Bounded Model Checking and Feature Omission Diversity

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Model Checking

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- The number of states is exponential in number of variables.
- The number of states is exponential in number of threads.

State-space explosion problem!
Remedies for state-space explosion problem

- *Symbolic model checking* uses binary decision diagrams to represent the transition system.
- *Abstraction* simplifies the model.
- *Partial order reduction* identifies the independent interleaving of threads.
Bounded Model Checking

In Bounded Model Checking (BMC) , the program is unrolled for a given length \( k \) and it is reduced to a SAT problem, s.t. the solution to the SAT problem is a counter-example for the program.

- Example: if \( R \) describes the relation between the current state and the next state and a safety property \( P \), the SAT problem looks like:

\[
I(S_0) \land \\
(R(S_0, S_1) \land R(S_1, S_2) \land ... \land R(S_{k-1}, S_k)) \land \\
(\neg P(S_0) \lor \neg P(S_1) \lor ... \lor \neg P(S_k))
\]
The problem is still there!

Even with the power of symbolic techniques, the state-space explosion is a fundamental problem for model checking:

- real-world systems have very large state spaces, and
- effective abstractions and symbolic representations are challenging to discover.
Realities to face

- There is usually limited time budget for model checking.
- In large systems, model checking techniques use lot of time and memory.
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**How to make them faster?**
Swarm verification exploits the multi-core processors to make exploration of new states faster by diversification of search strategies.

*Key idea:* When no heuristic is known to speed of the search, try several diverse search strategies in parallel.
Diversification of Search Strategies

Depth First Search

Breadth First Search

Randomized Search
Consider the following components in a program:

- functions,
- statements, or
- particular range of valuations for variables.
Features

Consider the following components in a program:

- functions,
- statements, or
- particular range of valuations for variables.

*Typically, a counterexample is made by some of them, not all of them!*
Swarm Testing

Swarm testing generalizes the search diversification of swarm verification beyond the choice of a depth-first search strategy to the selection of test features.

- A test feature is a predicate over test cases, controlled by the test generation process.
  - Example: In test of a file system, a test feature might be whether the test case includes calls to close.
- Swarm testing tries several test sessions with different test features in parallel.
- Swarm testing achieves better fault detection and code coverage.
Is there a way for swarm bounded model checking?
Example – stack

Assume log statements represent a feature.

```c
#define SIZE 64
int s = 0;
int stack[SIZE];
int top() {
    log("top");
    return stack[s];
}
void push(int i) {
    log("push");
    stack[s++] = i;
}
void pop() {
    log("pop");
    if (s > 0) {
        s--;    
    }
```
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Errors:

- Array out of bounds.
```
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    log("pop");
    if (s > 0) {
        s--;  
    }
}
```

Errors:
- Array out of bounds.
- top returns an invalid value!
#define TLEN 100
int main () {
    int v, action;
    for (int i = 0; i < TLEN; i++) {
        action = nondet_int();
        assume ((action >= 0) && (action <= 2));
        switch (action) {
            case 0:
                v = top();
                break;
            case 1:
                v = nondet_int();
                push(v);
                break;
            case 2:
                pop();
                break;
        }
    }
}
Algorithm For Swarm Bounded Model Checking

**Input:** program $p$, set $F$ of features

1. **while** budget allows
2. **for** all processors available
3. Pick a random set $F_i \subseteq F$
4. Build $sp$ by replacing log statements in $p$ for $F_i$ with `assume(false)` and Remove other log statements from
5. Propagate assumptions and slice $sp$
6. Perform BMC on $sp$

**Intuition:** By omitting features in a program’s execution, we can produce smaller and more easily checked SAT instances.
Example – Omitting the top feature in the stack

```
int top() {
    _CPROVER_assume(false);
    return stack[s];
}
void push(int i) {
    stack[s++] = i;
}
void pop() {
    if (s > 0) {
        s--;
    }
}
```
Experimental results

We used CBMC version 4.0 for bounded model checking on a four-processor Intel 2.8GHz system with 8 GB RAM on some data structures.
Early experiment results suggest that the swarm bounded model checking are faster in detecting counterexamples.
## Result of swarm bounded model checking on stack example

<table>
<thead>
<tr>
<th>Omitted Feature</th>
<th>Time without Slicing (Seconds)</th>
<th>Time with Slicing (Seconds)</th>
<th>Verification Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>–</td>
<td>325</td>
<td>49</td>
<td>Counterexample</td>
</tr>
<tr>
<td>push</td>
<td>40</td>
<td>4</td>
<td>Verified</td>
</tr>
<tr>
<td>pop</td>
<td>101</td>
<td>14</td>
<td>Counterexample</td>
</tr>
<tr>
<td>top</td>
<td>291</td>
<td>48</td>
<td>Counterexample</td>
</tr>
</tbody>
</table>
Experimental Results – Array Queue

The graph above illustrates the time (seconds) taken for different operations on an array queue as a function of depth. The operations include:

- None
- Enqueue
- IsEmpty
- Dequeue
- Front

The x-axis represents the depth, and the y-axis represents the time in seconds. The graph shows how the time increases with depth for each operation.
Experimental Results – Stack List
Related work

- **Swarm Verification:**

- **Swarm Testing:** Groce et al. *Swarm Testing*.

Conclusion

- By omitting features in a program’s execution, we can produce smaller and more easily checked SAT instances, while often preserving at least one counterexample trace.

- Early results suggest that bounded model checking with feature omission outperforms the traditional BMC in returning a counterexample. However, we need to apply swarm BMC to larger, more realistic examples that challenge the abilities of current BMC tools.