My Life With Bugs, or, Why I Believe in Combinatorial Testing

Paul E. Black

National Institute of Standards and Technology

http://www.nist.gov/

paul.black@nist.gov

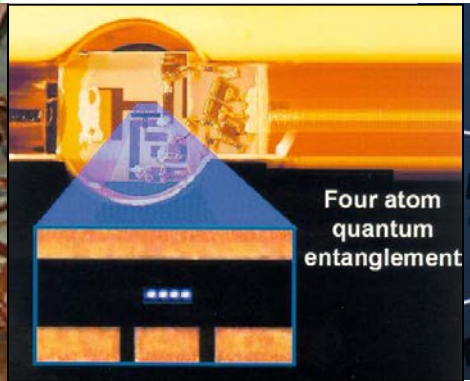
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

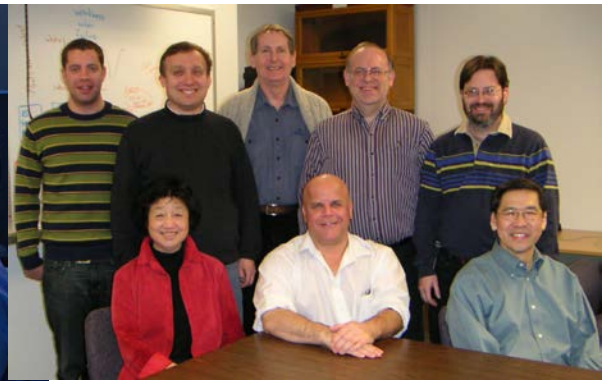
Outline

- **SAMATE, my current program, briefly**
- **Some tough and bizarre bugs**
- **How many conditions do faults need?**
- **Combinatorial Testing**
  - **What is it?**
  - **Why does it work?**
  - **State of the Art**

What is NIST?

- **U.S. National Institute of Standards and Technology**
- **A non-regulatory agency in Dept. of Commerce**
- **3,000 employees + adjuncts**
- **Gaithersburg, Maryland and Boulder, Colorado**
- **Primarily research, not funding**
- **Over 100 years in standards and measurements: from dental ceramics to text retrieval, from quantum computers to fire codes, from body armor to DNA forensics, from biometrics to whale blubber**

