Topics in Database Systems: Data Management in Peer-to-Peer Systems

Replication

Types of Replication

Two types of replication

- Index (metadata): replicate index entries
- Data/Document replication: replicate the actual data (e.g., music files)

Types of Replication

Caching vs Replication

Cache: Store data retrieved from a previous request (client-initiated)

Replication: More proactive, a copy of a data item may be stored at a node even if the node has not requested it

Reasons for Replication

Reasons for replication

- Performance
  - load balancing
  - locality: place copies close to the requestor
    - geographic locality (more choices of next step in search)
  - reduce number of search
- Availability
  - In case of failures
  - Peer departures

Besides **storage**, cost associated with replication: **Consistency Maintenance**

Make reads faster in the expense of slower writes

Issues

Which items (data/metadata) to replicate

Popularity

In traditional distributed systems, also rate of read/write

Where to replicate

"Database-Flavored" Replication Control Protocols

Lets assume the existence of a data item x with copies $x_1, x_2, \ldots, x_n$

x: logical data item

x_i's: physical data items

A replication control protocol is responsible for mapping each read/write on a logical data item (R(x)/W(x)) to a set of read/writes on a (possibly) proper subset of the physical data item copies of x

Correctness

A DBMS for a replicated database should behave like a DBMS managing a one-copy (i.e., nonreplicated) database insofar as users can tell

One-copy serializable (1SR)

the schedule of transactions on a replicated database be *equivalent* to a serial execution of those transactions on a one-copy database

Read One/Write All (ROWA)

A replication control protocol that maps each read to only *one* copy of the item and each write to a set of writes on *all* physical data item copies.

Even if one of the copies is unavailable an update transaction cannot terminate

Write-all-available

A replication control protocol that maps each read to only *one* copy of the item and each write to a set of writes on *all available* physical data item copies.

Read quorum V_r and a write quorum V_w to read or write a data item

If a given data item has a total of V votes, the quorums have to obey the following rules:

1. $V_r + V_w > V$
2. $V_w > V/2$

Rule 1 ensures that a data item is not read or written by two transactions concurrently (R/W)

Rule 2 ensures that two write operations from two transactions cannot occur concurrently on the same data item (W/W)

In the case of network partitioning,

determine which transactions are going to terminate based on the votes they can acquire

the rules ensure that two transactions that are initiated in two different partitions and access the same data item cannot terminate at the same time

Immediate writes

Deffered writes

Access *only one copy* of the data item, it delays the distribution of writes to other sites until the transaction has terminated and is ready to commit.

It maintains an *intention list* of deferred updates

After the transaction terminates, it send the appropriate portion of the intention list to each site that contains replicated copies

Optimizations – aborts cost less – may delay commitment – delays the detection of copies

Primary copy

Use the same copy of a data item

Eager vs Lazy Replication

Eager replication: keeps all replicas synchronized by updating all replicas in a single transaction

Lazy replication: asynchronously propagate replica updates to other nodes after replicating transaction commits

In p2p, lazy replication is the norm

Update Propagation

Who initiates the update:

Push by the server item (copy) that changes

Pull by the client holding the copy

When

- Periodic
- Immediate
- When an inconsistency is detected
- Threshold-based: Freshness (e.g., number of updates or actual time)
  Value
- Time-to-live: Items expire after that time

Stateless or State-full

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Replication in Structured P2P

From CHORD and CAN first papers

CHORD

Metadata replication or redundancy

Invariant to guarantee correctness of lookups:

Keep successors nodes up-to-date

Method: Maintain a successor list of its “r” nearest successors on the Chord ring

Why? Availability

How to keep it consistent: Lazy thought a periodic stabilization

CHORD

Data replication

Method: Replicate data associated with a key at the *k* nodes succeeding the key

Why? Availability

CAN

Metadata replication

Multiple realities

With *r* realities each node is assigned *r* coordinated zones, one on every reality and holds *r* independent neighbor sets

Replicate the hash table at each reality

Availability: Fails only if nodes at both *r* nodes fail

Performance: Better search, choose to forward the query to the neighbor with coordinates closest to the destination

CAN

Metadata replication

Overloading coordinate zones

Multiple nodes may share a zone

The hash table may be replicated among zones

Higher availability

Performance: choices in the number of neighbors, can select nodes closer in latency

Cost for Consistency

CAN

Metadata replication

Multiple Hash Functions

Use *k* different hash functions to map a single key onto *k* points in the coordinate space

Availability: fail only if all *k* replicas are unavailable

Performance: choose to send it to the node closest in the coordinated space or send query to all k nodes in parallel (k parallel searches)

