and so on, needed in `send_message`, but at the very least, the *looping* was redundant. Fortunately, when it's this kind of problem, with unreachable or redundant code, the solution is clear and easy, just rip out the extra junk that the mutant doesn't have. This will also make our code more *maintainable*, by getting rid of useless cruft.

Now that we've seen a few different examples, of spotting bad tests and redundant code, I'd like to address some . . .



. . . occasionally asked questions. (Mutation testing is still rare enough that I don't think there *are* any *frequently* asked questions!) First, this all sounds pretty weird, deliberately making tests fail, to prove that the code succeeds! Where did this whole bizarre idea come from anyway? Mutation testing has a surprisingly . . .



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Image: <https://pixabay.com/photos/egypt-education-history-egyptian-1826822/>

@davearonson

. . . long history -- at least in the context of computers. It was first proposed in 1971, in Richard Lipton's term paper titled "Fault Diagnosis of Computer Programs", at Carnegie-Mellon University. The first *tool* didn't appear until nine years *later*, in 1980, as part of Timothy Budd's PhD work at Yale. Even so, it was not *practical* for most people, with consumer-grade computers, until recently, maybe the past couple decades, with advances in CPU *speed*, *multi-core* CPUs, larger and cheaper memory, and so on.

That leads us to the next question: *why* is it so CPU-intensive? To answer that, we need do some math, but don't worry, it's pretty basic. Suppose our functions have, on average, . . .

# 10 lines

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. . . about ten lines each. And each line has about . . .

**x**      **10 lines**  
**5 mutation points**

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. . . five places where it can be mutated, to any of about . . .

**10 lines**  
**x 5 mutation points**  
**x 20 alternatives**

---

. . . twenty alternatives. That works out to about . . .

$$\begin{array}{r} 10 \text{ lines} \\ \times 5 \text{ mutation points} \\ \times 20 \text{ alternatives} \\ \hline = 1000 \text{ mutants/function!} \end{array}$$

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. . . a thousand mutants for each function! And for each one, we'll have to run somewhere between one test, if we're lucky and kill it on the first try, all the way up to *all* of that function's tests, if we kill it on the last try, or worse yet, it survives.

Suppose we wind up running just . . .

**10 lines**  
**x 5 mutation points**  
**x 20 alternatives**  

---

**= 1000 mutants/function!**  
**x 10 % of the tests, each**

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. . . one *tenth* of the tests for each mutant. Since we start with a thousand mutants, that's still . . .

**10 lines**  
**x 5 mutation points**  
**x 20 alternatives**  

---

**= 1000 mutants/function!**  
**x 10 % of the tests, each**  

---

**= 100 x as many test runs!**

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. . . a *hundred times* the test runs for that function, compared to regular testing. If our test suite normally takes a zippy ten seconds, then with these assumptions, mutation testing will take about a *thousand* seconds. That might not sound like much, because I'm saying "seconds", but do the math and it's *almost 17 minutes!*

But there is some . . .



. . . good news! Over the past decade or so, there has been a lot of research on trimming down the number of mutants, mainly by weeding out ones that are semantically equivalent to the original code, redundant with other mutants, or trivial in various ways such as creating an obvious error condition. Such things have reduced the mutant horde down to about one third! But even with that rare level of success, it's still . . .



