Optimistic Concurrency Control in a Distributed NameNode Architecture for Hadoop Distributed File System

Qi Qi

Instituto Superior Técnico - IST (Portugal)
Royal Institute of Technology - KTH (Sweden)
Swedish Institute of Computer Science - SICS (Sweden)

qiq@kth.se

8 October 2014

Motivation

Industrial Standard in Big Data Era

Apache Hadoop Ecosystem

Limits to growth in HDFS

Number of Files	**Memory Requirement**	**Physical Storage**
1 million	0.6 GB	0.6 PB
100 million	**60 GB**	**60 PB**
1 billion	600 GB	600 PB

Hops-HDFS and Its Limitation

Distributed NameNode Architecture
Maintain HDFS Strong Consistency Semantics
Concurrency Restricted

Problem Statement

HDFS

System-level Lock: Single Writer

MySQL Cluster

Read Committed Isolation Level: Anomalies

Hops-HDFS v1

System-level Lock: Single Writer + Network Latency

Hops-HDFS v2 (Pessimistic Concurrency Control - PCC)

Row-level Lock: Implicit Locking ->Single Writer + Network Latency

Contribution

Architecture and Namespace Concurrency Control Accessment

GFS, HDFS, Hops-HDFS

Performance Accessment and Limitation Analysis

HDFS v.s. Hops-HDFS v2 (PCC version)

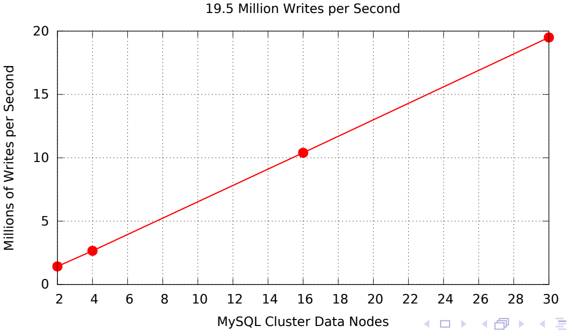
Solution for Hops-HDFS

- Optimistic Concurrency Control with Snapshot Isolation on Semantic Related Group
- Performance Increase Up to 70 %
- Correctness ensured by Passing 300+ Apache HDFS Unit Tests: maintain HDFS semantics

MySQL Cluster

Distributed, In-memory, Replicated Database

- Scalable
- Fault-tolerance
- High throughput
- **BUT**: Supports only **Read Committed** Isolation Level



