Can We Monitor All Multithreaded Programs?

A tutorial Using RV tools for Java Programs

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Instructions ↪ Prepare the tutorial files

1. The tutorial repository is hosted at
   `https://gitlab.inria.fr/monitoring/rv-multi`
2. Make sure to have docker installed (and running)
3. Set up the docker container (sudo is not needed if docker runs in userpace)

```
1 git clone https://gitlab.inria.fr/monitoring/rv-multi.git
2 cd rv-multi/docker
3 sudo make fetch
4 sudo make run
```

   You should see:

```
1 —— rv-multithreaded ——
2
3  root's password is 'root'
4
5 ——————————
6    Browse the README files:
7    http://localhost:8050/
8 ——————————
9
10 [user@rv-multi rv-multi]$
```

RV & Multithreaded Programs

Context ↪ Brief Overview of RV

- Lightweight verification technique
- Checks whether a run of a program conforms to a specification
  (As opposed to model checking which verifies all runs)
- The run is captured as a trace, typically seen as a sequence of events

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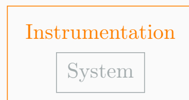

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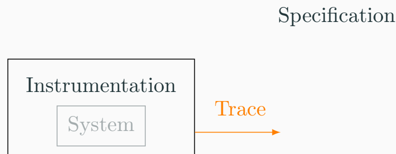

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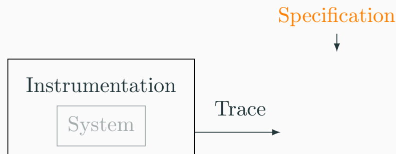

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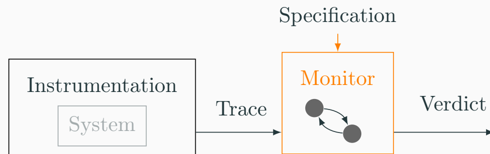

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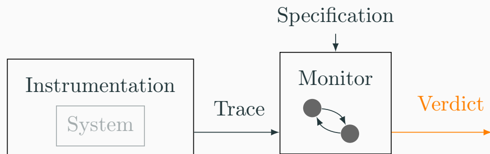
- The run is captured as a trace, typically seen as a sequence of events
- Monitors are synthesized (and integrated) to observe the system
- Monitors determine a verdict: $\mathbb{B}_3 = \{\top, \bot, ?\}$
    - $\top$ (true): run complies with specification
    - $\bot$ (false): run does not comply with specification
    - ?: verdict cannot be determined (yet)



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  - All threads access a shared queue
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- A correct execution complies with the following properties:
  1. (φ_1) Consumers must not remove an item unless the queue contains one
  2. (φ_2) All items placed on the queue must be eventually consumed

