Concurrency Errors

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Basic taxonomy of concurrency bugs

- Data race condition (unsynchronized access)
- Deadlock caused by incorrectly nested locking
- Deadlock caused by missed notification (early)
- Atomicity violation (inconsistent data values)
- Ordering violation (method calls in two threads)
- Spurious wake-up (forgotten condition check)

Data race condition

```
Producer.run() {
  while (true) {
    synchronized (buf) {
      buf.add(...);
    }
    count++;
  }
}
```

```
Consumer.run() {
  while (true) {
    if (count > 0) {
      synchronized (buf) {
        ... = buf.get(0);
      }
    }
    --count;
  }
}
```

```
public static List buf;

main() {
  (new Producer()).start();
  (new Consumer()).start();
}
```

Deadlock caused by incorrectly nested locks

```
Producer.run() {
  while (true) {
    synchronized (coord) {
      synchronized (buf) {
        buf.add(...);
      }
      count++;
    }
  }
}
```

```
Consumer.run() {
  while (true) {
    synchronized (buf) {
      synchronized (coord) {
        ... = buf.get(0);
      }
      --count;
    }
  }
}
```

```
public static List buf;

main() {
  (new Producer()).start();
  (new Consumer()).start();
}
```

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Deadlock caused by missed notification

```
Subject.run() {
  ...
  synchronized (events) {
    events.add(...);
    events.notify();
  }
  ...
}
```

```
Observer.run() {
  ...
  synchronized (events) {
    events.wait();
    ... = events.get(0);
  }
  ...
}
```

```
public static List events = ...

main() {
  (new Subject()).start();
  (new Observer()).start();
}
```

Atomicity violation

```
Reader.run() {
  ...
  synchronized (db) {
    x = db.value1;
  }
  synchronized (db) {
    y = db.value2;
  }
  ...
}
```

```
Writer.run() {
  ...
  synchronized (db) {
    db.value1 = 10;
    db.value2 = 20;
  }
  ...
}
```

```
Database db = ...

main() {
  (new Reader(db)).start();
  (new Writer(db)).start();
}
```

Ordering violation

```
Server.run() {
  ...
  startInit();
  for (Worker w : workers) {
    w.start();
  }
  finishInit();
  ...
}
```

```
Worker.run() {
  while (true) {
    waitForRequest();
    openDatabase();
    executeDBQuery();
    processResults();
    sendResponse();
  }
}
```

Spurious wake-up

```
Producer.run() {
  synchronized (buf) {
    while (count >= MAX) {
      buf.wait();
    }
    buf.add(...);
    count++;
    buf.notify();
  }
}
```

```
Consumer.run() {
  synchronized (buf) {
    if (count == 0) {
      buf.wait();
    }
    ... = buf.get(0);
    --count;
    buf.notify();
  }
}
```

```
public static List buf;

main() {
  (new Producer()).start();
  (new Consumer()).start();
  (new Consumer()).start();
}
```

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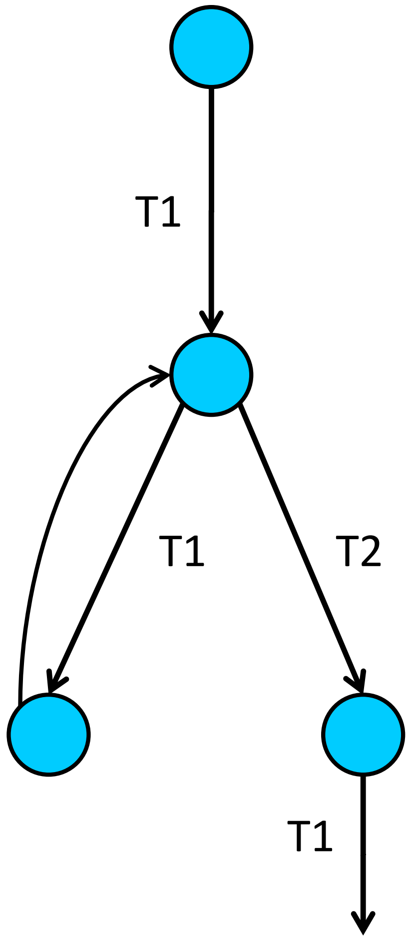
Detecting concurrency bugs

Detecting concurrency bugs

- Basic approach
  - Exhaustive state space traversal with non-deterministic thread choices by a model checker (JPF)
- Selected variants of state space traversal
  - Using custom runtime to control thread scheduling and synchronization operations
  - Bounding the number of thread preemptions
  - Optimizations (e.g., preemption sealing)
  - ➔ Systematic Concurrency Testing (SCT)
- Other approaches
  - Computing the lock-set analysis
  - Happens-before relation (order)

Exhaustive state space traversal with thread choices (JPF)

- Single root node
  - Initial program state
- Thread choices
- State matching
- Backtracking



Using custom runtime

- Controls thread scheduler in the operating system
- Custom library for synchronization primitives
  - source code instrumentation, dynamic linking
- Tracking execution of statements accessing the global state (heap objects, locks)
  - source code instrumentation, dynamic monitoring

Q: is there any problem with this approach ?

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Executing program with different schedules

- Restart program execution many times
  - Each time with a different thread interleaving
- Keep track of explored thread schedules
- Stateless traversal
  - no set of visited states, no state matching

Bounded number of preemptions

- Motivation: errors triggered with few thread preemptions (2-5) and few threads (2)
  - General principle: ***small scope hypothesis***
- Limit the number of thread preemptions
- Systematic exploration within the given bound
- Common alternative name: context bounding

Q: can we do even better (improve coverage) ?

