What New Bugs Live in the Cloud? (and how to exterminate them)

Haryadi Gunawi

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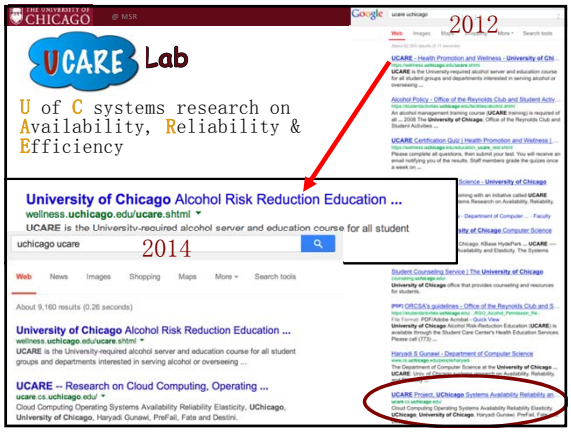


What new bugs live in the cloud?

Datacenter distributed systems

# of Bug Reports	Jan 2014	Jan 2016
Hadoop+MR+Yarn	17454	23811
HDFS	5710	9605
HBase	10263	15062
Cassandra	6535	10960
ZooKeeper	1854	2350

We studied 3000+ issues

"New" classes of bugs

- Distributed concurrency bugs
  - + Timings of multiple failures

  TaxDC [ASPLOS '16] SAMC [OSDI '14] FATE & DESTINI [NSDI '11]
- Non-deterministic performance bugs

  The Tail at Store [FAST '16] SPV [HotCloud '15] Limpware [SoCC '13] Tiny Tail [In Subm.] Path-Based Spec. Exec. [In Subm.]
- Scalability bugs

  SCk [In Subm.]
- Other outage-causing bugs:
  - SPOF/cascading bugs
  - Cross-layer upgrade bugs

  Cloud Bug Study [SoCC '14] Cloud Outage Study [In Subm.]

"New" classes of bugs

- Distributed concurrency (DC) bugs

  TaxDC [ASPLOS '16] **SAMC** [OSDI '14]
- Non-deterministic performance bugs
- Scalability bugs

Distributed concurrency (DC) bug

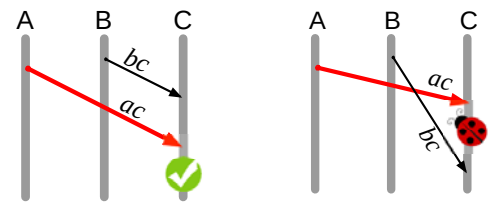
- Caused by non-deterministic timing of concurrent events involving more than one node
- Events: Messages, crashes, reboots, timeouts, local computations

6% of the bugs in our study

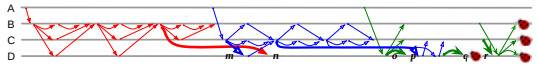
CAUTION

Data loss, downtimes, inconsistent replicas, hanging jobs, etc.

DC bug: a simple view



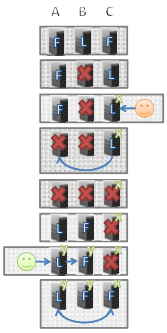
DC bug: a real view



- Cassandra **Paxos** Bug (# 6023)
- **3 concurrent updates**
  - Red, blue, green
- **3 msg-msg races** must happen
  - m = prepare message for ballot 2, **BEFORE**
  - n = commit message for ballot 1
  - o = prepare message for ballot 3, **BEFORE**
  - p = propose message for ballot 2
  - q = promise message for ballot 3, **BEFORE**
  - r = promise message for ballot 3
  - (24 hours to understand)

ZooKeeper (synchronization service)
Issue #335.

1. Nodes A, B, C start (w/ latex txid: 10)
2. B becomes leader
3. B crashes
4. C becomes leader
5. C commits new txid-value pair (11, X)
6. A crashes, before committing (11, X)
7. C loses quorum and C crashes
8. A and B are back online
9. A becomes leader
10. A's commits new txid-value pair (11, Y)
11. C is back online
12. C announces to B (11, X)
13. B replies the diff from tx 12
14. Inconsistency: A has (11, Y), C has (11, X)



PERMANENTLY INCONSISTENT REPLICA

ZooKeeper (synchronization service)
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14. Inconsistency: A has (11, Y), C has (11, X)

Specific Order

1. Out-of-order messages
2. Multiple crashes
3. Multiple reboots

(1) (2) (3) HAPPEN IN ANY ORDER

How can we catch **deep** concurrency bugs in distributed systems?

Distributed system model checker (dmck)

- Re-ordering all non-deterministic events
  - **Paths:** abcd, abdc, acbd, acdb, …
  - Find buggy paths/interleavings

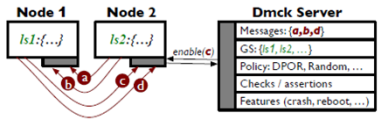
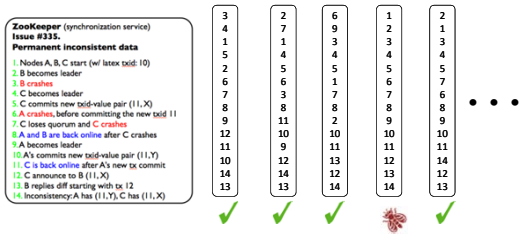


Figure 1: **DMCK.** *The figure illustrates a typical framework of a distributed system model checker (dmck).*

Event re-orderings by dmck



SAMC: Semantic-Aware Model Checking for Fast Discovery of Deep DC Bugs

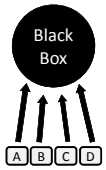
with Tanakorn Leesatapornwongsa,
Mingzhe Hao, Pallavi Joshi, and Jeffrey F. Lukman
[OSDI '14]

What's Wrong with Existing Model Checkers?

- Last 7 years
  - MaceMC [NSDI '07], Modist [NSDI '09], dBug [SSV '10], Demeter [SOSP '13], etc.
- **BUT**
  - Too many events to permute
  - Must add crashes and reboots
    - State-space explosion!
    - (skipped in existing checkers)
      - **Cannot find deep bugs!**

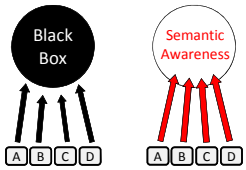
How can we catch deep bugs **REALLY FAST**?

