In-Parameter-Order: A Test Generation Strategy for Pairwise Testing

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Outline

- Introduction
- The IPO Strategy
- Related Work
- 3-Way Testing and Beyond
- Conclusion

Why Testing?

- Modern society is increasingly dependent on the quality of software systems.
- Software failure can cause severe consequences, including loss of human life
- Testing is the most widely used approach to ensuring software quality

The Testing Process

The testing process consists of three stages:

- Test Generation – Generate test data inputs
- Test Execution – Test setup and the actual test runs
- Test Results Evaluation – Check if the output is in line with expectations

The Challenge

- Testing is labor intensive and can be very costly
  - often estimated to consume more than 50% of the development cost
- Exhaustive testing is impractical due to resource constraints
- How to make a good trade-off between test effort and quality assurance?

Pairwise Testing

- Given any pair of input parameters of a system, every combination of valid values of the two parameters be covered by at least one test
- A special case of combinatorial testing that requires n-way combinations be tested
  - n can be 1, 2, …, or the total number of parameters in the system
- Based on simple specifications, and does not need to look into the implementation details

UTA

Example (1)

Component			
Web Browser	**Operating System**	**Connection Type**	**Printer Setting**
Netscape	Windows	LAN	Local
IE	Macintosh	PPP	Networked
Mozilla	Linux	ISDN	Screen

TABLE I

FOUR COMPONENTS, EACH WITH THREE SETTINGS

Exhaustive testing requires 81 tests = 3 * 3 * 3 * 3.

Example (2)

Test	Browser	OS	Connection	Printer
1	NetScape	Windows	LAN	Local
2	NetScape	Linux	ISDN	Networked
3	NetScape	Macintosh	PPP	Screen
4	IE	Windows	ISDN	Screen
5	IE	Macintosh	LAN	Networked
6	IE	Linux	PPP	Local
7	Mozilla	Windows	PPP	Networked
8	Mozilla	Linux	LAN	Screen
9	Mozilla	Macintosh	ISDN	Local

TABLE II

TEST SUITE TO COVER ALL PAIRS FROM TABLE I

Why Pairwise?

- Many faults are caused by the interactions between two parameters
  - 92% block coverage, 85% decision coverage, 49% p-uses and 72% c-uses
- Not practical to cover all the parameter interactions
  - Consider a system with n parameter, each with m values. How many interactions to be covered?
- A "good" trade-off between test effort and test coverage
  - For a system with 20 parameters each with 15 values, pairwise testing only requires less than 412 tests, whereas exhaustive testing requires 15^{20} tests.

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NP-Completeness

- The problem of generating a minimum pairwise test set is NP-complete.
  - Can be reduced to the vertex cover problem
- Unlikely to find a polynomial time algorithm to solve the problem.
  - Greedy algorithms are the first thing coming into the mind of a computer scientist

The Framework

```
Strategy In-Parameter-Order
begin
   /* for the first two parameters p1 and p2 */
   T := {(v1, v2) | v1 and v2 are values of p1 and p2, respectively}
   if n = 2 then stop;
   /* for the remaining parameters */
   for parameter pi, i = 3, 4, …, n do
   begin
      /* horizontal growth */
      for each test (v1, v2, …, vi-1) in T do
          replace it with (v1, v2, …, vi-1, vi), where vi is a value of pi
       /* vertical growth */
       while T does not cover all pairs between pi and
            each of p1, p2, …, pi-1 do
          add a new test for p1, p2, …, pi to T;
    end
end
```

Horizontal Growth

Algorithm $IPO\_H(\mathcal{T}, p_i)$
// $\mathcal{T}$ is a test set. But $\mathcal{T}$ is also treated as a list with elements in arbitrary order.
{ assume that the domain of p_i contains values $v_1, v_2, \ldots,$ and v_q;
  π = { pairs between values of p_i and values of $p_1, p_2, \ldots,$ and p_{i-1} };
  if ($|\mathcal{T}| \leq q$)
  { for $1 \leq j \leq |\mathcal{T}|$, extend the jth test in $\mathcal{T}$ by adding value v_j and
    remove from π pairs covered by the extended test;
  }
  else
  { for $1 \leq j \leq q$, extend the jth test in $\mathcal{T}$ by adding value v_j and
    remove from π pairs covered by the extended test;
    for $q < j \leq |\mathcal{T}|$, extend the jth test in $\mathcal{T}$ by adding one value of p_i
    such that the resulting test covers the most number of pairs in π, and
    remove from π pairs covered by the extended test;
  }
}

