Conditional Entropy and Failed Error Propagation in Software Testing

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Coverage criteria

- The most widely used type of test criterion.
- Mandated in some standards.
- Failing to achieve coverage clearly demonstrates that testing is weak.
- Syntactic: what does achieving coverage tell us?

Finding Faults

- To find a fault in statement *s* a test case must:
  - Execute *s*.
  - Infect *s*.
  - Propagate this to output.
- (The PIE framework.)

- Propagation is not just data dependence.
  - Consider e.g. statement y = y mod 2;

Failed Error Propagation (FEP)

- This occurs when:
  - A test case leads to execution and infection but not propagation.
- Makes testing less effective.
- Empirical evidence suggests:
  - Affects approximately 10% of test cases but this can be as high as 60% for some programs.

FEP and Coverage

- The ‘hope’ in coverage is that:
  - If a test case executes e.g. a statement s and this contains a fault then the test case will find this fault.
- This already looks weak (need ‘infection’).
  - Also need to avoid FEP.
- Could help explain evidence of limited effectiveness of coverage.

Failed Error Propagation (FEP)

The basic idea

- In test execution FEP occurs through the following:
  - The program state at statement s should be σ but is σ’.
  - The code after this maps σ and σ’ to the same output.
- There has been a *loss of information*.
- Underlying assumption: only one fault.

