Spanner

COS 418: Distributed Systems
Lecture 17

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Slides adapted from Haonan Lu, Wyatt Lloyd, and Mike Freedman's, which are adapted from the Spanner OSDI talk

Recap: Distributed Storage Systems

- Concurrency control
  - Order transactions across shards
- State machine replication
  - Replicas of a shard apply transactions in the same order decided by concurrency control

Google's Setting

- Dozens of datacenters (zones)
- Per zone, 100-1000s of servers
- Per server, 100-1000 shards (tablets)
- Every shard replicated for fault-tolerance (e.g., 5x)

Why Google Built Spanner

2005 – BigTable [OSDI 2006]

- Eventually consistent across datacenters
- Lesson: “don’t need distributed transactions”

2008? – MegaStore [CIDR 2011]

- Strongly consistent across datacenters
- Option for distributed transactions
    - Performance was not great…

2011 – Spanner [OSDI 2012]

- Strictly Serializable Distributed Transactions
- “We wanted to make it easy for developers to build their applications”

A Deeper Look at Motivation
-- Performance-consistency tradeoff

- Strict serializability
  - Serializability + linearizability
  - As if coding on a single-threaded, transactionally isolated machine
  - Spanner calls it “external consistency”

- Strict serializability makes building correct application easier

- But strict serializability is expensive
  - Performance penalty in concurrency control + Repl.
    - OCC/2PL: multiple round trips, locking, etc.

A Deeper Look at Motivation
-- Read-Only Transactions

- Transactions that only read data
  - Predeclared, i.e., developer uses READ_ONLY flag / interface

- Reads dominate real-world workloads
  - FB's TAO had 500 reads : 1 write [ATC 2013]
  - Google Ads (F1) on Spanner from 1? DC in 24h:
    - 31.2 M single-shard read-write transactions
    - 32.1 M multi-shard read-write transactions
    - 21.5 B read-only (~340 times more)

- Determines system's overall performance

Can we design a strictly serializable, geo-replicated, sharded system with very fast (efficient) read-only transactions?

Before we get to Spanner …

- How would you design SS read-only transactions?

- OCC or 2PL
  - Multiple round trips and locking

- Can you always read in local datacenters like COPS?
  - No but maybe can read from Paxos quorum?
  - Or must contact the leader

- Performance penalties
  - Round trips increase latency, especially in wide area
  - Distributed lock management is costly, e.g., deadlocks

Goal is to …

- Make read-only transactions efficient
  - One round trip
    - Could be wide-area
  - Lock-free
    - No deadlocks
    - Processing reads does not block writes, e.g., long-lived reads
  - Always succeed
    - Do not abort

- And strictly serializable

Leveraging the Notion of Time

- Strict serializability: a matter of real-time ordering
  - If T2 starts after T1 finishes, then T2 must be ordered after T1
    - If T2 is a RO txn, then T2 should see the effects of all writes that finished before T2 started.

- A similar scenario at a restaurant
  - Alice arrives, writes her name and the time she arrives (e.g., 5pm) on the waiting list
  - Bob then arrives, writes his name and the time (e.g., 5:10PM)
  - Then Bob is ordered after Alice on the waiting list
  - I arrive later at 5:15PM and check how many people are ahead of me by checking the waiting list by time

Leveraging the Notion of Time

- Idea 1: when committing a write, tag it with the current physical time

- Idea 2: when reading the system, check which writes were committed before the time this read started.

- How about the serializable requirement?
  - Physical time naturally gives a total order

Invariant:

If T2 starts after T1 commits (finishes), then T2 must have a larger timestamp

Trivially provided by perfect clocks

Challenges

- Clocks are not perfect
  - Clock skew: some clocks are faster/slower
  - Clock skew may not be bounded
  - Clock skew may not be known a priori

- T2 may be tagged with a smaller timestamp than T1 due to T2's slower clock

- Seems impossible to have perfect clocks in distributed systems. What can we do?

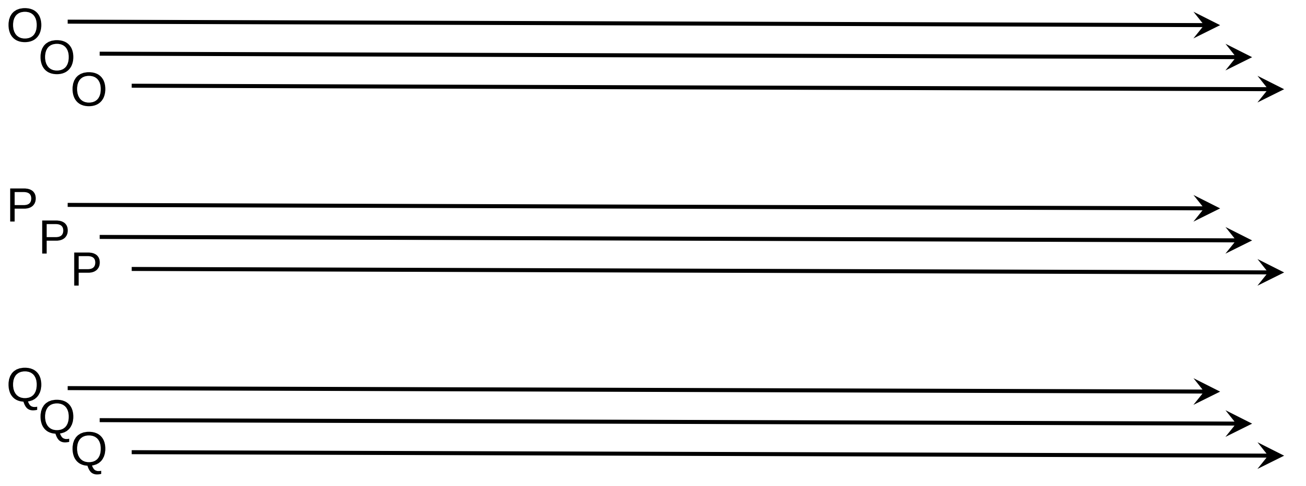
Nearly perfect clocks

- Partially synchronized
  - Clock skew is bounded and known a priori
  - My clock shows 1:30PM, then I know the absolute (real) time is in the range of 1:30 PM +/- X.
    - e.g., between 1:20PM and 1:40PM if X = 10 mins
- Clock skew is short
  - E.g., X = a few milliseconds
- Enable something special, e.g., Spanner!

