Testing Concurrent Java Programs Using Randomized Scheduling

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Goal

Pillars of Run-Time Verification
monitoring: identify interesting behavior in an execution
control: try to provoke interesting behavior

Java Language Spec. puts few constraints on thread scheduler. Scheduling may depend on load and run-time system.

During run-time verif., control the scheduling, at least partially, to help check robustness and portability.

Approach: Insert calls to *scheduling function* at selected points in bytecode. Sched fn causes context switches.

Outline

- How does sched fn choose which thread to switch to?

- Where to insert calls to sched fn?

probabilistic completeness: every error reachable according to the Java Language Spec. is reachable in the transformed program, independent of the underlying thread scheduler.

- Experiments

- Related work

Pseudo-Random Sched Fn

Semaphore Approach

Associate a semaphore sem(θ) with each thread θ.
Pseudo-randomly choose a runnable thread θ (possibly self), call sem(θ).up(), and then call sem(*currentThread*).down().

+ probabilistic completeness
+ the probability distribution can easily be controlled

Loop Approach

`while (nextFloat() < contextSwitchProb) contextSwitch();`
where `contextSwitch()` calls `yield` or `sleep`.

+ easy to implement
+ probabilistic completeness if underlying sched is fair

− less control over probability distribution

∘ without loop, not probabilistically complete (e.g., FIFO sched)

Heuristics in Sched Fn

Start with a coverage metric or abstraction.

Sched fn remembers what has been explored (covered)
in current and previous executions,
always tries to explore something new,
and chooses randomly when it can't.

Sample coverage metrics [Edelstein *et al.* 2002]:

- set of methods in which context switches occurred
- set of pairs of methods $\langle m1, m2 \rangle$ such that there was a context switch from a thread running $m1$ to a thread running $m2$.

Where to Insert Calls to Sched Fn?

Easy Answer: At every operation on potentially shared storage, namely:

- access to instance field of object (including arrays)
- access to static field
- synchronization operation
- class initialization (implicit shared state and sync.)

\+ probabilistic completeness

− frequent calls to sched fn cause run-time overhead and complicate counterexamples

Synchronization Primitives in Java Bytecode

Each object has a **recursive lock** and a **condition variable**.

acquire o	acquire o's lock
release o	release o's lock
o.wait()	release o's lock; wait to be notified or interrupted; acquire o's lock
o.notify()	notify a thread waiting on o, if any
o.notifyAll()	notify all threads waiting on o
t.interrupt()	interrupt thread t

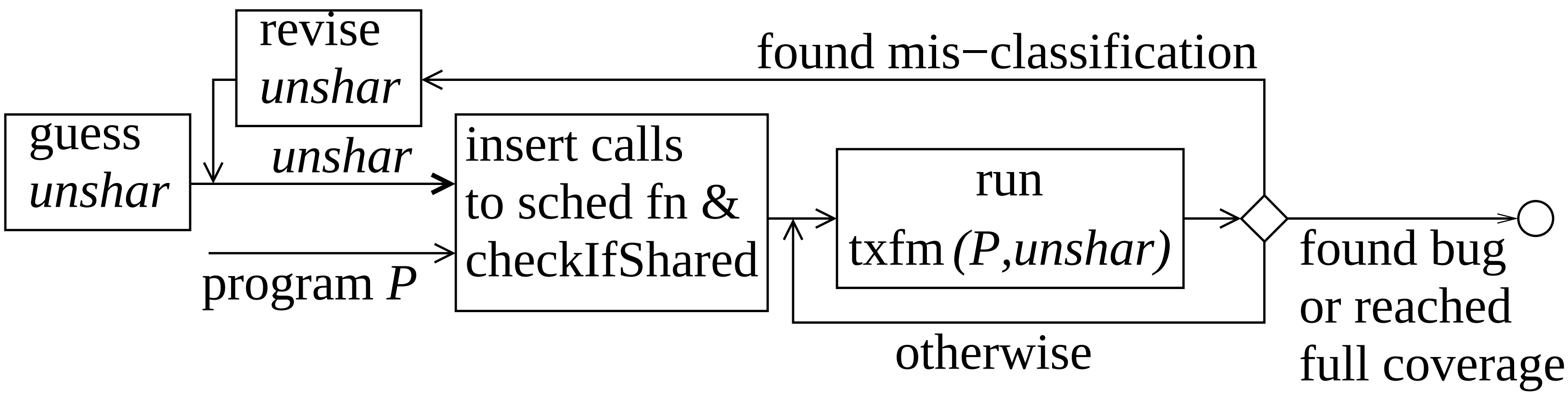
wait(), notify(), and notifyAll() require holding o's lock; otherwise, they merely throw an exception.

