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Automated Combinatorial Testing for Software

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What is NIST?

NIST
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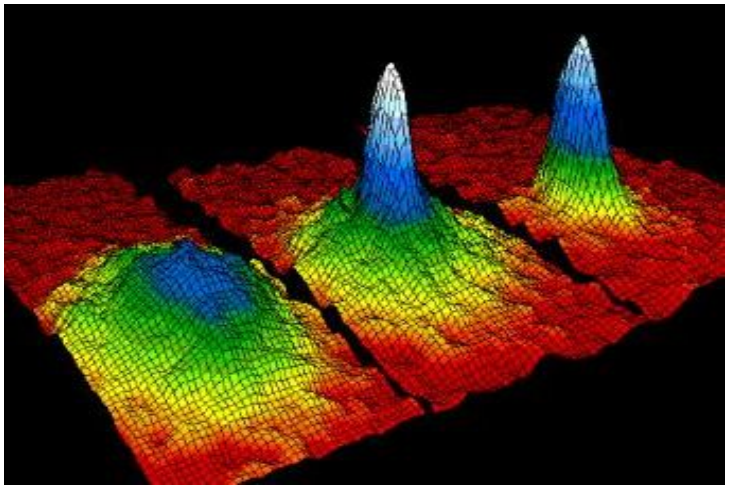
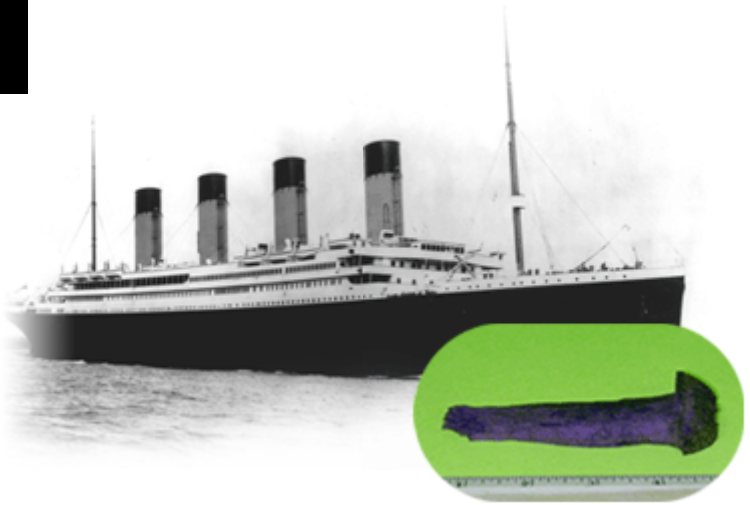
- A US Government agency
- The nation's measurement and testing laboratory – 3,000 scientists, engineers, and support staff including 3 Nobel laureates



Analysis of engineering failures, including buildings, materials …



Research in physics, chemistry, materials, manufacturing, computer science

Software Failure Analysis

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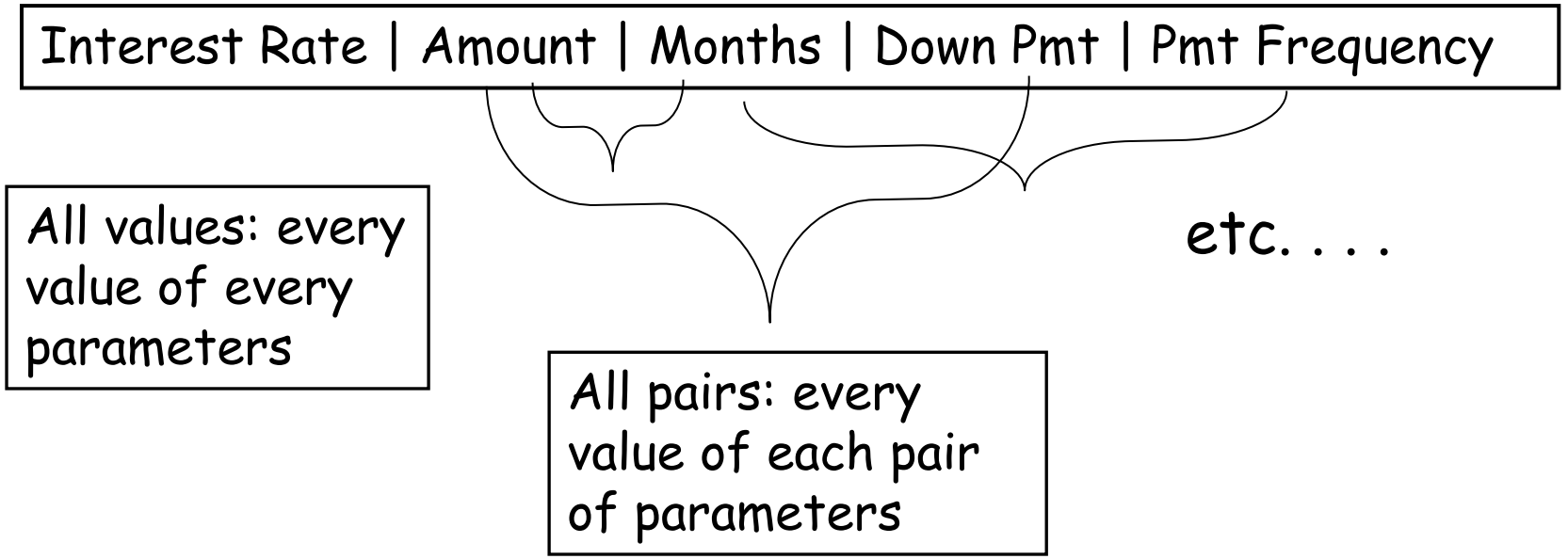
- NIST studied software failures in a variety of fields including 15 years of FDA medical device recall data
- What causes software failures?
- What testing and analysis would have prevented failures?
- Would all-values or all-pairs testing find all errors, and if not, then how many interactions would we need to test to find all errors?
- Surprisingly, no one had looked at this question before

Interaction testing



t-way interactions: every value of every t-way combination of parameters

How to find all failures?

