Week 9: Distributed Databases
Part 1: Google Bigtable
Bigtable

• Highly available distributed storage
• Built with semi-structured data in mind
  – URLs: content, metadata, links, anchors, page rank
  – User data: preferences, account info, recent queries
  – Geography: roads, satellite images, points of interest, annotations
• Large scale
  – Petabytes of data across thousands of servers
  – Billions of URLs with many versions per page
  – Hundreds of millions of users
  – Thousands of queries per second
  – 100TB+ satellite image data
Uses

At Google, used for:

- Google Analytics
- Google Finance
- Personalized search
- Blogger.com
- Google Code hosting
- YouTube
- Gmail
- Google Earth & Google Maps
- Dozens of others… over sixty products
Bigtable is NOT a relational database

Bigtable appears as a large table

“A Bigtable is a sparse, distributed, persistent multidimensional sorted map”*

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<table>
<thead>
<tr>
<th>rows</th>
<th>“language:”</th>
<th>“contents:”</th>
</tr>
</thead>
<tbody>
<tr>
<td>com.aaa</td>
<td>EN</td>
<td>&lt;!DOCTYPE html PUBLIC...</td>
</tr>
<tr>
<td>com.cnn.www</td>
<td>EN</td>
<td>&lt;!DOCTYPE HTML PUBLIC...</td>
</tr>
<tr>
<td>com.cnn.www/TECH</td>
<td>EN</td>
<td>&lt;!DOCTYPE HTML&gt;...</td>
</tr>
<tr>
<td>com.weather</td>
<td>EN</td>
<td>&lt;!DOCTYPE HTML&gt;...</td>
</tr>
</tbody>
</table>
```

*Bigtable: OSDI 2006

Web table example
Table Model

(row, column, timestamp) → cell contents

- Contents are arbitrary strings (arrays of bytes)

<table>
<thead>
<tr>
<th>Rows</th>
<th>“language:”</th>
<th>“contents:”</th>
<th>Versions</th>
</tr>
</thead>
<tbody>
<tr>
<td>com.aaa</td>
<td>EN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>com.cnn.www</td>
<td>EN</td>
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<td>t₂</td>
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<tr>
<td>com.cnn.www/TECH</td>
<td>EN</td>
<td><code>&lt;!DOCTYPE html...</code></td>
<td>t₄  t₇</td>
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<tr>
<td>com.weather</td>
<td>EN</td>
<td><code>&lt;!DOCTYPE html...</code></td>
<td>t₇ t₁₅</td>
</tr>
</tbody>
</table>
**Columns and Column Families**

**Column Family** = group of related columns ⇒ basic unit of data access
- Data in a column family is typically of the same type
- Implementation of Bigtable compresses data in the same column family

• **Operations**
  - (1) Create column family ⇒ this is an admin task done when the table is created
  - (2) Create a column and store data within the family ⇒ this can be done anytime

• There will typically be a small number of column families
  - ≤ hundreds of column families
  - A table may have an unlimited # of columns within a column family: *often sparsely populated*

• Columns are identified by **family:qualifier**
Column Families: example

Three column families
- “language:” – language for the web page
- “contents:” – contents of the web page
- “anchor:” – contains text of anchors that reference this page
  - www.cnn.com is referenced by Sports Illustrated (cnnsi.com) and My-Look (mlook.ca)

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Tables & Tablets

• Row operations are atomic

• Table partitioned dynamically by rows into tablets

• Tablet = range of contiguous rows
  – Unit of distribution and load balancing
  – Nearby rows will usually be served by the same server
  – Accessing nearby rows requires communication with a small # of machines
  – You need to select row keys to ensure good locality
    • E.g., reverse domain names:
Table splitting

• A table starts as one tablet
• As it grows, it is split into multiple tablets
  – Approximate size: 100-200 MB per tablet by default

<table>
<thead>
<tr>
<th>Table: “language:”</th>
<th>“contents:”</th>
</tr>
</thead>
<tbody>
<tr>
<td>com.aaa EN</td>
<td>&lt;!DOCTYPE html PUBLIC...</td>
</tr>
<tr>
<td>com.cnn.www EN</td>
<td>&lt;!DOCTYPE HTML PUBLIC...</td>
</tr>
<tr>
<td>com.cnn.www/TECH EN</td>
<td>&lt;!DOCTYPE HTML&gt;...</td>
</tr>
<tr>
<td>com.weather EN</td>
<td>&lt;!DOCTYPE HTML&gt;...</td>
</tr>
<tr>
<td>Domain</td>
<td>Language</td>
</tr>
<tr>
<td>-------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>com.aaa</td>
<td>EN</td>
</tr>
<tr>
<td>com.cnn.www</td>
<td>EN</td>
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<tr>
<td>com.cnn.www/TECH</td>
<td>EN</td>
</tr>
<tr>
<td>com.weather</td>
<td>EN</td>
</tr>
<tr>
<td>com.wikipedia</td>
<td>EN</td>
</tr>
<tr>
<td>com.zcorp</td>
<td>EN</td>
</tr>
<tr>
<td>com.zoom</td>
<td>EN</td>
</tr>
</tbody>
</table>
• Each column may contain multiple versions of data

• Version indexed by a 64-bit timestamp
  – Real time or assigned by client

• Per-column-family settings for garbage collection
  – Keep only latest $n$ versions
  – Or keep only versions written since time $t$

• Retrieve most recent version if no version specified
  – If specified, return version where timestamp $\leq$ requested time
API: Operations on Bigtable

- Create/delete tables & column families
- Change cluster, table, and column family metadata (e.g., access control rights)
- Write or delete values in cells
- Read values from specific rows
- Iterate over a subset of data in a table
  - All members of a column family
  - Multiple column families
    - E.g., regular expressions, such as anchor:*.cnn.com
  - Multiple timestamps
  - Multiple rows
- Atomic read-modify-write row operations
- Allow clients to execute scripts (written in Sawzall) for processing data on the servers