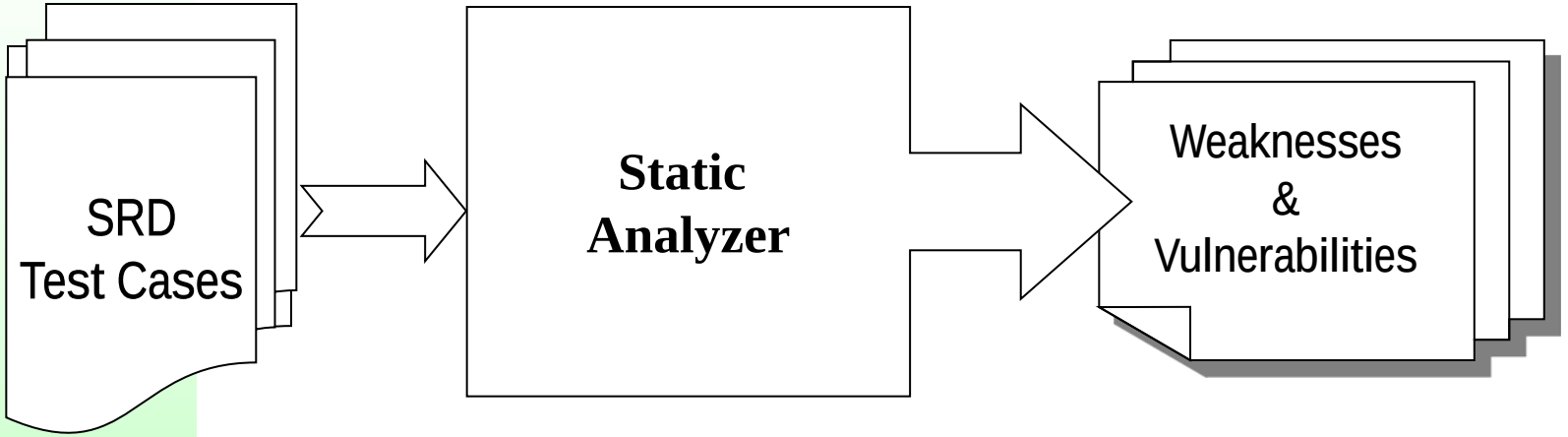




The NIST SAMATE Project

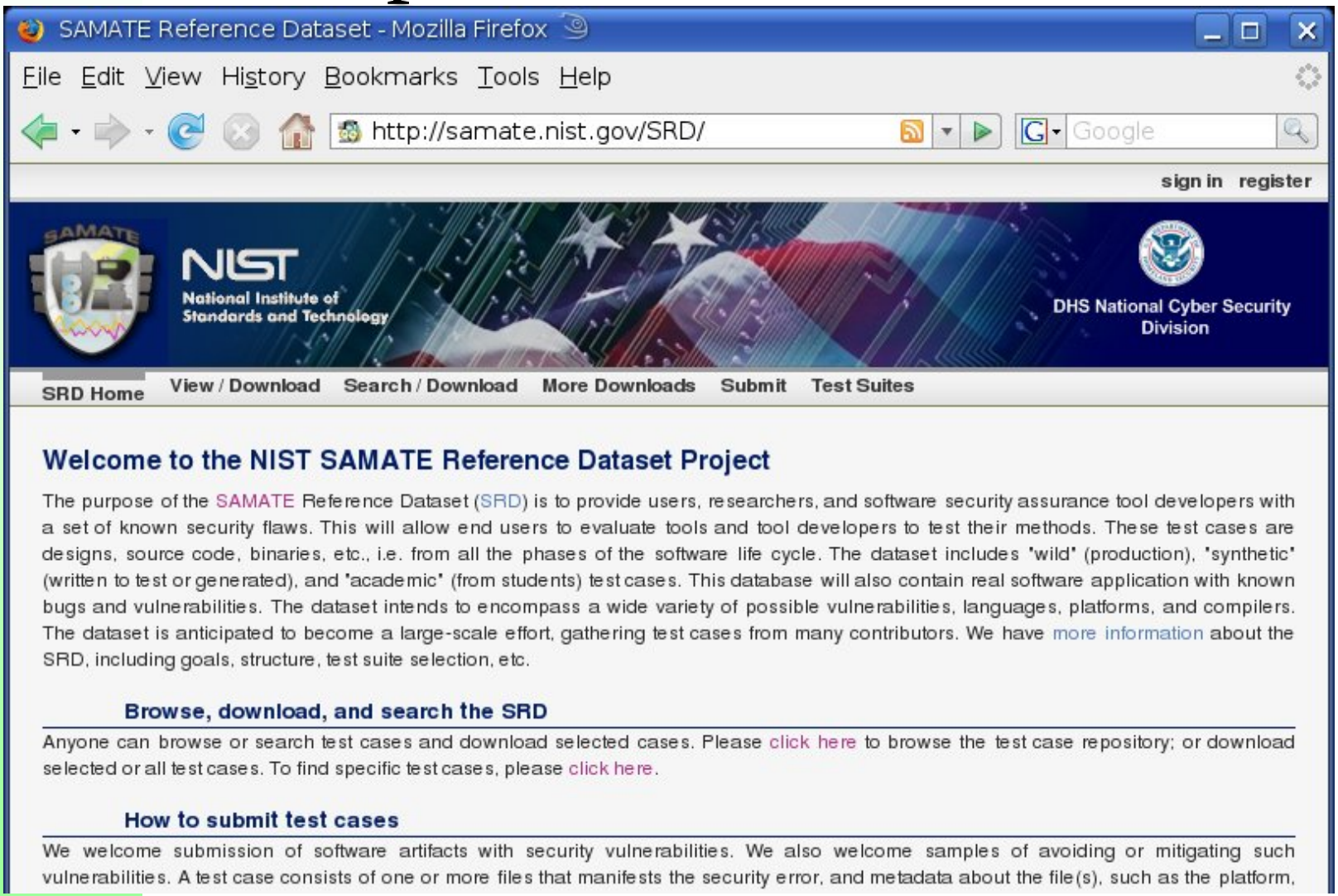
- ***Software Assurance Metrics And Tool Evaluation*** **(SAMATE) project is sponsored in part by DHS**
- **Began 2004 to help improve software assurance**
- **Current areas of concentration**
  - **Source code security analyzers**
  - **Studies of tool effectiveness**
  - **Web application scanners**
  - ***Binary analyzers***
  - ***Software labels***
- **Web site http://samate.nist.gov/**

Source Code Security Analyzers



- Examine source code or binary for adherence to guidelines, weaknesses, etc.
- To assess tools, we wrote and collected thousands of test cases in a SAMATE Reference Dataset (SRD)

SRD: an Open Resource



58	2005-11-02	Java	Source Code	SecureSoftware	C	Not using a a random initialization vector with Cipher Block ...	✗
71	2005-11-07	Java	Source Code	SecureSoftware	C	Omitting a break statement so that one may fall through is often ...	✗
1552	2006-06-22	Java	Source Code	Jeff Meister	C	Tainted input allows arbitrary files to be read and written.	✗
1553	2006-06-22	Java	Source Code	Jeff Meister	C	Tainted input allows arbitrary files to be read and written. ...	✓
1554	2006-06-22	Java	Source Code	Jeff Meister	C	Two file operations are performed on a filename, allowing a filenamer	✗
1567	2006-06-22	Java	Source Code	Jeff Meister	C	The credentials for connecting to the database are hard-wired ...	✗
1568	2006-06-22	Java	Source Code	Jeff Meister	C	The credentials for connecting to the database are hard-wired ...	✓
1569	2006-06-22	Java	Source Code	Jeff Meister	C	The credentials for connecting to the database are hard-wired ...	✓
1570	2006-06-22	Java	Source Code	Jeff Meister	C	An exception leaks internal path information to the user.	✗
1571	2006-06-22	Java	Source Code	Jeff Meister	C	An exception leaks internal path information to the user. (fixed ...	✓
1579	2006-06-22	Java	Source Code	Jeff Meister	C	Tainted output allows log entries to be forged.	✗

