Landslide: A New Race-Finding Tool for 15-410
more clever than “agility_drill” since 2011.

Ben Blum (bblum@andrew.cmu.edu)
Carnegie Mellon University - 15-410
2018, February 16
Outline

Theory: Seeing concurrency bugs in a new way
  ▶ Case study (example)
  ▶ Tabular execution traces
  ▶ The execution tree

Research Technique: “Systematic testing”
  ▶ Preemption points
  ▶ Challenges and feasibility

Tool: Landslide
  ▶ How it works
  ▶ Automatically choosing preemption points
  ▶ User study (that’s you!)
Case Study

Consumer thread

```c
mutex_lock(mx);
if (!work_exists())
  cond_wait(cvar, mx);
work = dequeue();
mutex_unlock(mx);
access(work->data);
```

Producer thread

```c
mutex_lock(mx);
enqueue(work);
signal(cvar);
mutex_unlock(mx);
```
Case Study

Consumer thread

```
mutex_lock(mx);
if (!work_exists())
    cond_wait(cvar, mx);
work = dequeue();
mutex_unlock(mx);
access(work->data);
```

Producer thread

```
mutex_lock(mx);
enqueue(work);
signal(cvar);
mutex_unlock(mx);
```

- See **Paradise Lost** lecture!
- **if vs while**: Two consumers can race to make one fail.
Thread Interleavings ("good" case)

<table>
<thead>
<tr>
<th>Thread 1</th>
<th>Thread 2</th>
<th>Thread 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>lock(mx);</code></td>
<td><code>lock(mx);</code></td>
<td><code>lock(mx);</code></td>
</tr>
<tr>
<td><code>if (!work_exists())</code></td>
<td><code>if (!work_exists())</code></td>
<td><code>if (!work_exists())</code></td>
</tr>
<tr>
<td><code>    wait(cvar, mx);</code></td>
<td></td>
<td><code>    wait(cvar, mx);</code></td>
</tr>
<tr>
<td></td>
<td><code>lock(mx);</code></td>
<td></td>
</tr>
<tr>
<td></td>
<td><code>enqueue(work);</code></td>
<td><code>lock(mx);</code></td>
</tr>
<tr>
<td></td>
<td><code>signal(cvar);</code></td>
<td><code>if (!work_exists())</code></td>
</tr>
<tr>
<td></td>
<td><code>unlock(mx);</code></td>
<td><code>    wait(cvar, mx);</code></td>
</tr>
<tr>
<td><code>work = dequeue();</code></td>
<td><code>lock(mx);</code></td>
<td></td>
</tr>
<tr>
<td><code>unlock(mx);</code></td>
<td><code>enqueue(work);</code></td>
<td></td>
</tr>
<tr>
<td><code>access(work-&gt;data);</code></td>
<td><code>signal(cvar);</code></td>
<td></td>
</tr>
<tr>
<td></td>
<td><code>unlock(mx);</code></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Thread Interleavings (different “good” case)

<table>
<thead>
<tr>
<th>Thread 1</th>
<th>Thread 2</th>
<th>Thread 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>lock(mx);</code></td>
<td><code>lock(mx);</code></td>
<td><code>lock(mx);</code></td>
</tr>
<tr>
<td><code>if (!work_exists())</code></td>
<td><code>enqueue(work);</code></td>
<td><code>if (!work_exists())</code></td>
</tr>
<tr>
<td><code>    wait(cvar, mx);</code></td>
<td><code>signal(cvar);</code></td>
<td><code>    wait(cvar, mx);</code></td>
</tr>
<tr>
<td><code>work = dequeue();</code></td>
<td><code>unlock(mx);</code></td>
<td></td>
</tr>
<tr>
<td><code>unlock(mx);</code></td>
<td></td>
<td><code>lock(mx);</code></td>
</tr>
<tr>
<td><code>access(work-&gt;data);</code></td>
<td></td>
<td><code>if (!work_exists())</code></td>
</tr>
<tr>
<td></td>
<td></td>
<td><code>    wait(cvar, mx);</code></td>
</tr>
</tbody>
</table>

Ben Blum (CMU 15-410)
# Thread Interleavings (race condition)