- Why are existing checkers slow?
- They treat target system as a black box
  - Must re-order everything

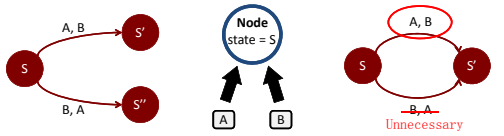


Black Box Model Checker
ABCD
ABDC
ACBD
ACDB
ADBC
. . .
(24 total)

- How can we make model checkers fast?
  - Exploit **semantic knowledge**
    - *E.g. knowledge of how messages are processed*
  - Reduce unnecessary re-orderings



Dependency vs. Independency

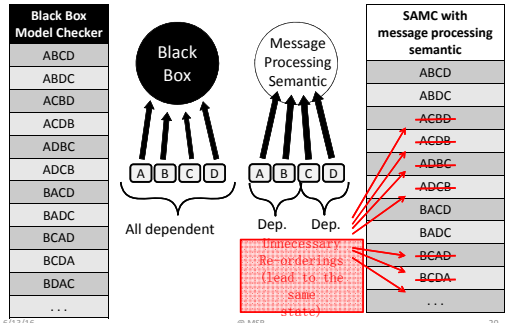


A, B = Dependent

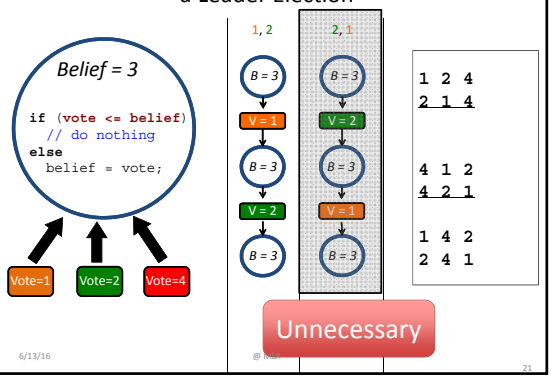
A, B = Independent

Independent = No need to reorder

Black Box vs. SAMC



Message Processing Semantic in a Leader Election



- **Discard pattern**

MESSAGE PROCESSING SEMANTIC

```
if (msg.vote <= state.belief)
  // do nothing
else
  belief = vote;
```

DISCARD PATTERN

```
if (isDiscard(msg, state)) {
    // do nothing;
}
```

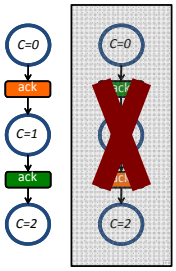
DISCARD PREDICATE

```
boolean isDiscard(msg, state) {
  if (msg.vote <= state.belief)
    return true;
  else
    return false;
}
```


- Discard pattern
- **Increment pattern**

```
if (msg.type == ack) {
  node.ackCount++;
}
```

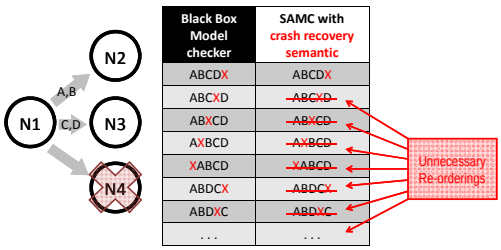
```
boolean isIncrement(msg, ls) {
  if (msg.type == ack)
    return true;
  else
    return false;
}
```



- **Constant pattern**

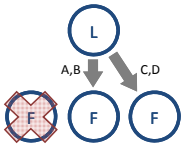
Local-Message Independence (LMI)

SAMC with Crashes



Crash-Msg Independence

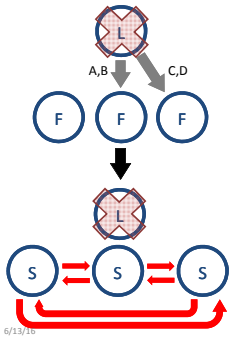
Black Box
ABCDX
~~ABCXD~~
~~ABXCD~~
~~AXBCD~~
~~XABCD~~
~~ABDCX~~
...




```
void handleCrash() {
  if (X == follower &&
isQuorum())
    followerCount--;
    // No new messages!!
}
```

Crash a **follower**
→
Local Impact
(no new messages &
only state changes in leader L)

Crash-Msg Independence

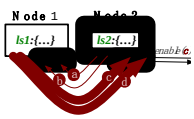



```
void handleCrash() {
  if (X == leader || !isQuorum())
    electLeader()
    // New messages created
}
```

Crash the **leader**
→ **Global Impact**
(cannot prune
re-orderings)

Black Box
ABCDX
ABCXD
ABXCD
AXBCD
XABCD
ABDCX
...

SAMC Architecture



SAMC

Protocol Specific Rules: Leader Election | Atomic Broadcast | ... | ...

Generic Reduction Policies

- Local-Message Indep. (LMI)
- Crash-Message Indep. (CMI)
- Crash Recovery Symmetry (CRS)
- Reboot Sync. Symmetry (RSS)

Protocol-specific predicates (extra)

(e.g. ZooKeeper Leader Election)

Local-Message Independence (LMI)

```
bool pd : !newVote(m, s);

bool pm : newVote(m, s);

bool newVote(m, s) :
  if (m.ep > s.ep)
    ret 1;
  else if (m.ep == s.ep)
    if (m.tx > s.tx)
      ret 1;
    else if (m.tx == s.tx &&
          m.lid > s.lid)
      ret 1;

ret 0;
```

Crash-Message Independence (CMI)

```
bool pg (s, X) :
  if (s.rl == F && X.rl == L)
    ret 1;
  if (s.rl == L && X.rl == F
      && !quorumAfterX(s)
    ret 1;
  if (s.rl == S && X.rl == S)
    ret 1;

bool pl (s, X) :
  if (s.rl == L && X.rl == F
      && quorumAfterX(s))
    ret 1;

bool quorumAfterX(s) :
  ret ((s.fol-1) >=
        s.all/2);
```

Crash Recovery Symmetry (CRS)

```
bool pr1(s,C):
  if (s.rl == L && C.rl == F
      && quorumAfterX(s))
    ret 1;
rals1:{rl,fol,all};

bool pr2(s,C):
  if (s.rl == L && C.rl == F
      && !quorumAfterX(s))
    ret 1;
rals2: {rl,fol,lid,ep,tx,clk}

bool pr3(s,C):
  if (s.rl == F && c.rl == L)
    ret 1;
rals3: {rl,fol,lid,ep,tx,clk}

bool pr4:
  if (s.rl == S)
    ret 1;
rals4: {rl,lid,ep,tx,clk}
```

- 35 LOC on average per protocol

Speed in Reaching Old Bugs

#executions/paths to reach the bugs (e.g., 2 paths = abcd, abdc)

Bug#	SAMC	Black-Box DPOR	Random	Random DPOR
ZooKeeper-335				
ZooKeeper-790				
ZooKeeper-975				
ZooKeeper-1075				
ZooKeeper-1419				
ZooKeeper-1492				
ZooKeeper-1653				
MapReduce-4748				
MapReduce-5489				
MapReduce-5505				
Cassandra-3395				
Cassandra-3626		5000+		

Speed in Reaching Old Bugs

#executions/paths to reach the bugs (e.g., 2 paths = abcd, abdc)