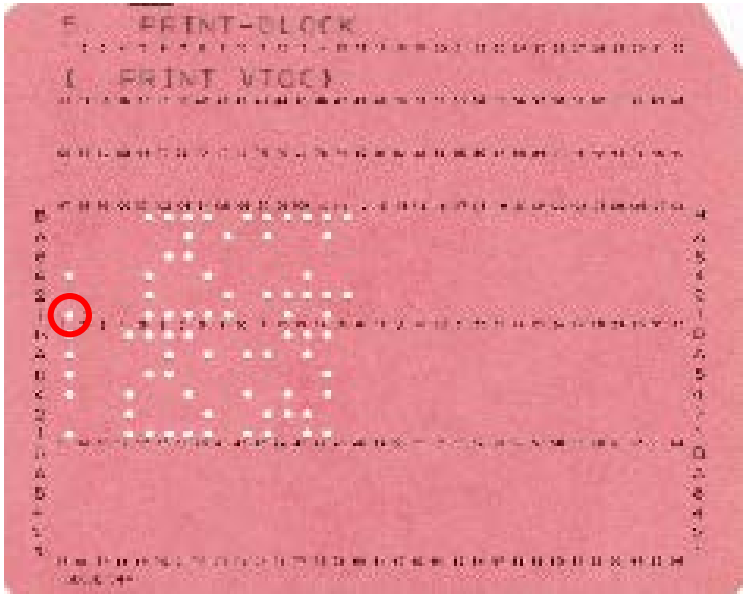
```
public class File1_bad extends HttpServlet
{
    public void doGet(HttpServletRequest req, HttpServletResponse res)
        throws ServletException, IOException
    {
        res.setContentType("text/html");
        ServletOutputStream out = res.getOutputStream();
        out.println("<HTML><HEAD><TITLE>Test</TITLE></HEAD><BODY><blockquote><pre>");

                String name = req.getParameter("name");
                String msg = req.getParameter("msg");
                if(name != null) {
                        try {
                                File f = new File("/tmp", name);                    /* BAD */
                                if(msg != null) {
                                        FileWriter fw = new FileWriter(f);          /* BAD */
                                        fw.write(msg, 0, msg.length());
                                        fw.close();
                                        out.println("message stored");
                                } else {
                                        String line;
                                        BufferedReader fr = new BufferedReader(new FileReader(f));
                                        while((line = fr.readLine()) != null)
                                                out.println(line);
                                }
                        } catch(Exception e) {
                                throw new ServletException(e);
                        }
                } else {
```

Outline

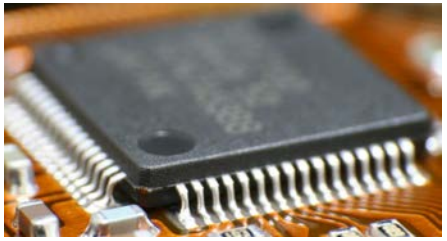
- SAMATE, my current program, briefly
- **Some tough and bizarre bugs**
- How many conditions do faults need?
- Combinatorial Testing
  - What is it?
  - Why does it work?
  - State of the Art

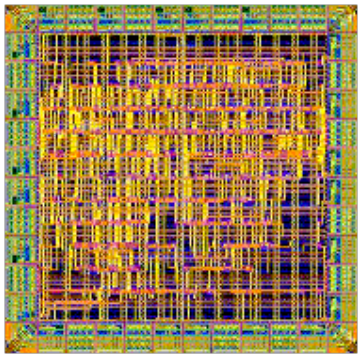
Wrong Date

- **IBM System 3/10 - punched card input**
- **Daily boot-up set system date with a card**
- **In 1979 the daily run didn't print any up-coming payment notices …**
- **Tiny program printed sys data as 1978!**
- **Checked date card, but it said 1979!**



Bad Character





- **Application: IC design parser**
  - **Input: computer chip design, 2D, WYSIWYG**
  - **Output: network list, plain text**
- **Failure: one strange character**

```
(V-WIRE_32 (A_[0..31] B_[0..31]) (Y_[0..31])
     ((G_0 (Y_0) T-WIRE (A_0 B_0)) (G_1 (Y_1) T-WIRE (A_1 B_1))
      (G_8 (Y_8) T-GIRE (A_8 B_8)) (G_9 (Y_9) T-WIRE (A_9 B_9))
      (G_10 (Y_10) T-WIRE (A_10 B_10)) (G_11 (Y_11) T-WIRE (A_11 B_11))
```

  - **Could not reproduce on my machine; *could* on engineer's**
  - **Different places or chars on other runs: memory overwrite?**
- **No hint of code overwrite (common in C)**
- **Made a table of *where* the failure was in output file: all had same low-order bits in hex**
- **Conclusion: flaky bit in output hardware**

Lisp Error

- **Circuit simulator driven by a built-in Lisp, a language with lists & garbage collection**
- **Designer had a bizarre error: some computations got wrong answers!**
- **I could reproduce that error, but it came and went and changed in similar cases**
- **In an attempt to track it down, I**
  - **Wrote a "shadow" floating point math module**
  - **Garbage collected after every operation**
  - **Changed the heap size**

