Replicated Data Consistency for Large Scale Distributed Systems

Operational Transformation Approaches
Conflict-free Replicated Data Structures

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January 16, 2018

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CAP Theorem [GL02]

- A system without network partition, can achieve consistency + availability
  - Client and storage system are part of the same environment
- In a large-scale distributed systems, network partitions exist

- Consistency and availability cannot be both achieved
  - Relax consistency, maintain availability
  - Maintain consistency, tolerate unavailability under certain conditions

Optimistic Replication

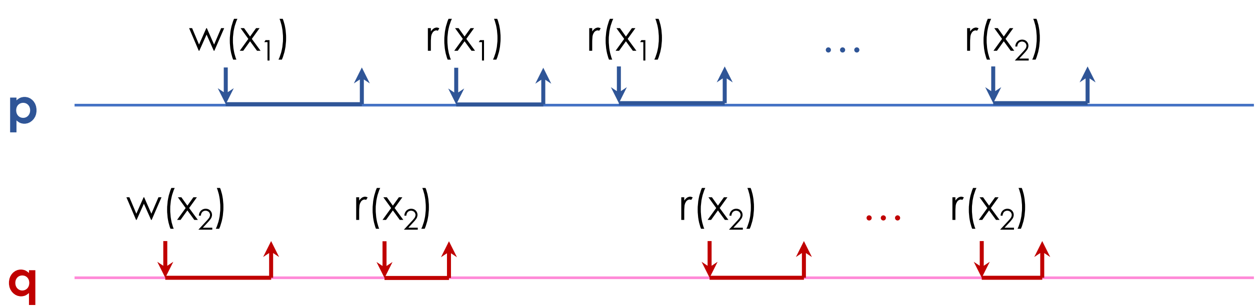
- To sidestep CAP theorem [GL02], a first solution is to avoid synchronizing replicas. Replicas simply reconcile their copies in the background.

- Trade-off between consistency and availability
  - allows replicas to diverge
- This approach is named lazy [LLS90], or optimistic replication [SS05]

- Examples: Bayou, Amazon S3, etc.

Consistency in Distributed Systems
Eventual Consistency

- **Definition** (*eventual consistency*)
  A history h is eventually consistent (EC) when for every object x if there is a bounded amount of write operations on x in h, then eventually all the read operation observer the same state.



Optimistic Replication
Strong Eventual Consistency

- Strong Eventual Consistency
  - Eventual delivery: « *An update executed at some correct replica eventually executes at all correct replicas* »
  - Strong convergence = correct replicas that have executed the same updates **have** equivalent state
  - No consensus in background, no need to rollback

Operational Transformation (OT)
Operation-based approach model

- *n* copies of an object hosted at *n* sites
- An object is modified by applying operations

- Each operation is
  - generated at a site (local execution),
    and applied immediately on the local copy
  - broadcasted to other sites
  - integrated at those sites (remote execution)

- System is correct if when it is idle all copies are identical (SEC)

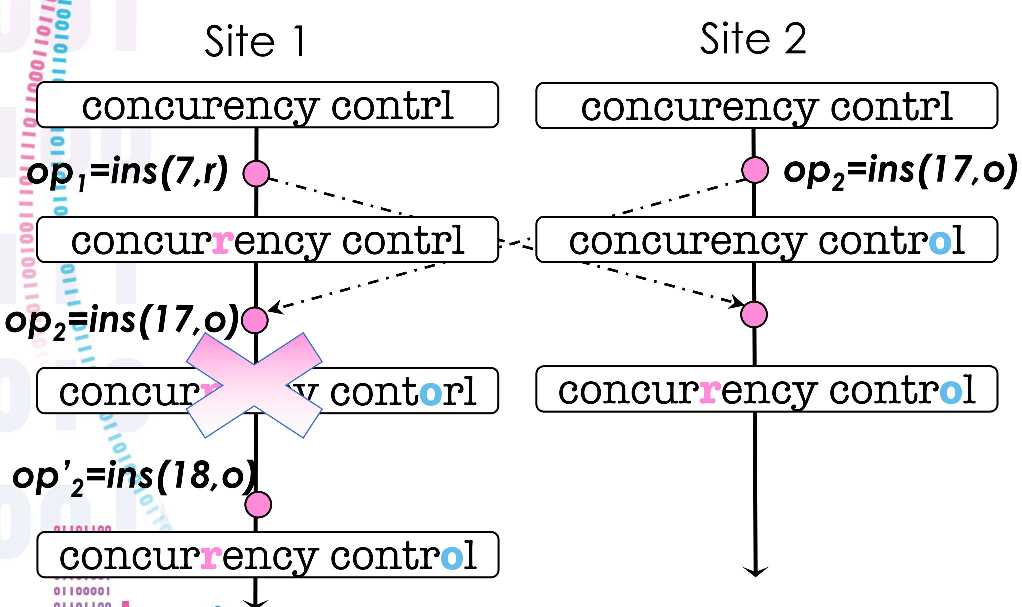
Operational Transformation [EG89]
General Architecture

- 2 components:
  - An integration algorithm (diffusion, integration)
  - A set of transformation functions (conflict resolution)

- 3 main issues:
  - Convergence (~ EC)
  - Causality violation
  - (Intention violation)

Operational Transformation
Running Example

- Textual document = sequence of characters
- Operations:
  - Ins(p, c) – inserts character ’c’ at position ’p’
  - Del(p) – removes character at position ‘p’



T(Ins(p1,c1), Ins(p2,c2)) :-
if (p1<p2) **return** Ins(p1,c1)
else return Ins(p1+1,c1)
endif

Operational Transformation
Example of Transformation Functions

T(Ins(p1,c1), Ins(p2,c2)) :-
    if (p1<p2) **return** *Ins(p1,c1)*
    else return *Ins(p1+1,c1)*

T(Ins(p1,c1), Del(p2)) :-
    if (p1≤p2) **return** *Ins(p1,c1)*
    else return *Ins(p1-1,c1)*
    endif

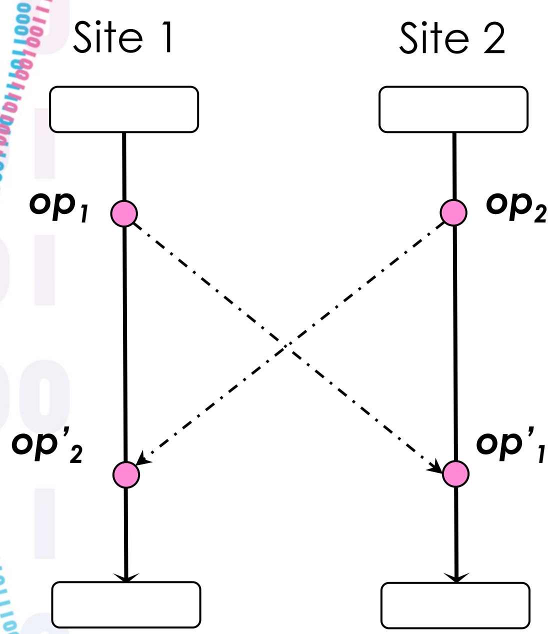
T(Del(p1), Ins(p2,c2)) :-
    if (p1<p2) **return** *Del(p1)*
    else return *Del(p1+1)*

T(Del(p1), Del(p2)) :-
    if (p1<p2) **return** *Del(p1)*
    else if (p1>p2) **return** *Del(p1-1)*
    else return *Id()*

Operational Transformation

Correctness [EG89]

(TP1) $op_1 \circ T(op_2, op_1) \equiv op_2 \circ T(op_1, op_2)$

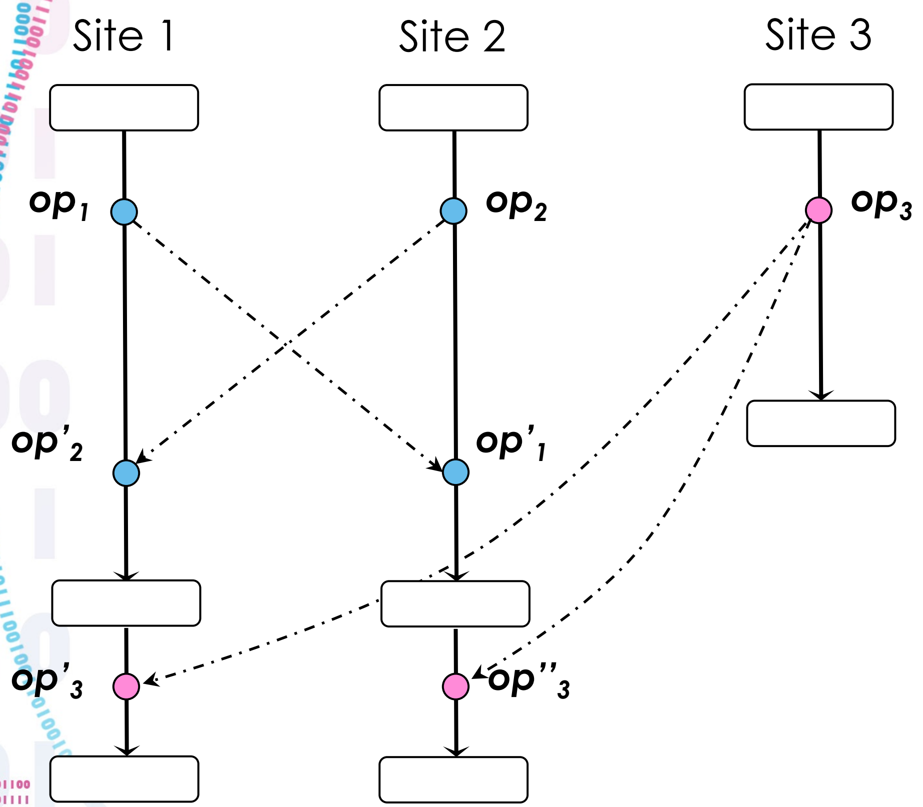


$T(op_2\text{: operation}, op_1\text{: operation}) = op'_2$

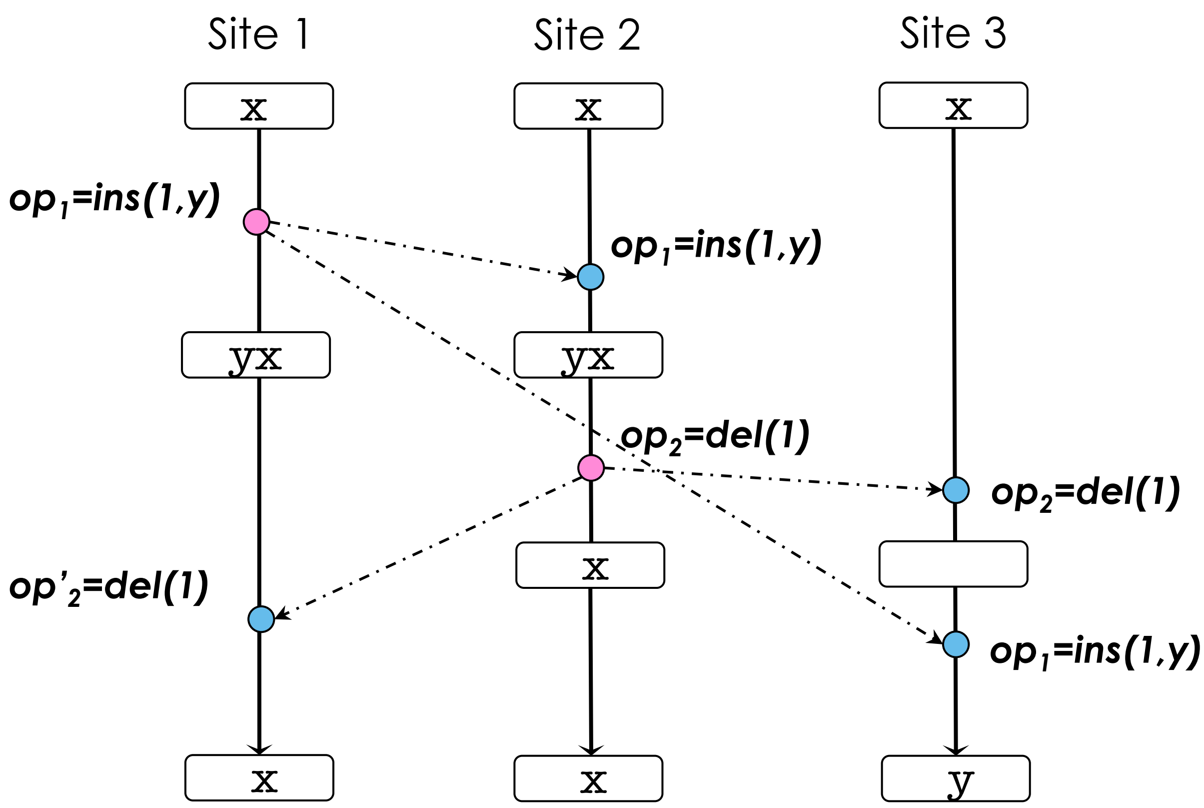
- op_1 and op_2 concurrent, defined on a state S
- op'_2 same effects as op_2, defined on $S.op_1$