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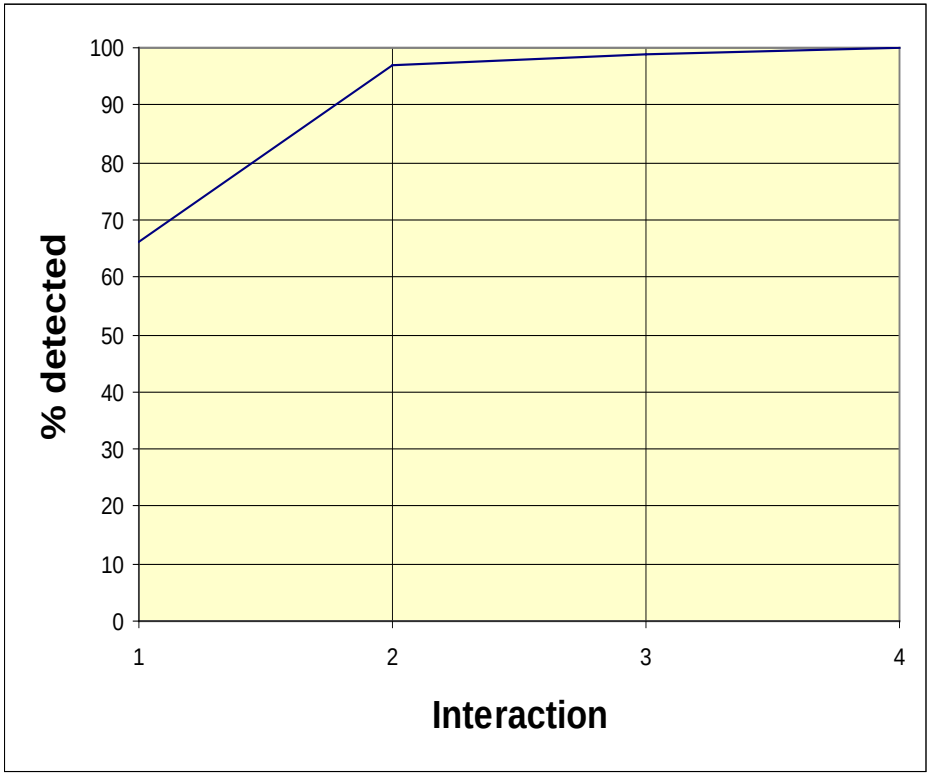
- Interactions:
  - E.g., failure occurs if
    pressure < 10 (1-way interaction)
    pressure < 10 & volume > 300
    (2-way interaction)

- Most complex failure required
  4-way interaction



How about other applications?