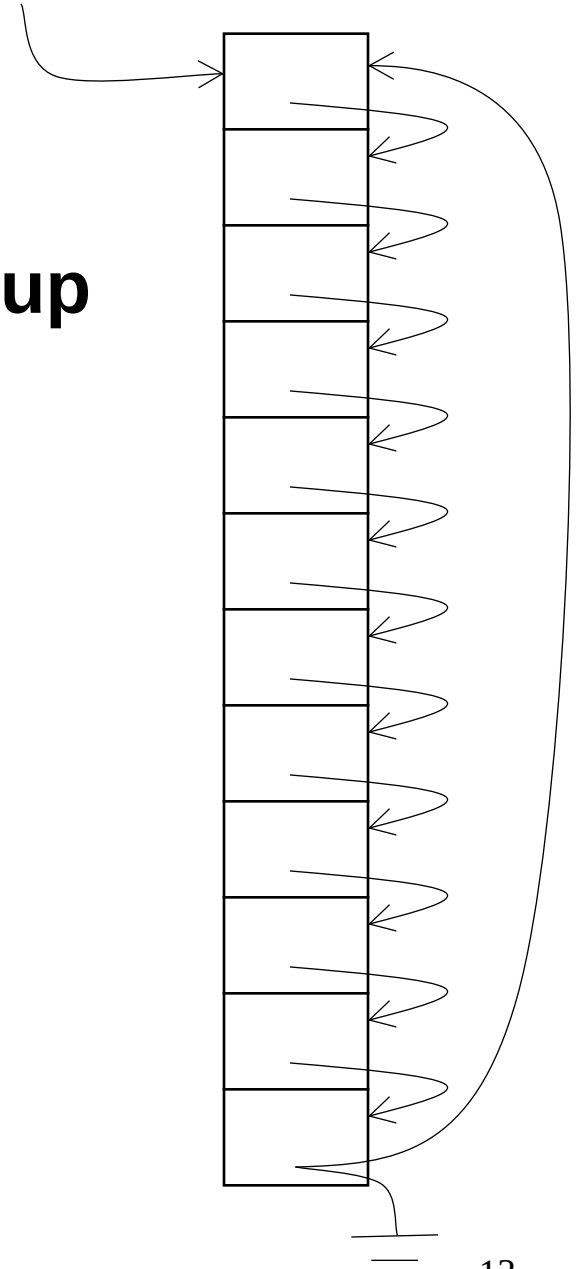
Lisp Error Solution

- **Problem: wrong free list set up**
- **Fix: change one line of code**

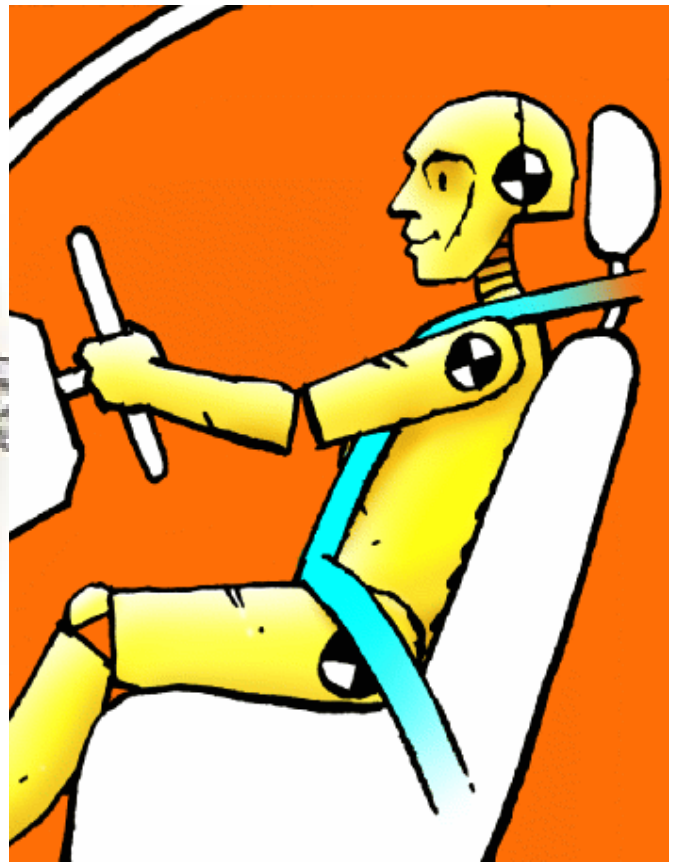
```
h->next = free;
```

- **to**

```
h->next = null;
```



Testing is like a seatbelt …



Outline

- SAMATE, my current program, briefly
- Some tough and bizarre bugs
- **How many conditions do faults need?**
- Combinatorial Testing
  - What is it?
  - Why does it work?
  - State of the Art

