IPO-MAXSAT: Combining the In-Parameter-Order Strategy for Covering Array Generation with MaxSAT solving

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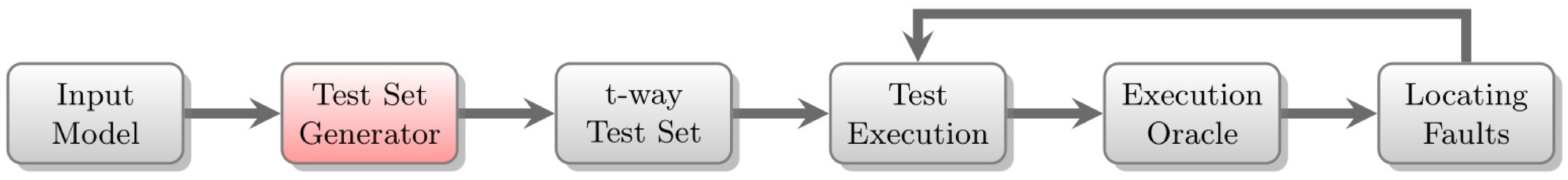
Generation of Covering Arrays for Abstract Combinatorial Test Suites

Covering Arrays for Combinatorial Testing

- Covering Arrays (CAs) provide the theoretical means for Combinatorial Testing (CT)
- Columns of a CA map to the parameters of a system under test (SUT).
- Rows of a CA encode the individual test cases.
- Their combinatorial properties guarantee that derived test sets **cover** all **t-way interactions**.
- To apply CT to arbitrary SUTs, we need to be able to generate arbitrary CAs.



The Covering Array Generation Problem

- Given a **strength t**, a number of columns k and an alphabet size v.
- Construct a covering array $\mathbf{CA}(N; t, k, v)$ minimizing the number of rows N.
- Exact and direct constructions of CAs exist only for some corner cases.
- **For general applications we need heuristic algorithms for arbitrary CA generation.**

The IPO Strategy for CA Generation

- A popular method for CA generation, realized in many algorithms.
- An array is extended horizontally and, if necessary, vertically until the desired CA is generated.
- **Initialization:** A $v^t \times t$ array is initialized with all v^t t-tuples.
  - First four rows of columns a and b in Figure 1.
- **Horizontal extension:** The CA is extended with an additional column. A greedy construction attempts to cover many t-way interactions.
  - Blue (new column) in Figure 1.
- **Vertical extension:** If any t-way interactions are not covered, then star-values can be assigned and the array is extended with new rows until all t-way interactions are covered.
  - Red (star-values) and green (new rows) in Figure 1.
- Star-values: Array cells that are not yet assigned a value. New rows in vertical extension are initialized with star-values.