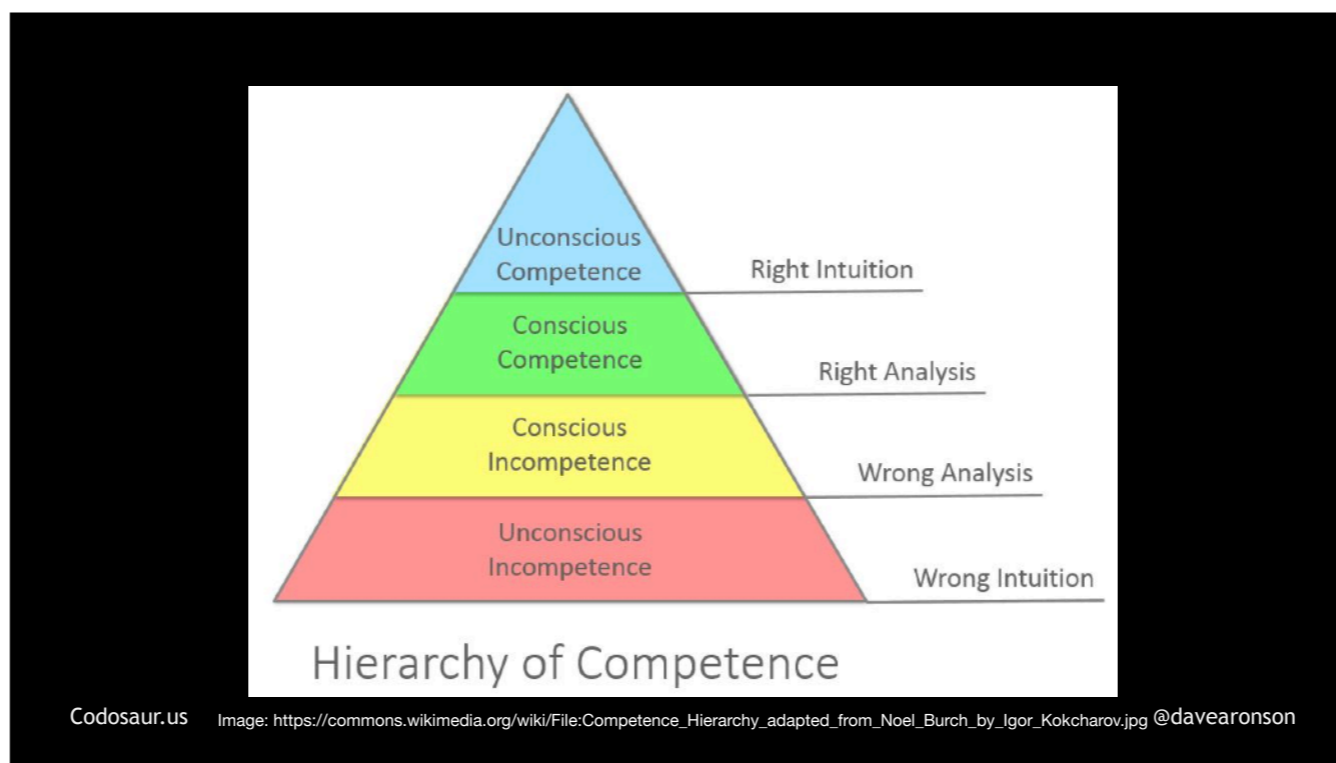
. . . no silver bullet, as this takes lots of CPU time itself -- and the remaining mutants are still quite a lot.

The next question is, when making each mutant, why change it in only . . .



. . . one way?

There are multiple reasons. First off, the main theoretical underpinning is . . .



. . . the Competent Programmer hypothesis. Let's give that a quick check. Raise your hand if you're competent! (PAUSE!) Okay, looks like most of us. The rest of you, you probably really are competent, so you might want to read up on Impostor Syndrome.

But anyway, what is the Competent Programmer Hypothesis? Long story short, it's the idea that we generally have a pretty good clue what we're doing, and when we make a mistake, it's usually a single small mistake, like adding when we should subtract, or comparing using "less than or equal" when we mean "strictly less than", or greater than, or whatever. Does this kind of simple substitution sound familiar? It's exactly what a mutation testing tool does. We can think of mutation testing as sort of a "did you mean" function, like how Google suggests something else if our search didn't have many hits.

There are also practical considerations. For one, it helps us poor humans . . .



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Image: <https://pixabay.com/vectors/arrow-one-way-right-sign-road-759223/>

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. . . FOCUS! It's much easier to tell what a surviving mutant is trying to say, if we're only talking about one thing in the first place. Another reason is that multiple changes may . . .



