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## Keynote: Large-scale trustworthy distributed collaborative systems - challenges and prospective solutions

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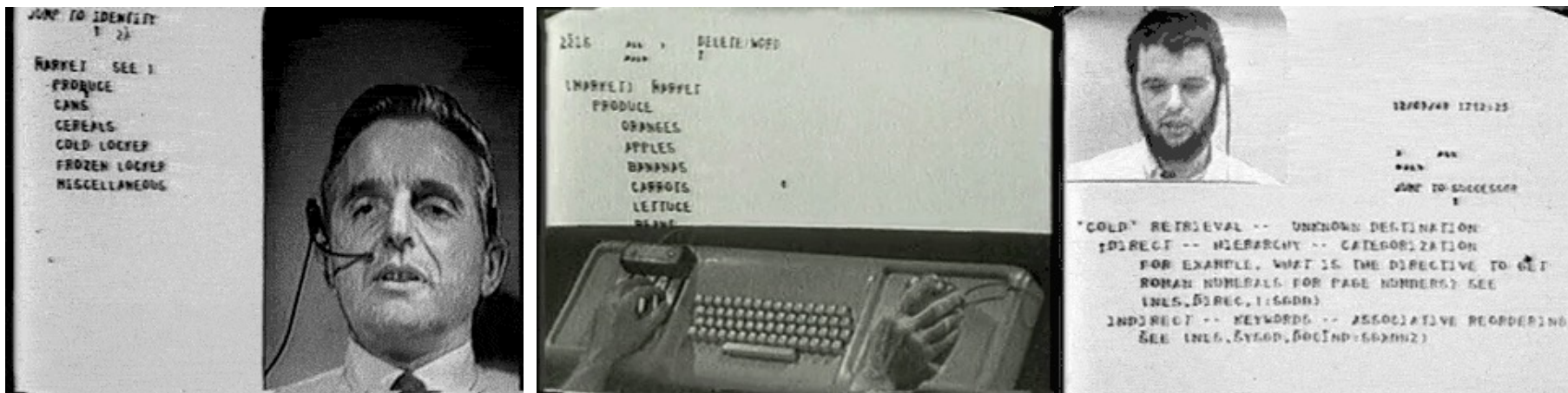
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informatics mathematics

# Large-scale trustworthy distributed collaborative systems: challenges and prospective solutions

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Inforsid 2024  
May 30, 2024  
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# Douglas Engelbart: Augmenting Human Intellect



The Mother of all Demos, December 9, 1968



NLS: Online System

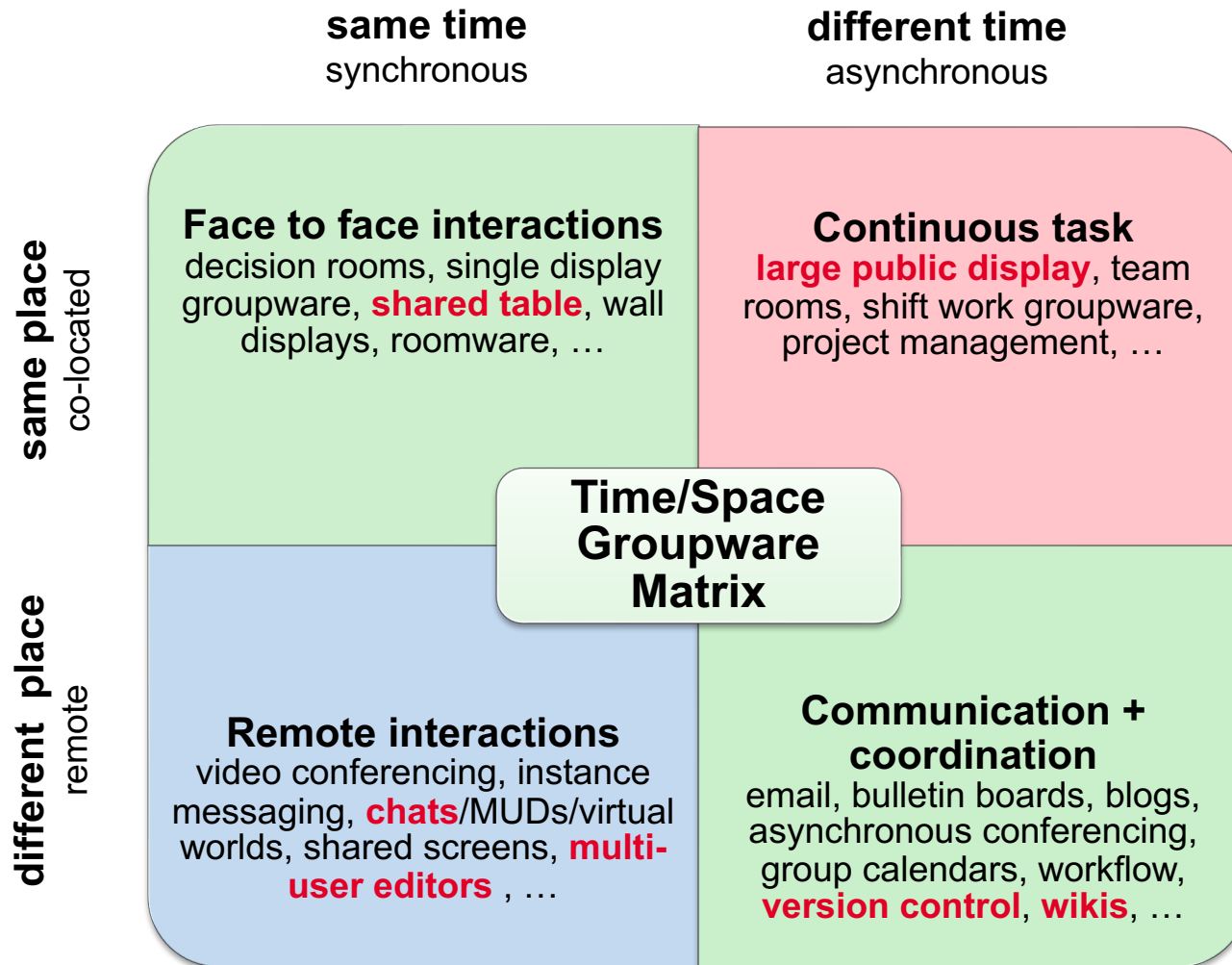
<https://archive.org/details/dougengelbartarchives>

## Groupware, early 1990s

*« Computer-based systems that support groups of people engaged in a common task (or goal) and that provide an interface to a shared environment. » [EGR91]*

- Lotus Notes (HCL Notes today), one of the first commercial groupware allowing remote group collaboration

# Groupware Time Space Matrix [J88]

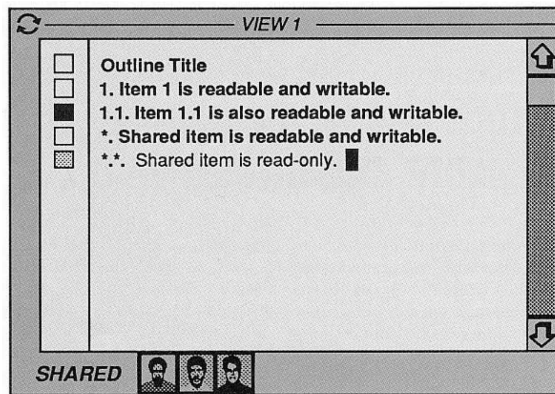


# Collaborative Systems: from users to community of users



*“Isn’t it chaotic to all edit in the same document, even the same paragraph, at the same time?”*

*“Why would a group ever want to edit in the same line of text at the same time?” [EGR91]*



GROVE, 1989

# From users to community of users: new practices



Main page  
Contents  
Current events  
Random article  
About Wikipedia  
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## United States Capitol: Revision history

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For any version listed below, click on its date to view it. For more help, see Help:Page history and Help:Edit summary. (cur) = difference from current version, (prev) = difference from preceding version,

m = minor edit, → = section edit, ← = automatic edit summary  
(newest | oldest) View (newer 20 | older 20) (20 | 50 | 100 | 250 | 500)

Compare selected revisions

- (cur | prev) 22:56, 6 January 2021 Sleyece (talk | contribs) ... (83,551 bytes) (+96) ... (Be Concise) (undo)
- (cur | prev) 22:53, 6 January 2021 Thanoscar21 (talk | contribs) m ... (83,455 bytes) (-39) ... (Rollback edit(s) by 49.195.0.222 (talk): per WP:NPOV (RW 16)) (undo) (Tag: Rollback)
- (cur | prev) 22:52, 6 January 2021 49.195.0.222 (talk) ... (83,494 bytes) (+39) ... (undo) (Tag: Reverted)
- (cur | prev) 22:52, 6 January 2021 Sleyece (talk | contribs) m ... (83,455 bytes) (-3) ... (Grammar) (undo)
- (cur | prev) 22:52, 6 January 2021 2605:a601:ada1:2a00:ad83:9ec8:20bc:44c5 (talk) ... (83,458 bytes) (+4) ... (→Major events: Fixed punctuation) (undo) (Tags: Mobile edit, Mobile web edit)
- (cur | prev) 22:51, 6 January 2021 Sleyece (talk | contribs) ... (83,454 bytes) (+423) ... (Bot Reverted too Much) (undo)
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- (cur | prev) 22:44, 6 January 2021 2605:a601:ada1:2a00:ad83:9ec8:20bc:44c5 (talk) ... (82,944 bytes) (+52) ... (→Major events: Rephrased "rioters") (undo) (Tags: Mobile edit, Mobile web edit)
- (cur | prev) 22:39, 6 January 2021 Meswinj (talk | contribs) ... (82,892 bytes) (-351) ... (undo) (Tag: Visual edit)
- (cur | prev) 22:39, 6 January 2021 ClueBot NG (talk | contribs) m ... (83,243 bytes) (-47) ... (Reverting possible vandalism by 2603:9001:4903:D811:9052:EFE:155C:2134 to version by 81.167.188.42. Report False Positive? Thanks, ClueBot NG. (3860441) (Bot)) (undo) (Tag: Rollback)
- (cur | prev) 22:39, 6 January 2021 2603:9001:4903:d811:9052:efe:155c:2134 (talk) ... (83,290 bytes) (+47) ... (undo) (Tags: Mobile edit, Mobile web edit, Reverted)
- (cur | prev) 22:35, 6 January 2021 81.167.188.42 (talk) ... (83,243 bytes) (+40) ... (undo)
- (cur | prev) 22:34, 6 January 2021 72.217.56.18 (talk) ... (83,203 bytes) (-58) ... (person shot has not been reported dead as of yet!) (undo)
- (cur | prev) 22:33, 6 January 2021 2600:1700:1c60:41d0:e5a9:3248:c03e:eb02 (talk) ... (83,261 bytes) (+73) ... (Adding the President's reaction to the event.) (undo) (Tag: extraneous markup)
- (cur | prev) 22:31, 6 January 2021 2603:8000:8e42:cb00:55ec:35dc:94e4:c9be (talk) ... (83,188 bytes) (+1) ... (undo) (Tag: Possible vandalism)
- (cur | prev) 22:29, 6 January 2021 92.21.72.53 (talk) ... (83,187 bytes) (+40) ... (Adding info) (undo) (Tags: Mobile edit, Mobile web edit, Visual edit, Possible vandalism)
- (cur | prev) 22:28, 6 January 2021 176.23.9.200 (talk) ... (83,147 bytes) (+10) ... (undo)