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Bounded number of preemptions

- Motivation: errors triggered with few thread preemptions (2-5) and few threads (2)
  - General principle: ***small scope hypothesis***
- Limit the number of thread preemptions
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- Common alternative name: context bounding

A: iteratively increasing the context bound

Bounded number of preemptions

- Method limitations
  - Ignores concurrency errors triggered by more context switches (preemptions)
  - Checks program behavior only for a single input
    - Remedy: **symbolic execution**

- Theoretical complexity: NP-complete

Preemption sealing

- Disable thread choices in
  - System libraries (e.g., core and collections)
  - Already explored state space fragments
    - Method tested during previous runs of the checker
    - Code triggering already known concurrency bugs

CHESS: Systematic Concurrency Testing

- Main features
  - Custom runtime with scheduler
  - Stateless traversal with fairness
  - Iterative context-bounding
- Supported platforms
  - C#, C/C++, Win32, .NET
  - Probably just 32-bit CPU
- Further information & source code
  - https://www.microsoft.com/en-us/research/project/chess-find-and-reproduce-heisenbugs-in-concurrent-programs

COYOTE: Concurrency Unit Testing

- Main features
  - Unit tests written in C# running multiple threads
  - Exploration strategies over possible interleavings
  - Debugging: reproduces errors, visualizing traces
- Target platform
  - Recent .NET frameworks on Windows/Linux
- Further information and source code (binaries)
  - https://www.microsoft.com/en-us/research/project/coyote/
  - https://microsoft.github.io/coyote/

Context bounding done another way

- Transforming concurrent programs to sequential programs
  - Approach: source-to-source translation

Q: how this can be done ?

Context bounding done another way

- Transforming concurrent programs to sequential programs
  - Approach: source-to-source translation
- Model checking the sequential program

- Thread preemption
  - non-deterministic data choice
  - jump to another code location
  - set up execution context (stack)
- Program state: cross-product of local variables of all threads and global variables

Lock-set analysis

- Find the set of locks held at each access to a shared global variable
- Check whether accesses to shared variables follow a consistent locking discipline
- Two concurrent accesses to a global variable
  - Empty intersection of lock sets → data race
- Every access to a shared variable protected by the same lock
  - Thread using a different lock than before → data race

Happens-before ordering (relation)

- Relationships between synchronization events
  - causal, temporal, execution flow
- Partial happens-before ordering
- Example 1: wait – notify
- Example 2: lock release – lock acquire
- Ordering between field accesses → no data race

Defining correctness of concurrent programs

Correctness conditions

- Example: LinkedList
  - Operations: add(o), get(i), remove(i), size()

- Data race freedom
- Serializability (atomicity)
  - No overlap between concurrent actions

- **Linearizability**

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Linearizability

- Concurrent history H
  - Operation: invoke, result
  - Partial order: $e_1 <_H e_2$ if res(e_1) precedes inv(e_2)
- Linearizable concurrent history H
  - Exists serial witness that respects partial order and every operation has the same result value as in H
- Set of concurrent operations
  - Every possible concurrent history is linearizable with respect to a sequential specification

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Verifying linearizability

- Linearization points
  - Operations must appear to take their effect at some instant between the call and return
- State space traversal
  - Phase 1: find all possible sequential histories
  - Phase 2: explore concurrent histories
    - Identify corresponding serial witness for each
- More complicated algorithmic techniques

Relaxed memory models

Relaxed memory models

- Defines valid program transformations
  - System: compiler, virtual machine, hardware
- Motivation: optimizing performance

- Possible transformations
  - Reordering write accesses to a shared variable in a given thread
  - Delaying propagation of the new value of a global variable to other threads (shared memory)

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Relaxed memory models

- Sequential consistency
- Data race free models

- Case study: Java Memory Model

- Case study: C++11 Memory Model
  - Various extensions: C++14/17/20

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Sequential consistency

- Memory accesses execute one at a given time
- Total order of memory accesses (read, write)
- Reads observe the most recent written value
- Each thread must respect the program order
  - Order defined by the source code (developer)

Java Memory Model

- Data race free programs behave correctly
  - Guaranteed sequentially consistent semantics
- Program with data races ➔ up to the developer
  - Model provides only weak guarantees
- Memory barriers
  - Boundaries of `synchronized` blocks
  - Accessing `volatile` variables
- Defined formally using the happens-before ordering
  - Very complex (many rules): lot of research papers about it
- Used since J2SE 5.0

Hardware memory models

- Total Store Order (TSO)
  - Delaying writes (stores) relative to subsequent reads (loads) on the same processor
  - CPU architecture: x86
- Partial Store Order (PSO)
  - Additionally, delaying stores relative to other stores (to different memory locations) on the same processor
- Partial Store Load Order (PSLO)
  - Additionally, permits reordering loads to execute before previous loads and stores on the same processor

Relaxed memory models: verification support

- Java PathRelaxer
- CHESS: limited
- COYOTE: not sure

- Some tools for checking program behavior on hardware memory models (especially TSO)

Data races

- Benign
  - Optimizing performance on multi-core CPUs
  - Exploiting properties of the memory model
  - Very hard to get the implementation right
  - Case study: `java.util.concurrent`
- Erroneous
  - Missing thread synchronization by a developer mistake
- Some people call for a "total ban" on data races

ABA problem

Q: can you tell me what it means ?

ABA problem

- Idea: same value but something changed
- Typical for lock-free data structures

Further reading

- M. Musuvathi and S. Qadeer. **Iterative Context Bounding for Systematic Testing of Multithreaded Programs**. PLDI 2007
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