. . . balance each other out, leading to more false alarms. For instance, remember that . . .

```
def power(x, y) do
  x ** y
end
```

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. . . first simple example, and . . .

```
function "power" (demo.ex:42)
has 2 surviving mutants:
```

```
42 - def power(x, y) do
```

```
42 + def power(y, x) do
```

```
43 -   x ** y
```

```
43 +   y ** x
```

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... its argument-swapping mutants? If one mutant ...

```
def power(y, x) do
  y ** x
end
```

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. . . had *both* of these mutations, . . .

Old x: y

Old y: x

. . . the first would swap the arguments, and the other would . . .

Old x:  $x$

Old y:  $y$

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. . . swap them right back, for no net effect, so such a mutant would survive *any* test.

Lastly, allowing multiple mutations would create a combinatorial . . .



. . . explosion of mutants, with the tool making many *orders of magnitude* more mutants per function, which would make it even *more* CPU-intensive. I'll spare you the math, but with our earlier code size assumptions, even if we manage to weed the mutants down to one third at each step, with . . .

# Mutations/Mutant vs Mutants/Function

1:

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. . . one mutation per mutant, we'd have . . .

# Mutations/Mutant vs Mutants/Function

1:

333

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. . . 333 mutants per function (and a third, but I'm rounding). With . . .

# Mutations/Mutant vs Mutants/Function

1:

333

2:

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. . . two, we'd already have . . .

# Mutations/Mutant vs Mutants/Function

1: 333  
2: almost 110\_000

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. . . almost 110,000, and with . . .

# Mutations/Mutant vs Mutants/Function

1: 333  
2: almost 110\_000  
3:

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. . . three we'd have . . .

## Mutations/Mutant vs Mutants/Function

1: 333  
2: almost 110\_000  
3: over 35\_000\_000

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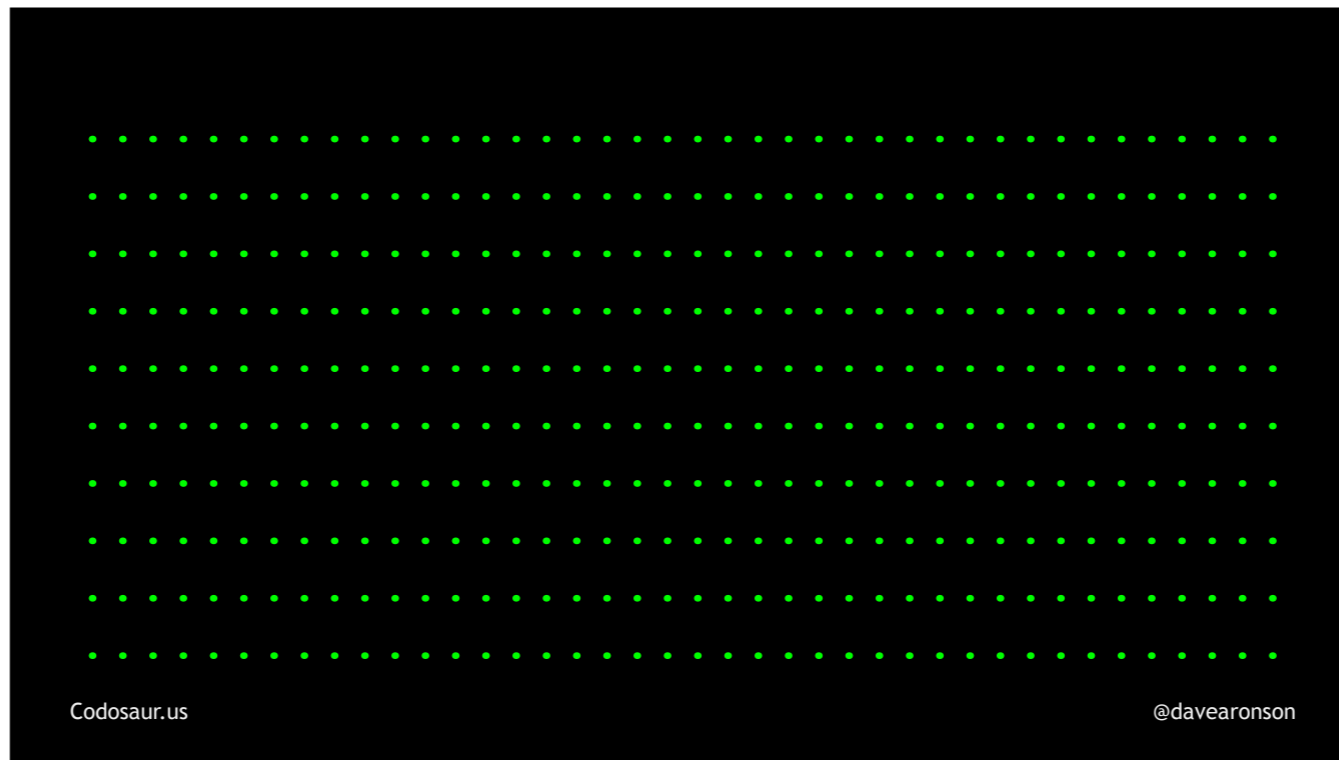
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. . . over 35 million! Never mind actually *running* the *tests*, just *creating* the *mutants* would get to be quite a heavy workload! But we can avoid this huge workload, *and* the increased false alarms, *and* the lack of focus, if we just . . .