https://www.brookings.edu/wp-content/uploads/2016/06/ND-Review-Chapter-1.pdf

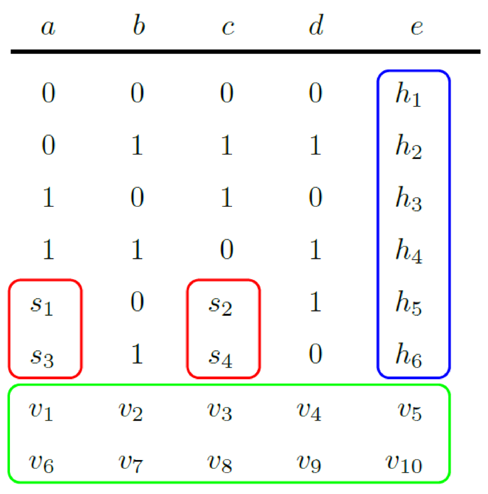
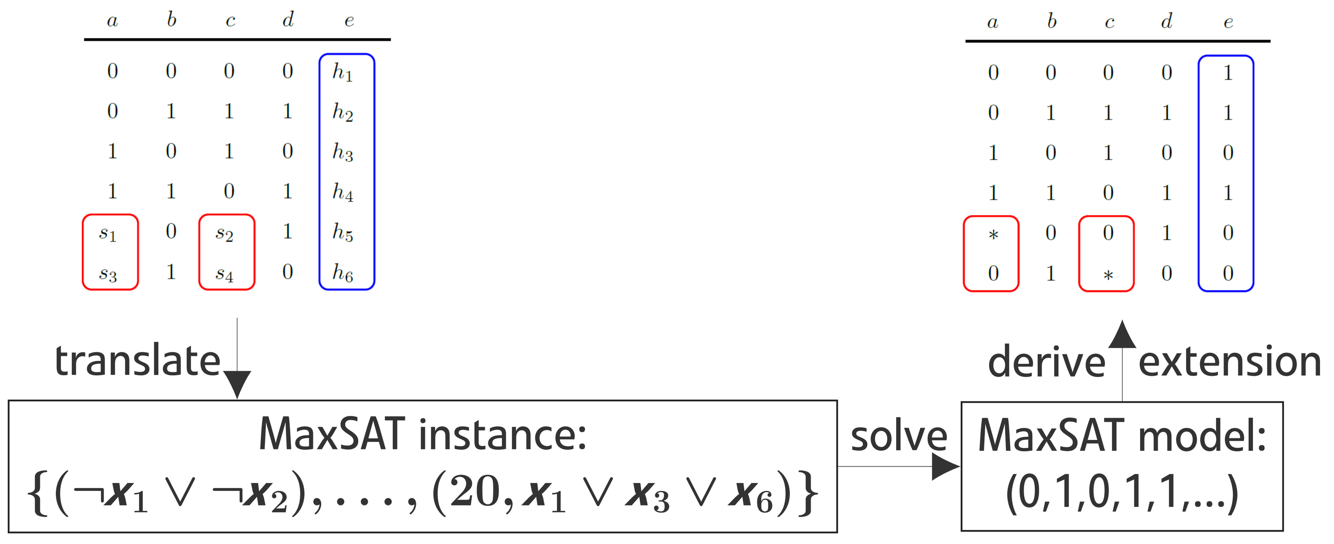


Figure 1: Schematics of the IPO strategy for a binary CA ($v = 2$) of strength $t = 2$.

IPO-MAXSAT

- Idea: Use MaxSAT solvers to find optimal horizontal extensions



- Star-value optimization is included in horizontal extension.
- Soft clauses encode our optimization goals:
  - Primary objective: Cover a maximal number of t-way interactions.
  - Secondary objective: Keep as many star-values as possible.

Results & Lessons learned

- We compare against:
  - SIPO: IPO strategy with Simulated Annealing [1];
  - FIPOG: a state-of-the-art IPO algorithm for CA generation [2];
  - NIST Tables: largest online repository of CAs [3], generated with IPOG-F [4];
  - CA Tables: the best known upper bound on the number of rows N for which a CA $\mathbf{CA}(N; t, k, v)$ exists [5].
- We present experimental results for $\mathbf{CA}(N; 3, k, 2)$:

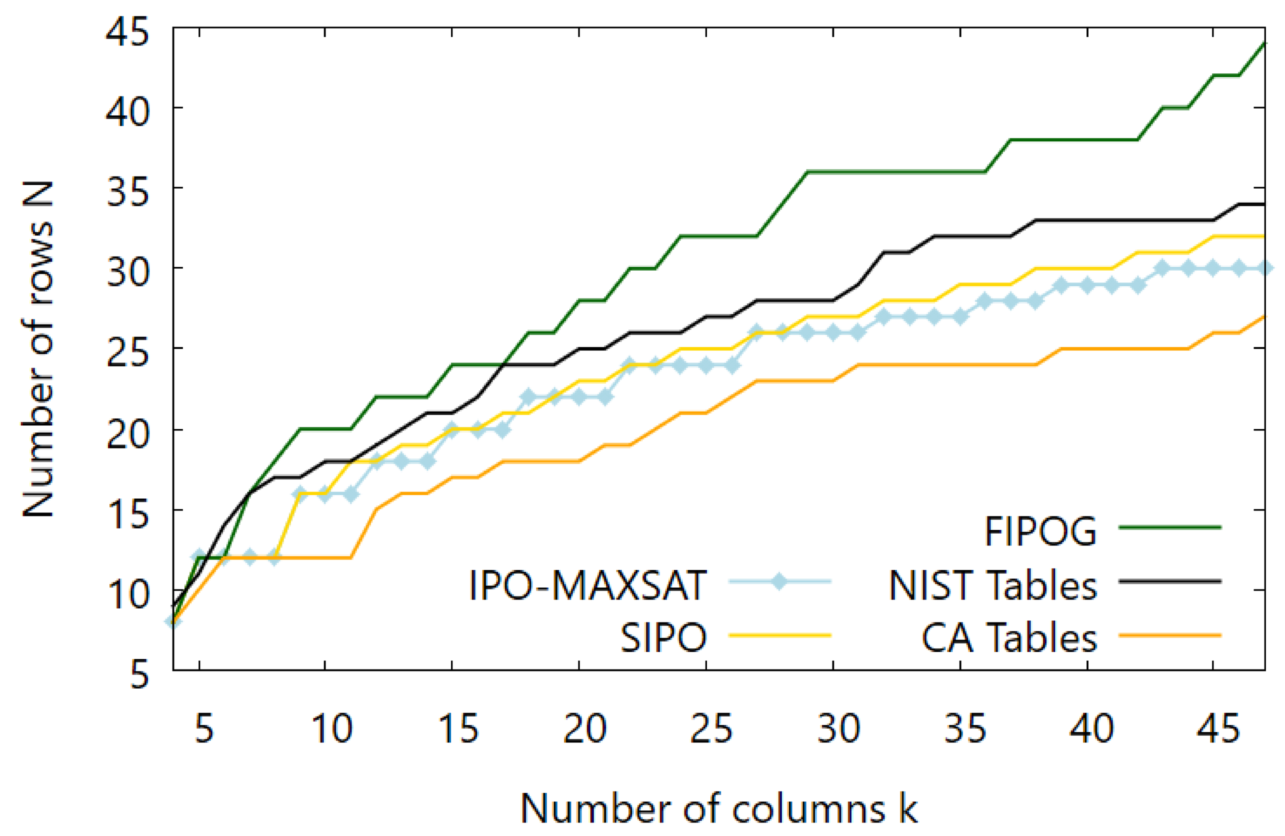


Figure 2: Size (number of rows N) of generated $\mathbf{CA}(N; 3, k, 2)$ for $k \leq 47$.

