Automated Combinatorial Testing for Software

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What is NIST?

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NIST National Institute of Standards and Technology

- The nation's measurement and testing laboratory
- 3,000 scientists, engineers, and support staff including 3 Nobel laureates
- Best known for atomic clock, standard reference materials (for instrument calibration) from aluminum alloy to whale blubber
- Basic and applied research in physics, chemistry, materials, electronics, computer science

Automated Combinatorial Testing

- Project to combine automated test generation with combinatorial methods

- Goals – reduce testing cost, improve cost-benefit ratio for formal methods

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Overview of useful results

- Proof of concept demo integrating combinatorial testing with model checking
- (Small) experimental result consistent with earlier interpretation of empirical data
- New combinatorial algorithms and tools, supporting development tradeoffs

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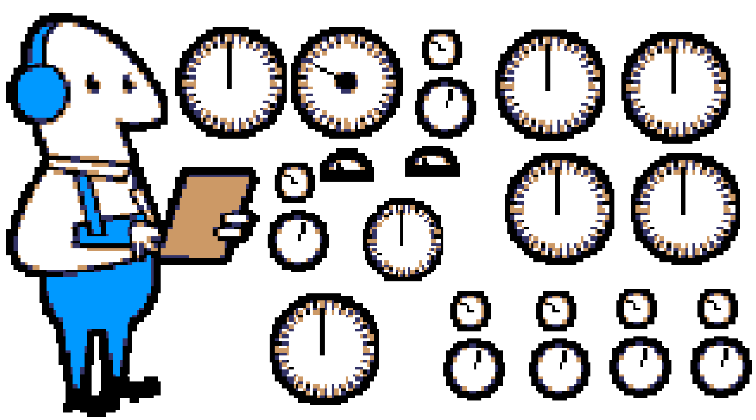
Problem: the usual ...

- Too much to test
- Even with formal specs, we still need to test
- Take advantage of formal specs to produce tests also – better business case for FM
- Testing may exceed 50% of development cost



- Example: 20 variables, 10 values each
- 10^{20} combinations
- Which ones to test?

Solution: Combinatorial Testing

- Suppose no failure requires more than a pair of settings to trigger
- Then test all pairs – 180 test cases sufficient to detect any failure

Yes, but aren't real-world failures more complicated?

Pairwise testing – what do we know?

- Mandl, 1985 – very effective for compiler test
- Brownlie, Prowse, Phadke - high coverage
- Cohen, Dalal, Parelius, Patton, 1995 – 90% coverage with pairwise, all errors in small modules found
- Dalal, et al. 1999 – effectiveness of pairwise testing, no higher degree interactions
- Smith, Feather, Muscetolla, 2000 – 88% and 50% of flaws for 2 subsystems,

What if finding ~90% of flaws is not good enough?

How many combinations do we need to test to find ALL errors?

- Surprisingly, no one had looked at this question when NIST studied medical device software in 1999
  - Wallace, Kuhn 2001 – medical devices – 98% of flaws were pairwise interactions, no failure required > 4 conditions to trigger
  - Kuhn, Reilly 2002 – web server, browser; no failure required > 6 conditions to trigger
  - Kuhn, Wallace, Gallo 2004 – large NASA distributed database; no failure required > 4 conditions to trigger
- Max failure triggering fault interaction (FTFI) number of these applications was 6
- Much more empirical work needed

Maybe the hard to find flaws weren't reported.