. . . limit it to one mutation per mutant.

The next question is: this sounds like mutation testing only makes sure that our . . .



. . . test *suite* as a *whole* is strict. Is there any way it can help us assess the quality of . . .



. . . *individual* tests?

Yes there is, but it would take a lot longer, and I don't think any of the current tools give us all the necessary information. You may remember how I said early on, that when . . .

Mutating function whatever, at something.ex:42

Test #	1	2	3	4	5	6	7	8	9	10	Result
Mutant #											
1	✓	✓	✓	✓	✗						In Progress
2											To Do
3											To Do
4											To Do
5											To Do

... a mutant makes a test fail, the tool will ...

Mutating function whatever, at something.ex:42

Test #	1	2	3	4	5	6	7	8	9	10	Result
Mutant #											
1	✓	✓	✓	✓	✗						Killed
2											To Do
3											To Do
4											To Do
5											To Do

. . . mark that mutant killed, . . .

Mutating function whatever, at something.ex:42

Test #	1	2	3	4	5	6	7	8	9	10	Result
Mutant #											
1	✓	✓	✓	✓	✗						Killed
2											To Do
3											To Do
4											To Do
5											To Do

. . . stop running any more tests against it, and . . .

Mutating function whatever, at something.ex:42											
Test #	1	2	3	4	5	6	7	8	9	10	Result
Mutant #											
1	✓	✓	✓	✓	✗						Killed
2	🕒										In Progress
3											To Do
4											To Do
5											To Do

. . . move on to the next one. So when we're done with a given function, we wind up with a chart like . . .

Mutating function whatever, at something.ex:42											
Test #	1	2	3	4	5	6	7	8	9	10	Result
Mutant #											
1	✓	✓	✓	✓	✗						Killed
2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Survived!
3	✓	✓	✗								Killed
4	✗										Killed
5	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Survived!

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. . . this. If we were to run the rest of the tests, those with blank cells in this table, that would take a lot longer, but it would give us . . .

Mutating function whatever, at something.ex:42											
Test # Mutant #	1	2	3	4	5	6	7	8	9	10	Result
1	✓	✓	✓	✓	✗	✓	✓	✗	✓	✗	Killed
2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Survived!
3	✓	✓	✗	✓	✓	✗	✗	✗	✓	✓	Killed
4	✗	✗	✓	✓	✗	✗	✓	✓	✓	✓	Killed
5	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Survived!

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. . . information that we can use to assess the quality of *some* individual tests. Look at . . .