Assume the program does not use real-time operations, e.g., o.wait(*timeout*), Thread.sleep(*duration*)

Fewer Calls to Sched Fn: Unshared Locations

Identify **unshared** static and heap locations.
unshar: set of classes (and pkgs) with all instances unshared
Do not insert calls to sched fn before operations on *unshar*.

How to determine *unshar*?
Statically: escape analysis
Dynamically: monitoring, iterative refinement
Insert calls to checkIfShared at operations on *unshar*.



Prob. Completeness for Finding Errors

Errors: We consider assertion violations and deadlocks.

Exec(P, *sched*): set of executions of program P
with scheduler *sched*

JLSched: non-deterministic scheduler in Java Language Spec.

Theorem: Suppose locations in *unshar* are unshared.
For every program P and scheduler *sched*, every error that occurs in Exec(P, JLSched) also occurs in Exec(txfm($P, unshar$), *sched*), *i.e.*, there exists a sequence of choices by the scheduling function that leads to it.
Caveat: We do not control non-determinism in notify().

Note: *sched* may cause add'l context switches at any point.

Prob. Completeness for Mis-Classifications

If *unshar* is incorrect, can we say anything about executions of txfm($P, unshar$)? Yes!

Theorem: Exec(P, JLSched) contains an execution in which a location in *unshar* is shared iff Exec(txfm($P, unshar$), *sched*) does.

$\Rightarrow$: Consider the first shared access to a location in *unshar* in an execution in Exec(P, JLSched). Show that it can also occur in an execution of Exec(txfm($P, unshar$), *sched*).

$\Leftarrow$: straightforward

Similar results: [Holzmann & Peled 1994], [Stoller 2000].

Fewer Calls to Sched Fn: Protected Locations

A location o is **protected** if, after **initialization** of o,
- all accesses to o are reads ("o is read-only")
- some lock ℓ is hold at every access to o ("ℓ protects o)

Initialization of a **static** field C.f ends when the class initializer for C terminates.

Initialization of a **heap** location o.f ends before o escapes from the thread that allocated it.

prot: set of classes (and pkgs) with all instances protected

Do not insert calls to sched fn at accesses to *prot*.
Insert calls to sched fn at acquire, wait, and notify.
Do not insert calls to sched fn at release and notifyAll.

Prob. Completeness with Protected Locations

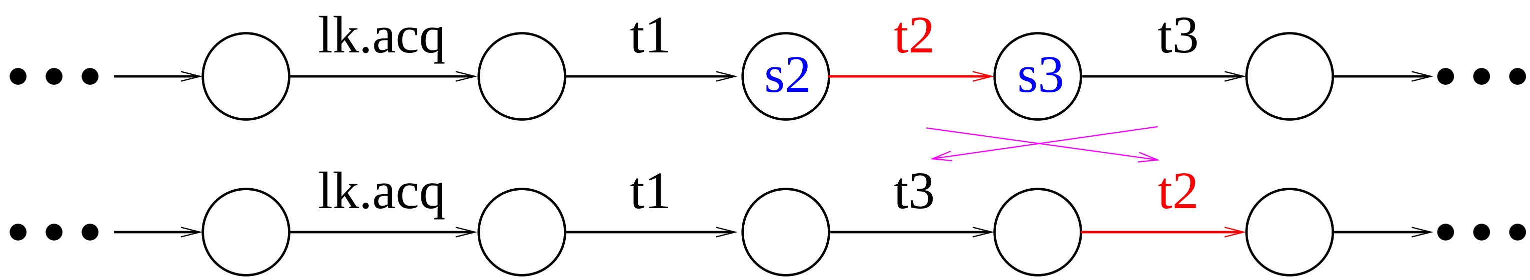
Prob. Completeness for Errors:
Suppose *unshar* and *prot* are correct.
Every error that occurs in Exec(P, JLSched) also occurs in Exec(txfm($P, unshar, prot$), *sched*), *i.e.*, there exists a sequence of choices by the scheduling function that leads to it.
Similar results: [Lipton 1975], [Cohen and Lamport 1998], [Stoller 2000].