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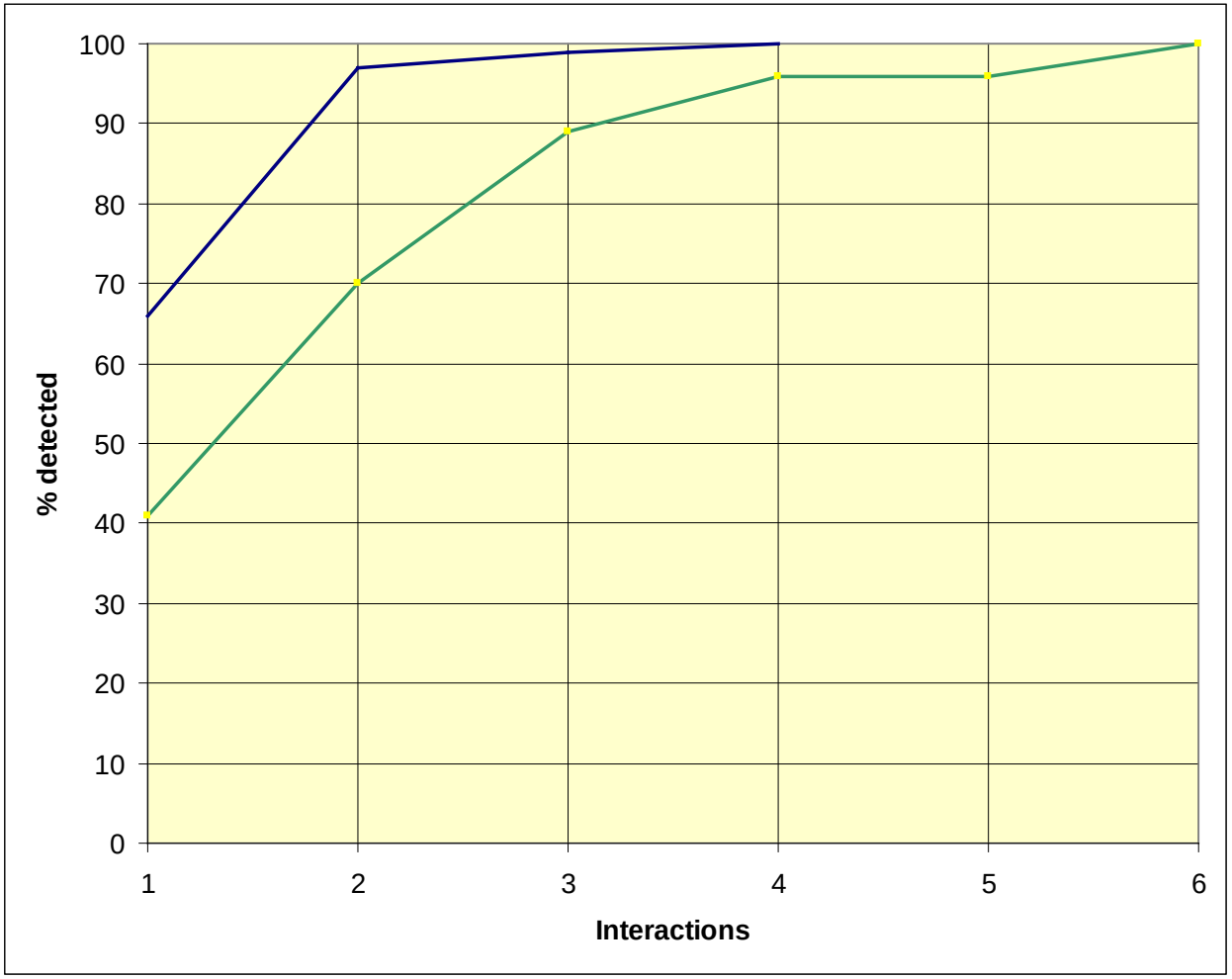
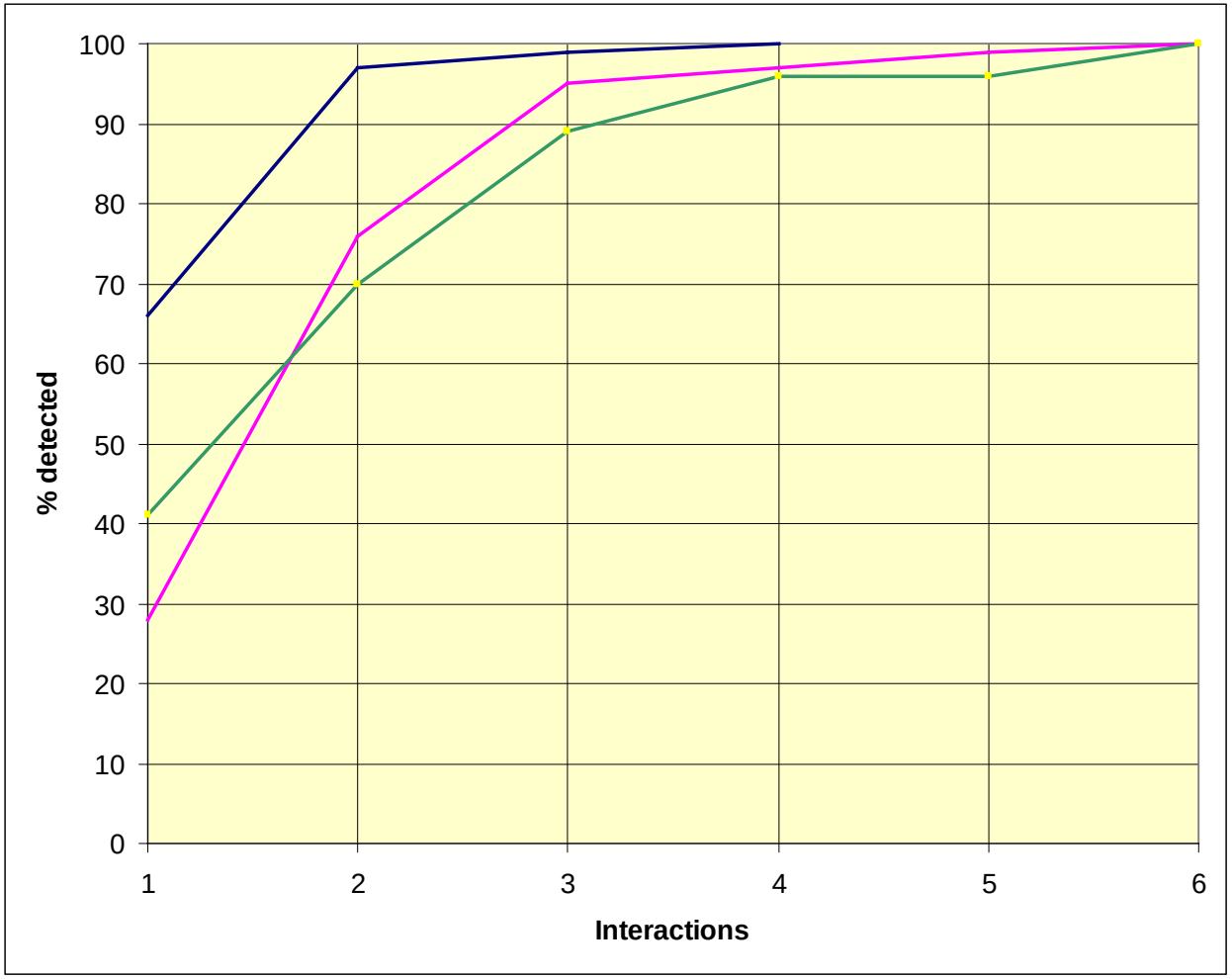
- Browser



