Software Model Checking

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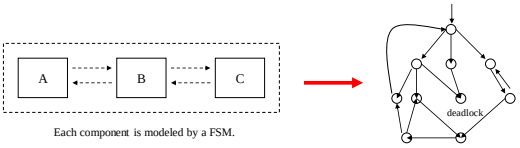
"Model Checking"

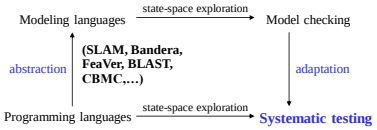


Each component is modeled by a FSM.

- Model Checking (MC) = systematic state-space exploration = exhaustive testing
- "Model Checking" = "check whether the system satisfies a temporal-logic formula"
  - Example: G(p->Fq) is an LTL formula
- Simple yet effective technique for finding bugs in high-level hardware and software designs (examples: FormalCheck for Hardware, SPIN for Software, etc.)
- Once thoroughly checked, models can be compiled and used as the core of the implementation (examples: SDL, VFSM, etc.)

Model Checking of Software

- How to apply model checking to analyze **software**?
  - "Real" programming languages (e.g., C, C++, Java),
  - "Real" size (e.g., 100,000's lines of code).
- Two main approaches to software model checking:



Concurrency: **VeriSoft, JPF, CMC, Bogor, CHESS,…**
Data inputs: **DART, EXE, SAGE,…**

Overview: Software Model Checking (SMC)

- Lecture 1: SMC via Systematic Testing - Concurrency
- Lecture 2: SMC via Systematic Testing - Data Inputs
- Lecture 3: SMC via Abstraction
- Lecture 4: May/Must Abstraction-based SMC
- Lecture 5: Combining Static and Dynamic SMC
- Lecture 6: What's Next? Compositional Testing & Verification
- Disclaimer:
  - emphasis on what influenced the speaker, not an exhaustive survey

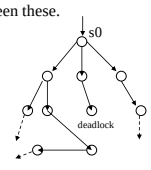
Lecture 1: Software Model Checking via Systematic Testing

Dealing with Concurrency

Dynamic Approach: Systematic Testing (VeriSoft)

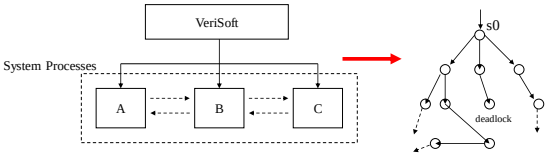
- State Space = "product of (OS) processes" (Dynamic Semantics)
  - Processes communicate by executing operations on com. objects.
  - Operations on com. objects are visible, other operations are invisible.
  - Only executions of visible operations may be blocking.
  - The system is in a global state when the next operation of each process is visible.
  - State Space = set of global states + transitions between these.

THEOREM: Deadlocks and assertion violations are preserved in the "state space" as defined above.



VeriSoft

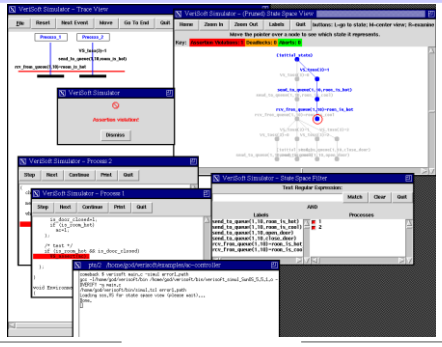
- Controls and observes the execution of concurrent processes of the system under test by intercepting system calls (communication, assertion violations, etc.).
- Systematically drives the system along all the paths (=scenarios) in its state space (=automatically generate, execute and evaluate many scenarios).
- From a given initial state, one can always guarantee a complete coverage of the state space up to some depth.
- Note: analyzes "closed systems"; requires test driver(s) possibly using "VS_toss(n)".



VeriSoft State-Space Search

- Automatically searches for:
  - deadlocks,
  - assertion violations,
  - divergences (a process does not communicate with the rest of the system during more than x seconds),
  - livelocks (a process is blocked during x successive transitions).
- A scenario (=path in state space) is reported for each error found.
- Scenarios can be replayed interactively using the VeriSoft simulator (driving existing debuggers).

The VeriSoft Simulator

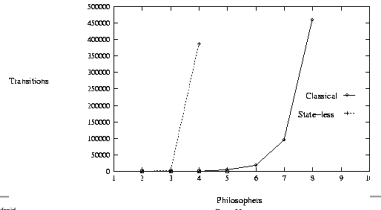


Originality of VeriSoft

- VeriSoft is the first systematic state-space exploration tool for concurrent systems composed of processes executing arbitrary code (e.g., C, C++,…) [POPL97].
- VeriSoft looks simple! Why wasn't this done before?
- Previously existing state-space exploration tools:
  - restricted to the analysis of models of software systems;
  - each state is represented by a unique identifier;
  - visited states are saved in memory (hash-table, BDD,…).
- With programming languages, states are much more complex!
- Computing and storing a unique identifier for every state is unrealistic!