Bug#	SAMC	Black-Box DPOR		Random		Random DPOR	
	#exe	#exe	speedup	#exe	speedup	#exe	speedup
ZooKeeper-335	117	5000+	43+	1057	9	5000+	43+
ZooKeeper-790	7	14	2	225	32	82	12
ZooKeeper-975	53	967	18	71	1	163	3
ZooKeeper-1075	16	1081	68	86	5	250	16
ZooKeeper-1419	100	924	9	2514	25	987	10
ZooKeeper-1492	576	5000+	9+	5000+	9+	5000+	9+
ZooKeeper-1653	11	945	86	3756	341	3462	315
MapReduce-4748	4	22	6	6	2	6	2
MapReduce-5489	53	5000+	94+	5000+	94+	5000+	94+
MapReduce-5505	40	1212	30	5000+	125+	1210	30
Cassandra-3395	104	2552	25	191	2	550	5
Cassandra-3626	96	5000+	52+	5000+	52+	5000+	52

Summary

- Distributed concurrency bugs → hard to catch
- **Semantic-awareness** for model checking is powerful
  - Find bugs **2 - 340x** faster, **49x** on average

TaxDC:
Taxonomy of Non-Deterministic Concurrency Bugs in Datacenter Distributed Systems

with Tanakorn Leesatapornwongsa,
Jeffrey F. Lukman and Shan Lu
[ASPLOS '16]

Google Scholar: local concurrency bug

(**LC** bug: multi-threaded single machine software)

Learning from mistakes: a comprehensive study on real world concurrency bug characteristics
S Lu, S Park, E Seo, Y Zhou - ACM Sigplan Notices, 2008 - dl.acm.org
Cited by 558

Top 10 most cited ASPLOS paper

≠

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Learning from mistakes: a comprehensive study on real world concurrency bug characteristics
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[PDF] **TaxDC**: A Taxonomy of Non-Deterministic Concurrency Bugs in Datacenter Distributed Systems
T Leesatapornwongsa, JF Lukman, S Lu, HS Gunawi - ucare.cs.uchicago.edu
Cited by 1

TaxDC

- Taxonomy of distributed concurrency bugs
- **104** bugs
- **4** varied distributed systems

cassandra, hadoop, APACHE HBASE, Apache Zookeeper

- Bugs in 2011-2014
- Study description, source code, patches

Detailed Characteristics

Input:
– 4 Protocol initiations

ZooKeeper-1264

1. Follower F crashes, reboots, and **joins** cluster
2. Leader L sync **snapshot** with F
3. Client requests new **update**, F applies this only in memory
4. Sync finishes
5. Client requests other **update**, F writes this to disk correctly
6. F crashes, reboots, and joins cluster again
7. This time L sends only diff after update in step 5.
8. F loses update in step 3.

Detailed Characteristics

Input:
– 4 Protocols
– 2 faults
– 2 reboots

ZooKeeper-1264

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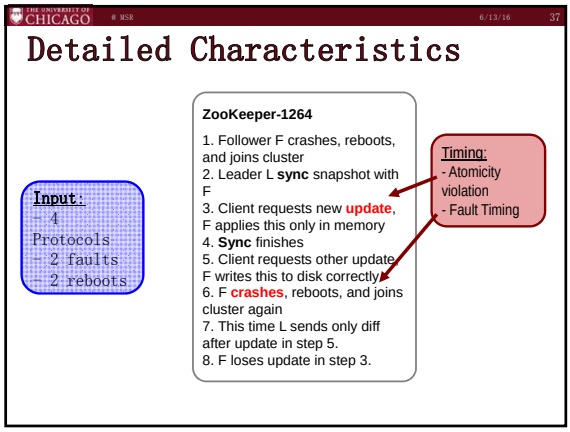
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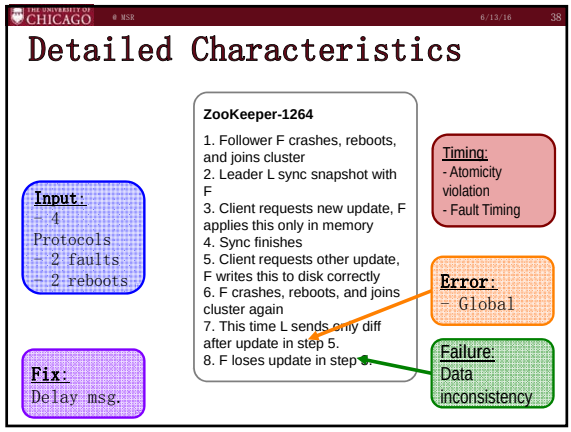
Input:
- 4 Protocols
- 2 faults
- 2 reboots
Timing:
- Atomicity violation
- Fault Timing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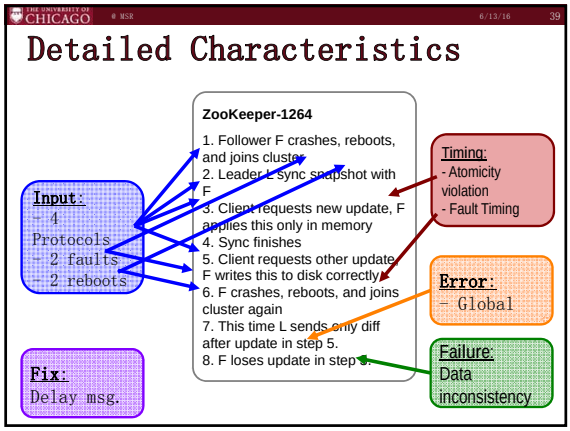
Input:
- 4 Protocols
- 2 faults
- 2 reboots
Fix:
Delay msg.
Timing:
- Atomicity violation
- Fault Timing
Error:
- Global
Failure:
Data inconsistency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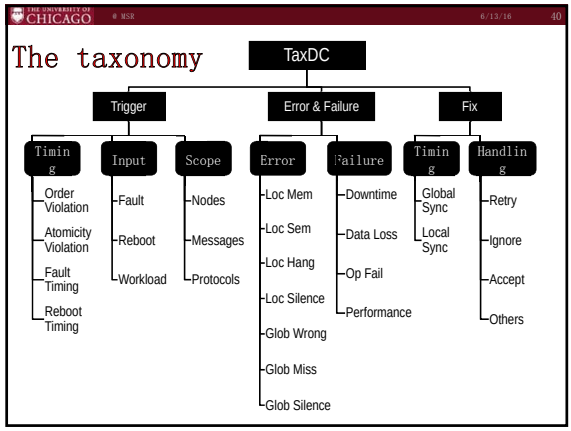
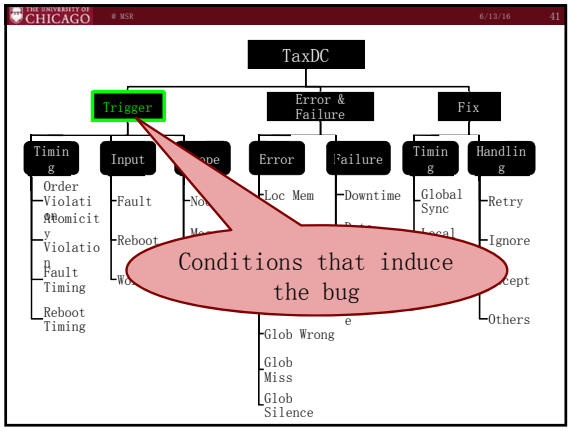
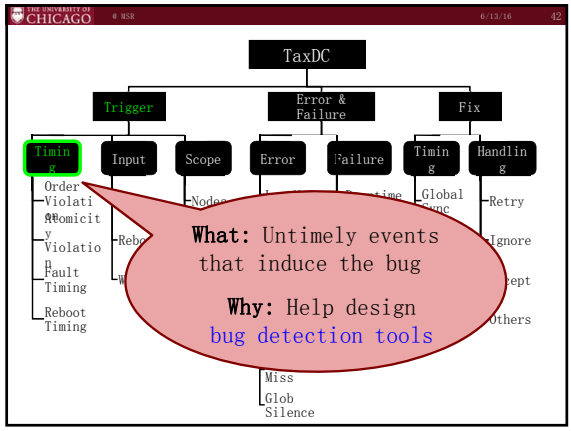