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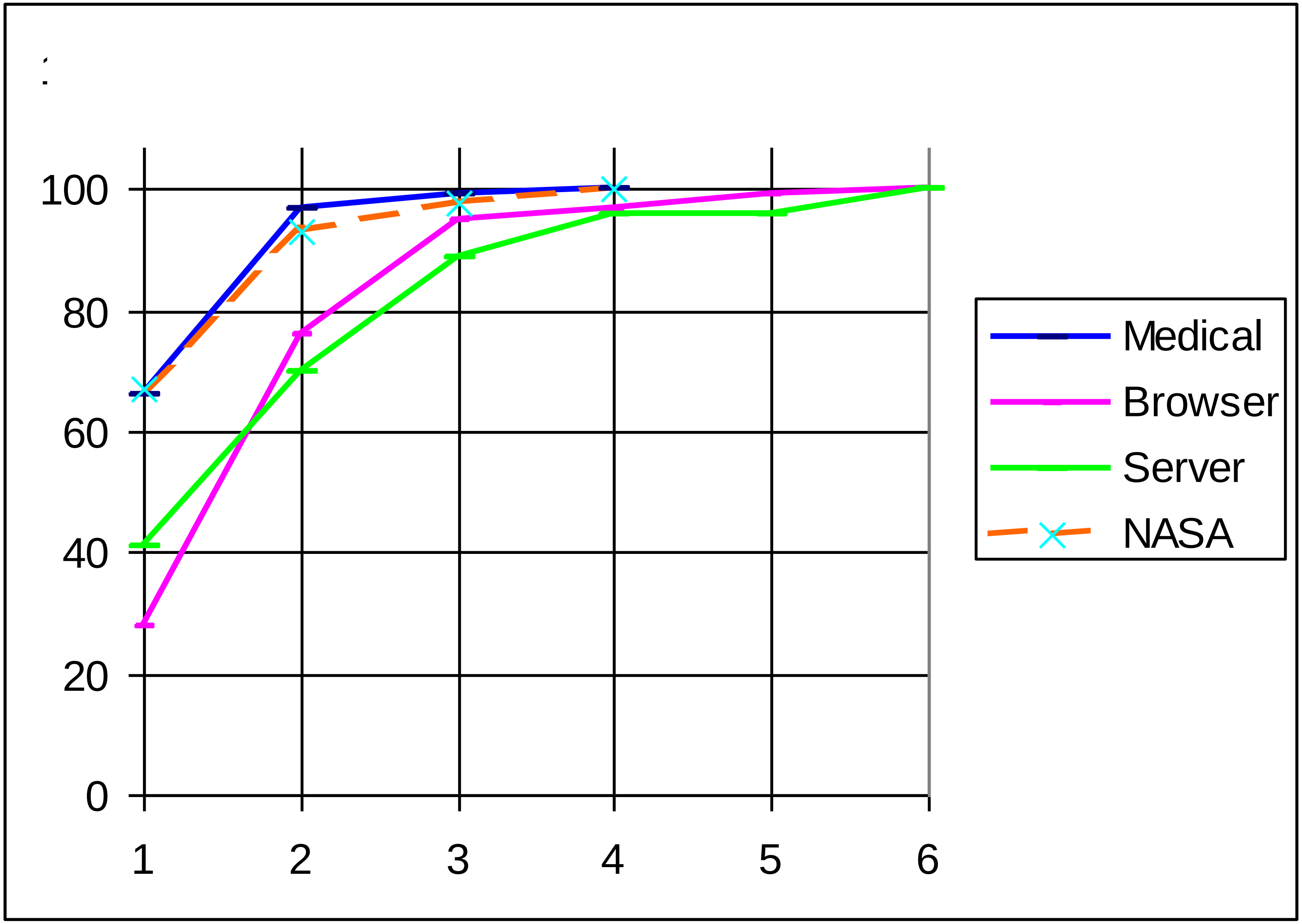
FTFI numbers for 4 application domains – failures triggered by 1 to 6 conditions



