Data-centric Programming for Distributed Systems

Chp2&3.2

by Peter Alvaro, 2015

presenter: Irene (Ying) Yu
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Outline

- Disorderly programming
- Overview for overlog
- Implementation in protocols (two-phase commit)
- Large-scale storage system (BOOM-FS)
- Revison for the implementation
- CALM Theroem
- Future work

Disorderly programming

- Hypothesis:
  - challenges of programming distributed systems arise from the mismatch between the sequential model of computation in which programs are specified as an ordered list of operations to perform
- What is disorderly programming
  - extends the declarative programming paradigm with a minimal set of ordering constructs

Why distributed programming is hard

The challenges of distributed programming systems

- concurrency
- asynchrony
- performance variability
- partial failure

asynchrony: uncertainty about the ordering and the timing

partial failure: some of computing components may fail to run, while others keep running without an outcome

Motivation

Problem

- All programmers must learn to be distributed programmers.
- Few tools exist to assist application programmers

- ❖ make distributed systems easier to program and reason about
- ❖ transform the difficult problem of distributed programming into problem of data-parallel querying
- ❖ design a new class of "disorderly" programming languages
  - ➢ concise expression of common distributed systems patterns
  - ➢ capture uncertainty in their semantics

Disorderly programming language

- encourages programmers to underspecify order(try to relax the dependence for order.)
- make it easy (and natural) to express safe and scalable computations
- extend the declarative programming paradigm with a minimal set of ordering constructs.

Background-Overlog

1.recursive query language extended from Datalog

2.combine data-centric design with declarative programming

head(A, C) :- clause1(A, B), clause2(B, C);

recv_msg(@A, Payload) :-
send_msg(@B, Payload), peers(@B, A);

least_msg(min<SeqNum>) :-
queued_msgs(SeqNum, _);

next_msg(Payload) :-
queued_msgs(SeqNum,
Payload),
least_msg(SeqNum);

→

SELECT payload FROM
queued_msgs
WHERE seqnum =
(SELECT min(seqnum) FROM
queued_msgs);

Features

add notation to specify the data location

provide some SQL like extensions such as primary keys and aggregation.

define a model for processing and generate changes to tables.

Implementation-Consensus protocols

Difficulty: high-level → low-level

- increase program size
- increase complexity

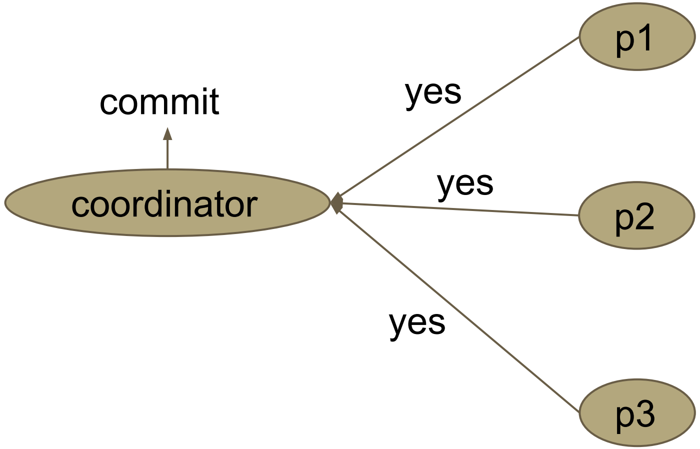
2PC(two-phase commit)

Paxos

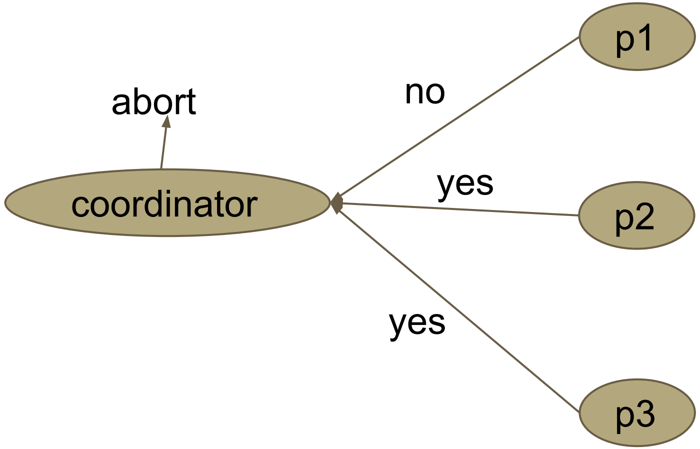
specifed in the literature in a high level:

messages, invariants, and state machine transitions.