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# From users to community of users: new practices



## Example: Intergovernmental Panel Climate Change (IPCC) assessment report editing

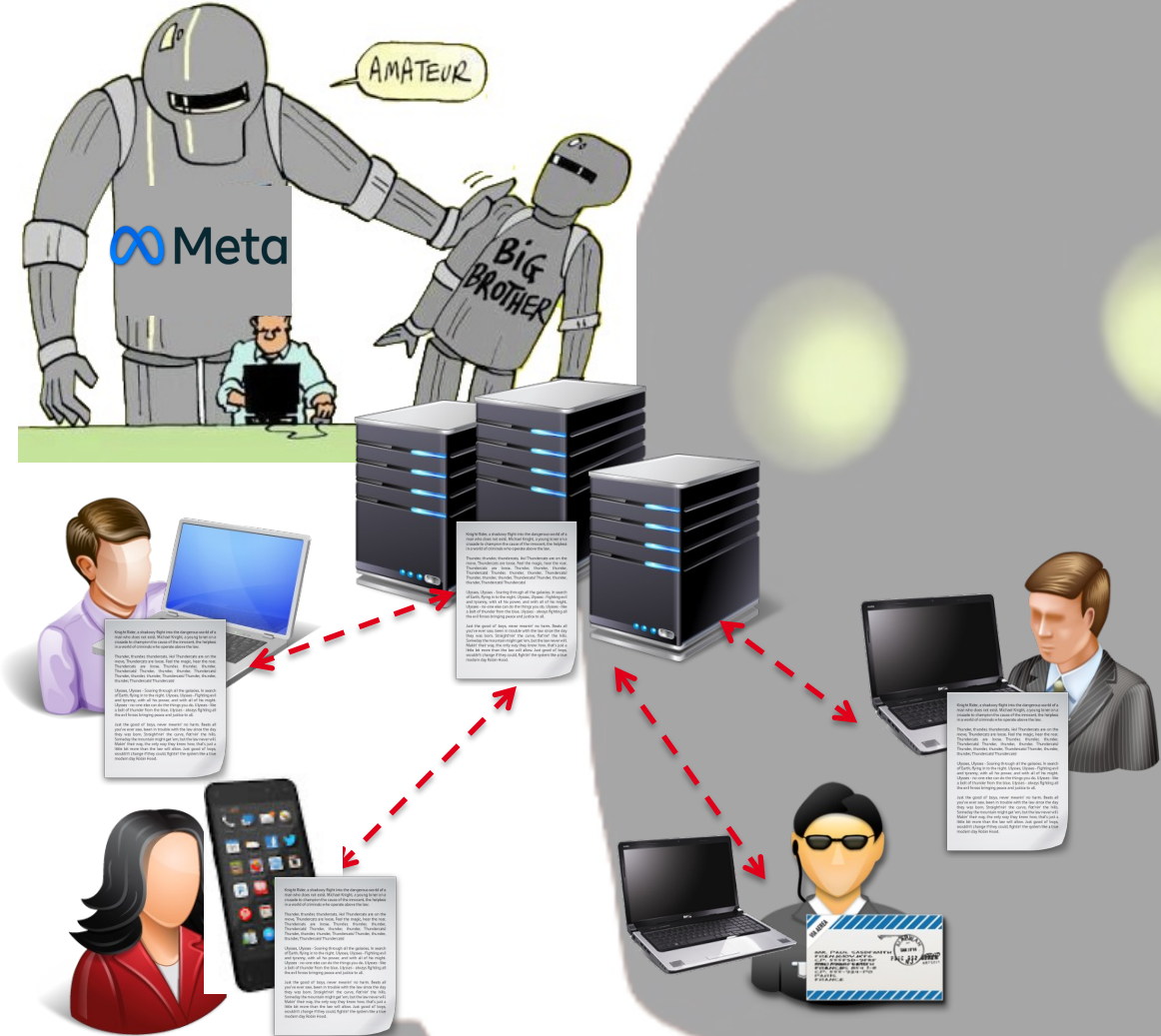
- Expert contributions: hundreds of scientists from different countries
- Review stages by experts and governments
- Approval sessions: government delegates and lead authors
- Editing teams: review editors



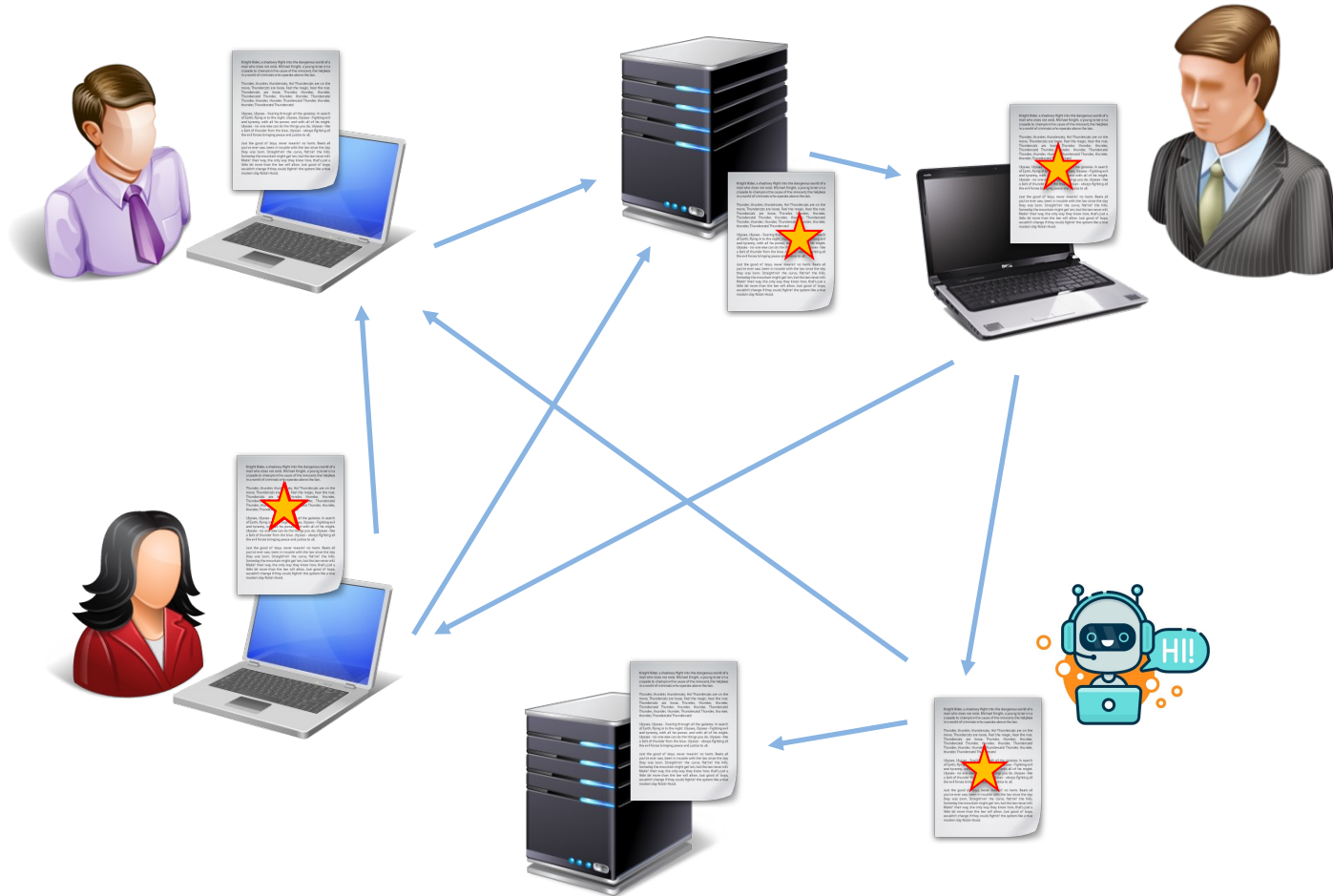
# Limitations of Central Authority Systems