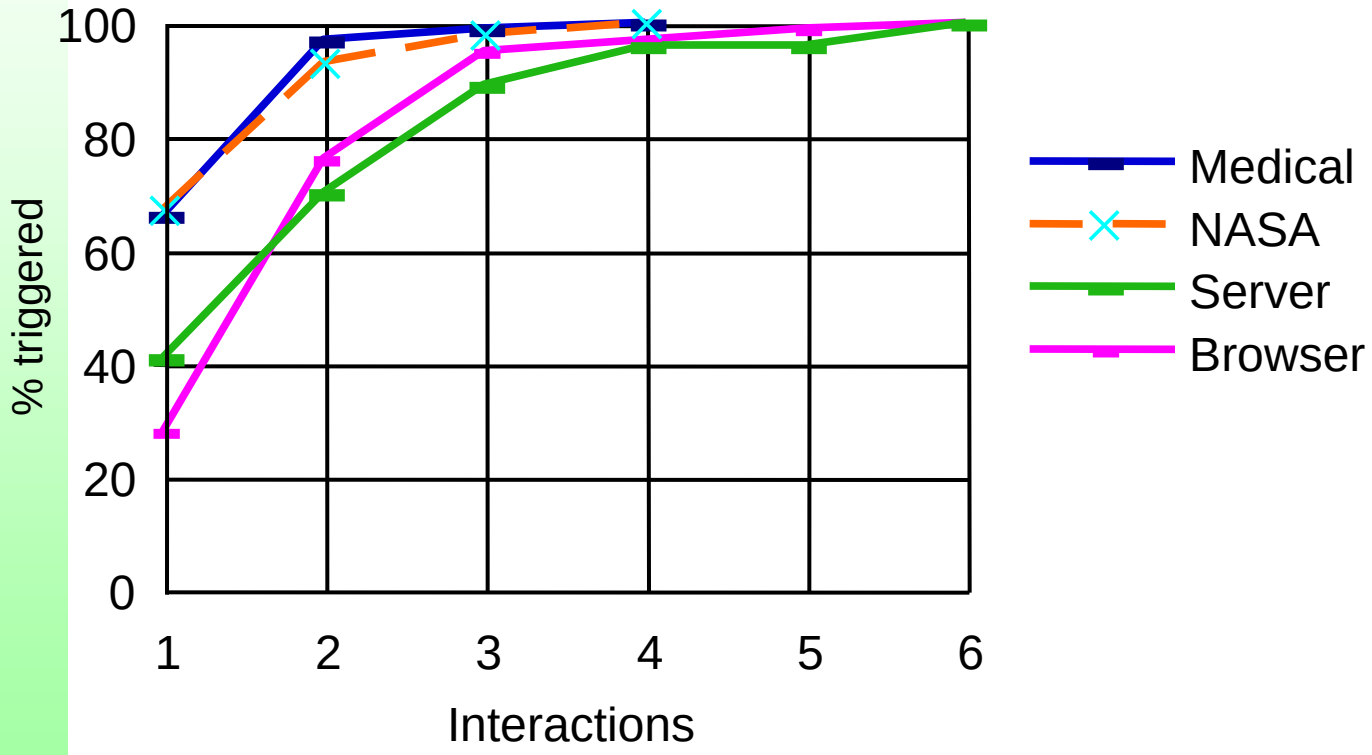
Software Failure Analysis

- **NIST studied software failures in many fields including 15 years of FDA medical device recalls**
- **Would pairwise testing find all errors?**
- **If not, then how many interactions would we need to test to find all errors?**
- **e.g., failure occurs if**
  pressure < 10 (1-way interaction)
  pressure < 10 & volume > 300
  (2-way interaction)

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

- **Maximum 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
- **Reasonable evidence that maximum interaction strength for fault triggering is relatively small**

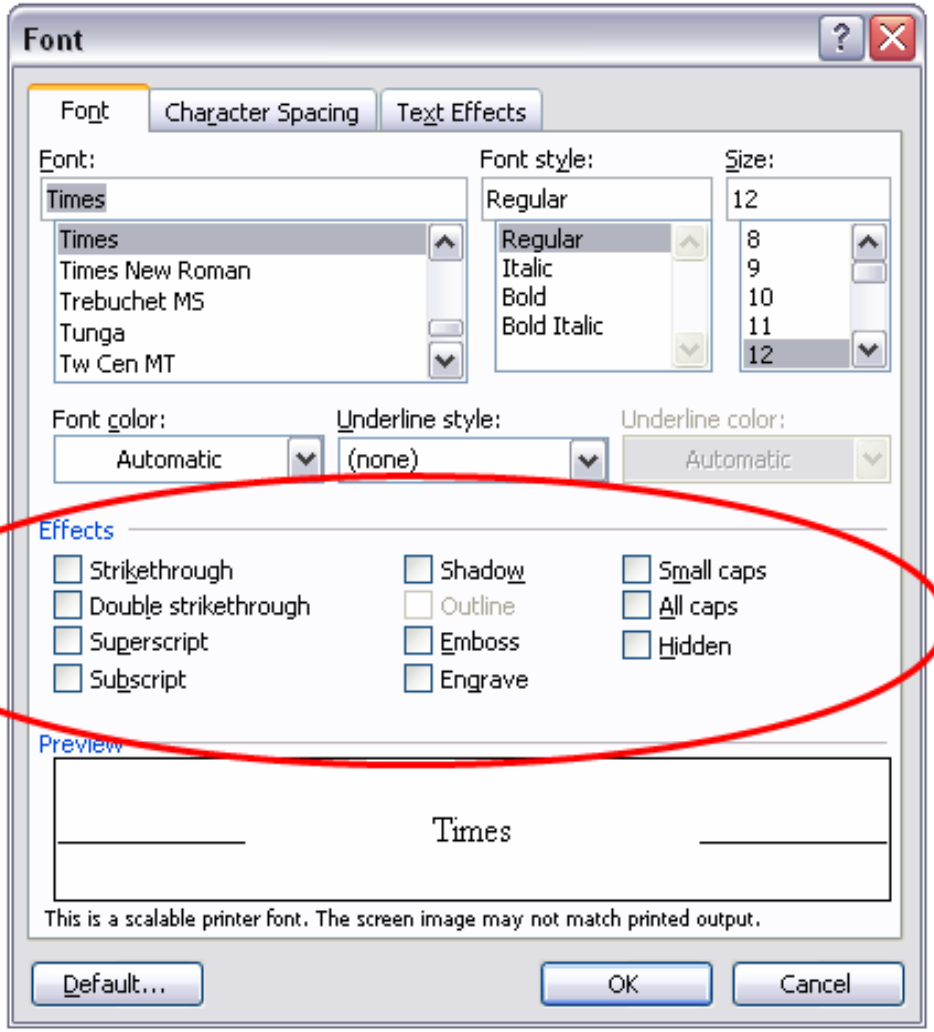
Maximum interactions for fault triggering for 4 domains



Outline

- SAMATE, my current program, briefly
- Some tough and bizarre bugs
- How many conditions do faults need?
- **Combinatorial Testing**
  - **What is it?**
  - Why does it work?
  - State of the Art

A simple example



How Many Tests Would It Take?

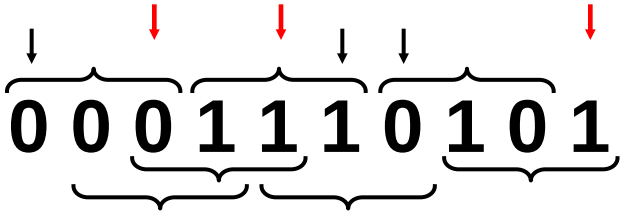
- **There are 10 effects, each can be on or off**
- **All combinations is 2^{10} = 1,024 tests**