Spanner: Google's Globally-Distributed Database

OSDI 2012

Scale-out vs. Fault Tolerance



- Every shard replicated via Multi-Paxos
- So every “operation” within transactions across tablets is actually a replicated operation within a Paxos RSM
- Paxos groups can span across datacenters!

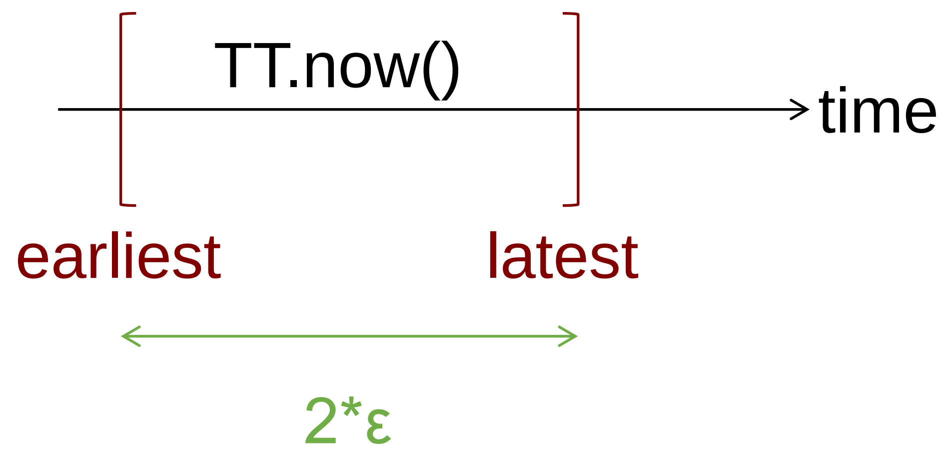
Strictly Serializable Multi-shard Transactions

- How are clocks made “nearly perfect”?

- How does Spanner leverage these clocks?
  - How are writes done and tagged?
  - How read-only transactions are made efficient?

TrueTime (TT)

- "Global wall-clock time" with bounded uncertainty
  - ε is worst-case clock divergence
  - Spanner's notion of time becomes intervals, not single values
  - ε is 4ms on average, 2 ε is about 10ms



Consider event e_{now} which invoked tt = TT.now():

Guarantee: $tt.earliest <= t_{abs}(e_{now}) <= tt.latest$

TrueTime (TT)

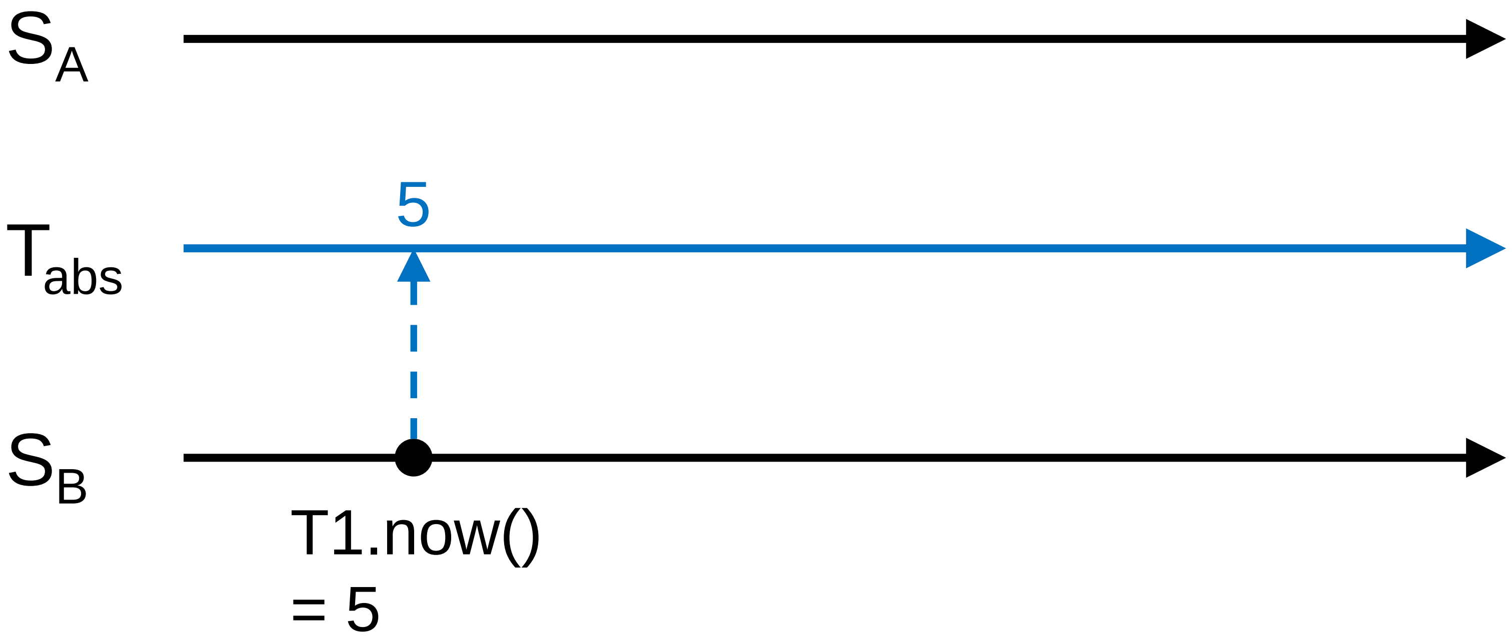
- Interface
  - TT.now() = [earliest, latest] # latest – earliest = 2*ε
  - TT.after(t) = true if t has passed
    - TT.now().earliest > t (b/c t_{abs} >= TT.now().earliest)
  - TT.before(t) = true if t has not arrived
    - TT.now().latest < t (b/c t_{abs} <= TT.now().latest)

- Implementation
  - Relies on specialized hardware, e.g., satellite and atomic clocks

