Boosting STM replication via speculation

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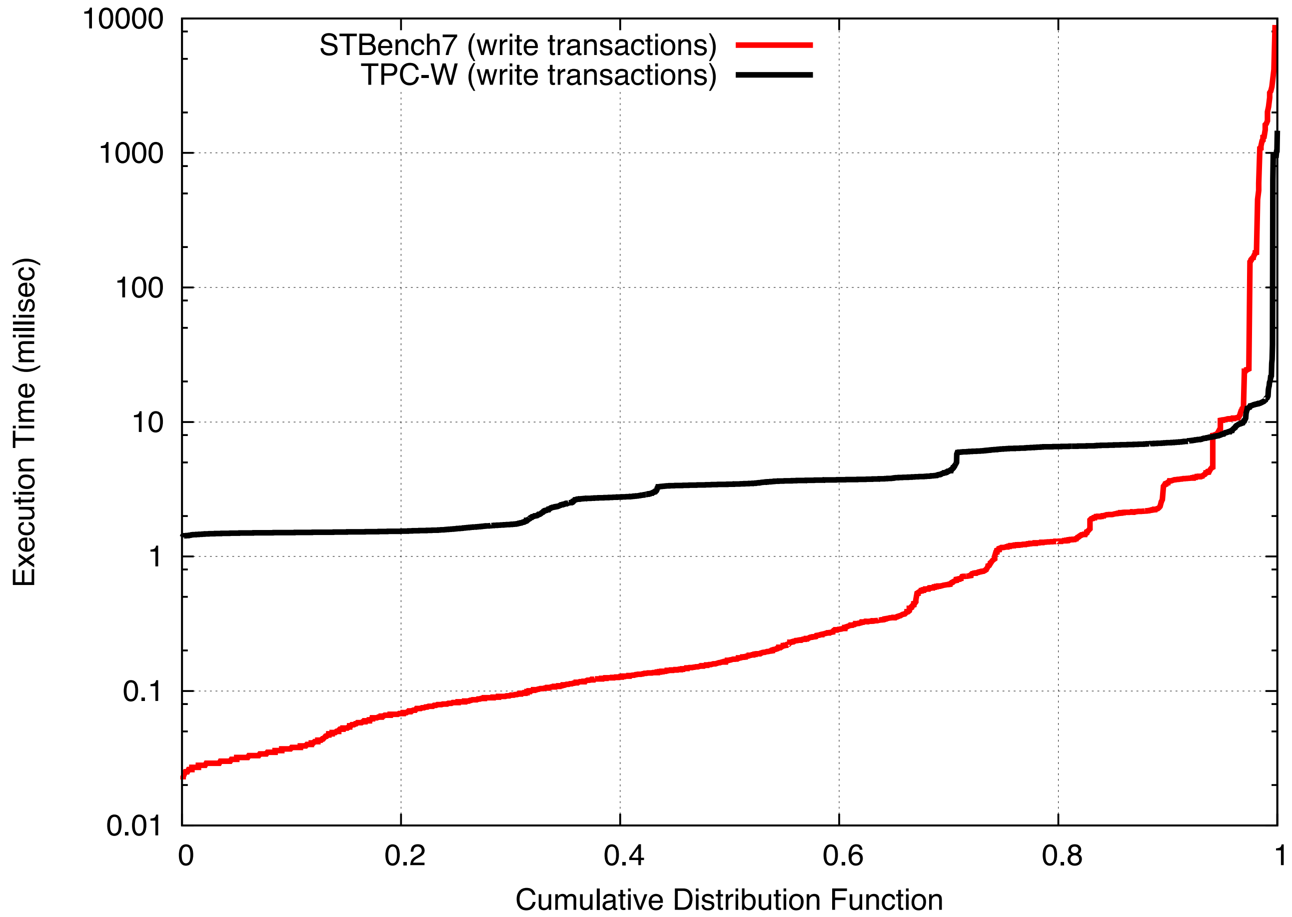
Replication and STMs

- STMs are being employed in new scenarios:
  - database caches in three-tier web apps (FenixEDU)
  - HPC programming languages (X10)
  - in-memory cloud data grids (Coherence, Infinispan)

- …and faced with new challenges:
  - scalability
  - fault-tolerance

← **REPLICATION**

Critical issue for STM replication



- >70% of transactions are 10-100 times in STMs than in DBMSs:
  ⇒ amplification of replica sync. cost when using DB replication schemes!

Active replication of transactional systems

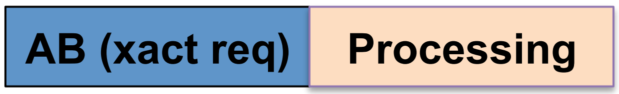
1. Agreement on request execution order
   – encapsulated by Total Order broadcast (TOB):
     + deadlock freedom
     - TOB is an expensive communication primitive

2. Deterministic request processing
   – concurrency is one of the possible sources of non-determinism:
     • concurrent execution of transactions needs to be equivalent to sequential exec. according to TOB order

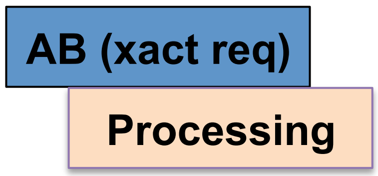
How to minimize replica synchronization costs?