Combinatorial test example: 5 parameters, 4 values each, 3-way combinations

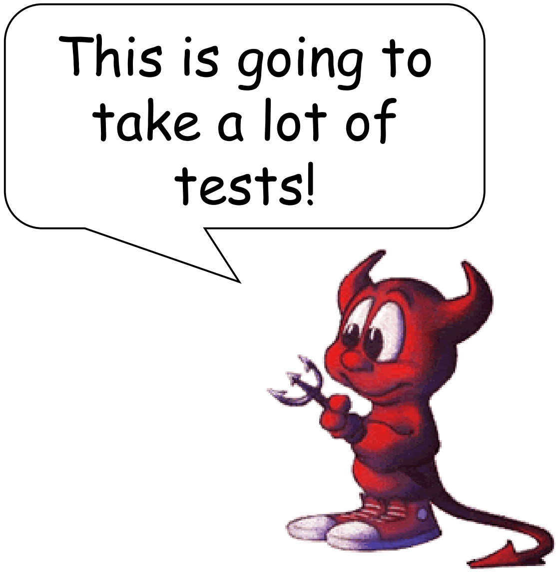
Parameters

Test	A	B	C	D	E
1	1	1	1	1	1
2	1	1	2	2	2
3	1	1	3	3	3
4	1	1	4	4	4
5	1	2	1	2	3
6	1	2	2	1	4
7	1	2	3	4	1
8	1	2	4	3	2
9	1	3	1	3	4
10	1	3	2	4	3

etc.....

All 3-way combinations of A,B,C values

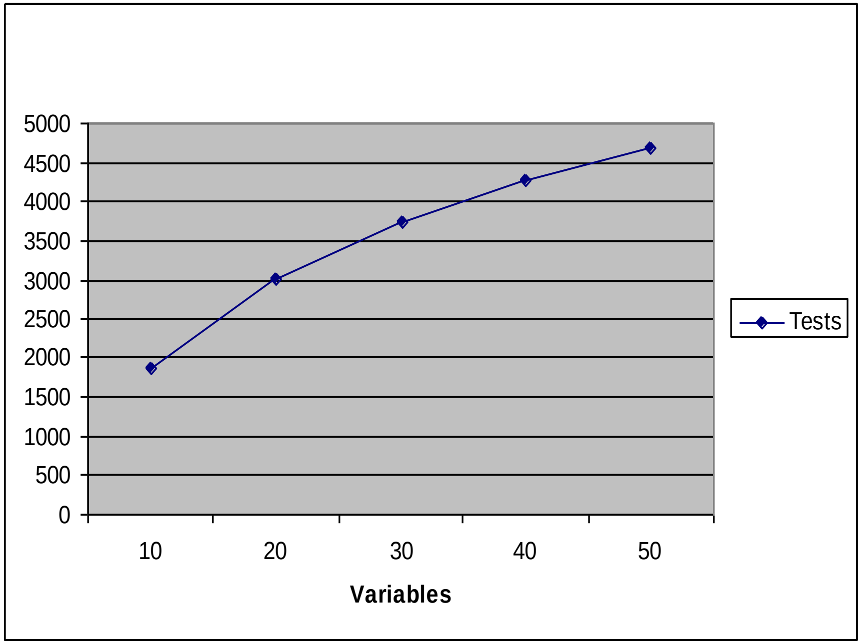
But also all 3-way combinations of
A,B,D;
A,B,E;
A,C,D;
...
B,D,E;
...
etc...



Problem: Combinatorial Testing Requires a Lot of Tests

- Number of tests: suppose we want all 4-way combinations of 30 parameters, 5 values each: 3,800 tests – too many to create manually
- Test set to do this is a covering array
- Time to generate covering arrays: problem is NP hard
- No. of combinations:

$$\binom{n}{k} v^k$$



For *n* variables with *v* values, *k*-way combinations

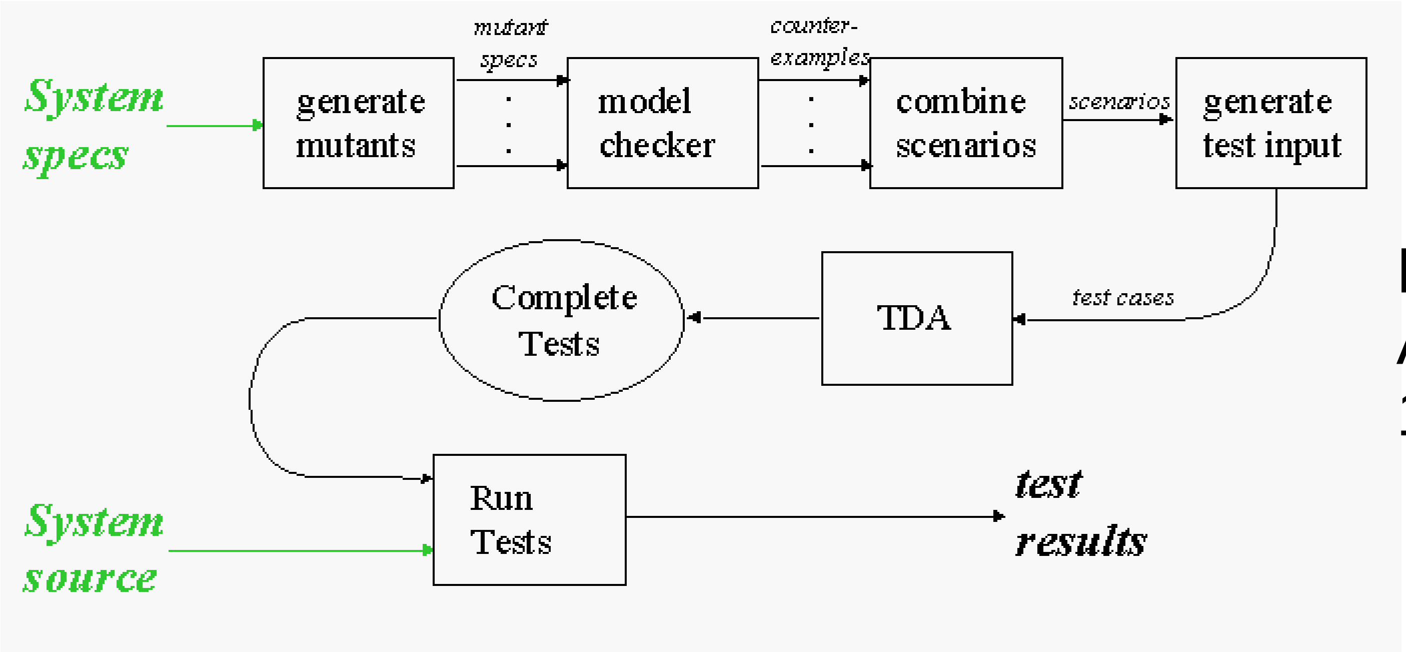
Solution: Automated Testing

Test data generation – easy

Test oracle generation – hard

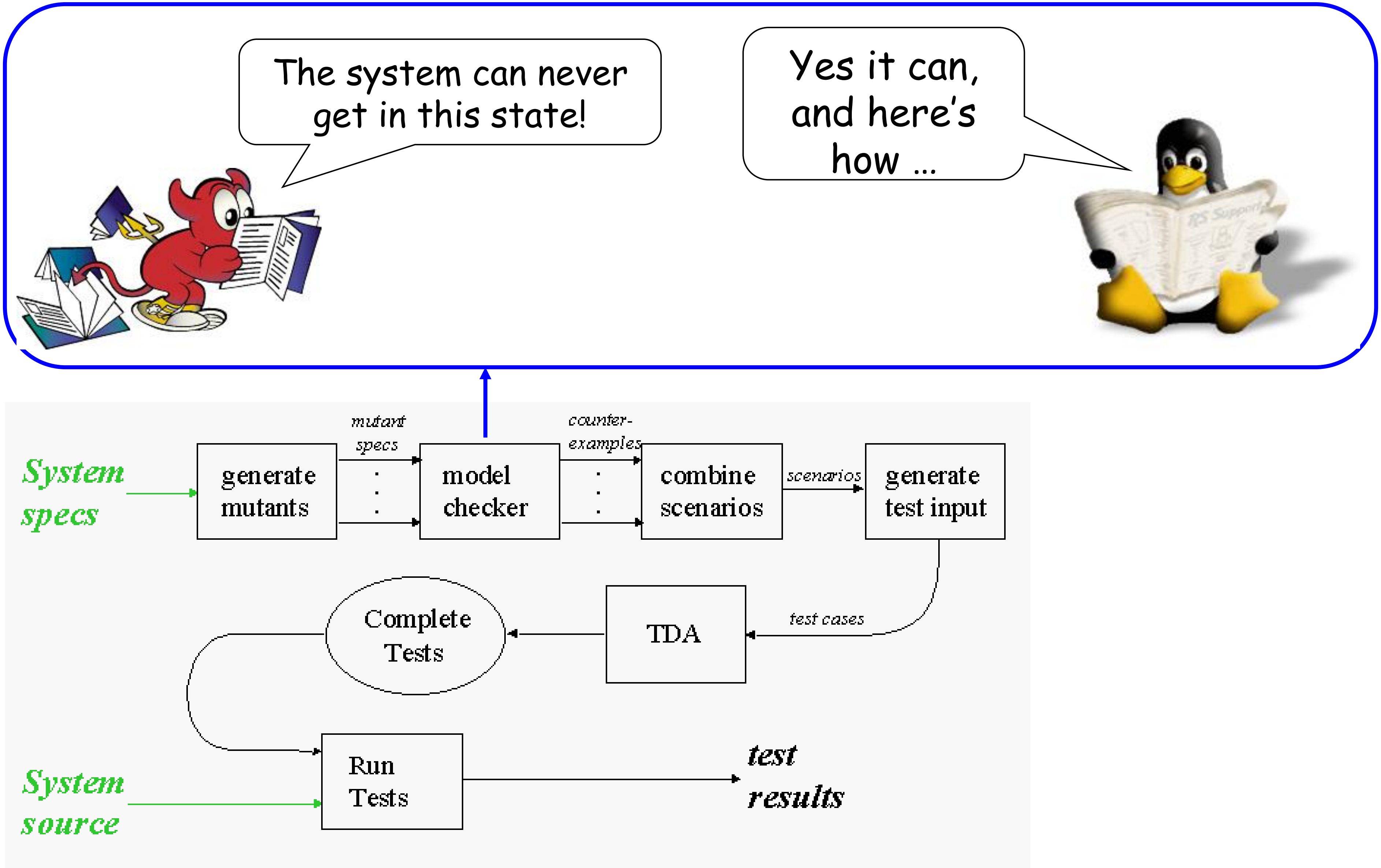
Creating test oracles – model checking and other state exploration methods

Model-checker test production: if assertion is not true, then a counterexample is generated. This can be converted to a test case.



Black & Ammann, 1999

Using model checking to produce tests



Model checking example

```
-- specification for a portion of tcas - altitude separation.
-- The corresponding C code is originally from Siemens Corp. Research
-- Vadim Okun 02/2002
MODULE main
VAR
  Cur_Vertical_Sep : { 299, 300, 601 };
  High_Confidence : boolean;
...
init(alt_sep) := START_;
  next(alt_sep) := case
    enabled & (intent_not_known | !tcas_equipped) : case
      need_upward_RA & need_downward_RA : UNRESOLVED;
      need_upward_RA : UPWARD_RA;
      need_downward_RA : DOWNWARD_RA;
      1 : UNRESOLVED;
    esac;
    1 : UNRESOLVED;
  esac;
...
SPEC AG ((enabled & (intent_not_known | !tcas_equipped) &
!need_downward_RA & need_upward_RA) -> AX (alt_sep = UPWARD_RA))
```

Computation Tree Logic

The usual logic operators,plus temporal:

- A φ - All: φ holds on all paths starting from the current state.
- E φ - Exists: φ holds on some paths starting from the current state.
- G φ - Globally: φ has to hold on the entire subsequent path.
- F φ - Finally: φ eventually has to hold
- X φ - Next: φ has to hold at the next state

[others not listed]

execution paths

states on the execution paths

```
SPEC AG ((enabled & (intent_not_known |
!tcas_equipped) & !need_downward_RA &
need_upward_RA)
-> AX (alt_sep = UPWARD_RA))
```

"FOR ALL executions,
IF enabled & (intent_not_known ....
THEN in the next state alt_sep = UPWARD_RA"

How can we integrate combinatorial testing with model checking?

