Cloud·TM

A novel programming paradigm for the Cloud

SEVENTH FRAMEWORK PROGRAMME

Autonomic mechanisms for transactional replication in elastic cloud environments

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2nd Workshop on Software Services, Timisoara, Romania, 6 June 2011

About me

- Master (2002) and PhD (2007) from Rome University "La Sapienza"
- Researcher & Lecturer at Rome University "La Sapienza" (2007-2008)
- Senior Researcher at Distributed Systems Group, INESC-ID, Lisbon (since 2008)

- Coordinator of the FCT Aristos Project (Jan 2010-Jan 2012)
  - Bilateral Italian-Portuguese project
  - Autonomic Replication of Transactional Memories
- Coordinator of the FP7 Cloud-TM Project (Jun 2010-Jun2012)
  - 4 international partners from industry and academy
  - Self-tuning, Distributed Transactional Memory platform for the Cloud
- Coordinator of the Cost Action Euro-TM (fall 2010-fall 2013)
  - Pan-European Research network on Transactional Memories
  - 56 experts, 42 institutions, 12 countries

Outline

- Overview of the Cloud-TM project
- Software Transactional Memories (STMs)
- Data Replication Protocols for STMs
  - No one size fits all solution
- Self-Optimizing Replication Protocols:
  - AB-based certification protocols
  - Single vs Multi-master schemes

Cloud-TM at a glance

Partners:

INESC ID (PT)

Algorithmica (IT)

C.I.N.I. (IT)

Red Hat (IE)

Project coordinator:
Paolo Romano, INESC ID (PT)

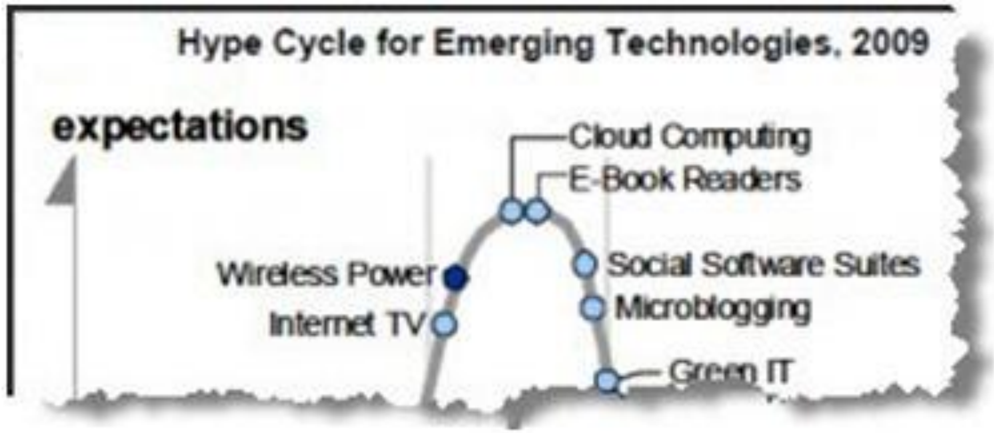
Duration:
From June 2010 to May 2013

Programme:
FP7-ICT-2009-5 – Objective 1.2

Further information:
http://www.cloudtm.eu

Project Motivations

- Cloud computing is at the peak of its hype…



SIMPLIFYING THE DEVELOPMENT AND ADMINISTRATION OF CLOUD APPLICATIONS

- How to materialize the vision and maximize actual productivity?

Key Goals

Develop an open-source middleware platform for the Cloud:

1. Providing a simple and intuitive programming model:
   - ➪ hide complexity of distribution, persistence, fault-tolerance
   - ➪ let programmers focus on differentiating business value

2. Minimizing administration and monitoring costs:
   - ➪ automate elastic resource provisioning based on applications QoS requirements

3. Minimize operational costs via self-tuning
   - ➪ maximizing efficiency adapting consistency mechanisms upon changes of workload and allocated resources

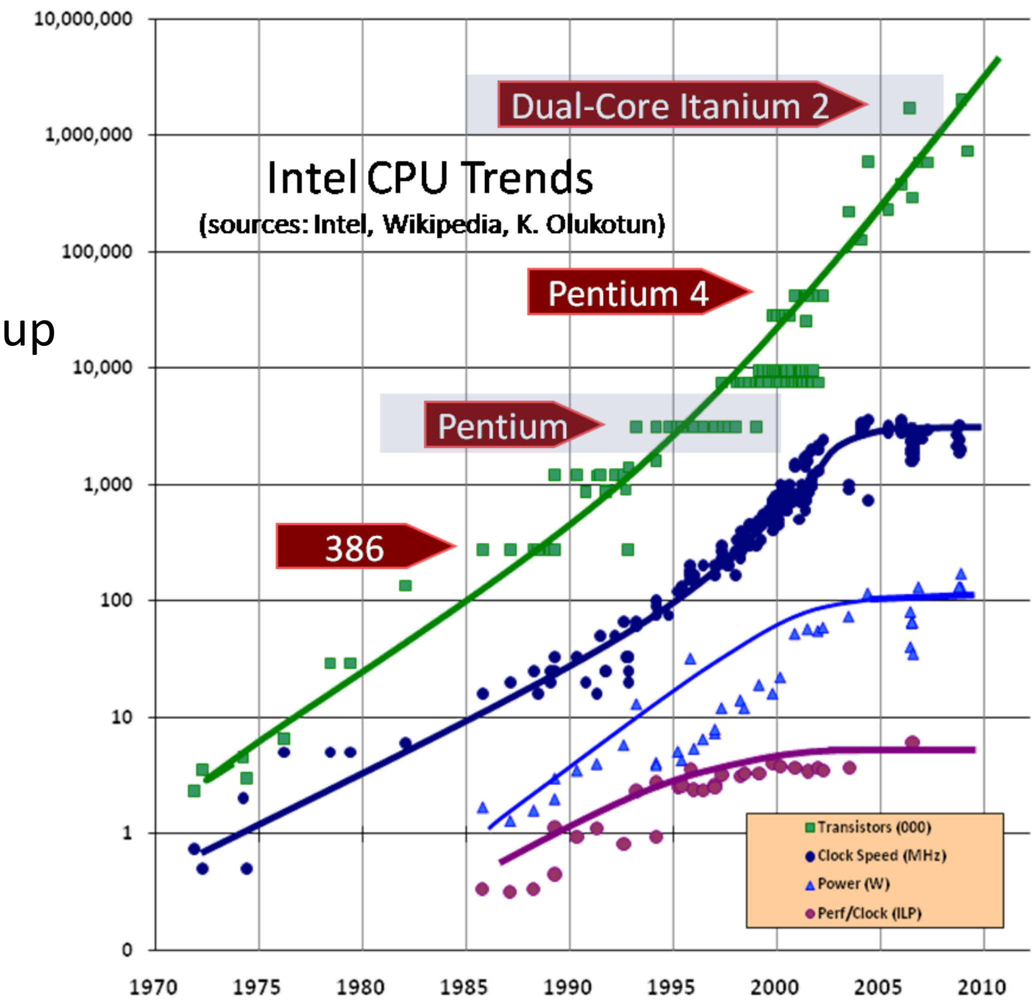
Background on the Cloud-TM Programming Paradigm….

TRANSACTIONAL MEMORIES

The era of free performance gains is over

- Over the last 30 years:
  - new CPU generation = free speed-up
- Since 2003:
  - CPU clock speed plateaued...
  - but Moore's law chase continues:
    - Multi-cores, Hyperthreading...

FUTURE IS PARALLEL



Fine grained locking?

- Simple grained locking is a **conundrum:**
  - need to reason about deadlocks, livelocks, priority inversions:
    - complex/undocumented lock acquistion protocols
    - scarce composability of existing software modules

  ... and a **verification nightmare:**
    - subtle bugs that are extremely hard to reproduce

- Make parallel programming **accessible to the masses!**

Transactional memories

- Key idea:
  - hide away synchronization issues from the programmer
  - replace locks with atomic transactions:
    - avoid deadlocks, priority inversions, convoying
    - way simpler to reason about, verify, compose
    - deliver performance of hand-crafted locking via speculation (+HW support)

An obvious evolution

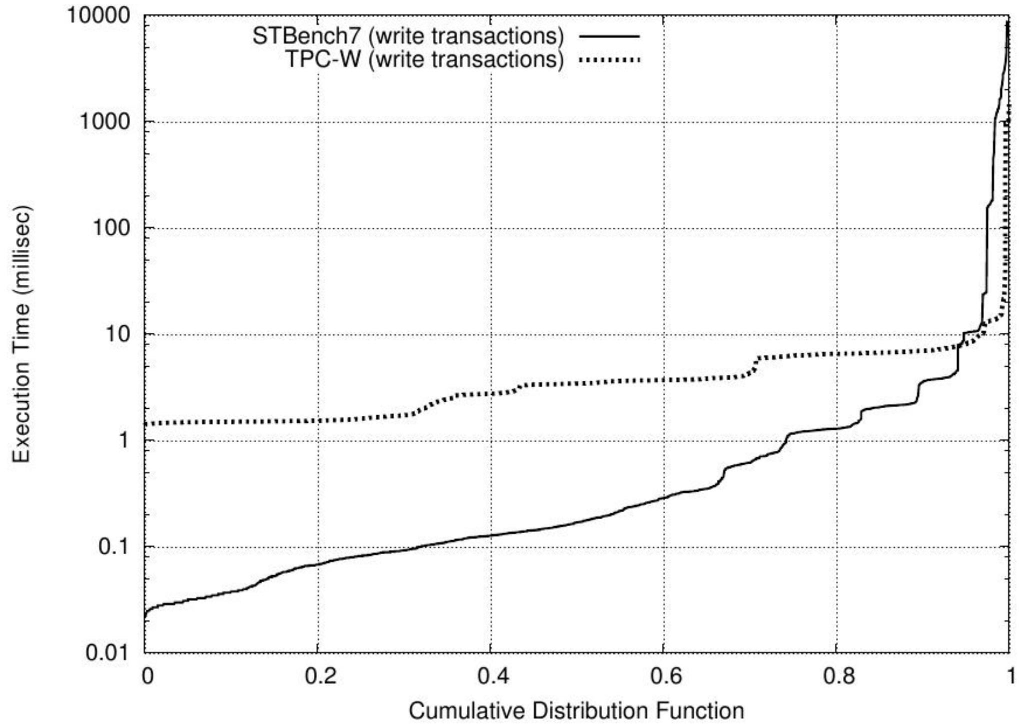
- Real, complex STM based applications are starting to appear:
  - Apache Web Server
  - FenixEDU
  - Circuit Routing
  - …
- …and are being faced with classic production environment's challenges:
  - scalability
  - high-availability
  - fault-tolerance

$\Big\}$ **Distributed STMs**

Distributed STMs

- At the convergence of two main areas:

>70% xacts are 10-100 times shorter:
- larger impact of coordination



2. Boost performance by batching any remote synchronization during the commit phase

unique, challenging requirements!

The Cloud-TM Programming Paradigm: Elastic Distributed Transactional Memory

- Elastic scale-up and scale-down of the DTM platform:
  - data distribution policies minimizing reconfiguration overhead
  - auto-scaling based on user defined QoS & cost constraints

- Transparent support for fault-tolerance via data replication:
  - self-tuning of consistency protocols driven by workload changes

- Language level support for:
  - transparent support of object-oriented domain model (incl. search)
  - highly scalable abstractions
  - parallel transaction nesting in distributed environments

Data replication

- Essential for in-memory data platforms for:
  - Performance
  - Fault-tolerance
- Performance
  - Read operations on local data
- Fault-tolerance
  - Ensure data availability in presence of crashes

Challenge

- Distributed coordination when:
  - The transaction commits (all-or-none the copies must be updated)
  - But also for ensuring same serialization order across all replicas!