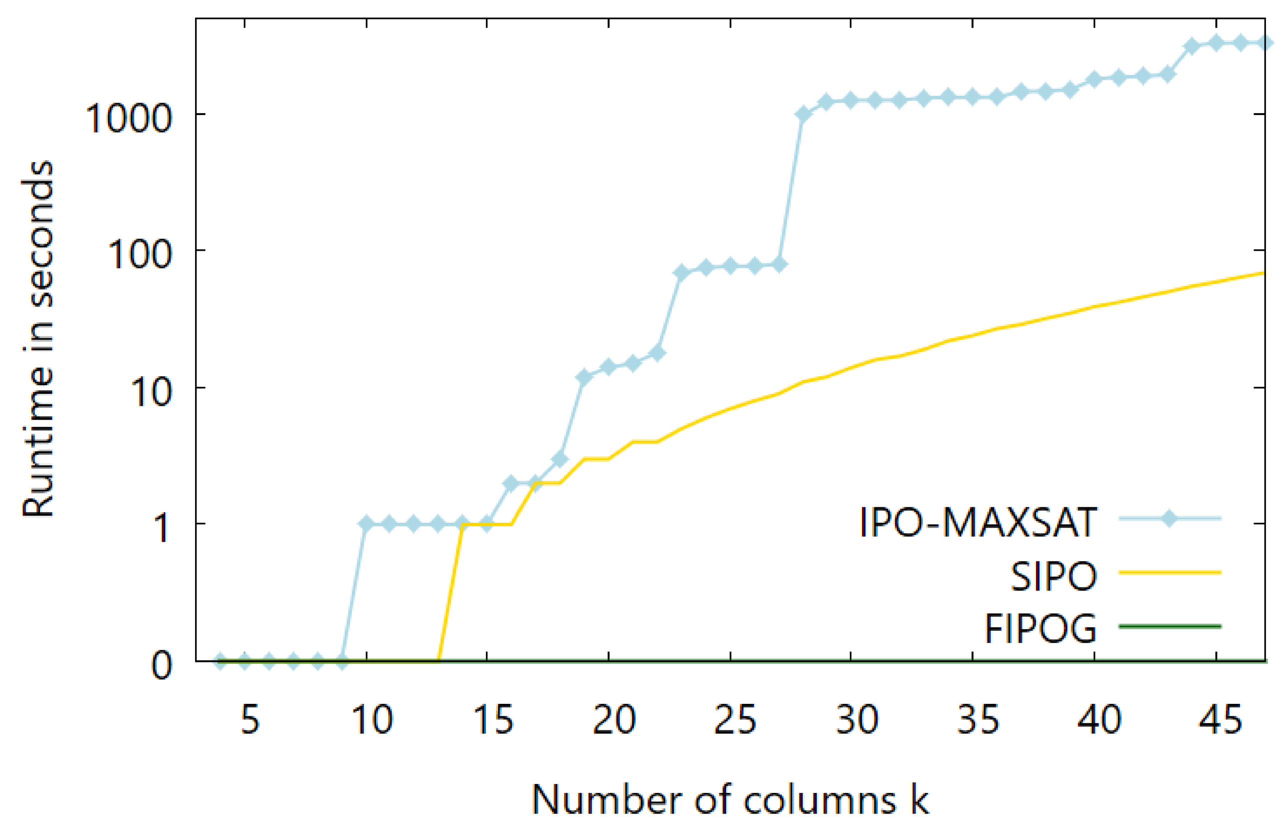


Figure 3: Runtimes in seconds for generating a $\mathbf{CA}(N; 3, k, 2)$ for $k \leq 47$.

- IPO-MAXSAT produces smaller CAs than similar approaches.
- Optimal extensions are not sufficient for optimal CA generation.
- Investing more time in the IPO extension steps yields smaller arrays.

[1] Michael Wagner, Ludwig Kampel, and Dimitris E. Simos. Heuristically enhanced ipo algorithms for covering array generation. In *Combinatorial Algorithms*, pages 571–586. Springer International Publishing, 2021.
[2] Kristoffer Kleine and Dimitris E. Simos. An efficient design and implementation of the in-parameter-order algorithm. *Mathematics in Computer Science*, 12(1):51–67, Mar 2018.
[3] Covering Arrays Team, National Institute of Standards and Technology (NIST). Covering Arrays generated by IPOG-F. Available at `https://math.nist.gov/coveringarrays/ipof/ipof-results.html`, Accessed on 2022-03-13, 2022.
[4] Michael Forbes, Jim Lawrence, Yu Lei, Raghu N Kacker, and D Richard Kuhn. Refining the in-parameter-order strategy for constructing covering arrays. *Journal of Research of the National Institute of Standards and Technology*, 113(5):287, 2008.
[5] Charles J Colbourn. Covering Array Tables for t=2,3,4,5,6. Available at `http://www.public.asu.edu/~ccolbou/src/tabby/catable.html`, Accessed on 2022-03-13, 2022.

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