A principled approach to programming distributed systems

Marc Shapiro

Summer School on Distributed and Replicated Environments
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CRDTs: not a silver bullet

CRDT:

- Extend sequential data type (commutative or not)
- Merge concurrent updates: commutative, associative, idempotent
- Guarantee availability + convergence

Designing distributed applications remains challenging

- Multiple CRDTs
- Correct interactions?

Experiments: calendar, student registration, game tournaments, auction, ticket reservations, file system, etc.

Real applications: LWW, Bet365, text editor, ???

CAP trade-offs

Strong consistency

- High system cost
  - One-off
- Low programmer cost
- Sequential bottleneck
- partition ⟹ ¬available

Too strong: slow

“Weak” consistency

- Responsive
- High programmer cost
  - Recurring
- Asynchronous
- Available

Too weak: buggy

“As fast as possible, as strong as necessary”

Strong enough; no stronger

Consistent ≜ maintains invariant

Invariant ≜ predicate over the state of the system

- Credit cards: $hash(n) = 0$
- Seat reservations: $\mathit{remaining\_seats} \geq 0$
- Social network: $\mathit{friend}\ (A,B) \Longleftrightarrow \mathit{friend}\ (B,A)$
- Bank: $\Sigma\ \mathit{accounts} = \mathit{constant}$
- File system: $\mathit{tree} \wedge \ldots$
- Student registration: $\mathit{attends}\ (\mathit{student, course}) \Longrightarrow \mathit{registered}\ (\mathit{student})$
- Storage backend: $\mathit{journal.low} \leq \mathit{checkpoint.high}$

Safe system ≜ invariant is true in every observable state

System guarantee vs. application-level effort

Sequential safety

Precondition, postcondition

$$\frac{Pre(\sigma) \qquad\qquad Post(\sigma')}{\sigma \xrightarrow{U} \sigma'}$$

Update *U*

Transitions the state from *σ to σ'*

Assuming *Pre(σ)=true*

then *U* ensures *Post(σ')*

$$\frac{x=0 \qquad\qquad x'=1}{x' = x+1}$$

weakest precondition

$$\frac{\qquad\qquad e \in S'}{S' = S \cup \{e\}}$$

$$\frac{t > 0 \qquad\qquad x' > x}{x' = x+t}$$

$$\frac{x \geq t \geq 0 \qquad\qquad x' \geq 0}{x' = x-t}$$

Precondition, postcondition

$$\frac{Pre(\sigma) \qquad\qquad Post(\sigma')}{\sigma \xrightarrow{U} \sigma'}$$

Update *U*

Transitions the state from *σ to σ'*

To ensure *Post(σ')*,

it must be that *Pre(σ)=true*

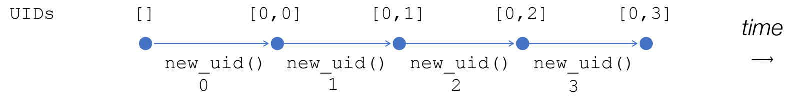
$$\frac{x=0 \qquad\qquad x'=1}{x' = x+1}$$

$$\frac{true \qquad\qquad e \in S'}{S' = S \cup \{e\}}$$

$$\frac{t > 0 \qquad\qquad x' > x}{x' = x+t}$$

$$\frac{x \geq t \geq 0 \qquad\qquad x' \geq 0}{x' = x-t}$$

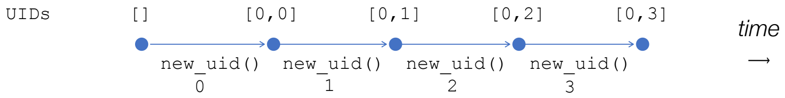
Ex.: Generate unique identifier



$$\frac{M \text{ is a set} \qquad n \notin M \qquad M' \text{ is a set}}{M' = M \cup \{n\}}$$

```
Inv() = { IDs = [0, last] }
static last = -1;
new_uid() = {
  precondition Inv();      // multiset is a set, max=last
  last++;                  // ∉ IDs
  return last;             // is unique
  postcondition Inv();
}
```

∀ update safe ⟹ seq. system safe



Individually Safe "C"

Safe state ≙ satisfies invariant

In a sequential system, if:

- The initial state satisfies *Inv*
- Every update *U* has precondition *wp(U, Inv)*

Then the system is safe

$$\forall U \qquad \frac{Inv(\sigma) \qquad wp(U,Inv) \qquad Inv(\sigma')}{\sigma \xrightarrow{U} \sigma'} \quad \Longrightarrow \text{safe}$$

Examples

Issue credit card

$$\frac{hash\ (n) = 0}{S' = S \cup \{n\}}$$

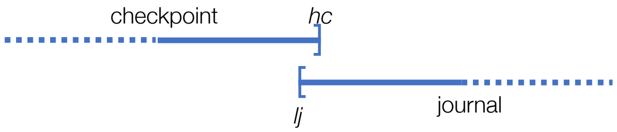
Deliver medication

- *Inv(r) { r ≥ 0}* *// r = remaining number of boxes*

Increase allocation: $\dfrac{Inv(r) \qquad\qquad Inv(r')}{r' = r+1}$

Deliver a box: $\dfrac{Inv(r) \qquad r \geq 1 \qquad Inv(r')}{r' = r-1}$

Ex.: maintain checkpoint



Inv(σ) = { σ.lj ≤ σ.hc} *// no gap*

Advance checkpoint: $\dfrac{Inv(\sigma) \wedge d \geq 0 \qquad\qquad Inv(\sigma')}{\sigma'.hc = \sigma.hc + d}$

Advance journal: $\dfrac{Inv(\sigma) \wedge d \geq 0 \qquad \sigma.lj + d \leq \sigma.hc \qquad Inv(\sigma')}{\sigma'.lj = \sigma.lj + d}$

Advance both: $\dfrac{Inv(\sigma) \wedge d \geq 0 \qquad\qquad Inv(\sigma'')}{\sigma'.hc = \sigma.hc + d;\ \sigma''.lj = \sigma'.lj + d}$