  too many to visually check …

- **Let's look at all 3-way interactions …**

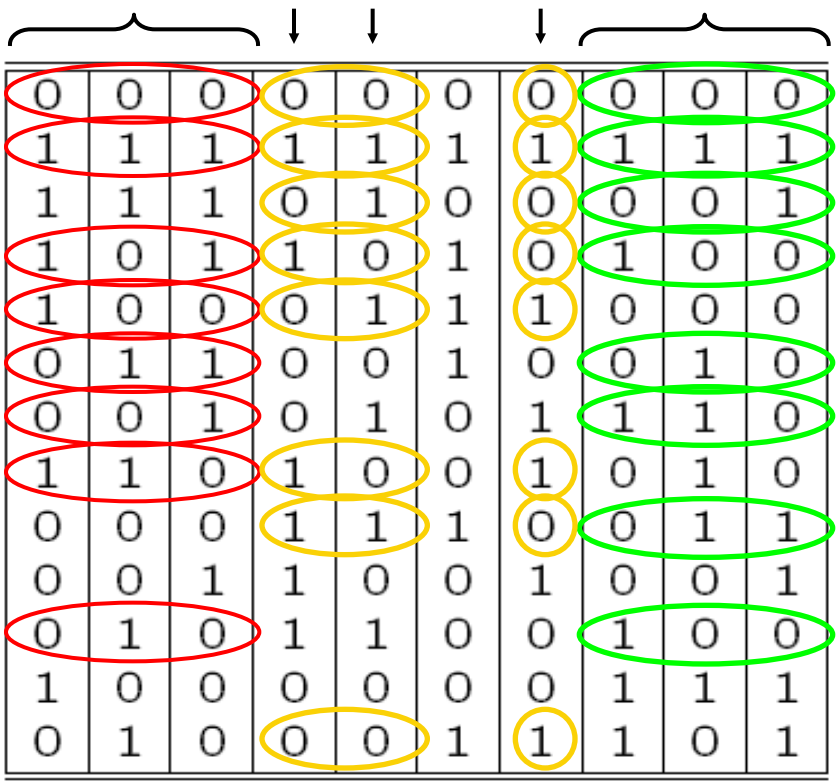
Now How Many Would It Take?

- There are $\binom{10}{3}$ = 120 3-way interactions.
- Naively 120 x 2^3 = 960 tests.
- Since we can pack 3 triples into each test, we need no more than 320 tests.
- Each test exercises many triples:



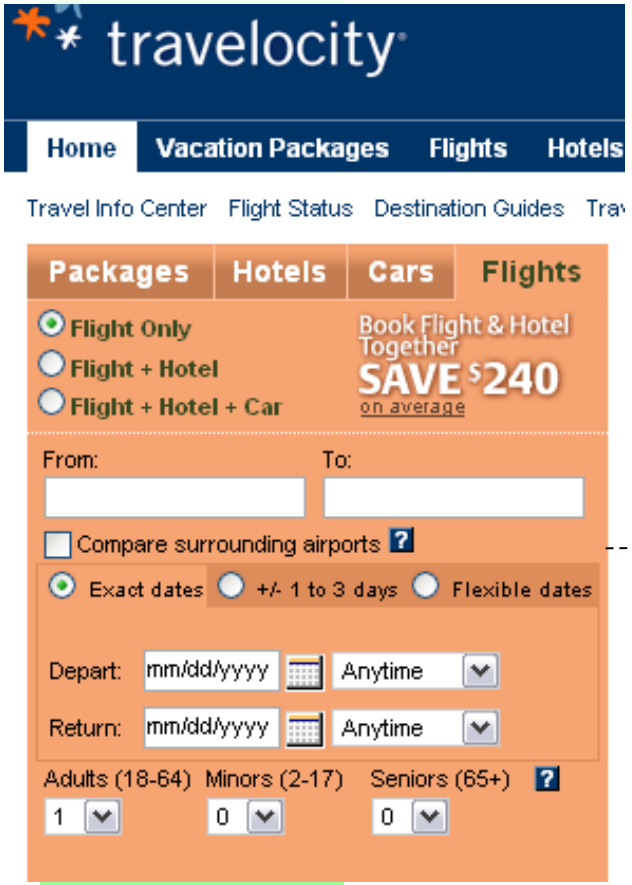
We oughta be able to pack a lot in one test, so what's the smallest number we need?

All Triples Take Only 13 Tests



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

A Real-World Example



No silver bullet because:

- Many values per variable
- Need to abstract values

But we can still increase information per test

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, 1yr, Sun, Mon …
Return: today, tomorrow, 1yr, Sun, Mon …
Adults: 1, 2, 3, 4, 5, 6
Minors: 0, 1, 2, 3, 4, 5
Seniors: 0, 1, 2, 3, 4, 5