Mutating function whatever, at something.ex:42

Test # Mutant #	1	2	3	4	5	6	7	8	9	10	Result
1	✓	✓	✓	✓	✗	✓	✓	✗	✓	✗	Killed
2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Survived!
3	✓	✓	✗	✓	✓	✗	✗	✗	✓	✓	Killed
4	✗	✗	✓	✓	✗	✗	✓	✓	✓	✓	Killed
5	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Survived!

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. . . tests four and nine. They don't kill *any* of these mutants! This isn't an absolute indication that they're no good, but it does mean that they may merit a closer look, somewhat like a code smell. We could look *next* at . . .

Mutating function whatever of something.ex:42

Test #	1	2	3	4	5	6	7	8	9	10	Result
Mutant #											
1	✓	✓	✓	✓	✗	✓	✓	✗	✓	✗	Killed
2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Survived!
3	✓	✓	✗	✓	✓	✗	✗	✗	✓	✓	Killed
4	✗	✗	✓	✓	✗	✗	✓	✓	✓	✓	Killed
5	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Survived!

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. . . those that only stop *one* mutant, then those that . . .

Mutating function whatever, at something.ex:42

Test # Mutant #	1	2	3	4	5	6	7	8	9	10	Result
1	✓	✓	✓	✓	✗	✓	✓	✗	✓	✗	Killed
2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Survived!
3	✓	✓	✗	✓	✓	✗	✗	✗	✓	✓	Killed
4	✗	✗	✓	✓	✗	✗	✓	✓	✓	✓	Killed
5	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Survived!

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... only stop *two* mutants, and so on, but I think it would rapidly reach a point of diminishing returns, probably at one.

This raises the question of whether we could also use such a full report to improve our test *suite* again. Yes we could, by looking at *pairs* or larger *sets* of tests, that kill exactly the same sets of mutants, such as ...

Mutating function whatever of something.ex:42

Test #	1	2	3	4	5	6	7	8	9	10	Result
Mutant # 1	✓	✓	✓	✓	✗	✓	✓	✗	✓	✗	Killed
Mutant # 2	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Survived!
Mutant # 3	✓	✓	✗	✓	✓	✗	✗	✗	✓	✓	Killed
Mutant # 4	✗	✗	✓	✓	✗	✗	✓	✓	✓	✓	Killed
Mutant # 5	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Survived!

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. . . tests one and two, or tests three and seven. We can take a closer look at those sets of tests, and decide if we need to keep the whole set. Maybe tests one and two are testing different important aspects, but three and seven are essentially testing the same thing, so we can get rid of one of those, not due to low mutant-stopping power of either test, but due to *redundancy between* them.

The last question is: as mentioned earlier, mutation testing *assumes* that we have . . .

```
$ run_tests
```

```
.....  
.....  
.....  
.....  
.....  
.....  
.....
```

```
280 tests, 420 assertions,  
0 failures, 0 errors, 0 excluded
```

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... tests already. What if ...

```
$ run_tests  
0 tests, 0 assertions,  
0 failures, 0 errors, 0 skips
```



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. . . we don't? Can mutation testing be of any help in *that* case?

Well, first of all, whoever wrote a substantial production codebase with no tests needs some educating about the value of tests, like with a clue-by-four. But yes, mutation testing can help us . . .



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Image: <https://www.pxfuel.com/en/free-photo-qzzxl>

