**VICTORIA UNIVERSITY OF WELLINGTON**
***Te Whare Wananga o te Upoko o te Ika a Maui***

# *Trade-offs in Cloud Databases*

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*SWEN 432*
*Advanced Database Design and Implementation*

# *Plan for Trade-offs in Cloud Databases*

- Features of relational SQL databases
- ACID properties
- NoSQL databases
- CAP Theorem
- BASE Properties
  - More about consistency/availability trade-offs

  - ***Readings:*** Have a look *at Useful Links at the Course Home Page*

# *Traditional Databases*

- Most traditional databases are relational
- Relational data model has been developed to serve applications that insist on data consistency and reliability
- RDBMSs are OLTP DBMSs
- Data consistency and reliability are guaranteed by ACID properties
- ACID stands for **A**tomicity, **C**onsistency, **I**solation, and **D**urability

# ACID Database Properties

- ***Atomicity***
  - Transactions must act as a whole, or not at all
  - No changes within a transaction can persist if any change within the transaction fails
- ***Consistency***
  - Changes made by a transaction respect all database integrity constraints and the database remains in a consistent state at the end of a transaction
- ***Isolation***
  - Transactions cannot see changes made by other concurrent transactions ,
  - Concurrent transactions leave the database in the same state as if the transactions were executed serially
- ***Durability***
  - Database data are persistent,
  - Changes made by a transaction that completed successfully are stored permanently

# *Techniques to Achieve ACID Properties*

- Relational databases:
  - Have a schema that provides a strict structure and integrity constraints for database data,
  - Schemes are normalized to avoid data redundancy and update anomalies,
  - Normalization is achieved by a vertical splitting of database tables,
  - Queries frequently ask for joins.
- Integrity constraints (checked by writes) provide for consistency
- Locking (to avoid transaction anomalies, e.g. lost update) provides for isolation
- Logging – provides for durability
  - But changes made by each transaction have to be written on disk **two** times

# *ACID Properties and Cloud Databases*

- Many cloud applications (like social networks) require databases that:
  - Are highly scalable and available,
  - Have high throughput, and
  - Be network partition tolerant
- These requirements are in a direct collision with ACID properties, particularly with integrity constraint checking, locking, logging, and performing joins
- These applications also consider strict data structuring not being suitable
- Also, consistency is considered to be of some lesser importance

# *NoSQL Database Systems*

- Many cloud databases are not relational
- They are termed **NoSQL** databases (Not only SQL)
  - NoSQL does not mean “NO to SQL”, but NO to “one size fits all”,
  - Different applications need different database paradigms
- Generally, NoSQL database systems:
  - Adopt the key-value data model for storing semi structured or unstructured data
  - Are either scheme less, or their schemes lack rigidity and integrity constraints of relational schemes
  - Use data partitioning, replication and distribution to several independent network nodes made of commodity machines for:
    - Scalability,
    - Availability, and
    - Network partition tolerance
  - Are not normalized, and do not support joins but store all data needed to answer a query in the same partition to achieve a high throughput

# *CAP Theorem*

- NoSQL database systems do not support ACID properties
  - Locking and logging would severely impair scalability, availability, and throughput
- Still, Consistency, Availability, and Network Partition Tolerance (CAP) represent their desirable properties
- But, according the CAP Theorem, also known as Brewer's Conjecture, any networked, shared data system can have at most two of these three desirable properties

# *CAP Theorem* *(2)*

- For a distributed database system as a service, the components of the CAP acronym stand for:
  - ***Consistency*** - A service is considered to be ***consistent*** if after an update operation of some writer all readers see the update in some shared data source (all nodes containing replicas of a datum have the same value),
  - ***Availability*** - A service is considered to have a high availability if it allows read and write operations a high proportion of time (even in the case of a node crush or some hardware or software parts are down due to upgrades)
  - ***Network partition tolerance*** is the ability of a service to perform expected operations in the presence of a network partition, unless the whole network crushes
    - A network partition occurs if two or more “islands” of network nodes cannot connect to each other
    - Dynamic addition and removal of nodes is also considered to be a network partition