1. Given `AG(P -> AX(R))` "for all paths, in every state, if P then in the next state, R holds"

- For k-way variable combinations, `v1 & v2 & ... & vk`
- vi abbreviates "var1 = val1"
- Now combine this constraint with assertion to produce counterexamples. Some possibilities:
  - `AG(v1 & v2 & ... & vk & P -> AX !(R))`
  - `AG(v1 & v2 & ... & vk -> AX !(1))`
  - `AG(v1 & v2 & ... & vk -> AX !(R))`

What happens with these assertions?

1. `AG(v1 & v2 & ... & vk & P -> AX !(R))`

   P may have a negation of one of the v_i, so we get

   `0 -> AX !(R))`

   always true, so no counterexample, no test.
   This is too restrictive

1. `AG(v1 & v2 & ... & vk -> AX !(1))`
   The model checker makes non-deterministic choices for variables not in v1..vk, so all R values may not be covered by a counterexample.
   This is too loose

2. `AG(v1 & v2 & ... & vk -> AX !(R))`
   Forces production of a counterexample for each R.
   This is just right

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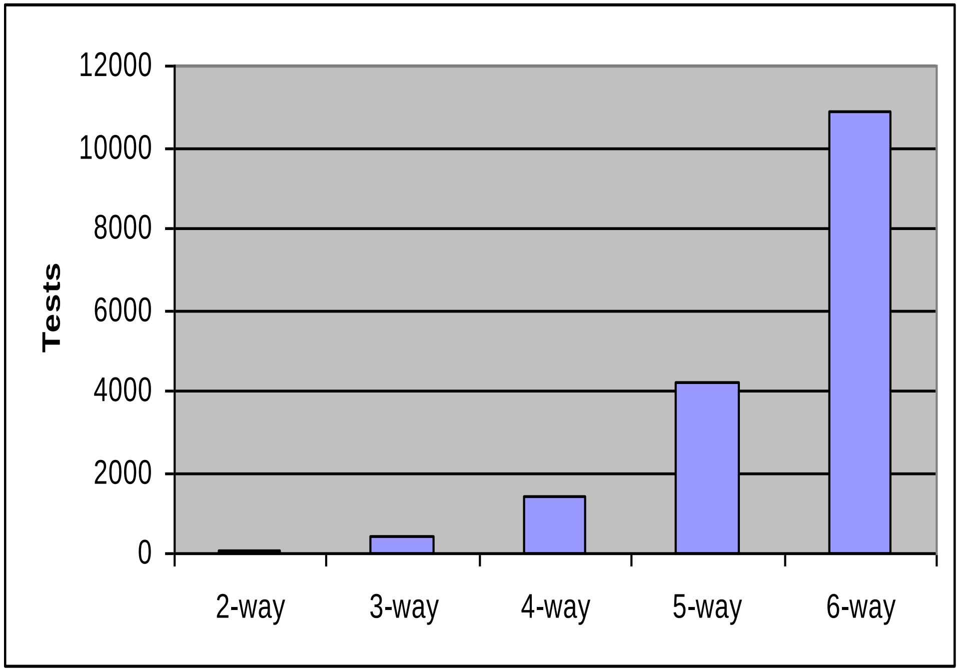
Proof-of-concept experiment

- Traffic Collision Avoidance System module
  - Small, practical example – 2 pages of SMV
  - Used in other experiments on testing
    – Siemens testing experiments, Okun dissertation
  - Suitable for model checking
- 12 variables: 7 boolean, two 3-value, one 4-value, two 10-value
- Tests generated w/ Lei “In Parameter Order” (IPO) algorithm extended for >2 parameters