"State-Less" Search

- Don't store visited states in memory: still terminates when state space is finite and acyclic… but terribly inefficient!
- Example: dining philosophers (toy example)
  - For 4 philosophers, a state-less search explores 386,816 transitions, instead of 708: every transition is executed on average 546 times!



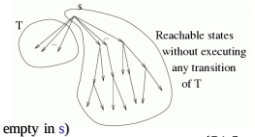
Partial-Order Reduction in Model Checking

- A state-less search in the state space of a concurrent system can be much more efficient when using "partial-order methods".
- POR algorithms dynamically prune the state space of a concurrent system by eliminating unnecessary interleavings while preserving specific correctness properties (deadlocks, assertion violations,...).
- Two main core POR techniques:
  - Persistent/stubborn sets (Valmari, Godefroid,…)
  - Sleep sets (Godefroid,…)

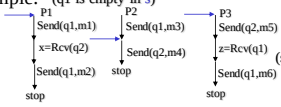
[Note: checking more elaborate properties require other extensions
  – Ex: ample sets (Peled) are persistent sets satisfying additional conditions sufficient for LTL model checking
Not used here as VeriSoft only checks reachability properties]

Persistent/Stubborn Sets

- Intuitively, a set T of enabled transitions in s are persistent in s if whatever one does from s *while remaining outside of T* does not interact with T.



- Example: (q1 is empty in s)



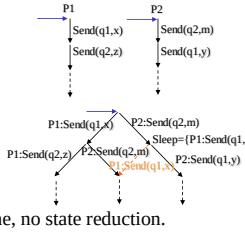
{P1:Send(q1,m1)} is persistent in s

The most advanced algorithms for (statically) computing persistent sets are based on "stubborn sets" [Valmari]

- Limitation: need info on (static) system structure.
  - VeriSoft only exploits info on next transitions and "system_file.VS".

Sleep Sets

- Sleep Sets exploit local independence (commutativity) among enabled transitions. One sleep set is associated with each state.
- Example:

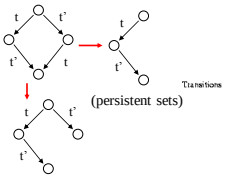


Transitions in Sleep are not explored!

- Limitation: alone, no state reduction.
  - Sleep sets are easy to implement in VeriSoft since they only require information on next transitions.

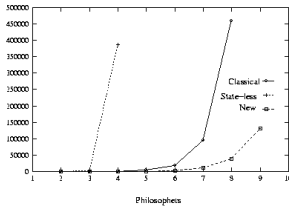
An Efficient State-Less Search

- With POR algorithms, the pruned state space looks like a tree!
- Thus, no need to store intermediate states!



(persistent sets)

(sleep sets)



- Without POR algorithms, a state-less search in the state space of a concurrent system is untractable.

VeriSoft - Summary

- Two key features distinguish VeriSoft from other model checkers
  - Does not require the use of any specific modeling/programming language.
  - Performs a state-less search.
- Use of partial-order reduction is key in presence of concurrency.
- In practice, the search is typically incomplete.
- From a given initial state, VeriSoft can always guarantee a complete coverage of the state space up to some depth.

Users and Applications

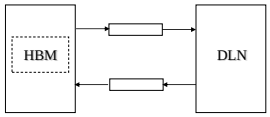
- Development of research prototype started in 1996.
- VeriSoft 2.0 available outside Lucent since January 1999:
  - 100's of licenses in 25+ countries, in industry and academia
  - Free download at http://www.bell-labs.com/projects/verisoft
- Examples of applications in Lucent:
  - 4ESS HBM unit testing and debugging (telephone switch maintenance)
  - WaveStar 40G R4 integration testing (optical network management)
  - 7R/E PTS Feature Server unit and integration testing (voice/data signaling)
  - CDMA Cell-Site Call Processing Library testing (wireless call processing)

Application: 4ESS HBM [ISSTA98]

- 4ESS switches control millions of calls every day.
- Heart-Beat Monitor (HBM) determines the status of elements connected to 4ESS switch by monitoring propagation delays of messages to/from these elements.
- HBM decides how to route new calls in 4ESS switch (i.e., decides to switch from out-of-band to in-band signaling - called NTH).
- November 1996: "field incident"; June 1997: 2nd field incident…
- HBM code = 100s of lines of EPL (assembly) code, 7/3 years old
- Hoes does this code work exactly???