- Overlapping communication and processing:
  - ***optimistic deliveries***: replicas receive messages long before their total order is established:
    - in LANs optimistic and final delivery order normally match
  - *speculatively* process transactions as soon as they are optimistically delivered

Conventional (Active) Replication Scheme



Speculative (Active) Replication Scheme

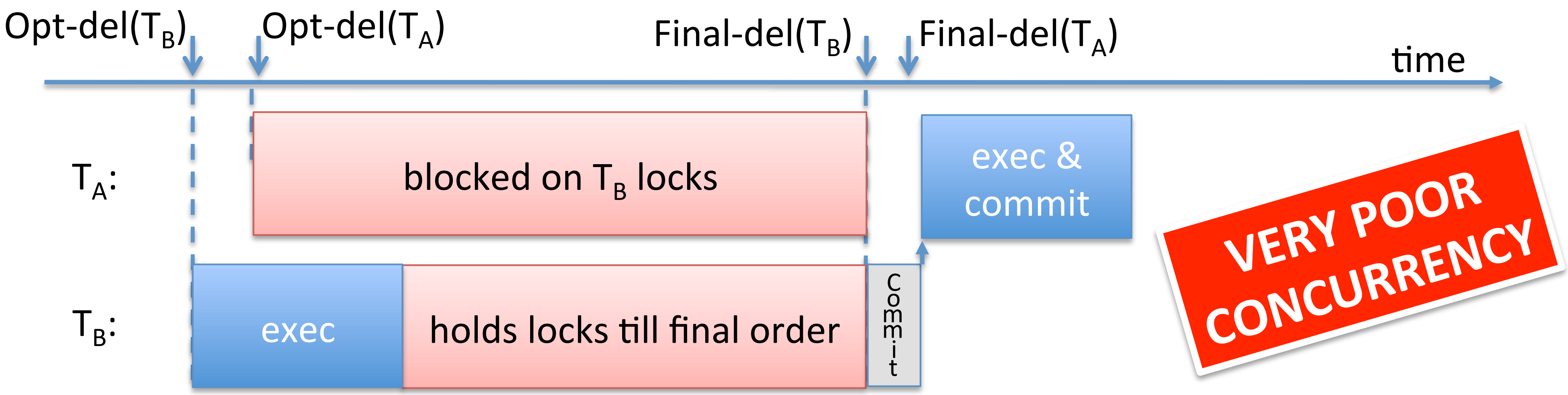


Easier said than done….

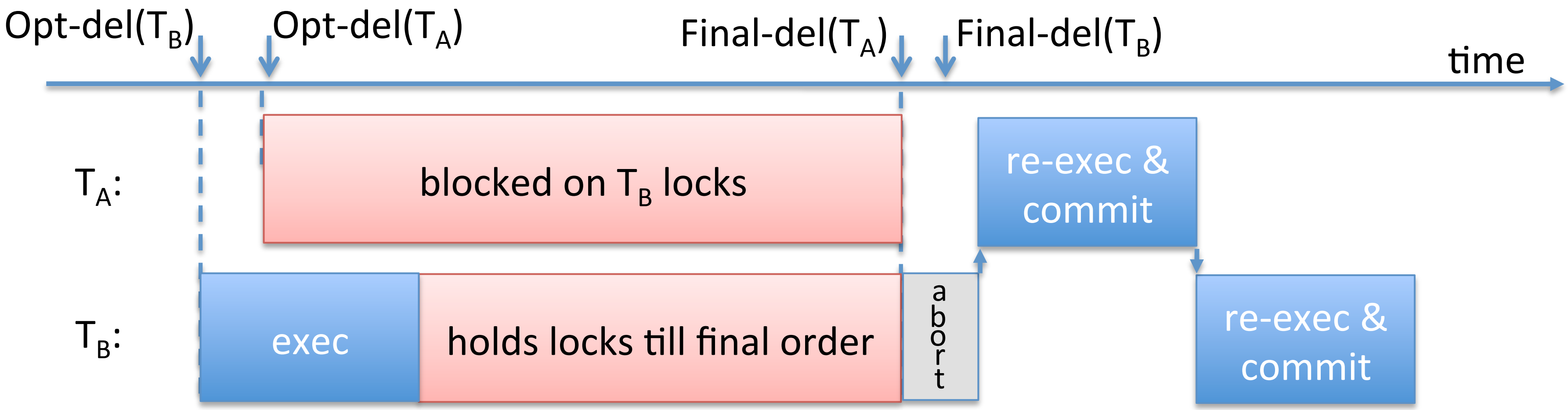
Problem 1: Deterministic transaction scheduling

Existing deterministic schedulers have significant limitations:

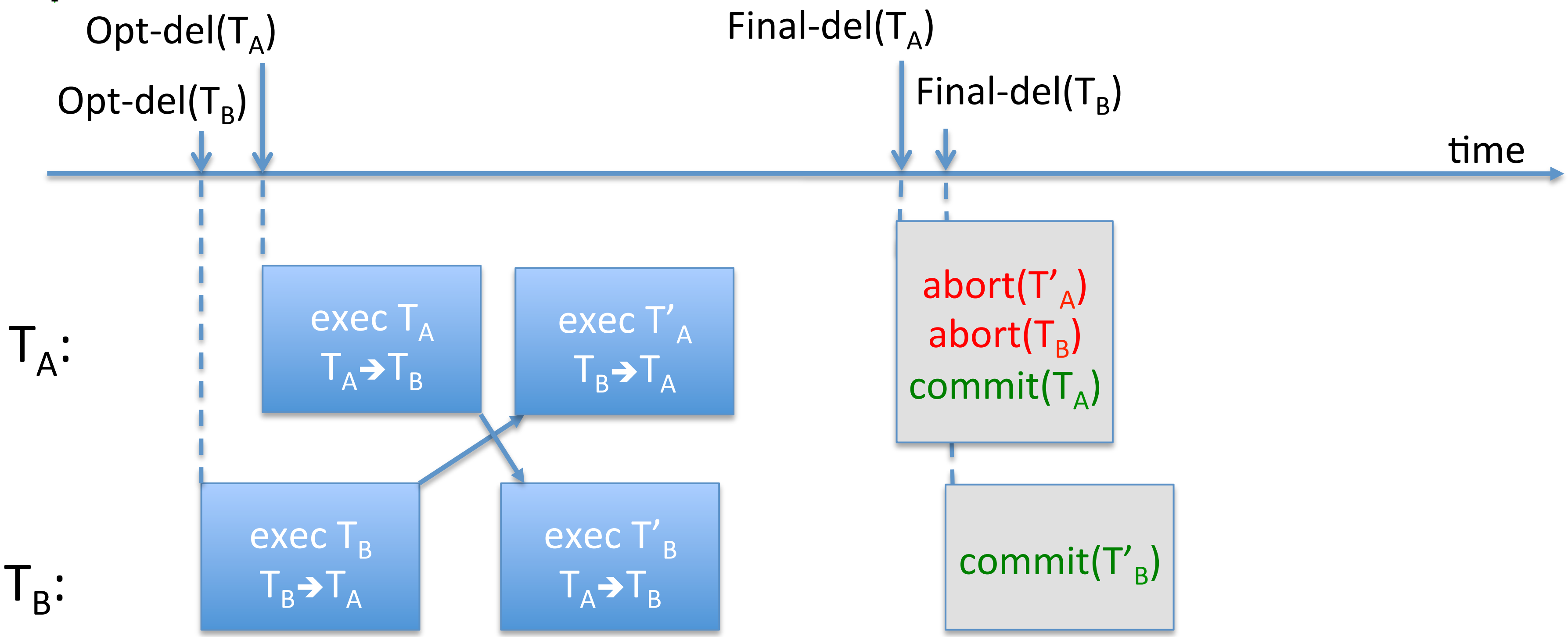
- a-priori knowledge of readsets/writesets:
  - may lead to large conflict over-estimation
- acquire **ALL** locks as xact begins, release when it's final-del.
  - way more pessimistic than classic 2PL



Problem 2: mismatches between optimistic and final delivery orders



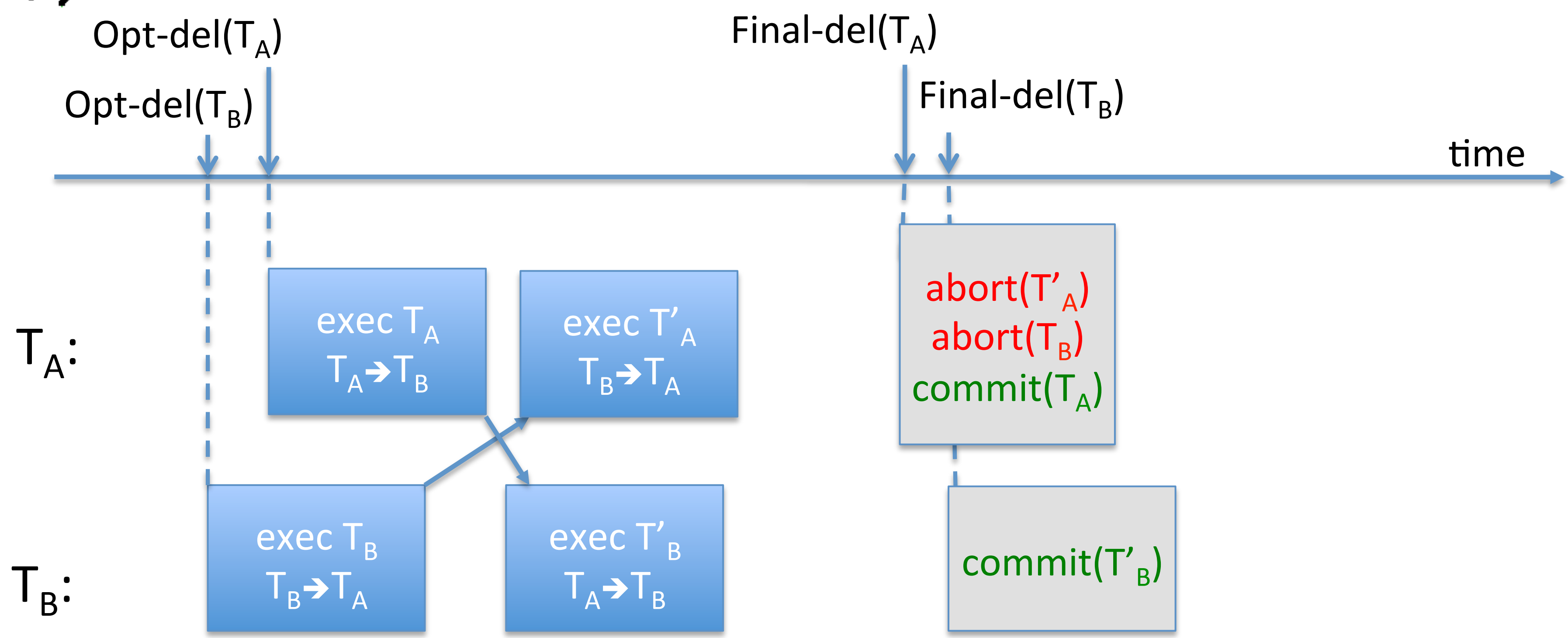
Don’t be pessimistic…be speculative!



