HIGH-CONCURRENCY DISTRIBUTED SNAPSHOTS

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Hello

About me

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13 years of helping people make PostgreSQL run fast

About this talk

- Overview of database concurrency.
- How we solve this today in PostgreSQL.
- Proposal for how to do it in the future.

What are snapshots

Lets start with ACID

We all love transactions!

- Atomicity - all or nothing!
- Consistency - there are rules!
- Isolation - none of this concurrency weirdness!
- Durability - stuff doesn't just disappear!

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- After the updates complete we want to run queries that can see these writes.
- Original query can still see original state.
- Therefore we need to have different versions of rows visible to different queries.

Snapshots to the rescue

- Tag every row version with transactions that added it and removed it.
- When starting a read, create a snapshot datastructure.
  - `XidInMVCCSnapshot(xid, snapshot) -> bool`
- Represents a point in time in the past.
- Divides world into past and future.
- Ideally, snapshots should agree on the order of things.
  - If we have snapshot that thinks txA is past, txB is future, then it should be impossible to get a snapshot that thinks txB is past, txA is future.

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- Transaction completion order does not match start order (xid order).
- While writing row versions we don’t know the completion order.
- Not feasible to go back and rewrite everything.

SQL isolation levels

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                      READ COMMITTED
                      REPEATABLE READ
                      SERIALIZABLE
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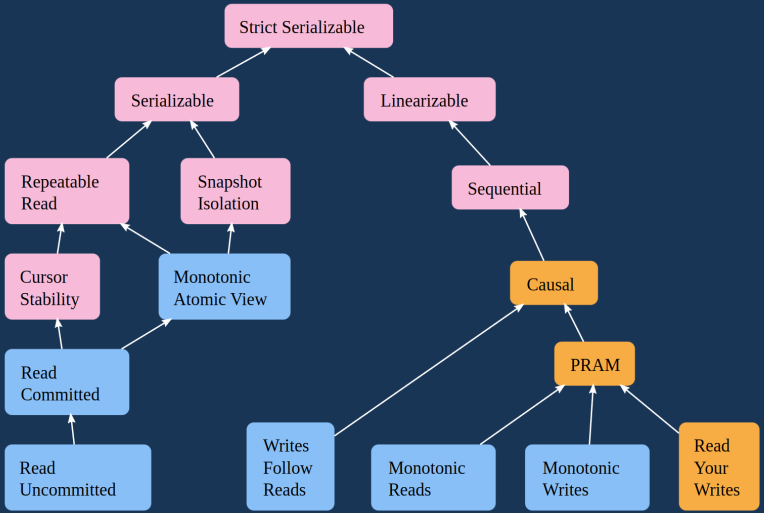
```

- Not well defined.
- Does not capture the space of possibilities.

Zoo of consistency levels



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Users must be able to pick a level suitable for their problem.

Where we are today

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- Still have to check `pg_xact` whether it was successful.
- Visibility order determined by `ProcArrayLock` acquisition.

ProcArray scalability issues

- Every commit acquires `ProcArrayLock` exclusively.
- Every read scans the whole `ProcArray` while holding a share lock.
- Size of `ProcArray` = number of connections.
  - More CPUs and more IO throughput means more connections needed.
- Larger proc array takes longer to scan.
- More writing transactions means more time spent locking exclusively.

Things we have done to make it faster

- New running transactions are published in a lock-free manner.
- Group commit batch updates ProcArray for many committers at once.
- Major improvements in PG14 by Andres Freund.
  - xids are stored as a dense array for faster scanning.
  - Snapshot contents are cached until next commit.

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  - xids are stored as a dense array for faster scanning.
  - Snapshot contents are cached until next commit.
- For most workloads works well enough

Things we could still do

- Vectorize the main loop in `GetSnapshotData()`.
- Lock free snapshot cache.
- Incremental snapshot creation.

Subtransactions

- Subtransactions mean multiple xids per transaction.
  - Potentially unlimited.
- Limited space in shared memory to track this.
- If filled up need a `Subtrans` lookup for every visibility check in `[xmin, xmax)`.

Consistency? Eventually...

- On primary the order of transactions is determined by ProcArray order
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```
CommitTransaction()
  RecordTransactionCommit()
    XactLogCommitRecord()
    if (synchronous_commit) // can be set per transaction
      XLogFlush()
      SyncRepWaitForLSN() // these two can take a looong time
  ProcArrayEndTransaction()
```


Pick three

- Commit order matches on primary and replica
- No wait when synchronous_commit = off
- Read-your-write consistency
- Single WAL record for commit

The non-synchronous commit

Problem scenario:

1. Client tries to book a room.
2. Synchronous commit blocks.
3. Client connection fails, commit becomes visible.
4. Client reconnects, checks that booking commit succeeded.
5. There is a failover, replica does not have that commit.