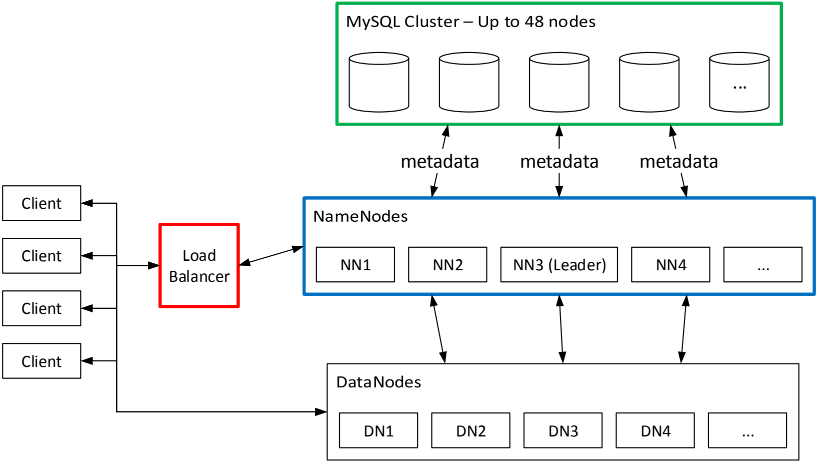
Hops [1]-HDFS

Overcome Limitations in HDFS NameNode

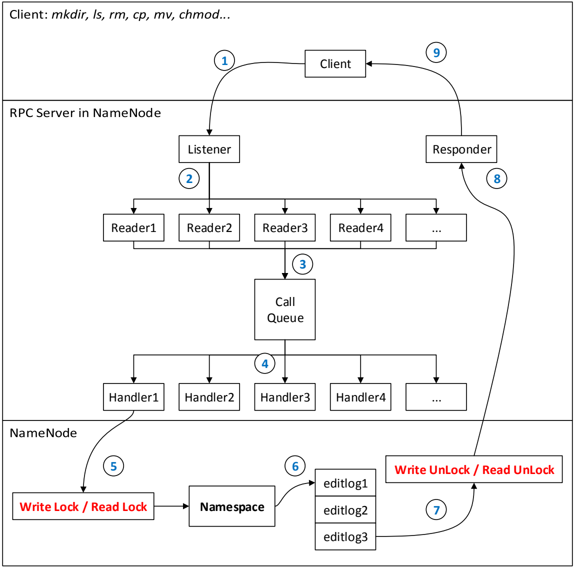
- Scalability of the Namespace
- Throughput Problem
- Failure Recovery

[1] Hadoop Open Platform-as-a-Service

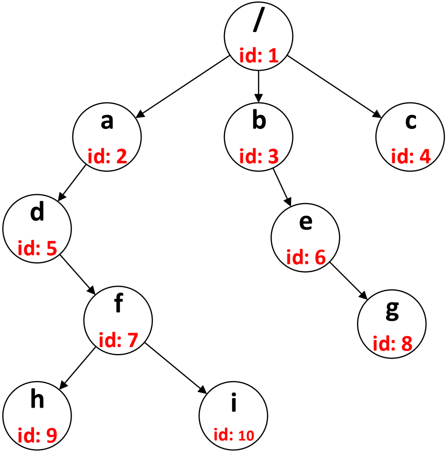
Hops-HDFS Architecture



HDFS Namespace Concurrency Control Assessment



Hops-HDFS Namespace Structure



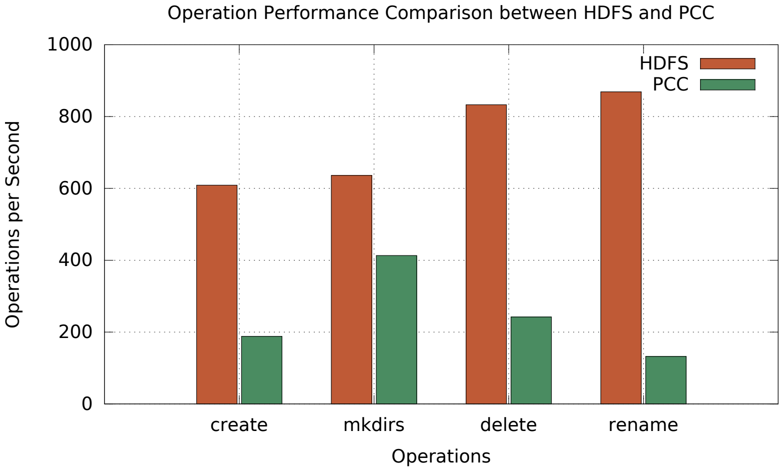
id	parent_id	name
1	0	/
2	1	a
3	1	b
4	1	c
5	2	d
6	3	e
7	5	f
8	6	g
9	7	h
10	7	i

Limitations in Hops-HDFS Namespace Concurrency Control (PCC)