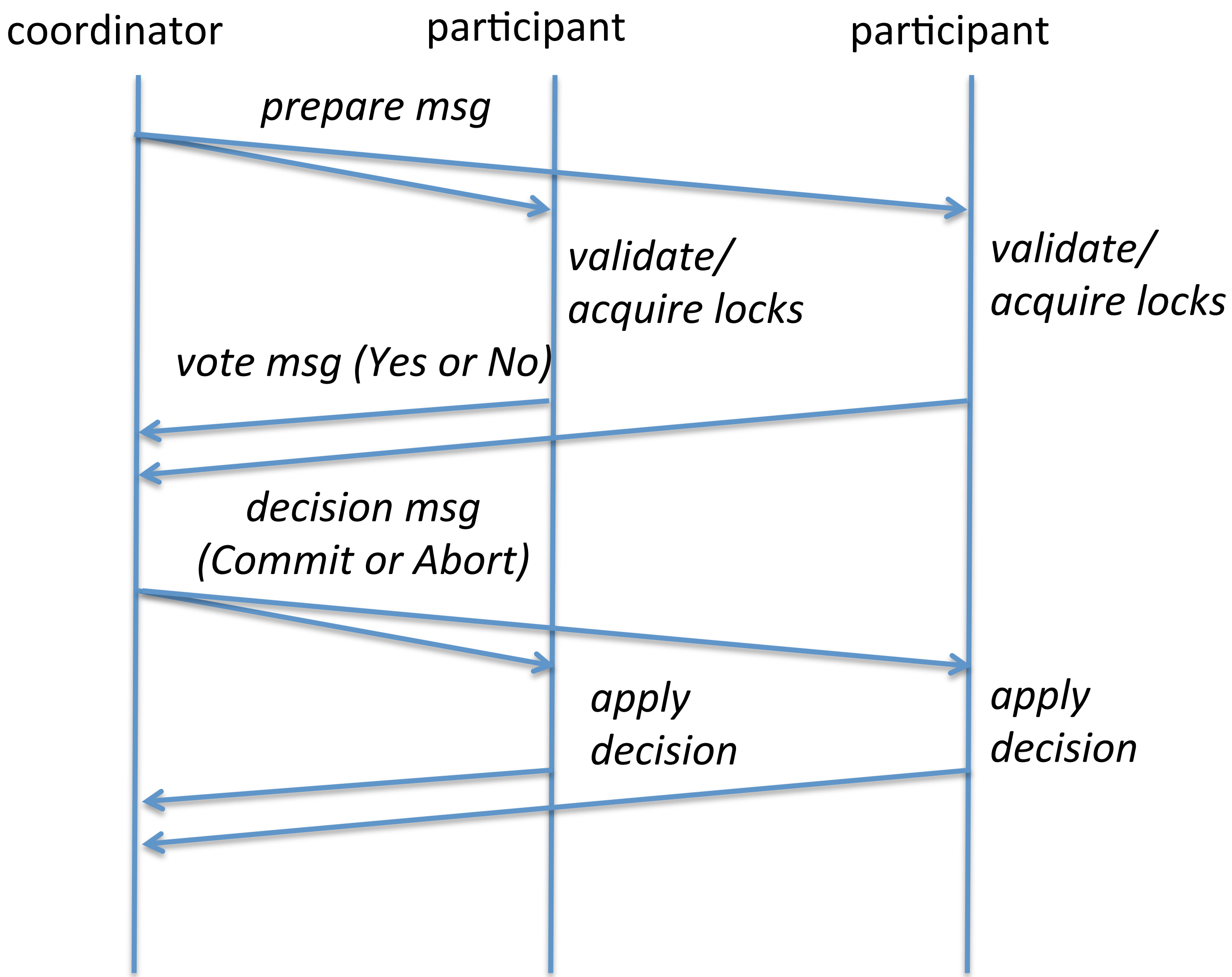
Toolbox for Replication

- **Atomic Commitment**
- Reliable Broadcast
- Atomic Broadcast

Atomic Commitment

- Set of nodes, each node has input:
  - CanCommit
  - MustAbort
- All nodes output same value
  - Commit
  - Abort
- Commit is only output if all nodes CanCommit

2-phase commit



Toolbox for Replication

- Atomic Commitment
- **Reliable Broadcast**
- Atomic Broadcast

(Uniform) Reliable Broadcast

- Allows to broadcast a message **m** to all replicas
- If a process delivers **m**, every correct node will deliver **m**
- Useful to propagate updates

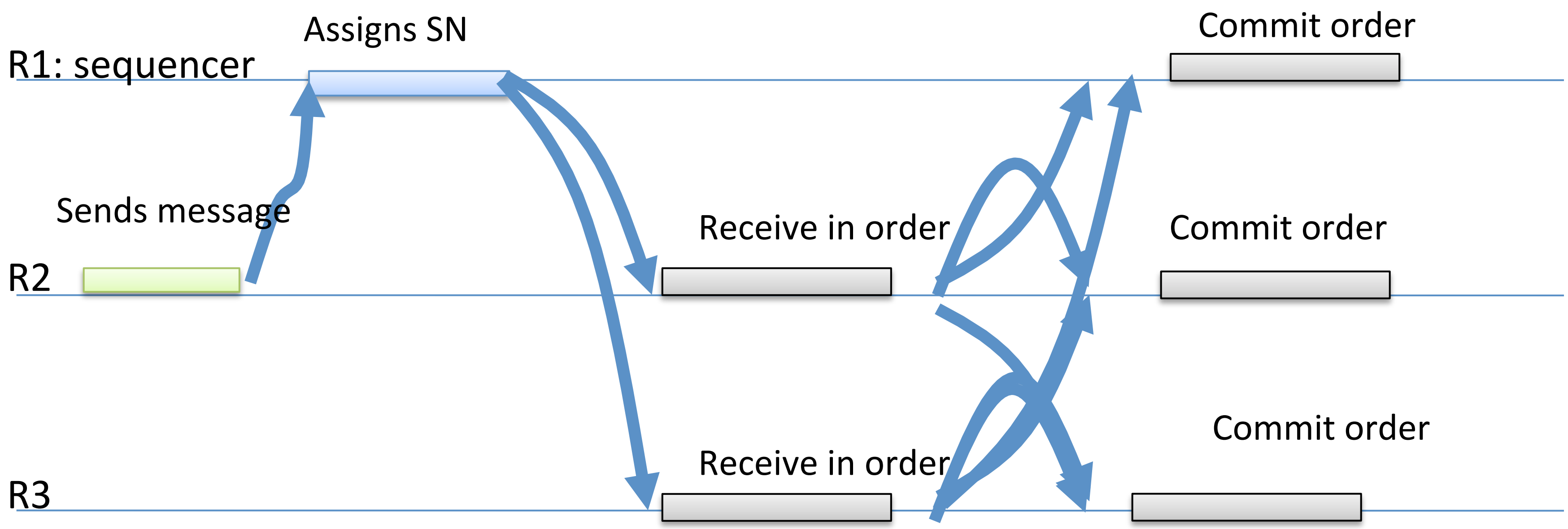
Toolbox for Replication

- Atomic Commitment
- Reliable Broadcast
- **Atomic Broadcast**

Atomic Broadcast

- Reliable broadcast with total order
- If replica R1 receives **m1** before **m2**, any other replica Ri also receives **m1** before **m2**
- Can be used to allow different nodes to obtain locks in the same order

Sequencer-based ABcast



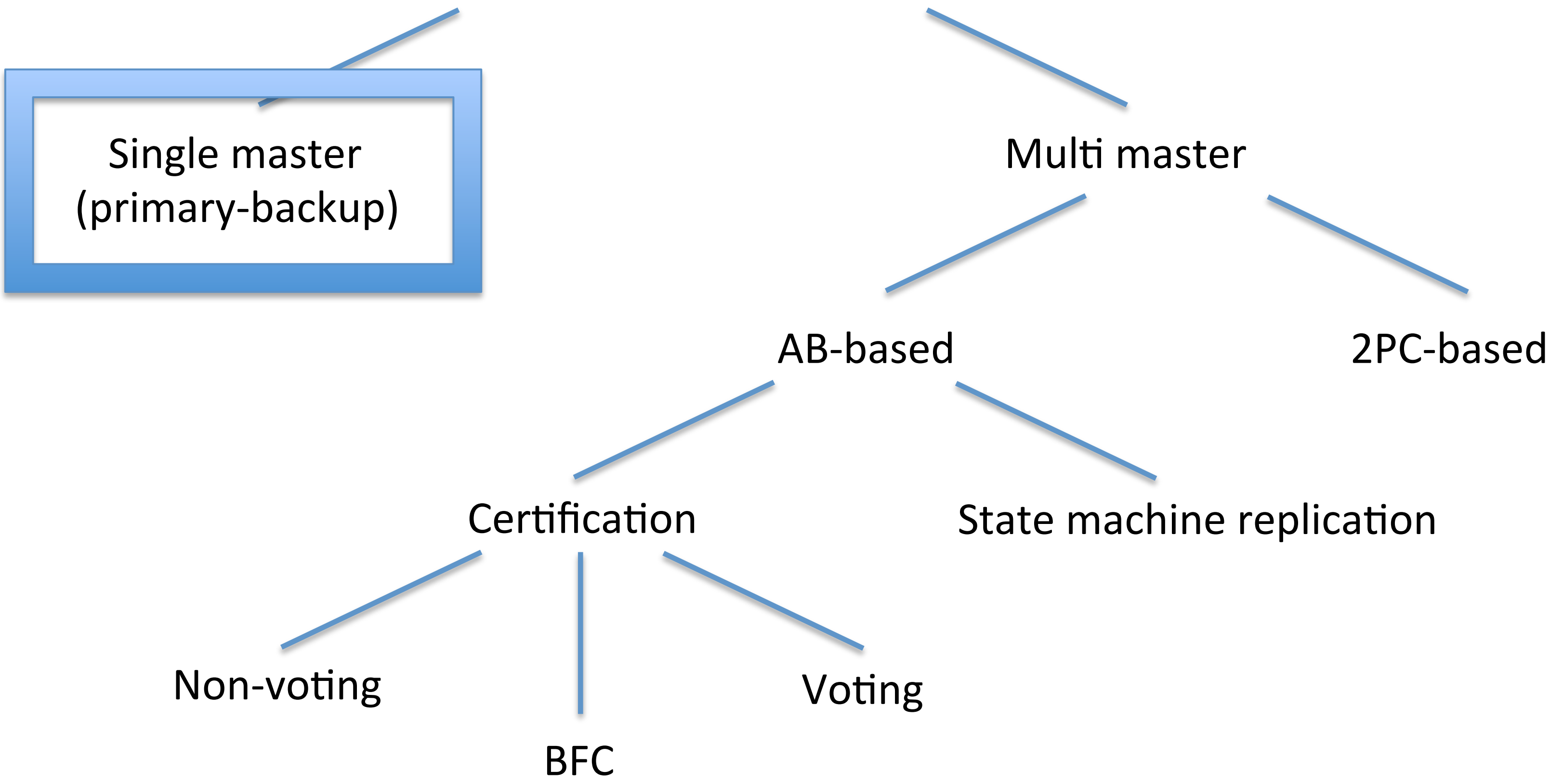
CLASSIC PROTOCOLS FOR TRANSACTIONAL REPLICATION

Classic Replication Protocols

- Focus on full replication protocols
  - Single master (primary-backup)
  - Multi master
    - AB-based
      - Certification
        - Non-voting
        - BFC
        - Voting
      - State machine replication
    - 2PC-based