Cost for Consistency

Query traffic (if parallel searches)

CAN

Metadata replication

Hot-spot Replication

A node that finds it is being overloaded by requests for a particular data key can replicate this key at each of its neighboring nodes

Them with a certain probability can choose to either satisfy the request or forward it

Performance: load balancing

CAN

Metadata replication

Caching

Each node maintains a a cache of the data keys it recently accessed

Before forwarding a request, it first checks whether the requested key is in its cache, and if so, it can satisfy the request without forwarding it any further

Number of cache entries per key grows in direct proportion to its popularity

Topics in Database Systems: Data Management in Peer-to-Peer Systems

Q. Lv et al, "Search and Replication in Unstructured Peer-to-Peer Networks", ICS'02

Search and Replication in Unstructured Peer-to-Peer Networks

Type of replication depends on the search strategy used

(i) A number of blind-search variations of flooding

(ii) A number of (metadata) replication strategies

Evaluation Method: Study how they work for a number of different topologies and query distributions

Methodology

Aspects of P2P

Performance of search depends on

- Network topology: graph formed by the p2p overlay network
- Query distribution: the distribution of query frequencies for individual files
- Replication: number of nodes that have a particular file

Assumption: fixed network topology and fixed query distribution

Results still hold, if one assumes that the time to complete a search is short compared to the time of change in network topology an in query distribution

Network Topology

(1) Power-Law Random Graph

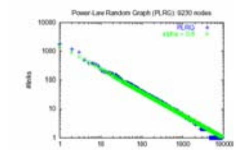
A 9239-node random graph

Node degrees follow a power law distribution

when ranked from the most connected to the least, the i-th ranked has

ω/i^{α}, where ω is a constant

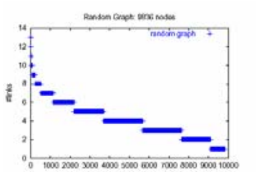
Once the node degrees are chosen, the nodes are connected randomly



Network Topology

(2) Normal Random Graph

A 9836-node random graph

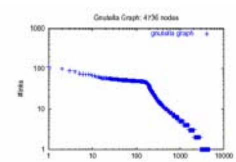


Network Topology

(3) Gnutella Graph (Gnutella)

A 4736-node graph obtained in Oct 2000

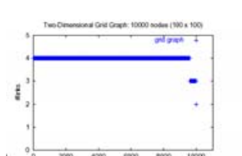
Node degrees roughly follow a two-segment power law distribution



Network Topology

(4) Two-Dimensional Grid (Grid)

A two dimensional 100x100 grid



Network Topology

	#nodes	total #links	avg. node degree	std. dev.	max degree	median degree
PLRG	9230	20599	4.46	27.9	1746	1
Random	9836	20099	4.09	1.95	13	4
Gnutella	4736	13022	5.50	10.7	136	2
Grid	10000	19800	3.96	0.20	4	4

Table 1: Key statistics of the network topologies

Query Distribution

Let q_i be the relative popularity of the i-th object (in terms of queries issued for it)

Values are normalized $\Sigma_{i=1,m} q_i = 1$

(1) Uniform: All objects are equally popular

$$q_i = 1/m$$

(2) Zip-like

$$q_i \propto 1 / i^{\alpha}$$

Replication

Each object i is replicated on r_i nodes and the total number of objects stored is R, that is

$$\Sigma_{i=1,m} r_i = R$$

(1) Uniform: All objects are replicated at the same number of nodes

$$r_i = R/m$$

(2) Proportional: The replication of an object is proportional to the query probability of the object

$$r_i \propto q_i$$

(3) Square-root: The replication of an object i is proportional to the square root of its query probability q_i

$$r_i \propto \sqrt{q_i}$$

Query Distribution & Replication

When the replication is uniform, the query distribution is irrelevant (since all objects are replicated by the same amount, search times are equivalent)

When the query distribution is uniform all three replication distributions are equivalent

Thus, three relevant combinations:

(1) Uniform/Uniform

(2) Zipf-like/Proportional

(3) Zipf-like/Square-root

Metrics

Pr(success): probability of finding the queried object before the search terminates

#hops: delay in finding an object as measured in number of hops

Metrics

#msgs per node: Overhead of an algorithm as measured in average number of search messages each node in the p2p has to process

#nodes visited

Percentage of message duplication

Peak #msgs: the number of messages that the busiest node has to process (to identify hot spots)

Simulation Methodology

For each experiment,

First select the topology and the query/replication distributions

For each object i with replication r_i, generate *numPlace* different sets of random replica placements (each set contains r_i random nodes, on which to place the replicas of object i)