Operational Transformation
Correctness [RNG96]

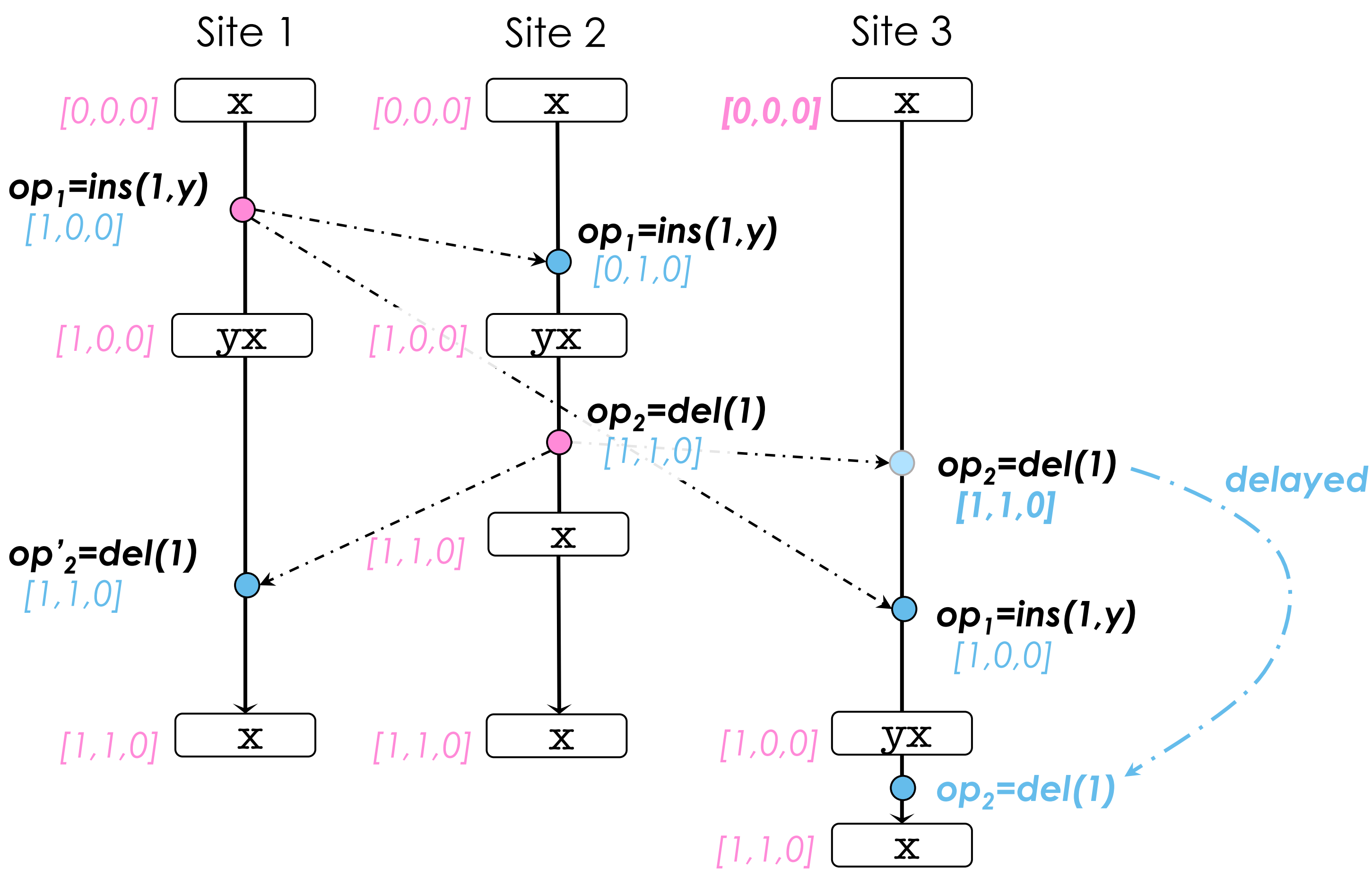
(TP2) $T(op_3, op_1 \circ T(op_2, op_1)) = T(op_3, op_2 \circ T(op_1, op_2))$



Operational Transformation
Causality Violation



Operational Transformation
Causality Preservation



Operational Transformation (OT)
Operation Intention

- Intention of an operation is the observed effect as result of its execution on its generation state

- Passing from an initial state ‘ab’ to a final state ‘aXb’ could be observed as:
  - ins(2,x)
  - ins(a < X < b)
  - ins(a < X)
  - ins(X < b)

Operational Transformation (OT)
Intention Preservation [SJZYC98]

- For any operation *op* the effects of executing *op* at all sites should be the same as the intention of op
- The effect of executing *op* does not change the effects of independent operations.

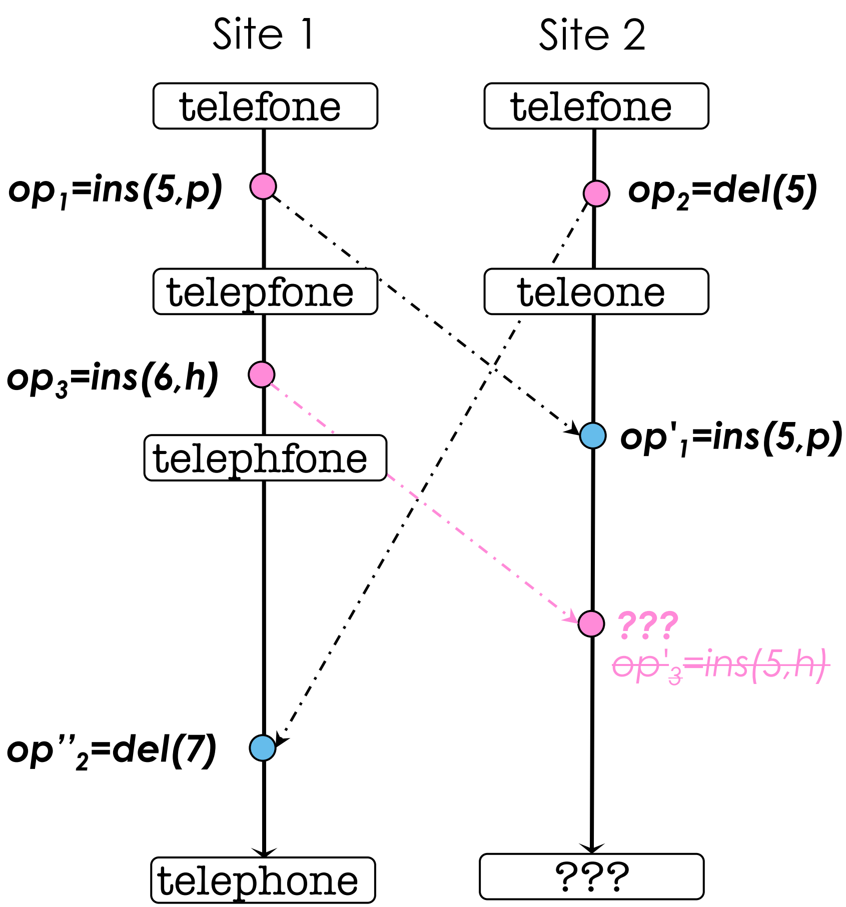
Operational Transformation (OT)
Existing Approaches

- Two main families:
  - Transformation functions satisfying both TP1 and TP2
  - Control algorithms avoiding (needs of) TP2

Operational Transformation (OT)
Existing Approaches

- Design and verify transformation functions T
- T also known as forward transposition (*transpose_fd)*
- Verification of conditions TP1 and TP2
  - Combinatorial explosion (>*100* cases for a string)
  - Iterative process
  - Repetitive and error prone task

Operational Transformation (OT)
Partial Concurrency



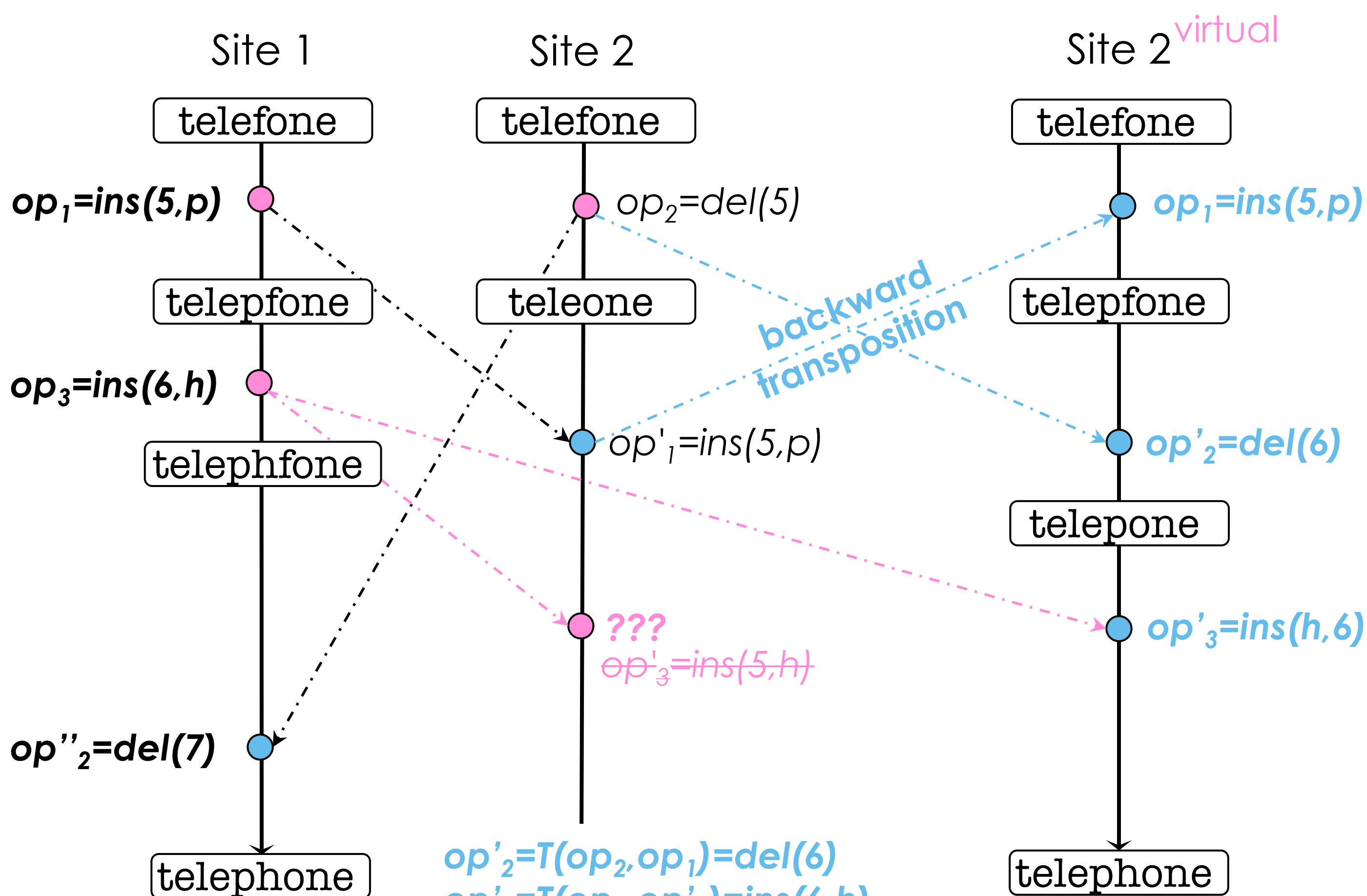
$op'_2=T(op_2,op_1)=del(6)$
$op''_2=T(op'_2,op_3)=del(7)$

$op'_1=T(op_1,op_2)=ins(5)$

$T(op_3,op_2)$
is not allowed to be performed

Nor $T(op_3,op'_1)$

Operational Transformation (OT)
Partial Concurrency

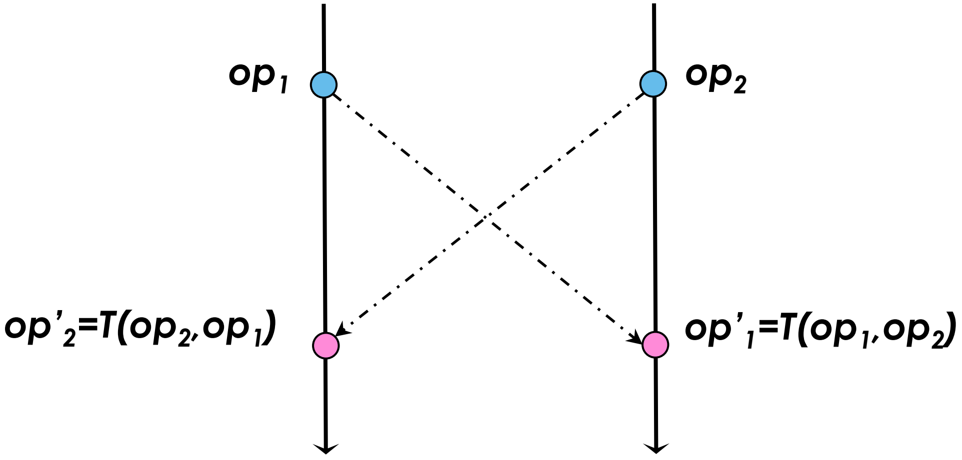


$op'_2=T(op_2,op_1)=del(6)$
$op'_3=T(op_3,op'_2)=ins(6,h)$

Operational Transformation (OT)
Backward Transposition [SJZYC98]