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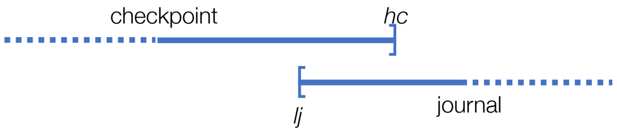

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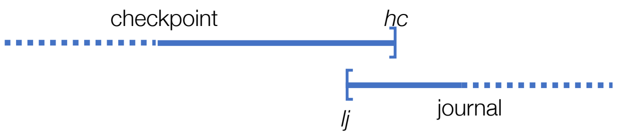

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Advance both:
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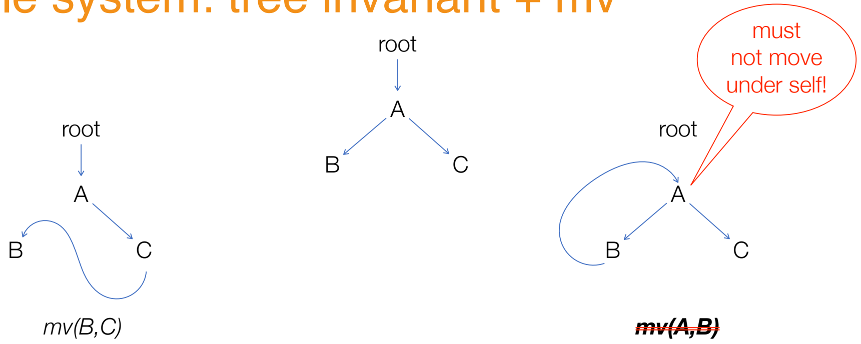
File system: tree invariant + mv



$$\frac{Inv(\sigma) \qquad \neg\ \sigma.path(c, np) \qquad Inv(\sigma')}{\sigma \xrightarrow{mv\ (c,\ np)} \sigma'}$$

Inv(σ) = *// Tree invariant*
- Every node is reachable from root
- A node has a single parent (but root has none)
- Names unique per directory
- Acyclic graph

Sequential safety: summary

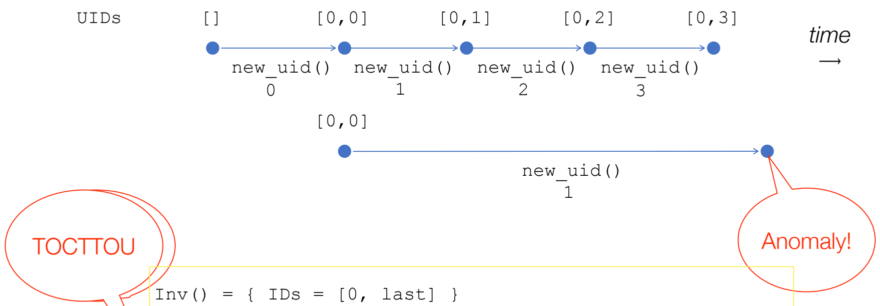
Safe state ≜ satisfies invariant *Inv*

In a sequential system, if:
- The initial state is safe
- Every update *U* is individually safe
  - i.e., has a precondition *Pre(U)* such that *Inv* remains true after *U*
  - i.e., *Pre(U)* ⟹ *wp(U, Inv)*

then every state of the system is safe

Concurrency anomalies

Concurrent generate UID



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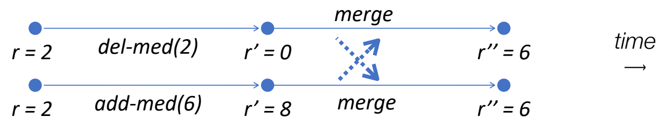
Concurrent delivery of medications (1)

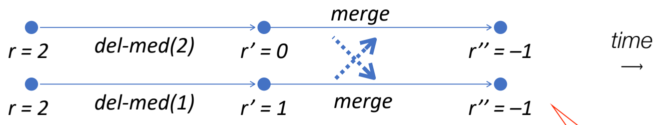


$$\textit{add-med}(n)\ \ \frac{r \geq 0 \qquad n \geq 0 \qquad r' \geq 0}{r' = r+n}$$

$$\textit{del-med}(n)\ \ \frac{r \geq 0 \qquad r \geq n \geq 0 \qquad r' \geq 0}{r' = r-n}$$

harmless TOCTTOU

Concurrent delivery of medications (2)



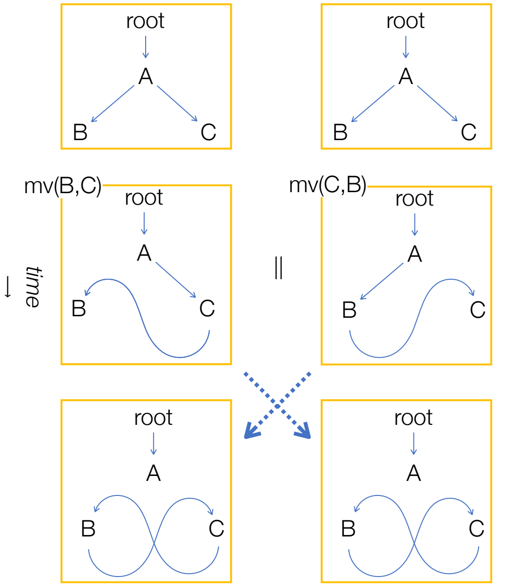
Anomaly!

harmful TOCTTOU

$$\textit{add-}\ \ \frac{\geq 0 \qquad n \geq 0 \qquad r' \geq 0}{r' = r+n}$$

$$\textit{del-med}(n)\ \ \frac{r \geq 0 \qquad r \geq n \geq 0 \qquad r' \geq 0}{r' = r-n}$$

FS: Concurrent move anomaly



TOCTTOU

$$\frac{Inv(\sigma) \qquad \neg\, \sigma.path(c, np) \qquad Inv(\sigma')}{\sigma \xrightarrow{mv\,(c,\,np)} \sigma'}$$

Concurrent moves

Converges

But violates invariant!

What went wrong?

File system: the DFS-R bug

2003: DFS-R: Windows NTFS replication layer

- large industrial customers
- unexplained data loss

2007: model checking exposes move anomaly: completely unexpected

2021: continues to bite developers

- Google Drive diverges
- Dropbox duplicates

Reasoning about concurrency is hard!