Classic Replication Protocols

- Focus on full replication protocols



Single Master

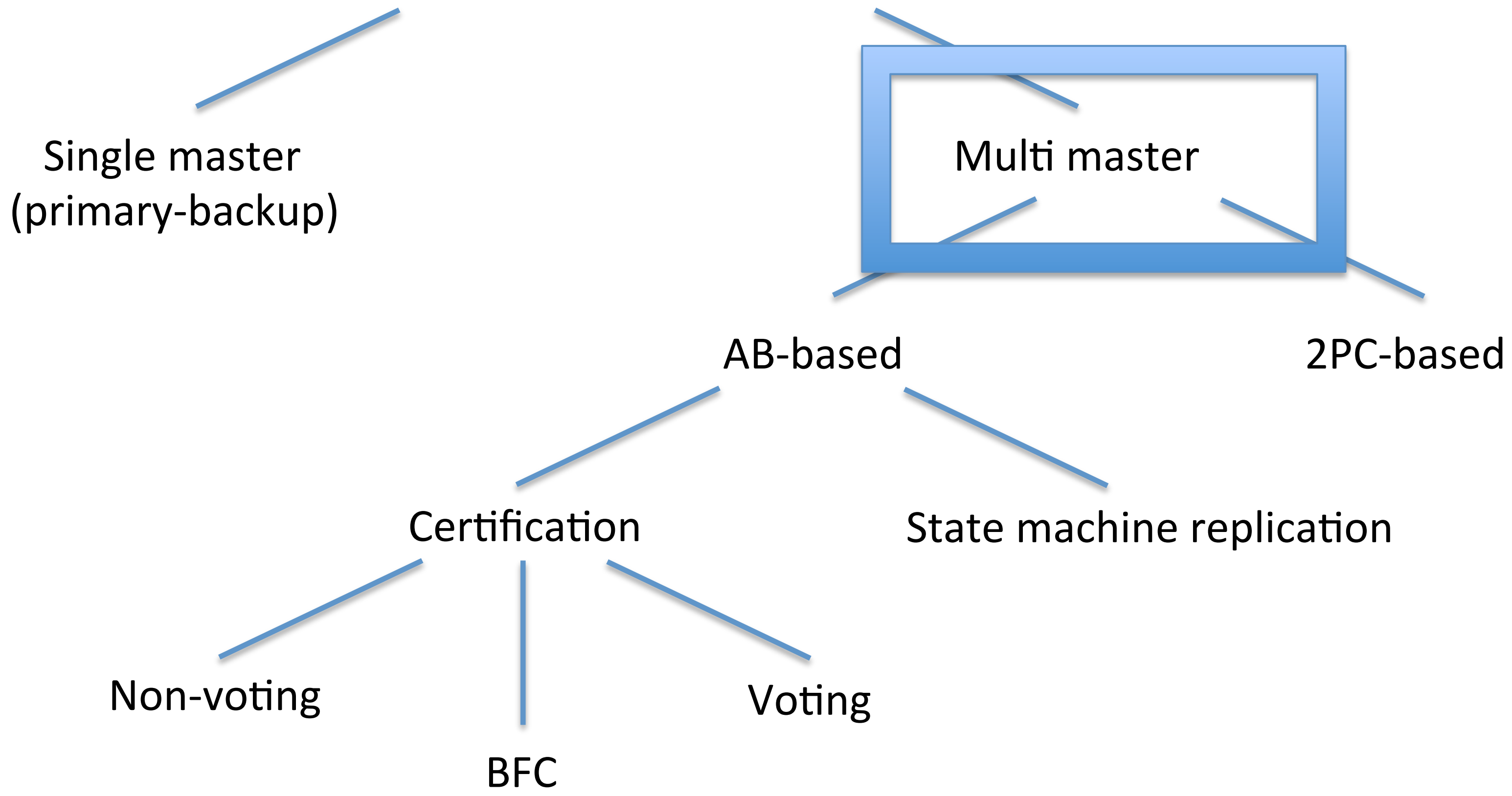
- Write transactions are executed entirely in a single replica (the primary)
- If the transaction aborts, no coordination is required.
- If the transaction is ready to commit, coordination is required to update all the other replicas (backups).
  - Reliable broadcast primitive.
- Read transactions can be executed on backup replicas.

- **No distributed deadlocks**
- **No distributed coordination during commit**

- **Throughput of write txs doesn't scale up with number of nodes**

Classic Replication Protocols

- Focus on full replication protocols

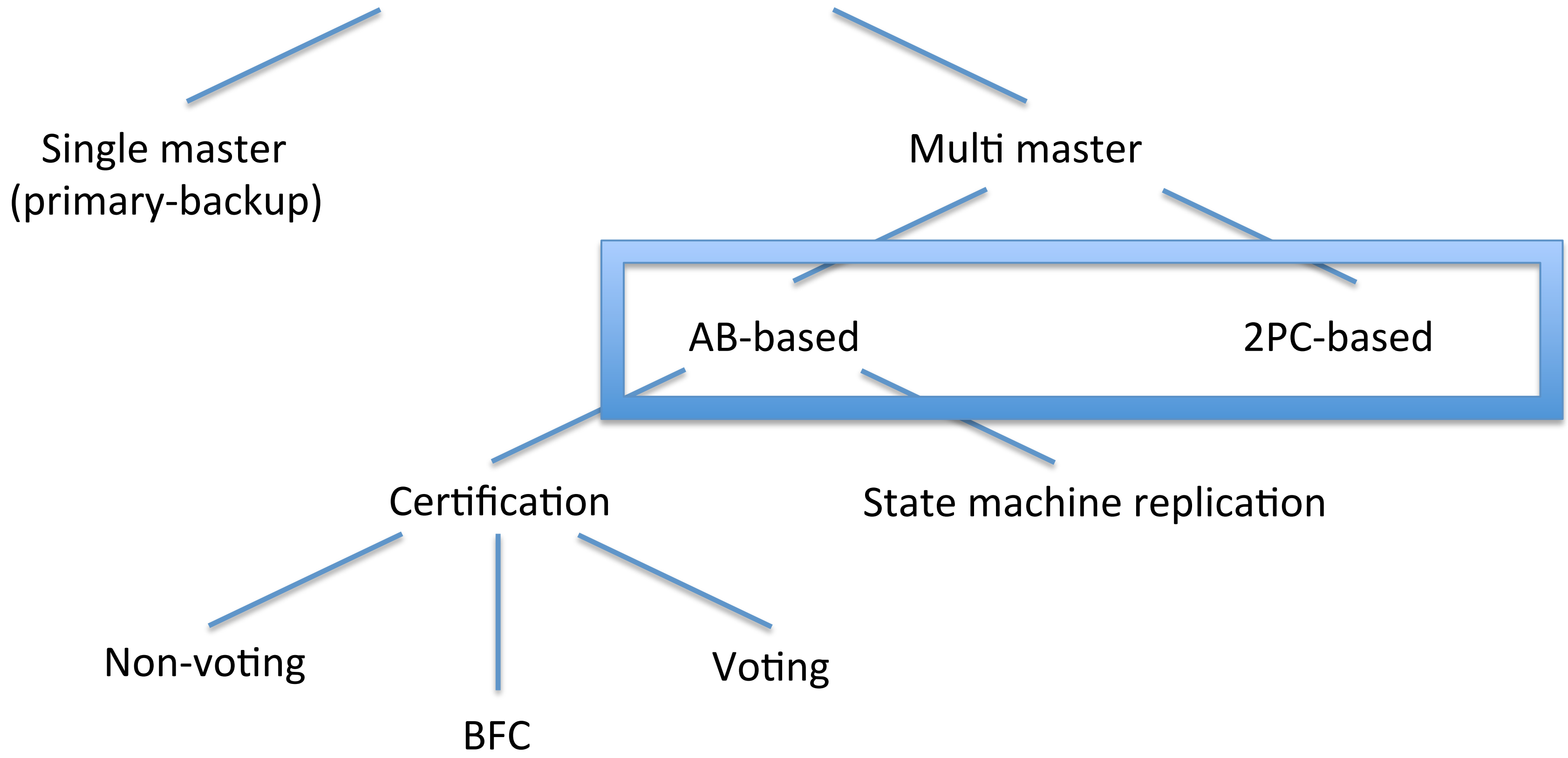


Multi master replication

- Write and read transactions can be processed anywhere
- Access Synchronization:
  - **Eager: upon each access (bad bad performance)**
  - Lazy: at commit time
- Lazy multi-master are classifiable as:
  - 2PC-based
  - AB-based

Classic Replication Protocols

- Focus on full replication protocols



2PC-based vs AB-based

2PC-based replication

- Transactions attempt to acquire atomically locks at all nodes
- 2PC materializes conflicts among remote transactions generating:

DISTRIBUTED DEADLOCKS

+ good scalability at low conflict

- thrashes at high conflict

AB-based replication

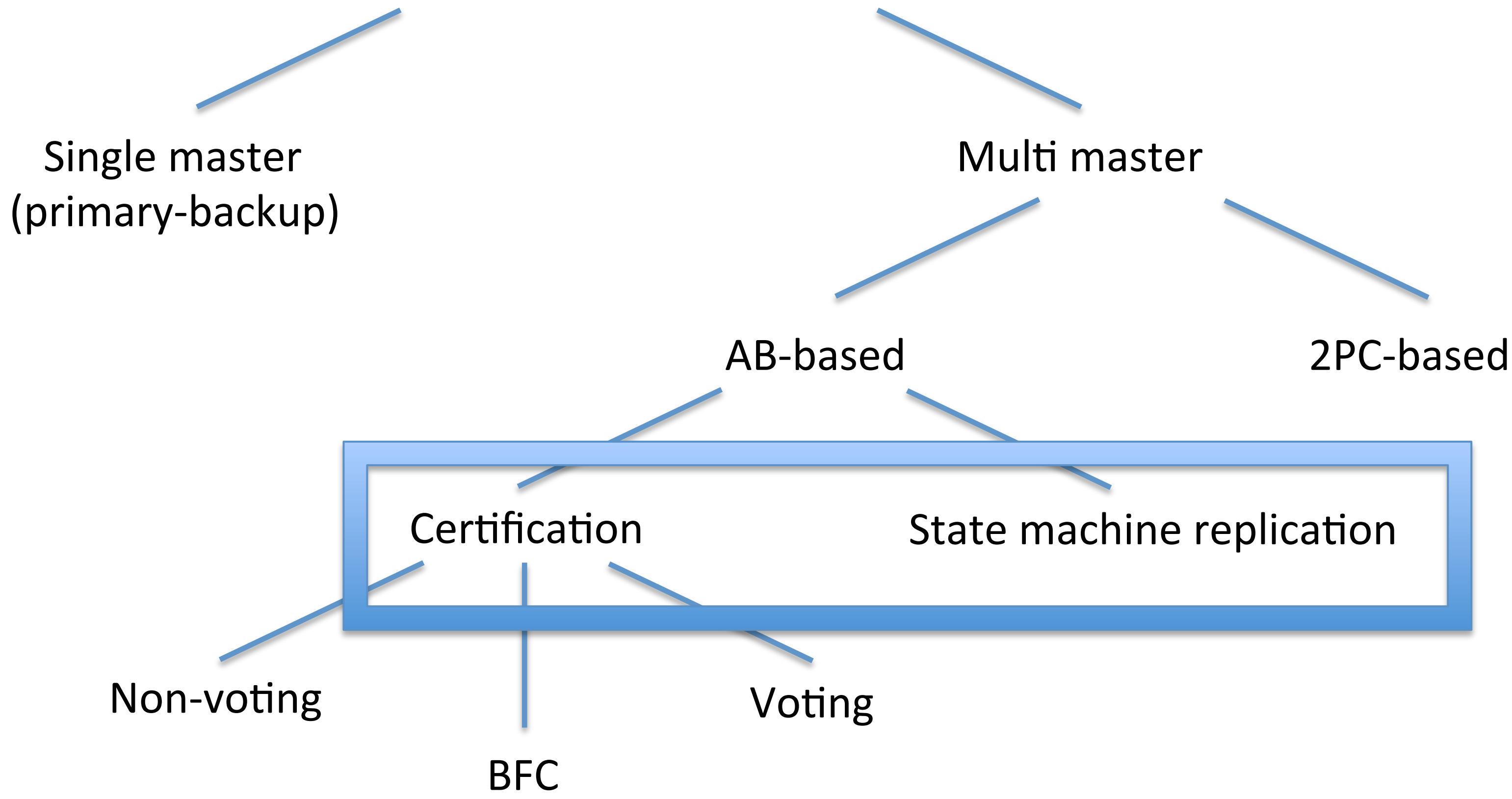
- family of (distributed) deadlock free algorithms
- Serialize transactions in the total order established by AB