Enforcing the Invariant

If T2 starts after T1 commits (finishes), then T2 must have a larger timestamp

Let T1 write S_B and T2 write S_A



Perfect Clocks

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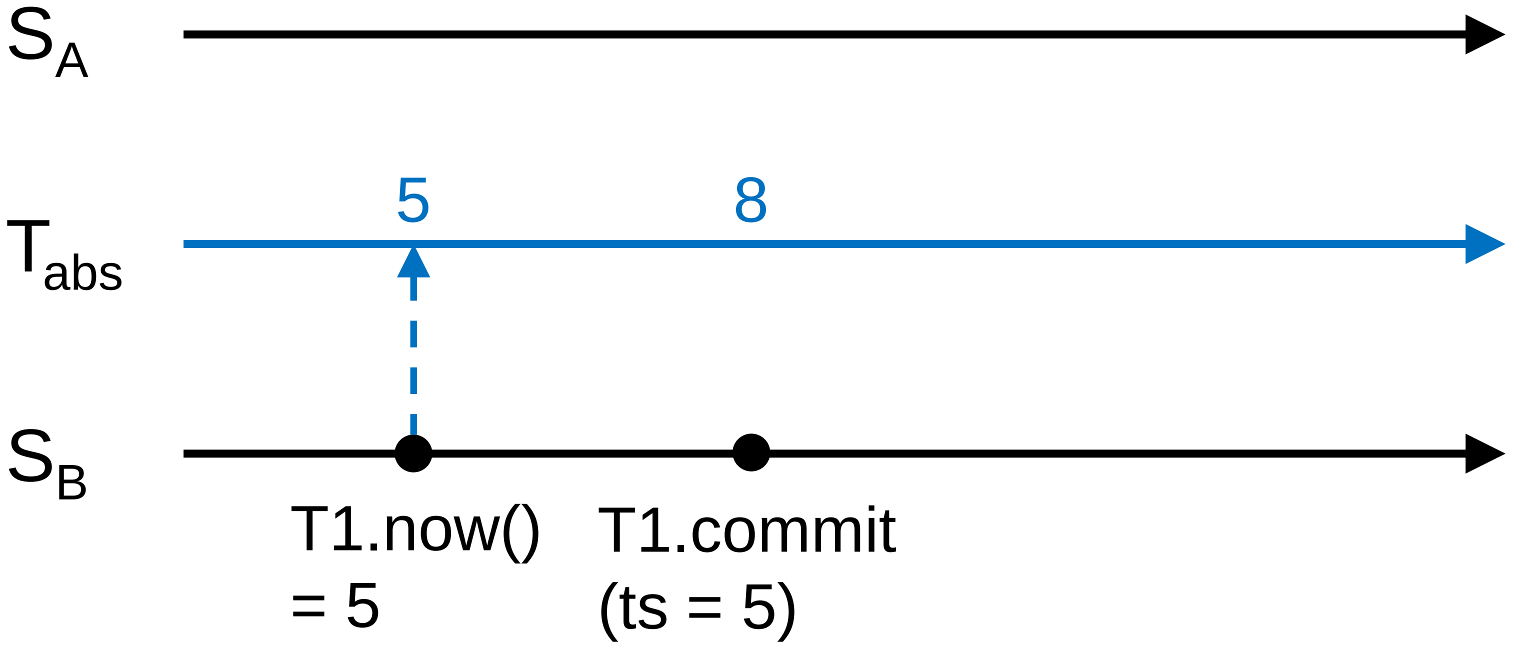

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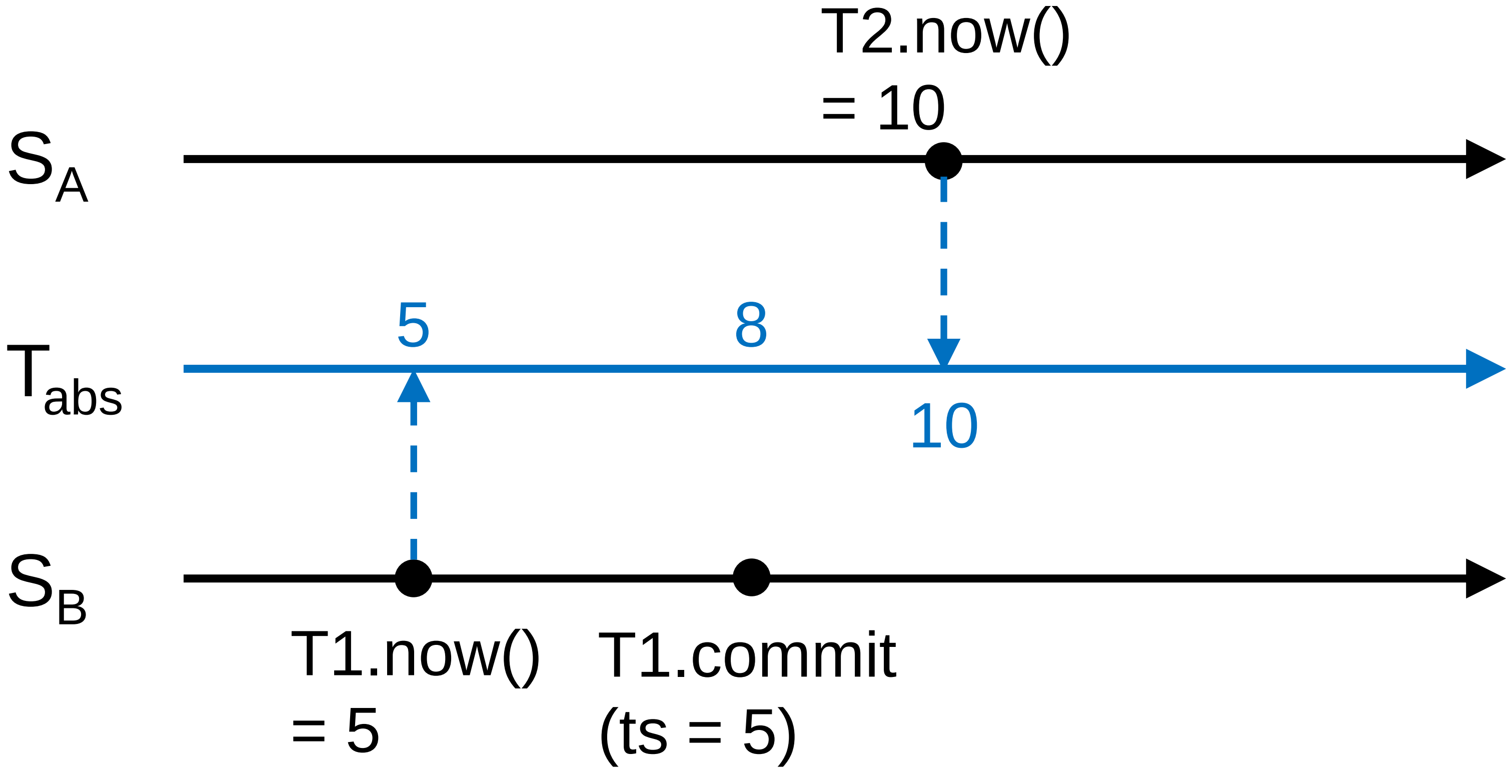