# SCALABILITY

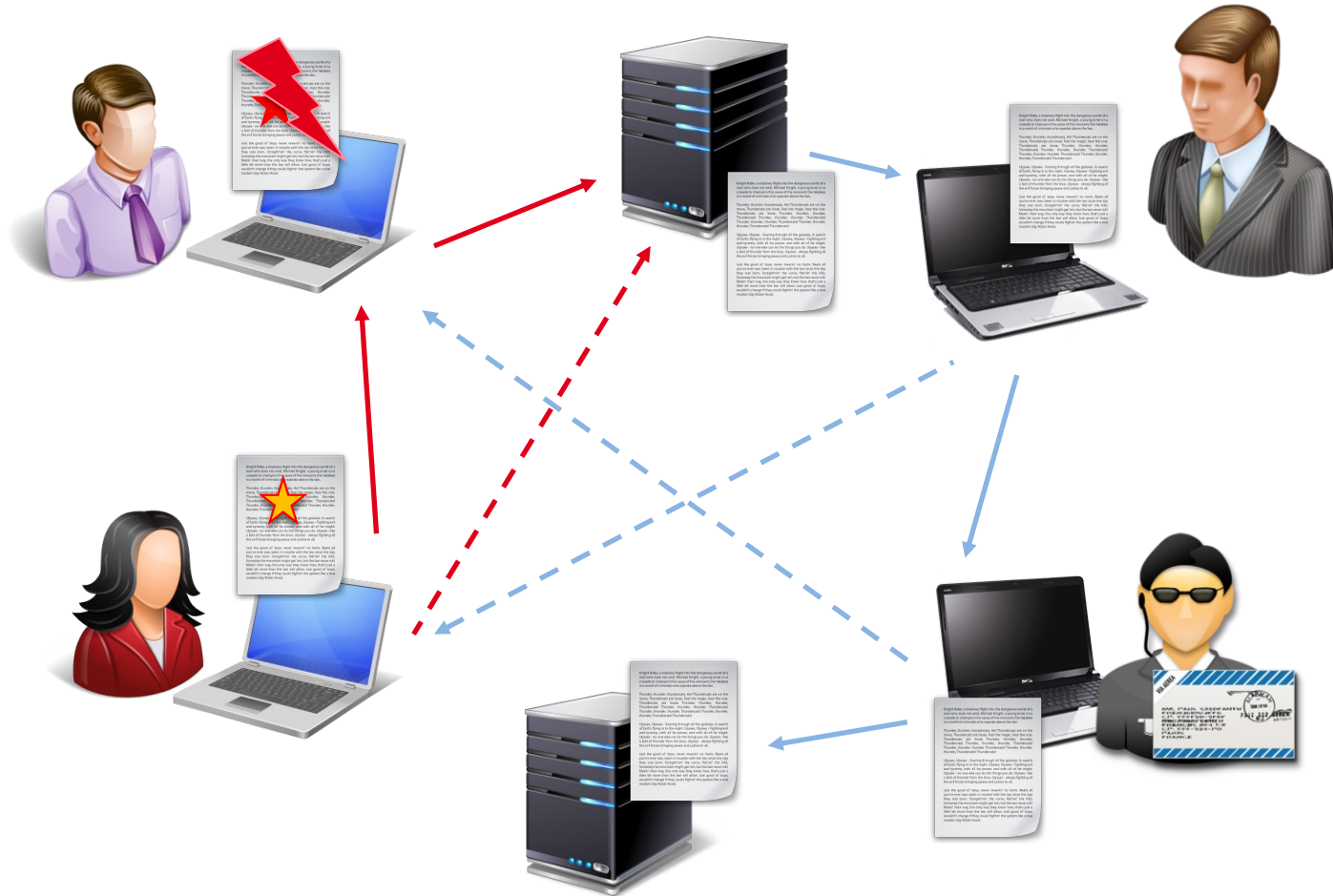
# PRIVACY



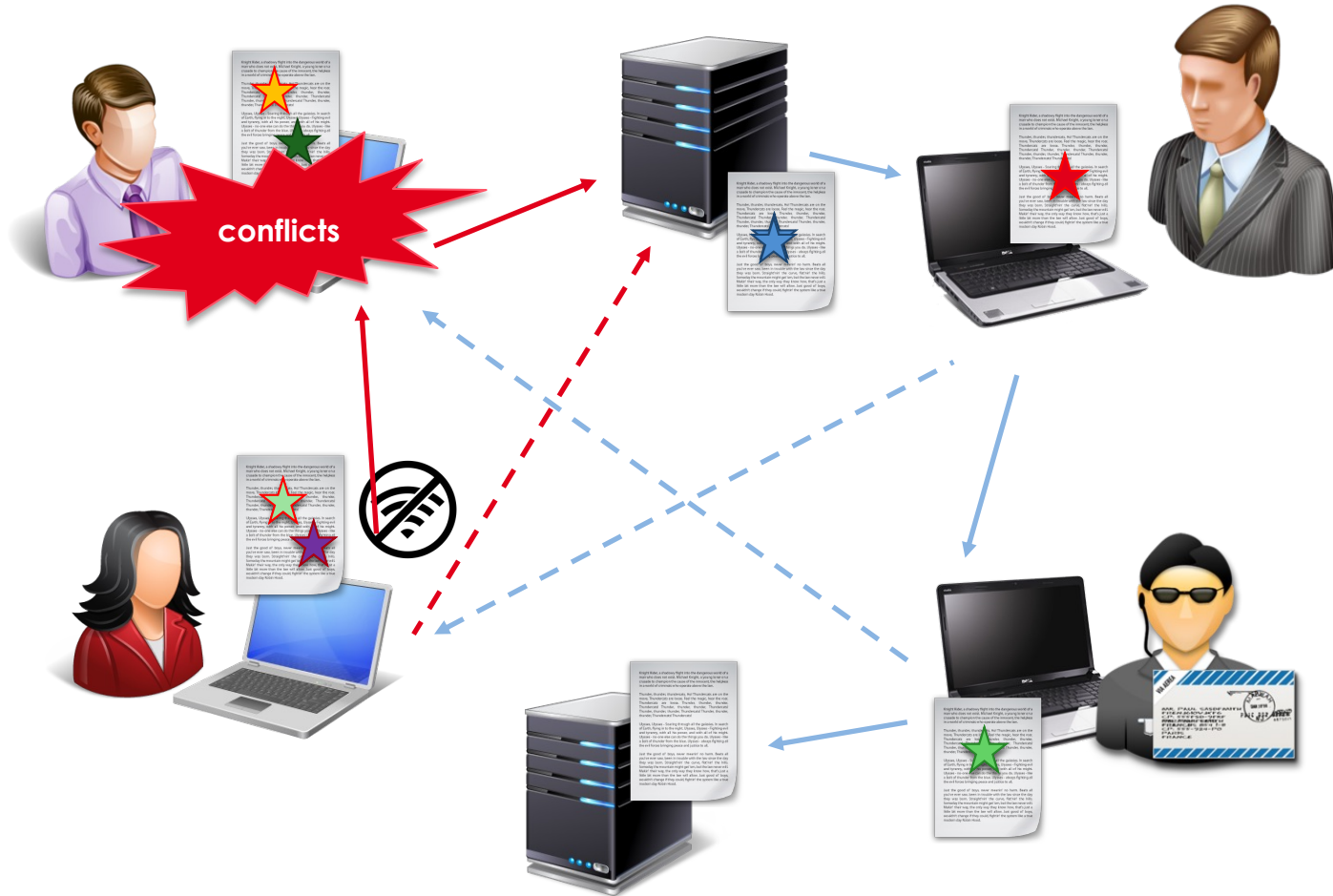
# Vision: Peer-to-Peer Collaborative Systems



# Collaboration Modes – Concurrent Changes



# Collaboration Modes – Offline Work



# Collaboration Modes – Ad-hoc Collaboration



# Research issues

- 1 How to **maintain consistency of different copies** in the face of concurrent modifications?
- 2 How to **secure collaboration data**?
- 3 How to make a collaboration **trustworthy**?

# Research issues

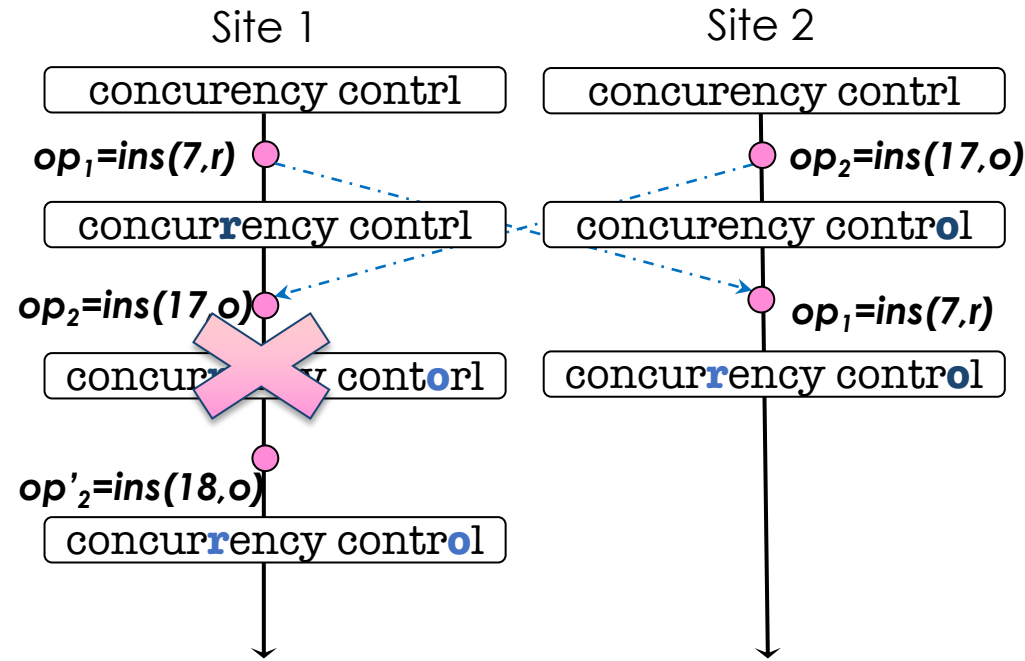
- 1 How to **maintain consistency of different copies** in the face of concurrent modifications?
- 2 How to **secure collaboration data**?
- 3 How to make a collaboration **trustworthy**?