Context ↪ Executions of Producer-consumer

```
1 public class SynchQueue {
2   private LinkedList<Integer> q = new LinkedList<Integer>();
3   public void    produce(Integer v)    { q.add(v); }
4   public Integer consume()        { return q.poll(); }
5 }
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Thread 0 (Producer)	Thread 1 (Consumer)
① `sq.produce(0);`	② `sq.consume(); //0`
③ `sq.produce(1);`	④ `sq.consume(); //1`

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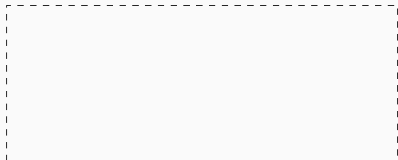
CHALLENGES

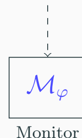
Instrumentation



Trace

Specification (φ)

Verdict



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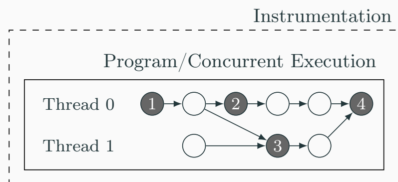
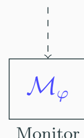


Trace Specification (φ) Verdict



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[1] Consistent with weak memory consistency models [AG96, ANB$^+$95, MPA05], Mazurkiewicz traces [Maz86, GK10], parallel series [LW01], Message Sequence Charts graphs [MR04], and Petri Nets [NPW81]

[2]

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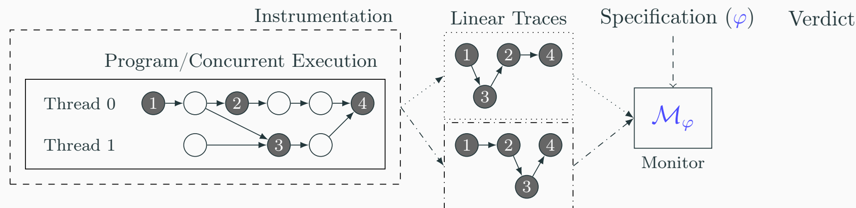

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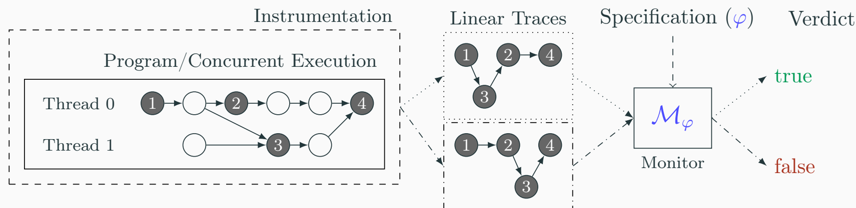

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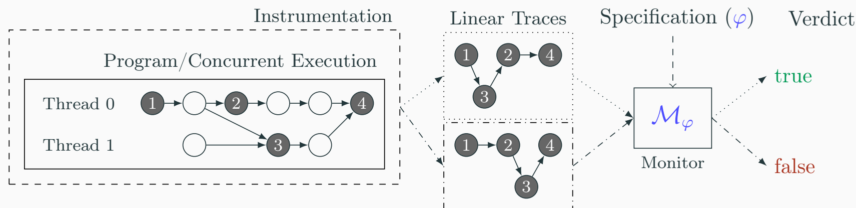

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★ An instrumented program must capture the order of events as it happens during the execution to pass it to monitors.

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★ (Q0) "Is the developer using the tool to automatically generate monitor logic?"

In this tutorial, we only concern ourselves with the tools that do so.

RV & Multithreaded Programs

Approaches Verifying Sequences of Events

Approaches Focusing on Concurrency Errors

Approaches Utilizing Multiple Traces

Conclusion

Approaches Verifying Sequences of Events

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- Alternatively:
  Write monitors manually + unsynchronized access to monitor

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- Example found in `scenarios/process`
- Let us begin by using a single monitor to check the property
- Follow the tutorial until reaching the end of "Developing The Global Monitor (Simplest)"

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⋆ (Q3) "Does there exist a model of the specification where events are generated by more than a single thread?"

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- Now let us monitor a non-synchronized producer-consumer.
- Follow tutorial in `scenarios/producer-consumer-v2`

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- Now let us monitor a non-synchronized producer-consumer.
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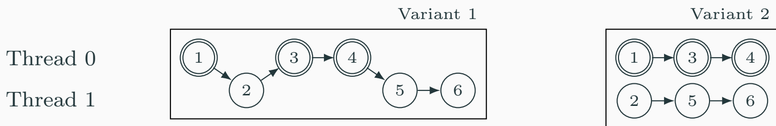
⚠ You will notice different verdicts reported for different runs

Global Monitoring ↪ (Cont'd)



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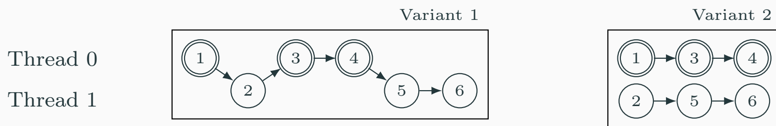
GLOBAL MONITORING ↪ (CONT'D)



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⚠ Does it suffice to simply use locks on the monitor?

DIFFERENCES IN VARIANTS AND TOOLS

V	Consumers	Tool	Advice	True #	True %	False #	False %	Timeout #	Timeout %
1	1-2	REF			-			0	(0%)
		JMOP	A	10,000	(100%)	0	(0%)	0	(0%)
			B	10,000	(100%)	0	(0%)	0	(0%)
		MarQ	A	10,000	(100%)	0	(0%)	0	(0%)
			B	10,000	(100%)	0	(0%)	0	(0%)
		LARVA	A	10,000	(100%)	0	(0%)	0	(0%)
			B	10,000	(100%)	0	(0%)	0	(0%)
2	1	REF			-			631	(6.3%)
		JMOP	A	4,043	(40.43%)	5,957	(59.57%)	0	(0%)
			B	7,175	(71.75%)	6	(0.06%)	2,819	(28.19%)
		MarQ	A	4,404	(44.04%)	5,583	(55.83%)	13	(0.13%)
			B	9,973	(99.73%)	16	(0.16%)	11	(0.11%)
		LARVA	A	4,755	(47.55%)	5,245	(52.45%)	0	(0%)
			B	9,988	(99.88%)	2	(0.02%)	10	(0.10%)
2	2	REF			-			4,785	(47.85%)
		JMOP	A	128	(1.28%)	9,220	(92.20%)	652	(6.52%)
			B	1,260	(12.60%)	7,617	(76.17%)	1,123	(11.23%)
		MarQ	A	33	(0.33%)	9,957	(99.57%)	10	(0.10%)
			B	432	(4.32%)	9,530	(95.30%)	38	(0.38%)
		LARVA	A	250	(2.50%)	9,488	(94.88%)	262	(2.62%)
			B	5,823	(58.23%)	4,131	(41.31%)	46	(0.46%)

Verifying 10,000 executions of the two variants of producer-consumer, using before/after instrumentation points with respect to φ_1 and φ_2.

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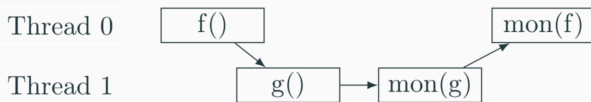

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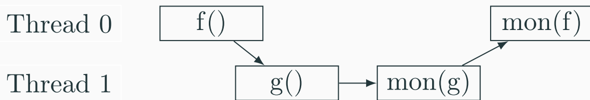

→ The trace does not represent the actual order of events in the execution.

INSTRUMENTATION

- To check for this behavior we will design a simple logging program.
- We have two functions `f()` and `g()` called by separate threads multiple times.
- The functions print `f` and `g`, respectively.
- We instrument before/after them to call a monitor which prints `f_trace` and `g_trace`, respectively.
- We compare the order of the events in the trace and actual calls.

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- Follow the tutorial in `scenarios/collect`

Instrumentation ↪ Results