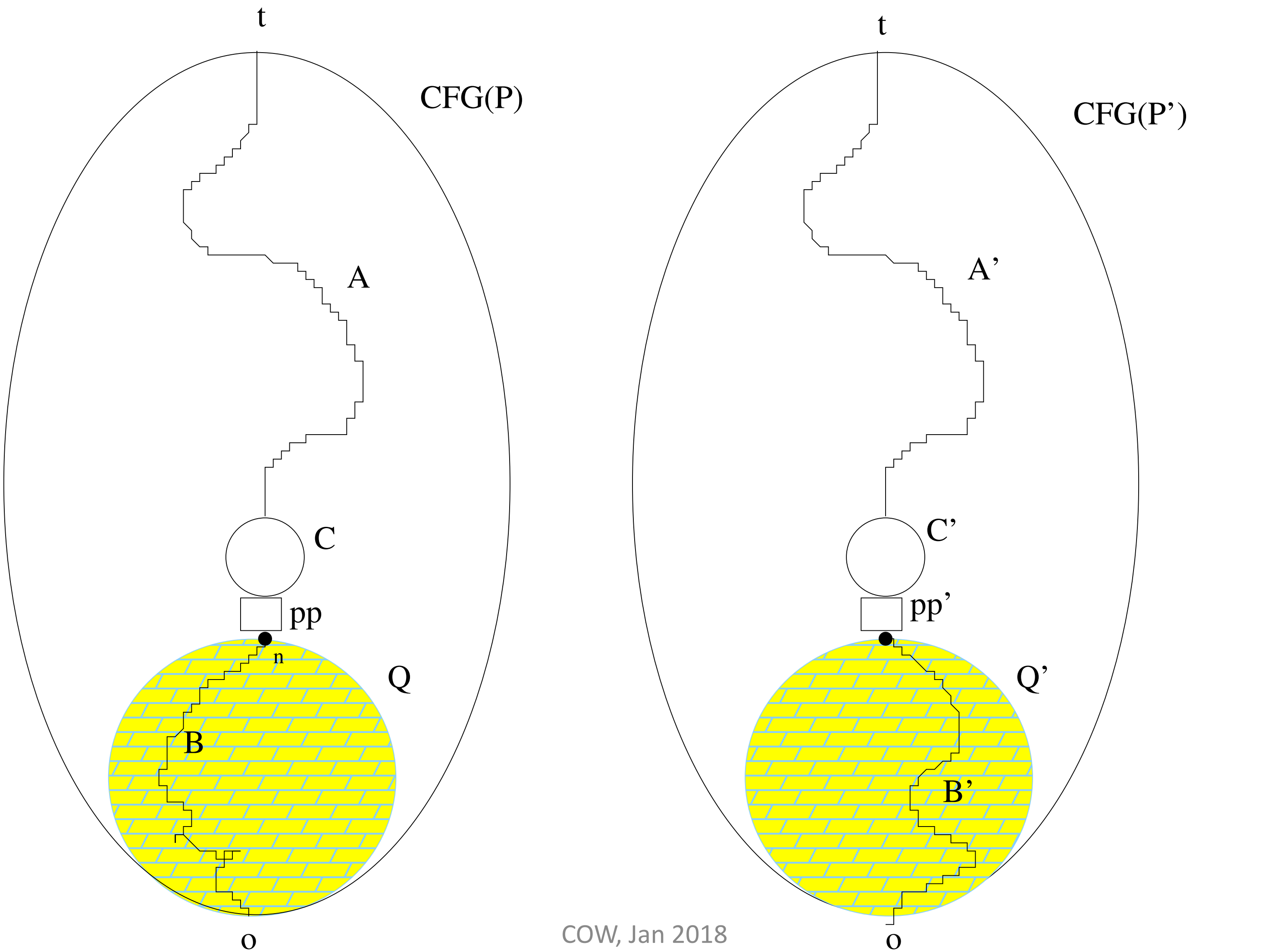
Squeeziness

- This is the loss of entropy (uncertainty) during computation.
- For function f with input domain I this is:

$$Sq(f, I) = \mathcal{H}(I) - \mathcal{H}(O)$$

- Where

$$\mathcal{H}(X) = -\sum_{x \in X} p(x) \log_2 p(x)$$



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Estimating the probability of FEP

- Using test case t, FEP is caused by a lack of information flow after a fault (in statement s).
- We could use:
  - The Squeeziness of the code that follows s.
    - The QIF of Q; or
    - The QIF of the path.
- The former captures the computation; the latter might approximate this.

- Should we consider the code *before* s?

Possible measures

- M1: Squeeziness of Q (on the states at pp')
- M2: M1 + Squeeziness of R (code before)
- M3: Squeeziness of Q on states reachable via a given upper path π
- M4: M3 + Squeeziness of (upper/initial) path π_u
- M5: Squeeziness of (lower/final) path π_l

Experimental study

- For a program p we:
  - Randomly generated a sample T of 5,000 inputs from a suitable domain.
  - Generated mutants of p.
  - For mutant m (mutated statement s), input t in T:
    - Determine whether m and p have the same state after s.
    - Determine whether m and p have the same output.
  - A different ‘outcome’ denotes FEP.

Comparison made

- We compared our measures with the true (for the sample) probability of FEP:

$$p(FEP) = \frac{\#\text{tests with different state after s but same output}}{\#\text{number of tests with different state after s}}$$

Experimental subjects

- Three groups, all written in C:
  - 17 toy programs.
  - 10 functions from R.
  - 3 functions from GRETL (Gnu Regression, Econometrics and Time-Series Library).
- R functions: between 137 and 2397 LOC.
- GRETL functions: between 270 and 688 LOC.