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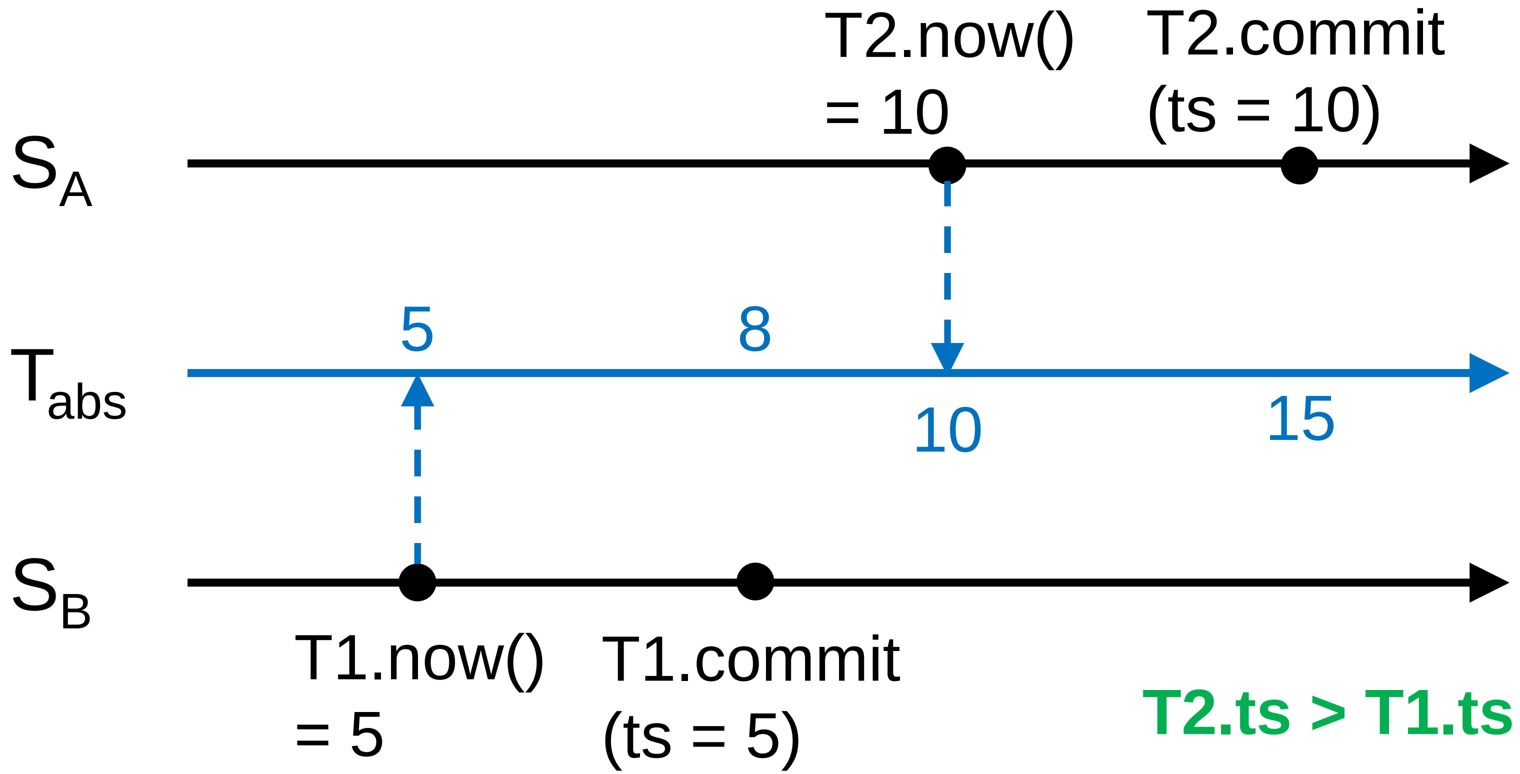

T2.ts > T1.ts

Perfect Clocks

Enforcing the Invariant

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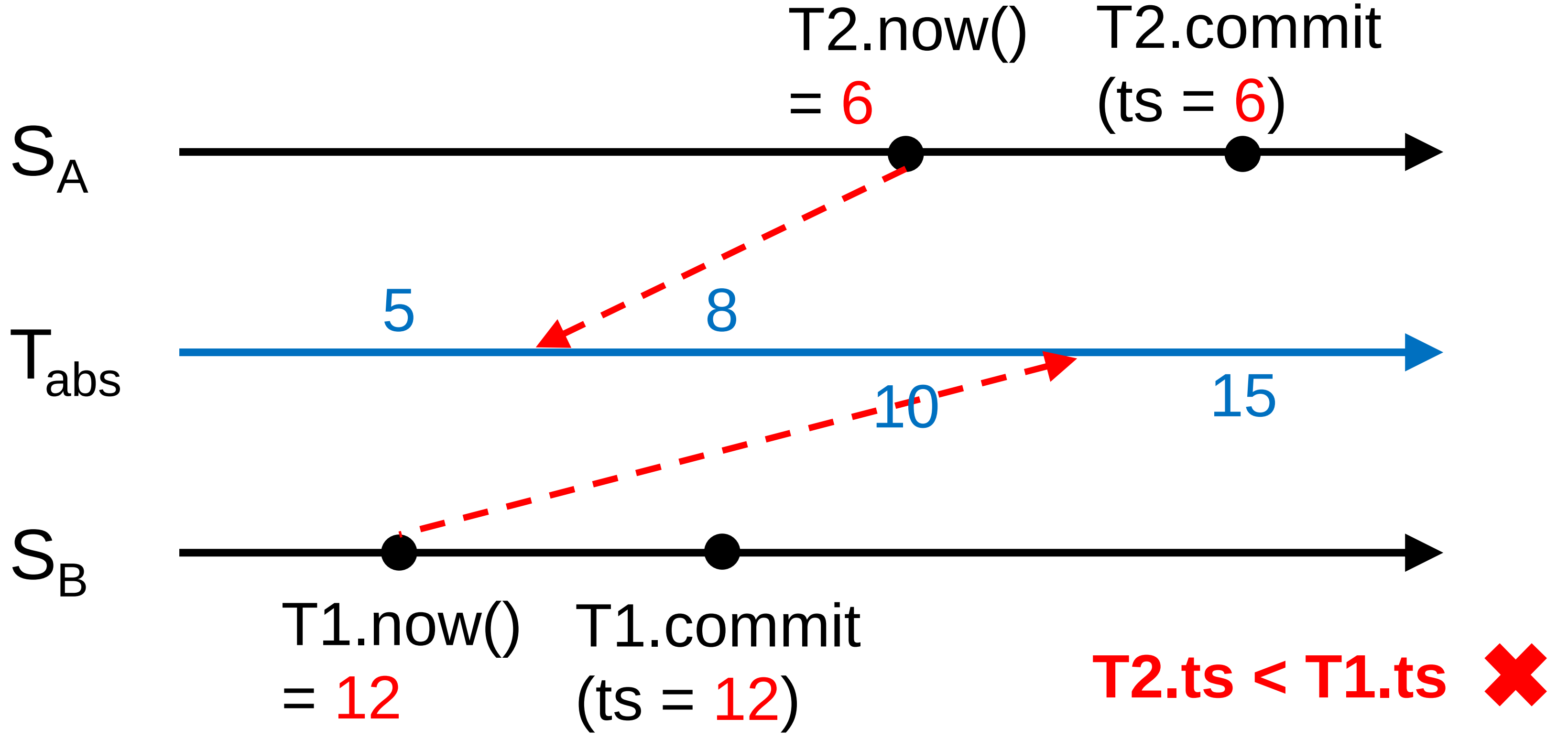