+ strong gains at high conflict rates

- AB latency typically higher than 2PC

Classic Replication Protocols

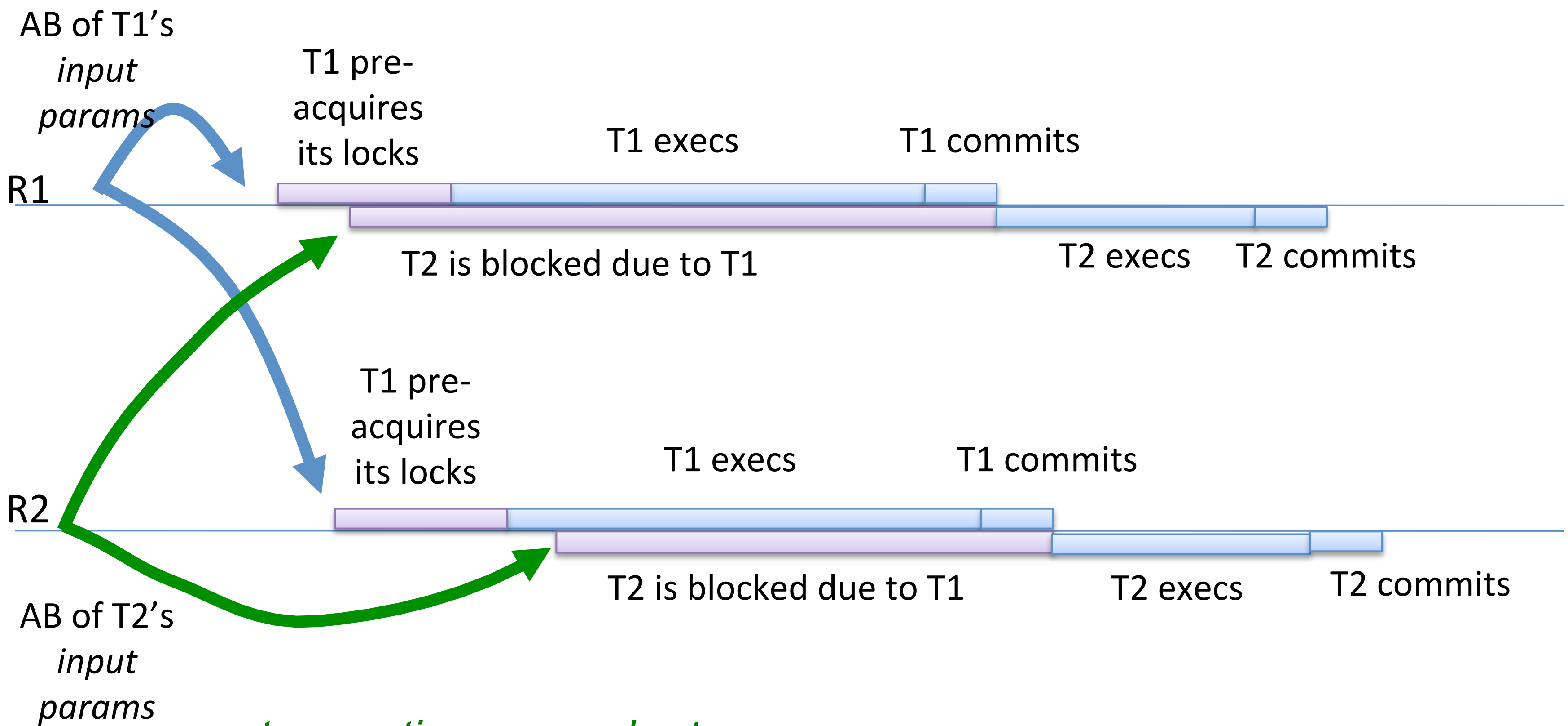
- Focus on full replication protocols



State-machine replication

- All replicas execute the same set of transactions, in the same order.
- Transactions are shipped to all replicas using total order broadcast.
- Replicas receive transactions in the same order.
- Replicas execute transaction by that order.
  - Transactions need to be deterministic!

State-machine replication



+ transaction never abort

- Write transactions fully executed by all replicas: low scalability

Certification
(a.k.a. deferred update)

- A transaction is executed entirely in a single replica.
- Different transactions may be executed on different replicas.
- If the transaction aborts, no coordination is required.
- If the transaction is ready to commit, coordination is required:
  - To ensure serializability
  - To propagate the updates

Certification

- Two transactions may update concurrently the same data in different replicas.
- Coordination must detect this situation and abort at least one of the transactions.
- Three alternatives:
  - – Non-voting algorithm
  - – Voting algorithm
  - – BFC

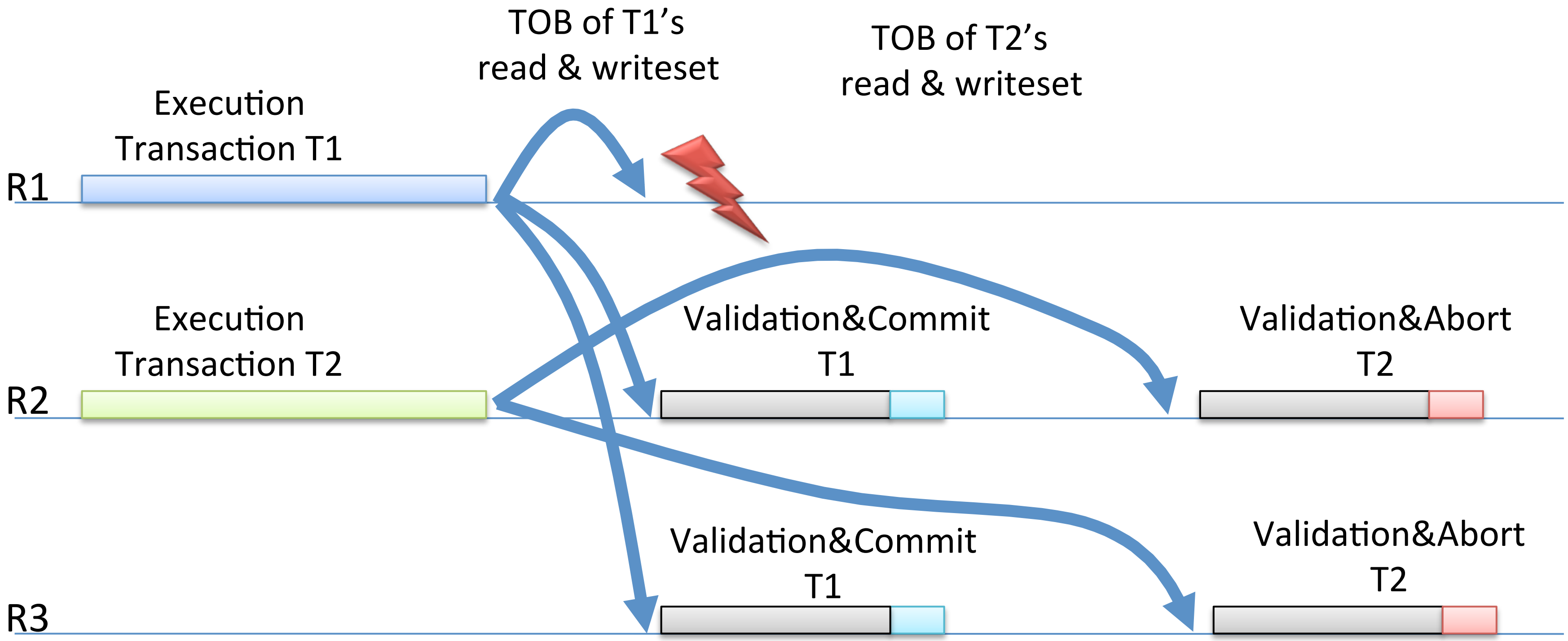
Classic Replication Protocols

- Focus on full replication protocols
  - Single master (primary-backup)
  - Multi master
    - AB-based
      - Certification
        - Non-voting
        - BFC
        - Voting
      - State machine replication
    - 2PC-based

Non-voting

- The transaction executes locally.
- When the transaction is ready to commit, the **read and write set** are sent to all replicas using total order broadcast.
- Transactions are certified in total order.
- A transaction may commit if its read set is still valid (i.e., no other transaction has updated the read set).