- Backward transposition (*transpose_bk*)

- transpose_bk(op_1, op'_2) = (op_2, op'_1)
  - $op'_2 = T(op_2, op_1)$
  - $op'_1 = T(op_1, op_2)$



- Note:
  - transpose_bk(op_a, op_b) = ($T^{-1}(op_b, op_a)$, $T(op_a, T^{-1}(op_b, op_a))$)

Operational Transformation
Example of Transformation Functions [RNG96]

T(Ins(p1,c1,u1), Ins(p2,c2,u2)) :-
if (p1<p2) or (p1=p2 and u1<u2) **return** *Ins(p1,c1,u1)*
else return *Ins(p1+1,c1,u1)*

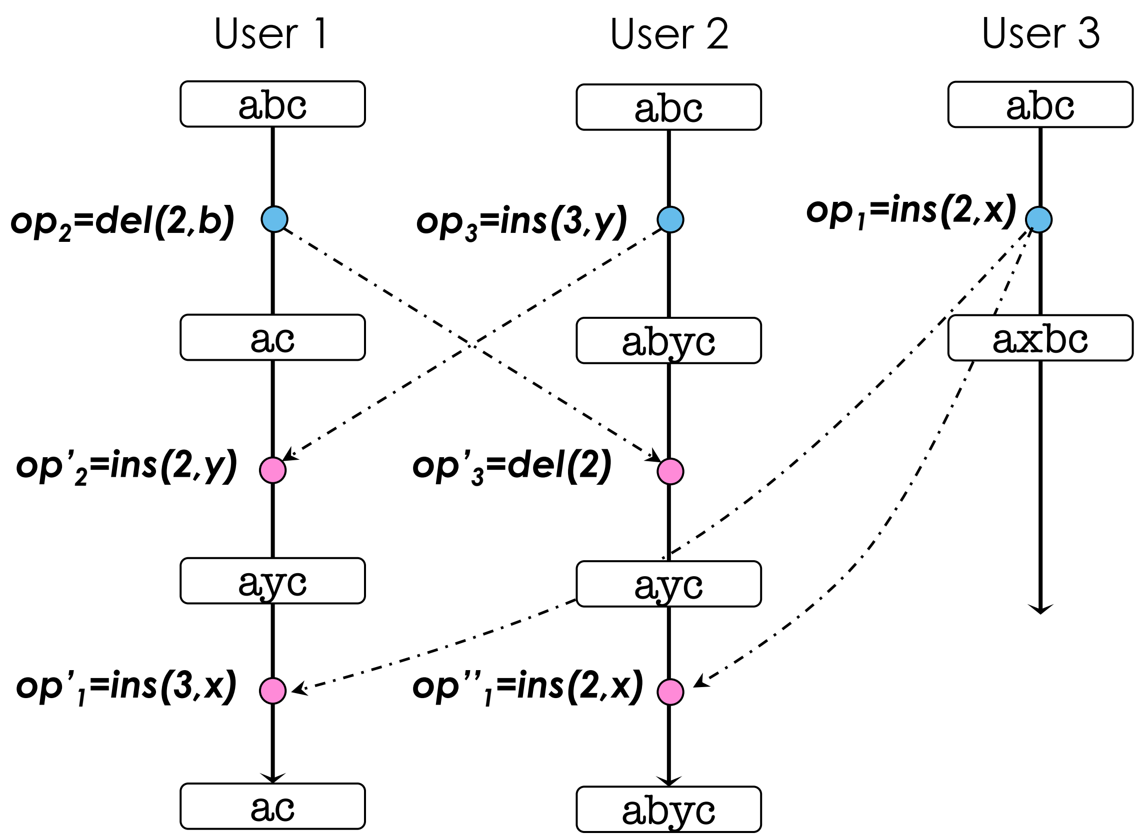
T(Ins(p1,c1,u1), Del(p2,u2)) :-
if (p1≤p2) **return** *Ins(p1,c1,u1)*
else return *Ins(p1-1,c1,u1)*
endif

Satisfy TP1 but not TP2!

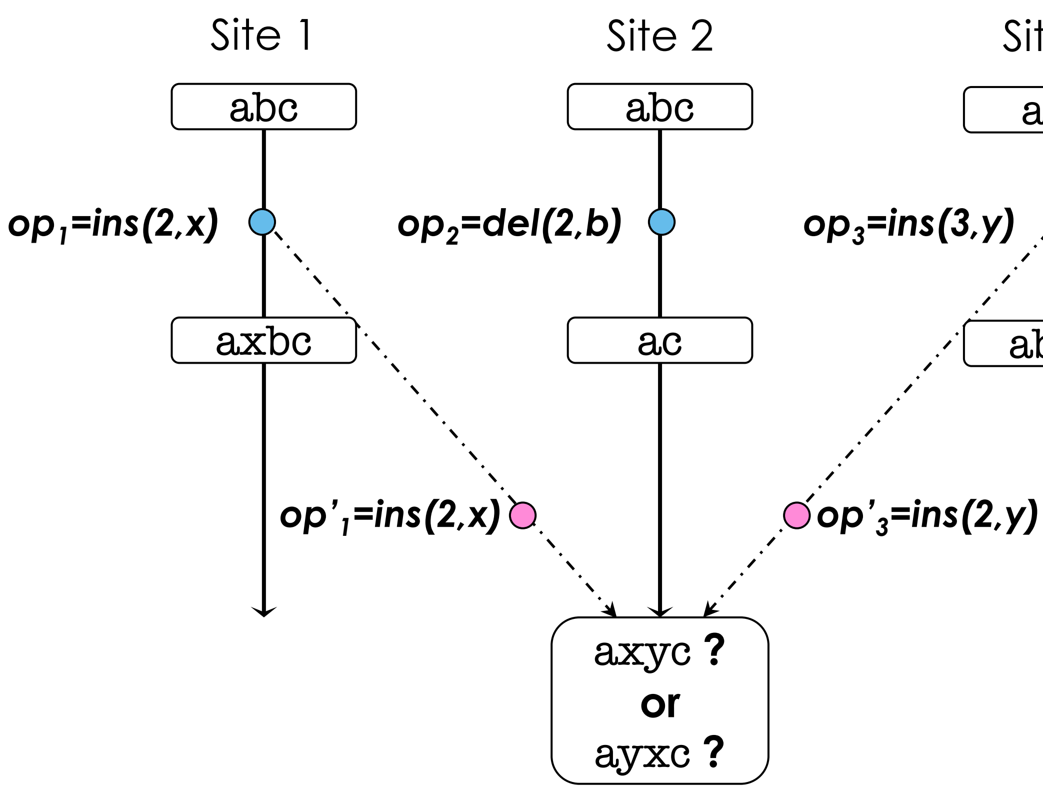
T(Del(p1,u1), Ins(p2,c2,u2)) :-
if (p1<p2) **return** *Del(p1,u1)*
else return *Del(p1+1,u1)*

T(Del(p1,u1), Del(p2,u2)) :-
if (p1<p2) **return** *Del(p1,u1)*
else if (p1>p2) **return** *Del(p1-1,u1)*
else return *Id()*

Operational Transformation
Example of Violation of TP2



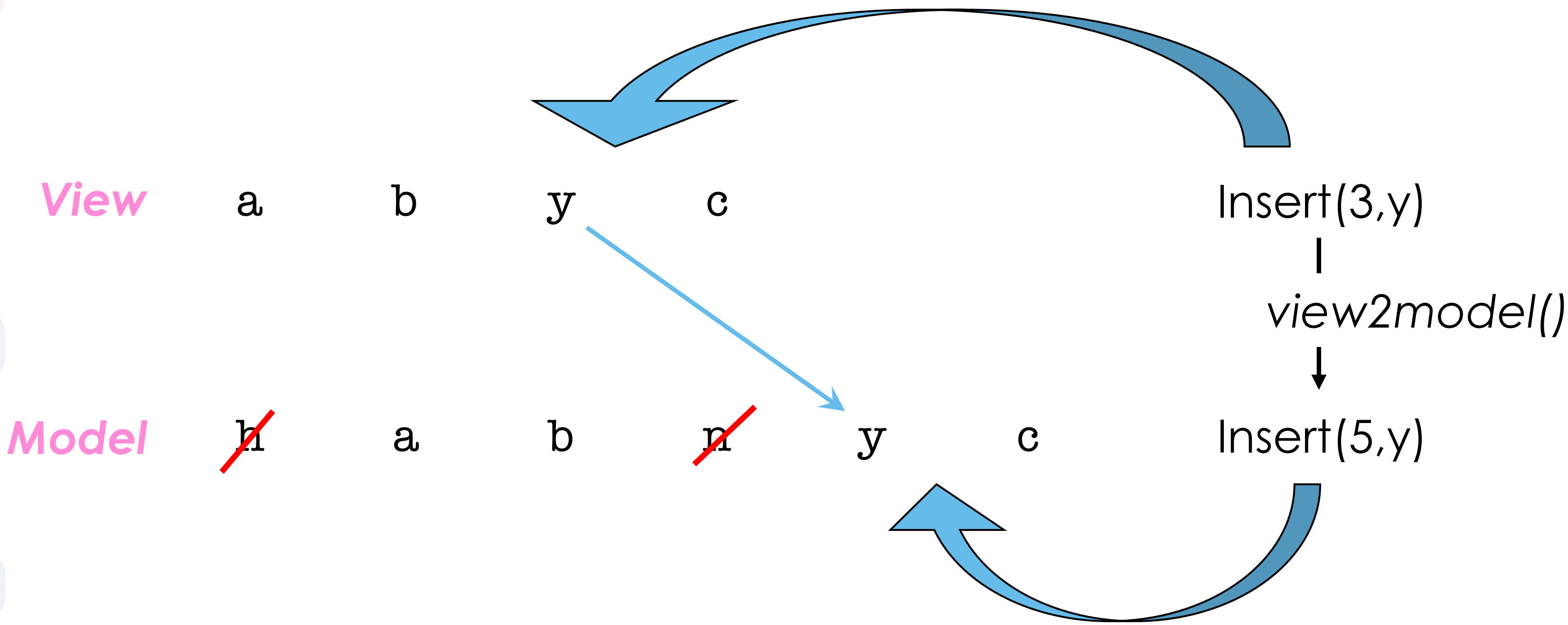
Operational Transformation (OT)
False-Tie Problem



Operational Transformation (OT)

Tombstone Transformation Functions [OUMI06]

- Keep 'tombstones' of deleted elements



Operational Transformation (OT)
Tombstone Transformation Functions

T(Ins(p1,c1,s1), Ins(p2,c2,s2)) :-
  if (p1<p2) or (p1=p2 and s1<s2) **return** *Ins(p1,c1,s1)*
  else return *Ins(p1+1,c1,s1)*

T(Ins(p1,c1,s1), Del(p2,s2)) :-
  return *Ins(p1,c1,s1)*

T(Del(p1,s1), Ins(p2,c2,s2)) :-
  if (p1<p2) **return** *Del(p1,s1)*
  else return *Del(p1+1,s1)*

T(Del(p1,s1), Del(p2,s2)) :-
  return *Del(p1,s1)*

Operational Transformation (OT)
Tombstone Transformation Functions – Compact Model

View	a	b	y	c			Insert(3,y)
							view2model()
Model	~~h~~	a	b	~~n~~	y	c	Insert(5,y)

Compacted model = sequence of (character, absolute-position)

View	a	b	y	c	Insert(3,y)
					view2model()
Compacted	a,2	b,3	y,5	c,6	Insert(5,y)

Operational Transformation (OT)

Tombstone Transformation Functions – Delta Model

View	a	b	y	c		Insert(3,y)
						view2model()
Compacted	a,2	b,3		y,**5**	c,*6*	Insert(5,y)

Delta model = sequence of (character, offset)