Imperfect Clocks

Enforcing the Invariant

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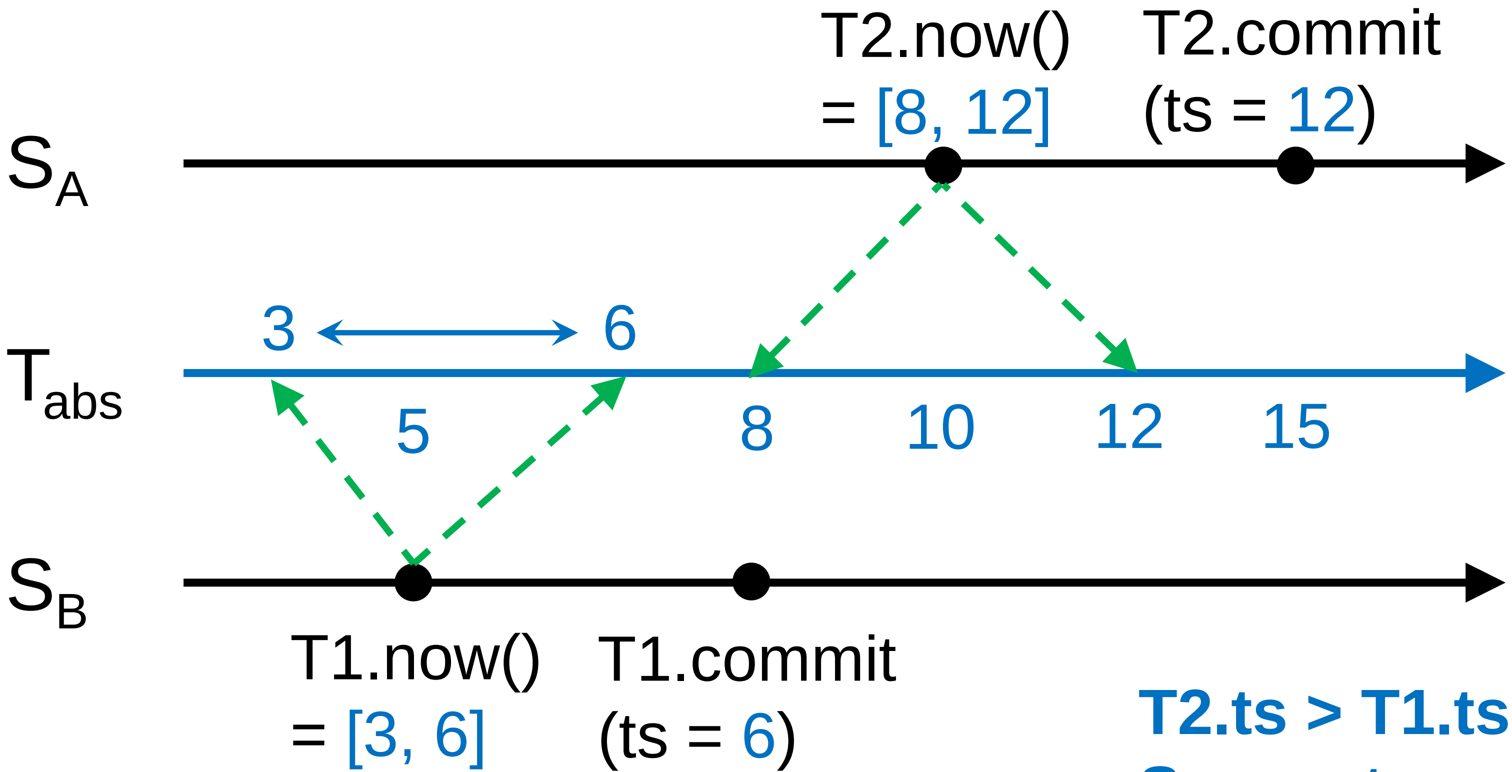