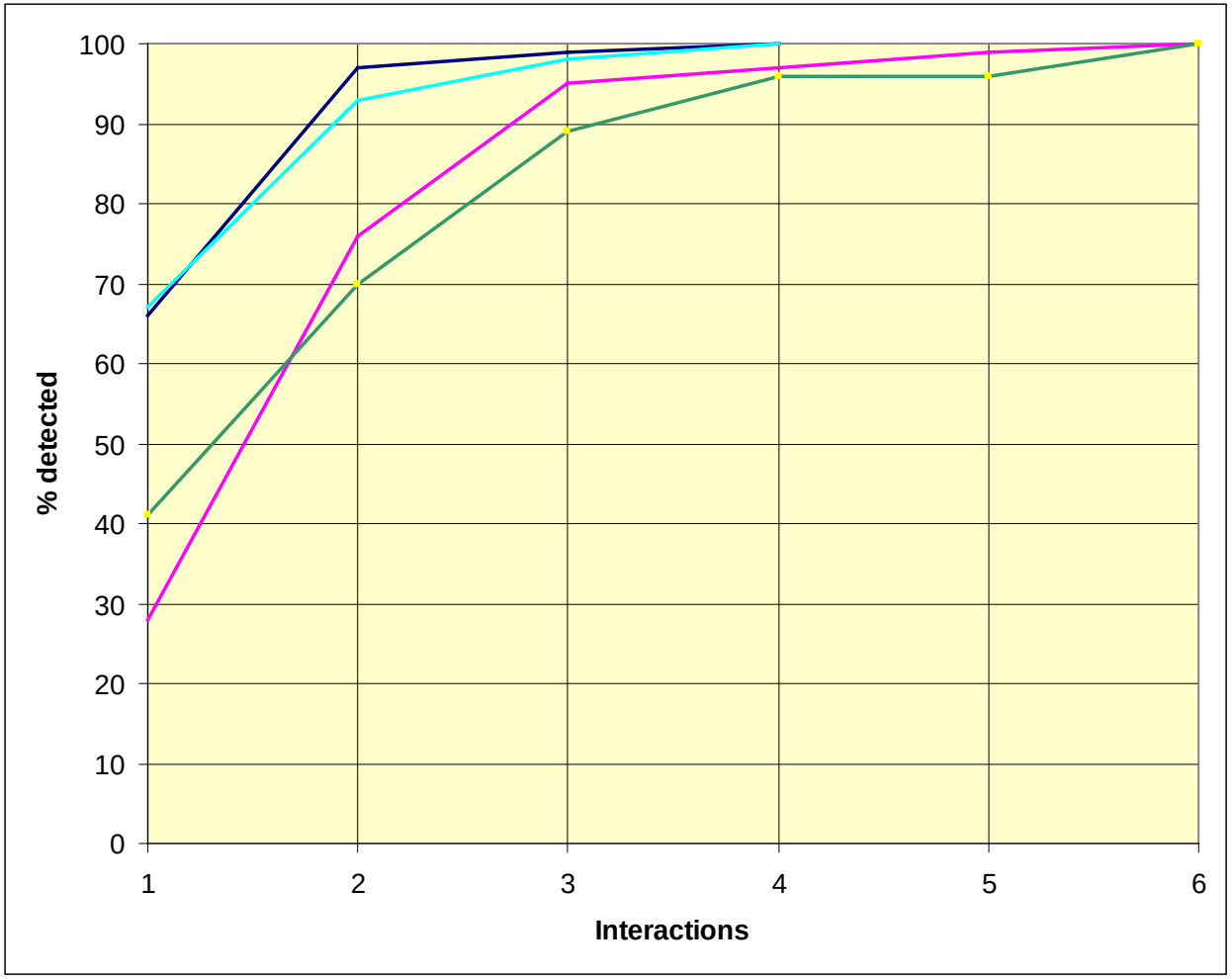
How about other applications?

- Server



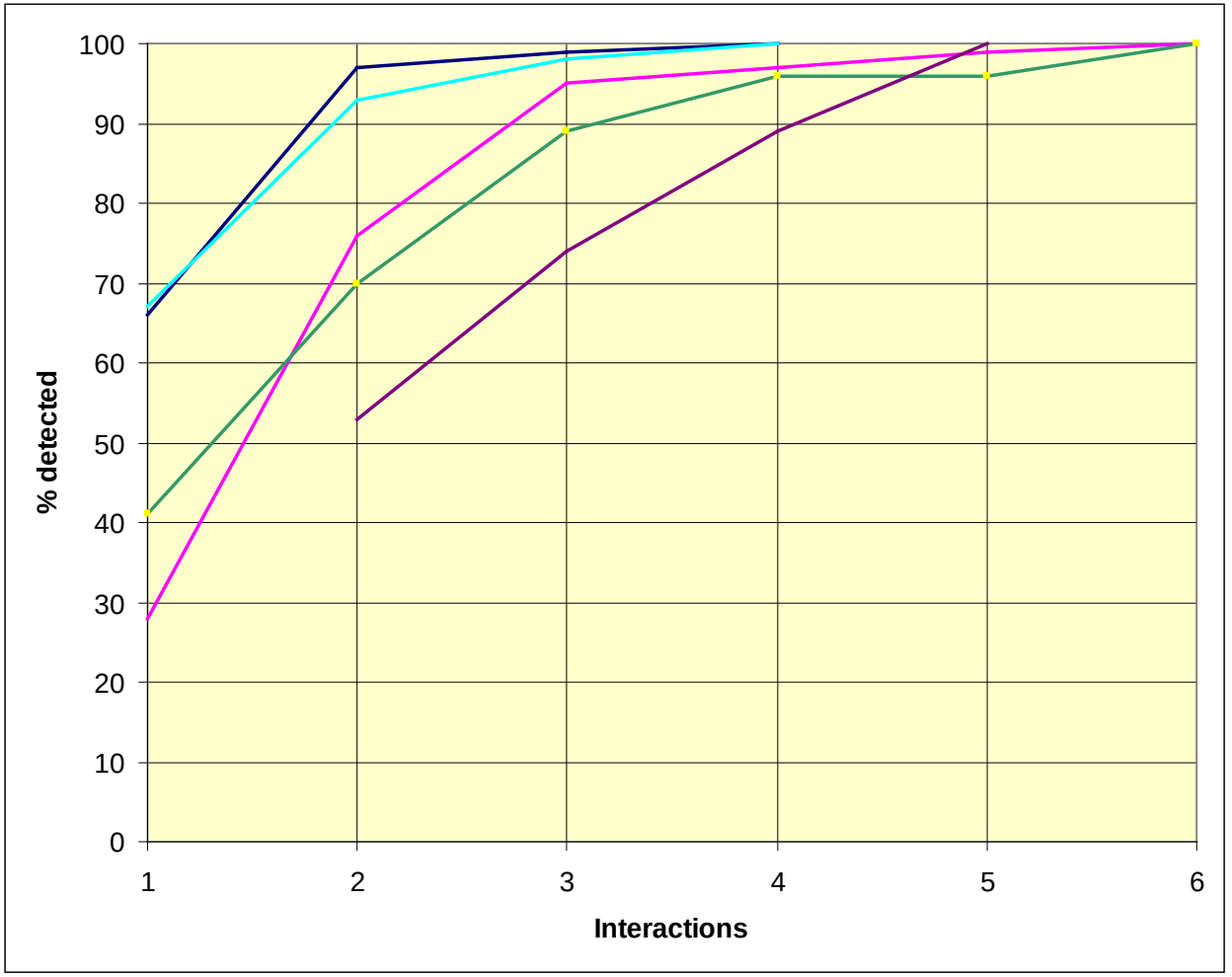
How about other applications?