# CAP Theorem [B00]

- Properties of shared-data systems
  - Data consistency
  - System availability
  - Tolerance to network partition
- Only two out of three properties can be achieved at a given time
- **Relax consistency for availability** in the presence of network partitions



# Operational transformation (OT) [EG89]



```

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

- Transforms non commuting operations to make them commute
- Genericity
- Time complexity
 

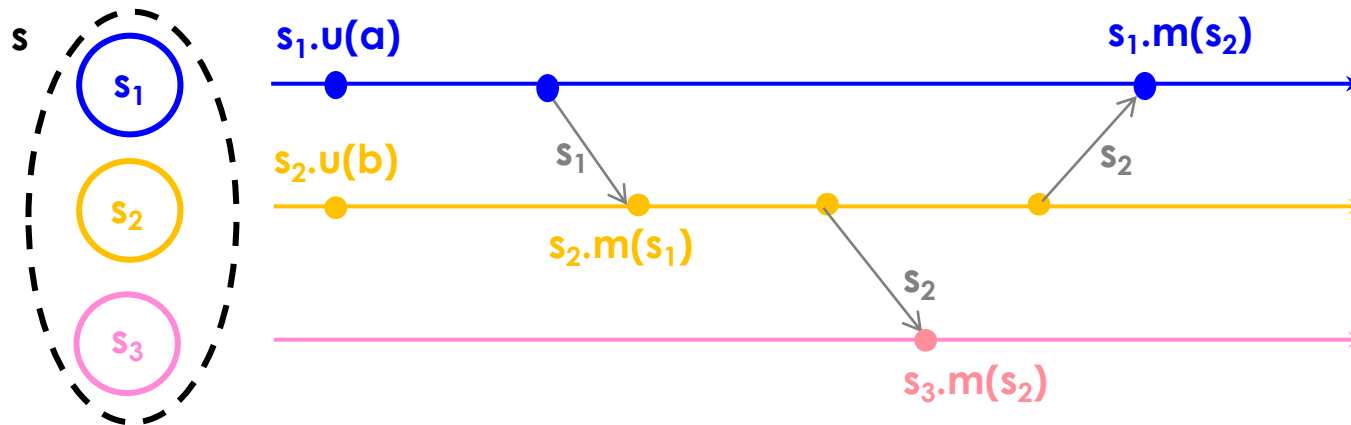
Average: $O(H \cdot c)$	H: #ops
Worst case: $O(H^2)$	c: avg. #conc. ops
- Difficult to write correct transformation functions
- State vectors used for detecting concurrency  $\Rightarrow$  scalability limitations
- **Not very suitable for large scale peer-to-peer collaboration**

# Conflict-free Replicated Data Types (CRDT) [SPBZ11]

- Design operations to be commutative by construction
- Abstract data types
  - Designed to be replicated at multiple sites
  - Any replica can be modified without coordination
  - State convergence is guaranteed
- State-based and operation-based approaches

# Conflict-free Replicated Data Types (CRDT)

## 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

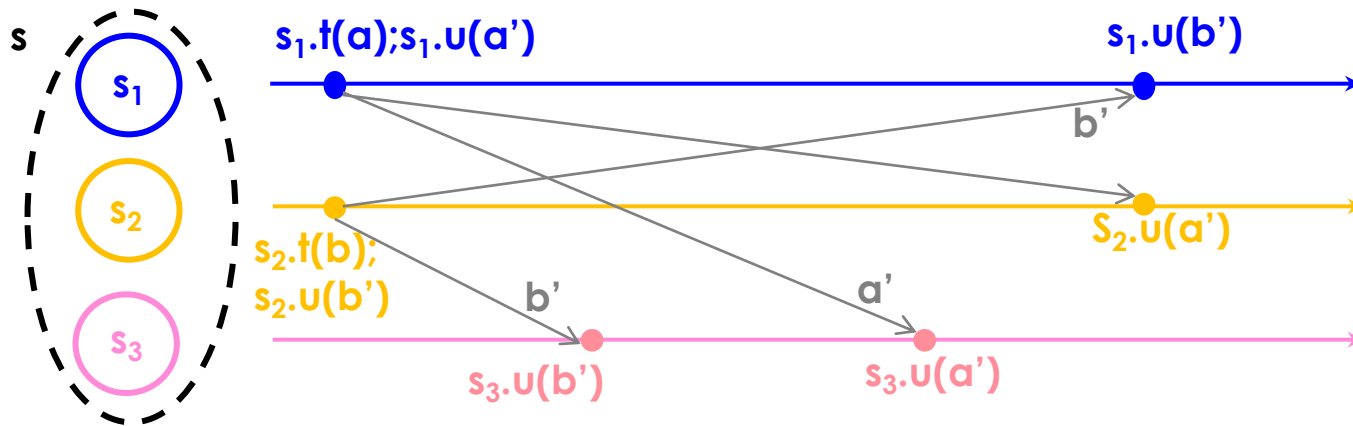
# Conflict-free Replicated Data Types (CRDT)

## State-based Replication

- Merge operator:
  - **Commutative:**  $x \bullet y = y \bullet x$
  - **Associative:**  $(x \bullet y) \bullet z = x \bullet (y \bullet z)$
  - **Idempotent :**  $x \bullet x = x$
- A semi-lattice is a 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  $\forall m', x \leq m' \wedge y \leq m' \Rightarrow x \leq m \wedge y \leq m \wedge m \leq m'$
  - It follows that  $\sqcup$  is commutative, associative and idempotent

# Conflict-free Replicated Data Types (CRDT)

## Operation-based Replication



- An update split into  $(t,u)$ :  $t$  is a side-effect-free *prepare-update method* and  $u$  is an *effect-update method*
- Algorithm
  - Updates delivered to all replicas
  - Causally-ordered broadcast, every message delivered to every node exactly once w.r.t. happen-before order
- Commutativity holds for concurrent updates

# Conflict-free Replicated Data Types (CRDT) Operation vs. State-based Replication

- 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 exactly once causally-ordered broadcast
- State-based:
  - Only require reliable broadcast
  - Communication overhead of shipping the whole state
- Delta State-based [\[ASB18\]](#) :
  - Small messages
  - Dissemination over unreliable communication channels