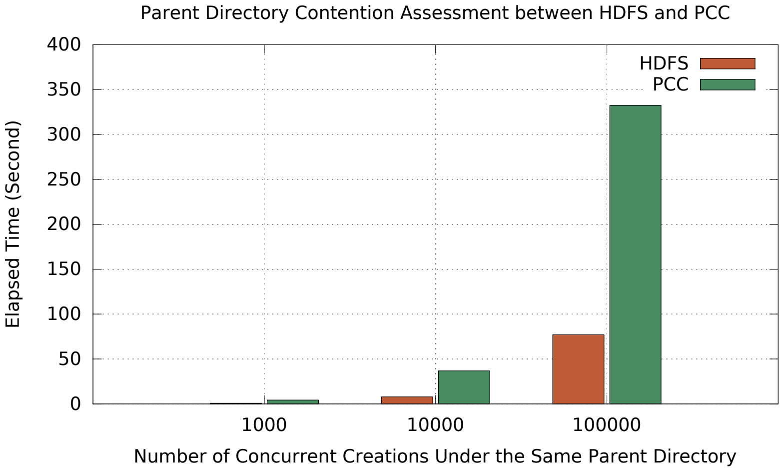
- Duplicated Round Trips
- Implicit Parent Locks:

id	parent_id	name	Locks by Tx1	Locks by Tx2
1	0	/	R	R
2	1	a	R	R
3	1	b		
4	1	c		
5	2	d	R	R
6	3	e		
7	5	f	W	W **(Block)**
8	6	g		
9	7	h (Tx1)	W (Implicit)	W (Implicit) **(Block)**
10	7	i (Tx2)	W (Implicit)	W (Implicit) **(Block)**

NameNode Throughput Benchmark - HDFS v.s. PCC



Parent Directory Contention Assessment - HDFS v.s. PCC



Resolving the Semantic Related Group

Path: /a/d/f/h

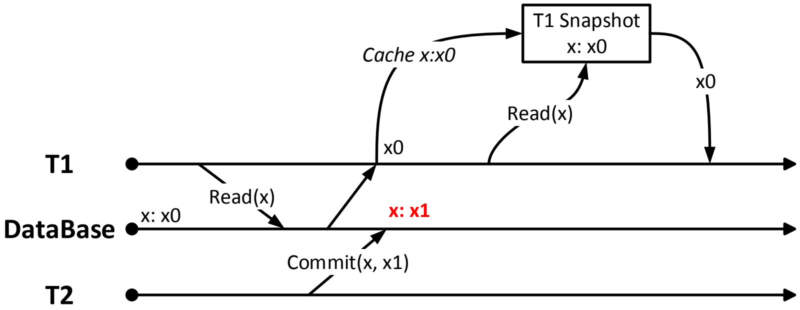
h: {/->a->d->f}

	id	parent_id	name	other parameters...
Related *	1	0	/	...
Related *	2	1	a	...
	3	1	b	...
	4	1	c	...
Related *	5	2	d	...
	6	3	e	...
Related *	7	5	f	...
	8	6	g	...
Selected ✓	9	7	h	...
	10	7	i	...

Per-Transaction Snapshot Isolation

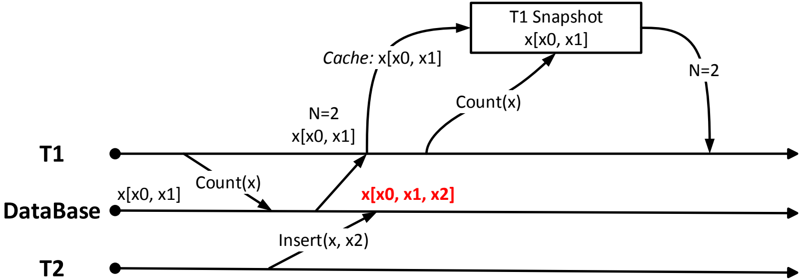
- Snapshot the whole Semantic Related Group
- Transaction performs on its own snapshot
- Preclude: **Fuzzy Read** & **Phantom Read**

Snapshot Isolation Precludes **Fuzzy Read** [2]



[2]Fuzzy Read: A transaction rereads data it has previously read and finds that another committed transaction has modified or deleted the data.

Snapshot Isolation with Semantic Related Group Precludes Phantom Read [3]



[3] Phantom Read: A transaction re-executes a query returning a set of rows that satisfies a search condition and finds that another committed transaction has inserted additional rows that satisfy the condition.