- NASA distributed database



How about other applications?

- TCAS module (seeded errors)



What interactions would we need to test to find ALL faults?

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- Max interactions for fault triggering for these applications was 6
  - Wallace, Kuhn 2001 – medical devices
    – 98% of flaws were pairwise interactions,
    no fault required > 4-way interactions to trigger
  - Kuhn, Reilly 2002 – web server, browser;
    no fault required > 6-way interactions to trigger
  - Kuhn, Wallace, Gallo 2004 – large NASA distributed database;
    no fault required > 4 interactions to trigger
- Much more empirical work needed
- Reasonable evidence that maximum interaction strength for fault triggering is relatively small

- **How can we apply what we have learned?**

Automated Combinatorial Testing

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- Merge automated test generation with combinatorial methods
- Goals – reduce testing cost, improve cost-benefit ratio for software assurance
- New algorithms and faster processors make large-scale combinatorial testing practical
- Accomplishments – huge increase in performance, scalability + proof-of-concept demonstration
- Also non-testing application – modelling and simulation

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MIT

Software Engineering Institute | Carnegie Mellon

Problem: the usual ...

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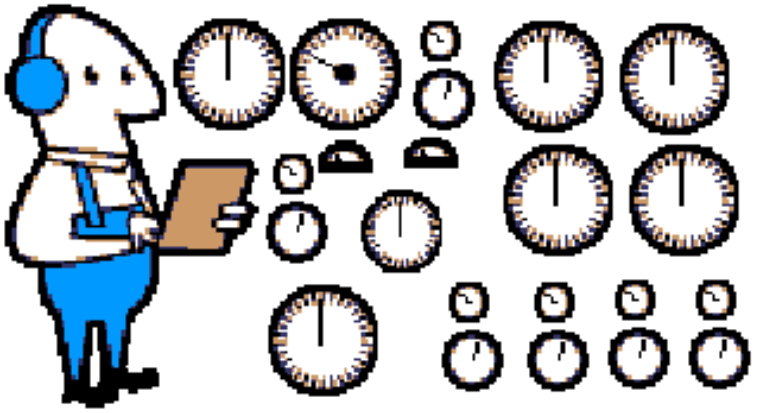
- Too much to test
- Testing may exceed 50% of development cost
- Even with formal methods, we still need to test
- Need maximum amount of information per test



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

Solution: Combinatorial Testing

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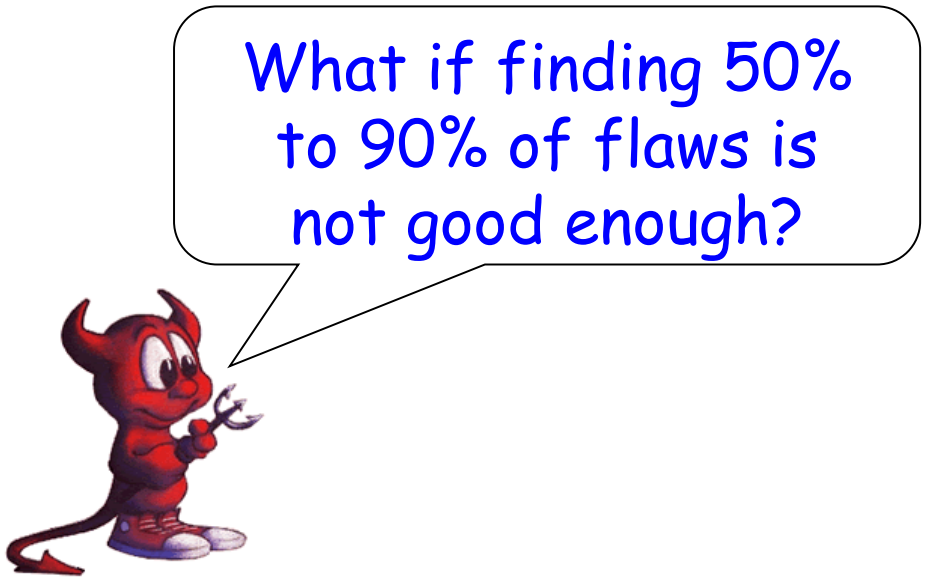
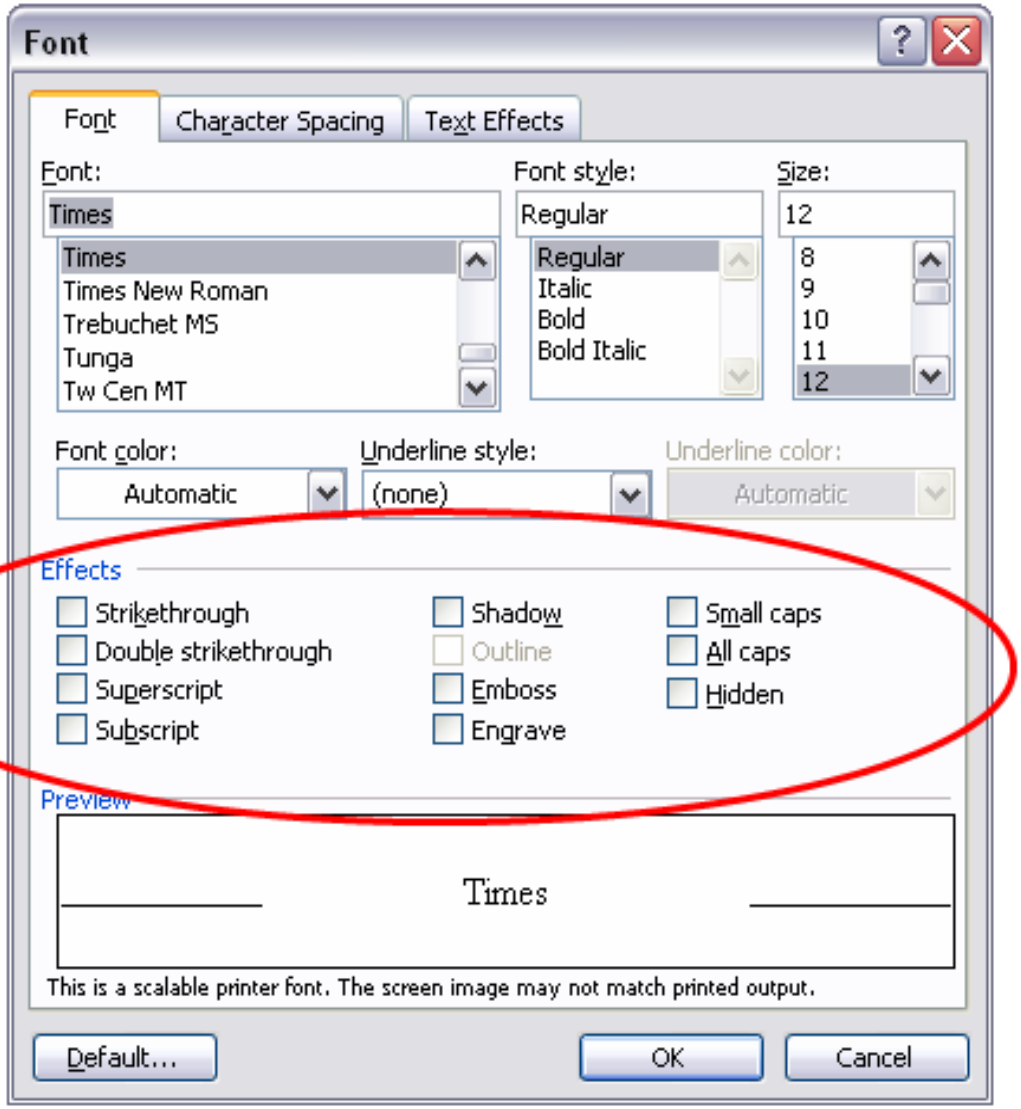
- Pairwise testing commonly applied to software
- Suppose no failure requires more than a pair of settings to trigger in previous example
- Then test all pairs – 180 test cases sufficient to detect any failure
- Pairwise testing can find 50% to 90% of flaws



