MODIST: Transparent Model Checking of Unmodified Distributed Systems

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Distributed system: hard to get right

- Complicated protocol + code
  - Node has no centralized view of entire system
  - Must correctly handle a large number of failures
    - Link failure, message delay, machine crash
  - Getting worse: larger scale, failures more likely

- Randomized testing
  - Low coverage
  - Non-deterministic
MODIST summary

- **MOdel checker for DISTributed systems**
  - **Comprehensive**: check many corner cases
  - **“In-situ:”**: check unmodified, real implementations
  - **Deterministic**: detected errors can be replayed

- **Results**
  - Checked Berkeley DB replication, Paxos-MPS (managing Microsoft production data centers) [D3S, NSDI08], and PacificA [MSR-TR]
  - 35 bugs, 31 confirmed
  - 10 protocol bugs, found in every system checked
Outline

- **Overview**
  - Real Berkeley DB bug
  - How MODIST finds the bug

- Implementation challenges

- Errors
Berkeley DB replication

- Based on Paxos
  - single primary, multiple secondaries
  - Primary can read and write
  - Secondary can only read

- When primary fails, secondaries can elect new primary

- When duplicate primary detected, degrade both and re-elect

- Bug is in leader election protocol
A real Berkeley DB bug

A-C link failure

"I'm new primary"

time

A degrades itself

OK

A is primary

"update"

"Duplicate primary!"

C degrades itself
A real Berkeley DB bug

A-C link failure

“I’m new primary”

C is primary

“Duplicate primary!”

C degrades itself

A degrades itself

time

“update”

Unexpected message!
$ cat bdb.conf

    # command                                             # working dir      # inject failure?
    ex_rep_mgr.exe –n 3 –m localhost:8000 …      ./node1                1
    ex_rep_mgr.exe –n 3 –m localhost:8001 …      ./node2                1
    ex_rep_mgr.exe –n 3 –m localhost:8002 …      ./node3                1

$ modist.exe bdb.conf

    spawning process 1: ex_rep_mgr.exe ...

    ... fail link from process 1 to process 3 ...
    ... process 3 send to process 1 ...
    restarting
    spawning process 1: ex_rep_mgr.exe ...

$ modist.exe bdb.conf –r traces/0/trace
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Core model checking idea

- **Goal:** explore all states and actions

- **Advantage:** rare actions appear as often as common ones, thereby quickly driving system into corner case for errors
Actions in Berkeley DB replication

- **Normal actions**
  - Send message
  -Recv message
  - Run thread
  -...

- **Rare actions**
  - Delay message
  - Fail link
  - Crash machine
  -...
Ideal: exploring all actions

- Built-in checks
  - Crash
  - Deadlocks
  - Infinite loops

- User-written checks
  - Local assertions
  - Global assertions
    - [D3S, NSDI 08]

- MODIST amplifies
Avoiding redundancy

- Explore only one interleaving of independent actions
  - Partial order reduction [Verisoft, POPL97] [DPOR, PLDI05]
  - Our implementation handles both message passing and thread synchronizations
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Challenges

- How to expose actions?
- How to check often-untested timeout code?
- How to simulate failures?
  - Must be realistic to avoid false positives
- How to schedule actions?
  - Must be deterministic for error replay
    - E.g., asynchronous IO
  - Must avoid deadlocks
  - Must be extensible
Challenges

- How to expose actions?
- How to check often-untested timeout code?
- How to simulate failures?
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Exposing actions

- To check, must know and control actions

- Previous work on distribute system model checking: users must expose actions
  - **MaceMC**: write app in special language
  - **CMC**: port app into fake environment
    - We used it to check FS [FiSC, OSDI06]
    - Difficult to check new app, OS

- **MODIST** uses *in-situ checking architecture* [EXPLODE, OSDI06]: interlace control needed into checked system
Architecture comparison

Traditional approach

MODIST

- Frontend intercept API call
  - RPC to backend

- Central scheduler of all intercepted API calls

- Transparent
- Easy to port to new OS
Frontend: simple

- Intercepted 82 API functions
  - E.g., networking, thread synchronization
- Most wrappers are simple: return failure or call real API function
  - No need to re-implement API functions
  - Average 67 lines per wrapper
Challenges

- How to expose actions?

- How to check often-untested timeout code?

- How to simulate failures?
  - Must be realistic to avoid false positives

- How to schedule actions?
  - Must be deterministic for error replay
    - E.g., asynchronous IO
  - Must avoid deadlocks
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Checking timeouts

- System code heavily uses \textit{implicit timers}

\begin{verbatim}
  db_timespec now;
  now = gettimeofday();  // return current time
  if (now >= t + 10 )  // timeout check
    ...  // timeout handling code
  else
    ...  // no timeout
\end{verbatim}

- Challenge: can intercept \texttt{gettimeofday()}, but what to return?
  - Want to explore both branches
  - \textbf{Must know} \texttt{t + 10}, but no API call
  - Previous work: \texttt{manual}
Static symbolic analysis

- Key observations
  - Time values are used in simple ways
    - Berkeley DB: `db_timespec`, mostly `+,-, sometimes *,/`
    - Static analysis can pick up time values easily
  - Programmers check timeout soon after current time
    - Intuition: want current time to be “fresh”
    - Berkeley DB: 12 out of 13 are within a few lines
    - Track only short flows of time values

- Our solution: static intra-procedural symbolic analysis to discover implicit timers
  - Much simpler than state of art symbolic analysis
    - [KLEE, OSDI08]
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- Errors
# Errors

- Large, complex systems
- Total 35 bugs, **all previously unknown**, 31 confirmed
- Protocol bugs in every system, total 10

<table>
<thead>
<tr>
<th>System</th>
<th>KLOC</th>
<th>Protocol bugs</th>
<th>Impl. bugs</th>
<th>Total</th>
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</thead>
<tbody>
<tr>
<td>Berkeley DB</td>
<td>172.1</td>
<td>2</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Paxos-MPS</td>
<td>53.5</td>
<td>2</td>
<td>11</td>
<td>13</td>
</tr>
<tr>
<td>PacificA</td>
<td>12</td>
<td>6</td>
<td>9</td>
<td>15</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>237.6</td>
<td><strong>10</strong></td>
<td><strong>25</strong></td>
<td><strong>35</strong></td>
</tr>
</tbody>
</table>
Conclusion

MODIST: in-situ model checker for distributed systems
- Comprehensive, transparent, deterministic
- Effective
  - Checked Berkeley DB, Paxos-MPS, PacificA
  - 35 bugs, 10 protocol bugs

Real distributed protocols are buggy
- Interestingly, based on proven-correct protocols
- Bugs stem from concretization or customizations