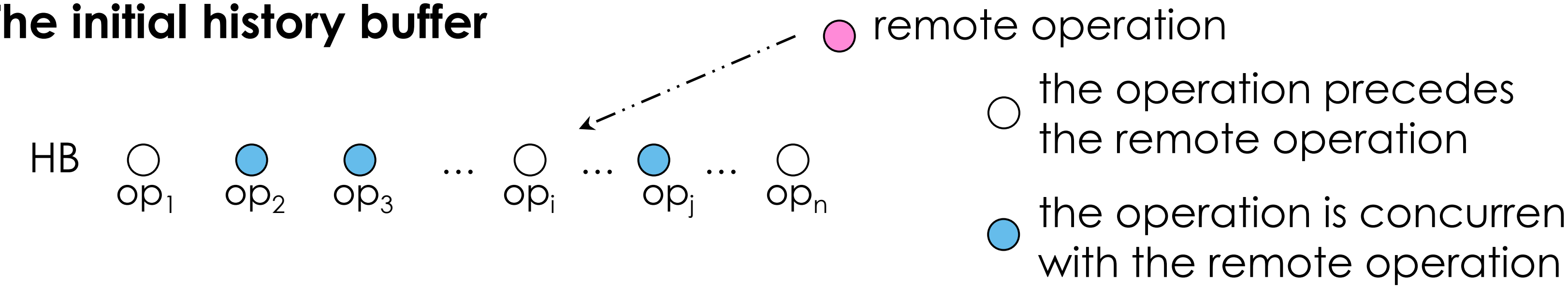
View	a	b	y	c	Insert(3,y)
					view2model()
Delta	a,+2	b,+1	y,**+2**	c,**+1**	Insert(5,y)

Operational Transformation (OT)
Tombstone Transformation Functions – Comparison

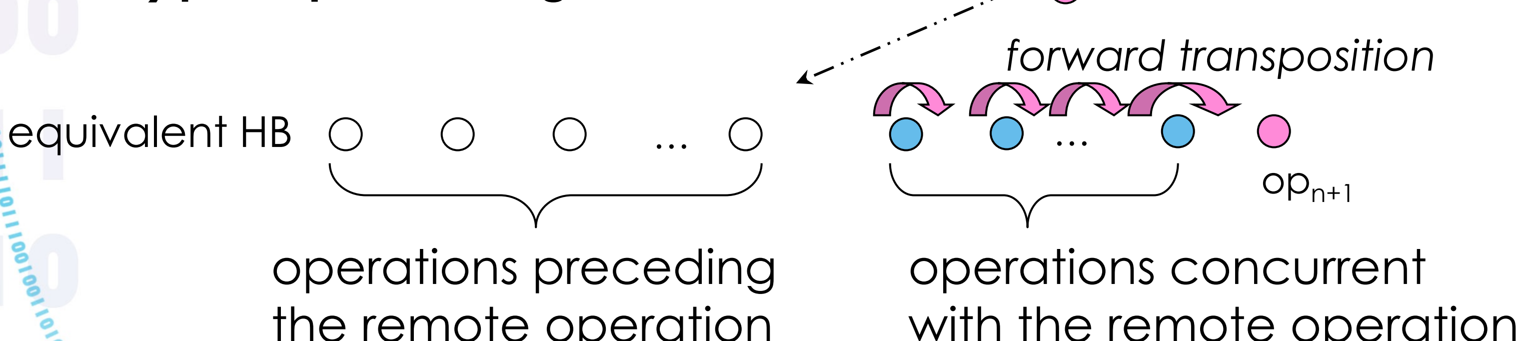
- Basic Model
  - Deleted characters are kept
  - Size of the model is growing infinitely
- Compacted Model
  - Update absolute position of all characters located after the effect position
- Delta Model
  - Update the offset of next character
- Observations
  - view2model can be optimized (caret position)
  - Overhead of view2model is not significant

Operational Transformation (OT)
General Control Algorithm – SOCT2 [SCF97]

a) The initial history buffer



b) principle of integration



Operational Transformation (OT)
Control Algorithms that avoid TP1 and/or TP2

- GOT algorithm [SJZYC98]
  - Does not need to satisfy TP1 and TP2
  - Requires a global serialization order
    - Sum of state vector components
    - If equality, then priority on sites
  - Requires very costly undo/redo mechanism
    - Does not ensure SEC (only EC)

Operational Transformation (OT)
Control Algorithms that avoid TP1 and/or TP2

- SOCT4 Algorithm [VCFS00]
  - No undo/redo mechanism, no state vectors
  - Eliminates TP2, but requires TP1
  - Global order of operations according to timestamps generated by a sequencer
  - Local operations executed immediately
  - Assigns a timestamp to the operation and transmits it to the other sites
  - Defers broadcast until execution of all preceding operations
  - Transformations performed by each site

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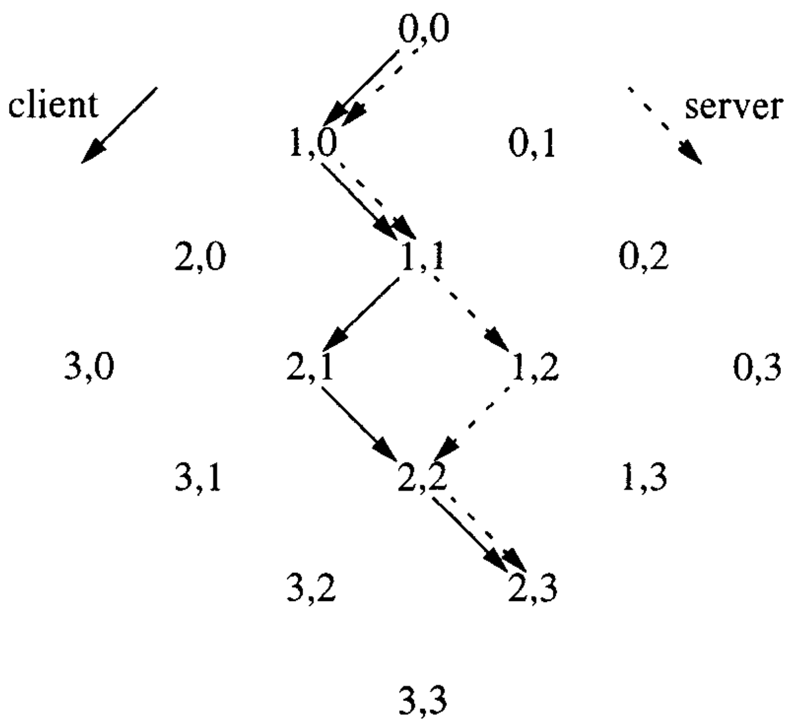
Operational Transformation (OT)
Control Algorithms that avoid TP1 and/or TP2

- Jupiter algorithm [NCDL95]
  - Used in GoogleDocs
  - Requires a central server
  - Eliminates TP2, but requires TP1
  - Does not need state vectors
  - Transformations done on the server + client side

Operational Transformation (OT)
Jupiter Algorithm



xform(c,s)={c',s'}

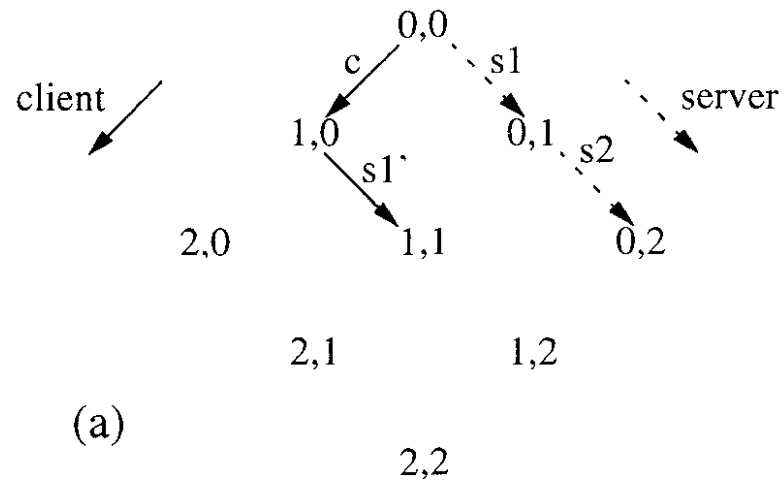
xform(del x, del y)=

{del x-1, del y} if x>y

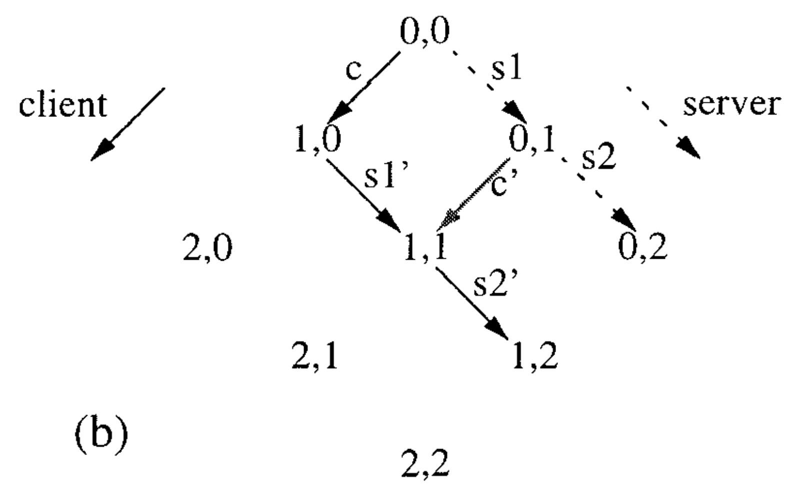
{del x, del y-1} if x<y

{no-op, no-op} if x=y

Operational Transformation (OT)
Jupiter Algorithm

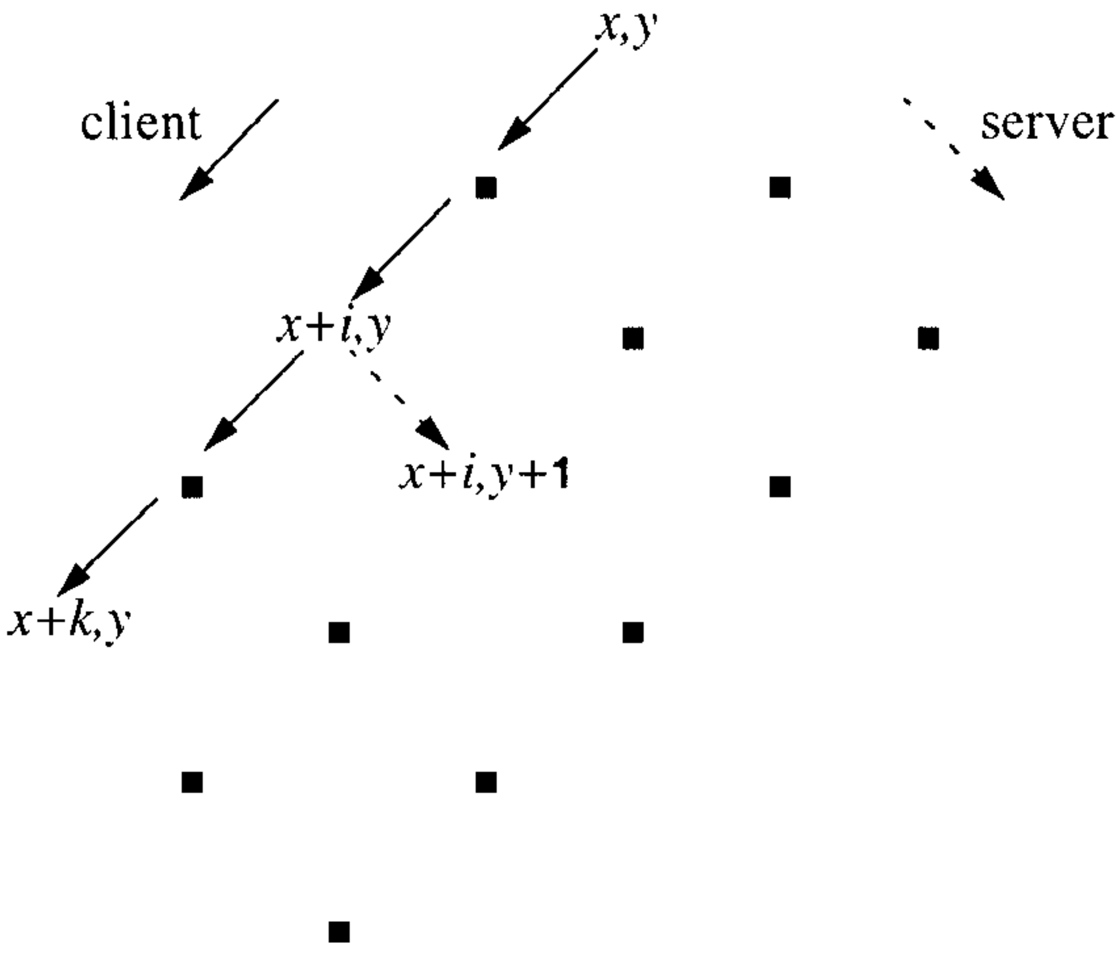


(a)