2PC implementation



2PC implementation



Two-phase commit

```
/* Count number of peers */
peer_cnt(Coordinator, count<Peer>) :-
  peers(Coordinator, Peer);

/* Count number of "yes" votes */
yes_cnt(Coordinator, TxnId, count<Peer>) :-
  vote(Coordinator, TxnId, Peer, Vote),
  Vote == "yes";

/* Prepare => Commit if unanimous */
transaction(Coordinator, TxnId, "commit") :-
  peer_cnt(Coordinator, NumPeers),
  yes_cnt(Coordinator, TxnId, NumYes),
  transaction(Coordinator, TxnId, State),
  NumPeers == NumYes, State == "prepare";

/* Prepare => Abort if any "no" votes */
transaction(Coordinator, TxnId, "abort") :-
  vote(Coordinator, TxnId, _, Vote),
  transaction(Coordinator, TxnId, State),
  Vote == "no", State == "prepare";

/* All peers know transaction state */
transaction(@Peer, TxnId, State) :-
  peers(@Coordinator, Peer),
  transaction(@Coordinator, TxnId, State);
```

multicast

“commit” or “abort”

NOT attempt to make progress in the face of node failures.

High level constructs(idioms) :

- multicast(join)
- sequence

Timer

```
/* Declare a timer that fires once per second */
timer(ticker, 1000ms);

/* Start counter when TxnId is in "prepare" state */
tick(Coordinator, TxnId, Count) :-
  transaction(Coordinator, TxnId, State),
  State == "prepare",
  Count := 0;

/* Increment counter every second */
tick(Coordinator, TxnId, NewCount) :-
  ticker(),
  tick(Coordinator, TxnId, Count),
  NewCount := Count + 1;

/* If not committed after 10 sec, abort TxnId */
transaction(Coordinator, TxnId, "abort") :-
  tick(Coordinator, TxnId, Count),
  transaction(Coordinator, TxnId, State),
  Count > 10, State == "prepare";
```

sequence

2 details for the impl:

- **timeouts**
- **persistence**

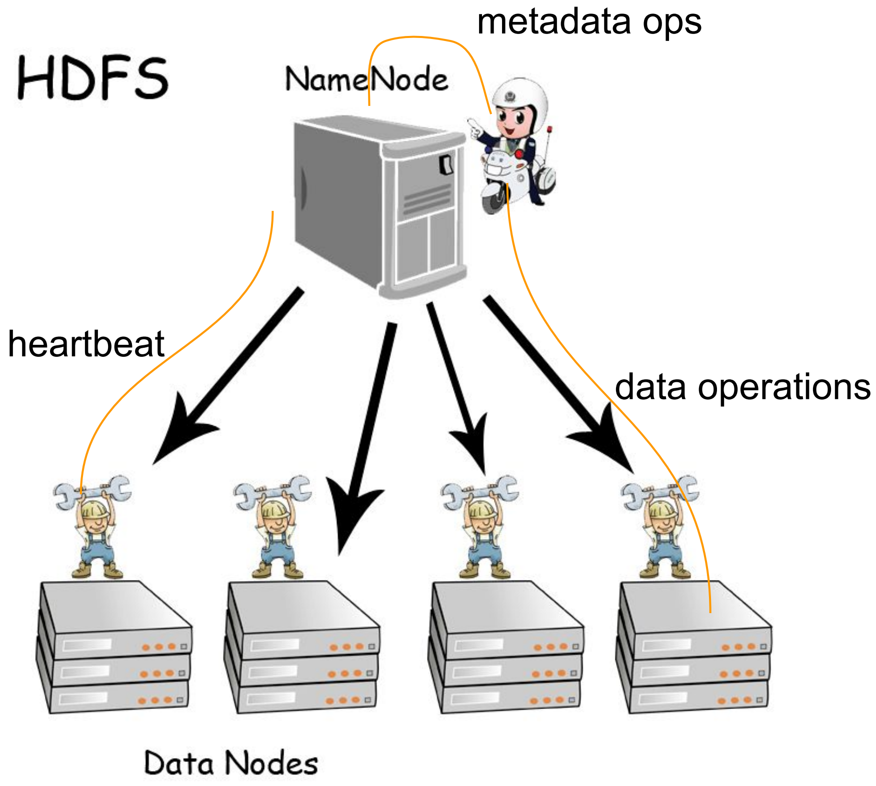
coordinator will choose to abort if response of peers takes too long

BOOM-FS(Berkeley Order of Magnitude)

An API-compliant reimplementation of the HDFS (Hadoop distributed file system) using overlog in internals

- high availability master nodes (via an implementation of MultiPaxos in Overlog)
- scale-out of master nodes to multiple machines (via simple data partitioning)
- unique reflection-based monitoring and debugging facilities (via metaprogramming in Overlog)

Working of HDFS



relations in file system

- represent the file system metadata as a collection of relations.
- query over this schema