Does not distribute

- For sharded databases would be nice to get a consistent snapshot.
- Would like to have ACID for cross-shard transactions:
  - If a tx visible on shard A it should also be visible on B
  - Transactions should not disappear and re-appear
- Having a distributed ProcArray and global locking does not scale:
  - Snapshots get even bigger.
  - Even more write transactions.
  - More likelihood of node failures.
- Consistent order of durability and visibility becomes even more important.

CSN snapshots

Core idea

- On transaction commit assign a Commit Sequence Number (CSN).
  - Thinking of it as a commit time is not totally wrong.
- Should only go forward, not backward.
- Store this in a way that we can easily calculate `xid -> csn`.
- A snapshot is just the latest committed CSN value.

Not a new idea

- Similar stuff is present all over distributed database landscape.
  - Google Spanner
  - YugabyteDB
  - CockroachDB

What to use as the CSN

- Free to use anything that fulfills the requirements.
- Could use a simple counter (we already have it as `SerCommitSeqNo`).
- Could use Commit record WAL position (we need to assign it anyway).
- Could use a combination of a monotonic wall clock and logical counter (see HybridTime).

Invariants

1. After a commit becomes visible no transaction with a lower CSN can commit.
   - Needed for immutable snapshots.
2. After a commit returns, all new snapshots should get equal or bigger CSN.
   - Read your writes. (can be relaxed a bit by applying Lamport timestamp)
3. After a read completes all subsequent reads must see equal or higher CSN.
   - Transactions don’t disappear and re-appear.

Storing XID to CSN mapping

- Simplest answer: add CSN SLRU.
- 8 byte CSN @ 100k TPS = 800 KB/s
  - 100k TPS = wraparound in 6h
- We already have `CommitTs`, maybe combine?
- Can replace `Xact` SLRU, or could be compressed to `Xact` after global xmin.
- Might be a performance issue for mixed short-long tx workloads, see `SubTrans` SLRU.
  - Some ideas how to get around it.

Adding concurrency

Main workflow:

```
MyCSN = AcquireCSN();
RecordXidToCsnMapping(MyXid, MyCSN);
WaitForDurability()
UpdateVisibleCSN(MyCSN)
```

- Definitely want to do the wait concurrently.
- Updating visible CSN needs to happen in CSN AcquireCSN order.
- Build a queue, wait on anyone ahead of us, if we are first, release everyone already waiting behind us.
  - Analogous to ProcArray group update.
- Fixes the non-synchronous commit.

Visibility checks

- Lookup XID in CSN mapping, compare with value in snapshot.

```
bool
XidVisibleToSnapshot(TransactionId xid, Snapshot snapshot)
{
  return LookupXidCsn(xid) <= snapshot->csn;
}
```

- Sometimes can skip lookups:
  - xmax can be used to reject early
  - some approximation of xmin is also useful

Subtransactions

- Option 1: Tag every committed subxid with CSN on commit.
- Option 2: Carve a bit of CSN space to identify subtransactions.
  - Lookup parent on visibility check.
  - Update XID to CSN mapping.
- Can get rid of `SubTrans` SLRU?

Resolving the synchronous commit quadrilemma

- `synchronous_commit = off` will wait for durability of anyone that is commiting ahead of us.
- Add `synchronous_visibility` that allows user to “fire and forget” write transactions.
  - (working title)
  - When disabled, just skip waiting in `UpdateVisibleCSN()` and let someone else make this transaction visible.
  - Not possible in all cases (DDL)
- Optionally add a way to “see into the future” by reading non-durable transactions
  - `BEGIN ISOLATION LEVEL READ UNCOMMITTED`
- Only affects users that run a mix of `synchronous_commit` and expect to see the results.

In a distributed system

- Some synchronization is needed to ensure that all other commits < commit CSN are done committing.
- Coordinating with every node on every commit is undesirable.
- Spanner uses realtime clock dervived timestamp with error bounds for CSN.
  - On commit waits until everybody in cluster must agree commit timestamp is in the past.
  - Adds non-trivial amount of latency.
- YugabyteDB HybridTime uses NTP clock with a logical counter on top. Ensures this never goes backwards.
  - By eagerly sharing this can get illusion of consistency with no waiting.
  - Can still do the waiting if so desired.
- Reading from replicas still needs to wait for WAL replay.