Speculatively explore multiple Serialization Orders (SO)

+ **take maximum benefit from modern multi-core architectures**
+ **shelter from network reordering**
+ **avoid lock convoying**

Don't be pessimistic…be speculative!



Speculatively explore multiple Serialization Orders (SO)

– **#SOs can grow factorially with #msgs not yet finally delivered**
  - true in worst case: every xact conflicts with every other, hardly the case in practice

\+ **#SOs in which a xact observes distinct snapshots depends on actual conflict graph**

THE SPECULATIVE TRANSACTIONAL REPLICATION (STR) PROBLEM [SPAA10]

STR Problem: **Model**

- Each replica holds a full copy of the STM
- Application generates a transactional request (or simply transaction), T_i, and propagates it via TOB
- TOB delivers two events:
  - opt-delivery(T_i): early guess of final order
  - final-delivery(T_i): agreed total order
- For each T_i, one or more speculative transactions, denoted as T_i^j, are locally executed by each replica

STR Problem: **Specification Overview**

In addition to classic 1-copy serializability, the STR problem is specified by the following three properties:

1. **consistency**
2. **non-redundancy**
3. **completeness**

STR problem - **Consistency**

Consistency: *opacity*.

Prevents transactions from observing inconsistent (non-serializable) snapshots

- important for safety in non-sandboxed environments
- avoids wasting computational resources in "useless" transactions:
  - not associated with any possible final AB-delivery order

STR problem - **Non-redundancy**

Non-redundancy: *no two speculative instances of the same transaction observe the same snapshot*.

Filters out trivial solutions that blindly enumerate all permutations of Opt-delivered transactions:

- force solutions to reason on conflict relationships among transactions before exploring new serialization orders

STR problem - **Completeness**

Completeness: *Let Σ be the set of Opt-delivered, but not yet TO-delivered, transactions.*
If the system stops Opt- and TO-delivering messages, eventually every permutation of Σ that produces a ***distinct snapshot*** *is explored.*

- Shelters from any possible mismatch between optimistic and final delivery orders

An STR Protocol [ISPA2010]
Key idea
Speculative Polygraph (SP)

- inspired by Papadimitriou's Polygraph [JACM79]:
  - originally used to identify view-serializable schedules
  - polygraphs embed a family of digraphs, each associated with a different equivalent serial history

- SPs support:
  - on-line identification of *all and only* non-equivalent serialization orders of a speculative transaction
  - tolerate the coexistence of speculative transactions in the same execution history

WARNING
This is just a teaser,
details in the paper!

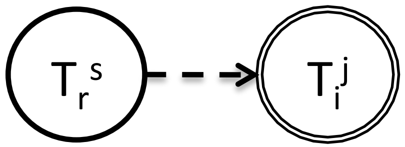
Speculative Polygraphs

SP(T_i^j)=(N,A,B) where:

N: set of vertexes, associated with (speculative) transactions

A: set of ***merging edges*** ***(T_r^s ⊙➔ T_i^j)*** which merges SP(T_r^s) and SP(T_i^j)

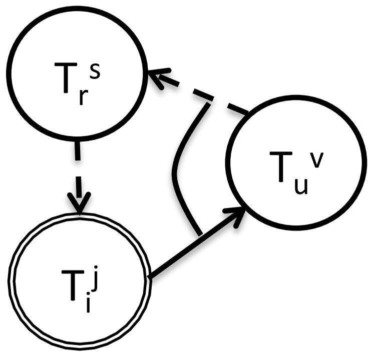
T_r^s: w(x_r^s)
T_j^j: r(x_r^s)