The taxonomy
TaxDC
Trigger
Error & Failure
Fix
Timing
Input
Scope
Error
Failure
Timing
Handling
Order Violation
Atomicity Violation
Fault Timing
Reboot Timing
Fault
Reboot
Workload
Nodes
Messages
Protocols
Loc Mem
Loc Sem
Loc Hang
Loc Silence
Glob Wrong
Glob Miss
Glob Silence
Downtime
Data Loss
Op Fail
Performance
Global Sync
Local Sync
Retry
Ignore
Accept
Others


TaxDC
Trigger
Error & Failure
Fix
Conditions that induce the bug


TaxDC
Trigger
Error & Failure
Fix
What: Untimely events that induce the bug
Why: Help design bug detection tools

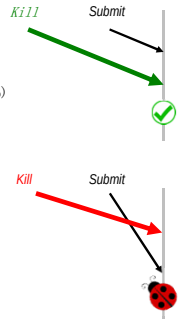
Trigger
- Timing
  - Message

Messages arrive in untimely order

Trigger
- Timing
  - Message
    - Order violation (44%)

*Y must happen **after** X*
*But Y happens **before** X*

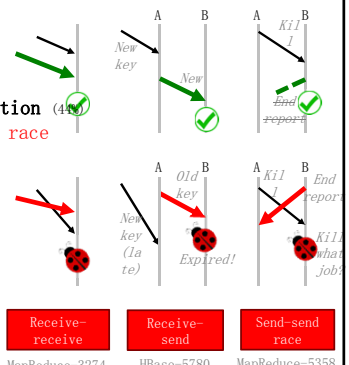
Trigger
- Timing
  - Message
    - Order violation (44%)
      - Msg-msg race



*Y must happen **after** X*
*But Y happens **before** X*

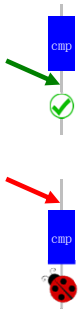
Ex: MapReduce-3274

Trigger
- Timing
  - Message
    - Order violation (44%)
      - Msg-msg race



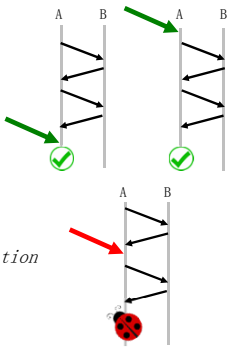
MapReduce-3274 HBase-5780 MapReduce-5358

Trigger
- Timing
  - Message
    - Order violation (44%)
      - Msg-msg race
      - Msg-compute race



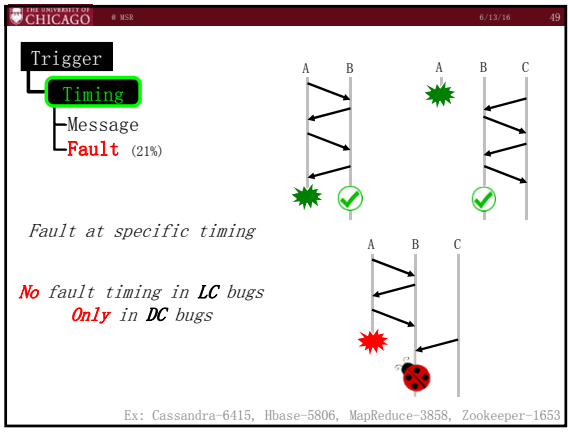
Ex: MapReduce-4157

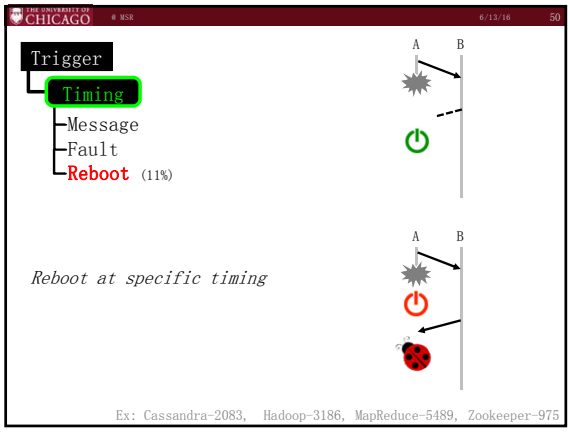
Trigger
- Timing
  - Message
    - Order violation (44%)
    - Atomicity violation (20%)

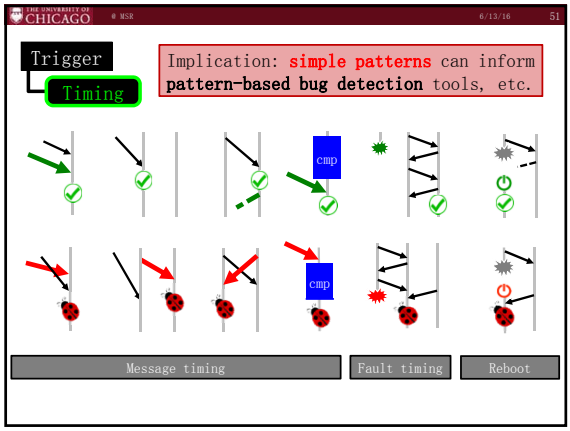


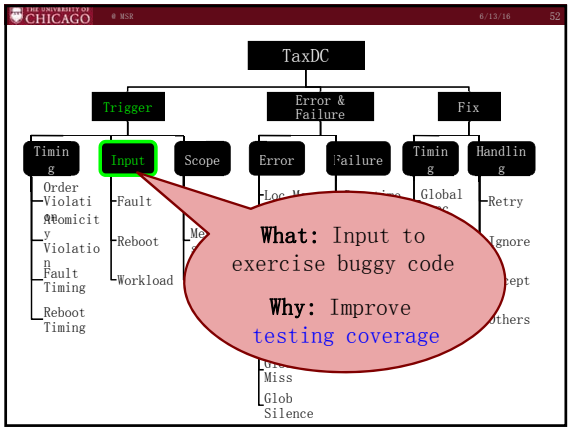
*A message comes in the **middle** of "atomic" operation*

