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Java Replay for Dependence-based Debugging

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Introduction

Setting

- Concurrent Programming course at Aalto University
- Java used in lectures, exercises and assignments

Goals of our research

- Assist students in understanding concurrency in Java.
- Assist students and teaching assistants in understanding what the students' programs do.

Introduction

Approach

- Develop and introduce a tool to show what happens in a concurrent Java program.
- We base the tool on post-mortem analysis of execution trace file to make it possible for e.g. a TA to give a failing execution to a student.
- We use **dynamic dependence analysis** to make it easier to trace interactions between parts of the program.

Introduction

Approach

- Replay is used to avoid the need to try to reproduce an execution to collect more information.
- Support a slicing debugging strategy:
  - Start with a symptom of the failure (e.g. a deadlock, incorrect output or similar).
  - Work backwards along a chain of incorrect behaviour until you reach the correct behaviour.
- Make it easier to trace unexpected interactions between threads and different parts of the program.

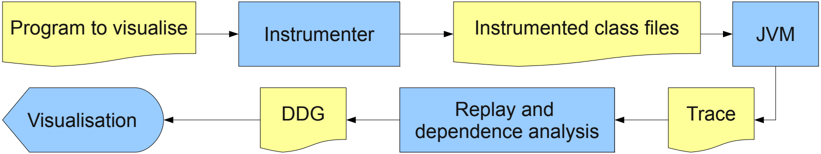
Overview of Atropos

Instrumenter Adds code to gather traces to the user's program.

JVM The instrumented code is executed in a normal JVM, producing a trace.

Replay and dependence analysis The trace is re-executed in a dependence analyser, forming a DDG.

Visualisation The DDG can be explored graphically.



Collecting execution information

Approach

- Bytecode instrumentation:
  - Compatibility: no need to implement a full JVM with associated libraries and keep that up to date
  - Portability: runs on any JVM
  - Keeping the execution environment as similar to the underlying JVM as possible
- Traces saved to files for later use.

Collecting execution information

Implementation

- Each thread collects information on its own execution.
- Only operations that may interact with other threads are recorded.
  - Shared memory (fields) operations
  - Concurrency primitives

Collecting execution information

Implementation

- Happens-before relationships allow the instrumentation can safely transfer data between threads.
  - If x happens-before y, store an identifier (thread and operation id) for x in a field associated with the interaction before x; read this after y and put it in the execution trace.
  - Locks and `volatile` variables get their own fields.
- Consistency in unlock/lock pairs guaranteed by lock itself.
- Consistency in `volatile` variables is guaranteed by replacing the field with a reference to an identifier/value pair.

Collecting execution information

Limitations

- Access to locks and fields from uninstrumented code cannot be tracked.
- Instrumenting `Object` leads to crashes, so locking can only be tracked for instances of selected classes.
- If many writes in a data race wrote the value that was read, one cannot say which write was the one that the read read its value from.
  - Since the value is known, this does not affect replay.
  - The read could have read any one of these values, so they are all relevant to exploring the program's (mis-)behaviour.

Collecting execution information

Limitations

- Objects need to be identified uniquely when the trace is saved.
  - Assign objects unique ids from a global table when writing to disk.
  - This leads to a trade-off between memory use and precision.
- Effects of instrumentation highly JVM-dependent

Replay and dependence analysis

Approach

- Dependence analysis is based around replaying the trace in a JVM that calculates vector timestamps and dependency relations while executing.
- Replay is performed in an order consistent with happens-before.
- In the case of data races, execution order becomes unclear, possibly even circular. In this case, the data dependency must be determined later.
- Control dependencies can be replaced with simpler constructs.

Visualisation

Approach

- Obvious representations exist for vertices and edges.
- If x happens-before y, x is placed above y.
- Use executions of lines of code as a suitable level of detail.
- Visualise only the part of the DDG relevant to the task at hand; let the user explore the graph along dependency edges.

Evaluation

Performance

- Performance loss by factor of about 5
- Trace file sizes manageable with ZIP compression
- Size of in-memory representation of DDG problematic

Usability

- The DDG visualisation itself is reasonably easy to understand.
- Finding the relevant information in the DDG is problematic.

Conclusion

Future work

- Making execution traces shorter
  - Model checking or manual execution instead of testing
  - Shorter test runs
- Less memory-intensive DDG calculation
- Storing execution traces more efficiently
  - Eliminate race-free reads and writes
- Additional navigation
  - Forwards and backwards
  - Alternative visualisations
- More explicit guidance on how to use Atropos