Lock Mode in MySQL Cluster

Read_Committed [4] Lock Mode: Consistent nonlocking reads (based on MVCC)

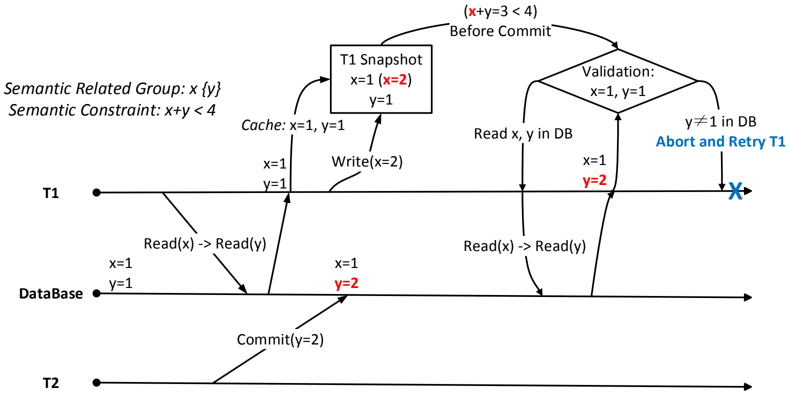
Lock Mode	Shared	Exclusive	Read_Committed
Shared	✓	Block	✓
Exclusive	Block	Block	✓
Read_Committed	✓	✓	✓

[4] Read_Committed here is the name of *lock mode* used in MySQL Cluster, not referring to *Isolation Level*

Optimistic Concurrency Control

- Read Phase: **Read_Committed** lock on snapshot
- Validation Phase: **Shared** lock on related Rows, **Exclusive** lock on modified rows ->Compare versions with snapshot ->Abort & Retry or Update
- Preclude: **Write Skew**

OCC with Snapshot Isolation on Semantic Related Group Precludes **Write Skew** [5]



[5]Write Skew: Two concurrent transactions read the same data, but update different data that are related and the combination of updates leads to an inconsistency.

Total Order Update, Abort & Retry, and Version Increase

- Total order update by *ids* ->preclude lock cycles
- Abort and retry transactions if "new" rows already exist
- Increase versions for successful *update phase*

Four Phases in Algorithm

- **Read Phase**: resolve semantic related group & cache it as transactions snapshot copy
- **Execution Phase**: transactions operate on its own snapshot
- **Validation Phase**: validate snapshot versions with values in database ->abort & retry or go to update
- **Update Phase**: total order update, abort & retry and version increase

Experimental Testbed

MySQL Cluster

6 data nodes, 1 Gbps LAN, Intel Xeon X5660 CPU @ 2.80GHz, 6*6=36 GB RAM, 2 data replicas