For each replica placement, randomly choose numQuery different nodes form which to initiate the query for object i

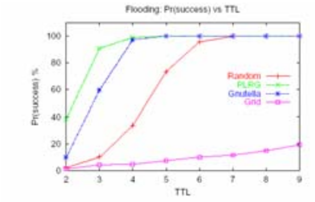
Thus, we get numPlace x numQuery queries

In the paper, numPlace = 10 and numQuery = 100 -> 1000 different queries per object

Limitation of Flooding

Choice of TTL

- Too low, the node may not find the object, even if it exists
- Too high, burdens the network unnecessarily



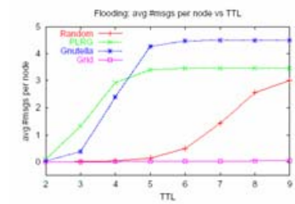
Search for an object that is replicated at 0.125% of the nodes (~11 nodes if total 9000)

Note that TTL depends on the topology

Also depends on replication (which is however unknown)

Limitation of Flooding

Choice of TTL



Overhead

Also depends on the topology

Limitation of Flooding

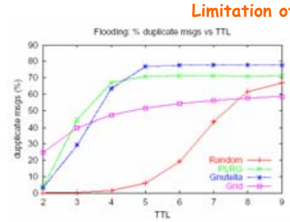
There are many duplicate messages (due to cycles) particularly in high connectivity graphs

Multiple copies of a query are sent to a node by multiple neighbors

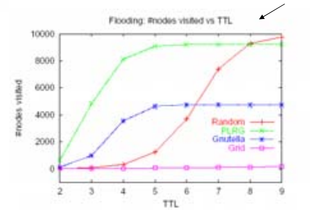
Duplicated messages can be detected and not forwarded

BUT, the number of duplicate messages can still be excessive and worsens as TTL increases

Limitation of Flooding



Different nodes



Limitation of Flooding: Comparison of the topologies

Power-law and Gnutella-style graphs particularly bad with flooding

Highly connected nodes means higher duplication messages, because many nodes' neighbors overlap

Random graph best,

Because in truly random graph the duplication ratio (the likelihood that the next node already received the query) is the same as the fraction of nodes visited so far, as long as that fraction is small

Random graph better load distribution among nodes

Two New Blind Search Strategies

1. Expanding Ring – not a fixed TTL (iterative deepening)
2. Random Walks (more details) – reduce number of duplicate messages

Expanding Ring or Iterative Deepening

Note that since flooding queries node in parallel, search may not stop even if the object is located

Use successive floods with increasing TTL

- A node starts a flood with a small TTL
- If the search is not successful, the node increases the TTL and starts another flood
- The process repeats until the object is found

Works well when hot objects are replicated more widely than cold objects

Expanding Ring or Iterative Deepening (details)

Need to define

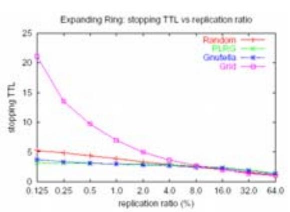
- A *policy*: at which depths the iterations are to occur (i.e. the successive TTLs)
- A time period *W* between successive iterations
    - after waiting for a time period W, if it has not received a positive response (i.e. the requested object), the query initiator resends the query with a larger TTL

Nodes maintain ID of queries for W + ε

A node that receives the same message as in the previous round does not process it, it just forwards it

Expanding Ring

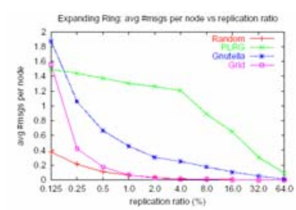
Start with TTL = 1 and increase each time by a step of 2



For replication over 10%, search stops at TTL 1 or 2

Expanding Ring

Comparison of message overhead between flooding and expanding ring



Even for objects that are replicated at 0.125% of the nodes, even if flooding uses the best TTL for each topology, expending ring still halves the per-node message overhead

Expanding Ring

More pronounced improvement for Random and Gnutella graphs than for the PLRG partly because the very high degree nodes in PLGR reduce the opportunity for incremental retries in the expanding ring

Introduce slight increase in the delays of finding an object:

From 2 to 4 in flooding to 3 to 6 in expanding ring

Random Walks

Forward the query to a randomly chosen neighbor at each step

Each message a walker

k-walkers

The requesting node sends *k* query messages and each query message takes its own random walk

k walkers after T steps should reach roughly the same number of nodes as 1 walker after kT steps