```
 1  g    f_trace
 2  f    g_trace
 3  f    f_trace
 4  g    g_trace
 5  f    f_trace
 6  g    g_trace
 7  f    f_trace
 8  g    g_trace
 9  f    f_trace
10  g    f_trace
11  f    g_trace
12  f    f_trace
13  g    g_trace
14  g    g_trace
```

Tool	Advice	Sync	Identical	Different
AspectJ	A	✓	4,912	5,088
	B		9,170	830
Java-MOP	A	✓	1,737	8,263
	B		9,749	251
LARVA	A	✓	8,545	1,455
	B		9,992	8
Java-MOP	A	✗	2,026	7,974
	B		9,517	483

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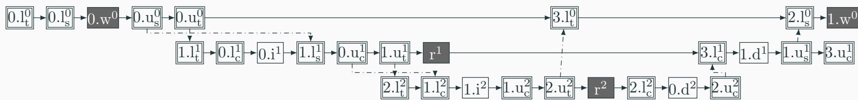

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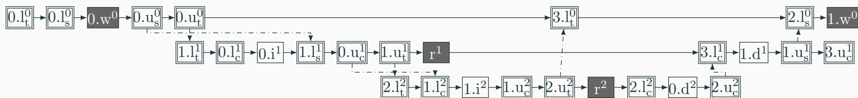

⋆ (Q4) "Is the satisfaction of the specification sensitive to the order of concurrent events?"

Approaches Focusing on Concurrency Errors

VERIFYING CONCURRENCY CORRECTNESS

Tool	Properties	Theroetical Model	Online
JPAX [HR04]	DRF/DF + LTL	Lockset-based/ERASER [SBN+97], sequential consistency only	✓

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- These tools verify specific hard-coded ("low-level") concurrency properties.
  - DRF: data race freedom
  - DF: deadlock freedom
- General behavior properties are not always checked.

★ GPredict allows for behavioral properties but offline

GPREDICT