Implementation: Supporting Services

Google SSTable (Sorted String Table)
- Internal file format optimized for streaming I/O and storing <key,value> data
- Provides a persistent, ordered, *immutable* map from keys to values
  - Append-only
- Memory or disk-based; indexes are cached in memory
- If there are additions/deletions/changes to rows
  - New SSTables are written out with the deleted data removed
  - Periodic compaction merges SSTables and removes old retired ones

GFS
- For storing log and data files

For a description of SSTable please see https://www.igvita.com/2012/02/06/sstable-and-log-structured-storage-leveldb/
Implementation: Supporting Services

**Chubby**

- Ensure there is only one active master
- Store bootstrap location of Bigtable data
- Discover tablet servers
- Store Bigtable schema information
- Store access control lists

**Cluster management system**

- For scheduling jobs, monitoring health, dealing with failures
Implementation

1. Many tablet servers – coordinate requests to tablets
   - Can be added or removed dynamically
   - Each manages a set of tablets (typically 10-1,000 tablets/server)
   - Handles read/write requests to tablets
   - Splits tablets when too large

2. One master server
   - Assigns tablets to tablet server
   - Balances tablet server load
   - Garbage collection of unneeded files in GFS
   - Schema changes (table & column family creation)

3. Client library
   Client data does not move through the master
   Clients communicate directly with tablet servers for reads/writes
Implementation: METADATA table

Three-level hierarchy
- Balanced structure similar to a B+ tree
- Root tablet contains location of all tablets in a special METADATA table
- Row key of METADATA table contains location of each tablet 
  \( f(\text{table ID}, \text{end row}) \Rightarrow \text{location of tablet} \)
Implementation

• Tablet assigned to one tablet server at a time

• When master starts:
  – Grabs a \textit{unique master lock} in Chubby (to prevent multiple masters)
  – Scans the \textit{servers} directory in Chubby to find live tablet servers
  – Contacts \textit{each tablet server} to discover what tablets are assigned to that server
  – Scans the METADATA table to learn the full set of tablets
    • Build a list of tablets not assigned to servers
      – These will be assigned by choosing a tablet server & sending it a \textit{tablet load} request
Fault Tolerance

Fault tolerance is provided by GFS & Chubby

• **Dead tablet server**
  – Master is responsible for detecting when a tablet server is not working
    • Asks tablet server for status of its lock
    • If the tablet server cannot be reached or has lost its lock
      – Master attempts to grab that server’s lock
      – If it succeeds, then the tablet server is dead or cannot reach Chubby
      – Master moves tablets that were assigned to that server into an unassigned state

• **Dead master**
  – Master kills itself when its Chubby lease expires
  – Cluster management system detects a non-responding master

• **Chubby**: designed for fault tolerance (5-way state machine replication)

• **GFS**: stores underlying data – designed for \( n \)-way replication
Bigtable Replication

- Each table can be configured for replication to multiple Bigtable clusters in different data centers

- Bigtable uses an *eventual consistency* model
  - Replicas may be updated asynchronously
Sample applications

Google Analytics

- **Raw Click Table (~200 TB)**
  - Row for each end-user session
  - Row name: {website name and time of session}
    - Sessions that visit the same web site are sorted & contiguous

- **Summary Table (~20 TB)**
  - Contains various summaries for each crawled website
  - Generated from the Raw Click table via periodic MapReduce jobs
Sample applications

Personalized Search

• One Bigtable row per user (unique user ID)

• Column family per type of action
  – E.g., column family for web queries (your entire search history!)

• Bigtable timestamp for each element identifies when the event occurred

• Uses MapReduce over Bigtable to personalize live search results
Sample applications

- **Google Maps / Google Earth**
  - Preprocessing
    - Table for raw imagery (~70 TB)
    - Each row corresponds to a single geographic segment
    - Rows are named to ensure that adjacent segments are near each other
    - Column family: keep track of sources of data per segment (this is a large # of columns – one for each raw data image – but sparse)
  - MapReduce used to preprocess data
  - Serving
    - Table to index data stored in GFS
    - Small (~500 GB) but serves tens of thousands of queries with low latency
Bigtable outside of Google

Apache HBase
- Built on the Bigtable design
- Small differences (may disappear)
  - Access control not enforced per column family
  - Millisecond vs. microsecond timestamps
  - No client script execution to process stored data
  - Built to use HDFS or any other file system
  - No support for memory mapped tablets
  - Improved fault tolerance with multiple masters on standby
Bigtable vs. Amazon Dynamo

- Dynamo targets apps that only need key/value access with a primary focus on high availability
  - Dynamo: key-value store versus Bigtable’s column-store (column families and columns within them for each key that's accessed)
  - Bigtable: distributed DB built on GFS
  - Dynamo: distributed hash table
  - Bigtable supports iterating over rows in a table
  - Dynamo updates are not rejected even during network partitions or server failures
The End