(b)

Operational Transformation (OT)
Jupiter Algorithm

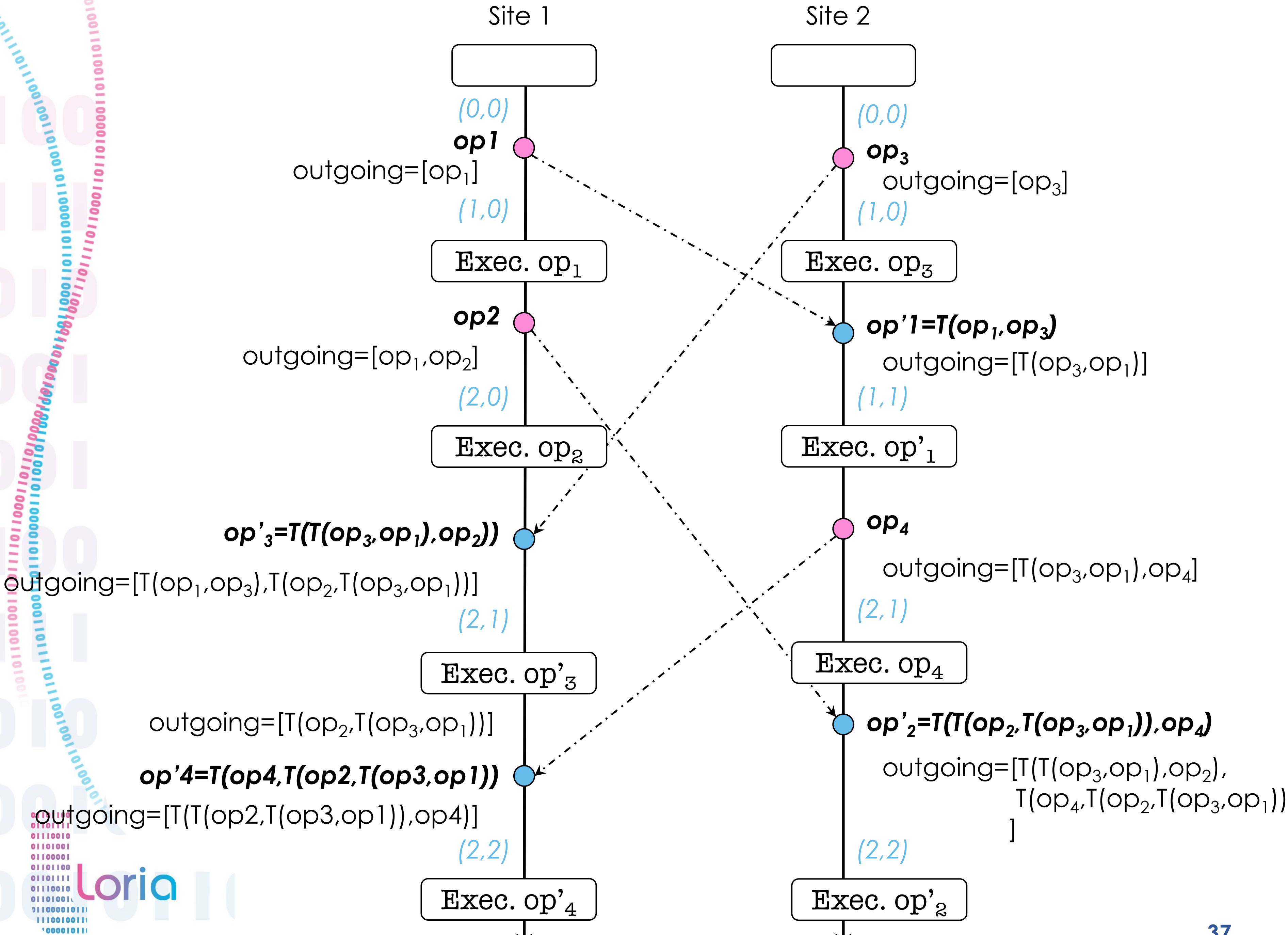


Operational Transformation (OT)

Jupiter Algorithm

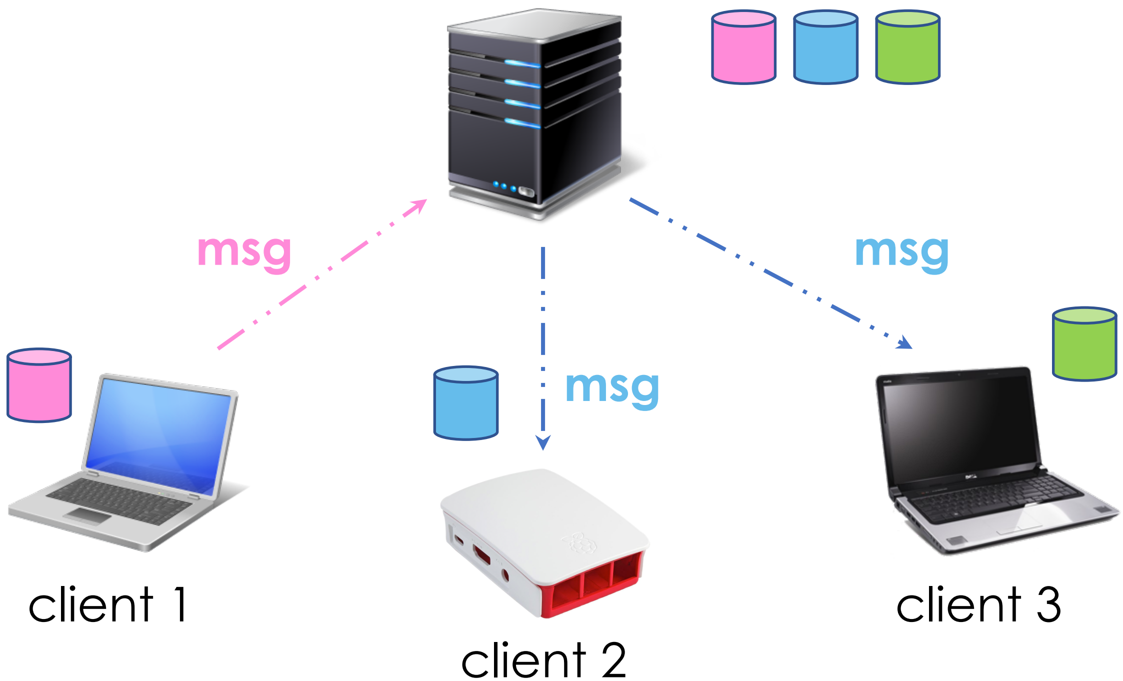
```
int myMsgs = 0; /* number of messages generated */
int otherMsgs = 0; /*number of messages received */

generate(op) {
  apply op locally;
  send(op, myMsgs, otherMsgs);
  add(op, myMsgs) to outgoing;
  myMsgs = myMsgs + 1;
}
receive(msg) {
  /* discard acknowledged messages */
  for m in (outgoing) {
    if (m.myMsgs < msg.otherMsgs)
      remove m from outgoing;
  }
  /* ASSERT: msg.myMsgs == otherMsgs */
  for i in [1..length(outgoing)] {
    /* transform new messages and the ones in the queue */
    { msg, outgoing[i] } = xform(msg, outgoing[i]);
  }
  apply msg.op locally;
  otherMsgs = otherMsgs + 1;
}
```


Site 1
Site 2
(0,0)
op1
outgoing=[op_1]
(1,0)
Exec. op_1
op2
outgoing=[op_1,op_2]
(2,0)
Exec. op_2
$op'_3=T(T(op_3,op_1),op_2))$
outgoing=[$T(op_1,op_3)$,$T(op_2,T(op_3,op_1))$]
(2,1)
Exec. op'_3
outgoing=[$T(op_2,T(op_3,op_1))$]
op'4=T(op4,T(op2,T(op3,op1))
outgoing=[T(T(op2,T(op3,op1)),op4)]
(2,2)
Exec. op'_4
(0,0)
op_3
outgoing=[op_3]
(1,0)
Exec. op_3
$op'1=T(op_1,op_3)$
outgoing=[$T(op_3,op_1)$]
(1,1)
Exec. op'_1
op_4
outgoing=[$T(op_3,op_1)$,op_4]
(2,1)
Exec. op_4
$op'_2=T(T(op_2,T(op_3,op_1)),op_4)$
outgoing=[$T(T(op_3,op_1),op_2)$,
$T(op_4,T(op_2,T(op_3,op_1)))$
]
(2,2)
Exec. op'_2

Operational Transformation (OT)

Jupiter Algorithm – Generalization to n clients [Z01]



apply msg.op locally;

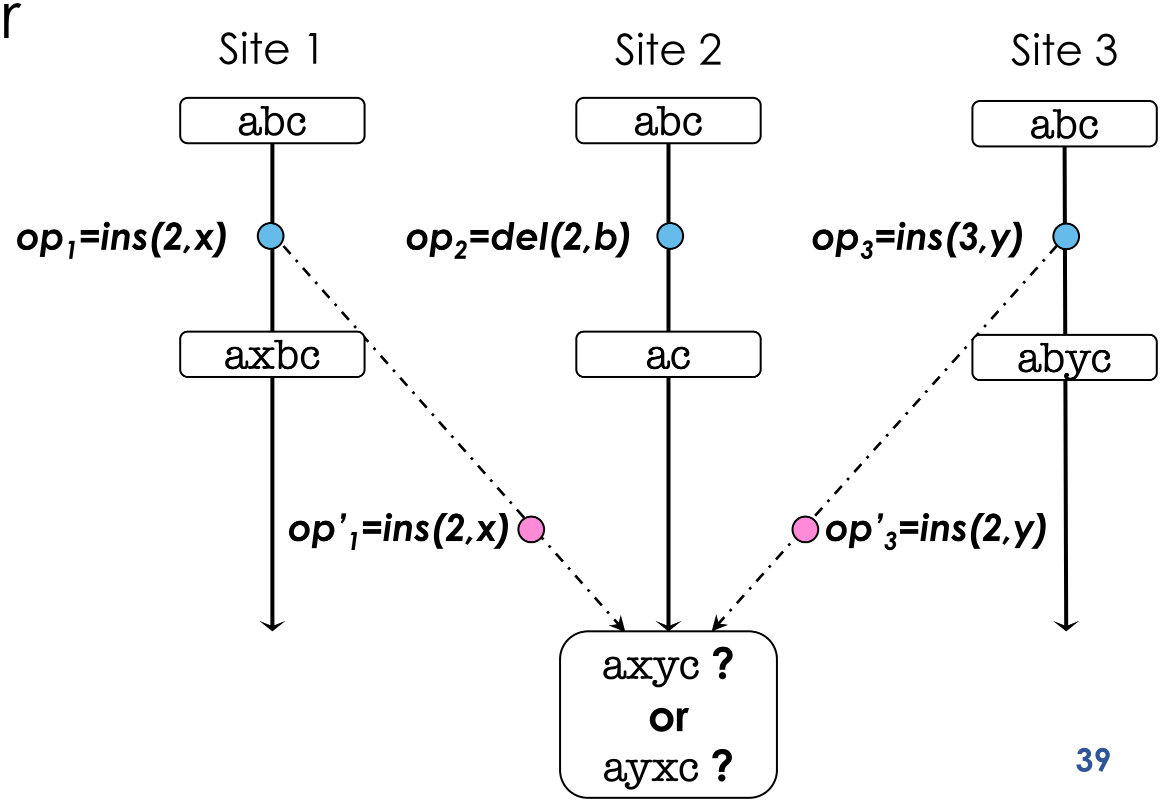
Algorithm changes
at server side

apply msg.op locally;
for (c in client list) {
  if (c != client)
    send(c, msg);
}