A simple example

0	0	0	0	0	0	0	0	0	0
1	1	1	1	1	1	1	1	1	1
1	1	1	0	1	0	0	0	0	1
1	0	1	1	0	1	0	1	0	0
1	0	0	0	1	1	1	0	0	0
0	1	1	0	0	1	0	0	1	0
0	0	1	0	1	0	1	1	1	0
1	1	0	1	0	0	1	0	1	0
0	0	0	1	1	1	0	0	1	1
0	0	1	1	0	0	1	0	0	1
0	1	0	1	1	0	0	1	0	0
1	0	0	0	0	0	0	1	1	1
0	1	0	0	0	1	1	1	0	1



0 = effect off
1 = effect on

13 tests for **all 3-way combinations**

2^{10} = **1,024** tests for **all combinations**

A covering array:
10 parameters, 2 values each, 3-way combinations

Any 3 columns contain all possible combinations

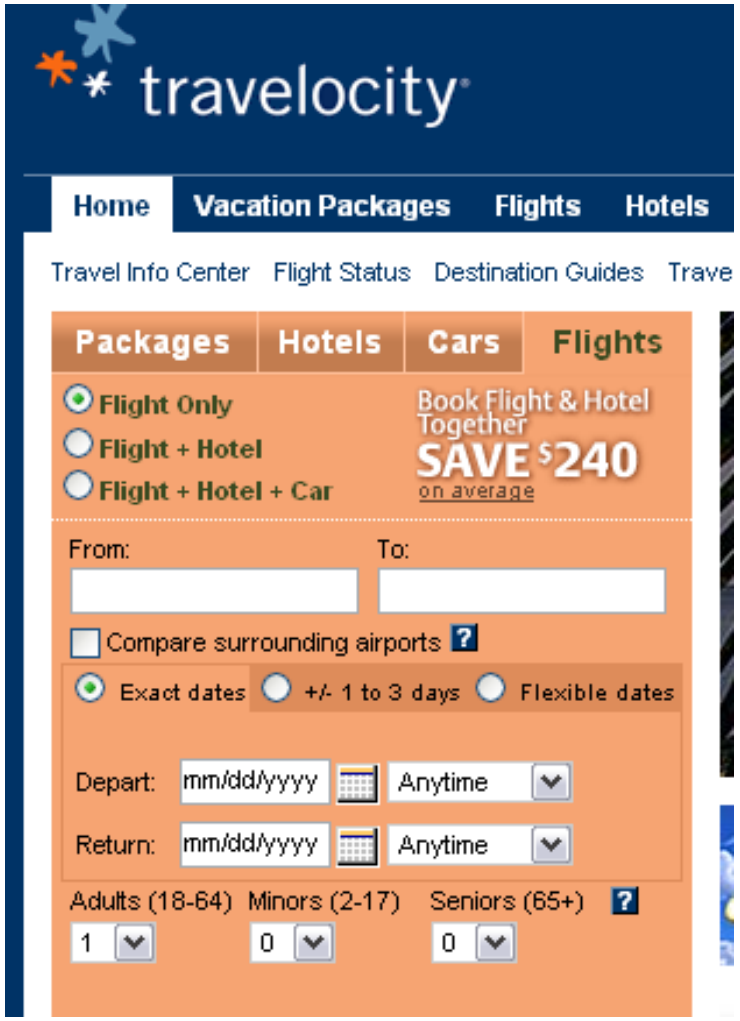
0	0	0	0	0	0	0	0	0	0
1	1	1	1	1	1	1	1	1	1
1	1	1	0	1	0	0	0	0	1
1	0	1	1	0	1	0	1	0	0
1	0	0	0	1	1	1	0	0	0
0	1	1	0	0	1	0	0	1	0
0	0	1	0	1	0	1	1	1	0
1	1	0	1	0	0	1	0	1	0
0	0	0	1	1	1	0	0	1	1
0	0	1	1	0	0	1	0	0	1
0	1	0	1	1	0	0	1	0	0
1	0	0	0	0	0	0	1	1	1
0	1	0	0	0	1	1	1	0	1