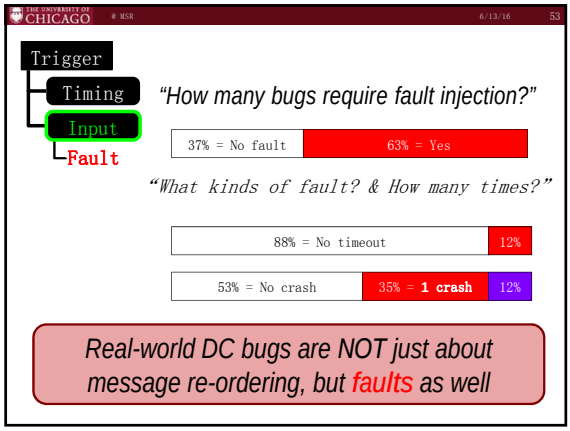
Ex: Cassandra-1011, Hbase-4729, MapReduce-5009, Zookeeper-1496

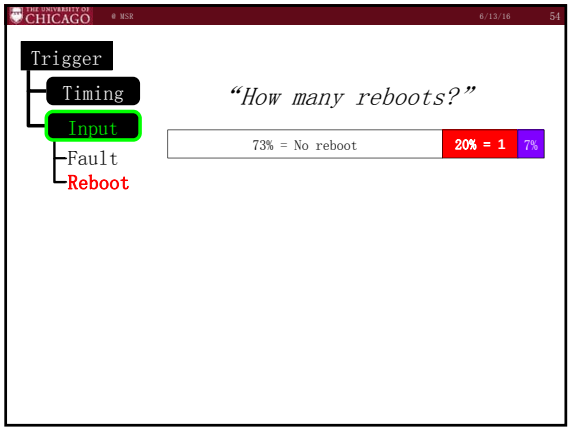

THE UNIVERSITY OF CHICAGO
@ MSR
6/13/16
49
Trigger
Timing
Message
Fault (21%)
A B
A B C
Fault at specific timing
No fault timing in LC bugs
Only in DC bugs
A B C
Ex: Cassandra-6415, Hbase-5806, MapReduce-3858, Zookeeper-1653

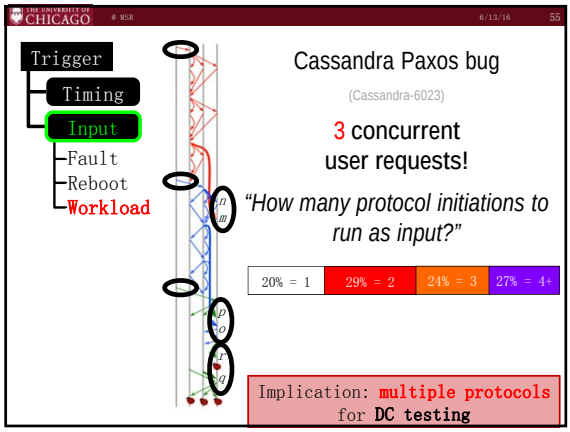

THE UNIVERSITY OF CHICAGO
@ MSR
6/13/16
50
Trigger
Timing
Message
Fault
Reboot (11%)
A B
Reboot at specific timing
A B
Ex: Cassandra-2083, Hadoop-3186, MapReduce-5489, Zookeeper-975

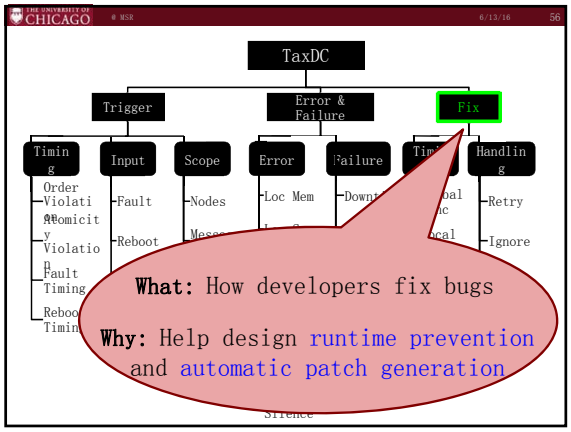

THE UNIVERSITY OF CHICAGO
@ MSR
6/13/16
51
Trigger
Timing
Implication: simple patterns can inform pattern-based bug detection tools, etc.
cmp
cmp
Message timing
Fault timing
Reboot

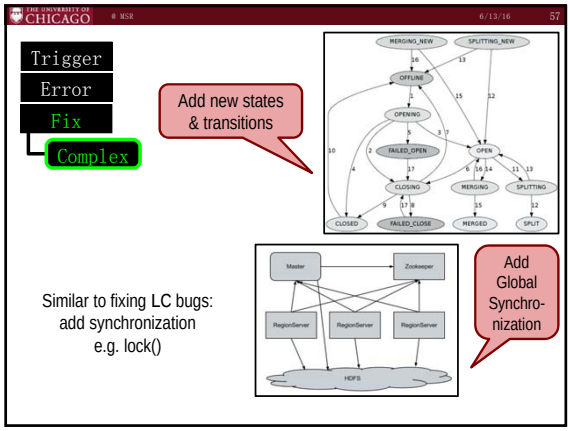

THE UNIVERSITY OF CHICAGO
@ MSR
6/13/16
52
TaxDC
Trigger
Error & Failure
Fix
Timing
Input
Scope
Error
Failure
Timing
Handling
Order Violation
Fault
Reboot
Workload
Fault Timing
Reboot Timing
Global
Retry
Ignore
Others
Miss
Silence
What: Input to exercise buggy code
Why: Improve testing coverage

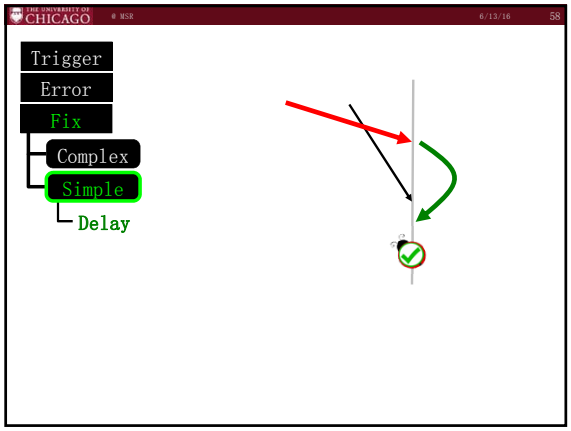

THE UNIVERSITY OF CHICAGO
@ MSR
6/13/16
53
Trigger
Timing
Input
Fault
"How many bugs require fault injection?"
37% = No fault
63% = Yes
"What kinds of fault? & How many times?"
88% = No timeout
12%
53% = No crash
35% = 1 crash
12%
Real-world DC bugs are NOT just about message re-ordering, but faults as well