read-from relationships

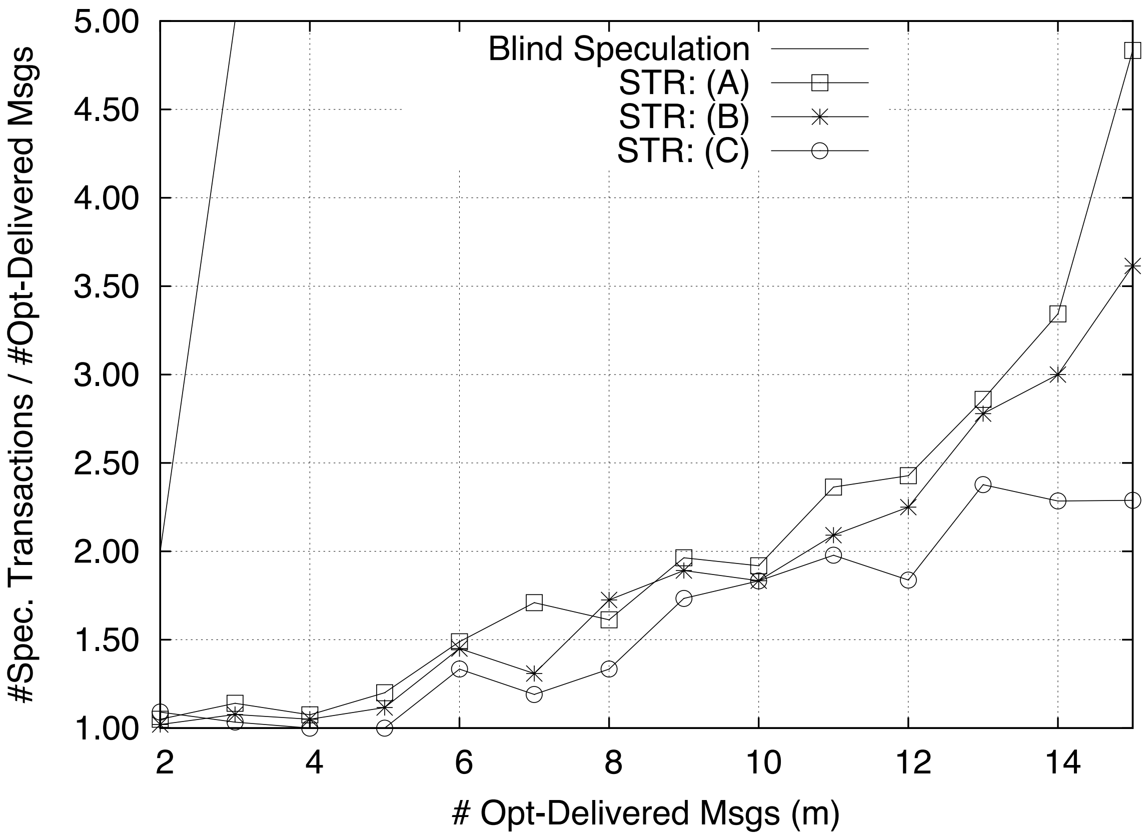
B: set of ***asymmetric bipaths*** denoted as <***(T_u^v ⊙➔ T_i^j), (T_i^j ➔ T_u^v)***>

T_r^s: w(x_r^s)
T_j^j: r(x_r^s)
T_u^v: w(x_u^v)



not read-from relationships

The importance of being … non-redundant



Simulation study based on real (STM) workloads:

Optimal STR scheme: #SOs≈[2.5-5] with 15 opt-delivered xacts

Blind enumeration: #SOs≈1,000,000 with 10 opt-delivered xacts

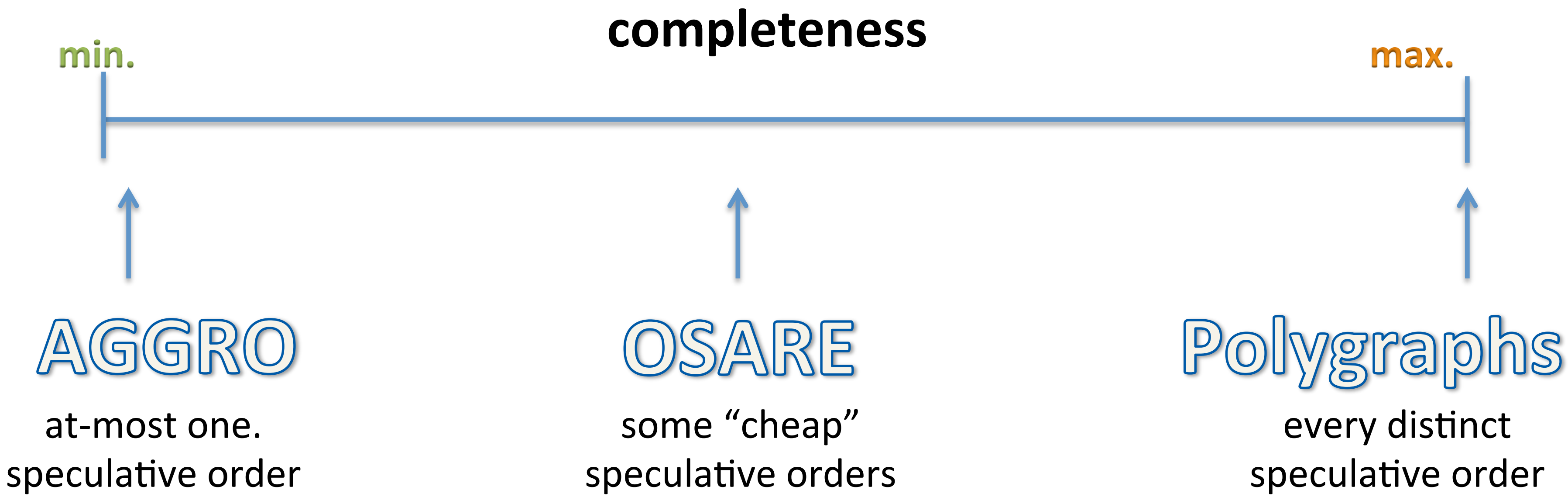
To be or not be… complete?