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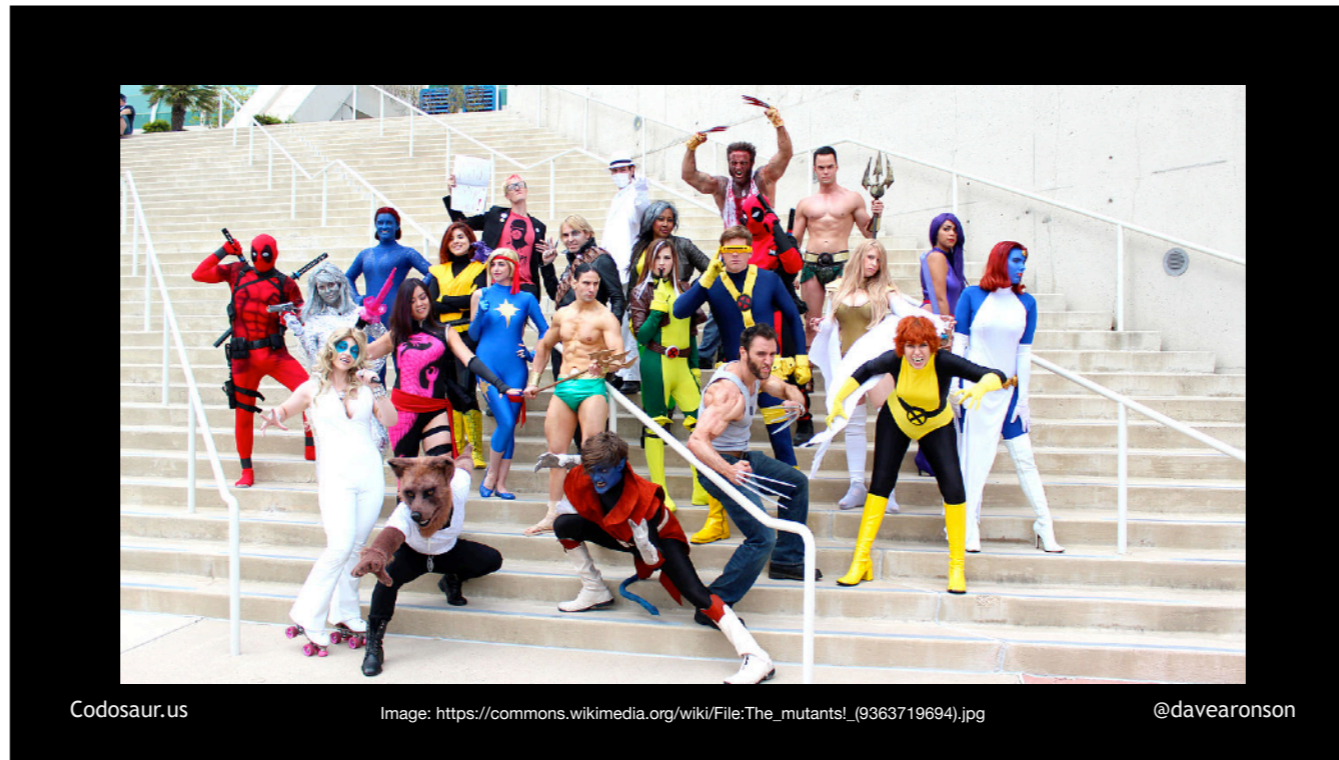
. . . *build* our test suite in the first place! We can start with a . . .

```
test "nothing" do
  assert true
end
```

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. . . meaningless test, and run our mutation testing tool. We'll probably get a . . .



. . . lot of mutants, including many duplicates telling about the same problem, especially as any basically viable mutant will survive our meaningless test.  
Now, for each function with surviving mutants, . . .



. . . pick a mutant. We can just do it randomly, no need to overthink it. Add one test that we think would kill it. As mentioned before, this will probably kill other mutants of the same function, so move on to the next function, until we've killed a mutant from each function with survivors. Then we can rerun our tool, and lather, rinse, repeat, though on further iterations we might *improve* a test rather than *add* any. Now, this won't . . .



. . . *guarantee* that we wind up with a great test suite. A lot of code will probably remain . . .

```
defmodule Conway do
  @alive "*"
  @dead " "

  def next_state(@alive, neighbors),
    do: if Enum.member?([3, 4], neighbors),
         do: @alive, else: @dead

  def next_state(@dead, neighbors),
    do: if neighbors == 3,
         do: @alive, else: @dead
end
```

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. . . untested. However, this idea will get us off to a decent start. Then we can look at what code is untested, and write more tests to cover that, subjecting them to mutation testing of course. At this point, never mind computer science, at least psychologically it will be a much less daunting task than writing our whole test suite from scratch.