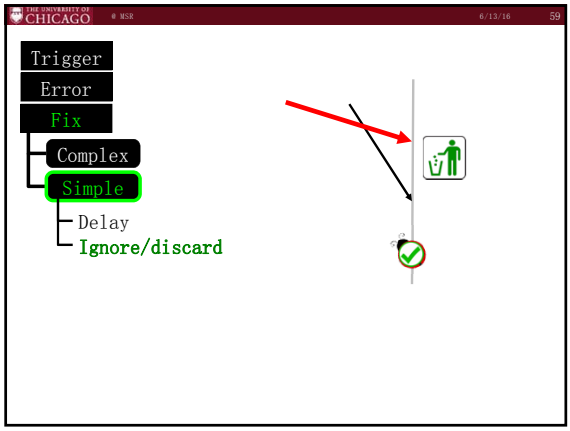

THE UNIVERSITY OF CHICAGO
@ MSR
6/13/16
54
Trigger
Timing
Input
Fault
Reboot
"How many reboots?"
73% = No reboot
20% = 1
7%

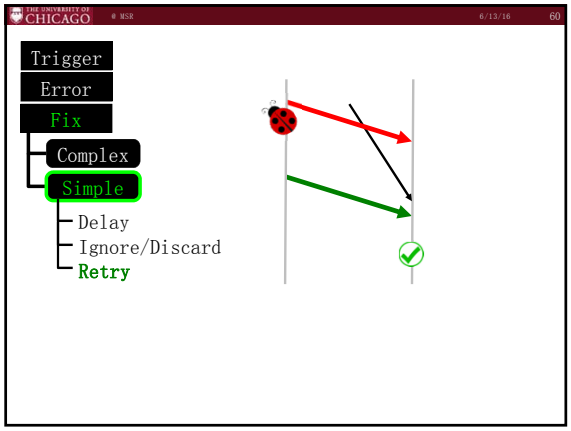

Trigger
Timing
Input
Fault
Reboot
Workload
Cassandra Paxos bug
(Cassandra-6023)
3 concurrent user requests!
"How many protocol initiations to run as input?"
20% = 1
29% = 2
24% = 3
27% = 4+
Implication: multiple protocols for DC testing


TaxDC
Trigger
Error & Failure
Fix
Input
Scope
Error
Handling
Fault
Reboot
Nodes
Loc Mem
Retry
Ignore
What: How developers fix bugs
Why: Help design runtime prevention and automatic patch generation

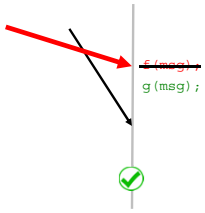

Trigger
Error
Fix
Complex
Add new states & transitions
Similar to fixing LC bugs: add synchronization e.g. lock()
Add Global Synchro-nization


Trigger
Error
Fix
Complex
Simple
Delay


Trigger
Error
Fix
Complex
Simple
Delay
Ignore/discard

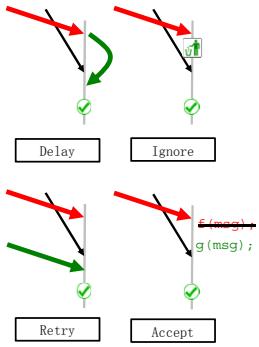

Trigger
Error
Fix
Complex
Simple
Delay
Ignore/Discard
Retry

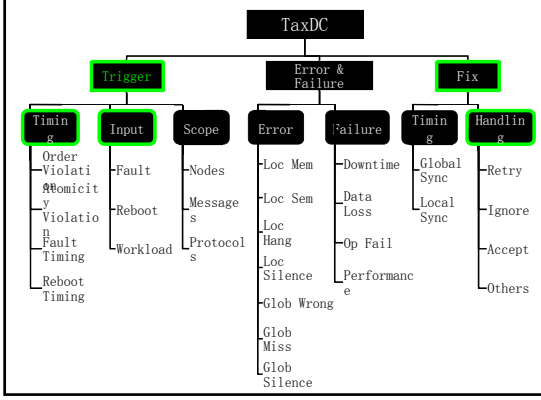
Trigger
Error
Fix
Complex
Simple
- Delay
- Ignore/Discard
- Retry
- Accept



Trigger
Error
Fix
Complex
Simple

40% are easy to fix
(***no*** *new computation logic*)





Challenges & Opportunities in …

- Distributed system model checker
- Formal verification
- DC bug detection
- Runtime prevention

Distributed System Model Checkers

Event	Modist *NSDI' 11*	Demeter *SOSP' 11*	MaceMC *NSDI' 07*	SAMC *OSDI' 14*	Reality
Message	✓	✓	✓	✓	✓
Crash	✓	✓	✓	✓	✓
Multiple crashes	✗	✗	✗	✓	✓
Reboot	✗	✗	✓	✓	✓
Multiple reboots	✗	✗	✗	✓	✓
Timeout	✓	✓	✓	✗	✓
Computation	✓	✓	✗	✗	✓
Disk fault	✗	✗	✗	✗	✓

Formal Verification

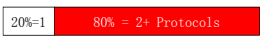
- State-of-the-art
  - Verdi *[PLDI '15]*
    - Raft update protocol
  - IronFleet *[SOSP '15]*
    - Paxos update protocol
    - Lease-based read/write

Only verify foreground protocols

- Challenges

Foreground & Background

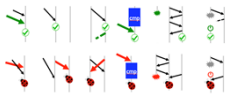
#Protocol interactions



Foreground & background

DC Bug Detection

- State-of-the-art: LC bug detection
  - Pattern-based detection
  - Error-based detection
  - Statistical bug detection
- Opportunities: DC bug detection?
  - Pattern-based detection

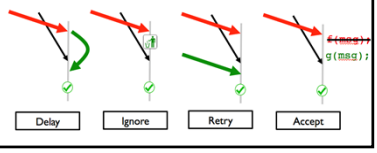


Runtime Failure Prevention

- State-of-the-art: LC bug prevention
  - Deadlock Immunity [*OSDI '08*]
  - Aviso [*ASPLOS '13*]
  - ConAir [*ASPLOS '13*]
  - *(many more)*
- Opportunities: DC bug prevention

Fixes

60% = Complex	40% = Simple



Dev's comments on DC bugs

- *"Do we have to rethink this entire [HBase] root and meta 'huh hah'? There isn't a week going by without some new bugs about races between splitting and assignment [distributed protocols]."* — *hbase4397*
- *"That is one monster of a race!"* — *mr3274*
- *"This has become quite messy, we didn't foresee some of this during design, sigh."* — *mr4819*
- *"Great catch, Sid! Apologies for missing the race condition"* — *mr4099*
- *"We have already found and fix many cases ... however it seems exist many other cases."* — *hb6147*

"New" classes of bugs …

- Distributed concurrency bugs
- Non-deterministic performance bugs
  - Limpware [SoCC '13]
  - Detect performance bugs [HotCloud '15]
  - Path-Based Spec. Exec. [In Subm.]
- Scalability bugs

A "limpware" anecdote

(limping hardware)

Limping NIC!