Concurrent anomalies: summary

Concurrency allows anomalies

- Incorrect behavior ≜ violates invariant
- Violation does not occur in a sequential execution

Anomalies seem to be caused by TOCTTOU race on precondition

Design objectives:

- Minimise remote coordination
- Allow benign TOCTTOUs
- Avoid harmful TOCTTOUs

But concurrency reasoning is too hard!

CISE: a sound approach to safe distributed systems

’Cause I’m Strong Enough (CISE)

Distributed system with CRDTs

Systematic method to prove whether two updates may execute concurrently without harm

- Concurrency not provably harmless is assumed harmful

Fully formalized, proven sound

- Generalises sequential correctness
- An application of the rely-guarantee logic

My presentation is informal

Gotsman et al., *‘Cause I'm strong enough: Reasoning about consistency choices in distributed systems*, POPL 2016, DOI 10.1145/2837614.2837625

CISE conditions

For all updates *U, U'*:

(1) Sequentially safe:

- Initial state satisfies invariant *Inv*
- Precondition of *U* satisfies the weakest-precondition of the invariant *wp(U,Inv)*

Individually Safe

(2) Convergent:

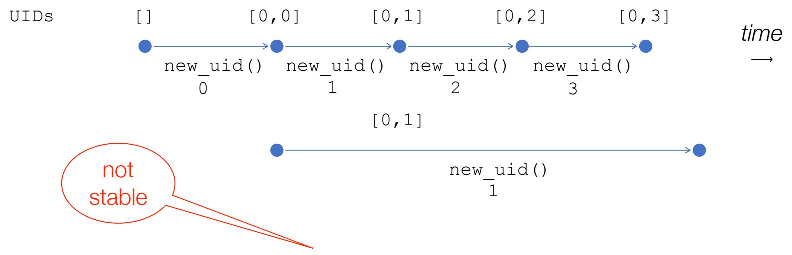
- When *U* concurrent to *U'*
- replace *U* || *U'* with *merge(U,U')*
- *merge(U,U')* commutative, associative, idempotent
- *merge(U,U')* preserves *Inv*

(3) Stable precondition:

- When *U* concurrent to *U'*
- the precondition of *U* is not made false by *U'*

harmless TOCTTOU

CISE Concurrent generate UID

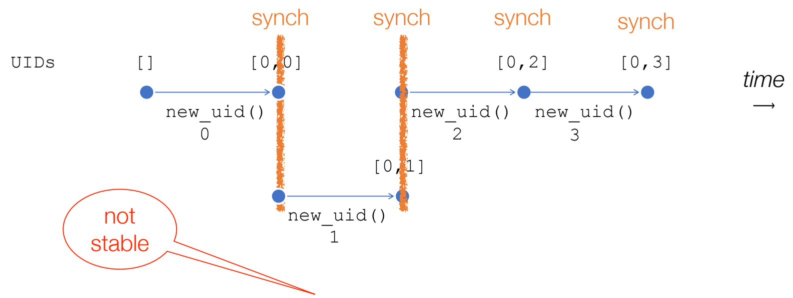


not stable

$$\frac{M \text{ is a set} \qquad n \notin M \qquad M' \text{ is a set}}{M' = M \cup \{n\}}$$

Solution: serialise ⟹ consensus

CISE Concurrent generate UID



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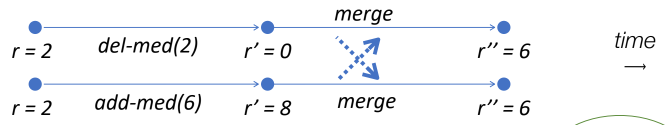
CISE Concurrent delivery of medications (1)



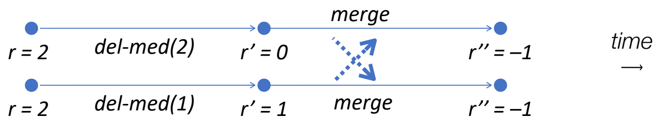
Stable w.r.t. add, deliver

$$\textit{add-med(n)} \quad \frac{r \ge 0 \qquad n \ge 0 \qquad r' \ge 0}{r' = r+n}$$

$$\textit{del-med(n)} \quad \frac{r \ge 0 \qquad r \ge n \ge 0 \qquad r' \ge 0}{r' = r-n}$$

- *add-med* || *add-med* OK
- *del-med* || *add-med* OK

CISE Concurrent delivery of medications (2)



$$\textit{add-med}(n)\quad \frac{r \geq 0 \qquad n \geq 0 \qquad r' \geq 0}{r' = r+n}$$

$$\textit{del-med}(n)\quad \frac{r \geq 0 \qquad r \geq n \geq 0 \qquad r' \geq 0}{r' = r-n}$$

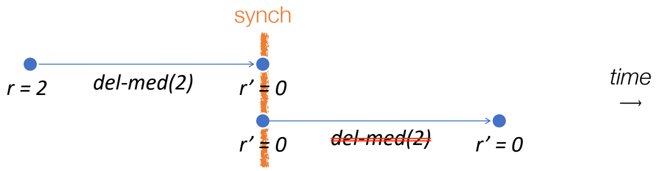
Not stable w.r.t. deliver

del-med design alternatives:

- Allow over-delivery ⟶ possibly punish after the fact
- Synchronise *del-med; del-med* ⟶ lose availability

weaken invariant, compensate

CISE Concurrent delivery of medications (3)



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Not stable w.r.t. deliver

del-med design alternatives:

- Allow over-delivery ⟶ possibly punish after the fact
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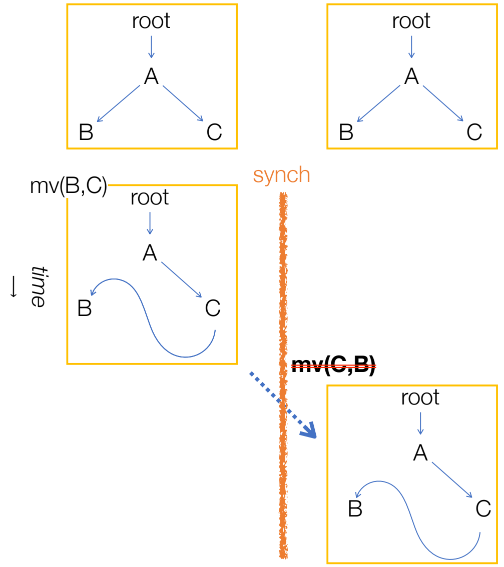
CISE Tree: serialise move