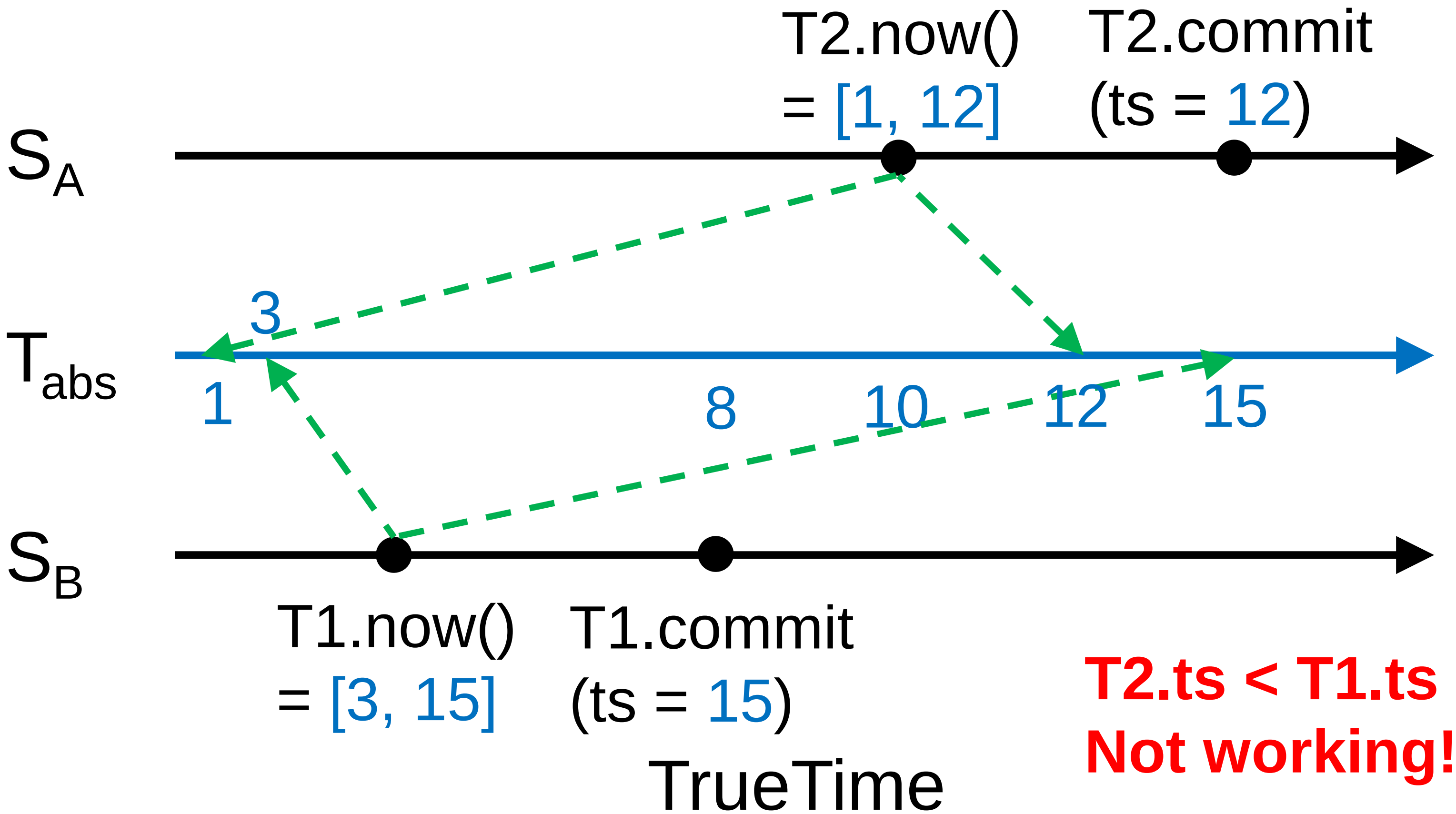
TrueTime

T2.ts > T1.ts
Seems to work?

Enforcing the Invariant

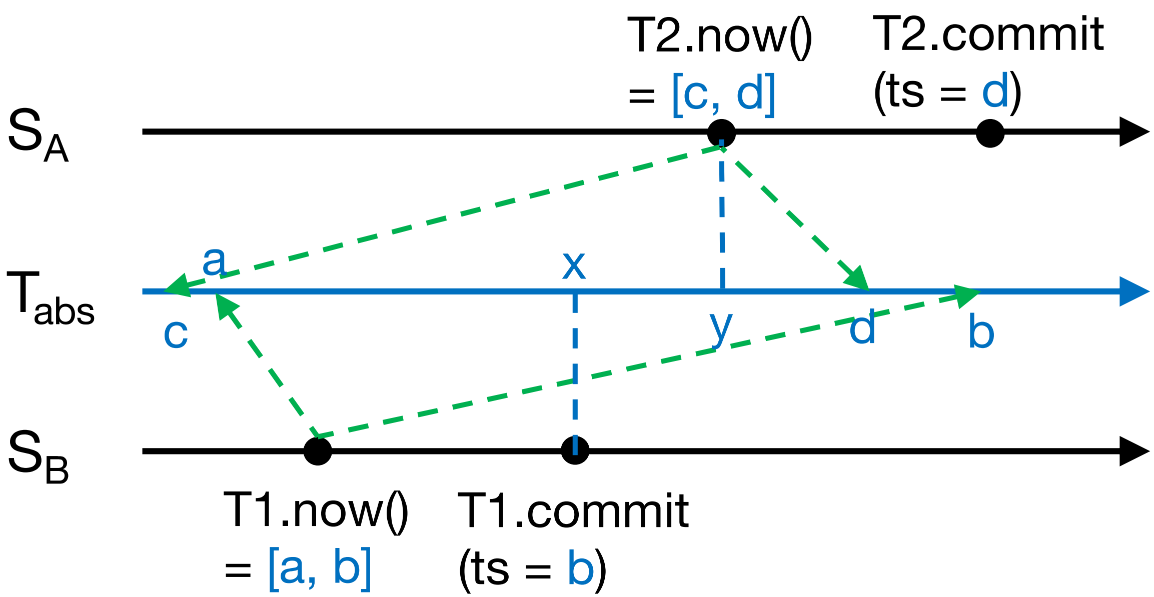
If T2 starts after T1 commits (finishes), then T2 must have a larger timestamp

Let T1 write S_B and T2 write S_A



T2.ts < T1.ts
Not working!

A brain teaser

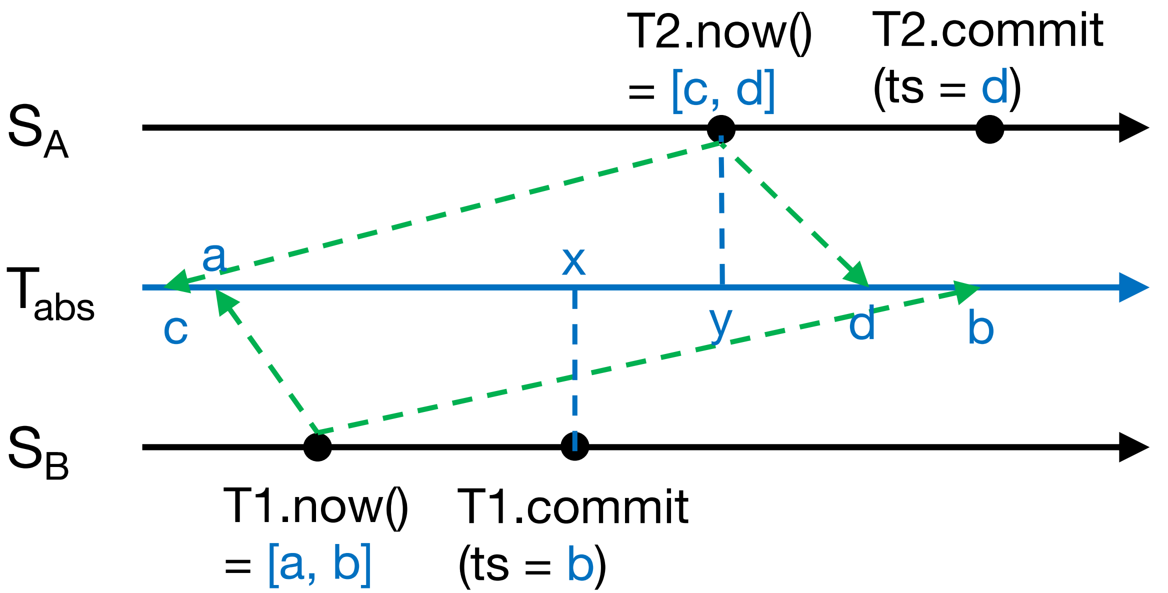


We know:

1. x < y, b/c T2 in real-time after T1 (the assumption)
2. c <= y <= d, b/c TrueTime
3. T1.ts = b, T2.ts = d, b/c how ts is assigned

We want: b < d to always be true, how?

A brain teaser puzzle



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We want: b < d to always be true, how?

1 and 2 → x < d; we need to ensure b < x; then b < x < d, done.

Enforcing the Invariant with TT

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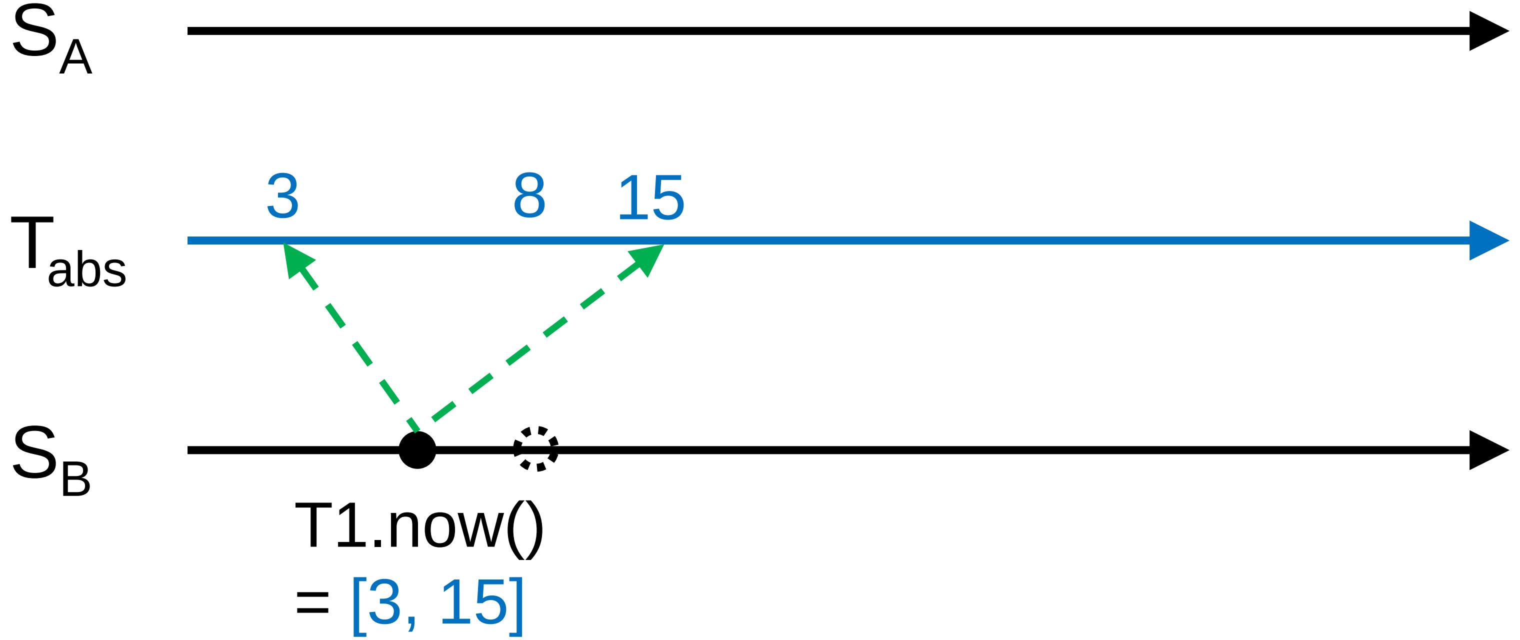
Let T1 write S_B and T2 write S_A