- *"… 1Gb NIC card on machine that suddenly only transmits at 1 kbps,*
- *this slow machine caused a chain reaction upstream*
- *in such a way that the 100 node cluster began to crawl at a snail's pace,*
- *making the system non-available for all practical purposes."* – Bo… Facebook

Cascading impact!

Limpware, really?

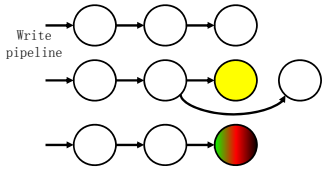
- *"In 2011, one of the DDN 9900 units had 4 servers having high wait times on I/O for a certain set of disk LUNs. The maximum wait time was 103 seconds. This was left uncorrected for 50 days."* – Kasick of CMU, Harms of Argonne
- *"The disk attempts to re-read each block multiple times before responding."* – Baptist of Cleversafe
- *"On Intrepid, we had a bad batch of optical transceivers with an extremely high error rate. That results in an effective throughput of 1-2 Kbps."* – Harms of Argonne
- Many others: ***"Yes, we've seen that in production"***

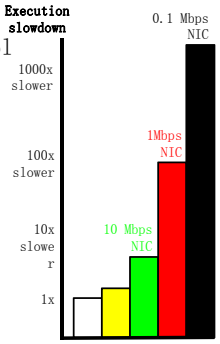
Limpware impacts?

- Modern distributed systems are …
  - … fault tolerant
  - … limpware tolerant?
- Limpware-injection experiments
  - Run HDFS, Hadoop, ZooKeeper, Cassandra, Hbase
  - Run load-intensive workload + inject limpware
    - E.g. slow a NIC to 1 Mbps, 0.1 Mbps, etc.

An example

- Run a distributed protocol
  - E.g., write pipeline in HDFS
- Measure slowdowns under:
  - No failure, crash, a limping NIC



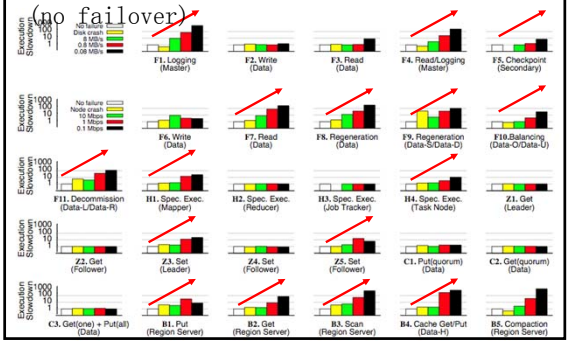


Benchmarks

	ID	Protocol	Limp-ware	Injected Node	Workload	Base Latency
HDFS	F1	Logging	Disk	Master	Create 8000 empty files	12
	F2	Write	Disk	Data	Create 30 64-MB files	182
	F3	Read	Disk	Data	Read 30 64-MB files	120
	F4	Metadata Read/Logging	Disk	Master	Stats 1000 files + heavy updates	9
	F5	Checkpoint	Disk	Secondary	Checkpoint 60K transactions	39
	F6	Write	Net	Data	Create 30 64-MB files	208
	F7	Read	Net	Data	Read 30 64-MB files	104
	F8	Regeneration	Net	Data	Regenerate 90 blocks	432
	F9	Regeneration	Net	Data-S/Data-D	Scale replication factor from 2 to 4	11
	F10	Balancing	Net	Data-O/Data-U	Move 3.47 GB of data	4105
	F11	Decommission	Net	Data-L/Data-R	Decommission a node having 90 blocks	174
Hadoop	H1	Speculative execution	Net	Mapper	WordCount: 512 MB dataset	80
	H2	Speculative execution	Net	Reducer	WordCount: 512 MB dataset	80
	H3	Speculative execution	Net	Job Tracker	WordCount: 512 MB dataset	80
	H4	Speculative execution	Net	Task Node	1000-task Facebook workload	4320
ZooKeeper	Z1	Get	Net	Leader	Get 7000 1-KB znodes	4
	Z2	Get	Net	Follower	Get 7000 1-KB znodes	5
	Z3	Set	Net	Leader	Set 7000 1-KB znodes	23
	Z4	Set	Net	Follower	Set 7000 1-KB znodes	26
	Z5	Set	Net	Follower	Set 20KB data 6000 times to 100 znodes	64
Cassandra	C1	Put (quorum)	Net	Data	Put 240K KeyValues	66
	C2	Get (quorum)	Net	Data	Get 45K KeyValues	73
	C3	Get (one) + Put (all)	Net	Data	Get 45K KeyValues + heavy puts	36
HBase	B1	Put	Net	Region Server	Put 300K KeyValues	61
	B2	Get	Net	Region Server	Get 300K KeyValues	151
	B3	Scan	Net	Region Server	Scan 300K KeyValues	17
	B4	Cache Get/Put	Net	Data-H	Get 100 KeyValues + heavy puts	4
	B5	Compaction	Net	Region Server	Compact 4 100-MB sstables	122

Fail-stop tolerant, but not limpware tolerant

(no failover)



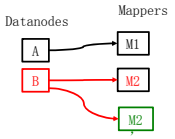
(The root causes are in Limpware paper [SOCC '13]; this talk focuses on Hadoop MapReduce)

Hadoop MapReduce

- Supposedly tail tolerant
- Why **not** limpware tolerant?
- Why Speculative Execution fails?

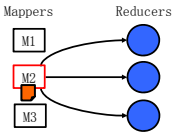
Loophole #1

- Backup task reads from the same slow datanode
  - Hadoop and HDFS don't cooperate
  - No history of bad "paths"



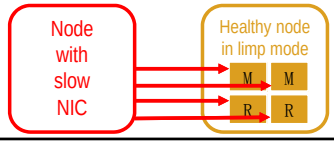
Loophole #2

- All reducers fetch from a mapper with a slow NIC
  - All reducers slow → no straggler
  - M2 reads data locally (not slow)
- *(many other loopholes in the paper)*



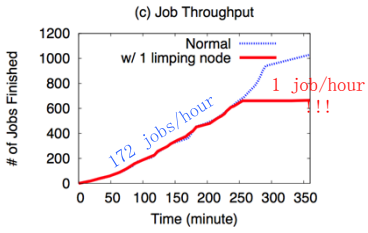
Cascading failures

- A limping NIC → limping tasks
  - (Limping tasks are slower by orders of magnitude)
- Limping tasks use up slots → limping node
  - If all slots are used → node is "unavailable"
- All nodes in limp mode → limping cluster



Cluster collapse

- Macrobenchmark: Facebook Hadoop workload
  - **30-node cluster**
  - One node w/ limping NIC (0.1 Mbps)