Vertical Growth

Algorithm $IPO\_V(\mathcal{T}, \pi)$
{ let $\mathcal{T}'$ be an empty set;
  for each pair in π
  { assume that the pair contains value w of p_k, $1 \leq k < i$, and value u of p_i;
    if ($\mathcal{T}'$ contains a test with "–" as the value of p_k and u as the value of p_i)
      modify this test by replacing the "–" with w;
    else
      add a new test to $\mathcal{T}'$ that has w as the value of p_k, u as the value of p_i,
      and "–" as the value of every other parameter;
  };
  $\mathcal{T} = \mathcal{T} \cup \mathcal{T}'$;
};

Example (1)

Consider a system with the following parameters and values:

- parameter *A* has values *A1* and *A2*
- parameter B has values B1 and B2, and
- parameter C has values C1, C2, and C3

Example (2)

A	B
A1	B1
A1	B2
A2	B1
A2	B2

A	B	C
A1	B1	C1
A1	B2	C2
A2	B1	C3
A2	B2	C1

Horizontal Growth

A	B	C
A1	B1	C1
A1	B2	C2
A2	B1	C3
A2	B2	C1
A2	B1	C2
A1	B2	C3

Vertical Growth

PairTest

- A Java tool that implements the IPO strategy
- Supports the following types of test generation
  - Account for relations and constraints
  - Extend from an existing test set
  - Modify/extend an existing test set after changes of parameters, values, relations and constraints
- Has been used in IBM and software engineering classes at NCSU

Empirical Results (1)

Let n be the number of parameters, and d the domain size of each parameter. The size of a pairwise test set is in the order of $O(\log n)$ and $O(d^2)$.

Results of PairTest for Systems with n 4-Value Parameters

n (# of parameters)	10	20	30	40	50	60	70	80	90	100
s (# of tests)	31	34	41	42	48	48	51	51	51	53
t (time in seconds)	0.11	0.16	0.22	0.44	0.77	0.99	1.37	1.81	2.23	2.96

Results of PairTest for Systems with 10 Parameters, Each Having d Values

d (# of values)	5	10	15	20	25	30
s (# of Tests)	47	169	361	618	956	1355
t (time in seconds)	0.05	0.28	0.72	1.54	2.96	5.16

Empirical Results (2)

Sizes of Pairwise Test Sets Generated by AETG and PairTest

System	S1	S2	S3	S4	S5	S6
AETG	11	17	35	25	12	193
PairTest	9	17	34	26	15	212

S1: 4 3-value parameters
S2: 13 3-value parameters
S3: 61 parameters (15 4-value parameters, 17 3-value parameters, 29 2-value parameters)
S4: 75 parameters (1 4-value parameter, 39 3-value parameters, 35 2-value parameters)
S5: 100 2-value parameters
S6: 20 10-value parameters