TrueTime

Enforcing the Invariant with TT

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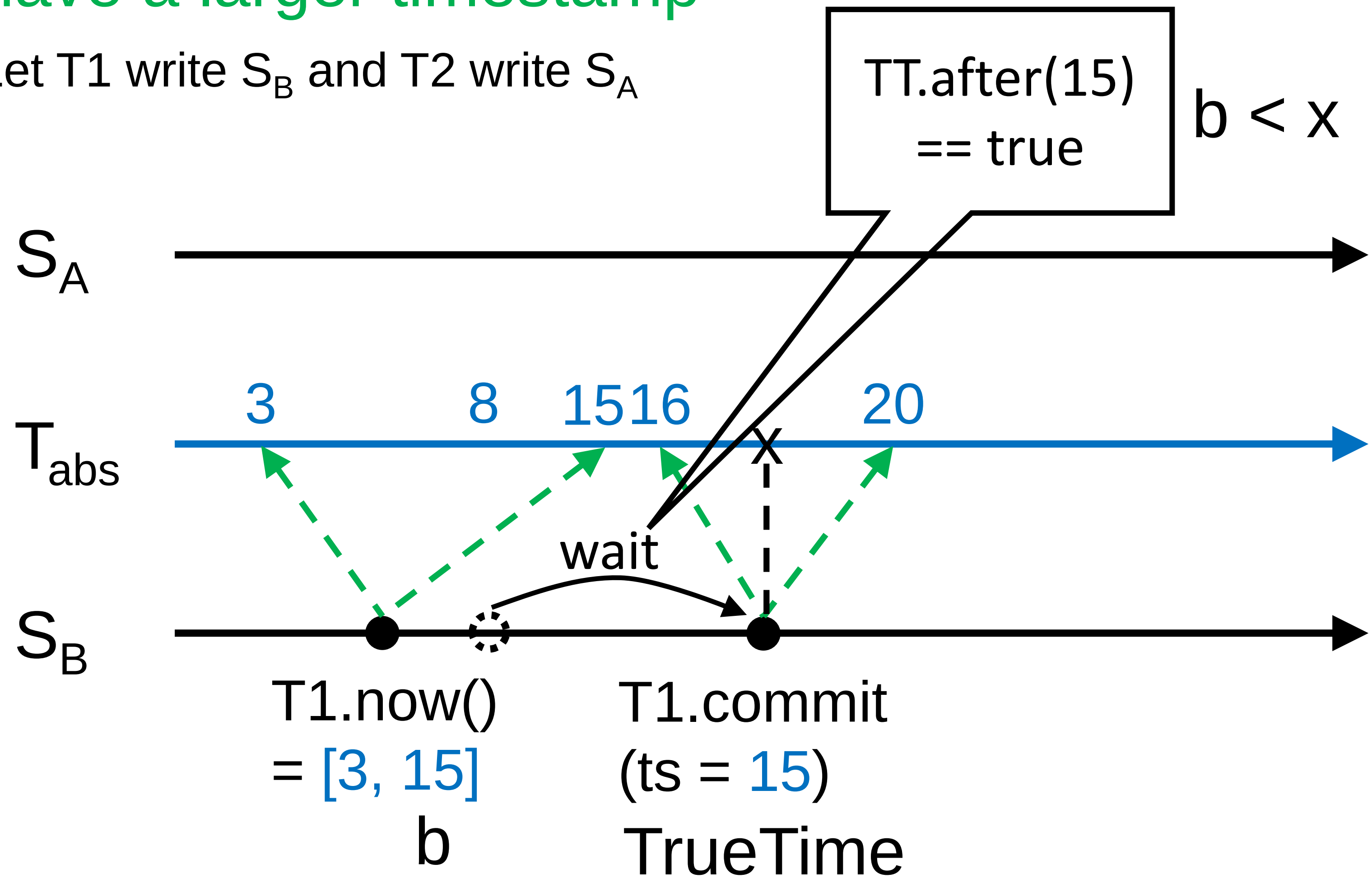

Enforcing the Invariant with TT

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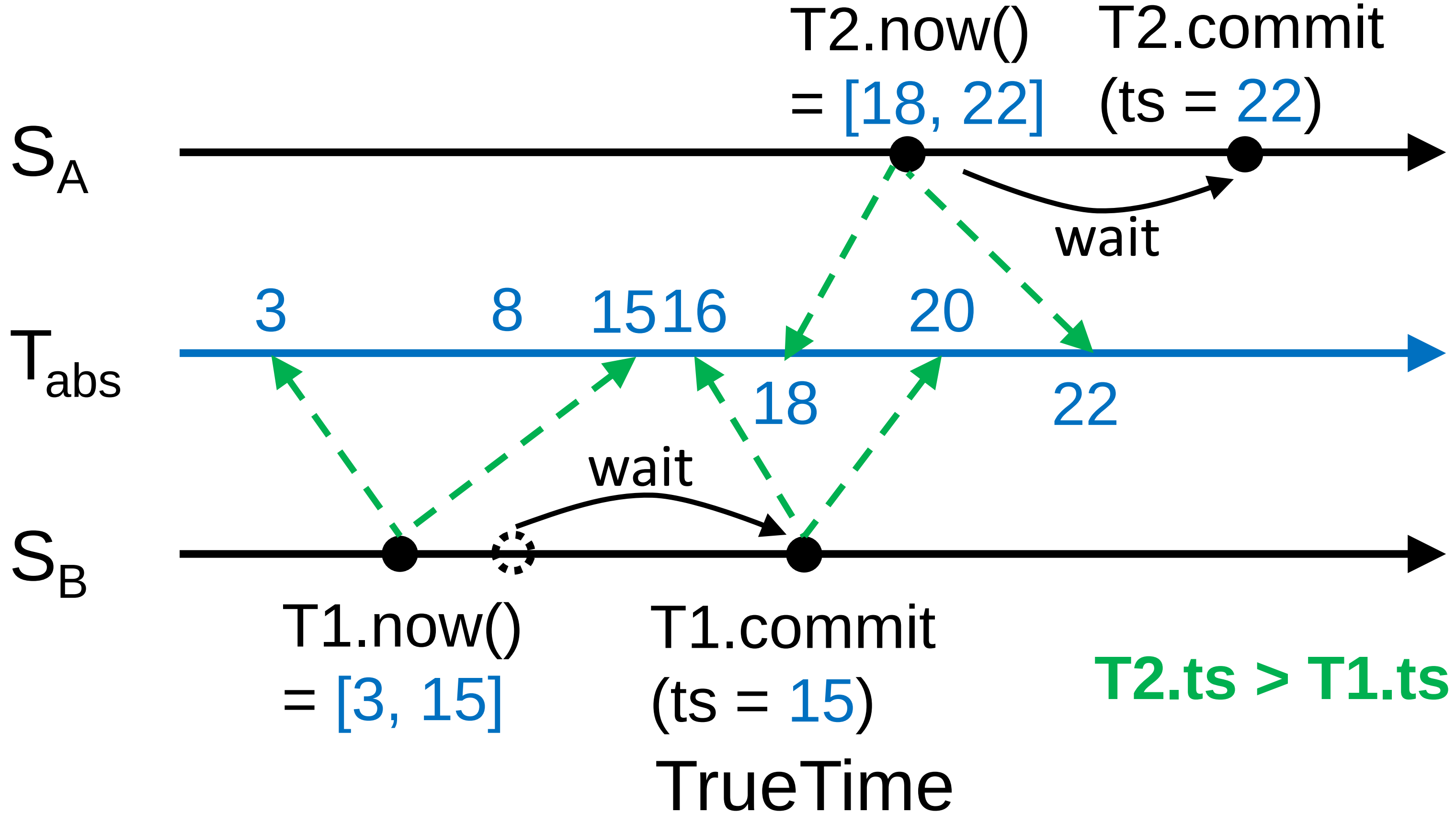

Takeaways

- The invariant is always enforced: If T2 starts after T1 commits (finishes), then T2 must have a larger timestamp
- How big/small ε is does not matter for correctness
- Only need to make sure:
  - TT.now().latest is used for ts (in this example)
  - Commit wait, i.e., TT.after(ts) == true
- ε must be known a priori and small so commit wait is doable!

After-class Puzzles

- Can we use TT.now().earliest for ts?
- Can we use TT.now().latest – 1 for ts?
- Can we use TT.now().latest + 1 for ts?
- Then what's the rule of thumb for choosing ts?