<table>
<thead>
<tr>
<th>Thread 1</th>
<th>Thread 2</th>
<th>Thread 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>lock(mx); &lt;br&gt; if (!work_exists()) &lt;br&gt; wait(cvar, mx);</td>
<td>lock(mx); &lt;br&gt; enqueue(work); &lt;br&gt; signal(cvar); &lt;br&gt; unlock(mx);</td>
<td>lock(mx); &lt;br&gt; work = dequeue(); &lt;br&gt; unlock(mx);</td>
</tr>
<tr>
<td>work = dequeue(); &lt;br&gt; unlock(mx); &lt;br&gt; // SIGSEGV 😞</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Testing

How can programmers be confident in the correctness of their code?

- Unit tests
  - good for basic functionality, bad for concurrency
- Stress tests
  - state of the art in 15-410
- Theorem proving
  - heavy burden on the programmers
- Releasing to paying customers and worrying about correctness later

Motivation: Can we do better than stress testing?
Testing Mechanisms

**Stress testing**: largeTest, mandelbrot and friends

- Attempting to exercise as many interleavings as practical
- Exposes race conditions at random
  - “If a preemption occurs at just the right time. . .”
- Cryptic panic messages when failure occurs

What if. . .

- Make educated guesses about when to preempt
- Preempt enough times to run *every single* interleaving
- Overlook fewer bugs!
A different way of looking at race conditions...
**Execution Tree**

```
work_exists?
  cond_wait()
work_exists?
  cond_wait()
  cond_signal()
  enqueue()
  dequeue()
work != NULL
  (no bug)
```
Systematic Testing

Execution Tree

work_exists?
cond_wait()

work_exists?

cond_wait()

cond_signal()

enqueue()

dqueue()

work != NULL
(no bug)
Execution Tree

```
work_exists?
  cond_wait()

  work_exists?
    cond_wait()
      work_exists?
        cond_wait()
          work_exists?
            cond_wait()
              work_exists? cond_wait()
                work != NULL
                  no bug

            cond_signal()
              enqueue()

work != NULL
  no bug

cond_signal()

  enqueue()
    lock(mx);
    if (!work_exists())
      wait(cvar, mx);
    enqueue(work);
    signal(cvar);
    unlock(mx);

  dequeue()
    work = dequeue();
    unlock(mx);
    access(work->data);

  ???
```
Execution Tree

- `work_exists?`
- `cond_wait()`
- `work_exists?`
- `cond_wait()`
- `cond_wait()`
- `work_exists?`
- `cond_wait()`
- `cond_signal()`
- `enqueue()`
- `cond_signal()`
- `enqueue()`
- `cond_signal()`
- `enqueue()`

**Thread 1**
- lock(mx);
- if (!work_exists())
  - wait(cvar, mx);

**Thread 2**
- lock(mx);
- enqueue(work);
- signal(cvar);
- unlock(mx);

**Thread 3**
- lock(mx);
- work = dequeue();
- unlock(mx);

\[\text{work} \neq \text{NULL} \quad \text{(no bug)}\]
\[\text{work} \neq \text{NULL} \quad \text{(no bug)}\]
\[\text{work} == \text{NULL} \quad \text{Segfault!}\]
Goal: Force the system to execute every possible interleaving.

- On 1st execution, schedule threads arbitrarily until program ends.
  - This represents one branch of the tree.
- At end of each branch, rewind system and restart test.
- Artificially preempt to interleave threads differently.
- Intuitively: Generate many “tabular execution traces”.

Okay, wait a sec...
Systematic Testing - The Big Picture

Goal: Force the system to execute every possible interleaving.

- On 1st execution, schedule threads arbitrarily until program ends.
  - This represents one branch of the tree.
- At end of each branch, rewind system and restart test.
- Artificially preempt to interleave threads differently.
- Intuitively: Generate many “tabular execution traces”.

Okay, wait a sec...
Goal: Force the system to execute every possible interleaving.

- On 1st execution, schedule threads arbitrarily until program ends.
  - This represents one branch of the tree.
- At end of each branch, rewind system and restart test.
- Artificially preempt to interleave threads differently.
- Intuitively: Generate many “tabular execution traces”.