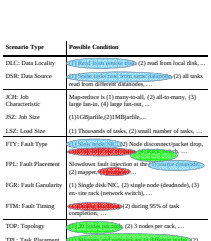
Formalizing the problem

- A job = **various** deployment scenarios
- Untriggered speculative execution
  - (DSR_1 & FTY_1 & FPL_1 & DLC_1) or
  - (JCH_1 & TPL_1 & FTY_1 & FPL_2) or …

Unanticipated scenario

Scenario Type	Possible Conditions
DLC: Data Locality	(1) Read from remote disk, (2) read from local disk, …
DSR: Data Source	(1) Some tasks read from same datanode, (2) all tasks read from different datanodes, …
JCH: Job Characteristic	Map-reduce is (1) many-to-all, (2) all-to-many, (3) large fan-in, (4) large fan-out, …
JSZ: Job Size	(1) 1 GB jar file, (2) 1 MB jar file, …
LSZ: Load Size	(1) Thousands of tasks, (2) small number of tasks, …
FTY: Fault Type	(1) Slow disk/NIC, (2) Node disconnect/packet drop, (3) Disk error/out of space, (4) Rack switch, …
FPL: Fault Placement	Slowdown fault injection at the (1) source datanode, (2) mapper, (3) reducer, …
FGR: Fault Granularity	(1) Single disk/NIC, (2) single node (deadnode), (3) entire rack (network switch), …
FTM: Fault Timing	(1) During shuffling, (2) during 95% of task completion, …
TOP: Topology Scenario	(1) 30 nodes per rack, (2) 3 nodes per rack, …
TPL: Task Placement	(1) Mappers and reducers are in different nodes, (2) AM and reducers in different nodes, (3) Mappers are in the same node, (4) Most of reducers placed in the same rack

Non-deterministic performance bugs



- Untriggered Speculative Execution
  - MR-7001 = JCH_1 & TPL_1 & FPL_2 & FTY_1
  - MR-7002 = DSR_1 & DLC_1 & FPL_1 & FTY_1
  - MR-5533 = FTY_2 & FPL_3 & TPL_3
  - …
- O(n) Recovery
  - MR-5251 = FTY_3 & FPL_3 & FTM_1
  - MR-5043 = TPL_1 & TPL_3 & FTY_1 & FPL_2
  - MR-1800 = TPL_1 & TPL_4 & FTY_4 & TOP_1
  - …
- Long lock contention
  - MR-9141 = FTY_3 & FPL_3 & FTM_1
  - MR-9292 = TPL_1 & TPL_3 & FTY_1 & FPL_2
  - MR-9393 = TPL_1 & TPL_4 & FTY_4 & TOP_1
  - …

Perf. Model Checking [HotCloud '15]

- **Goal**: Permute many topological/failure/placement scenarios
- Real Java code → Colored Petri Nets (CPN) model
  - Automated conversion ("compiler")
  - Abstract system-level constructs
    - E.g., queues, tasks, resources, locks
- Permute the scenarios in CPN
- Abstract performance faults
  - Boolean result: limping or not
  - No need for precise latency/bandwidth predictions
- Test the buggy scenarios in real runs

Path Based Spec. Exec. [In Subm.]

- Hadoop SE:
  - **Straggler**: if task **T**'s progress is **slower** than the rest
  - Task T is just a progress score → fundamental flaw
- Our observation:
  - Task T is a **path**
  - **Map path**: source datanode → map node
  - **Shuffle path**: map node → reduce node
  - **Output path**: reduce node → pipeline of datanodes
- **PBSE**: Path-based speculative execution
  - It's about the progress of individual "paths"
  - SE algorithm is based on path progress
  - Diverse paths: no single point of path failure

Conclusion

- Distributed concurrency bugs
- Non-deterministic performance bugs
- Scalability bugs
- Other outage-causing bugs:
  - SPOF/cascading bugs
  - Cross-layer upgrade bugs

The complexity of cloud-scale hardware and software ecosystem has outpaced existing testing, debugging, and verification tools.

Many new classes of bugs to hunt!

Thank you! Questions?

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CERES Center for Unstoppable Computing

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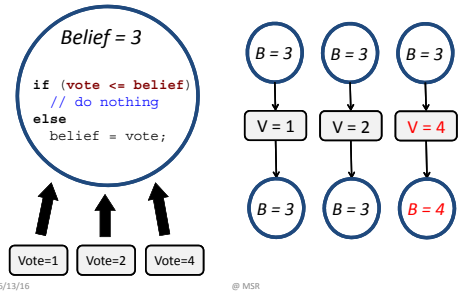
EXTRA

Extra -- SAMC

Message Processing Semantic in a Leader Election



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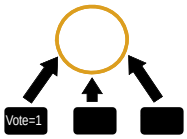
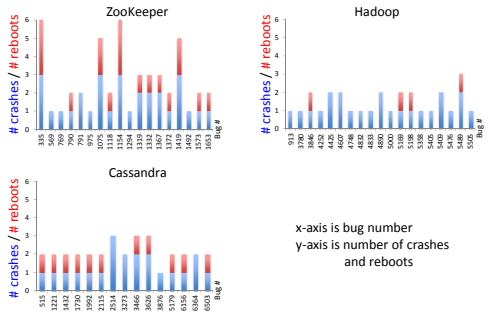
SAMC server logic (extra)



vote	belief	isDiscard
1	3	true
2	3	true
4	3	false

m_x	m_y	discard(m_x)	discard(m_y)	Independent
1	2	true	true	✔
1	4	true	false	x
2	4	true	false	x

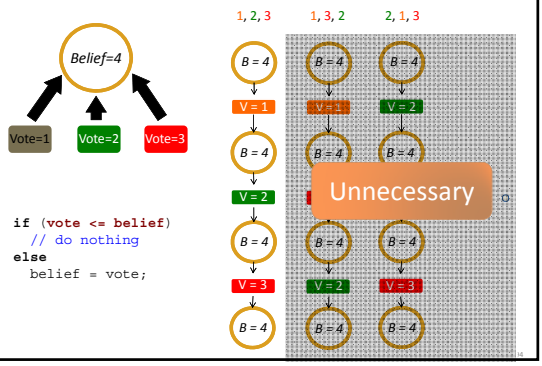
+ Crashes and Reboots (sometimes multiple of them)



x-axis is bug number
y-axis is number of crashes and reboots

6/13/16 @ MSR 92

Checking Re-orderings via Message Processing Semantic




```
if (vote <= belief)
  // do nothing
else
  belief = vote;
```

Errors, Faults, Failure

- To quote the Software Engineering Body of Knowledge
- Different cultures and standards may use somewhat different meanings for these terms, which have led to attempts to define them.
- Partial definitions taken from standard (IEEE610.12-90) are:
- Error: “A difference…between a computed result and the correct result”
- Fault: “An incorrect step, process, or data definition in a computer program”
- Failure: “The [incorrect] result of a fault”
- Mistake: “A human action that produces an incorrect result”

6/13/16 @ MSR 95