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Combinatorial Testing

- Introduction
- Combinatorial Coverage Criteria
- Pairwise Test Generation
- Summary

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Motivation

- The behavior of a software application may be affected by many factors, e.g., input parameters, environment configurations, and state variables.
- Techniques like equivalence partitioning and boundary-value analysis can be used to identify the possible values of individual factors.
- It is impractical to test all possible combinations of values of all those factors. (Why?)

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Combinatorial Explosion

- Assume that an application has 10 parameters, each of which can take 5 values. How many possible combinations?

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Example - sort

```
> man sort
Reformatting page.  Wait... done

User Commands                                   sort(1)

NAME
    sort - sort, merge, or sequence check text files

SYNOPSIS
    /usr/bin/sort [ -cmu ] [ -o output ] [ -T directory ]
        [ -y [ kmem ]] [ -z recsz ]  [  -dfiMnr  ]  [  -b  ]  [
    -t char ]
        [ -k keydef ] [ +pos1 [ -pos2 ]] [ file...]
 ...
```

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Combinatorial Design

- Instead of testing all possible combinations, a subset of combinations is generated to satisfy some well-defined combination strategies.
- A key observation is that not every factor contributes to every fault, and it is often the case that a fault is caused by interactions among a few factors.
- Combinatorial design can dramatically reduce the number of combinations to be covered but remains very effective in terms of fault detection.

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Fault Model

- A t-way interaction fault is a fault that is triggered by a certain combination of t input values.
- A simple fault is a t-way fault where t = 1; a pairwise fault is a t-way fault where t = 2.
- In practice, a majority of software faults consist of simple and pairwise faults.

Example – Pairwise Fault

```
begin
   int x, y, z;
   input (x, y, z);
   if (x == x1 and y == y2)
      output (f(x, y, z));
   else if (x == x2 and y == y1)
      output (g(x, y));
   else
      output (f(x, y, z) + g(x, y))
end
```

Expected: x = x1 and y = y1 => f(x, y, z) – g(x, y); x = x2, y = y2 => f(x, y, z) + g(x, y)

Example – 3-way Fault

```
// assume x, y ∈ {-1, 1}, and z ∈ {0, 1}
begin
   int x, y, z, p;
   input (x, y, z);
   p = (x + y) * z // should be p = (x – y) * z
   if (p >= 0)
      output (f(x, y, z));
   else
      output (g(x, y));
end
```

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All Combinations Coverage

- Every possible combination of values of the parameters must be covered
- For example, if we have three parameters P1 = (A, B), P2 = (1, 2, 3), and P3 = (x, y), then all combinations coverage requires 12 tests: {(A, 1, x), (A, 1, y), (A, 2, x), (A, 2, y), (A, 3, x), (A, 3, y), (B, 1, x), (B, 1, y), (B, 2, x), (B, 2, y), (B, 3, x), (B, 3, y)}

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Each Choice Coverage

- Each parameter value must be covered in at least one test case.
- Consider the previous example, a test set that satisfies each choice coverage is the following: {(A, 1, x), (B, 2, y), (A, 3, x)}

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Pairwise Coverage

- Given any two parameters, every combination of values of these two parameters are covered in at least one test case.
- A pairwise test set of the previous example is the following:

P1	P2	P3
A	1	x
A	2	x
A	3	x
A	-	y
B	1	y
B	2	y
B	3	y
B	-	x

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T-Wise Coverage

- Given any t parameters, every combination of values of these t parameters must be covered in at least one test case.
- For example, a 3-wise coverage requires every triple be covered in at least one test case.
- Note that all combinations, each choice, and pairwise coverage can be considered to be a special case of t-wise coverage.

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Base Choice Coverage

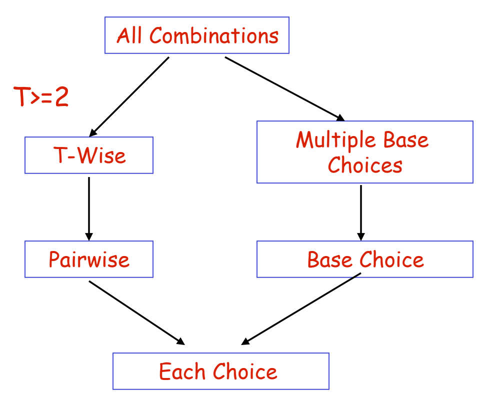
- For each parameter, one of the possible values is designated as a base choice of the parameter
- A base test is formed by using the base choice for each parameter
- Subsequent tests are chosen by holding all base choices constant, except for one, which is replaced using a non-base choice of the corresponding parameter:

P1	P2	P3
A	1	x
B	1	x
A	2	x
A	3	x
A	1	y

Multiple Base Choices Coverage

- At least one, and possibly more, base choices are designated for each parameter.
- The notions of a base test and subsequent tests are defined in the same as Base Choice.

Subsumption Relation



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Why Pairwise?

- Many faults are caused by the interactions between two parameters
  - 92% statement coverage, 85% branch coverage
- 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 trade-off must be made between test effort and fault detection
  - 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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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

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Example (2)

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

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

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

The IPO Strategy

- First generate a pairwise test set for the first two parameters, then for the first three parameters, and so on
- A pairwise test set for the first n parameters is built by extending the test set for the first n – 1 parameters
  - Horizontal growth: Extend each existing test case by adding one value of the new parameter
  - Vertical growth: Adds new tests, if necessary

Algorithm IPO_H (T, p_i)

Assume that the domain of p_i contains values v_1, v_2, …, and v_q;
π = { pairs between values of p_i and values of p_1, p_2, …, and p_{i-1}
if (|T| <= q)
  for 1 <= j <= |T|, extend the j^{th} test in T by adding value v_j and remove from π pairs covered by the extended test
else
  for 1 <=j <= q, extend the j^{th} test in T by adding value v_j and remove from π pairs covered by the extended test;
  for q < j <= |T|, extend the j^{th} test in 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

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Algorithm IPO_V(T, π)

let T' be an empty set;
for each pair in π
  assume that the pair contains value w of p_k, $1 \le k < i$, and value u of p_i;
  if (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 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;
 $T = T \cup T'$

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Example Revisited

Show how to apply the IPO strategy to construct the pairwise test set for the example system.

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Summary

- Combinatorial testing makes an excellent trade-off between test effort and test effectiveness.
- Pairwise testing can often reduce the number of dramatically, but it can still detect faults effectively.
- The IPO strategy constructs a pairwise test set incrementally, one parameter at a time.
- In practice, some combinations may be invalid from the domain semantics, and must be excluded, e.g., by means of constraint processing.