13 tests for **all 3-way combinations**

2^{10} = **1,024** tests for **all combinations**

So what happens for realistic examples?

A real-world example



Input data to web application:

Plan: flt, flt+hotel, flt+hotel+car

From: CONUS, HI, AK, Europe, Asia...

To: CONUS, HI, AK, Europe, Asia...

Compare: yes, no

Date-type: exact, 1to3, flex

Depart: today,tomorrow, 1month, 1yr...

Return: today,tomorrow, 1month, 1yr...

Adults: 1,2,3,4,5,6

Minors: 0,1,2,3,4,5

Seniors: 0,1,2,3,4,5

No silver bullet because:

Many values per variable

Requires more tests and practical limits

Need to abstract values

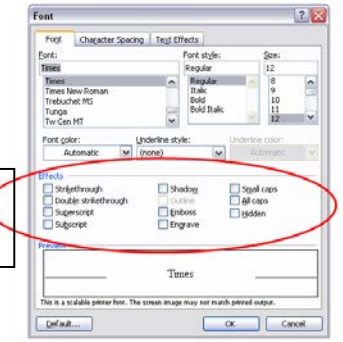
But we can still increase information per test

Two ways of using combinatorial testing

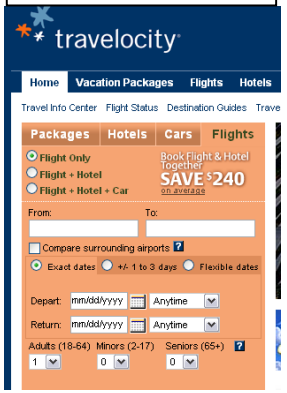
Use combinations here

or here

Configuration



Test data inputs



System under test

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Combinatorial testing requires a lot of tests, but now we can do this

- Generating covering arrays is a hard problem, one reason why anything beyond pairwise testing is rarely used
- Number of tests: suppose we want all **4-way** combinations of **30 parameters**, **5 values** each: **3,800 tests**
- May need 10^3 to 10^7 tests for realistic systems
- With new algorithms we can produce large covering arrays quickly

New algorithms

- Smaller test sets faster, with a more advanced user interface
- First parallelized covering array algorithm
- More information per test

IPOG (Lei, 06)

T-Way	IPOG		ITCH (IBM)		Jenny (Open Source)		TConfig (U. of Ottawa)		TVG (Open Source)	
	Size	Time	Size	Time	Size	Time	Size	Time	Size	Time
2	100	0.8	120	0.73	108	0.001	108	>1 hour	101	2.75
3	400	0.36	2388	1020	413	0.71	472	>12 hour	9158	3.07
4	1363	3.05	1484	5400	1536	3.54	1476	>21 hour	64696	127
5	4226	18.41	NA	>1 day	4580	43.54	NA	>1 day	313056	1549
6	10941	65.03	NA	>1 day	11625	470	NA	>1 day	1070048	12600

Traffic Collision Avoidance System (TCAS): $2^7 3^2 4^1 10^2$

Paintball (Kuhn, 06)

	10		15		20	
	tests	sec	tests	sec	tests	sec
1 proc.	46086	390	84325	16216	114050	155964
10 proc.	46109	57	84333	11224	114102	85423
20 proc.	46248	54	84350	2986	114616	20317
FireEye	51490	168	86010	9419	**	**
Jenny	48077	18953	**	**	**	**

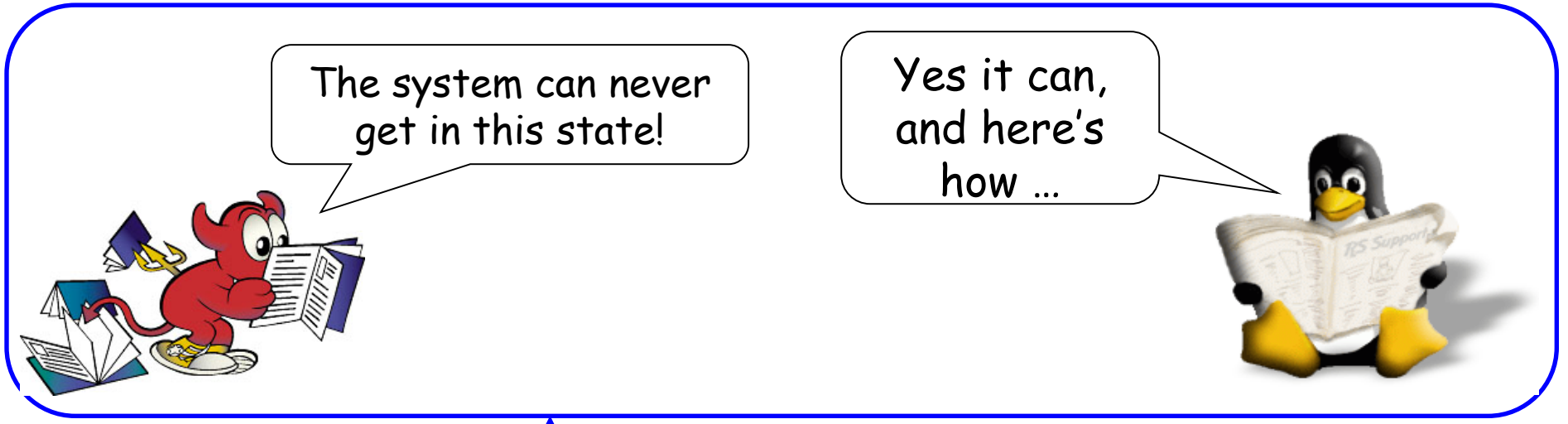
Table 6. 6 way, 5^k configuration results comparison
** insufficient memory