Okay, wait a sec...

- How can you possibly execute *every possible* interleaving?
- How did you know to draw that tree’s branches where they matter?
Preemption Point Example (remember this?)

```java
boolean want[2] = { false, false };

1  want[i] = true;  // (preemption point A)

2  while (want[j])  // (preemption point B)

3    continue;     // (preemption point C)

4  // ...critical section...  // (preemption point D)

5  want[i] = false;
```

Some preemption points will expose bugs.
Some preemption points don’t matter.
boolean want[2] = { false, false };

1 want[i] = true;  
(preemption point A)

2 while (want[j])

3     continue;

4     // ...critical section...

5 want[i] = false;

Here, only preemption point A will trigger a deadlock.
All other interleavings are benign.
**Preemption Points**

**Preemption points** (PPs) are code locations where being preempted may cause different behaviour.

- IOW, somewhere that interesting interleavings can happen around.

Systematic tests are *parameterized* by the set of PPs.

- $n$ PPs and $k$ threads $\Rightarrow$ state space size is $O(n^k)$.
- Need to choose PPs very carefully for test to be effective.
  - “Effective” = both comprehensive and feasible.
Preemption Points

What does “all possible interleavings” actually mean?

One extreme: Preempt at *every instruction*
- Good news: Will find every possible race condition.
- Bad news: Runtime of test will be impossibly large.

Other extreme: *Nothing* is a preemption point
- Good news: Test will finish quickly.
- Bad news: Only one execution was checked for bugginess.
  - No alternative interleavings explored.
  - Makes “no race found” a weak claim.
Preemption Points

**Sweet spot**: Insert a thread switch everywhere it “might matter”.

When are preemptions dangerous?

- Threads becoming runnable (`thr_create()`, `cond_signal()` etc.)
  - Preemptions may cause it to run before we’re ready
- Synchronization primitives (`mutex_lock()`/`unlock()`, etc.)
  - If buggy or used improperly...
- Unprotected shared memory accesses (“data races”)
  - May result in data structure corruption
  - More on this later...
Landslide
About The Project

About me: Final year graduate student, advised by Garth Gibson

- TAed 15-410 for 3 semesters during undergrad
- Landslide’s publication history
  - Master’s thesis
  - Conference paper (OOPSLA 2016)
    - [http://www.contrib.andrew.cmu.edu/~bblum/oopsla.pdf](http://www.contrib.andrew.cmu.edu/~bblum/oopsla.pdf)
About The Project

About me: Final year graduate student, advised by Garth Gibson

- TAed 15-410 for 3 semesters during undergrad
- Landslide’s publication history
  - Master’s thesis
  - Conference paper (OOPSLA 2016)

About Landslide

- Simics module, which traces:
  - Every instruction executed
  - Every memory access read/written

- *Landslide* shows how your *Pebbles* programs may not be stable.
Big Picture: Execution Tree Exploration

Backtracking

- Each time test completes, identify a PP to replay differently
- Reset machine state and start over
- Implemented using Simics bookmarks
  - set-bookmark and skip-to
- Replay test from the beginning, with a different interleaving

Controlling scheduling decisions

- Tool must control all sources of nondeterminism
- In 15-410, just timer and keyboard interrupts
- Landslide repeatedly fires timer ticks until desired thread is run.
Big Picture: Execution Tree Exploration

Backtracking

- Each time test completes, identify a PP to replay differently
- Reset machine state and start over
- Implemented using Simics bookmarks
  - set-bookmark and skip-to
- Replay test from the beginning, with a different interleaving

Controlling scheduling decisions

- Tool must control all sources of nondeterminism
- In 15-410, just timer and keyboard interrupts
- Landslide repeatedly fires timer ticks until desired thread is run.
Landslide & You

- **Simics (hardware emulation)**
- **Pebbles (reference kernel)**
- **P2 (thread library)**

- System calls
- Hardware drivers
Landslide & You

P2 (thread library)
- examines memory
- reads/writes

Pebbles (reference kernel)
- system calls
- hardware drivers
- injects timer
- interrupts

Simics (hardware emulation)
- manages multiple executions

Landslide

Ben Blum (CMU 15-410)
Identifying Bugs

Landslide can *definitely discover*:
- Assertion failures
- Segfaults
- Deadlock
- Use-after-free / double-free

Landslide can *reasonably suspect*:
- Infinite loop (halting problem)
- Data race bugs
What is a Data Race?