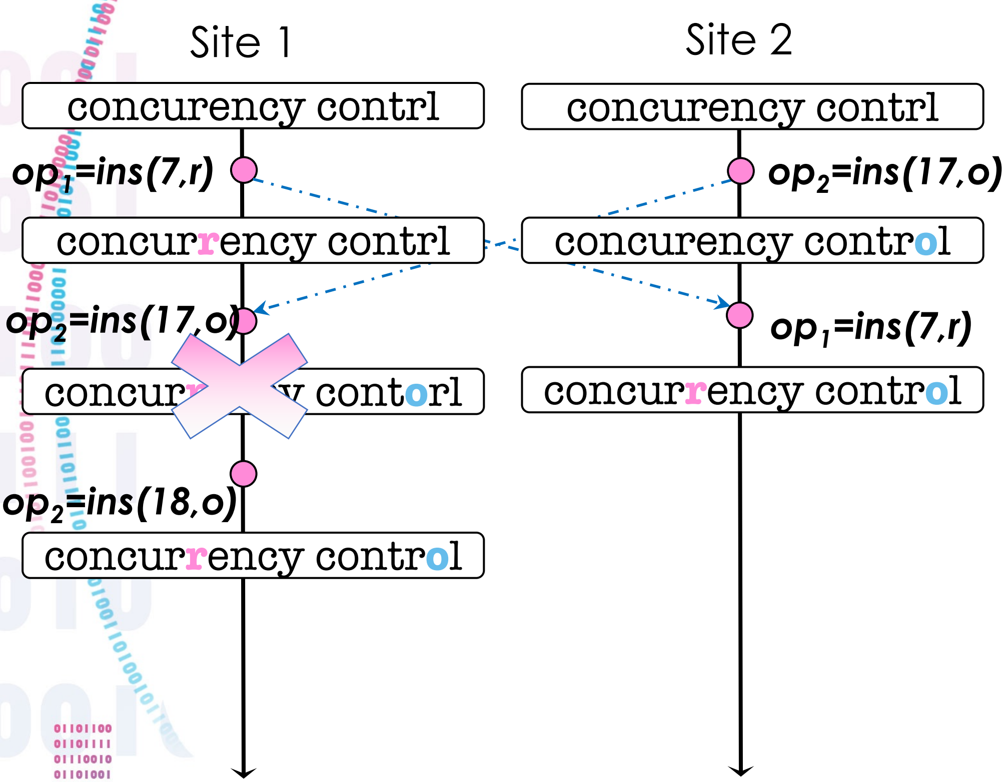
Operational Transformation (OT)

Jupiter Algorithm – Summary

- Requires a server that performs transformations
- Not suitable for P2P environments
- False tie scenario gives different results according to integration order



Operational Transformation (OT)
Summary



- Transforms non commuting operations to make them commute
- Genericity
- Time complexity
  Average: O(H.c)
  Worst case: $O(H^2)$
- Difficult to write correct transformation functions
- State vectors used for detecting concurrency ⇒ scalability limitations
- **Not very suitable for large scale peer-to-peer collaboration**

Conflict-free Replicated Data Types (CRDT) [SPBZ09]

- Data structures
  - Same semantics (w/o concurrency) as classical data-structures
  - **Designs operations to be commutative**
- Replicated
  - At multiple sites
- Available
  - Replica is updated without coordination
  - Convergence is (formally) guarantee
  - Decentralized / Peer-to-peer

- State-based and Operation-based approaches

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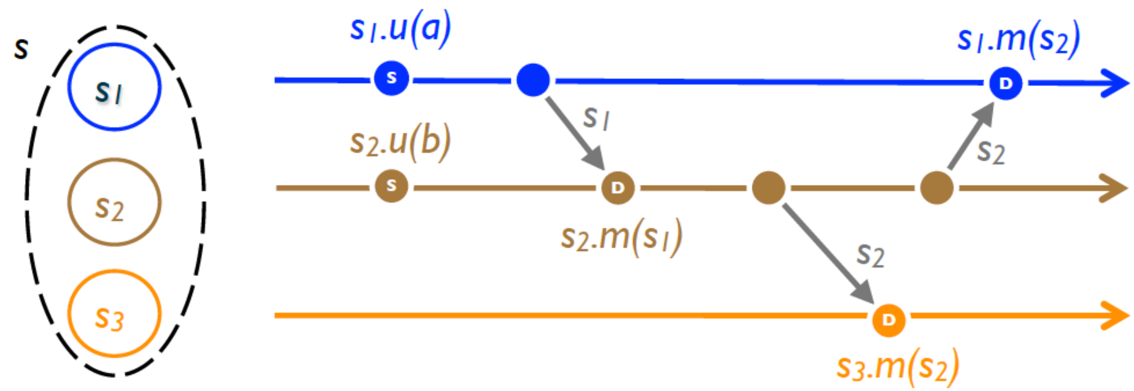
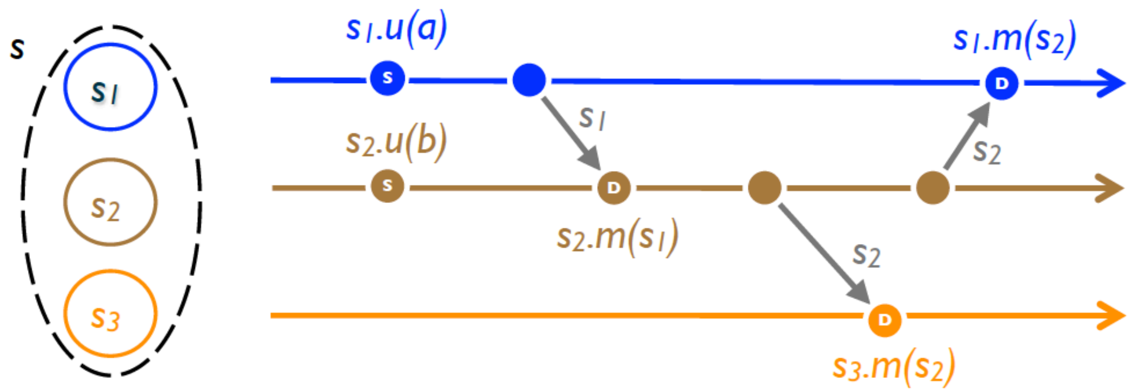
Conflict-free Replicated Data Types
State-based Replication



- Replicated object: a tuple (S, s_0, q, u, m)
  - S: state domain
  - Replica at process p_i has state $s_i \in S$
  - s_0: initial state
- Each replica can execute one of following commands
  - q: query object's state
  - u: update object's state
  - m: merge state from a remote replica

Conflict-free Replicated Data Types
State-based Replication



- Algorithm
  - Periodically, replica at p_i sends its current state to p_j
  - Replica p_j merges received state into its local state by executing m
- After receiving all updates (irrespective of order), each replica will have same state

Conflict-free Replicated Data Types
Semi-lattice

- Partial order $\leq$ set S with a least upper bound (LUB), denoted $\sqcup$
  - $m = x \sqcup y$ is a LUB of $\{ x, y \}$ under $\leq$ if and only if $\forall\ m', x \leq m' \land y \leq m' \Rightarrow x \leq m \land y \leq m \land m \leq m'$

- It follows that $\sqcup$ is:
  - commutative: $x \sqcup y = y \sqcup x$
  - idempotent: $x \sqcup x = x$
  - associative: $(x \sqcup y) \sqcup z = x \sqcup (y \sqcup z)$

Conflict-free Replicated Data Types

Semi-lattice – Example on integers

- Partial order $\leq$ on set of integers
- Least upper bound $\sqcup$: max (maximum function)

- Therefore, we have:
  - commutative: max(x, y) = max(y, x)
  - idempotent: max(x, x) = x
  - associative: max(max(x, y), z) = max(x, max(y, z))

Conflict-free Replicated Data Types
Semi-lattice – Example on sets

- Partial order $\subseteq$ on sets
- Least upper bound $\sqcup$: $\cup$ (set union)

- Therefore, we have:
  - commutative: $A \cup B = B \cup A$
  - idempotent: $A \cup A = A$
  - associative: $(A \cup B) \cup C = A \cup (B \cup C)$

Conflict-free Replicated Data Types
Monotonic Semi-lattice Object

- A state-based object with partial order $\leq$, noted $(S, \leq, s_0, q, u, m)$, that has following properties, is called a monotonic semi-lattice:
  1. Set S of values forms a semi-lattice ordered by $\leq$
  2. Merging state s with remote state s' computes the LUB of the two states, i.e., $s \bullet m(s') = s \sqcup s'$
     (**delivery order is not important**)
  3. State is monotonically non-decreasing across updates, i.e., $s \leq s \bullet u$
     (**updates have effect, no rollback**)

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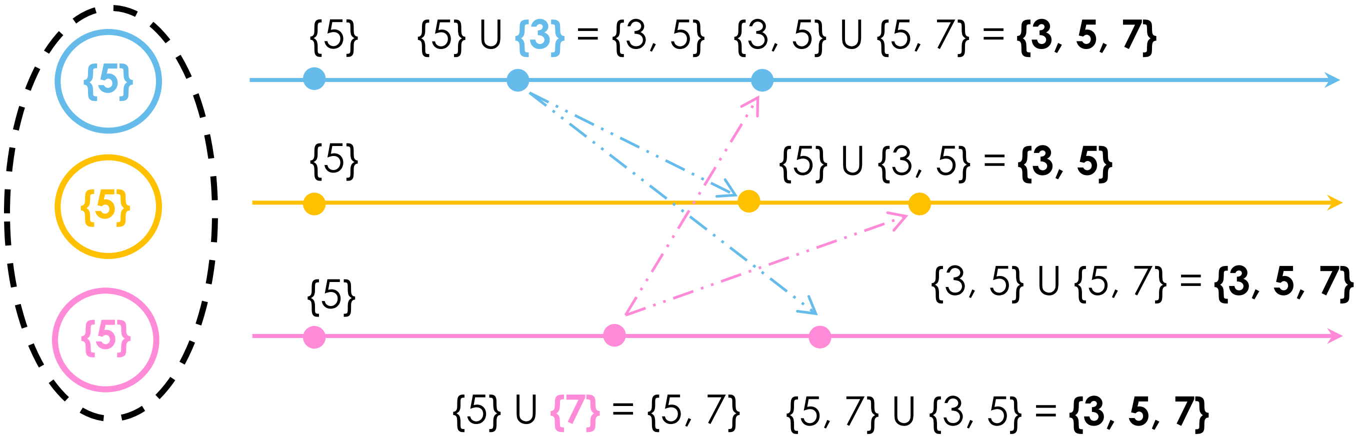
Conflict-free Replicated Data Types
Convergent Replicated Data Type (CvRDT)

- **Theorem:** Assuming eventual delivery and termination, any replicated state-based object that satisfies the monotonic semi-lattice property is SEC

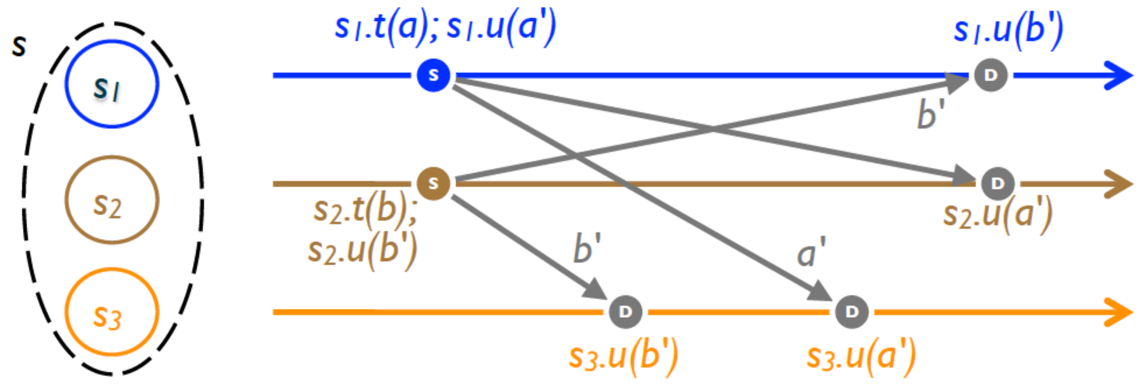
- Since:
  - Merge is both **commutative** and **associative**
    - We do not care about order
  - Merge is **idempotent**
    - We do not care about delivering more than once

Convergent Replicated Data Types
Example



- Each replica can execute one of following commands
  - query q: returns entire set
  - update u: adds new element (e, α)to local set
  - merge m: compute unions between local set and remote set

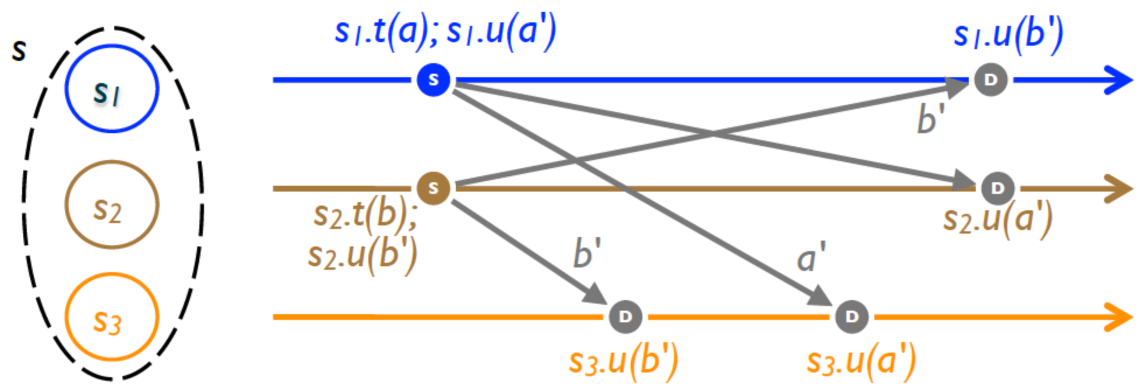
Conflict-free Replicated Data Types
Operation-based Replication