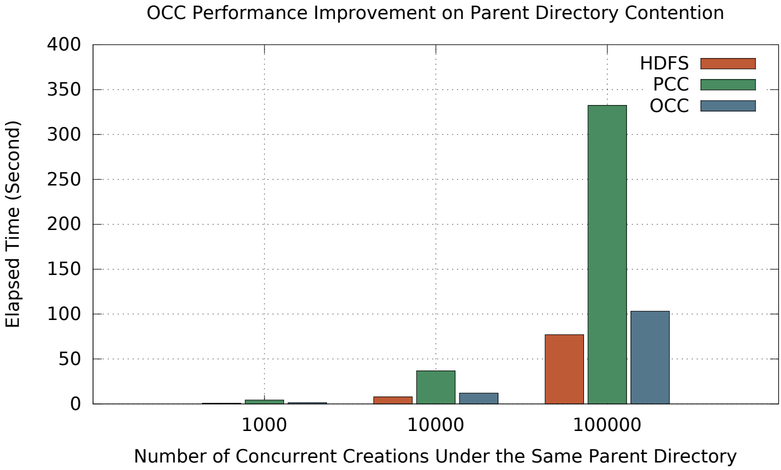
NameNode and Clients

Intel i7-4770T CPU @ 2.50GHz and 16 GB RAM

MySQL Cluster and NameNode

100 Mbps LAN

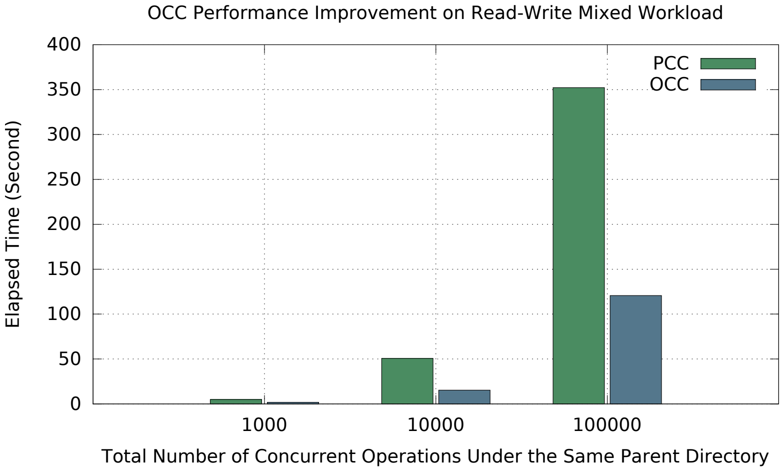
Parent Directory Contention Assessment (1/2)



Parent Directory Contention Assessment (2/2)

Num. of Concurrent Creation	**1000**	**10000**	**100000**
HDFS	0.82s	7.83s	77.13s
PCC	4.35s	36.74s	332.36s
OCC	1.36s	12.01s	103.23s
PCC / HDFS	530.5%	469.2%	430.9%
OCC / HDFS	165.9%	153.4%	133.8%
OCC Improvement: (PCC-OCC) / PCC	**68.7%**	**67.3%**	**68.9%**

Read-Write Mixed Workload (1/2)



Read-Write Mixed Workload (2/2)

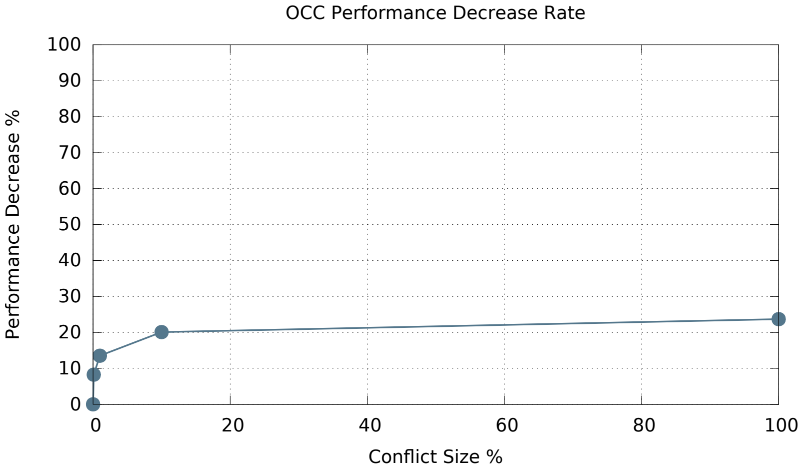
Concurrent Read+Creation	**1000**	**10000**	**100000**
PCC	4.92s	50.69s	352.25s
OCC	1.78s	15.31s	120.64s
OCC Improvement: (PCC-OCC) / PCC	**63.8%**	**69.8%**	**65.8%**

OCC Performance with Different Size of Conflicts (1/2)

Performance Decrease compares to *0% conflict size*

Creations for 10000 Operations	Conflict Size	Elapsed Time (Second)	Performance Decrease
1	100%	14.53	23.7%
10	10%	14.11	20.1%
100	1%	13.51	15.0%
1000	0.1%	12.72	8.23%
10000	0%	11.75	0%

OCC Performance Decrease Rate (2/2)



Implementation Correctness Assessment

Ensured by passing 300+ Apache HDFS Unit Tests

Conclusion & Future Work

Conclusion

- Increase Performance up to 70 %
- Bounded Performance Degradation for OCC conflict
- Maintain HDFS Strong Consistency Semantics

Future Work

- OCC implementation on other operations
- OCC evaluation on Hops-HDFS with multiple NameNodes: prove that it outperforms HDFS with single NameNode

Thank you!