To summarize at last, mutation testing is a powerful technique to . . .

😊 Checks that code is meaningful

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. . . help ensure that our code is meaningful and . . .

😊 Checks that code is meaningful

😊 Checks that tests are strict

. . . our tests are strict. It's . . .

- 😊 Checks that code is meaningful
- 😊 Checks that tests are strict
- 😊 Easy to get started with

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easy to get started with, in terms of setting up most of the tools and annotating our tests if needed (which may be *tedious* and *time-consuming* but at least it's *easy*), but it's . . .

😊 Checks that code is meaningful

😊 Checks that tests are strict

😊 Easy to get started with

😞 Difficult to interpret results

. . . not so easy to interpret the results, nor is it . . .

😊 Checks that code is meaningful

😊 Checks that tests are strict

😊 Easy to get started with

😞 Difficult to interpret results

😞 Hard labor on the CPU

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. . . easy on the CPU.

Even if these drawbacks mean it's not a good fit for our particular current projects, though, I still think it's just . . .

😊 Checks that code is meaningful

😊 Checks that tests are strict

😊 Easy to get started with

😞 Difficult to interpret results

😞 Hard labor on the CPU

😎 Fascinating concept! 😎

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. . . a really cool idea . . . in a geeky kind of way.

If you'd like to try mutation testing for yourself . . .

Alloy:	MuAlloy
Android:	mdroid+
C:	mutate.py, SRCIROR
C/C++:	accmut, dextool, MART, MuCPP, Mutate++, mutate_cpp, SRCIROR
C#/ .NET/Mono:	nester, NinjaTurtles, Stryker.NET, Testura.Mutation, VisualMutator
Clojure:	mutant
Crystal:	crytic
Dart:	mutation_test
Elixir:	exavier, exmen, mutation, Muzak [Pro]
Erlang:	mu2
Etherium:	vertigo
FORTRAN-77:	Mothra (written in mid 1980s!)
Go:	go-mutesting
Haskell:	fitspec, muCheck
Java:	jumble, major, metamutator, muJava, pit/pitest, and many more
JavaScript:	stryker, <del>grunt-mutation-testing</del>
PHP:	infection, <del>humbug</del>
PL/SQL:	MuPLSQL
Python:	cosmic-ray, mutmut, xmutant
Ruby:	mutant, <del>mutest</del> , heckle
Rust:	mutagen
Scala:	scalamu, stryker4s
Smalltalk:	mutalk
Solidity:	RegularMutator
SQL:	SQLMutation
Swift:	muter
Anything on LLVM:	llvm-mutate, mull
Tool to make more:	Wodel-Test ( <a href="https://gomezabajo.github.io/Wodel/Wodel-Test/">https://gomezabajo.github.io/Wodel/Wodel-Test/</a> )

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. . . here is a list of tools for some popular languages and platforms . . . and some others; I doubt many of you are doing FORTRAN-77 these days. I'll talk a bit so you can take pictures or screenshots, especially since it's much too small to read easily. Just be aware that many of these are outdated; I don't know or even follow quite *all* of these languages and platforms, let alone the tools. The ones I *know* are outdated, are crossed out. There's also a promising tool called *Wodel-Test*, a *language-independent* mutation engine, with which you can make language-specific mutation testing tools. (Sorry, I haven't looked into it much myself.)

Is everybody done taking pictures? Before we get to Q&A, I'd like to give a shoutout to . . .



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**<https://toptal.com/#accept-only-candid-coders>**

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. . . Toptal, a consulting network I'm in, whose Speakers Network helped me prepare and practice this presentation. (Please use that referral link if you want to hire us or join us, and that's also where that QR code goes. The anchor part tells them it's me, and we'll both get some bounty.)

And now . . .



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. . . it's your turn! If you have any questions, I'll take them now. If you think of anything later, I'll be around for the rest of the conference. If it's too late by then, there's my contact information up there, plus the URL where you can get the slides, complete with script. And of course I have cards. Any questions?