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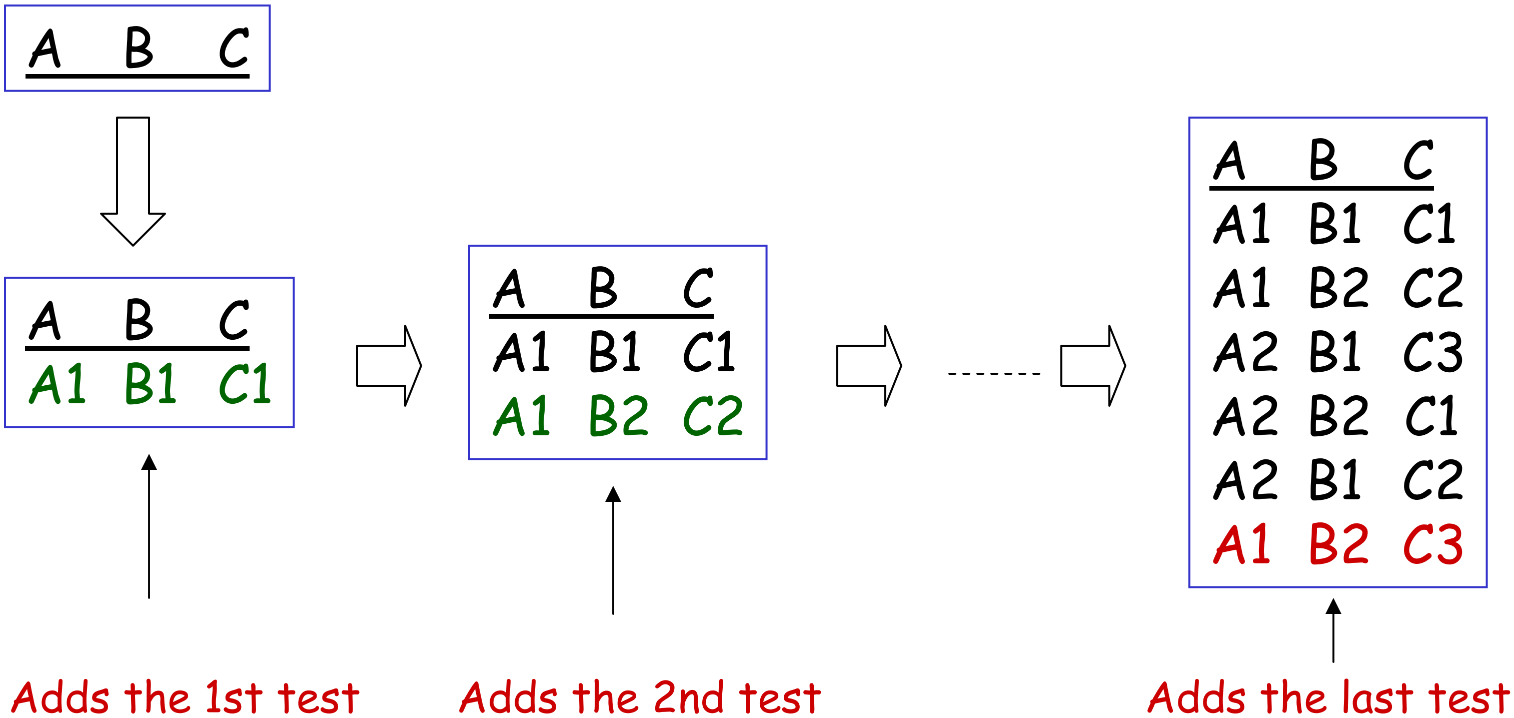
Classification

- Computational methods that are mainly developed by computer scientists
  - AETG (from Telcordia), TCG (from JPL/NASA), DDA (from ASU), PairTest
- Algebraic methods that are mainly developed by mathematicians
  - Orthogonal Arrays
  - Recursive Construction

AETG (1)

- Starts with an empty set and adds one (complete) test at a time
- Each test is locally optimized to cover the most number of missing pairs:
  - Generate a random order of the parameters
  - Use a greedy algorithm to construct a test that covers the most uncovered pairs
  - Repeat the above two steps for a given number of times (suggested 50), and select the best one

AETG (2)



A B C
A B C
A1 B1 C1
A B C
A1 B1 C1
A1 B2 C2
A B C
A1 B1 C1
A1 B2 C2
A2 B1 C3
A2 B2 C1
A2 B1 C2
A1 B2 C3
Adds the 1st test
Adds the 2nd test
Adds the last test

AETG vs IPO

- AETG is fundamentally non-deterministic, whereas IPO is deterministic
- AETG has a higher order of complexity, both in terms of time and space, than IPO
- AETG is a commercial tool, and its license is very expensive, whereas IPO is open to the public.