Results: all programs

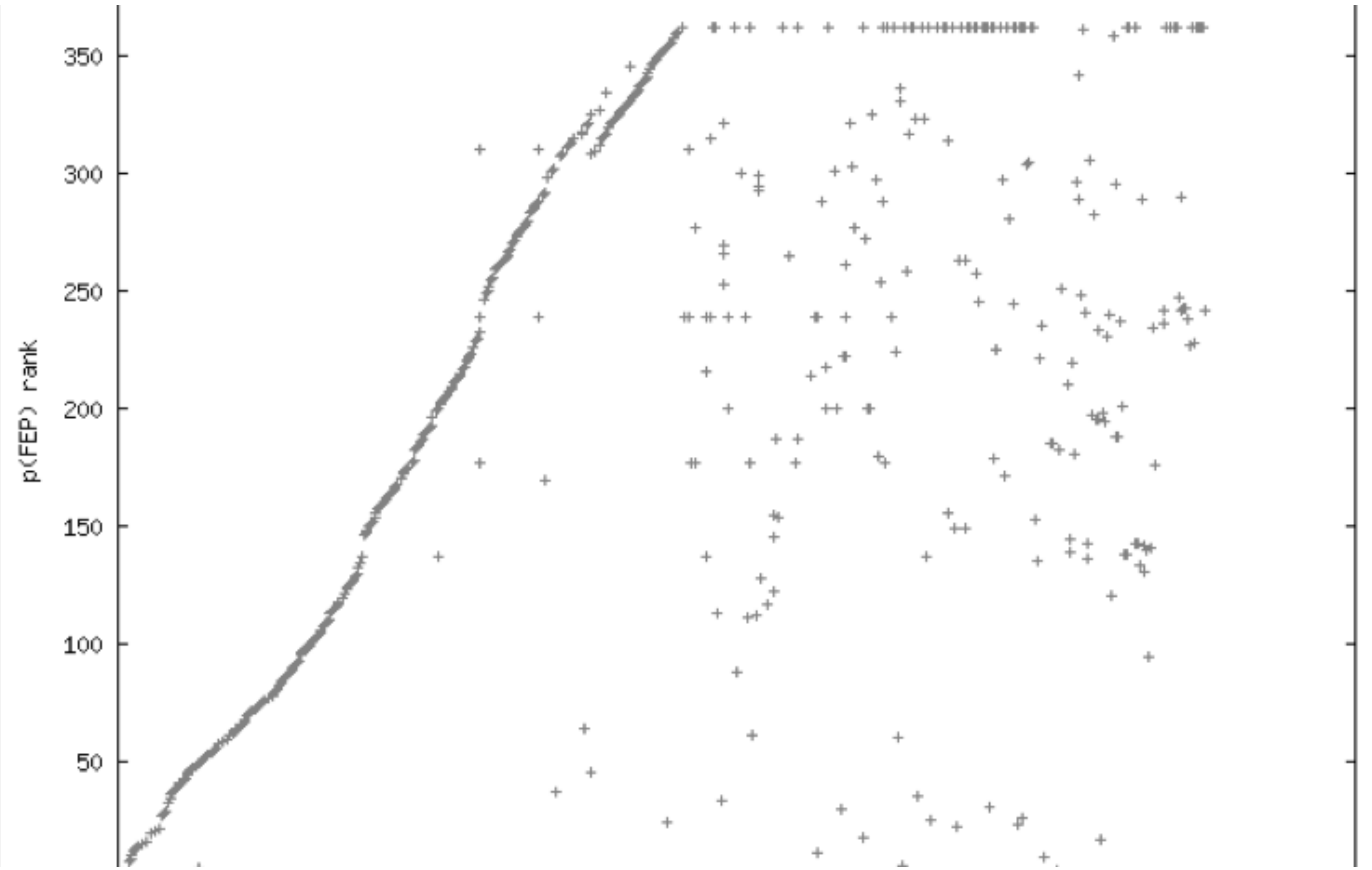
- Rank correlations:

Experiment	**Correlation**
EXP1	0.715267
EXP2	0.699165
EXP3	0.955647
EXP4	0.948299
EXP5	0.031510