# 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 (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:  $\langle p_1, s_1, h_1 \rangle \langle p_2, s_2, h_2 \rangle \dots \langle p_k, s_k, h_k \rangle$

$p_i$  integer

$s_i$  site identifier

$h_i$  logical clock at site  $s_i$

<b>&lt;1,2,1&gt;</b>	<b>c</b>
<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

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

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

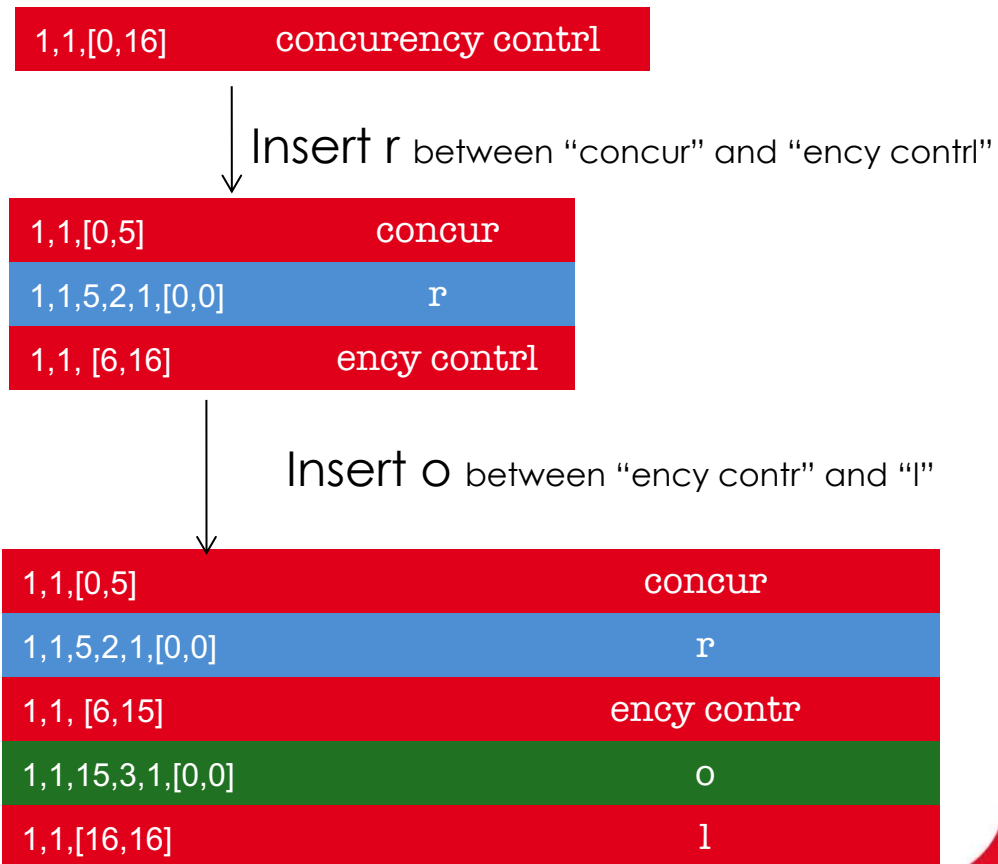
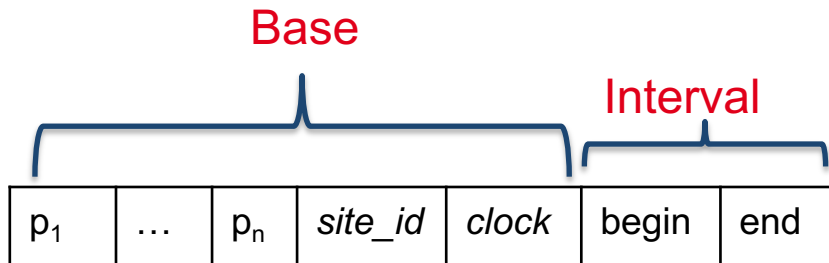
- Time complexity
  - Average:  $O(k \log(n))$
  - Worst case:  $O(H * \log(H))$
  - H: #ops
  - n: doc. size (non deleted chars.)
  - k: avg. size of Logoot identifier
- No need for concurrency detection
- Identifiers storage cost
- New design for each data type
- Suitable for large-scale collaboration**

# Conflict-free Replicated Data Types (CRDT)

## LogootSplit [AM0113]

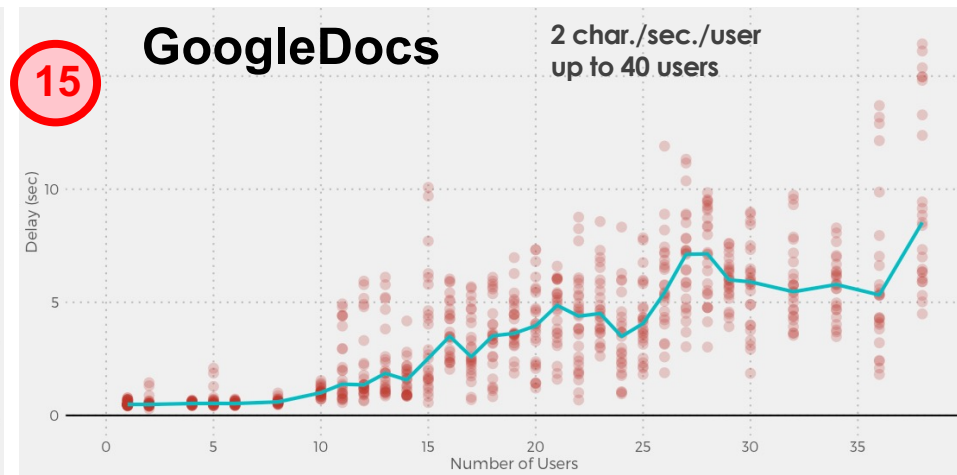
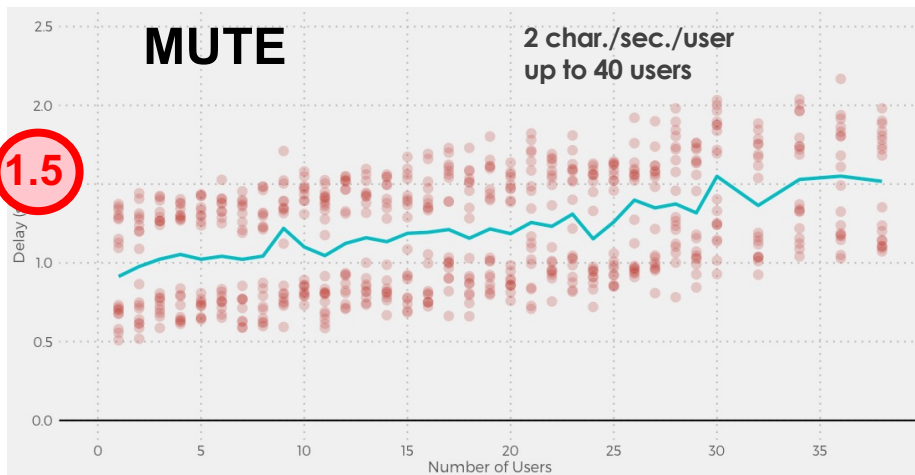
**Aggregation of elements** to limit metadata

LogootSplit identifiers



# Conflict-free Replicated Data Types (CRDT) LogootSplit - Impact

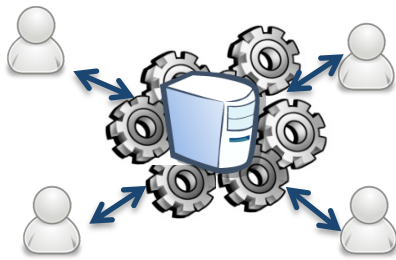
- Implemented in MUTE P2P collaborative editor [[NEOIC17](#)] [[github.com/coast-team/mute](#), OpenPaaS::NG, ADT MUTE]
- Better performances than GoogleDocs [[DI16a](#)]



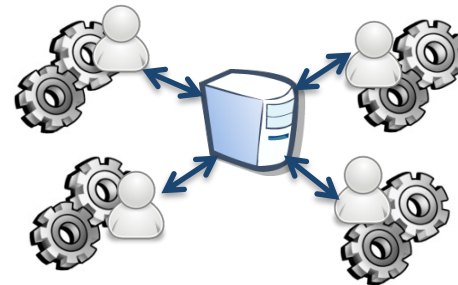
- Related approach on wikis transferred to XWiki [[IA021](#)]

# User Study: The effect of delay on users [IOFSC15]

- Delays in seeing modifications of other users
  - Network delay
  - Time complexity of consistency maintenance algorithms
  - Types of architecture



Thin client architecture



Thick client architecture

- How does **delay influence group performance?**

# Experiment design

- 20 groups of 4 students
  - Perform several collaborative editing tasks
    - A proofreading task
    - A sorting task
    - **A note taking task**
  - Use the provided collaborative editor (Etherpad) + chat
  - Each group experienced a **certain delay** (0, 4, 6, 8, 10 s)
- Registration of user keyboard inputs
- Video recording of user activities on desktop

# Note-taking [IOFSC15]

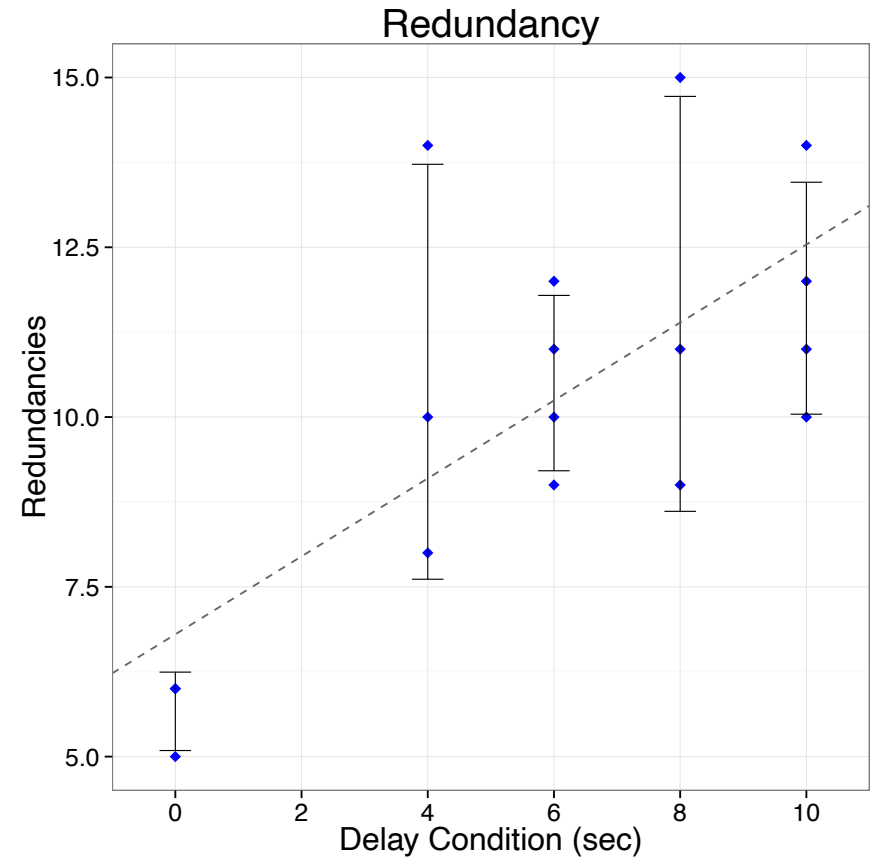
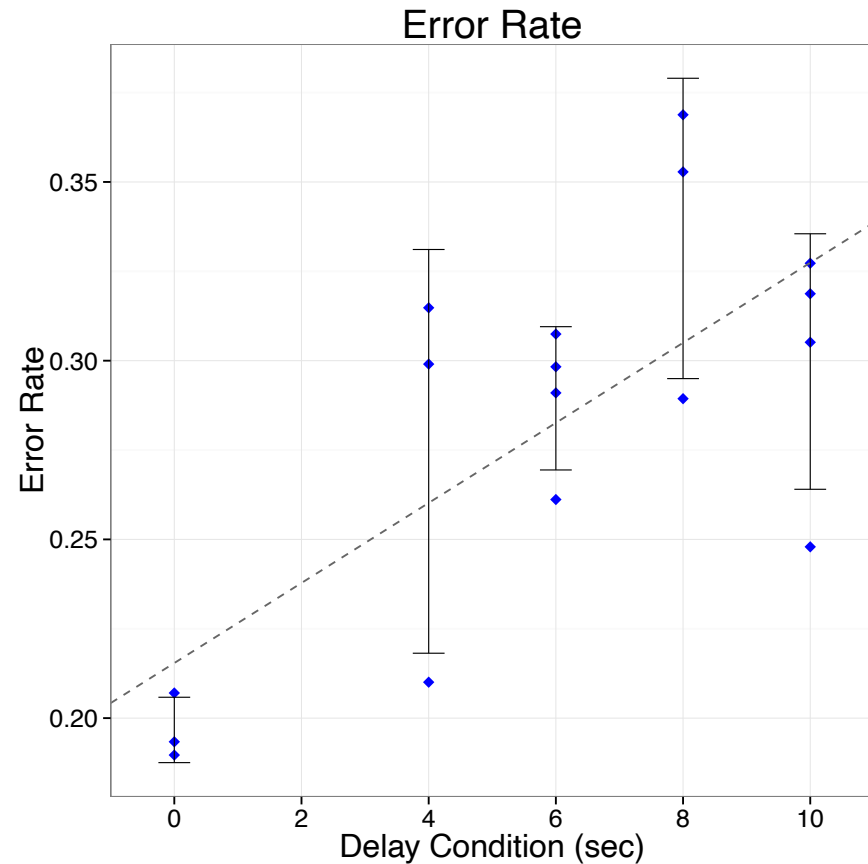
The image shows a screenshot of a web browser window displaying a document editor. The browser's address bar shows the URL `ec2-184-72-75-76.compute-1.amazonaws.com/p/notes005`. The document editor contains a list of notes about cloud computing, with several lines highlighted in purple, blue, and yellow. A black box labeled "Editing zone" is positioned over the top of the document. Three circular callouts are drawn around specific text in the document: "un data matérialisé", "le cloud représente un marché gigantesque", and "matérialisé". A black box labeled "Chat dialogue" is positioned over a chat window in the bottom right corner. The chat window shows a list of messages from different users.