Combinations /tests generated

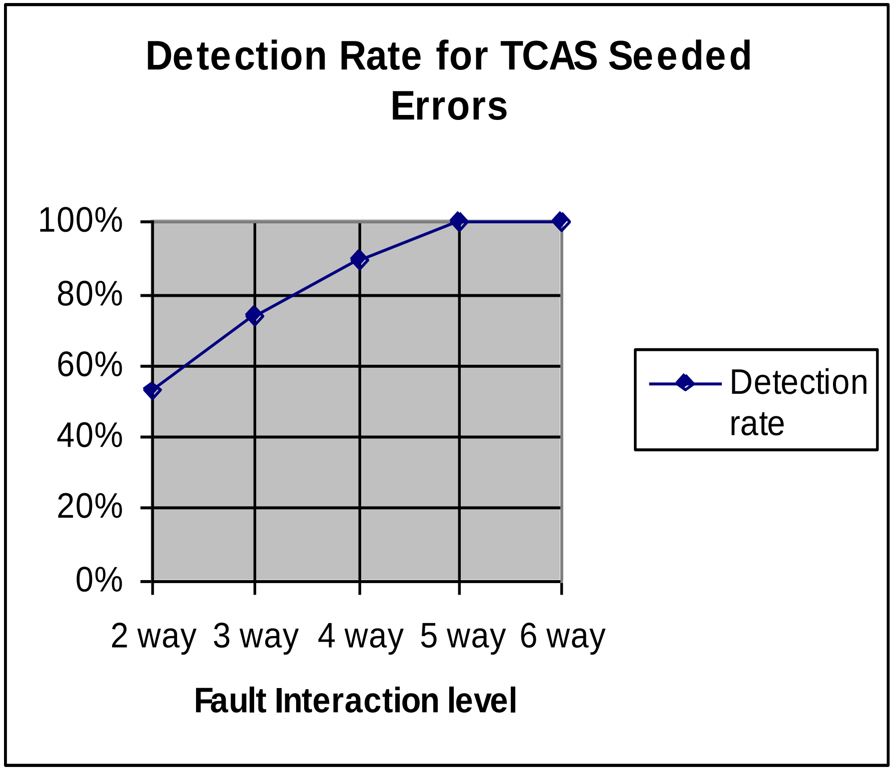
t	Comb.	Test cases
2-way:	100	156
3-way:	405	461
4-way:	1,375	1,450
5-way:	4,220	4,309
6-way:	10,902	11,094