- Completeness can have a considerable price:
  1. querying Speculative Polygraphs has an exponential cost in the number of bi-paths
  2. the number of serialization orders in which a transaction T needs to be re-executed grows factorially with the number of transaction T conflicts with

What about relaxing completeness?

Relaxing completeness

- The relevance of the completeness property depends on the likelihood of mismatches between final and optimistic delivery orders
- This led us to design two additional protocols:



AGGRO [NCA10] – Main Idea

BASE ASSUMPTION: "*optimistic and final delivery order coincide with high probability*"

- Transactions are speculatively started immediately after their optimistic delivery…
- and ***try*** to execute in a serialization order compliant with the optimistic delivery order:
  - speculative snapshot are aggressively propagated along chains of speculative conflicting transactions

AGGRO – Key Problem

- To maximize parallelism, transactions are activated without waiting for previously opt-delivered ones to be committed

- Two consequences:
  - writes of prev. xacts may be observed too soon:
    - non-opaque schedules
  - writes of prev. xacts may be missed:
    - different serialization order **(snapshot miss event)**

AGGRO – algorithm in a nutshell (i)

- If T_i writes X:
  - mark X as Work in Progress (WIP) by T_i
  - kill all T_j that:
    1. already read X, and
    2. follow T_i in opt-delivery order

    ⇒ ensure T_j is aligned with opt-delivery order

snapshot miss

- If T_i reads X:
  - if X is marked as WIP by a xact that precede T_i in the opt-delivery order: wait till T_i unmarks X as WIP
  - return the version created by the most recent xact preceding T_i

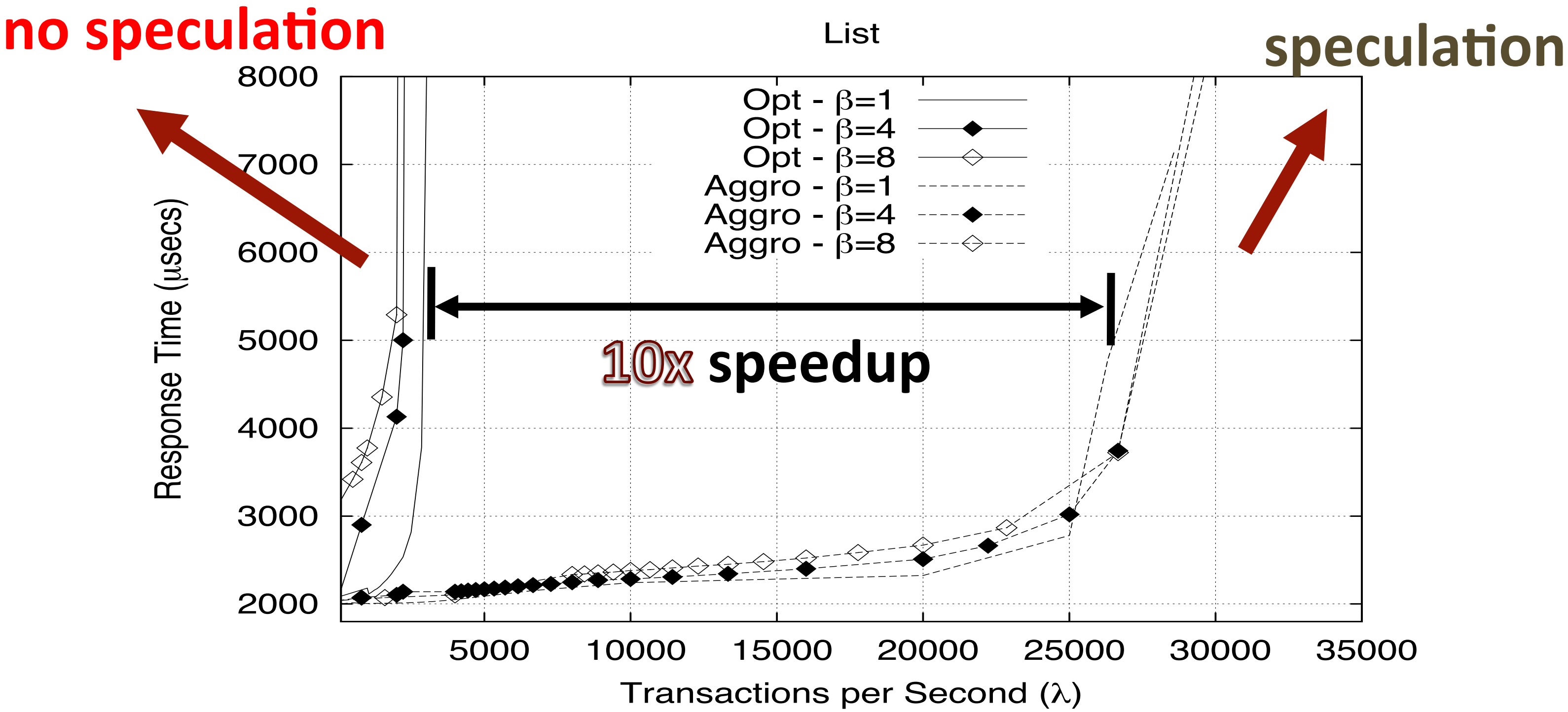
AGGRO – algorithm in a nutshell (ii)