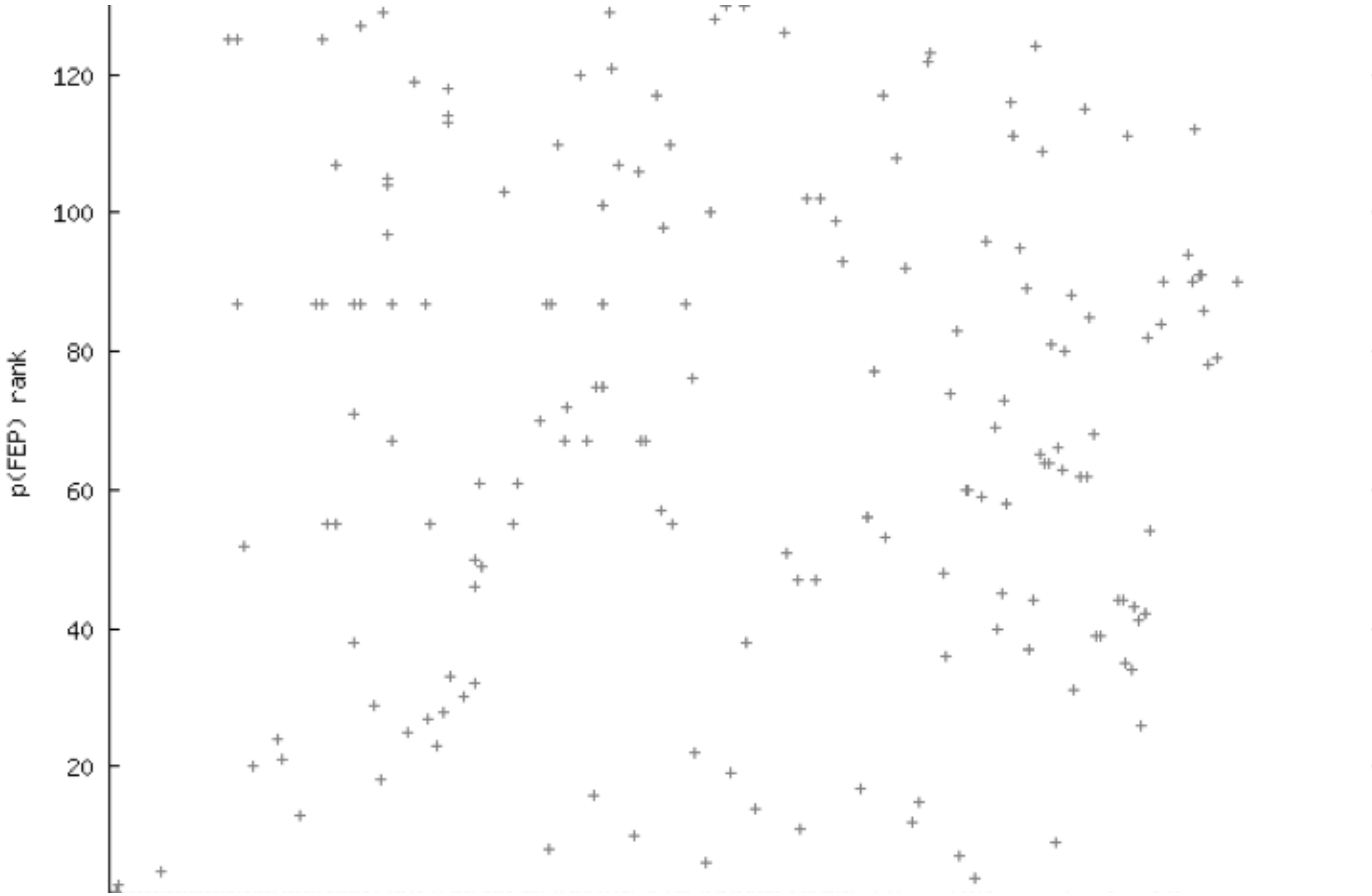
Results – real programs

Experiment	**Correlation**
EXP1	0.974459
EXP2	0.974459
EXP3	0.998526
EXP4	0.998526
EXP5	-0.001361