# Comments on CAP Properties

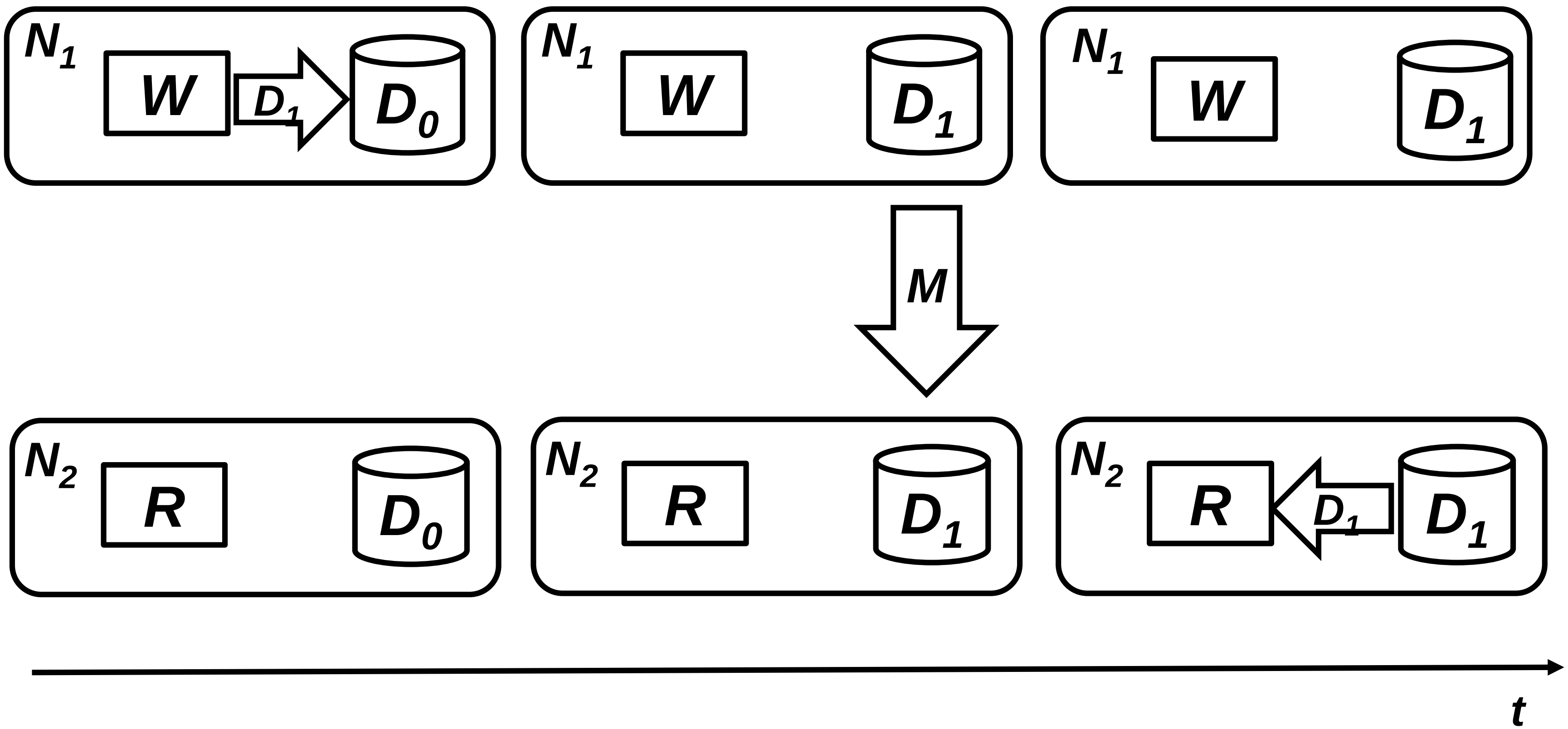
- Contrary to traditional databases, many cloud database are not expected to satisfy any integrity constraints
- High availability of a service is often characterized by small latency
  - Amazon claims that raise of 0.1 sec in their response time will cost them 1% in sales,
  - Google claims that just .5 sec in latency caused traffic to drop by 20%
- It is hard to draw a clear border between availability and network partitions
  - Network partitions may induce delays in operations of a service, and hence a greater latency

# An Informal Proof of the CAP Theorem (1)

- Eric Brewer presented his conjecture in 2000, Gilbert&Lynch proved it formally in 2002
- Here is an informal presentation of their proof showing that a highly available and partition tolerant service may be inconsistent
- Let us consider two nodes $N_1$ and $N_2$
  - Both nodes contain the same copy of data $D$ having a value $D_0$,
  - A program $W$ (write) runs on $N_1$
  - A program $R$ (read) runs on $N_2$

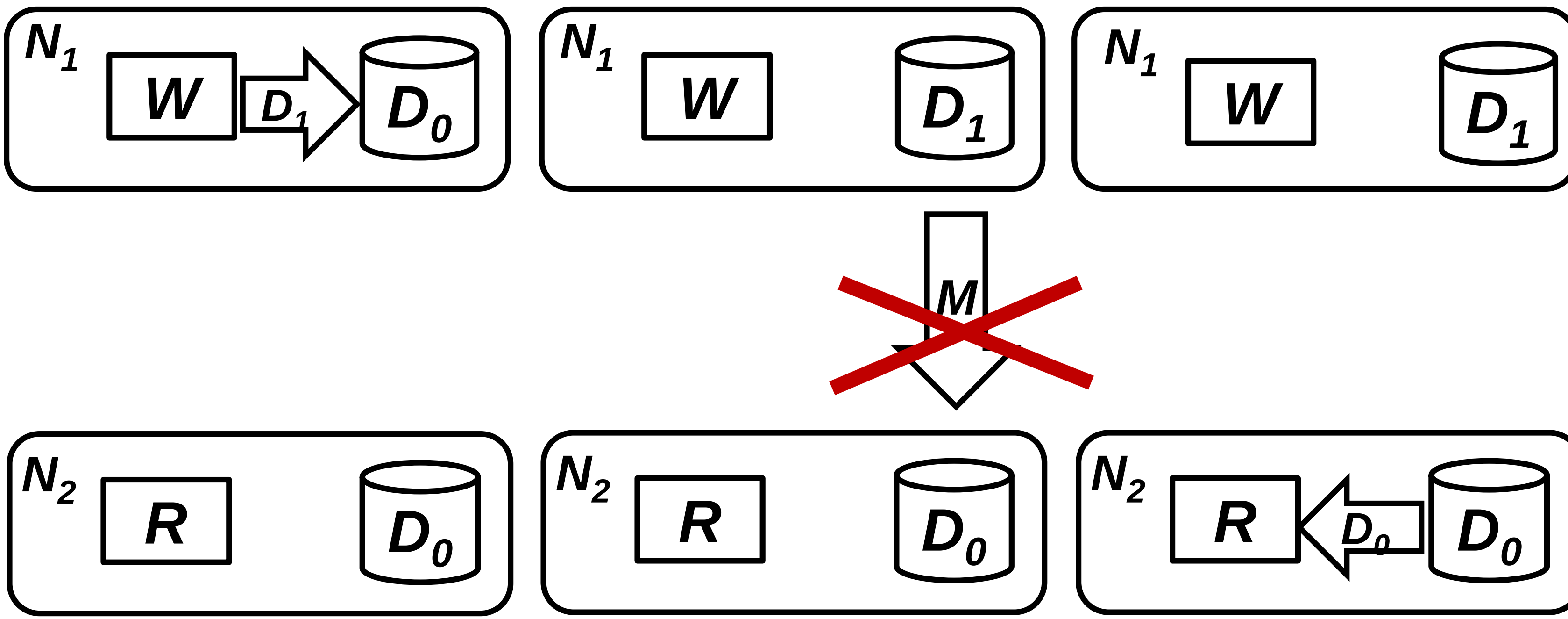
# An Informal Proof of the CAP Theorem (2)

- In a regular situation:
  - The program $W$ writes a new value of $D$, say $D_1$ on $N_1$
  - Then, $N_1$ sends a message $M$ to $N_2$ to update the copy of $D$ to $D_1$,
  - The program $R$ reads $D$ and returns $D_1$



# *An Informal Proof of the CAP Theorem (3)*

- Assume now the network partitions and the message from $N_1$ to $N_2$ is not delivered




  – The program *R* reads *D* and returns $D_0$

# Comments on the Informal Proof (1)

- The service is **highly available**, since it performed both W and R without delay.
- The service is **partition tolerant** since it performed its tasks in spite the network partition.
- The service is **inconsistent**, since it delivered stale data.

# Comments on the CAP Theorem (2)

- If an application in a distributed and replicated network have to be:
  - Highly available (i.e. working with minimal latency), and
  - Tolerant to network partitions (performs expected user initiated operations), then
  - It has to perform an update even if not all nodes are able to acknowledge it
  - Hence the (strict) consistency can't be achieved
  - So, it may happen that some of $N_i$ ($i = 1, 2, \ldots$) nodes have stale data, or even are unavailable
- The decision on which of {CA, CP, AP} property pairs to satisfy is made in early stages of a cloud application design, according to requirements and expectations defined for the application
- Most NoSQL database systems fall either in the AP class, or in the CP class

# *BASE Properties of Cloud DBs (1)*

- BASE (as defined by Eric Brewer) stands for:
  - **BA** (**B**asically **A**vailable) meaning that the system is always available, although there may be intervals of time when some of its components are not available
    - A basically available system answers each request in such a way that it appears that system works correctly and is always available and responsive
  - **S** (**S**oft State) means that the system has not to be in a consistent state after each transaction
    - The database state may change without user's intervention (due to an automatic replica convergence)
  - **E** (**E**ventually Consistent) guarantees that:
    - If no new updates are made to a given data item, accesses to each replica of that item will ***eventually*** return the last updated value
    - A system that has eventually achieved consistency is often said to have **converged**, or achieved **replica convergence**

# BASE Properties of Cloud DBs (2)

- The reconciliation of differences between multiple replicas requires exchanging and comparing versions of data between nodes
  - Usually "last writer wins“
  - The reconciliation is performed as a:
    - read,
    - write, or
    - asynchronous repair
    - Asynchronous repairs are performed in a background non transactional process
- ***Stale*** and ***approximate*** data in answers are tolerated

# ***Consistency – Availability Trade-offs (1)***

- Assume:
  - A cloud database is divided into $p$ partitions and each partition is replicated on $n$ ($\geq 3$) servers (replica nodes),
  - The database is unavailable if any of its parts is unavailable,
  - Each node stores only one replica (to simplify analysis), and
  - Each reader may contact any of $n$ replica nodes in a partition

# Consistency – Availability Trade-offs (2)

- ***Strict*** consistency: any read of a shared data item X returns the value stored by the most recent write on X
  - Requires $n$ servers to be available in each partition
  - This is hard to achieve with commodity hardware,
  - If only one node fails, the database is unavailable
- ***Strong*** consistency requires $w + r > n$ for each partition
  - $w$ and $r$ are numbers of nodes acknowledging a write and returning a read, respectively
  - At least *1* node in each partition can fail and the database is still available
  - A special case: ***quorum*** consistency, requires al least $q = \lfloor n/2 \rfloor + 1$ replica nodes to be available in each partition
  - For $w = n$ and $r = 1$, strong consistency turns into the strict one
- ***Eventual*** consistency requires at least *1* node to be available in each partition in every moment
  - At least one node has to acknowledge a write,
  - At least one node has to return a read,
  - These two nodes do not have to be the same

# *Example: Consistency vs. Availability (1)*

- Let the number of partitions $p = 10$ and the replication factor $n = 3$
  - So, the database is stored on 30 nodes
- Assume a client has requested the service to has ***strong*** consistency under ***quorum***
- Question
  - How many nodes can fail and still the whole database to be available?
- Answer:
  - Since $n = 3$, quorum $q = 2$,
  - In the ***worst case***, all unavailable nodes belong to the same partition
    - Then, to have the whole database available under strong consistency, only ***1*** node in total is allowed to be unavailable for both writing and reading
  - In the ***best case***, all [illegible]vailable no[illegible] are evenly distributed over all partitions
    - Then, to have the w[illegible]e available under strong consistency, one node in eac[illegible]on is [illegible] to be unavailable for both writing and reading, allo[illegible]ng at most ***10*** [illegible]des being simultaneously unavailable in total

# ***Example: Consistency vs. Availability (2)***

- Let the number of partitions *p = 10* and the replication factor *n = 3*
  - So, the database is stored on 30 nodes
- Assume a client has requested the service to has ***eventual*** consistency
- Question
  - How many nodes can fail and still the whole database to be available?
- Answer:
  - In the ***worst case***, all unavailable nodes belong to the same partition
    - Then, to have the whole database available under eventual consistency, only ***2*** nodes in total are allowed to be unavailable
  - In the ***best case***, all unavailable nodes are evenly distributed over all partitions
    - Then, to have the whole database available under eventual consistency, two nodes in each partition are allowed to be unavailable, giving ***20*** nodes in total

# *Summary* *(1)*

- NoSQL cloud databases are scalable, highly available and tolerate network partitions
- Cloud database system can have only two out of Consistency, Availability, and Network Partition Tolerance
- BASE represents a "best effort" approach to ensuring database reliability
  - BASE forfeits ACID properties, also by its name (base versus acid, as found in chemistry)
  - Basically Available,
  - Soft state,
  - Eventually consistent

# Summary (2)

- Eventual Consistency is a model used in distributed systems that guarantees that all accesses to replicas of an updated item will eventually return the last updated value
- Consistency levels:
  - Strict consistency,
  - Strong consistency,
  - Eventual consistency
- Consistency and availability mutually restrict each other:
  - As greater the consistency requirement as lower the database availability