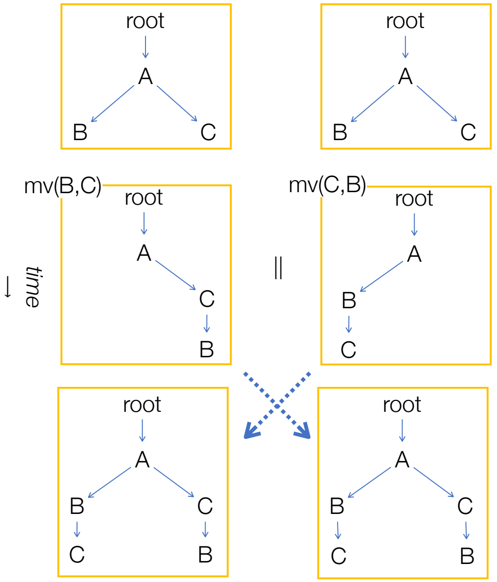
Not stable w.r.t. concurrent mv

$$\frac{Inv(\sigma) \qquad \neg\, \sigma.path(c, np) \qquad Inv(\sigma')}{\sigma \xrightarrow{mv\,(c,\, np)} \sigma'}$$

Impossible to satisfy both moves without violating the invariant!

- serialise conc. moves

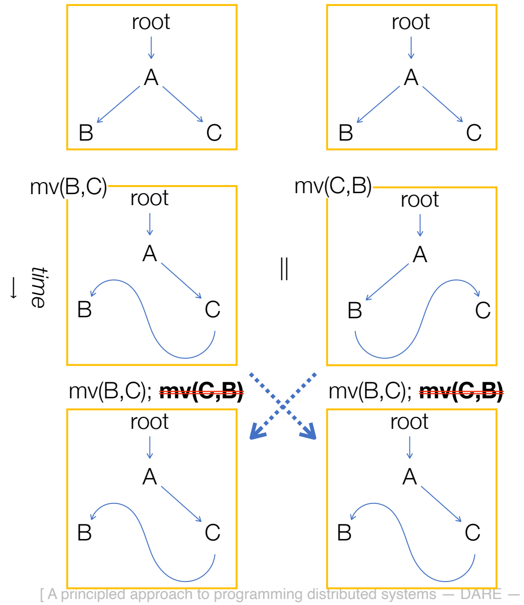
Dropbox: *mv* as cut & paste



Impossible to satisfy both moves without violating the invariant!

- implement move as cut & paste

Tree + mv: Kleppmann’s approach



$$\frac{Inv(\sigma) \qquad \neg\, \sigma.path(c, np) \qquad Inv(\sigma')}{\sigma \xrightarrow{mv\,(c,\, np)} \sigma'}$$

Impossible to satisfy both moves without violating the invariant!

If concurrent moves cause cycle:

- roll back
- serialise

Not “monotonic reads”

Summary: Tree + mv

Sequentially correct: sequential moves are OK

- Weakest precondition: not mv under self

CISE: precondition not stable under concurrent *mv*

Known design options:

- no *mv* op (XML)
- no *mv* op, copy-paste ⟹ duplicates (Dropbox)
- *up-mv* vs. *down-mv* [Nair 2021]
  - *up-mv* || *up-mv* stable
  - *up-mv* || *down-mv* stable
  - *down-mv* || *down-mv* not stable
- serialise *a priori:* lock [Najafzadeh 2018]
- serialise *a posteriori*: non-monotonic [Kleppmann 2022]

CISE conditions (again!)

For all updates *U, U':*

(1) Sequentially safe:

- Initial state satisfies invariant *Inv*
- Precondition of *U* satisfies the weakest-precondition of the invariant *wp(U,Inv)*

(2) Convergent:

- When *U* concurrent to *U'*
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(3) Stable precondition:

- When *U* concurrent to *U'*
- the precondition of *U* is not made false by *U'*

Using CISE in practice

Manual:

1. Individually correct: manual, testing
2. Convergence: CRDT library
3. Stability: consider all pairs of possibly concurrent updates

Tools

- Library: Bounded Counter [Balegas SRDS 2015]
- Stand-alone: specification language + SMT solver
  - CISE Tool [Najafzadeh 2015]
  - Soteria [Nair ESOP 2020]
  - BLOOM [Alvaro CIDR 2011]
- Integrated language/compiler
  - Conflict-Aware Replicated Data Types [arXiv 1802.08733]
  - LoRe [Haas ECOOP 2023]

Summary: As fast as possible

U, U' individually safe ∧ convergent ∧ mutually stable

- May execute concurrently
- Availability
- Perfect scalability

Summary: As strong as necessary

U, U' must not execute concurrently if:
    not commutative ∧ not convergent
∨ not mutually stable

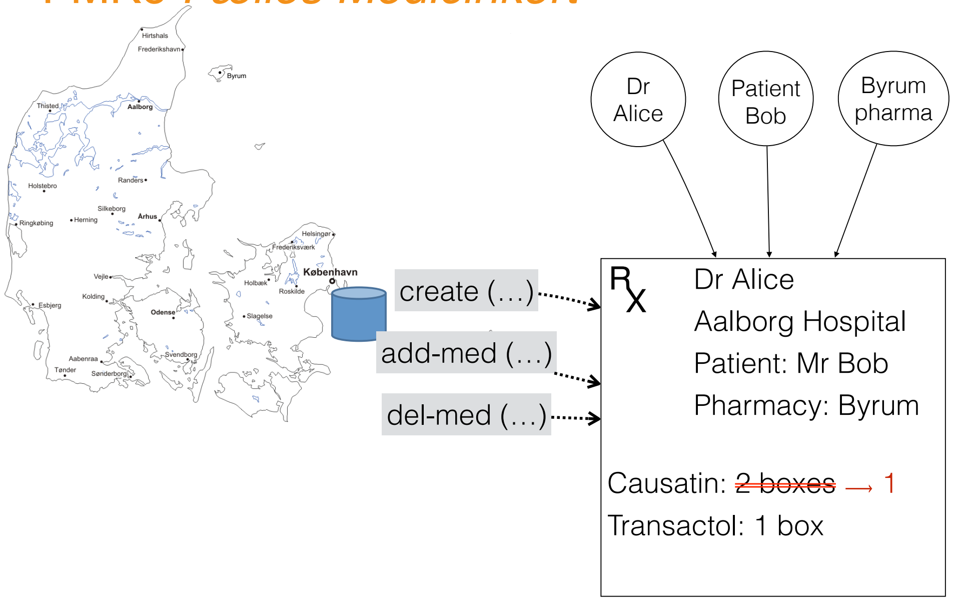
Design options:

- Refine invariant (e.g., bank account number)
- Downgrade invariant
  - from *"require x≥0"* to *"prefer x≥0"*
- Compensate: Weaken invariant, repair
- Serialise: *U; U'* or *U'; U*
  - Lock, single server, social convention, etc.
  - Monotonic, a priori: consensus
  - A posteriori: rollback. Finality?

Analyse again!

Classifying invariants by their coordination protocol

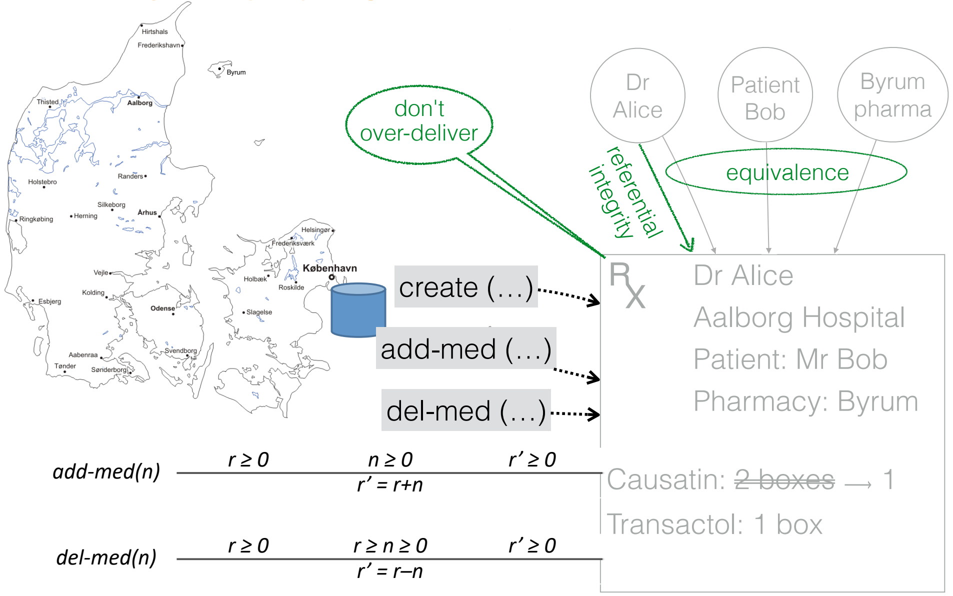
FMKe *Fælles Medicinkort*



Dr Alice
Aalborg Hospital
Patient: Mr Bob
Pharmacy: Byrum

Causatin: ~~2 boxes~~ → 1
Transactol: 1 box

FMKe invariants



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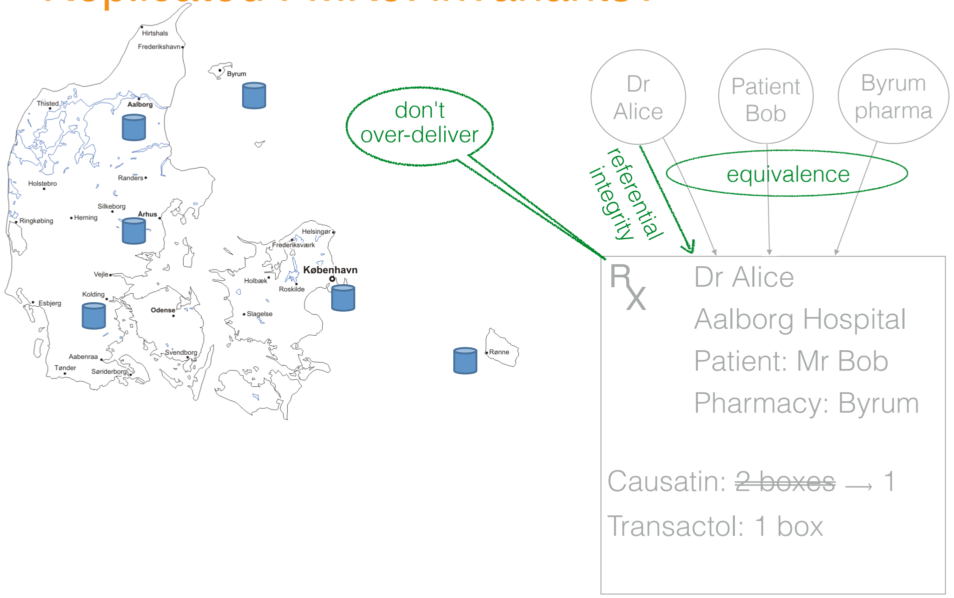
Replicated FMKe: invariants?



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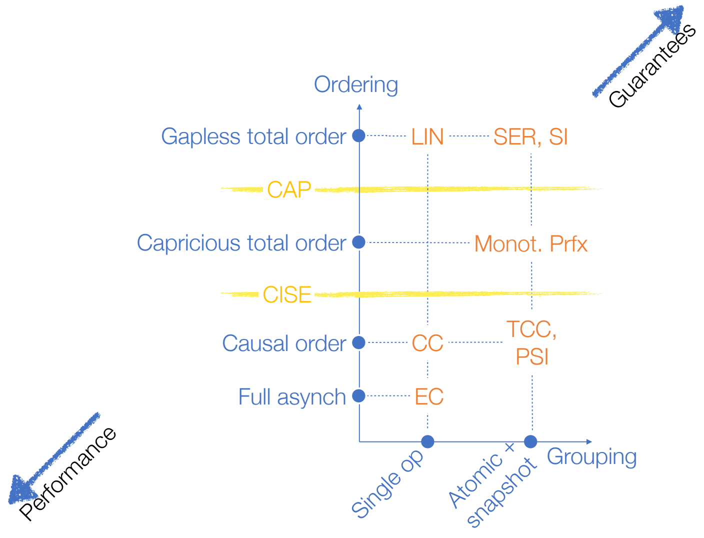
What protocols for what invariants?



Fully commutative updates

Some examples:

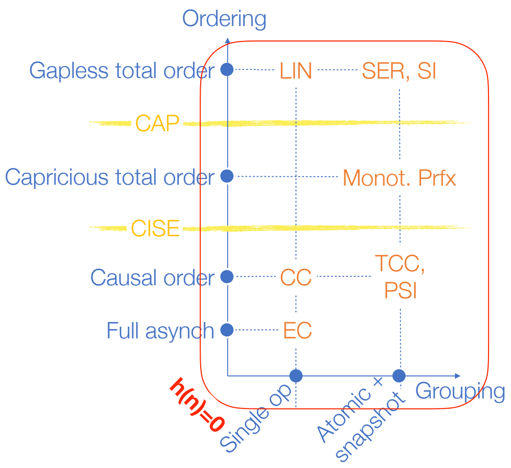
- Non-shared state
- Local blind: e.g., credit card number *hash(n)* = *0*
- Empty invariant + fully-commuting CRDTs
    - LWW
    - Grow-only set
    - PN counter
    - Vector clock

Convergent

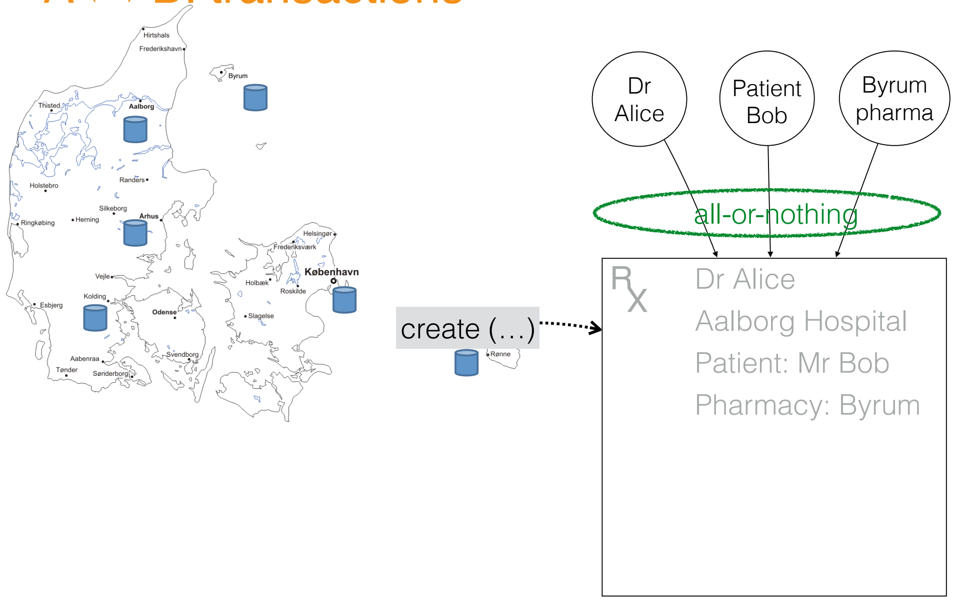
Asynchronous propagation

- Perfect scalability
- Perfect availability under partition

What protocols for fully commutative?



A ⟺ B: transactions



Transaction: Atomic writes + snapshot reads

create-p updates doctor, patient & pharmacy record

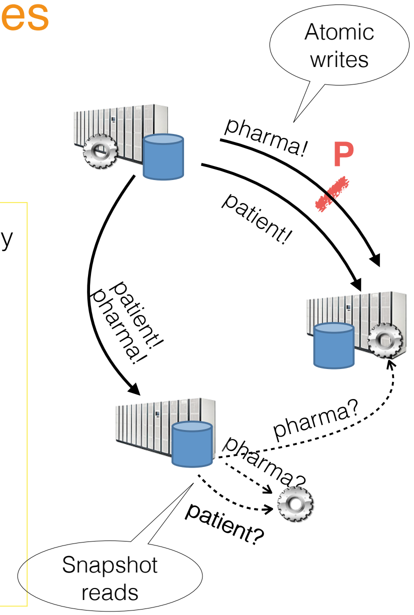
Atomic:

- = All-or-Nothing (A of ACID)
- Transmit joint updates together
- asynchronous

Snapshot: single database state

- multi-version concurrency control
- asynchronous

Asynch: Available under partition

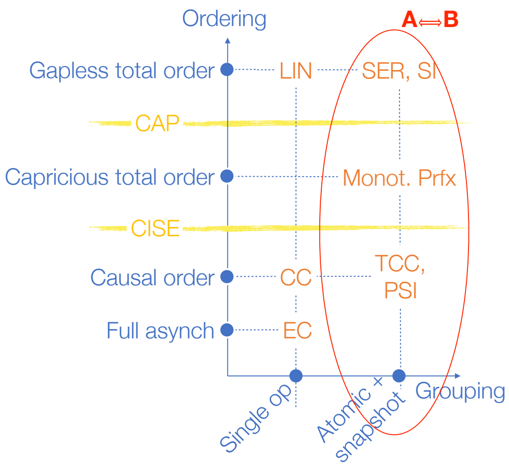


"A ⟺ B" style invariants

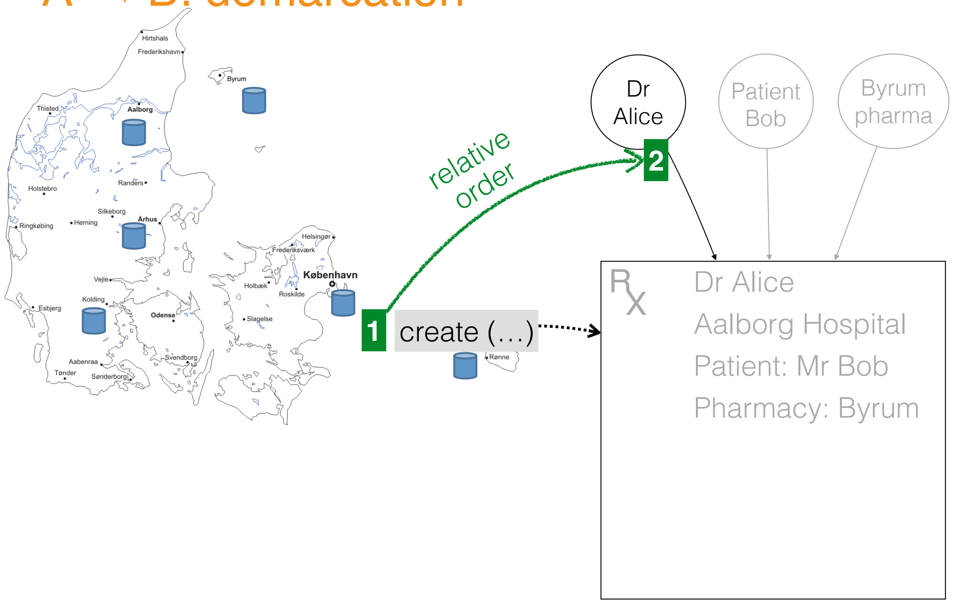
Some example cases:

- *A=B*
- *A = ¬B*
- *friend(x,y)* ⟺ *friend(y,x)*
- *x≤y: <x++;y++>* (one actor)

What protocols for A ⟺ B?



A ⟹ B: demarcation



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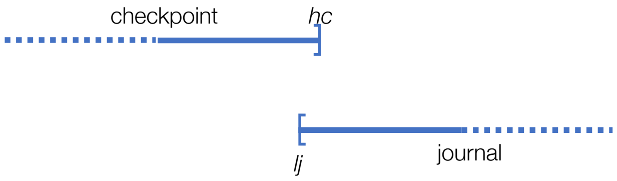
Distributed checkpoint: demarcation

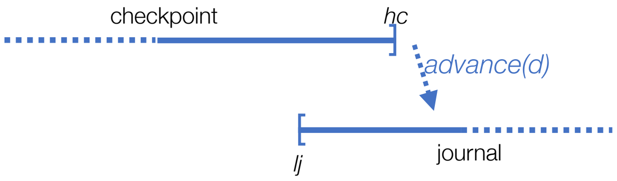


Inv(σ) = { σ.lj ≤ σ.hc}   *// no gap*

Demarcation protocol

- Journal dæmon: lower bound += d
- Journal: Send message to Checkpoint *advance(d)*
- Checkpoint dæmon: upper bound += d

Distributed checkpoint: demarcation



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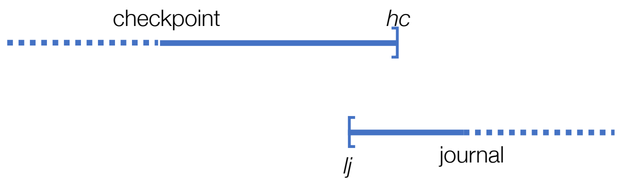
Distributed checkpoint: demarcation



$Inv(\sigma) = \{ \sigma.lj \leq \sigma.hc \}$ *// no gap*

Demarcation protocol

- Journal dæmon: lower bound += d
- Journal: Send message to Checkpoint *advance(d)*
- Checkpoint dæmon: upper bound += d

Non-commuting, demarcation

Non-commuting CRDTs

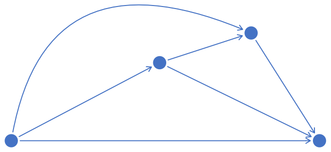
- Empty invariant
  - Set
  - Map
  - MVR
- Universally-stable operations
  - Acyclic graph: add-parallel, remove
  - Sequence: insert-at, remove

2-actor implication invariants

- A ⟹ B
- Referential integrity
- Chicken/fox/grain: *grain* ⟹ ¬*chicken*
- *x≤y*

Preserve order across processes

⟶ Causal Consistency



Causal Consistency

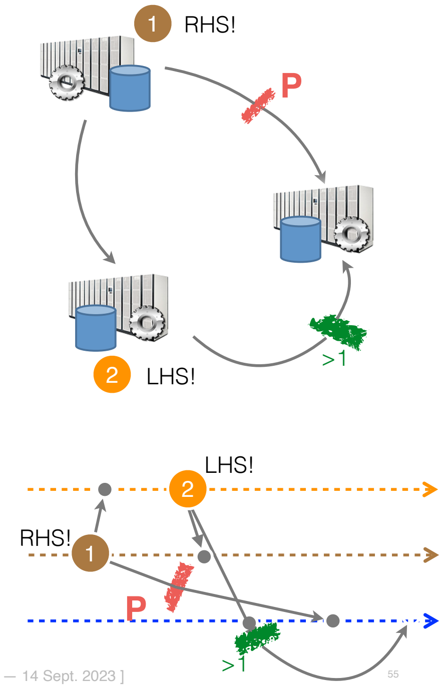
create-p before *add-med*

- “Bob points to Rx ⟹ Rx valid”
  - Referential integrity
- General case: LHS ⟹ RHS
- pattern: RHS!; LHS!

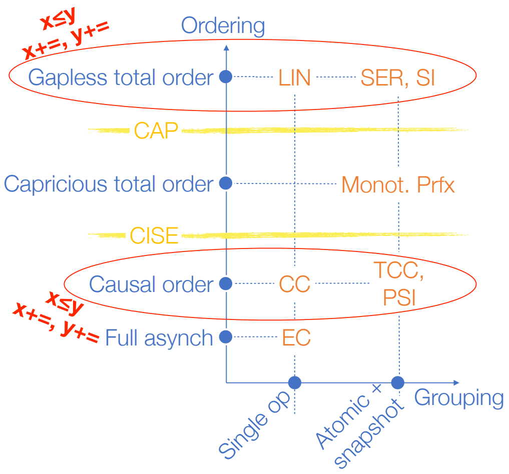
Deliver in the right order: Causal Consistency

Local decision:

- requires metadata
- available



What protocols for demarcation?



x≥0 x—: total/mutual order

u(), v() not mutually stable

- “Conflicting”
- Either *u()* before *v()*, or *v()* before *u()*

Protocols:

- General case: total order, consensus
- 1 lock / set of mutually-conflicting operations
  - Coarser locks OK
- Single server / conflict set (flat combining)
- Social

Bounded Counter

Specific, common case

Shared counter:

- *x ≥ 0*
- *increment (n)*
- *decrement (n)* // precondition *x ≥ n*

Escrow:

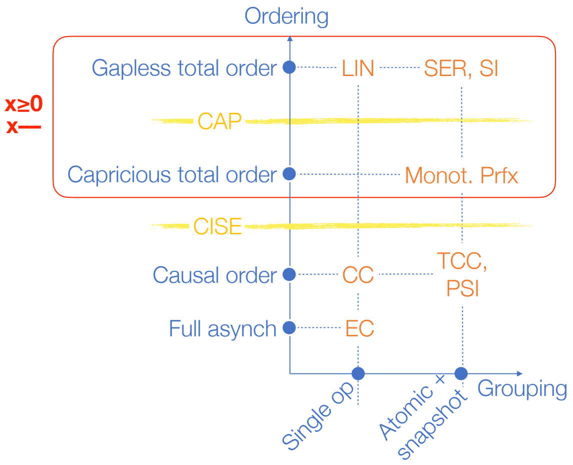
- Local share, decrement *share* −= *n*
- decrement disallowed if *share* < *n*
- Donate share

Mostly AP

Encapsulated, proven correct (CISE)

Causal ordering essential

What protocols for x≥0 x—?



Mutual order: *a posteriori* vs. *a priori*

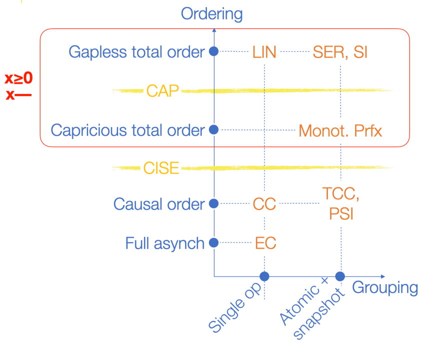
A posteriori, Capricious, Monotonic-Prefix:

- Execute
- Pick a number
- Propagate
- Sort
- Roll back; roll forward
- Iterate

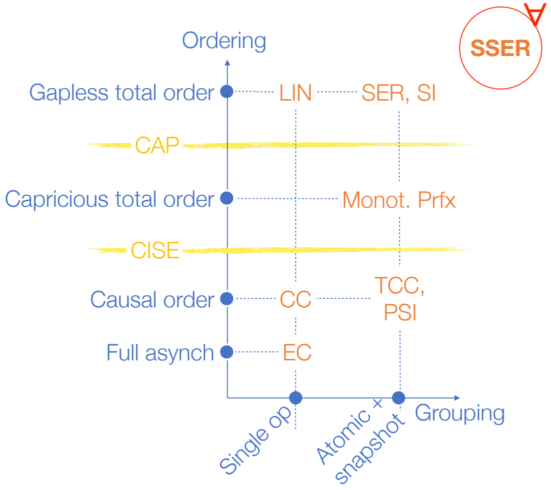
A priori, Gapless, Monotonic Reads:

- Consensus on a number
- Wait for my turn
- Execute & propagate

Capricious + finality ⟹ consensus



What protocols for arbitrary invariants?



Sweet spot: Transactional Causal Consistency + optional consensus

TCC =

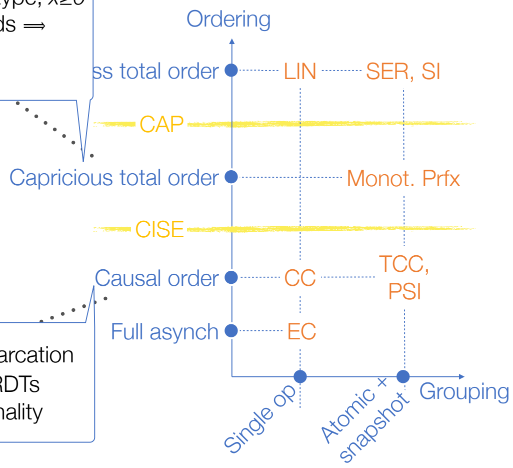
- Causal consistency
  - *x≤y,* demarcation
- Snapshot reads + Atomic writes
  - *A⟺B*
- System: AntidoteDB

Available: not *x≥0*

- Strengthen when necessary
- System: Colony

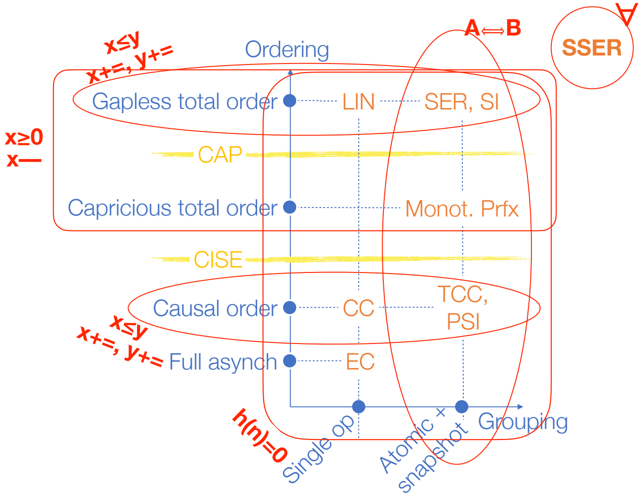
Strongest AP protocol(s)

Total order
Any sequential data type, *x≥0*
Non Monotonic Reads ⟹ rollbacks
No finality



Partial order ⟶ demarcation
Requires Merge / CRDTs
Monotonic Reads; finality

What protocols for what invariants?



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