Non-voting



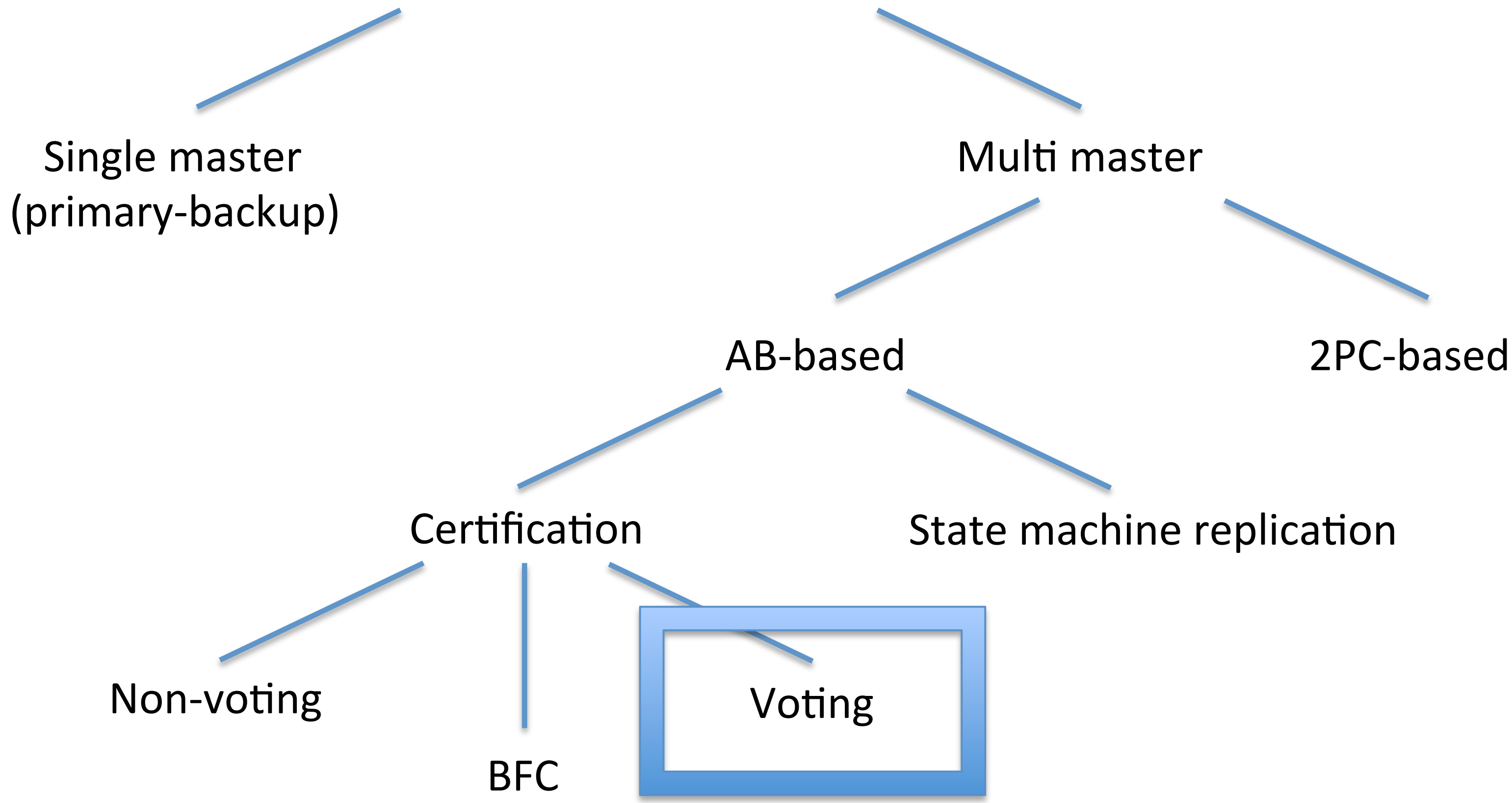
+ only validation executed at all replicas:

high scalability with write intensive workloads

- need to send also readset: often very large!

Classic Replication Protocols

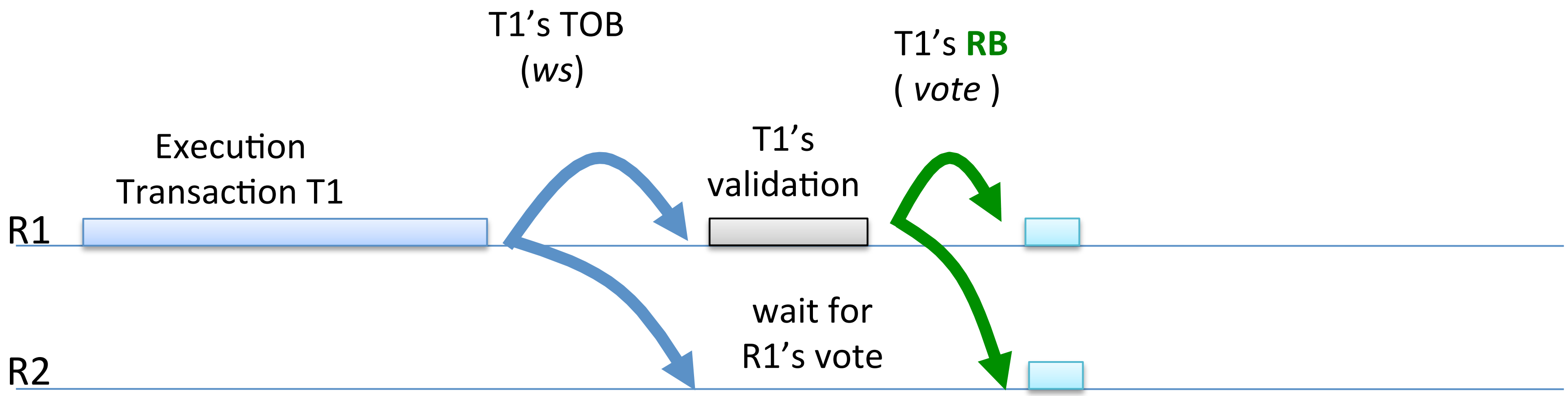
- Focus on full replication protocols



Voting

- The transaction executes locally at replica R
- When the transaction is ready to commit, **only the write set** is sent to all replicas using total order broadcast
- Commit requests are processed in total order
- A transaction may commit if its read set is still valid (i.e., no other transaction has updated the read set):
  - **Only R can certify the transaction!**
- R send the outcome of the transaction to all replicas:
  - Reliable broadcast

Voting

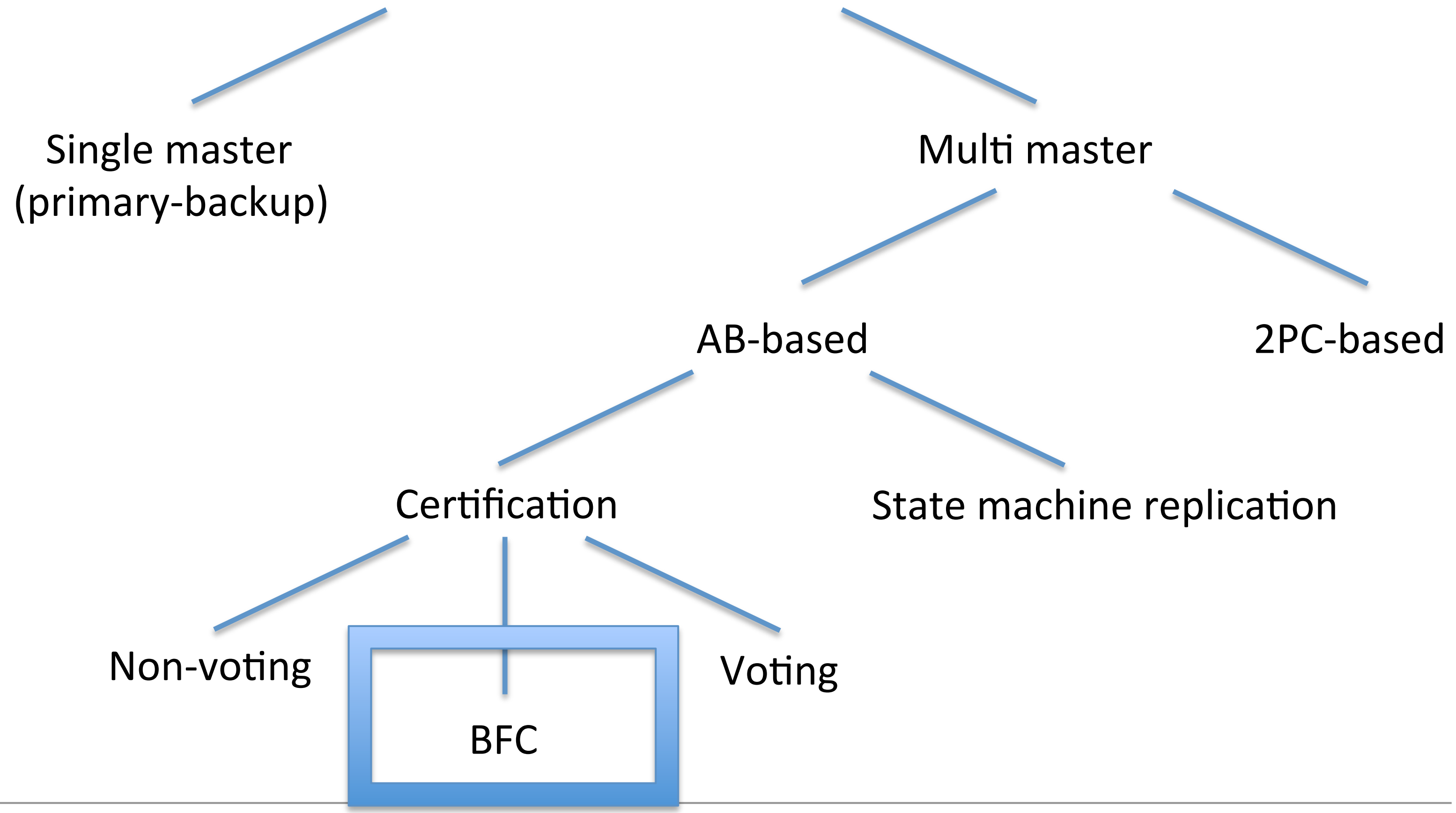


+ sends only write-set (much smaller than read-sets normally)

- Additional communication phase to disseminate decision (vote)

Classic Replication Protocols

- Focus on full replication protocols



Bloom Filter Certification (BFC)

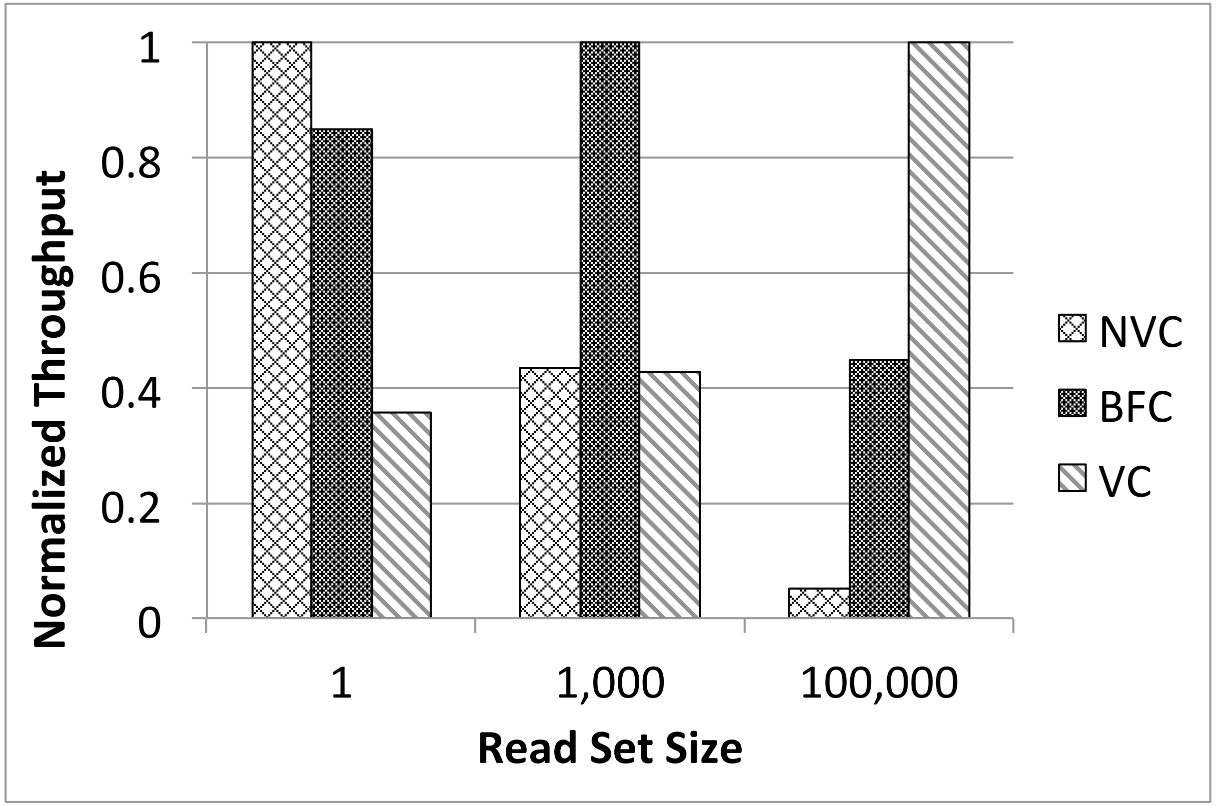
- Bloom filters:
  - space-efficient data structure for test membership queries
  - Probabilistic answer to "Is elem contained in BF?"
    - No false negatives: A "no" answer is always correct
    - False positives: A "yes" answer may be false
  - Compression is a function of a (tunable) false positive rate