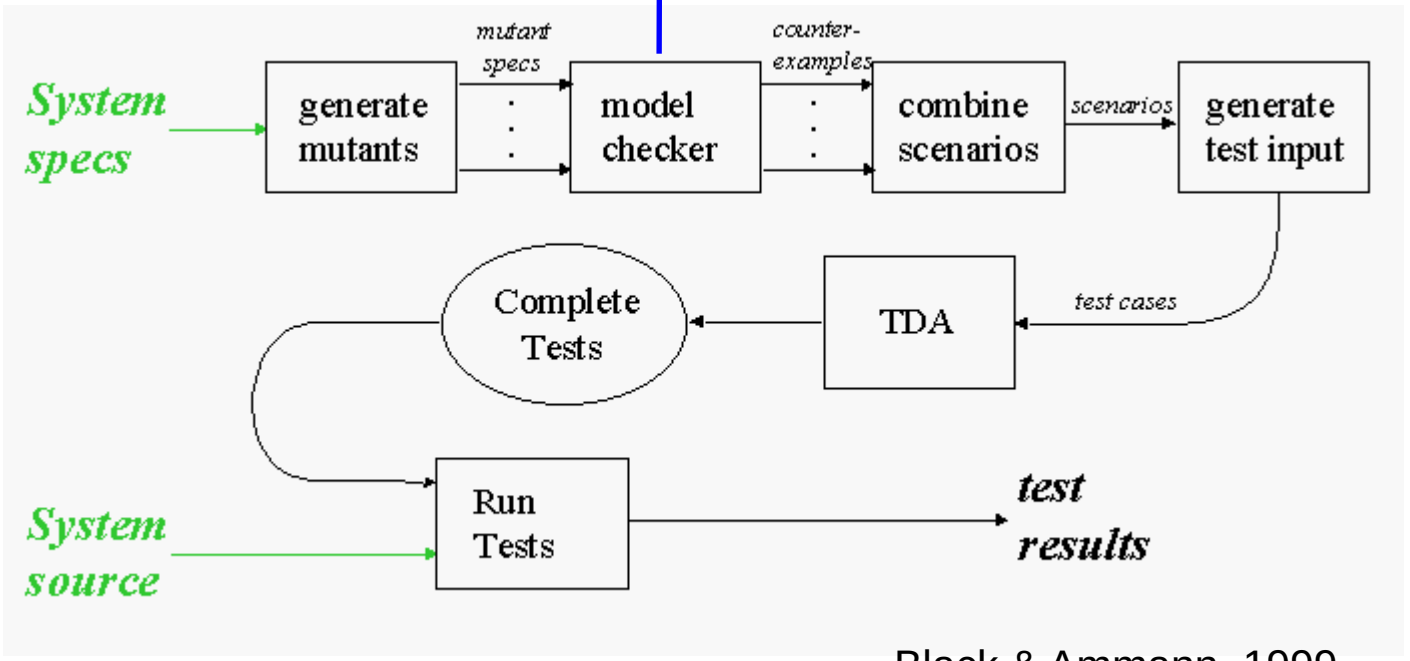
So what? You still have to check the results!

Result Checking

- Creating test data is the easy part!
- How do we check that the code worked correctly on the test input?
  - **Configuration coverage**, using existing test set
    - Easy, if test set exists
  - **Crash testing** server or other code to ensure it does not crash for any test input
    - Easy but limited correctness check
  - Use basic **consistency checks on system output**
    - Better but more costly
  - **White box testing** – incorporate assertions in code to check critical states at different points in the code, or print out important values during execution
  - **Full scale model-checking** using mathematical model of system and model checker to generate expected results for each input
    - expensive but tractable

Using model checking to produce tests





Black & Ammann, 1999

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

Proof-of-concept experiments

- FAA Traffic Collision Avoidance System module
  - Mathematical model of system and model checker for results
  - 41 versions seeded w/ errors, used in previous testing research
  - 12 variables: 7 boolean, two 3-value, one 4-value, two 10-value
  - Tests generated w/ Lei algorithm extended for >2 parameters
  - >17,000 complete test cases, covering 2-way to 6-way combinations generated and executed in a few minutes
  - All flaws found with 5-way coverage
- Grid computer simulator
  - Preliminary results
  - Crashes in >6% of tests w/ valid values
  - "Interesting" combinations discovered

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Where does this stuff make sense?

- More than (roughly) 8 parameters and less than 300-400
- Processing involves interaction between parameters (numeric or logical)

Where does it not make sense?

- Small number of parameters
  (where exhaustive testing is possible)
- No interaction between parameters

Summary

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- Empirical research suggests that all software failures caused by interaction of few parameters
- Combinatorial testing can exercise all t-way combinations of parameter values in a very tiny fraction of the time needed for exhaustive testing
- New algorithms and faster processors make large-scale combinatorial testing possible
- Project could produce better quality testing at lower cost for US industry and government
- Beta release of tools in December, to be open source
- New public catalog of covering arrays

Future directions

- No silver bullet - but does it improve cost-benefit ratio?
  What kinds of software does it work best on?
  What kinds of errors does it miss?
- Large real-world examples will help answer these questions
- **Other applications:**
  - Modelling and simulation
    - Testing the simulation
    - Finding interesting combinations:
      performance problems, denial of service attacks
- Maybe biotech applications. Others?

Please contact us if you are interested!

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