- Replicated object: a tuple (S, s_0, q, t, u, P).
  - S: state domain
  - Replica at process p_i has state $s_i \in S$
  - s_0: initial state
- Each replica can execute one of following commands
  - q: query object's state
  - t: side-effect-free prepare-update method (at local replica)
  - u: effect-free update method (at all replicas)
  - P: delivery precondition

Conflict-free Replicated Data Types

Operation-based Replication



- Algorithm
  - Updates are delivered to all replicas
  - Use causally-ordered broadcast communication protocol, i.e., deliver every message to every node exactly once, w.r.t. happen-before order
  - Happen-before: updates from same replica are delivered in the order they happened to all recipients (effectively delivery precondition, P)
  - Note: concurrent updates can be delivered in any order

Conflict-free Replicated Data Types
Commutativity Property

- Updates (t, u) and (t', u') commute, if and only if for any reachable replica state s where both u and u' are enabled:
  - u (resp. u') remains enabled in state $s \bullet u'$ (resp. $s \bullet u$)
  - $s \bullet u \bullet u' \equiv s \bullet u' \bullet u$

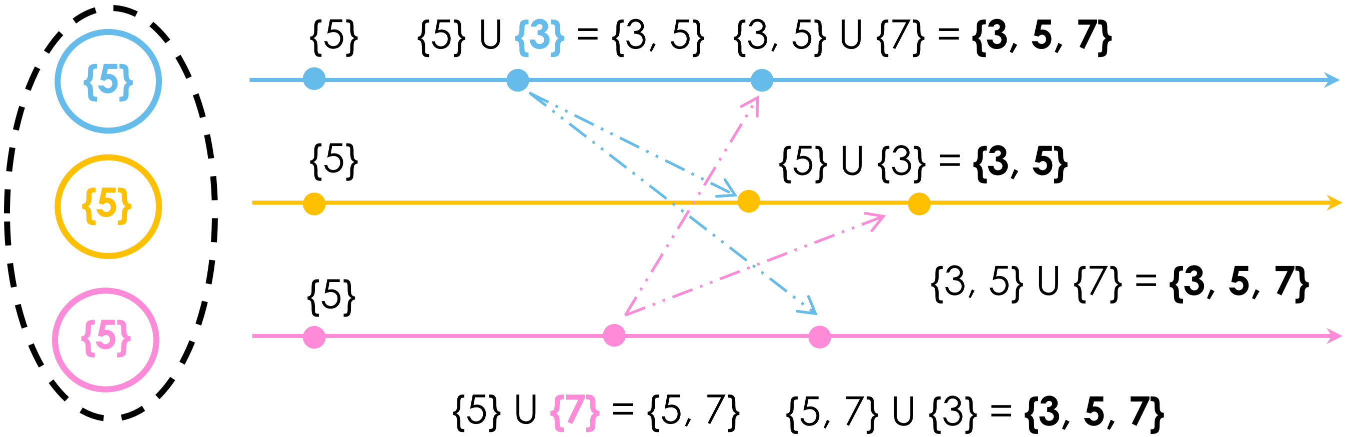
- Commutativity holds for concurrent updates

Conflict-free Replicated Data Types
Commutative Replicated Data Type (CmRDT)

- **Theorem:** Assuming causal delivery of updates and method termination, any replicated op-based object that satisfies the commutativity property for all concurrent updates is SEC

Commutative Replicated Data Types

Example

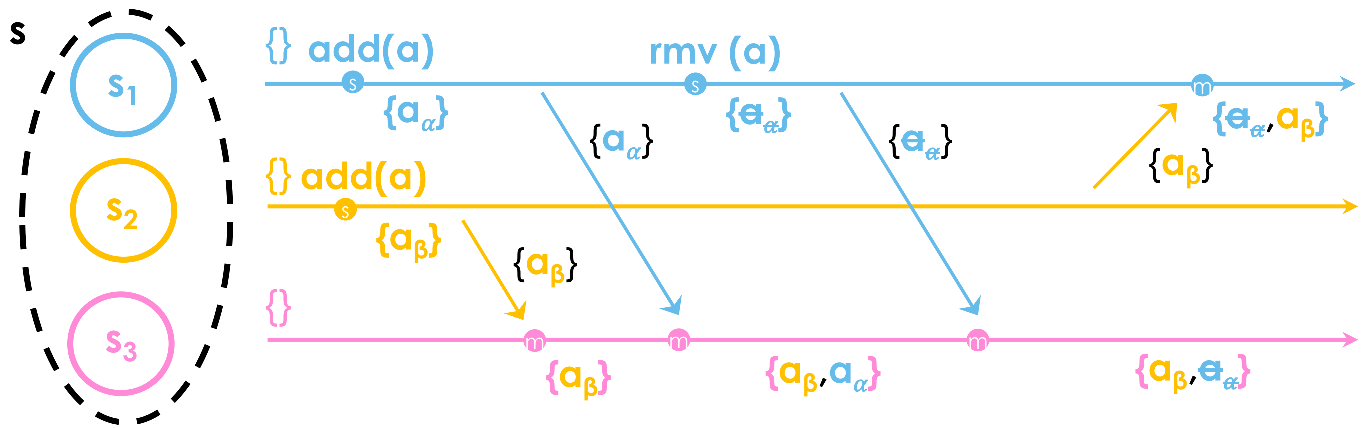


- query q: returns entire set
- prepare method t: adds new element (e,α) to local set
- update u: add delta to any remote replica

Consistency Maintenance
Conflict-free Replicated Data Types (CRDT)

- Register
  - Last-Writer Wins
  - Multi-Value
- Set
  - Grow-Only
  - 2-Phase
  - **Observed-Remove**
  - Observed-Update-Remove
- Map
- **Counter**
- Graph
  - Directed
  - Monotonic DAG
  - Edit graph
- **Sequence**

Conflict-free Replicated Data Types
Observed-Remove Set (CvRDT)



- Payload: (A,R) - added/removed sets of *(element, unique-token)*
- Operations:

  add(e): A := A U {(e,α)}

  remove(e): R := R U {(e,-)∈A} **remove all unique elements observed**

  lookup(e): ∃(e,-)∈A\R

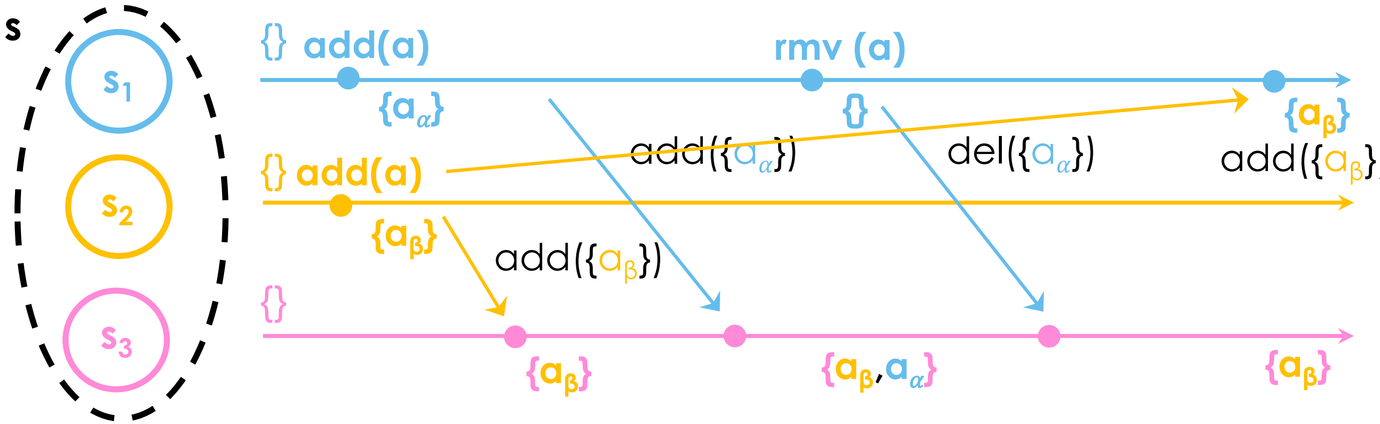
  merge(S, S'): *(A U A', R U R')*
- *{true} add(e) ‖ remove(e) {e∈S}*

Optimised OR-set

- summarise received *adds* in a vector
- check vector during merge

Conflict-free Replicated Data Types

Observed-Remove Set (CmRDT)



- Payload:

  $S = \{(e,\alpha), (e,\beta), (e,\gamma), \ldots\}$ where α, β, γ,… are unique token

- Operations:

  add(e): $S := S \cup \{(e,\alpha)\}$ where α is a fresh unique token

  lookup(e): $\exists \alpha: (e,\alpha) \in S$

  remove(e): $R := \{(e,\alpha) \mid \exists \alpha\ (e,\alpha) \in S\}$ (at source) no tombstones

  $S := S \setminus R$

  $\{true\}\ add(e) \parallel remove(e)\ \{e \in S\}$

Conflict-free Replicated Data Types
P-Counter (CvRDT)

- Payload:
  - P = [int, int, …]
- Operations:
  - value(): $\sum_i P[i]$
  - increment(): P[MyID]++
  - merge(S,S'): $S \sqcup S' = [\ldots, \max(s.P[i], s'.P[i]), \ldots]_i$
- Positive

Conflict-free Replicated Data Types
PN-Counter (CvRDT)

- Payload:
  - P = [int, int, ...], N = [int, int, ...]
- Operations:
  - value(): $\sum_i P[i] - \sum_i N[i]$
  - increment(): P[MyID]++
  - decrement(): N[MyID]++
  - merge(S,S'): $S \sqcup S' = ([\ldots,\max(s.P[i],s'.P[i]),\ldots]_i, [\ldots,\max(s.N[i],s'.N[i]),\ldots]_i)$
- Positive or negative

Conflict-free Replicated Data Types
CvRDT vs. CmRDT

- Both approaches are equivalent
  - A state-based object can emulate an operation-based object, and vice-versa

- Operation-based:
  - More efficient since you only ship small updates
  - But require causally-ordered broadcast
- State-based:
  - Only require reliable broadcast

CRDT Examples (cont'd)

- Integer vector (virtual clock):
  - u: increment value at corresponding index by one
  - m: maximum across all values, e.g., m([1, 2, 4], [3, 1, 2]) = [3, 2, 4]
- Counter: use an integer vector, with query operation
  - q: returns sum of all vector values (1-norm), e.g., q([1, 2, 4]) = 7
- Counter that decrements as well:
  - Use two integer vectors:
    - I updated when incrementing
    - D updated when decrementing
  - q: returns difference between 1-norms of I and D

Conflict-free Replicated Data Types (CRDT)

(Text) Sequence [PMSL09] [WUM09]

- Document = linear sequence of elements
  - Each element has a unique identifier
  - Identifier constant for the lifetime of the document
  - Dense total order of identifiers consistent with element order:
    - $\forall\ id_x, id_y: id_x < id_y \Rightarrow \exists\ id_z : id_x < id_z < id_y$

- Different approaches for generating identifiers:
  - TreeDoc, Logoot, LogootSplit, …

Conflict-free Replicated Data Types (CRDT)

Logoot [WUM09]

Logoot identifiers: $<p_1,s_1,h_1><p_2,s_2,h_2> \cdots <p_k,s_k,h_k>$

p_i integer

s_i site identifier

h_i logical clock at site s_i

ins(<3,2,5><13,1,7>, r)

ins(<12,3,1><7,8,2><13,3,6><7,2,9>, o)

<1,2,1>	c
<1,2,2>	o
<2,1,2>	n
<3,1,3>	c
<3,1,3><8,4,5>	u
<3,2,5>	r
<4,1,7>	e
<4,1,7><9,2,6>	n
<7,2,8>	c
<9,1,7>	y
<10,2,8>	
<12,3,1>	c
<12,3,1><6,5,1>	o
<12,3,1><7,8,2>	n
<12,3,1><7,8,2><12,3,5>	t
<12,3,1><7,8,2><13,3,6>	r
<12,3,1><7,8,2><14,3,7>	l

- Time complexity
  Average: O(k.log(n))
  Worst case: O(H.log(H))
- No need for concurrency detection
- Identifiers storage cost
- New design for each data type
- **Suitable for large-scale collaboration**

Conflict-free Replicated Data Types (CRDT)

LogootSplit [AMOI13]

LogootSplit identifiers

$\underbrace{p_1 \mid \ldots \mid p_n \mid \textit{site\_id} \mid \textit{clock}}_{\text{Base}} \mid \underbrace{\text{begin} \mid \text{end}}_{\text{Interval}}$

p_1	…	p_n	*site_id*	*clock*	begin	end

1,1,[0,16]	concurency contrl

Insert r between “concur” and “ency contrl”

1,1,[0,5]	concur
1,1,5,2,1,[0,0]	r
1,1, [6,16]	ency contrl

Insert o between “ency contr” and “l”