- Key idea:
  - encode readset in a BF and test if any of the items written by concurrent transactions results in BF:
    - False positives: additional (deterministic) abort
  - strongly reduce network traffic:
    - 1% false positive up to 30x compression

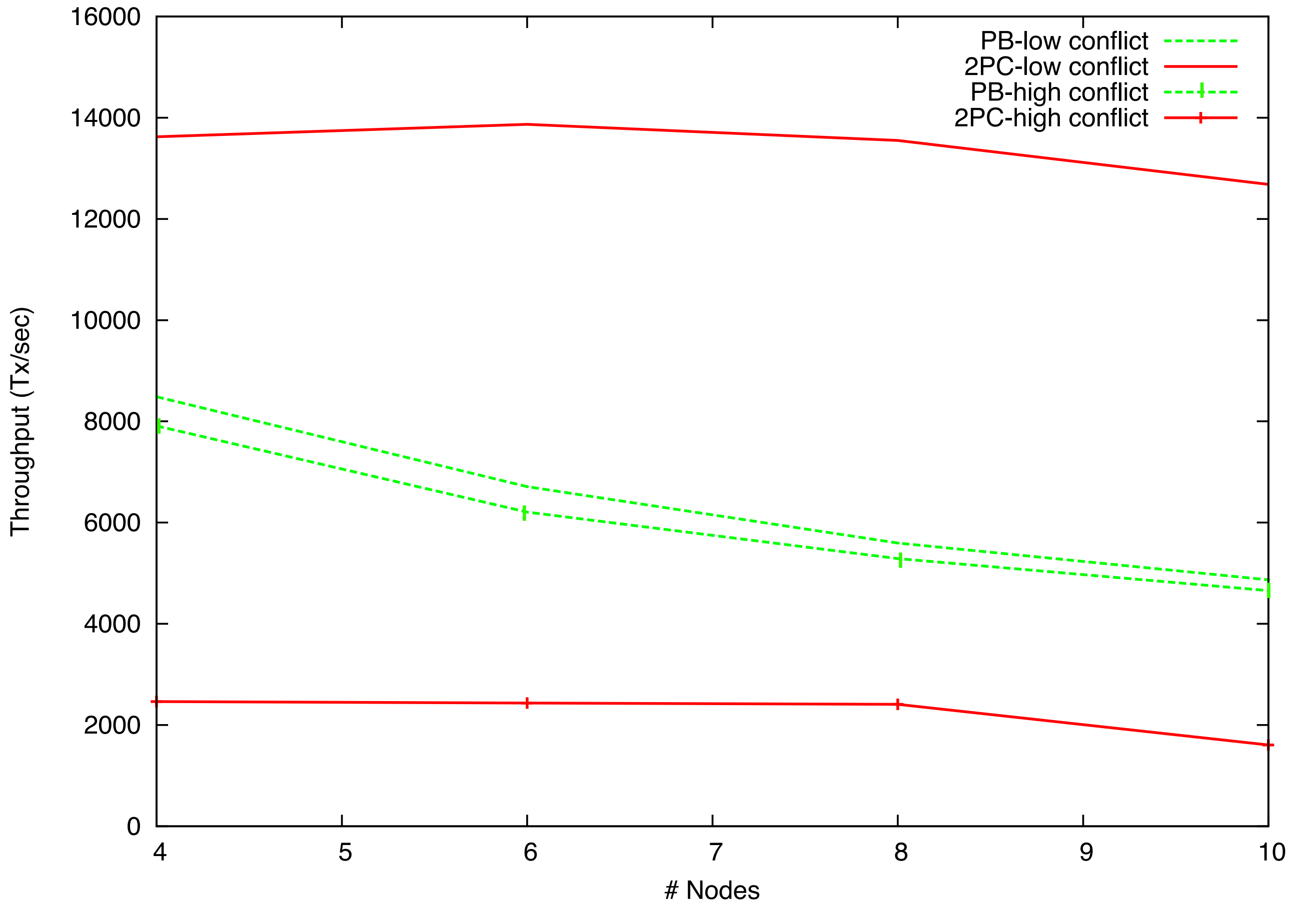
BFC vs Voting vs Non-Voting

+ optimal for "medium sized" readsets

- suboptimal for large and small readset sizes

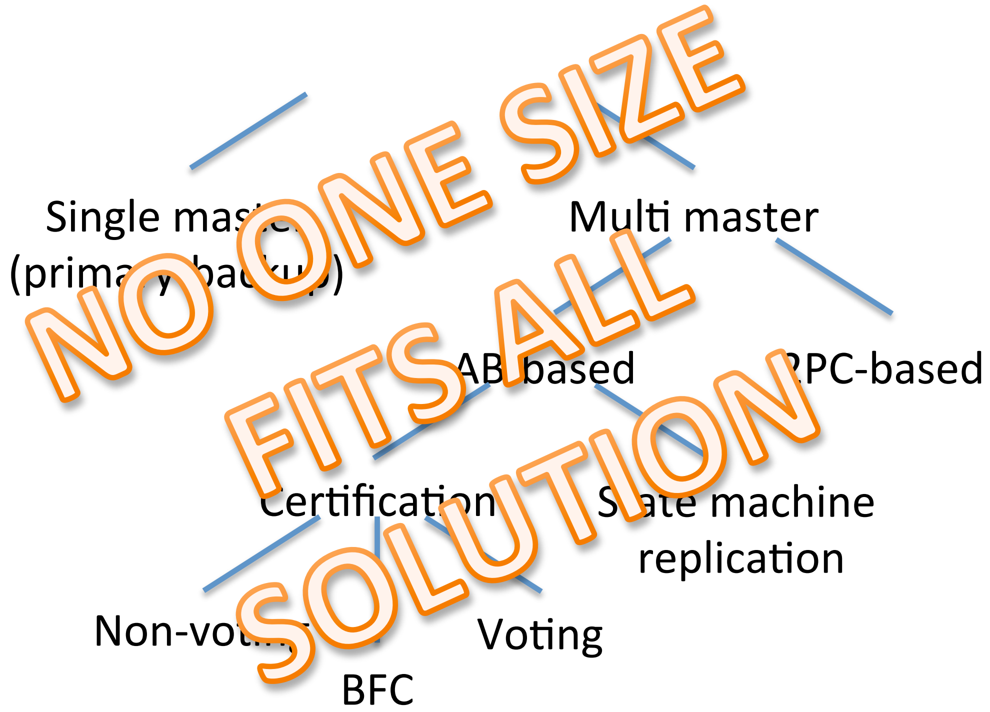


2PC-based vs single master

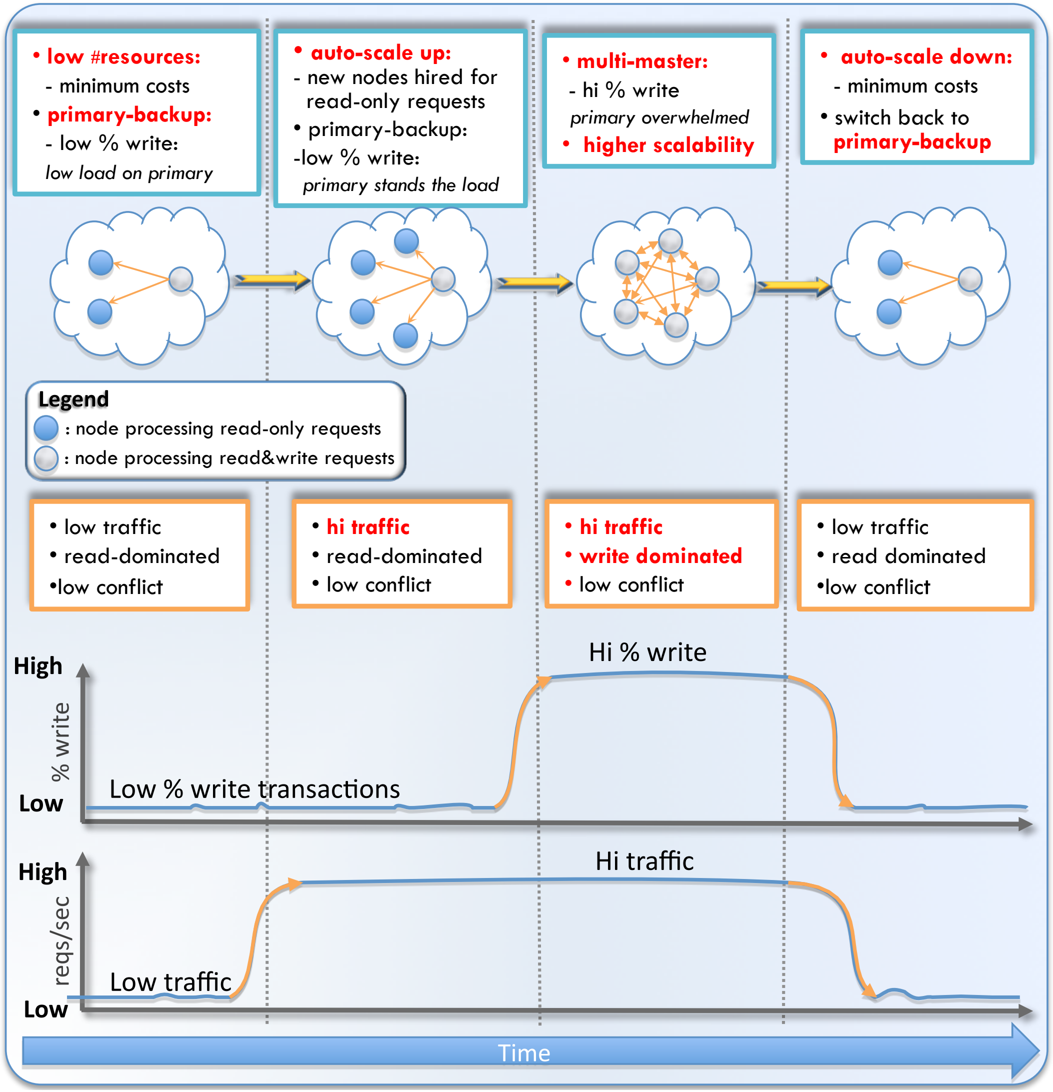


Summing up

- Existing solutions are optimized for specific workload/scale scenarios



Autonomic adaptation at play

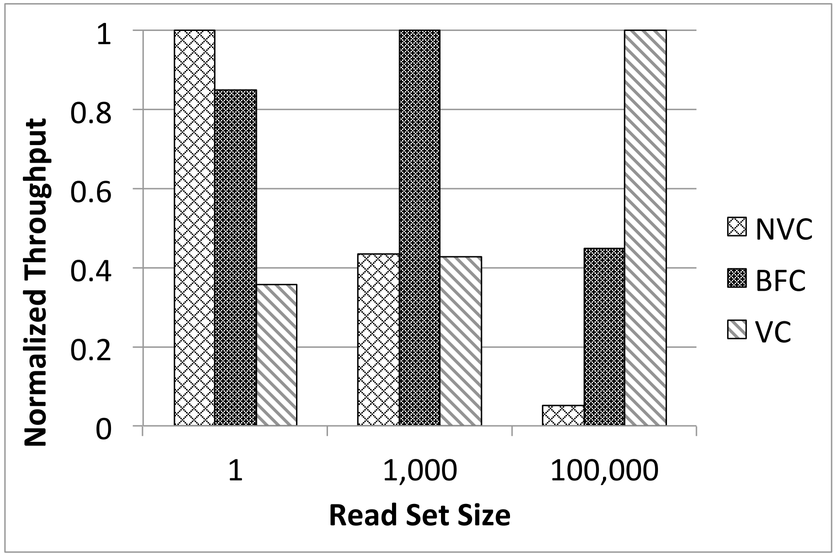


Self-optimizing replication

- Entails devising solutions to 2 keys issues:
  – Allow coexistence/efficient switch among multiple replication protocols:
    - Avoid blocking transaction processing during transitions
  – Determine the optimal replication strategy given the current (or foreseen) workload characteristics:
    - machine learning methods (black box)
    - analytical models (white box)
    - hybrid analytical/statistical approaches (gray box)