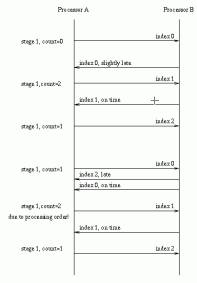
Application: 4ESS HBM (continued)

- Translate EPL code to C code (using existing partial translator)
- Build test harness for HBM C code, model its environment (using "VS_toss(n)"), add "VS_assert(0)" where HBM code hits NTH (took only a few hours!)



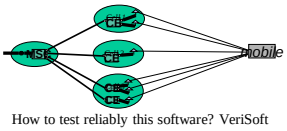
- Check properties (reverse eng./testing)
- Discovered several flaws in software and its documentation... [ISSTA98]

Example of scenario found:

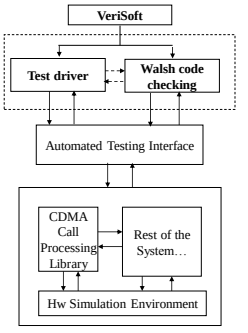


Example of Industrial Application: CDMA

- CDMA Base Station Call-processing software library involves complex dynamic resource-allocation algorithms and handoffs scenarios (100,000's lines of C/C++ code).



- How to test reliably this software? VeriSoft
  - Increased test coverage from O(10) to O(1,000,000) scenarios.
  - Automatic regression testing for multiple cell-sites and releases (more than 1,500 VeriSoft runs in 2000-2001).
  - Found several critical bugs…[ICSE2002]



Discussion: Strengths of VeriSoft

- Used properly, very effective at finding bugs
  - can quickly reveal behaviors virtually impossible to detect using conventional testing techniques (due to lack of controllability and observability)
  - compared with conventional model checkers, no need to model the application!
    - Eliminates this time-consuming and error-prone step
    - VeriSoft is WYSIWYG: great for reverse-engineering
- Versatile: language independence is a key strength in practice
- Scalable: applicable to very large systems, although incomplete
  - the amount of nondeterminism visible to VeriSoft can be reduced at the cost of completeness and reproducibility (not limited by code size)

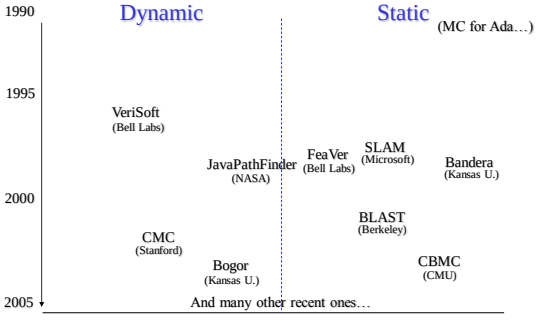
Discussion: Limitations of VeriSoft

- Requires test automation:
  - need to run and evaluate tests automatically (can be nontrivial)
  - if test automation is already available, getting started is easy
- Need be integrated in testing/execution environment
  - minimally, need to intercept VS_toss and VS_assert
  - intercepting/handling communication system calls can be tricky...
- Requires test drivers/environment models (like most MC)
- Specifying properties: the more, the better… (like MC)
  - Restricted to safety properties (ok in practice); use Purify!
- State explosion... (like MC)

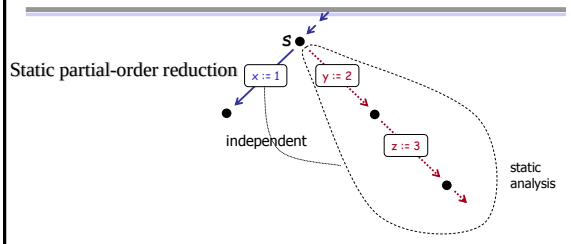
Discussion: Conclusions

- VeriSoft (like model checking) is not a panacea.
  - Limited by the state-explosion problem,…
  - Requires some training and effort (to write test drivers, properties, etc.).
  - "Model Checking is a push-button technology" is a myth!
- Used properly, VeriSoft is very effective at finding bugs.
  - Concurrent/reactive/real-time systems are hard to design, develop and test.
  - Traditional testing is not adequate.
  - "Model checking" (systematic testing) can rather easily expose new bugs.
- These bugs would otherwise be found by the customer!
- So the real question is "How much ($) do you care about bugs?"