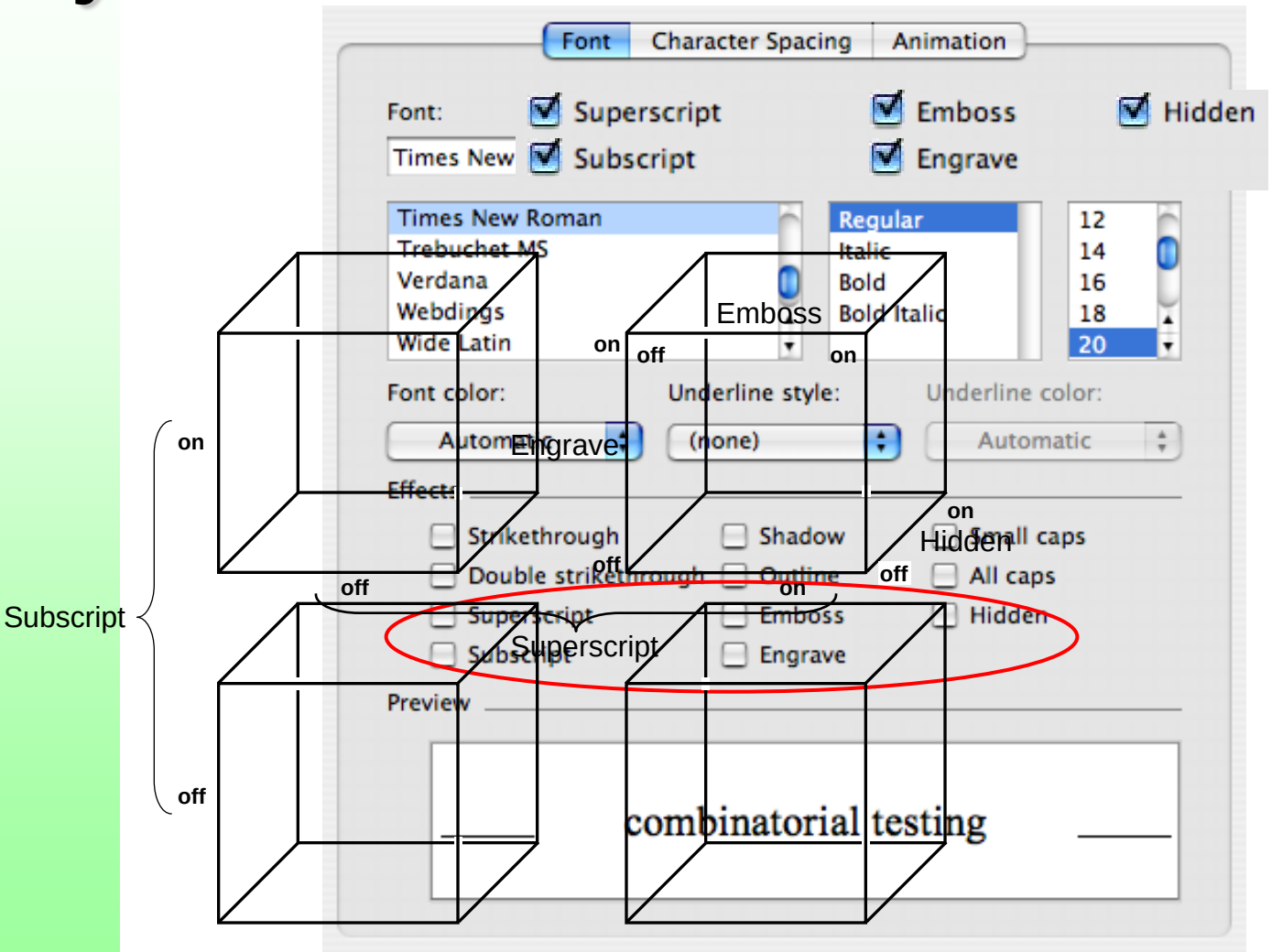
Does It Really Work?

- **Traffic Collision Avoidance System (TCAS) module**
  - **Used in previous testing research**
  - **41 versions seeded with errors**
  - **12 variables: 7 boolean, two 3-value, one 4-value, two 10-value**
  - **All flaws found with 5-way coverage**

Outline

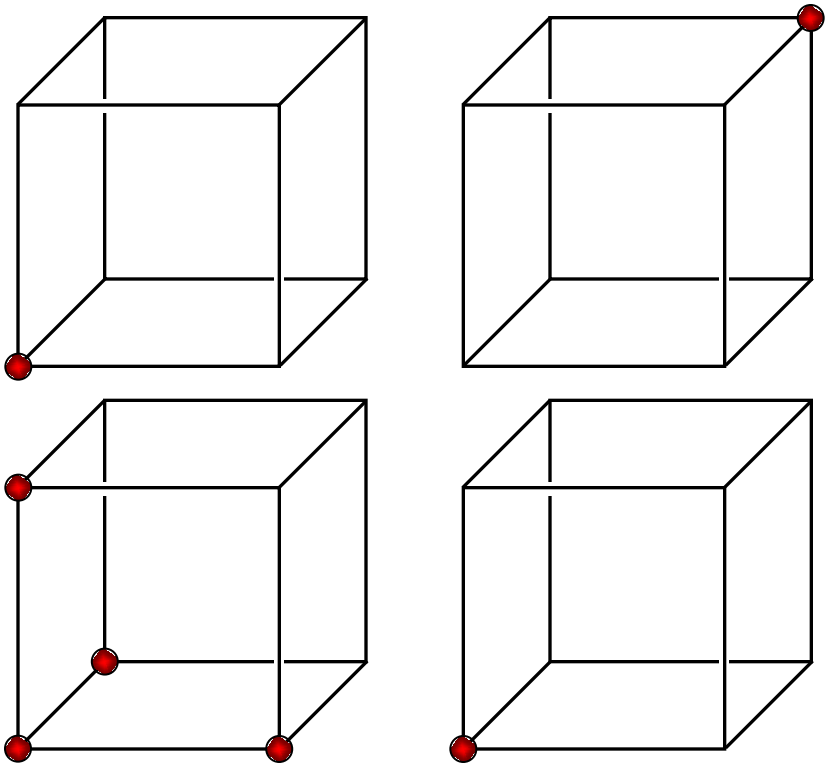
- SAMATE, my current program, briefly
- Some tough and bizarre bugs
- How many conditions do faults need?
- Combinatorial Testing
  - What is it?
  - **Why does it work?**
  - State of the Art