Hybrid snapshots

Preface

Maybe this complexity is not needed.

Almost certainly a bad idea for initial version.

Demonstrates potential solutions to problems that may or may not become important.

Core insight

Given a snapshot (xmin, csn, xmax) we can build the same snapshot that we would have gotten from `ProcArray` by scanning XidToCSN mapping.

```
for (xid = xmin; xid < xmax; xid++)
    if (LookupXidCsn(xid) > snapshot->csn)
        xip[n++] = xid;
```


Core insight part 2

Snapshots can be converted incrementally by keeping track of a threshold:

```
struct SnapshotData
{
    TransactionId xmax
    CSN csn;
    TransactionId csn_xmin;
    TransactionId *xip;
    TransactionId xmin;
    //...
}
```


But why?

- XidToCSN lookups can get expensive when done per row.
- Only have to do when looking at rows touched between `[xmin, xmax)`
- Long running transactions can make this range big -> lots of lookups.
- If we stick long running transactions in a separate xip array we can tighten the range.
  - Less CSN lookups needed.
- By having a limited xid range where lookups are needed can use a ring buffer to store CSNs.
  - One indirection less.
  - Simpler to make lock free.
- Long running read transactions will also need conversion.

Shared memory structures

- L1 mapping: `CSN ringbuffer[N]`
- Has the following “clock hands”
  - nextXid - next slot to hand out
  - csnXmin - every running transaction before this is in L2
  - globalCSNXmin - every snapshot has higher csnxmin
- L2 mapping:

```
XidCSNPair longTx[]
```


Built on hope

- Hopefully most transactions will have committed when we have to move `csnXmin` hand past them.
- Hopefully most snapshots are released before we hit their csnXmin.

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A large enough ringbuffer will ensure hopes come true.

Common operations

- AssignTransactionId():
  - If there is room, bump nextXid
  - If not, make some.
- GetSnapshotData()
  - Read visible_csn, xmax, csn_xmin
  - Scan L2 for long running transactions. (could do this lazily?)
  - Publish csn_xmin
- CommitTransaction()
  - If we are still in L1, write CSN
  - If we are in L2, look up our entry, tag with CSN

Batch operation

- Every now and then move clock hands up.
  - Reduce contention on shared datastructures by this factor.
- Scan L1 from csnXmin for still running transactions, move them to L2.
  - Write Xact entries for the rest
- Scan procarray for new global CSNXmin.
- Signal all snapshot holders with old enough `csnXmin` to advance their CSN xmin.
- To advance snapshot `csnXmin`, scan L1.
- A few extra clock hands and careful coordination can make a lot of this lock free.

Visibility check

```
bool
XidVisibleToSnapshot(TransactionId xid, Snapshot snapshot)
{
    if (xid > xmax) return false;
    if (xid < xmin) return true;
    if (xid < snapshot->csn_xmin)
        return pg_lfind32(xid, snapshot->xip, snapshot->xcnt);

    csn = pg_atomic_read_u64(&ringBuffer[xid % RING_SIZE]);
    read_barrier();
    if (pg_atomic_read_u64(ringBufferCtl->globalCSNXmin) > xid)
        goto evicted;
    return csn <= snapshot->csn;
    evicted: // TBD
```


Existing work

Andrey Lepikhov, et. al

- Last state: 2021-11-19.
- Thread “Global Snapshots”.
- CSN is assigned during ProcArrayEndTransaction().
- CSN assignment is WAL logged.
- On replicas transaction visibility is postponed until visibility record arrives.

Heikki Linnakangas

- Based on “Global Snaphshots” patch.
- Heavily changed to only use CSN based snapshots on standbys.
- CSN = Commit LSN.
- Main goal is to get rid of KnownAssignedXids hackery.
- Reduced scope to get something more easily committable.
- Intention to get it into 18.

Recap

Where are we today

- Our current snapshot mechanism has some major issues when running across multiple machines.
- Some of those issues are implementation details exposed as bad semantics.
- CSN snapshots provide an easy to reason about way to fix those problems.
- CSN snapshots also make it easier to implement distributed transactions.
- Performance penalty/gain remains to be proven by an actual implementation.

Thanks!