Name	*Description*	*Relevant attributes*
file	Files	fileid, parentfileid, name, isDir
fqpath	Fully-qualified pathnames	path, fileid
fchunk	Chunks per file	chunkid, fileid
datanode	DataNode heartbeats	nodeAddr, lastHeartbeatTime
hb_chunk	Chunk heartbeats	nodeAddr, chunkid, length

Table 2.2: BOOM-FS relations defining file system metadata.

eg. derive fqpath from file

```
// fqpath: Fully-qualified paths.
// Base case: root directory has null parent
fqpath(Path, FileId) :-
    file(FileId, FParentId, _, true),
    FParentId = null, Path = "/";

fqpath(Path, FileId) :-
    file(FileId, FParentId, FName, _),
    fqpath(ParentPath, FParentId),
    // Do not add extra slash if parent is root dir
    PathSep = (ParentPath = "/" ? "" : "/"),
    Path = ParentPath + PathSep + FName;
```

Listing 2.6: Example Overlog for computing fully-qualified pathnames from the base file system metadata in BOOM-FS.

- a recursive query language like Overlog was a natural fit for expressing file system policy.

protocols in BOOM-FS

- **metadata protocol**

  clients and NameNodes use it to exchange file metadata

- **heartbeat protocol**

  DataNodes use it to notify the NameNode

- **data protocol**

  clients and DataNodes use it to exchange chunks.

metadata protocol

```
// The set of nodes holding each chunk
compute_chunk_locs(ChunkId, set<NodeAddr>) :-
    hb_chunk(NodeAddr, ChunkId, _);

// Chunk exists => return success and set of nodes
response(@Src, RequestId, true, NodeSet) :-
    request(@Master, RequestId, Src,
            "ChunkLocations", ChunkId),
    compute_chunk_locs(ChunkId, NodeSet);

// Chunk does not exist => return failure
response(@Src, RequestId, false, null) :-
    request(@Master, RequestId, Src,
            "ChunkLocations", ChunkId),
    notin hb_chunk(_, ChunkId, _);
```

Listing 2.7 return the set of DataNodes that hold a given chunk in BOOM-FS

namenode rules

- specify the result tuple should be stored at client
- handle errors and return failure message

Evaluation

System	*Lines of Java*	*Lines of Overlog*
HDFS	21,700	0
BOOM-FS	1,431	469

Table 2.3: Code size of two file system implementations

- similar performance, scaling and failure-handling properties to those of HDFS
- can tolerate DataNode failures but has a single point of failure and scalability bottleneck at the NameNode.
- consists of simple message handling and management of the hierarchical file system namespace.

Validation for the performance

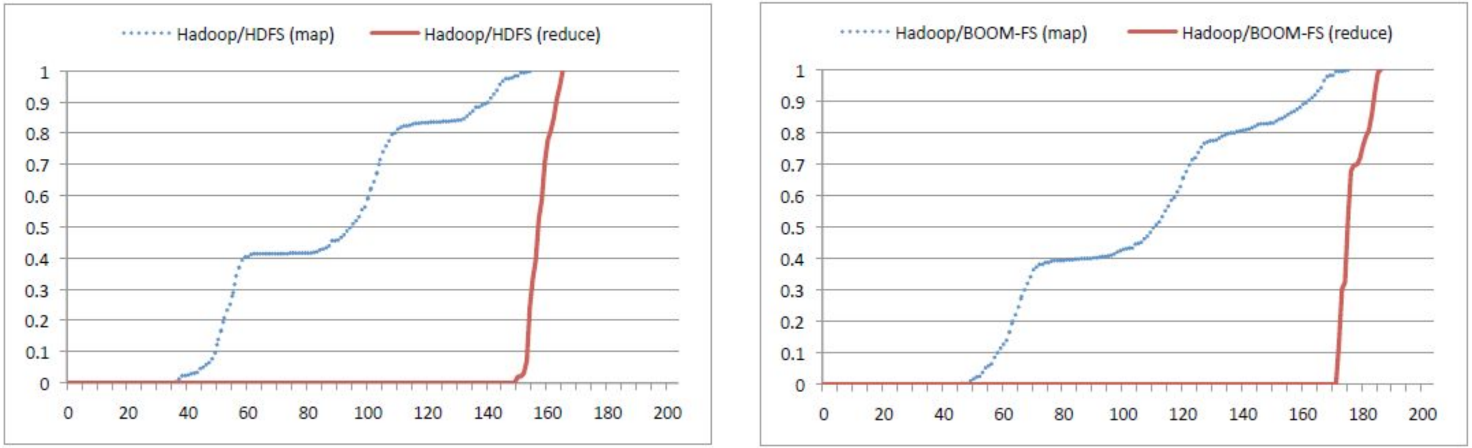


Figure 2.2: CDFs representing the elapsed time between job startup and task completion for both map and reduce tasks.