**Editing zone**

**Chat dialogue**

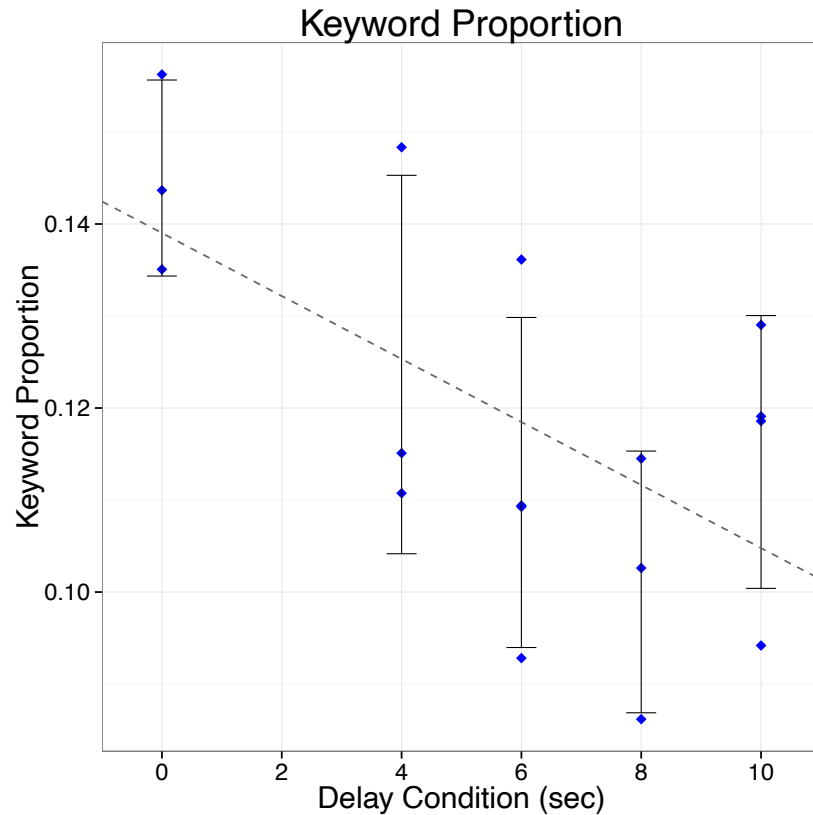
Chat	
user4: test	16:15
user2: test user 2	16:15
user2: great	16:15
user3: test	16:15

# Delay reduces Group Performance



- Delay increases error rate and redundancy

# Delay reduces Group Performance



- Delay decreases proportion of keywords



## Design implications

- Reduce the delay by the choice of the architecture and synchronisation algorithms
- Make users aware of existing delays such that they can compensate for the delay by coordination strategies
- Analyse real collaboration traces to understand collaboration patterns and behavior [NI18]

## Perspectives – Replication for complex data

- Composition of replication mechanisms for simple data
  - Maintaining global invariants (e.g. integrity constraints) over CRDTs for replicated relational databases [IEB24]
  - Replication mechanisms for P2P cloud storage [AII23]
  - Automated approach to combine CRDTs meeting expressed constraints
- Validate with users the defined merge semantics

# Research issues

- 1 How to **maintain consistency of different copies** in the face of concurrent modifications?
- 2 How to **secure collaboration data**?
- 3 How to make a collaboration **trustworthy**?

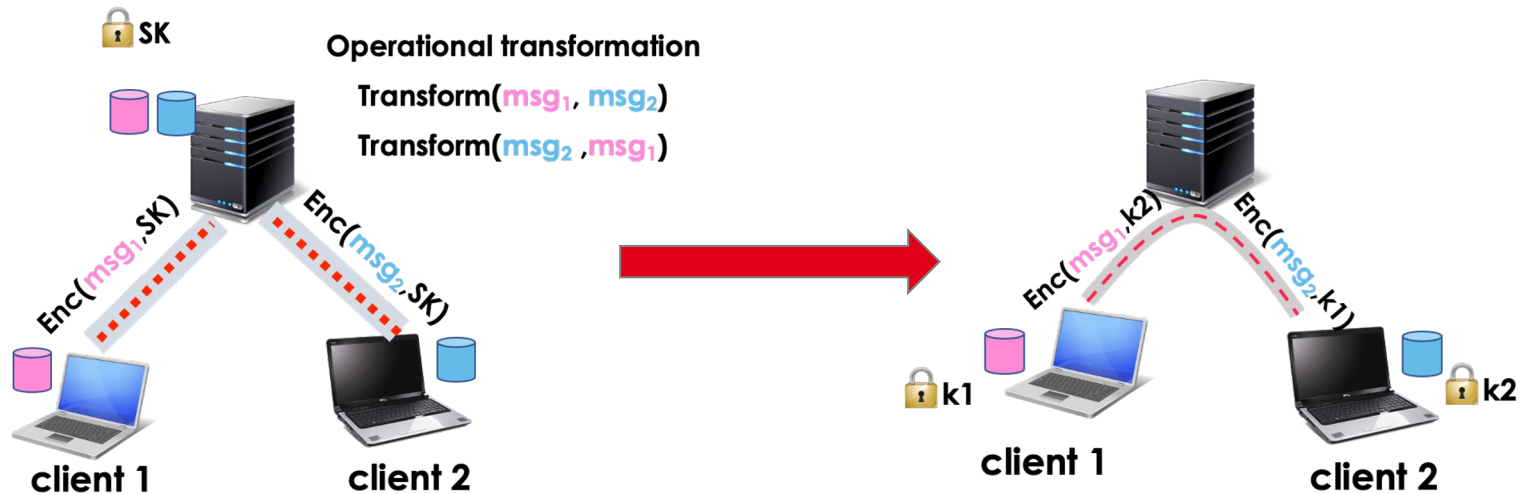
# Security in peer-to-peer collaboration



- Client-side E2E encryption
- Group key management
- Access control without central authority

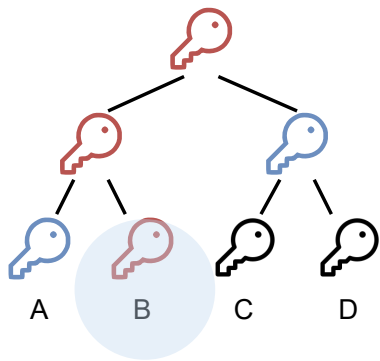
# Encryption for mutable data by means of CRDTs

- CRDTs suitable for client-side E2E encryption

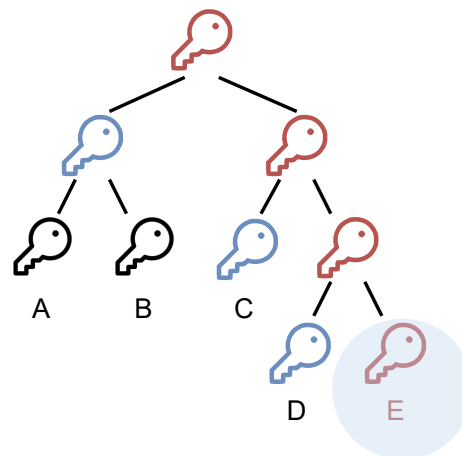


# Group key management for large and dynamic groups

- TreeKEM - Message Layer Security (MLS) RFC 9420
  - Operations: Add, Remove and Update



Updating member B



Adding member E



Modified/updated keys



Keys on co-path, used to encrypt new keys to subgroups

- Delivery Service: a central server that resolves conflicts among operations
- **Goal: Distribute the Delivery Service** [PIFTI23]
  - Use of reliable broadcast protocols for operation delivery
  - Use consensus between group members for operation commits

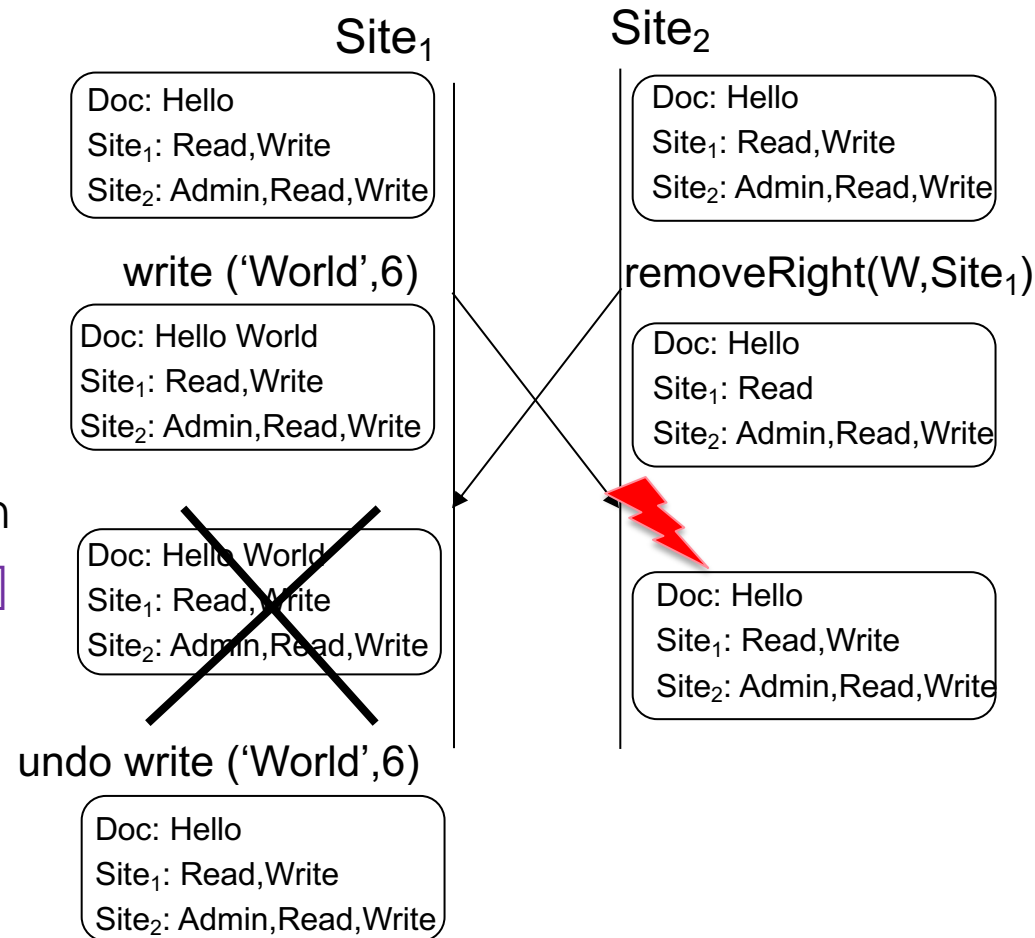
# Access control for peer-to-peer systems without central authority

## Goals

- Replicated data
- Replicated access rights
- Multiple administrators

## Approach

- Compose CRDTs for data with CRDTs for access rights [RIP23]