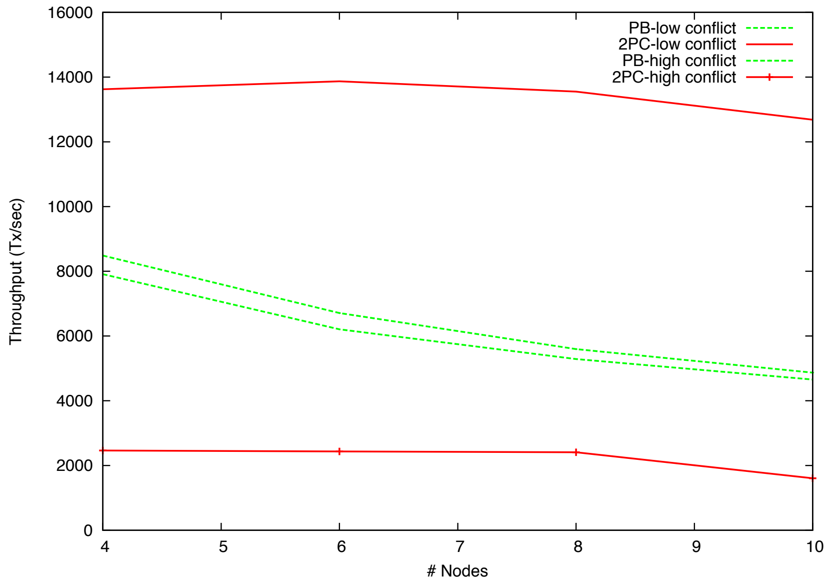
Two case studies

Certification Schemes
NVC vs VC vs BFC



joint work with
M. Couceiro, and L. Rodrigues

Single vs multi-master
2PC vs PB



joint work with
D. Didona, S. Peluso and F. Quaglia

Two case studies

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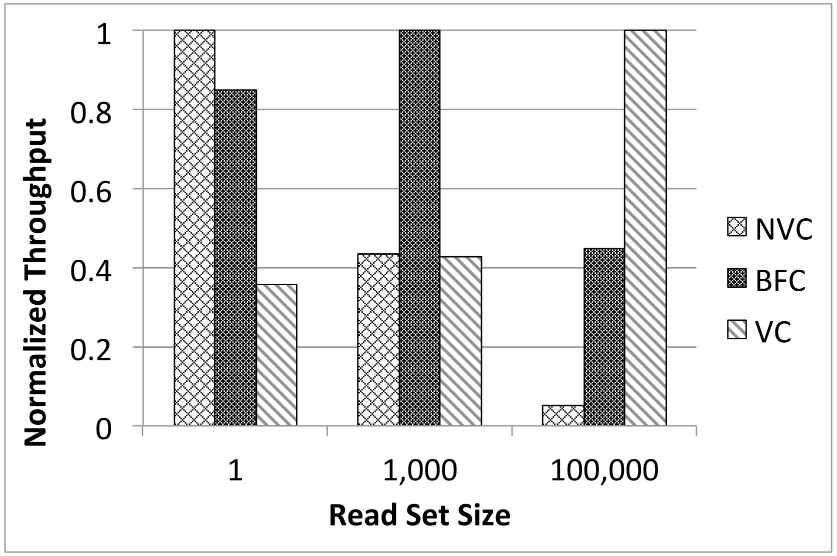

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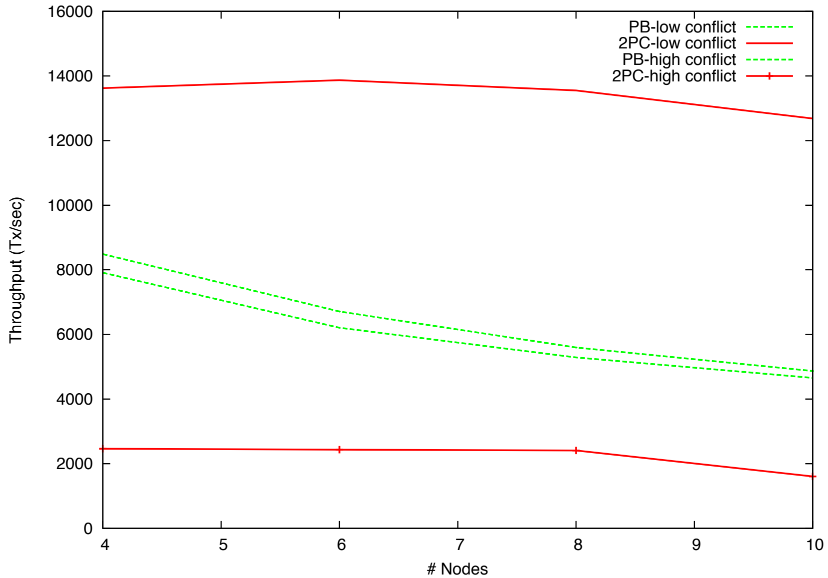

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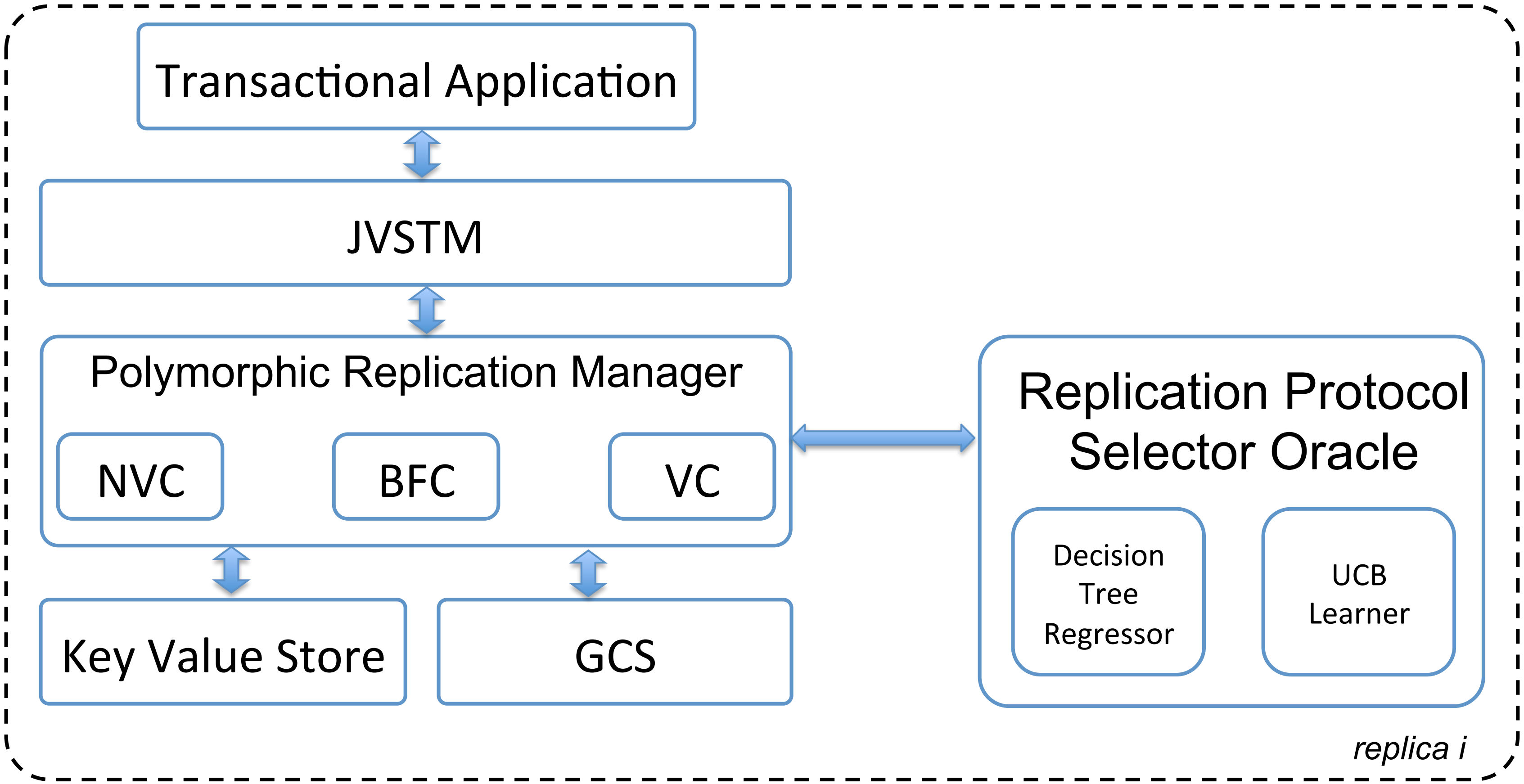
Certification Schemes NVC vs VC vs BFC

- The famous 2 keys issues:
  - Allow coexistence of multiple certification schemes via the Polymorhic Certification (PolyCert) protocol:
    - simultaneous presence of txs using NVC/VC/BFC
  - Determine the optimal replication strategy depending on workload characteristics:
    - machine learning methods to predict certification latency
      - off-line: decision-trees, neural network, SVM
      - on-line: reinforcement learning (UCB)