1,1,[0,5]	concur
1,1,5,2,1,[0,0]	r
1,1, [6,15]	ency contr
1,1,15,3,1,[0,0]	o
1,1,[16,16]	l

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Conflict-free Replicated Data Types (CRDT)

LogootSplit [AMOI13]

Site 3

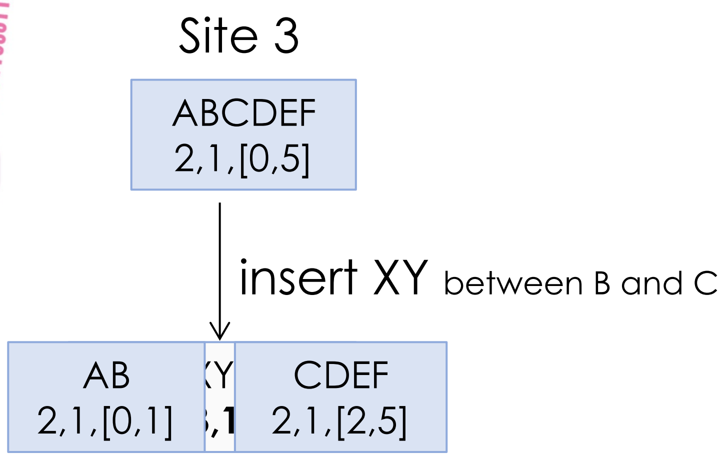
ABCDEF
2,1,**[0,5]**

insert XY between B and C

Site 4

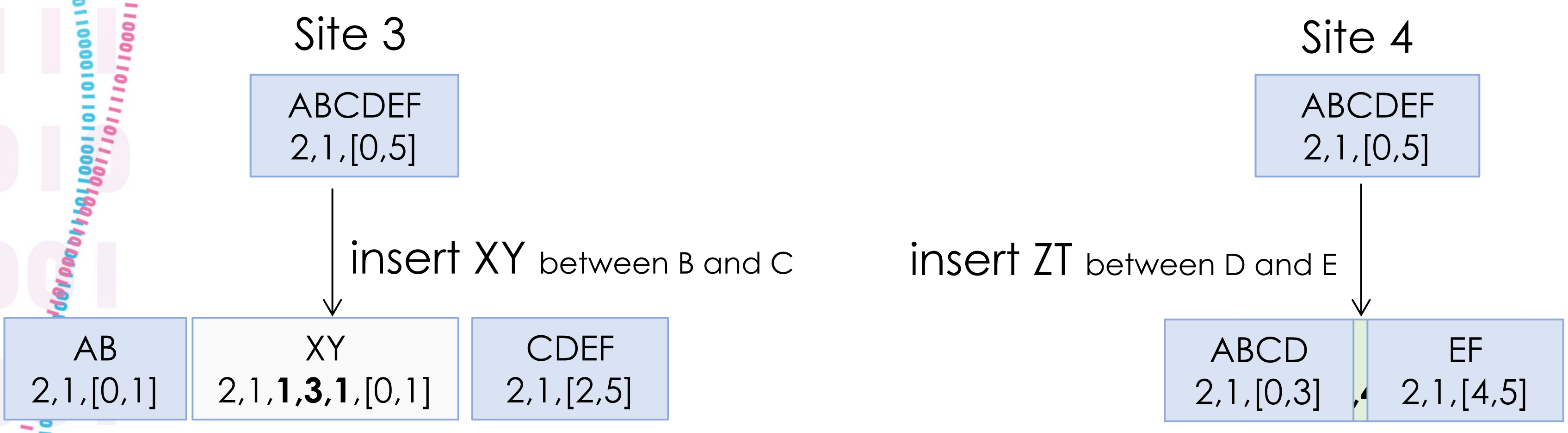
ABCDEF
2,1,**[0,5]**

Conflict-free Replicated Data Types (CRDT)
LogootSplit [AMOI13]



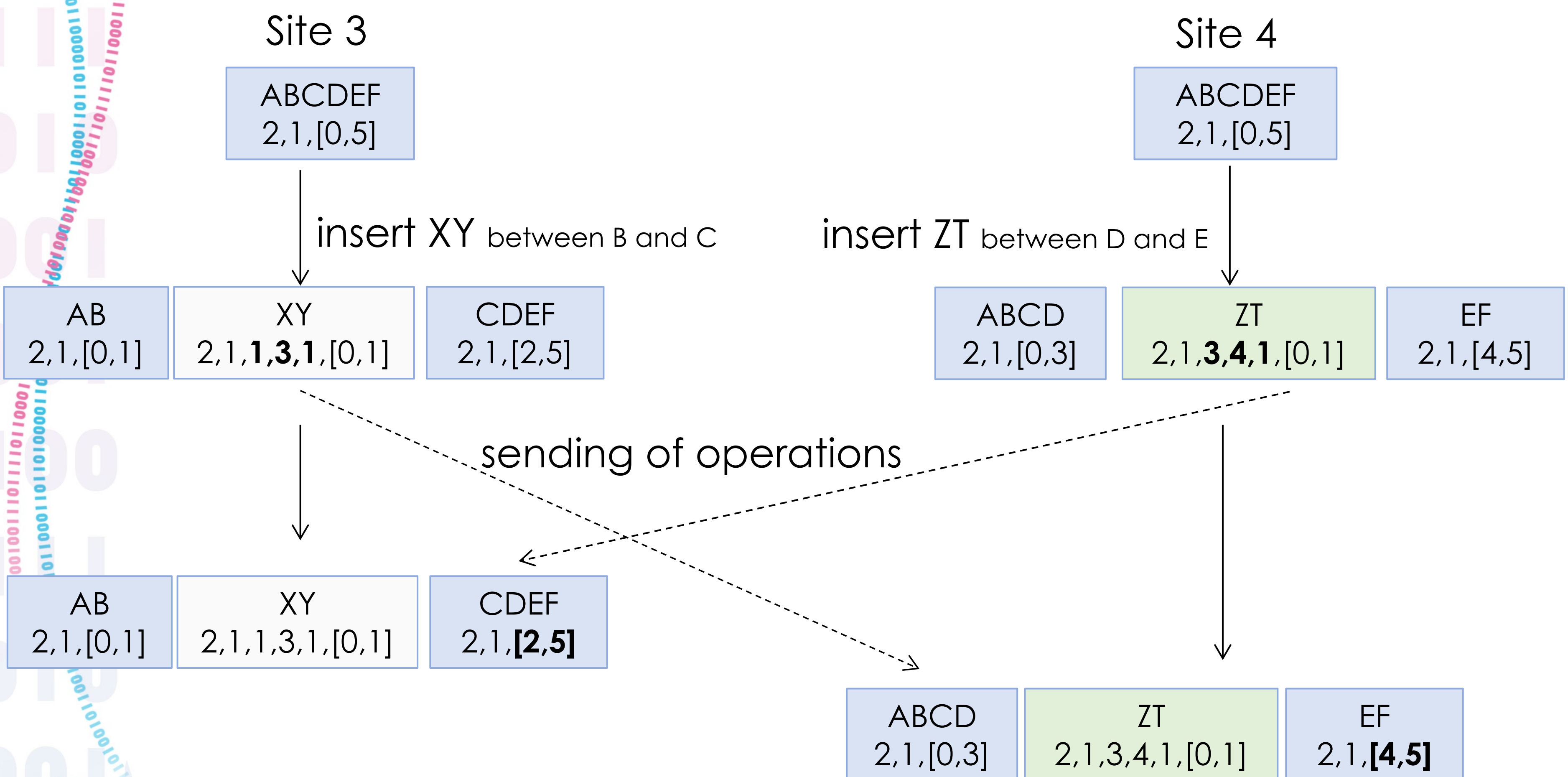
Conflict-free Replicated Data Types (CRDT)

LogootSplit [AMOI13]



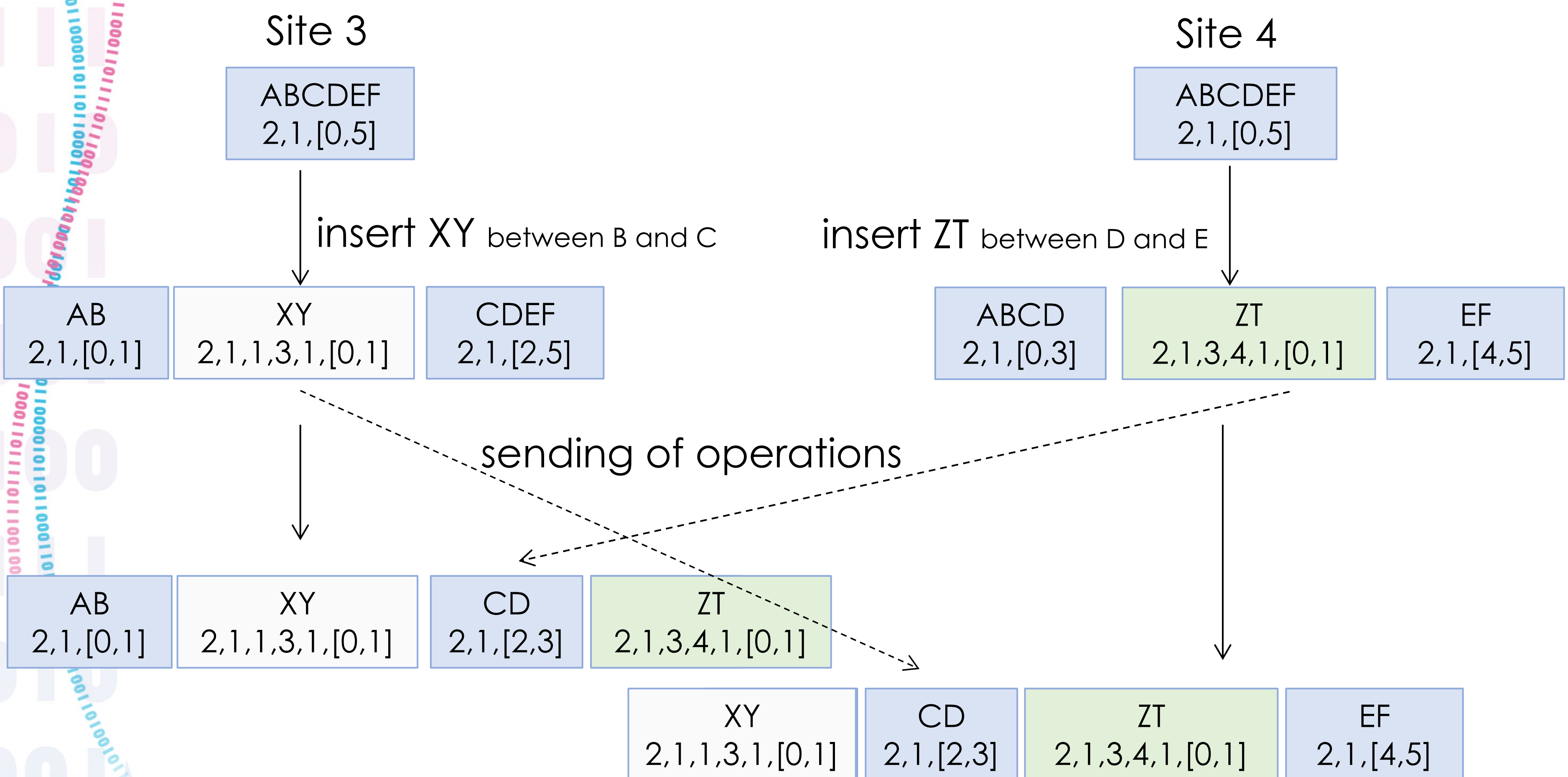
Conflict-free Replicated Data Types (CRDT)

LogootSplit [AMOI13]



Conflict-free Replicated Data Types (CRDT)

LogootSplit [AMOI13]



Conflict-free Replicated Data Types (CRDT)
Take away

- Strong eventual consistency
  - Parallel and unsynchronized updates
  - Deterministic merge
- State-based approach (CvRDT):
  - Monotonic semi-lattice
  - Reliable broadcast (epidemic propagation)
- Operation-based approach (CmRDT):
  - Commutative concurrent updates
  - Causally-ordered broadcast

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- **[AMOI13]** Supporting Adaptable Granularity of Changes for Massive Scale Collaborative Editing, L. André, S. Martin and G. Oster C.-L. Ignat. CollaborateCom 2013.

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Materials

Some of the presented materials are coming from:

- "Conflict-free Replicated Data Types (CRDTs) for collaborative environments", Marc Shapiro, Nuno Preguiça, Carlos Baquero and Marek Zawirski. Keynote WETICE 2011
  http://events.telecom-sudparis.eu/wetice/invited_speakers/ShapiroKeyNote.pdf
- "Data Replication and Consistency", Claudia-Lavinia Ignat. Lectures at Université de Lorraine
  https://members.loria.fr/CIgnat/replication/

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Thank you

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