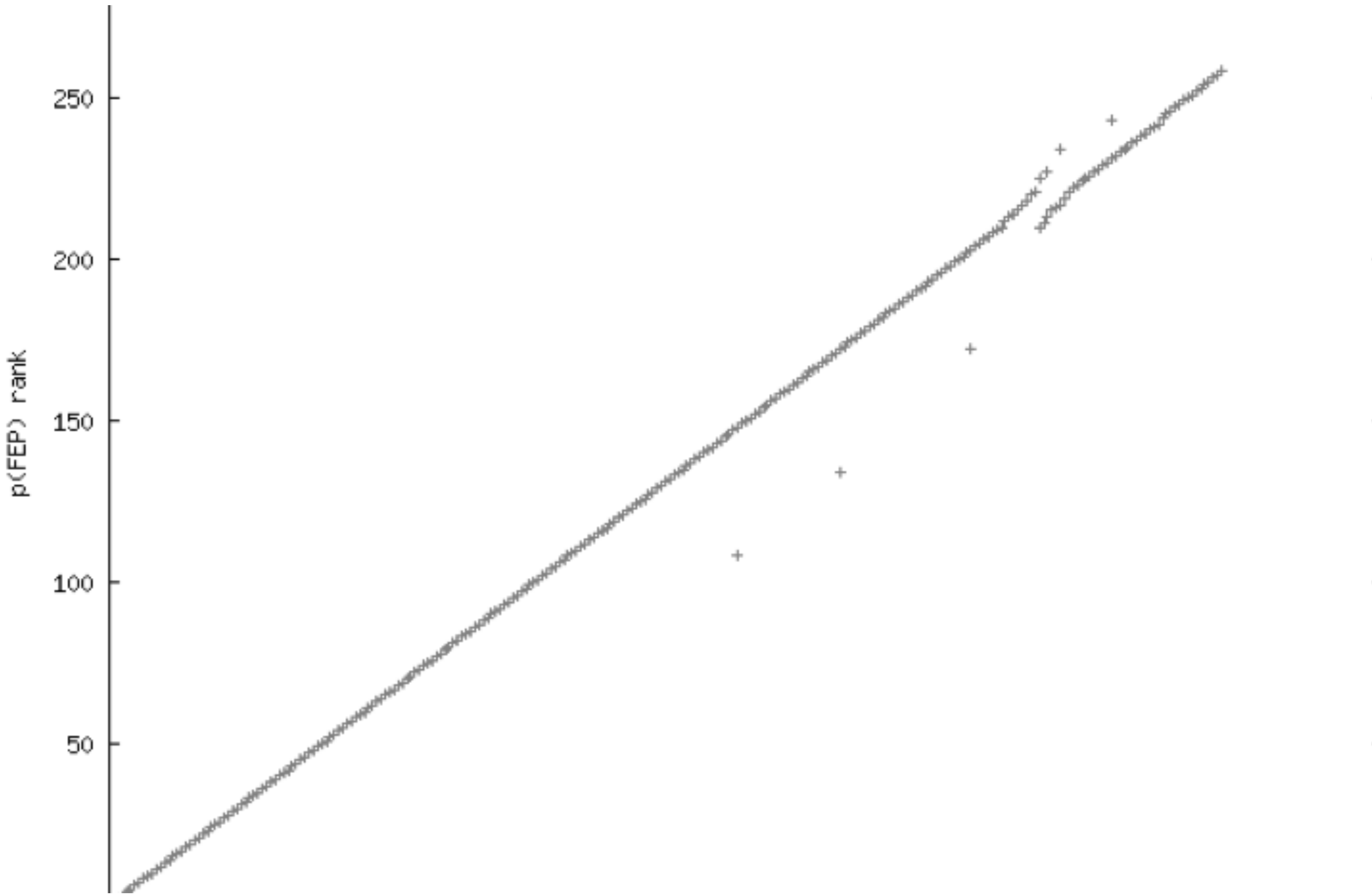
All programs (M2)



Toy programs (M2)



Real programs (M2)



Consequences

- Potential to use Information Theory based measures to predict the likelihood of FEP.
- In practice might:
  – Use as measure of testability (help us to decide e.g. how many tests cases to use?).
  – Try to cover e.g. a statement s with a test that follows it with code that has low FEP.
  – Have more test cases for ‘hard to test’ parts of the code.

References

- The work is contained in:
  - D. Clark and R. M. Hierons, Squeeziness: An Information Theoretic Measure for Avoiding Fault Masking, *Information Processing Letters*, 112, pp. 335-340, 2012.
  - K. Androutsopoulos, D. Clark, H. Dan, R. M. Hierons, and M. Harman: An Analysis of the Relationship between Conditional Entropy and Failed Error Propagation in Software Testing, *36th International Conference on Software Engineering (ICSE 2014)*.
- Other work includes:
  - W. Masri, R. Abou-Assi, M. El-Ghali, and N. Al-Fatairi. An empirical study of the factors that reduce the effectiveness of coverage-based fault localization. In the 2nd International Workshop on Defects in Large Software Systems, DEFECTS ’09, pages 1–5, Chicago, Illinois, USA, 2009. ACM
  - W. Masri and A. Podgurski. Measuring the strength of information flows in programs. ACM Transactions on Software Engineering and Methodology, 19(2), 2009.

Questions?