Isolation Level

Berenson, Hal, et al. "A Critique of ANSI SQL Isolation Levels." ACM SIGMOD Record 24.2 (1995): 1-10.

Isolation Level	**Lost Update**	**Fuzzy Read**	**Phantom**	**Read Skew**	**Write Skew**
Read Uncommitted	✓	✓	✓	✓	✓
Read Committed	✓	✓	✓	✓	✓
Cursor Stability	sometimes	sometimes	✓	✓	sometimes
Repeatable Read	X	X	✓	X	X
Snapshot	X	X	sometimes	X	✓
Serializable	X	X	X	X	X

GFS Namespace Concurrency Control (1/3)

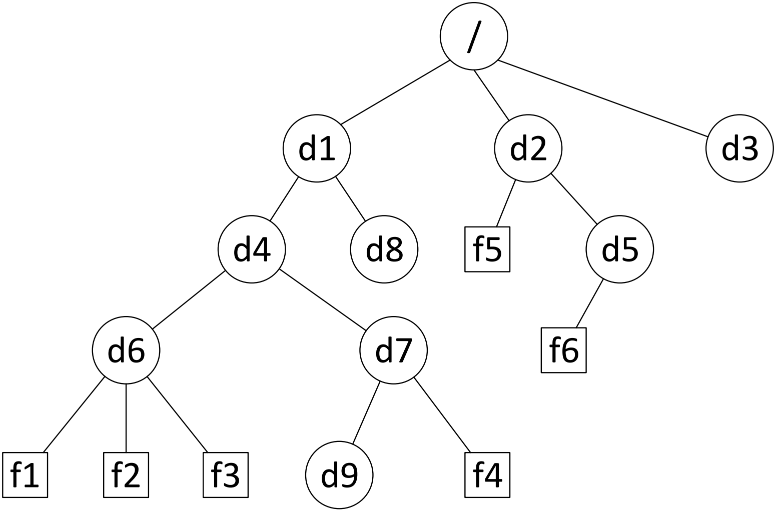


Figure : A Graphical Tree Representation for the Namespace in GFS

GFS Namespace Concurrency Control (2/3)

Total Order Locks	Op1	Op2	Op3	Op4	Op5
/	Read1	Read2	Read3	Read4	Read5
/d1	Read1	Read2	Read3	Read4	Read5
/d1/d4	Read1	Read2	Read3	Read4	Read5
/d1/d4/d6	Read1	Read2	Read3		
/d1/d4/d7				Read4	Read5
/d1/d4/d6/f1	Write1				
/d1/d4/d6/f2		Write2			
/d1/d4/d6/f3			Write3		
/d1/d4/d7/d9				Write4	
/d1/d4/d7/f4					Write5

Table : Concurrent Mutations for different files/directories and Related Read-Write Lock Sets

GFS Namespace Concurrency Control (3/3)

Total Order Locks	**Operation1**	**Operation2**
/	Read1	Read2
/**d1**	Read1	Read2
/**d3**	Read1	
/d1/**d8**	Write1	Read2 **(Conflicts: Write1)**
/d3/**d8**	Write1	
/d1/d8/**Qi.txt**		Write2

Table : Serialized Concurrent Mutations and Conflict Locks

The Size of Semantic Related Group

1. HDFS limits number of levels and length of full path name
2. 100 concurrent operations running under same parent directory: