CAP Theorem Impact in Reliable Data Processing

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OUTLINE

1) CAP Theorem
   a) Explanation
   b) Difficulties, misunderstandings, implications

2) Proof of CAP Theorem
   a) Asynchrnous network model
   b) Partialy synchrnous network model

- Eric Brewer, 2000, University of California
- *"A shared-data system can have at most two of the three following properties:*

  - ***C**onsistency*

  - ***A**vailability*

  - ***P**artition tolerance"*

CONSISTENCY

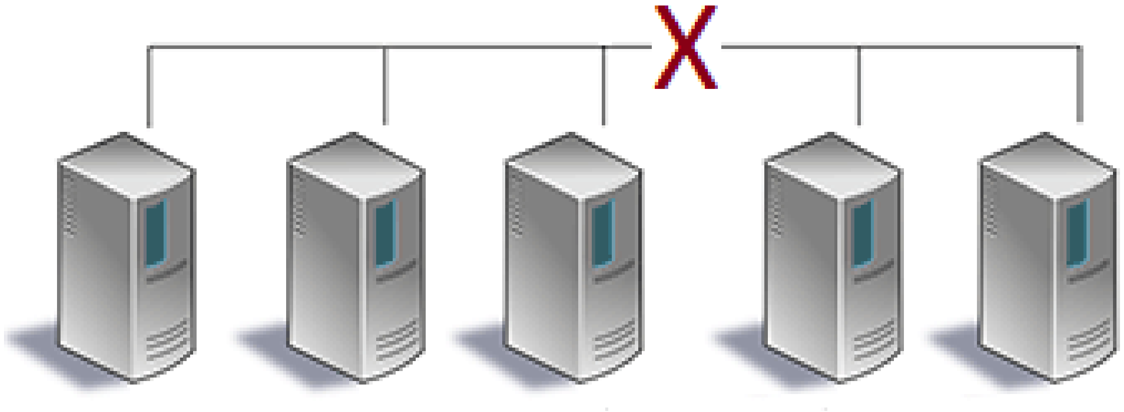
- Equivalent to having single up-to-date copy of data
- Formal definition uses an existence of total order on all operations
- Any read operation must return a result of the last write operation

Availability

- Access to the data at any time
- *„Every request by a non-failing node in a distributed system must result in a response"*
- Every request has to terminate

PARTITION TOLERANCE

- Ability to operate as usual when a network partition occurs
- *„All messages sent from nodes in one component of the partition to nodes in another component are lost "*



Never sacrifice partition tolerance

- **We can never sacrifice partition tolerance**
- Every networked distributed system experiences a network partition at some point
- Trade-off between consistency and availability

CONSISTENCY VS. AVAILABILITY

- Not a binary decision
- Both have its use in particular use cases
- Prefer **C**: refuse/postpone some requests (writes mainly)
- Prefer **A**: always response, even if results will not be complete and writes could be conflicting

PROOF – ASYNCHRONOUS NETWORK MODEL (I.)

- Seth Gilbert and Nancy Lynch
- Asynchronous network model from the book ‘Distributed algorithms’:
    - No clock
    - Nodes makes decisions based only on the received messages and local computations

PROOF – ASYNCHRONOUS NETWORK MODEL (II.)

- Distributed system component by **I/O automaton**:
  - Simple state machine with transitions
  - Transitions associated with actions:

    Input } communicaton
    Output

    Internal – visible only for automaton itself

- Fariness, liveness, safety

Proof – asynchronous network model (III.)

- Theorem **T1**:

  "It is impossible in the asynchronous network model to implement read/write data object that guarantees:

  - *availability and*
  - *atomic consistency*

  in all fair executions (including those in which messages are lost)."

- Proof by contradiction

PROOF – ASYNCHRONOUS NETWORK MODEL (IV.)

- Algorithm **A** that meets: atomicity, availability, partition tolerance
- Construct an execution of **A** with an inconsistent response
- Network:
  - at least two nodes
  - could be divided into two disjoint, non-empty sets: $\{\mathbf{G_1},\mathbf{G_2}\}$
  - all messages between $\mathbf{G_1}$ and $\mathbf{G_2}$ are lost
- Write in $\mathbf{G_1}$, later read in $\mathbf{G_2}$ -> ***read cannot return result of earlier write*** *(no messages between G1 and G2 during network partition)*

- $\mathbf{v_0}$ - initial value of the atomic object
- $\boldsymbol{\alpha_1}$ - prefix of an execution of **A**.

  - single write of value in $\mathbf{G_1}$ (value is not equal to $\mathbf{v_0}$)
- $\boldsymbol{\alpha_2}$ - prefix of an execution of **A**.

  - single read of value in $\mathbf{G_2}$ (value is not equal to $\mathbf{v_0}$)
- No other client requests
- No messages between $\mathbf{G_1}$ and $\mathbf{G_2}$ in $\boldsymbol{\alpha_1}$ or $\boldsymbol{\alpha_2}$
- $\boldsymbol{\alpha}$ – execution **A** of beginning $\boldsymbol{\alpha_1}$ with continuing with $\boldsymbol{\alpha_2}$

- In the **α** execution the read from **α_2** must still return **v_0**
- Read request does not begin until write from **α_1** completes
- ***Atomic consistency is broken -> no such algorithm exists***

□

- Partially synchronous network model from the book ‘Distributed algorithms’:
  - Every node has a clock (increase at the same rate, but not synchronously)
  - Clocks can be observed to measure how much time has passed

- Every message is either:
  - Delivered within given, known time $\mathbf{t_{msg}}$ or lost
  - Processed by node in given, known time $\mathbf{t_{local}}$
- General timed automata – from Timed automaton, with fairness conditions replaced with lower and upper bound on time.

- Theorem **T1** holds also in partialy synchronous network model:
- Again divide network to $\{\mathbf{G_1},\mathbf{G_2}\}$
- Construct similar execution as in case of **T1** – write in $\mathbf{G_1}$, later read in $\mathbf{G_2}$ -> ***read cannot return result of earlier write*** *(no messages between G1 and G2 during network partition)*

- $\mathbf{v_0}$ - initial value of the atomic object
- $\boldsymbol{\alpha_1}$ - same as in the case **T1** proof
- $\boldsymbol{\alpha_2}$´ - slightly different then $\boldsymbol{\alpha_2}$

  - begins with time interval at least as long as duration of $\boldsymbol{\alpha_1}$ followed by events of $\boldsymbol{\alpha_2}$
- No other client requests
- No messages between $\mathbf{G_1}$ and $\mathbf{G_2}$ in $\boldsymbol{\alpha_1}$ or $\boldsymbol{\alpha_2}$´
- $\boldsymbol{\alpha}$ – execution **A** of begining $\boldsymbol{\alpha_1}$ with continuing with $\boldsymbol{\alpha_2}$´

- Again, In the **α** execution the read from $\boldsymbol{\alpha_2}'$ must still return $\mathbf{v_0}$
- Read request return initial value instead of new value from write request in **G1**
- ***Atomic consistency is broken -> no such algorithm exists***

□

- CAP Theorem: properties of distributed systems – can have at most two of **C** – **A** – **P**.
- We could never sacrifice **P**artition tolerance
- Always trade-off between **C**onsistency and **A**vailability
- Proven in asynchronous and partialy synchronous network models

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Thank You For Your Attention