A **data race** is a pair of memory accesses between two threads, where:

- At least one of the accesses is a write
- The threads are not holding the same mutex
- The threads can be reordered (e.g., no `cond_signal()` in between)
What is a Data Race?

A **data race** is a pair of memory accesses between two threads, where:

- At least one of the accesses is a write
- The threads are not holding the same mutex
- The threads can be reordered (e.g., no `cond_signal()` in between)

Data races are *not necessarily* bugs, just highly suspicious!

- Bakery alg: Is `number[i]=max(number[0],number[1])+1` bad?
- What about unprotected `next_thread_id++`?
- “If threads interleaved the wrong way here, it *might* crash later.”
  - Hmmmm...
Choosing the Right Preemption Points

How can we address exponential state space explosion?
Choosing the Right Preemption Points

How can we address exponential state space explosion?

State of the art tools choose a fixed set of preemption points.

- E.g., “all thread API calls” or “all kernel mutex locks/unlocks”
- Depending on length of test, completion time is unpredictable.
- More often, a subset is better in terms of time/coverage.
Choosing the Right Preemption Points

How can we address exponential state space explosion?

State of the art tools choose a fixed set of preemption points.
  ▶ E.g., “all thread API calls” or “all kernel mutex locks/unlocks”
  ▶ Depending on length of test, completion time is unpredictable.
  ▶ More often, a subset is better in terms of time/coverage.

Current systematic testing model is not user-friendly.
  ▶ Tool: “I want to use these PPs, but can’t predict completion time.”
  ▶ User: “I have 16 CPUs and 24 hours to test my program.”

*Stress testing allows user to choose total run time – can we offer this too?*
Iterative Deepening in Landslide

Landslide automatically iterates through different configurations of PPs.

- Manages work queue of jobs with different PPs
- Each job represents a new state space for Landslide to explore
- Prioritizes jobs based on estimated completion time

Repeat state space explorations, adding preemption points, until time is exhausted.

*Only required argument is CPU budget*
Iterative Deepening

Minimal state space includes only “mandatory” context switches

- e.g., `yield()`, `cond_wait()`.

![Diagram showing iterative deepening with yield() nodes and context switches.]
Iterative Deepening

Adding different PPs can produce state spaces of different sizes; Landslide tries them in parallel.
Iterative Deepening

If time allows, Landslide will combine PPs into larger, more comprehensive state spaces.
Demo
Test Suite

Landslide ships with 6 approved test cases:

Standard P2 tests
- thr_exit_join
- paraguay
- rwlock_downgrade_read_test

New tests
- broadcast_test
- paradise_lost
- mutex_test
What makes a Landslide-friendly test

“Why not largetest, juggle, cyclone, agility_drill...?”

Sample code from cyclone:

```c
for (i = 0; i < MAX_MISBEHAVE /* 64 */; i++) {
    misbehave(i);
    tid = thr_create(child_fn, i);
    thr_join(tid, &status);
}
```
What makes a Landslide-friendly test

“Why not large test, juggle, cyclone, agility_drill...?”

Sample code from cyclone:

```c
for (i = 0; i < MAX_MISBEHAVE /* 64 */; i++) {
    misbehave(i);
    tid = thr_create(child_fn, i);
    thr_join(tid, &status);
}
```

Stress tests expose various interleavings using big loops/many threads;

Landslide finds many interleavings itself; even if the test case has no loops.

How long do you think Landslide would take to test cyclone..?
Previous Semesters

S’15, F’15, S’16, F’16, S’17, F’17: 94 groups signed up to use Landslide; 71 found bugs

109 deterministic bugs (e.g. swexn, initialization)

122 distinct non-deterministic bugs (among 49 groups)

- 36 groups (73%) fixed $\geq 1$ such bug
  - (as verified by running Landslide again – not a guarantee!)