So cut delay by a factor of k

16 to 64 walkers give good results

Random Walks

When to terminate the walks

- TTL-based
- Checking: the walker periodically checks with the original requestor before walking to the next node (again use a large TTL, just to prevent loops)

Experiments show that

> checking once at every 4th step strikes a good balance between the overhead of the checking message and the benefits of checking

Random Walks

When compared to flooding:

The 32-walker random walk reduces message overhead by roughly two orders of magnitude for all queries across all network topologies at the expense of a slight increase in the number of hops (increasing from 2-6 to 4-15)

When compared to expanding ring,

The 32-walkers random walk outperforms expanding ring as well, particularly in PLRG and Gnutella graphs

Random Walks

Keeping State

- Each query has a unique ID and its k-walkers are tagged with this ID
- For each ID, a node remembers the neighbor it has forwarded the query
- When a new query with the same ID arrives, the node forwards it to a *different* neighbor (randomly chosen)

Improves Random and Grid by reducing up to 30% the message overhead and up to 30% the number of hops

Small improvements for Gnutella and PLRG

Principles of Search

- Adaptive termination is very important
  - Expanding ring or the checking method
- Message duplication should be minimized
  - Preferably, each query should visit a node just once
- Granularity of the coverage should be small
  - Increase of each additional step should not significantly increase the number of nodes visited

Replication

How many copies?

Theoretically addressed in another paper, three types of replication:

- Uniform
- Proportional
- Square-Root

Replication: Problem Definition

How many copies of each object so that the search overhead for the object is minimized, assuming that the total amount of storage for objects in the network is fixed

Replication Theory

Assume *m* objects and *n* nodes

Each object *i* is replicated on r_i distinct nodes and the total number of objects stored is R, that is

$$\Sigma_{i=1, m} r_i = R$$

Assume that object i is requested with relative rates q_i, we normalize it by setting

$$\Sigma_{i=1, m} q_i = 1$$

For convenience, assume $1 \ll r_i \leq n$

Replication Theory

Assume that searches go on until a copy is found

Searches consist of randomly probing sites until the desired object is found

The probability Pr(k) that the object is found at the k'th probe is given

Pr(k) =

Pr(not found in the previous k-1 probes) Pr(found in one (the kth) probe) =

$(1 - r_i/n)^{k-1} * r_i/n$

Replication Theory

We are interested in the average search size *A* of all the objects (average number of nodes probed per object query)

Average search size is the inverse of the fraction of sites that have replicas of the object

$A_i = n/r_i$

Average search size for all the objects

$A = \Sigma_i q_i A_i = n \Sigma_i q_i/r_i$

Replication Theory

If we have no limit on r_i, replicate everything everywhere

Average search size is the inverse of the fraction of sites that have replicas of the object

$A_i = n/r_i = 1$

Search becomes trivial

average number of replicas per site $\rho = R/n$ is fixed

How to allocate these R replicas among the m objects, how many replicas per object

Uniform Replication

Create the same number of replicas for each object

$r_i = R/m$

Average search size for uniform replication

$A_i = n/r_i = m/\rho$

$A_{uniform} = \Sigma_i q_i m/\rho = m/\rho$

Which is independent of the query distribution

It makes sense to allocate more copies to objects that are frequently queried, this should reduce the search size for the more popular objects

Proportional Replication

Create a number of replicas for each object proportional to the query rate

$r_i = R q_i$

Average search size for uniform replication

$A_i = n/r_i = n/R q_i$

$A_{proportioanl} = \Sigma_i q_i n/R qi = m/\rho = A_{uniform}$

Which is again independent of the query distribution

Why? Objects whose query rate are greater than average (>1/m) do better with proportional, and the other do better with uniform

The weighted average balances out to be the same

So what is the optimal way to allocate replicas so that A is minimized?

Square-Root Replication

Find r_i that minimizes A,

$$A = \Sigma_i\, q_i\, A_i = n\, \Sigma_i\, q_i/r_i$$

This is done for $r_i = \lambda \sqrt{q_i}$ where $\lambda = R/\Sigma_i \sqrt{q_i}$

Then the average search size is

$$A_{optimal} = 1/\rho\, (\Sigma_i \sqrt{q_i})^2$$

Replication (summary)