- Dependencies
  - Between access rights operations
  - Between document and access rights



# P2P Cloud Storage – Défi Alvearium with hive Replication and security mechanisms application

- A distributed peer-to-peer cloud exploiting unused capacity of computers
  - +20% of computing resources remain unused
  - Allows users to share these computing resources
  - Builds a virtual cloud to offer compute and **storage services**



- Sustainable
- Secure & private
- Data sovereignty
- Affordable



# P2P Cloud Storage – collaboration with hive

## Research topics

- How to place data in the peer-to-peer storage in order to ensure high availability?
- How to manage data that can be modified by different peers?
- How to deal with Byzantine nodes? How to handle Sybil attacks?
- How to define a peer-to-peer security mechanism (manage access rights, client-side E2E encryption, group key management)

# Research issues

- 1 How to **maintain consistency of different copies** in the face of concurrent modifications?
- 2 How to **secure collaboration data**?
- 3 How to make a collaboration **trustworthy**?

# Trust in collaborative tools [L21]

- Crisis management – issues on information sharing
- Technical issues: tools' complexity, network delay, no interoperability
- Communicational issues



# Peer-to-peer user trust

- Prediction of future collaborative user behavior based on the quality of user contributions

## Should I Trust You?

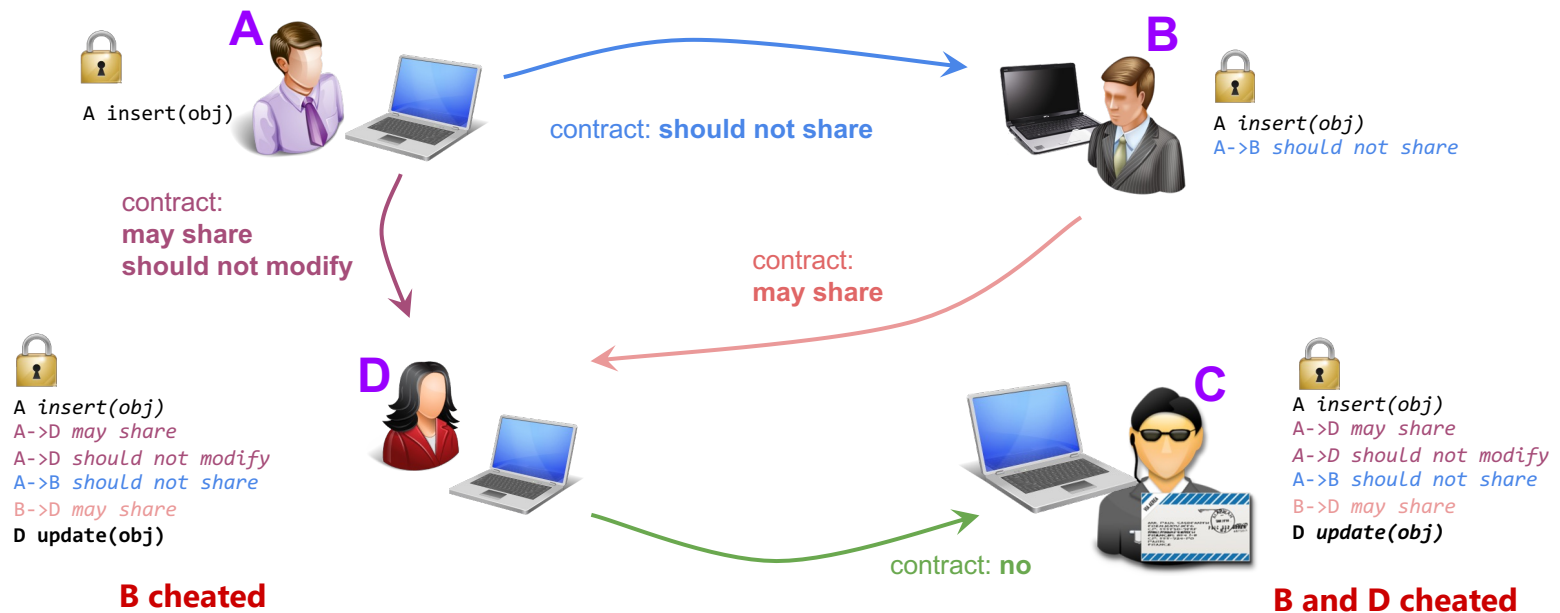


# Trust computation - contribution

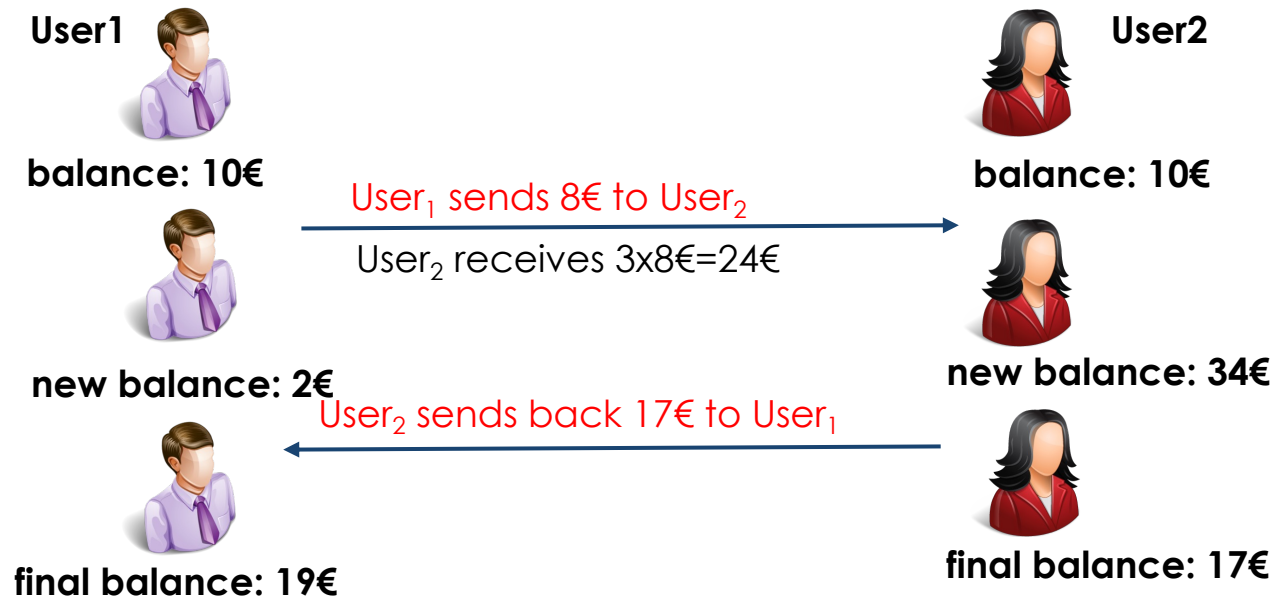
- Evaluate collaborators trust based on their past behavior
  - Contract-based collaborative editing
  - Trust game

# Trust computation in collaborative editing

- Respect/Violation of contracts [TI11, TIBM11, TIM12, ID21]



# Peer-to-peer trust metric in trust game [BDM95]



- **Design a trust metric** dealing with fluctuating user behaviour [DI16a]

- For a round:  $current\_trust_t = \log(send\_proportion_t * (e - 1) + 1)$

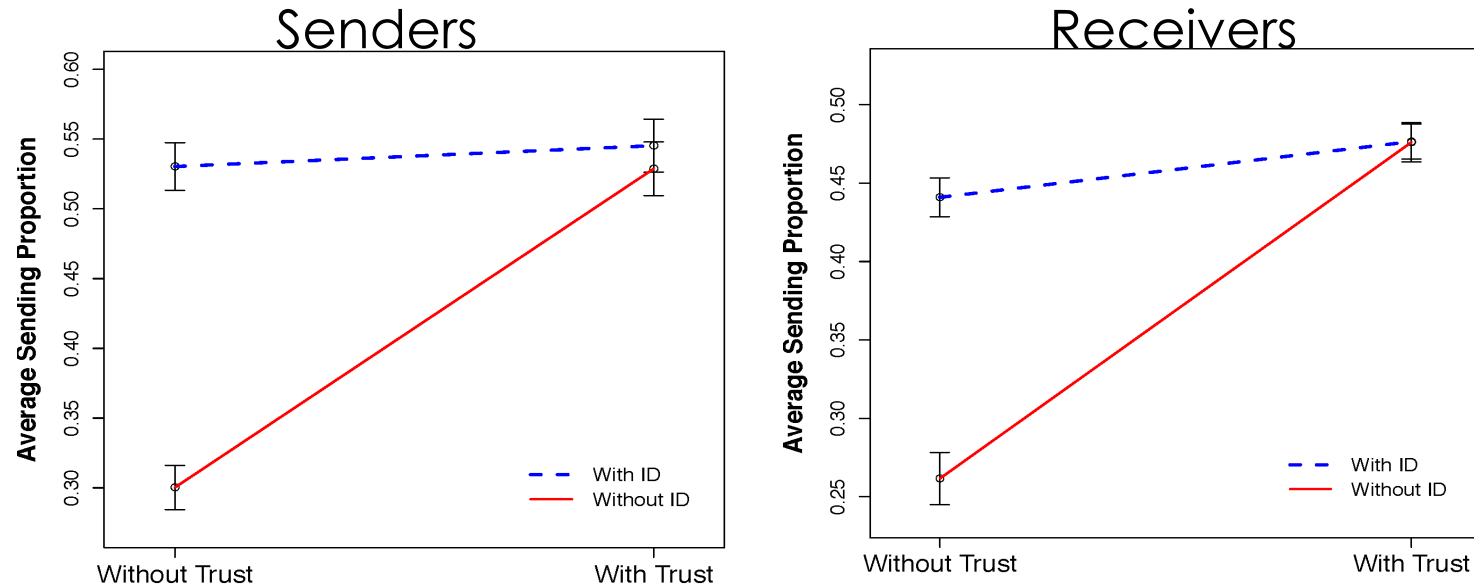
$$send\_proportion_t = \frac{sending\_amount_t}{max\_sending\_amount}$$

- For accumulated rounds:

$$aggregate\_trust_t = \alpha_t * current\_trust_t + (1 - \alpha_t) * aggregate\_trust_{t-1}$$

# Validation of the trust metric – experimental design [IDS19]

- **Experiment with users** on 4 trust games: Simple Game, Identity Game, Score game and Combine game



- Showing either trust score or identity improves the measure
- Showing both of them does not change the measure
- **Trust-based systems can be a replacement of identity-based systems**