```
1  AtomicityViolation (Object o){
2    event begin before(Object o) : execution(m());
3    event read  before(Object o) : get(* s) && target(o);
4    event write before(Object o) : set(* s) && target(o);
5    event end   after(Object o)  : execution(m());
6
7    pattern: begin(t1, <r1)
8             read(t1) write(t2) write(t1)
9             end(t1,>r1)
0    pattern: read(t1) || write(t2)
1  }
```

GPredict specification (from [HLR15])

Approaches Utilizing Multiple Traces

Multi-trace RV ↪ Stream-Based RV

- ⋆ Tools that utilize multiple traces as input (or it can be seen that way)
- → Techniques/tools need adaptation for multithreaded context

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1. Stream-based Runtime Verification:
   - Utilizes operations (arbitrary functions) that aggregate streams (of events): timing/delays, filters, and statistical
   - Tools/specification languages:
     LOLA [DSS+05],TeSSLa [LSS+18, CHL+18], BEEPBEEP [HK17]

Multi-trace RV $\hookrightarrow$ Stream-Based RV

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→ Streams for each thread, and determine aggregation function in a multithreaded context.

Multi-trace RV ↪ Decentralized Monitoring

2. Decentralized monitoring/specifications
   - Monitoring over multiple components, each having its own trace
   - Tools: DecentMon [BF16, CF16], THEMIS [EF17b]
   - Automata-based [FCF14, EF17a], distributed systems (predicate detection [NCMG17, BFRT16], (pt)DTL [SS14])

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→ Each thread is seen as a component, communication between components need to be efficient in a multithreaded context

Multi-trace RV ↪ Hyperproperties

3. Hyperproperties [FRS15]
   - Consider multiple traces of the same program (possibly different executions)
   - Used for verifying security policies
   - Tool: RVHyper [FHST18]

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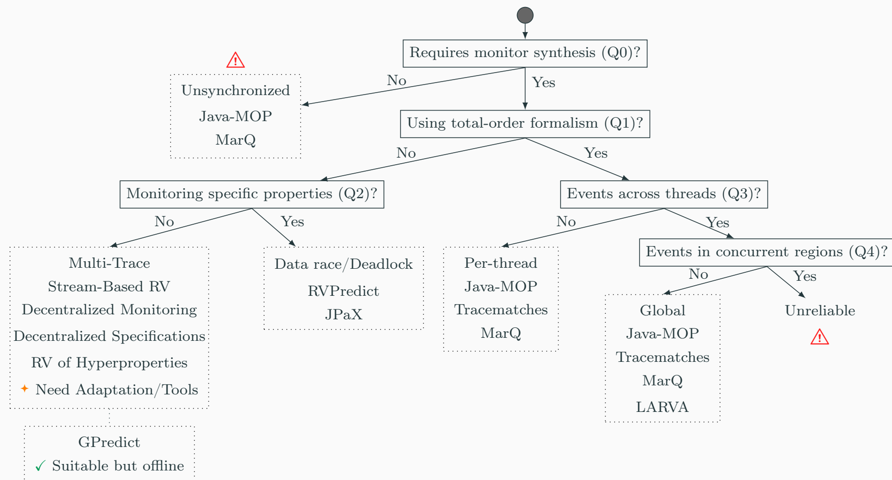
→ Multiple traces → express multiple possible re-orderings → concurrency as a hyperproperty

Conclusion

CONCLUSION



: Non-determinism and trace collection issues.

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