Each object i is replicated on r_i nodes and the total number of objects stored is R, that is

$$\Sigma_{i=1,m}\, r_i = R$$

(1) Uniform: All objects are replicated at the same number of nodes

$$r_i = R/m$$

(2) Proportional: The replication of an object is proportional to the query probability of the object

$$r_i \propto q_i$$

(3) Square-root: The replication of an object i is proportional to the square root of its query probability q_i

$$r_i \propto \sqrt{q_i}$$

Other Metrics: Discussion

Utilization rate, the rate of requests that a replica of an object i receives

$$U_i = R\, q_i/r_i$$

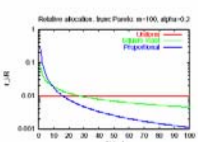
- For *uniform replication*, all objects have the same average search size, but replicas have utilization rates proportional to their query rates

- *Proportional replication* achieves perfect load balancing with all replicas having the same utilization rate, but average search sizes vary with more popular objects having smaller average search sizes than less popular ones

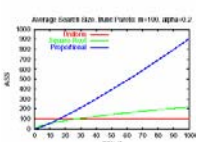
Replication: Summary

	Uniform	Proportional	Square-Root
A	$\rho^{-1}m$	$\rho^{-1}m$	$\rho^{-1}(\sum_i \sqrt{q_i})^2$
r_i	R/m	$q_i R$	$R\sqrt{q_i}/\sum_j \sqrt{q_j}$
$A_i = n/r_i$	$\rho^{-1}m$	$(\rho q_i)^{-1}$	$\rho^{-1}\sum_j \sqrt{q_j}/\sqrt{q_i}$
$U_i = Rq_i/r_i$	$q_i m$	1	$\sqrt{q_i}\sum_j \sqrt{q_j}$

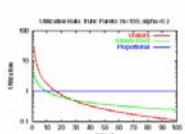
Pareto Distribution



Relative allocation r_i/R



Average search size ρA_i



Utilization rate U_i

Achieving Square-Root Replication

How can we achieve square-root replication in practices?

- Assume that each query keeps track of the search size
- Each time a query is finished the object is copied to a number of sites proportional to the number of probes

On average object i will be replicated on c n/r_i times each time a query is issued (for some constant c)

It can be argued that this gives square root

Achieving Square-Root Replication

What about replica deletion?

The lifetime of replicas must be independent of object identity or query rate

FIFO or random deletions is ok

LRU or LFU no

Replication - Conclusion

Square-root replication is needed to minimize the overall search traffic:

an object should be replicated at a number of nodes that is proportional to the number of probes that the search required

Replication - Implementation

Two strategies are easily implementable

Owner Replication

When a search is successful, the object is stored at the requestor node only (used in Gnutella)

Path Replication

When a search succeeds, the object is stored at all nodes along the path from the requestor node to the provider node (used in Freenet)

Replication - Implementation

If a p2p system uses k-walkers, the number of nodes between the requestor and the provider node is 1/k of the total nodes visited

Then, path replication should result in square-root replication

Problem: Tends to replicate nodes that are topologically along the same path

Replication - Implementation

Random Replication

When a search succeeds, we count the number of nodes on the path between the requestor and the provider

Say p

Then, randomly pick p of the nodes that the k walkers visited to replicate the object

Harder to implement

Replication: Evaluation

Study the three replication strategies in the Random graph network topology

Simulation Details

- Place the m distinct objects randomly into the network
- Query generator generates queries according to a Poisson process at 5 queries/sec
- Zipf-distribution of queries among the m objects (with a = 1.2)
- For each query, the initiator is chosen randomly
- Then a 32-walker random walk with state keeping and checking every 4 steps
- Each sites stores at most objAllow (40) objects
- Random Deletion
- Warm-up period of 10,000 secs
- Snapshots every 2,000 query chunks

Replication: Evaluation

For each replication strategy

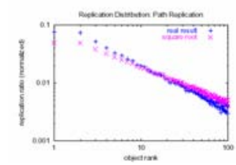
- What kind of replication ratio distribution does the strategy generate?

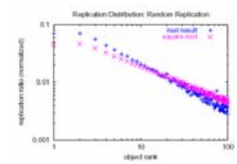
- What is the average number of messages per node in a system using the strategy

- What is the distribution of number of hops in a system using the strategy

Replication: Evaluation

Both path and random replication generates replication ratios quite close to square-root of query rates





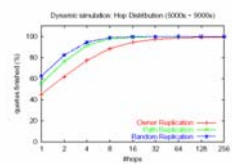
Replication: Evaluation

Path replication and random replication reduces the overall message traffic by a factor of 3 to 4

	Owner Replication	Path Replication	Random Replication
avg #msgs per node	56542.6	19155.5	14463.0
factor of improvement	1	2.95	3.91

Replication: Evaluation

Much of the traffic reduction comes from reducing the number of hops



Path and random, better than owner

For example, queries that finish with 4 hops, 71% owner, 86% path, 91% random