- Upon completion of transact. execution:
  - release locks on writeset:
    - this makes write-set readable only when it's stable
    - avoiding leakage of intermediate snapshots

- Upon final delivery of T_i
  - wait until all xacts preceding T_i in final order commit
  - validate(T_i) and accordingly commit/abort it

AGGRO - What speedups?

- no mismatch between optimistic and final delivery
- baseline uses opt-deliveries but does not propagate snapshots



OSARE [SRDS11] – Main Idea

- As in AGGRO, attempt to serialize xacts according to opt-delivery order.

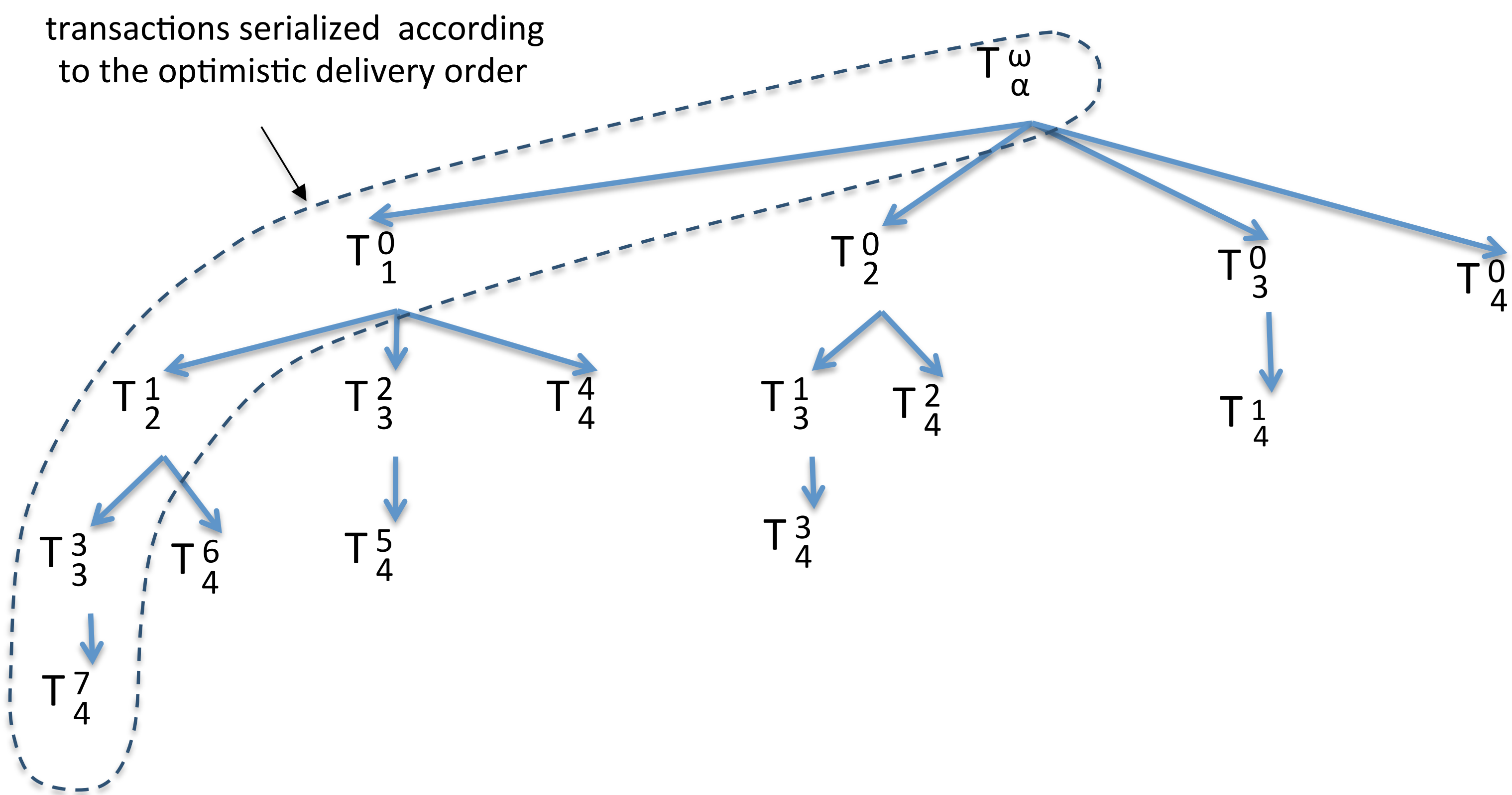
- Unlike AGGRO, if a xact T undergoes a snapshot miss, don't abort it, but
  - explore new speculative serialization orders in an ***opportunistic*** fashion:
    - avoiding expensive polygraphs' manipulations
  - activate a new instance of T realigned with optimistic delivery order