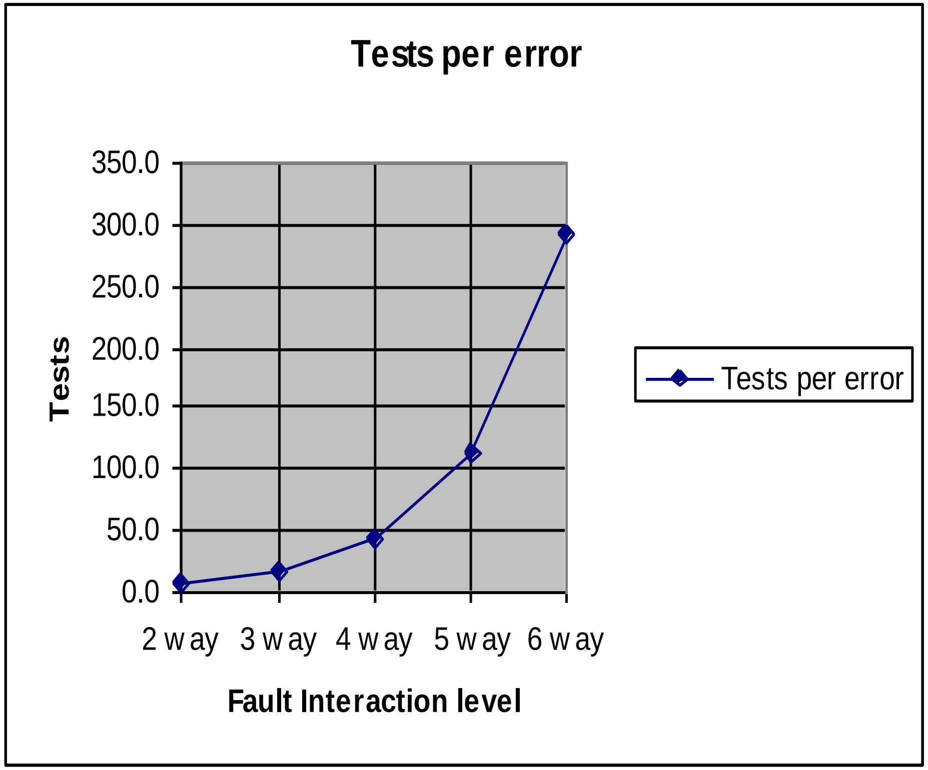


(more "don't care" conditions at lower interaction levels)

Results

- Roughly consistent with data on large systems
- But errors harder to detect than real-world examples





What do we need to make this practical?

- This approach would not have been practical 10 years ago
- Now we have high performance model checkers, better covering array algorithms, and cheap processors
- Generating ~ 10^6 – 10^7 tests can be done
- Proof of concept experiment completed

So what? Finding covering arrays is an NP hard problem!

Solution: new covering array algorithms

- **Tradeoffs to minimize calendar/staff time:**
- FireEye (extended IPO) – Lei – roughly optimal, can be used for most cases under 40 or 50 parameters
  - Produces minimal number of tests at cost of long run time
  - Currently integrating algebraic methods
- Adaptive distance-based strategies – Bryce – dispensing one test at a time w/ metrics to increase probability of finding flaws
  - Highly optimized covering array algorithm
  - Variety of distance metrics for selecting next test
- Paintball – Kuhn –for more variables or larger domains
  - Randomized algorithm, generates tests w/ a few tunable parameters; computation can be distributed
  - Better results than other algorithms for larger problems

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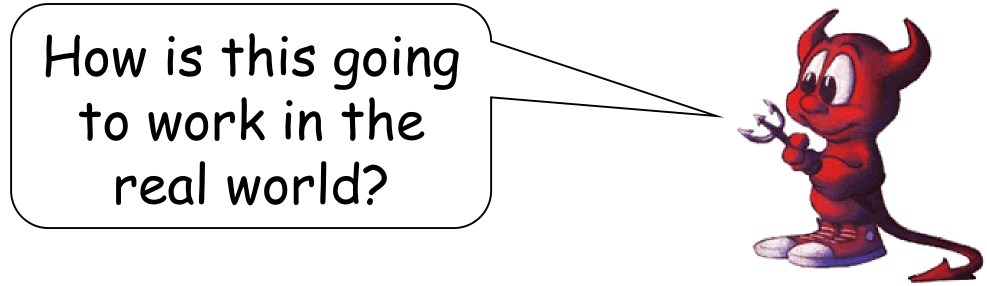
Will automated combinatorial testing work in practice?

The usual potential pitfalls:

- Faithfulness of model to actual code
    - Always a problem
    - Being able to generate tests from specification helps make formal modeling more cost effective
- Time cost of generating tests
    - Model checking very costly in run time
    - Inherent limits on number of variable values even with ideal covering array generation: need at least $C(n,k) * v^k$
- Abstraction needed to make this tractable
    - Equivalence classes for variable values may miss a lot that matters
    - Not all software is suited to this scheme – e.g., good for code with lots of decisions, not so good for numerical functions.

Scaling up



- Two real-world trials planned – US Govt Personal Identity Verification (PIV) card, machine tool specification exchange software
- Plan to experiment with both SMV model checker and TVEC
- Generate 10^5 to 10^6 tests per module, probably up to 5-way combinations

Summary and conclusions

- Proof of concept is promising – integrated w/ model checking
- Appears to be economically practical
- New covering array algorithms help make it more tractable
- Cluster implementation of covering array algorithm
- Many unanswered questions
  - Is it cost-effective?
  - What kinds of software does it work best on?
  - What kinds of errors does it miss?
  - What failure-triggering fault interaction level testing is required? 5-way? 6-way? more?
- Large real-world example will help answer these questions

Please contact us if you are interested!

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