PolyCert: System Architecture



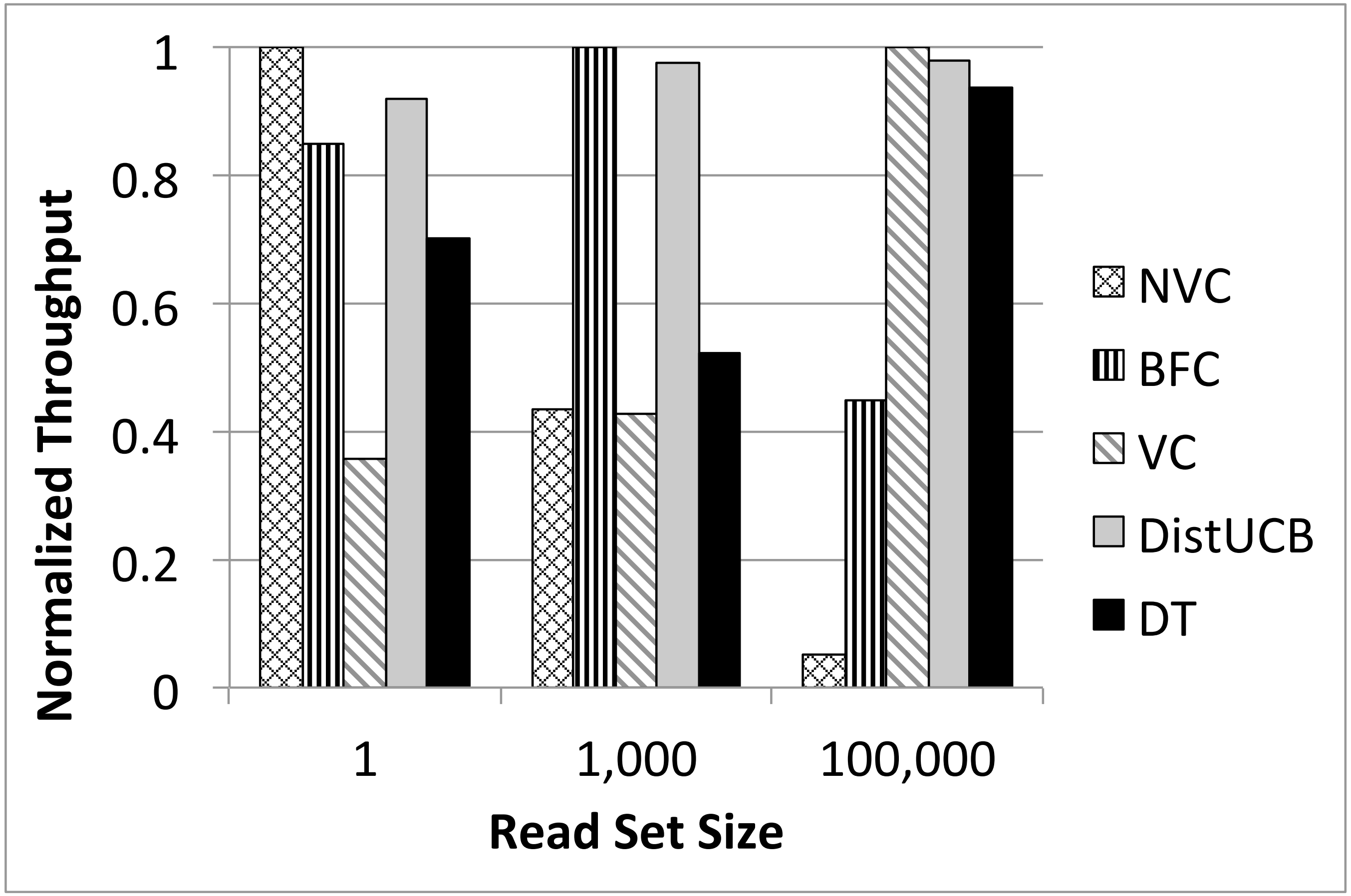
Off-line ML techniques

- Per each transaction:
  - predict size of AB message *m* for the various certification schemes
  - forecast AB latency for each message size. We evaluated several ML approaches:
    - **decision trees → best results**
    - neural networks
    - support vector machine
  - uses up to 53 monitored system attributes:
    - CPU
    - Memory
    - Network
    - Time-series
  - requires computational intensive training phase

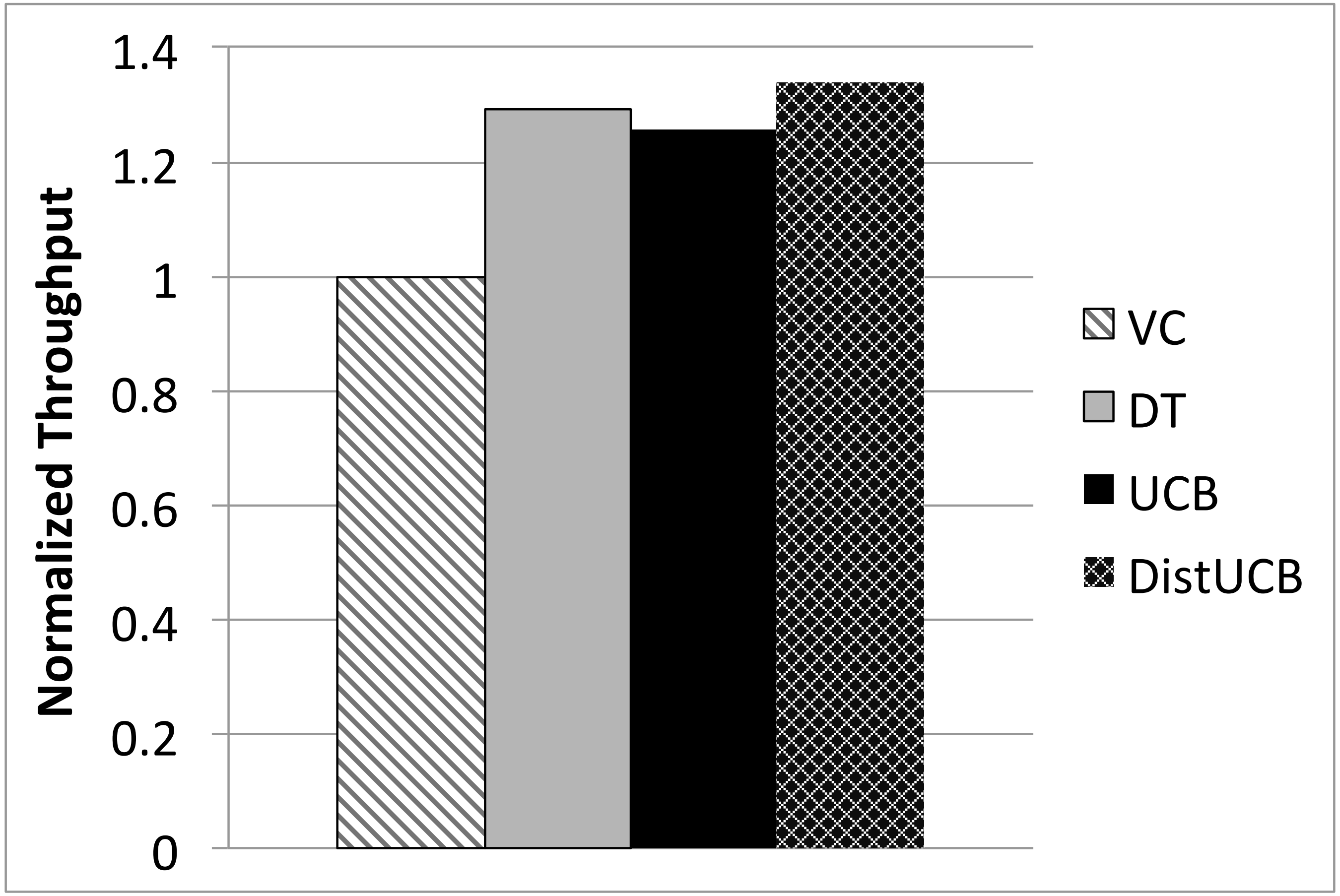
On-line reinforcement learning

- Each replica builds on-line expectations on the rewards of each protocol:
  – no assumption on rewards' distributions
- Solves the exploration-exploitation dilemma:
  – did I test this option sufficiently in this scenario?
- Distinguishes workload scenario solely based on read-set's size
  – exponential discretization intervals to minimize training time
- Replicas exchange statistical information periodically to boost learning

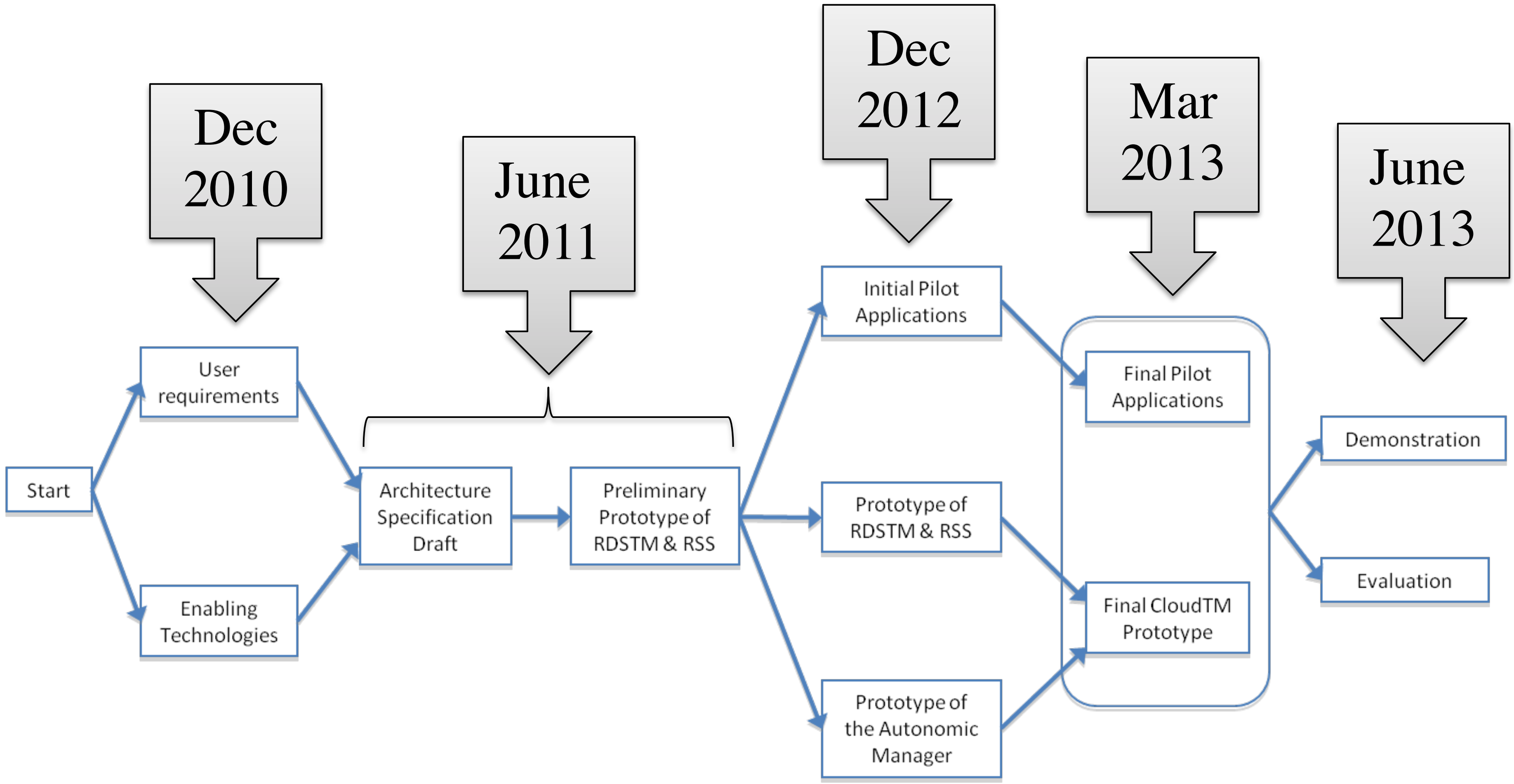
Chasing the optimum…



...and beating it!



Project's timeline



Opportunities for collaboration

- Standards/tools to specify and negotiate SLAs
  - focus in Cloud-TM is on performance, reliability and cost
- Tools for monitoring provided QoS
- Auto-scaling/proactive reconfiguration:
  - challenging goal common to very projects
  - in Cloud-TM we will target data intensive applications
- Achieve interoperability with storage solutions for the cloud developed by other projects

Conclusions

- Cloud computing raises a number of research challenges for transactional replication:
  - elasticity:
    - self-tuning as an essential requirement
  - non-uniform transaction synchronization costs:
    - multi-core ⇒ rack ⇒ data-center ⇒ cloud federation
  - unprecedented scalability challenge

Thanks for the attention

Q&A

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