Orthogonal Arrays (1)

- An orthogonal array $OA_\lambda(N; k, v, t)$ is an $N \times k$ array on v symbols such that every $N \times t$ sub-array contains all tuples of size t from v symbols exactly λ times.
  - N – Number of test cases
  - k – Number of parameters
  - v – Number of values of each parameter
  - t – Degree of interaction
  - λ - 1 for software testing and is often omitted
- For example, Table 2 is an orthogonal array $OA(9; 4, 3, 2)$

Orthogonal Arrays (2)

OA (9; 4, 3, 2)

(b0, b1)	A = b1	B = b0 + b1	C = b0 + 2 * b1	D = b0
(0, 0)	0	0	0	0
(0, 1)	1	1	2	0
(0, 2)	2	2	1	0
(1, 0)	0	1	1	1
(1, 1)	1	2	0	1
(1, 2)	2	0	2	1
(2, 0)	0	2	2	2
(2, 1)	1	0	1	2
(2, 2)	2	1	0	2

Orthogonal Arrays (3)

- Orthogonal arrays can be constructed very fast and are always optimal
  - Any extra test will cause a pair to be covered for more than once
- However, there are several limitations:
  - Orthogonal arrays do not always exist
  - Existing methods often require |v| be a prime power and k be less than |v| + 1.
  - Every parameter must have the same number of values
  - Every t-way interaction must be covered at the same number of times

Recursive Construction (1)

- Covering arrays are a more general structure, which requires every t-way interaction be covered at least once
- Constructing a covering array from one or more covering arrays with smaller parameter sets
- Recursive construction can be fast, but it also has restrictions on the number of parameters and the domain sizes

Recursive Construction (2)

Use *OA*(27; 4, 3, 3) and *OA*(9; 4, 3, 2) to construct *CA*(27; 8, 3, 3) = 27 + 9 + 9 = 45

0000 →	00 00 00 00
0012 →	00 00 11 22
0021 →	00 00 22 11
	…
2212 →	22 22 11 22
2220 →	22 22 22 00

Double each column

0000 →	01 01 01 01
0111 →	01 12 12 12
0222 →	01 20 20 20
1021 →	12 01 20 12
1102 →	12 12 01 20
1210 →	12 20 12 01
2012 →	20 01 12 20
2120 →	20 12 20 01
2201 →	20 20 01 12

0 -> 01
1 -> 12
2 -> 20

0000 →
0111 →
0222 →
1021 →
1102 →
1210 →
2012 →
2120 →
2201 →

0 -> 02
1 -> 10
2 -> 21

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Why beyond 2-way?

- Software failures may be caused by more than two parameters
  - A recent NIST study by Rick Kuhn indicates that failures can be triggered by interactions up to 6 parameters
- Increased coverage leads to a higher level of confidence
  - Safety-critical applications have very strict requirements on test coverage

The Challenges

- The number of tests may increase rapidly as the degree of interactions increases
  - Assume that each parameter has 10 values. Then, pairwise testing requires at least 100 tests, 3-way testing at least 10^3 tests, 4-way testing at least 10^4 tests.
- Test generation algorithms must be more sensitive in terms of both time and space requirements
- The need for test automation becomes even more serious
  - Impractical to manually execute and inspect the results of a large number of test runs

State-of-the-Art

- Both algebraic and computational methods can be extended to 3-way testing and beyond
- However, algebraic methods have fundamental restrictions on the systems they can apply.
- Computational methods are more flexible, but none of them are optimized for n-way testing with $n > 2$.

Opportunities (1)

- Possible ideas to reduce the number of tests
  - Domain partitioning – identify equivalence values of each parameter
  - Parameter constraints – exclude combinations that are not meaningful from the domain semantics
  - Fault-oriented test generation – only include combinations that may contribute to one or more specific classes of faults
  - Test budget – maximize the coverage of n-way interactions within a given number of tests

Opportunities (2)

- Possible ways to improve the test generation algorithms
  - Combination of algebraic and computational methods,
    - e.g., computational methods can be used to compute a starter covering array and then recursive construction can be used to expand the array

Opportunities (3)

- Possible ideas for test automation
  - Test harness that can automate test setup, test execution, and test results evaluation
  - Automatically generate test oracles from a high level specification or by integration with tools based on formal methods, e.g., model checkers

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Conclusion

- The problem of combinatorial testing is well-defined and has been used widely in practice.
- The IPO strategy is deterministic, has a lower order of complexity, and still produces competitive results.
- Algebraic methods, if applicable, are fast and can be optimal, whereas computational methods are heuristic but very flexible.
- Going beyond 2-way testing presents challenges and opportunities to the area of combinatorial testing.