Why? A Geometric Intuition

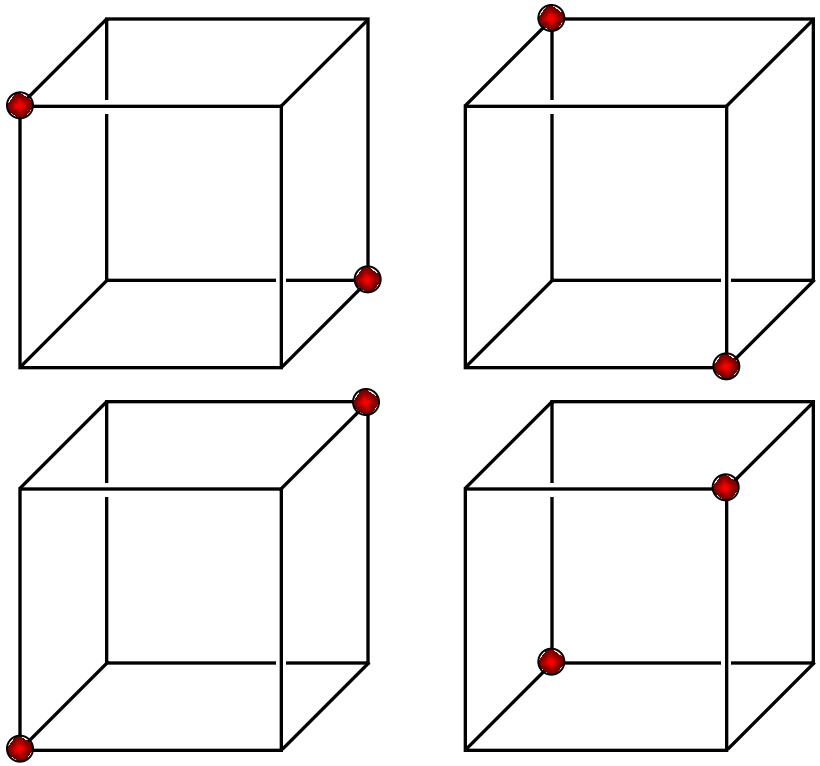


Naïve Test Approach

- **Test all off, all on, each one on**
  - **7 tests total**



How Combinatorial Tests Look



Outline

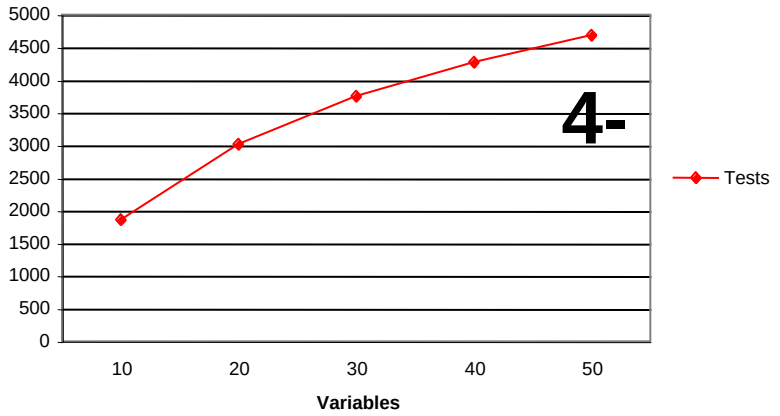
- SAMATE, my current program, briefly
- Some tough and bizarre bugs
- How many conditions do faults need?
- Combinatorial Testing
  - What is it?
  - Why does it work?
  - **State of the Art**

Combinatorial Testing Requires a Lot of Tests

- **For *n* variables with *v* values each, the number of *k*-way combinations is**

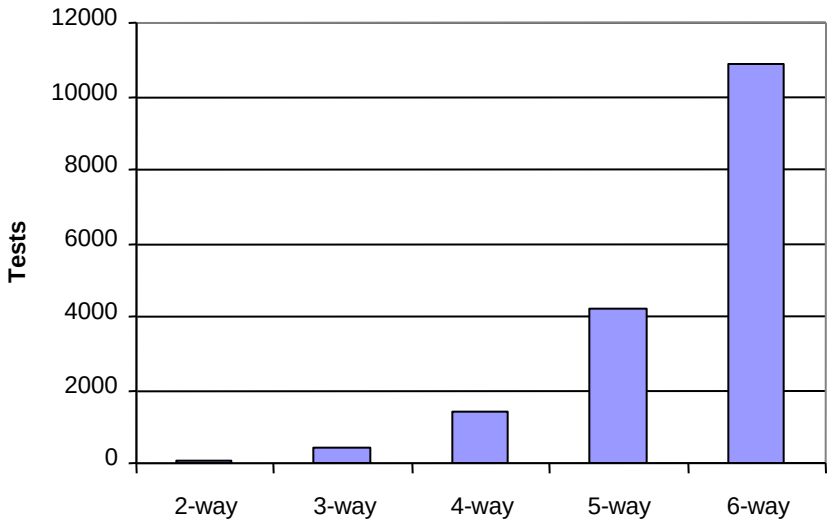
$$\binom{n}{k} v^k$$

- **The test set is a covering array**
- **Finding a covering array is NP hard**
- **Assume 30 parameters with 5 values each. All 4-way combinations are covered by 3,800 tests**



Lots of Tests (cont.)

k	# test cases
2-way	156
3-way	461
4-way	1,450
5-way	4,309
6-way	11,094



Combinatorial Testing Research

- **Huge increases in performance & scalability**
- **Proof-of-concept demonstrations**
- **Applied modeling and simulation**

Software Engineering Institute | Carnegie Mellon

Summary

- **Combinatorial testing makes sense where**
  - **More than ~8 variables and less than 300 - 400**
  - **Logical or numeric interaction of variables**
- **New algorithms make large-scale combinatorial testing possible**
- **Beta release of open source tools in December**
- **New public catalog of covering arrays**

http://csrc.nist.gov/acts

Seeking Participants

- **Contribute test cases to SRD**
- **Comment on specifications and tests**
- **Join SAMATE email list with ideas on**
  - **Static binary analyzers**
  - **Software labels**
- **Use Combinatorial Test Generation Tools**

Paul E. Black
SAMATE Project Leader
paul.black@nist.gov

Rick Kuhn
Combinatorial Testing
kuhn@nist.gov

Society has 3 options:

- **Learn how to make software that *works***
- **Limit size or authority of software**
- **Accept failing software**