Prob. Completeness for Mis-Classifications:
Exec(P, JLSched) contains an execution in which a location in *unshar* or *prot* is mis-classified iff Exec(txfm($P, unshar, prot$), *sched*) does.
Similar results: [Stoller 2000].

Prob. Completeness for Errors: Proof Sketch

Show: Context switch at access to a protected location x is unnecessary. Context switch at acquire of protecting lock suffices.

Consider an execution with a context switch at an access to x. Repeatedly swap adjacent transitions to eliminate that context switch, while preserving errors.



Suppose $t3$ accesses x and is not an acquire.
In states s3 and s2, θ_{black} owns the lock lk that protects x.
In s2, θ_{red} does not own lk or access x. So t_2 and t3 commute.

How to Identify Protected Locations?

Statically: race-free type systems [Flanagan & Freund 2000], [Boyapati & Rinard 2001]. Types are augmented with parameters indicating how objects are protected.

Example:
```
class C<thisOwner> {
    Data<this> a = new Data<this>;
    Data<thisOwner> b;
    Data<readOnly> c;
}
```

Dynamically: monitoring, iterative refinement.
Start with a guess. Use **lockset algorithm** [Savage *et al.* 1997] to check whether objects in *prot* are protected.

Lockset Algorithm

o.lockSet: set of locks that protected o so far after init.
o.readOnly: whether all accesses to o after init were reads.

At end of initialization of o:

$$\begin{aligned} \text{o.readOnly} &= \text{true} \\ \text{o.lockSet} &= \{\text{all locks}\} \end{aligned}$$

At each subsequent access to o:

$$\begin{aligned} \text{o.readOnly} &= \text{o.readOnly} \wedge (\text{current access is a read}) \\ \text{o.lockSet} &= \text{o.lockSet} \cap \text{heldLocks(currentThread)} \end{aligned}$$

o is **protected** iff o.readOnly $\vee$ o.lockSet$\neq \emptyset$

Experiments

Current implementation supports dynamic checking of *unshar*, not *prot*.

Application	**Size**	**Result**
Clean [Brat *et al.* '00]	57 LOC	deadlock
Fund Managers [JDC '00]	123 LOC	assertion violation
Xtango Animation Library	1.3 KLOC	minor oddities
ArgoUML design envir.	5+ MB of .class	exception in AWT event handler thread

Future experiments:

- Evaluate reduction in # of context switches in counterexamples
- Dynamic checking: compare cost of checkIfShared and lock-set alg with cost of sched fn. (Static checking is a pure win.)
- Experiment with heuristics in sched fn.

Related Work

Traditional Model Checkers

Special run-time system captures and stores entire state.

Examples: SMV, Spin, Murphi, Java PathFinder

Applying them to large Java or C programs typically requires significant effort for translation or abstraction, even with tool support.

State-less Model Checkers and Testers

Use standard run-time system.

Insert code to (partially) control non-determinism.

Related Work: State-less Checkers and Testers

VeriSoft [Godefroid 1997]

Controls non-determinism in **inter-process scheduling**.
Systematic exploration of possible transition sequences.
Not targeted at control of thread scheduling.

JavaChecker [Stoller 2000]

Controls non-determinism in **thread scheduling**.
Systematic search, as in VeriSoft.
rstest is "JavaChecker lite".

ConTest [Edelstein *et al.* 2002]

Controls non-determinism in **thread scheduling**.
Randomization and **heuristics**, not systematic search.
Calls sched fn at **all** operations on shared objects.