- 26 groups (53%) fixed all such bugs

- Most ambitious group: 11 distinct races found + fixed!
User Study

Try Landslide on your P2!

- Bare minimum effort: No more than 1 hour
  - Clone a github URL, run setup script, run tests, answer survey
  - Landslide will automatically report test results (as described below)
- Full study plan: 4-8 hours of active attention
  - (Estimated, including time to diagnose and fix bugs)
  - However, many tests should run passively overnight – start soon!
User Study

Try Landslide on your P2!

- Bare minimum effort: No more than 1 hour
  - Clone a github URL, run setup script, run tests, answer survey
  - Landslide will automatically report test results (as described below)
- Full study plan: 4-8 hours of active attention
  - (Estimated, including time to diagnose and fix bugs)
  - However, many tests should run passively overnight – start soon!

Prerequisites

- You must pass the P2 hurdle before using Landslide.
  - startle, agility_drill, cyclone, join_specific_test, thr_exit_join
- Recommended to attempt several stress tests, e.g.:
  - juggle 4 3 2 0, multitest, racer, paraguay
User Study - Additional Information

Human Subjects Research

- CMU IRB has approved this study
- Landslide will collect results while you use it
  - Record commands issued, take snapshots of your P2 code
  - All data will be anonymized before publication
- No coercion: *There is no penalty for not participating.*
  - I am not on course staff, cannot influence your grade
  - Course staff will not have access to study data during semester
User Study - Additional Information

Human Subjects Research

- CMU IRB has approved this study
- Landslide will collect results while you use it
  - Record commands issued, take snapshots of your P2 code
  - All data will be anonymized before publication
- No coercion: *There is no penalty for not participating.*
  - I am not on course staff, cannot influence your grade
  - Course staff will not have access to study data during semester

Risks & Benefits

- Benefit: Landslide may help you find/fix bugs, improving your grade!
- Risk: Landslide may find no bugs and be a waste of your time.
- Benefit: You might learn something...
User Study - How to Participate

Interested?

To participate...

- Meet prerequisites of passing P2 tests
- Complete sign-up form online to get further instructions
  - (watch your email for the link)
- Optional “Landslide clinic” for in-person tech (or moral) support
  - Next week, room and time TBD
Questions?
Coping with State Space Explosion

Serious problem: State spaces grow exponentially

- With $p$ preemption points and $k$ runnable threads, size $p^k$.
- Threatens our ability to explore everything.
- Fortunately, some sequences result in identical states.

**Partial Order Reduction** identifies and skips “equivalent” interleavings.

- After each execution, compare memory reads/writes of each thread.
- Find when reordering threads couldn’t possibly change behaviour.
- Example follows...
State Space Reduction

**Thread 1** | **Thread 2**
---|---
$x = 5$ | $y = 5$
$x++$; | $y--$
$x = 6$ | $y = 4$

**Thread 1** | **Thread 2**
---|---
$x = 5$ | $y = 5$
$x++$; | $y--$
$x = 6$ | $y = 4$
State Space Reduction

<table>
<thead>
<tr>
<th>Thread 1</th>
<th>Thread 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x = 5$</td>
<td>$y = 5$</td>
</tr>
<tr>
<td>$x++;$</td>
<td>$y--;$</td>
</tr>
<tr>
<td>$x = 6$</td>
<td>$y = 4$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thread 1</th>
<th>Thread 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x = 5$</td>
<td>$y = 5$</td>
</tr>
<tr>
<td>$x++;$</td>
<td>$y--;$</td>
</tr>
<tr>
<td>$x = 6$</td>
<td>$y = 4$</td>
</tr>
</tbody>
</table>
State Space Reduction

<table>
<thead>
<tr>
<th>Thread 1</th>
<th>Thread 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x = 5$</td>
<td>$y = 5$</td>
</tr>
<tr>
<td>$x++;$</td>
<td>$y--;$</td>
</tr>
<tr>
<td>$x = 6$</td>
<td>$y = 4$</td>
</tr>
</tbody>
</table>

Avoided exploring a subtree!