Software Model Checking Tools

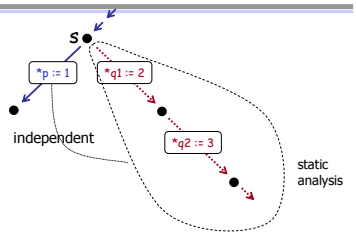


Dynamic Partial Order Reduction [POPL'05]



- Use static analysis to predict locations red accesses after ***s***
  - if static analysis proves that red thread only accesses y and z
  - then `x := 1` is a persistent transition from ***s***

Static Partial-Order Reduction



- Use static analysis to predict locations red accesses after ***s***
- Pointers?
  - coarse analysis information => limited POR => state explosion

Example: static partial-order reduction

```
Global vars
  lock m
  int t1,t2
  int x=0
  int n=100
  char[] a
```

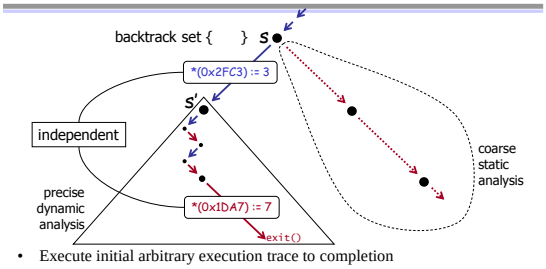
```
Thread 1
  lock(m)
    t1 := x++
  unlock(m)
  for( ;t1<n; t1+=2)
    a[t1] := 'b'
```

```
Thread 2
  lock(m)
    t2 := x++
  unlock(m)
  for( ;t2<n; t2+=2)
    a[t2] := 'r'
```

may-alias (according to static analysis)
never alias (in practice)

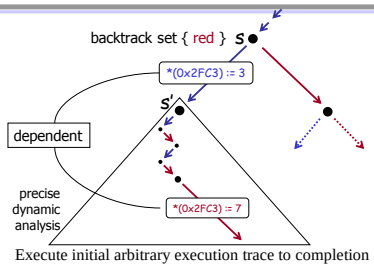
- Static analysis gives
  - t1, t2 are thread-local
  - x is protected by m
  - but `a[t1]` and `a[t2]` may alias
- Static POR gives $O(n^2)$ explored states and transitions
  - but only two possible terminating states

New Idea: Dynamic Partial-Order Reduction



- Execute initial arbitrary execution trace to completion
- Examine transitions performed by each thread
  - identify and explore other interleavings that may behave differently
  - dynamic alias analysis is easy

Dynamic partial-order reduction



- Execute initial arbitrary execution trace to completion
- Examine transitions performed by each thread
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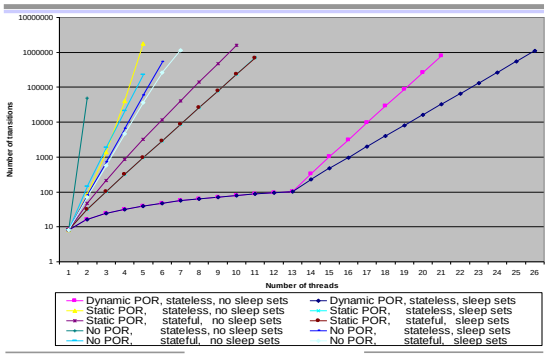
Dynamic partial-order reduction algorithm

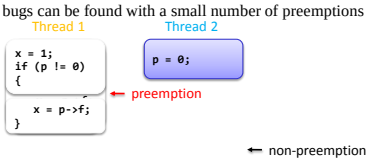
- Dynamic POR algorithm for
  - safety properties (deadlocks, assertion violations, etc.)
  - acyclic state spaces
- Dynamically computes a persistent set in each explored state
  - compatible and complementary with *sleep sets*
- Complexity: $O(m^2.r)$
  - m = number of threads
  - r = size of reduced state space
  - some assumptions on dependence relation
- See [POPL'05, with Cormac Flanagan]

Filesystem Benchmark



CHESS (MSR): Preemption Bounding

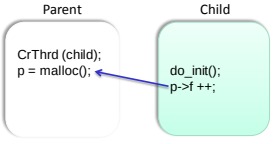
- Focus on multi-threaded concurrent software (Win32, CLR)
- Focus on executions with small number of preemptions
  - Heuristic: most bugs can be found with a small number of preemptions



- Many bugs found this way; CHESS is available on the web
  - Can deal with very large state spaces, complementary to (D)POR

Other Related Work: Heuristics

- Other heuristics for partially exploring large state spaces
  - Genetic algorithms (with property-specific fitness functions)
  - Heuristics based on concurrent dependencies

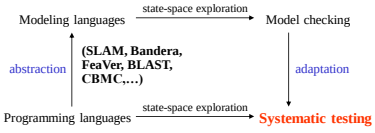


If dereference before initialization, BUG!
Thus, ONE ordering constraint is sufficient for this bug
→ heuristic = delay malloc() as much as possible!

  - "Principled random searches" (e.g., see Cuzz from MSR)

Conclusion

- Software Model Checking via Systematic Testing
  - Lecture 1: Dealing with Concurrency



Concurrency: VeriSoft, JPF, CMC, Bogor, CHESS,…
Data inputs: DART, EXE, SAGE,…