OSARE(*): Opportunistic Speculation in Active Replication

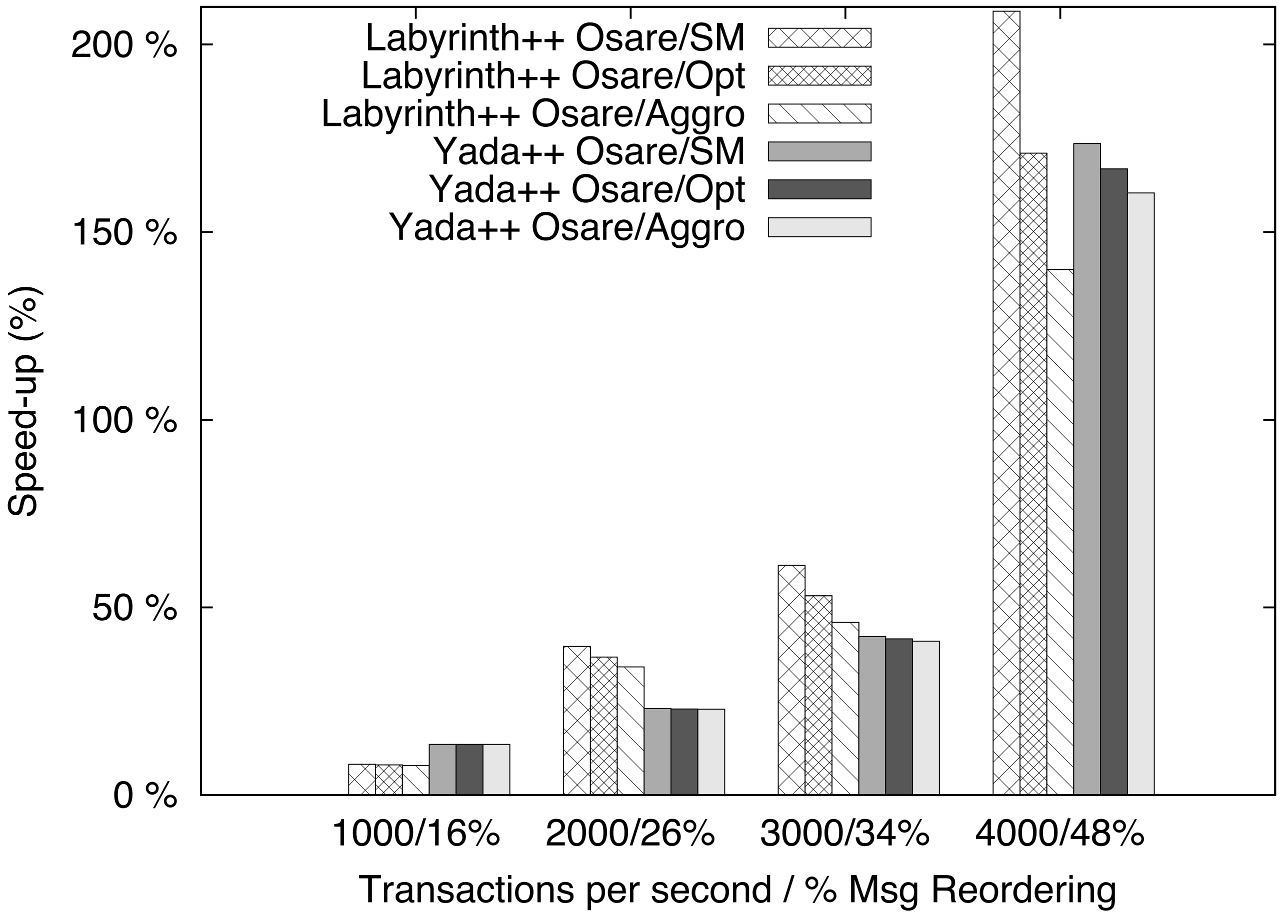
(*) OSARE means "to dare" in Italian

OSARE – how complete?

- Largest set of explored speculative serialization orders: $O(2^n)$
  - Full permutation tree is $O(n!)$



OSARE – what speedups?



Conclusions

- Bad news:
  - Replication overhead are strongly amplified in STMs
- Good news:
  - Active replication costs can be strongly reduced by speculatively overlapping processing and communication
- We formalized the Speculative Transactional Replication (STR) problem…
- …and proposed three protocols exploring different trade-offs for what concerns completeness

Open questions

- Are there other interesting **trade-offs** for what concerns **completeness**?
- How to apply speculative techniques to replication protocols **other than active replication**?
  - deferred update replication technique (a.k.a. certification or DBSM [DPD03]):
    - in [Systor11] we proposed a non-complete (à-la AGGRO) speculative protocol
    - what about different degrees of completeness?
  - lease based certification protocols [Middleware10]?
  - partial replication protocols [SRDS10,PRDC11]?
  - your favorite replication protocol!

Thanks for the attention

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