- Collaboration with Department of Psychology Wright State University



# PEPR eNSEMBLE (<https://pepr-ensemble.fr/>)

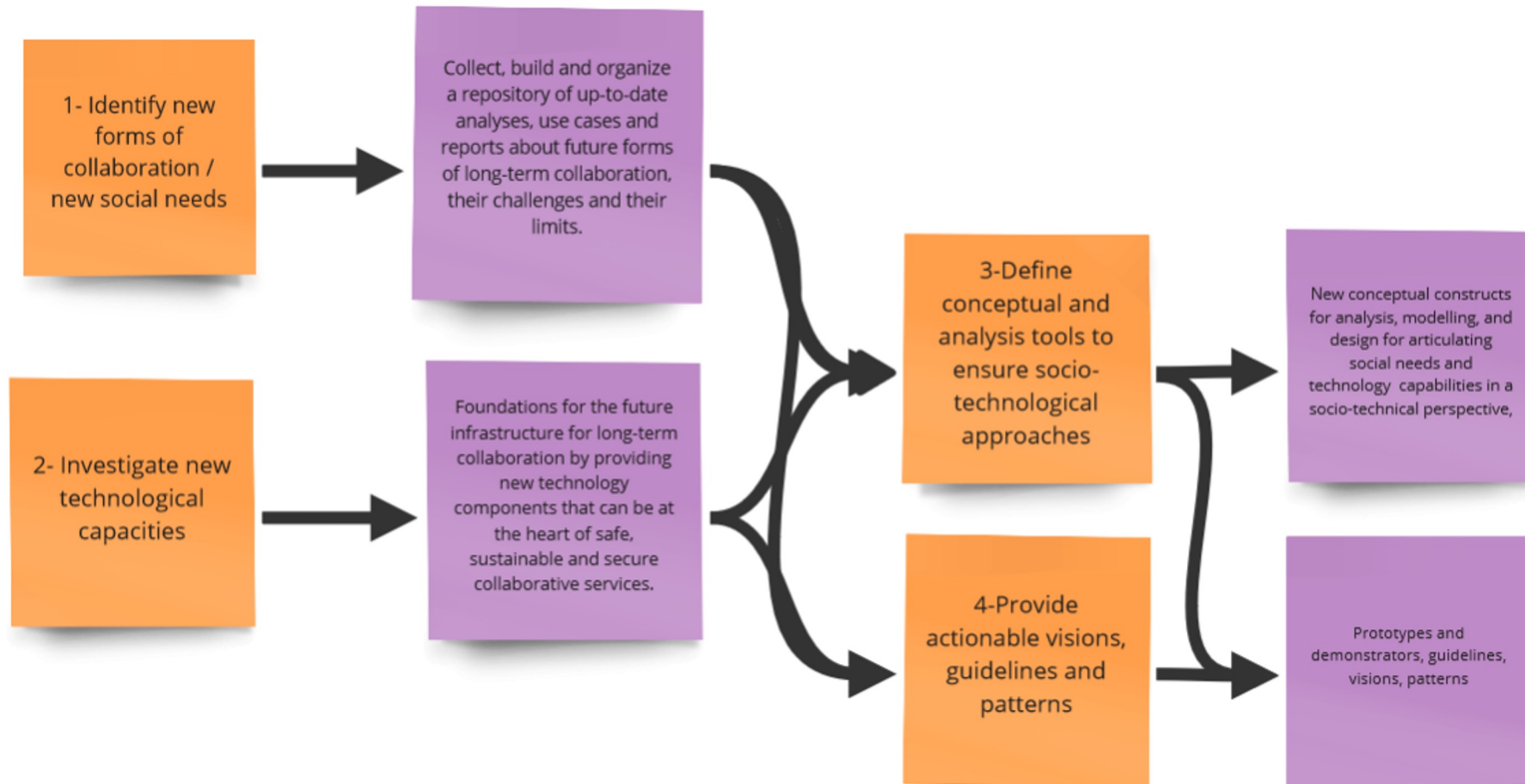
## PILOT – Practices and infrastructure for long term collaboration

- Socio-technical models for long-term collaboration
- Multi-organizational, sovereign, secure, interoperable collaboration platforms promoting trust and digital well-being
- Coordinators
  - Claudia-Lavinia Ignat, Inria
  - François Charoy, Université de Lorraine
  - Myriam Lewkowicz, Université de Technologie de Troyes

# PILOT – Project axes

- Axis 1: Understanding current and future forms of long-term collaboration
- Axis 2: Open technical frameworks and protocols for long-term collaboration
- Axis 3: Conceptual Frameworks for long-term collaboration
- Axis 4: Actionable guidelines and demonstrators for long term collaboration

# PILOT architecture



# PILOT – Resources

- Budget: 5 M€
- Period: 7 years (Sept. 2023 – Aug. 2030)
- Non permanent resources
  - 18 PhD theses
  - 4 postdocs of 2 years
  - 2 engineers of 4 years
  - 12 internships of 6 months
- 14 partner institutions: Inria, CNRS, Univ. Paris-Saclay, Univ. Grenoble Alpes, Sorbonne Univ., IMT, UTT, INSA Lyon, UCB, Nantes Université, ENSAM, Univ. de Lille, Univ. de Toulouse

# Large-scale trustworthy distributed collaborative systems

- New uses and new practices due to large scale adoption
- New challenges
  - Consistency of replicated complex data
  - Security mechanisms without a central authority
  - Trust in collaborative platforms and trust among collaborators

# Thank you

COAST Team

<http://team.inria.fr/coast/>

## modifications operation-based

documents  
management  
operations-based  
work  
granularity  
conflicts

web-based  
compro-mising  
round-free  
securing  
development

assessment  
networks  
peer-to-peer  
awareness  
environments  
peer-to-peer  
collaborative  
development

undo  
studying  
multi-mode  
web  
cdrts  
adaptable  
wiki  
push-pull  
text  
repository  
structures  
xml

contract  
tree-based  
writing  
model  
editor  
real-time  
distributed  
data  
user  
resolution  
multi-level  
processes  
concurrent  
trust

organisations  
auditing  
merging  
drawing  
editing  
algorithms  
hi story  
multi-part

information  
log  
multi-pair  
model  
authoring  
communication

changes  
software  
note  
evaluating  
optimistic  
authenticating

framework  
state-based  
privacy  
massive-scale  
draw-together

## documents systems multi-level

un-grouping  
asynchronous

multiple-granularity  
programmability

performance  
inter-document  
co-authoring

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