conclusion：BOOM-FS performance is slightly worse than HDFS, but remains very competitive

Revision

- Availability
- Scalability
- Monitoring

Availability Rev

Goal: retrofitting BOOM-FS with high availability failover

- Implemented using a globally-consistent distributed log represented using Paxos
  - Guarantees a consistently ordered sequence of events over state replicas
  - Supports replication of distributed filesystem metadata
- All state-altering events are represented in BOOM_FS as Paxos Decrees
  - Passed into Paxos as a single Overlog rule
  - Stores tentative actions in intermediate table (actions not yet complete)
- Actions are considered complete when they are visible in a table join with the local Paxos log
  - Local Paxos log contains completed actions
  - Maintains globally accepted ordering of actions

Availability Rev - Validation

Number of NameNodes	Failure Condition	Avg. Completion Time (secs)	Standard Deviation
1	None	101.89	12.12
3	None	102.70	9.53
3	Backup	100.10	9.94
3	Primary	148.47	13.94

Table 2.4: Job completion times with a single NameNode, 3 Paxos-enabled NameNodes, backup NameNode failure, and primary NameNode failure

- Criteria
  - Paxos operation according to specs at fine grained level
  - Evaluate high availability by triggering master failures

- What is the impact of the consensus protocol on system performance?
- What is the effect of failures on completion time?
- how the implementation will perform when the matser fails?

Scalability Rev

NameNode is scalable across multiple NameNode-partitions.

- adding a "partition" column to the Overlog tables containing NameNode state
- use a simple strategy based on the hash of the fully qualified pathname of each file
- modified the client library
- No support atomic "move" or "rename" across partitions

Monitoring and Debugging Rev

Singh et al. idea: Overlog queries can monitor complex protocols

- convert distributed overlog rules into global invariants
- added a relation called *die to JOL*
  - *java event listener is triggered when tuples are inserted into die relation*
  - *body: overlog rule with invariant check*
  - *head: die relation*

increase the size of a program VS improve readability and reliability.

Monitoring via Metaprogramming

- replicate the body of each rule in an Overlog program
- send its output to a log table

```
quorum(@Master, Round) :-
priestCnt(@Master, Pcnt),
lastPromiseCnt(@Master, Round, Vcnt),
Vcnt > (Pcnt / 2);
```

eg. the Paxos rule that tests whether a particular round of voting has reached quorum:

→

```
trace_r1(@Master, Round, RuleHead, Tstamp) :-
priestCnt(@Master, Pcnt),
lastPromiseCnt(@Master, Round, Vcnt),
Vcnt > (Pcnt / 2),
RuleHead = "quorum",
Tstamp = System.currentTimeMillis();
```

CALM Theorem

Consistency And Logical Monotonicity (CALM).

- logically monotonic distributed code is *eventually consistent* without any need for coordination protocols (distributed locks, two-phase commit, paxos, etc.)

- eventual consistency can be *guaranteed* in any program by protecting non-monotonic statements (“points of order”) with coordination protocols.

Monotonic logic:

As input set grows, output set does not shrink

"Mistake-free"

Order independent

Expressive but sometimes awkward

e.g., selection, projection and join

Non-Monotonic Logic

New inputs might invalidate previous outputs

Requires coordination

Order sensitive

e.g., aggregation, negation

Monotonic programs are therefore easy to distribute and can tolerate message reordering and delays

Minimize Coordination

When must we coordinate?

- In cases where an analysis cannot guarantee monotonicity of a whole program

how should we do to coordinate?

- Dedalus, Bloom

Use CALM principle

monotonicity: develop checks for distributed consistency (**no coordination)**

- non-monotonic symbols are not contained(NOT, IN)
- semantics of predicates eg. MIN(x)<100

non-monotonicity: provide a conservative assessment (**need coordination)**

- flag all non-monotonic predicates in a program
- add coordination logic at its points of order.
- visualize the Points of Order in a dependency graph

Conclusion

- Using tables as a uniform data representation simplified the problem of state management
- natural to express these systems and protocols with high-level declarative queries, describing continuous transformations over that state.
- The uniformity of data-centric interfaces also enabled interposition of components in a natural manner
- timestepped dataflow execution model is simpler than traditional notions of concurrent programming

Weaknesses of overlog

- ambiguous temporal semantics:
  - not easy to express the info accumulation and state change using implication
- semantics does not model asyn communication.
  - unable to characterize uncertainty about when or whether the conclusions of such an implication will hold.

Future work

- disorderly debugging of large-scale data management systems
- unify the analysis techniques developed in this thesis
- explore hybrid approaches that use data lineage to communicate details about consistency anomalies back to programmers

reference: http://bloom-lang.net/calm/, http://boom.cs.berkeley.edu/

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Thanks!