



**HAL**  
open science

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

Claudia-Lavinia Ignat

► **To cite this version:**

Claudia-Lavinia Ignat. Keynote: Large-scale trustworthy distributed collaborative systems - challenges and prospective solutions. INFORSID (INformatique des ORganisations et Systèmes d'Information et de Décision) 2024, May 2024, Nancy, France. hal-04595294

**HAL Id: hal-04595294**

**<https://inria.hal.science/hal-04595294v1>**

Submitted on 31 May 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

01101100  
01101111  
01110010  
01101001  
01100001  
01101100  
01101111  
01110010  
01101001  
0110000111  
111000010111  
1110010011  
\*00010111  
\*11111

Loria



UNIVERSITÉ  
DE LORRAINE



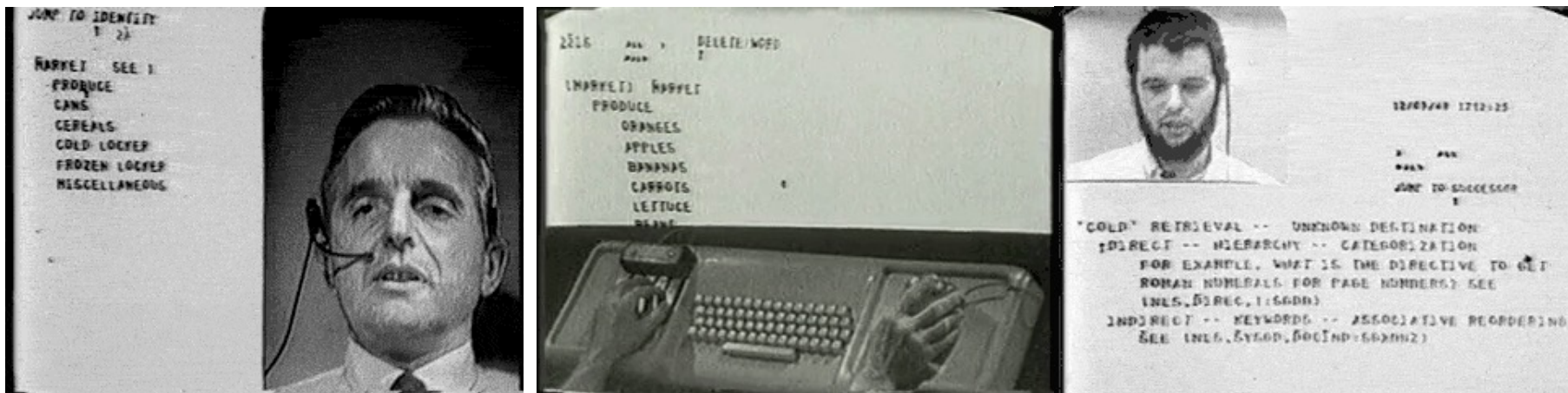
*Inria*  
informatics mathematics

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

Claudia-Lavinia Ignat  
COAST - Centre Inria de l'Université de Lorraine

Inforsid 2024  
May 30, 2024  
[claudia.ignat@inria.fr](mailto:claudia.ignat@inria.fr)

# Douglas Engelbart: Augmenting Human Intellect



The Mother of all Demos, December 9, 1968



NLS: Online System

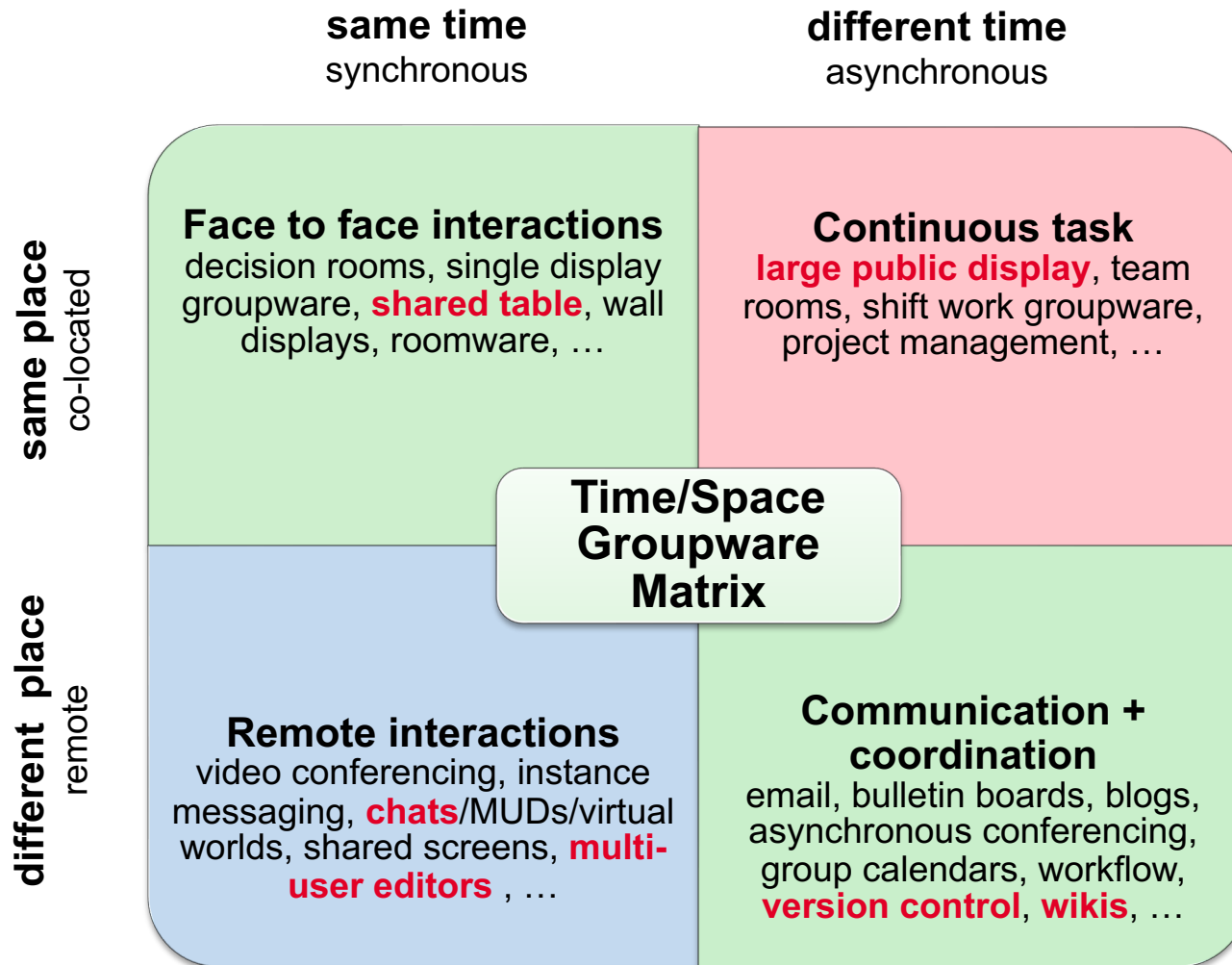
<https://archive.org/details/dougengelbartarchives>

## 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]



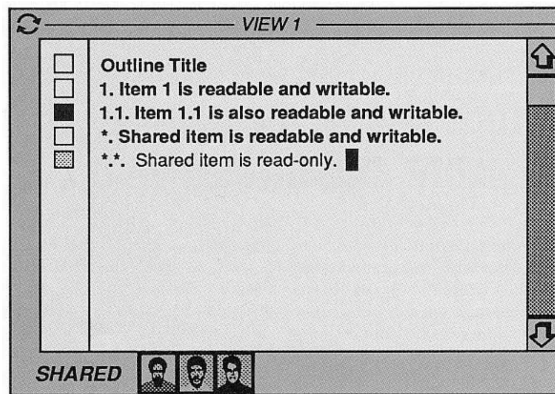


# Collaborative Systems: from users to community of users



*“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  
Contact us  
Donate

Contribute  
Help  
Learn to edit  
Community portal  
Recent changes  
Upload file

Tools  
What links here  
Related changes  
Atom  
Special pages  
Page information  
Wikidata item

Languages

Not logged in [Talk](#) [Contributions](#) [Create account](#) [Log in](#)

Article [Talk](#)

[Read](#) [Edit](#) [View history](#)

## United States Capitol: Revision history

[Help](#)

[View logs for this page \(view filter log\)](#)

### Filter revisions

External tools: [Find addition/removal \(Alternate\)](#) · [Find edits by user](#) · [Page statistics](#) · [Pageviews](#) · [Fix dead links](#)

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](#))
- [\(cur | prev\)](#) [22:49, 6 January 2021](#) [2605:a601:ada1:2a00:ad83:9ec8:20bc:44c5 \(talk\)](#) [...](#) (83,031 bytes) (+15) [..](#) (*→Major events: Cleaned up wording on Trump recorded message*) ([undo](#)) ([Tags: Mobile edit, Mobile web edit](#))
- [\(cur | prev\)](#) [22:47, 6 January 2021](#) [2605:a601:ada1:2a00:ad83:9ec8:20bc:44c5 \(talk\)](#) [...](#) (83,016 bytes) (-1) [..](#) (*→Major events: Replaced one other instance of "rioters" with "people"*) ([undo](#)) ([Tags: Mobile edit, Mobile web edit](#))
- [\(cur | prev\)](#) [22:45, 6 January 2021](#) [2605:a601:ada1:2a00:ad83:9ec8:20bc:44c5 \(talk\)](#) [...](#) (83,017 bytes) (-8) [..](#) (*→Major events: Typo*) ([undo](#)) ([Tags: Mobile edit, Mobile web edit](#))
- [\(cur | prev\)](#) [22:45, 6 January 2021](#) [2600:1700:2b9c:5010:a145:6992:7d5a:8714 \(talk\)](#) [...](#) (83,025 bytes) (+81) [..](#) (*→Major events*) ([undo](#))
- [\(cur | prev\)](#) [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](#) [Weswinj \(talk | contribs\)](#) [...](#) (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*) ([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](#))

### Compare selected revisions

(newest | oldest) [View \(newer 20 | older 20\) \(20 | 50 | 100 | 250 | 500\)](#)

# From users to community of users: new practices



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

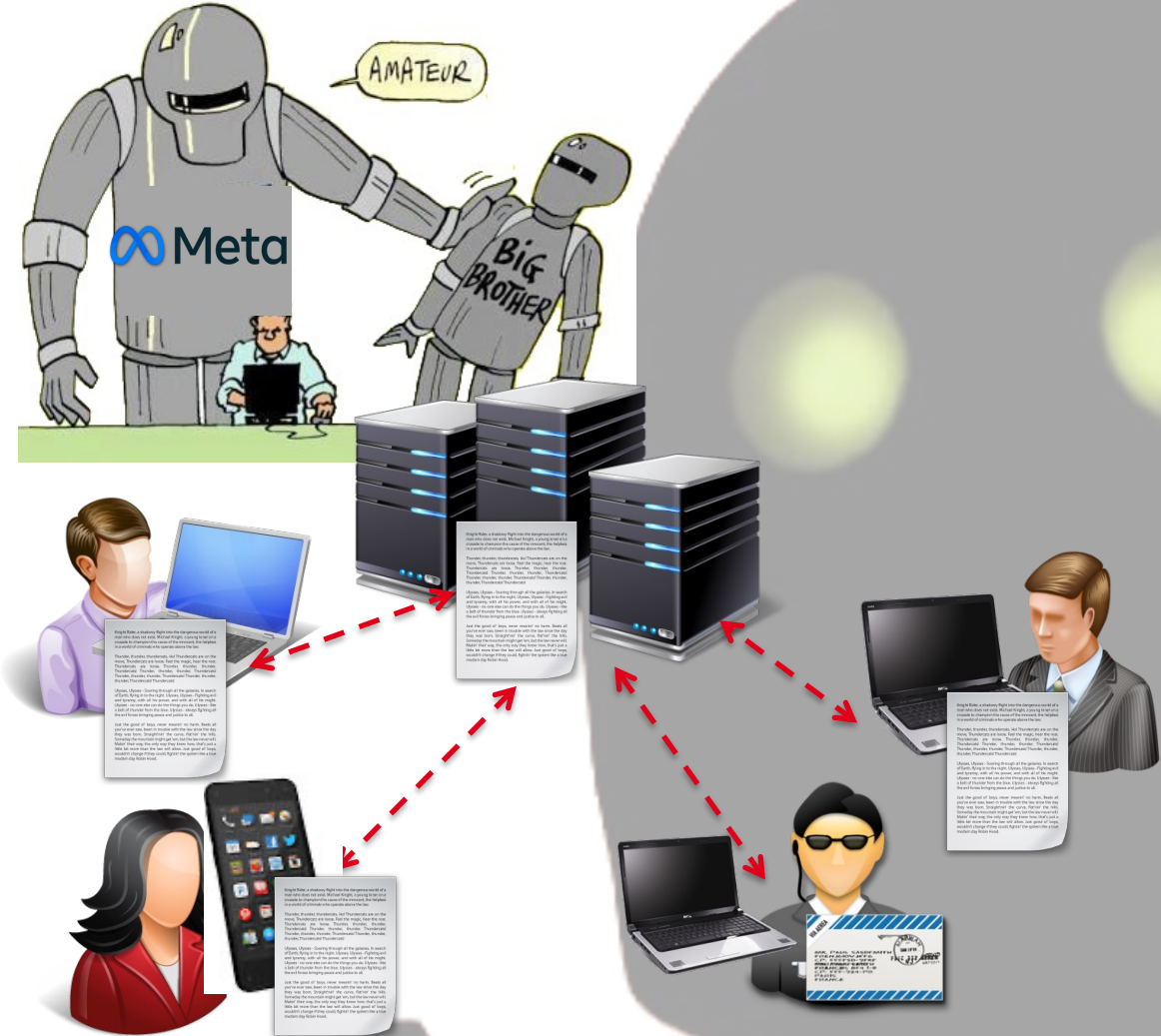
- Expert contributions: hundreds of scientists from different countries
- Review stages by experts and governments
- Approval sessions: government delegates and lead authors
- Editing teams: review editors



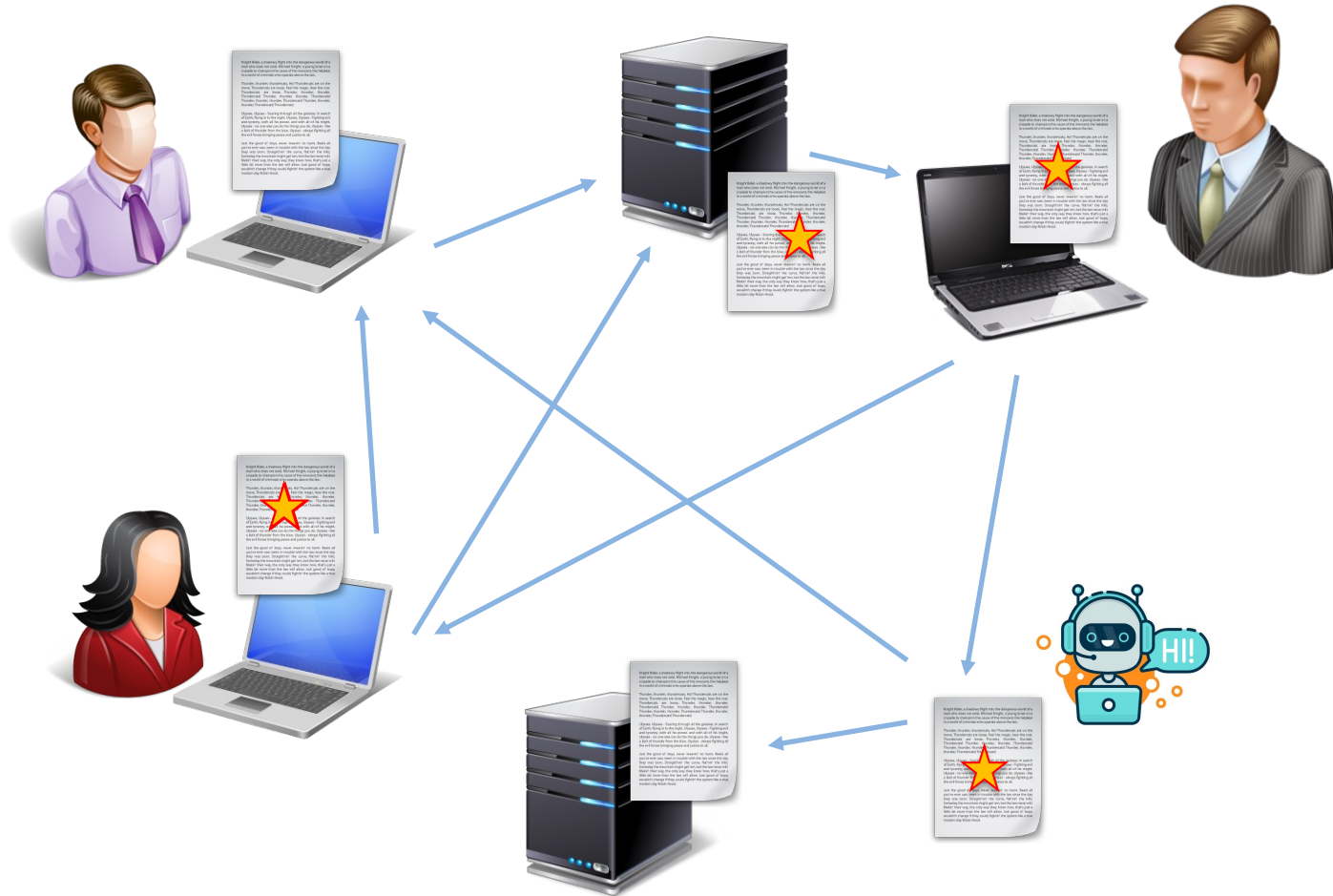
# Limitations of Central Authority Systems

# SCALABILITY

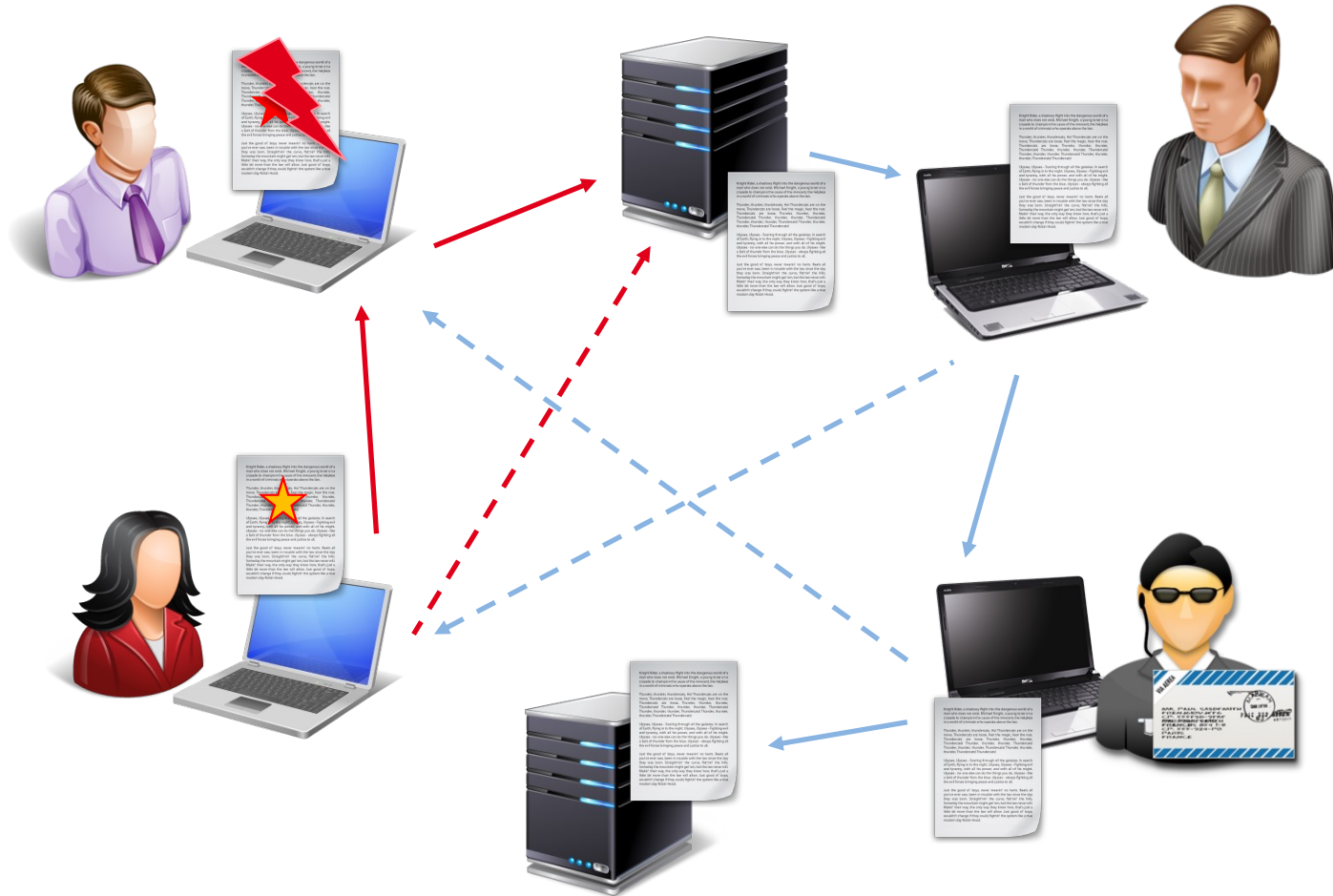
# PRIVACY



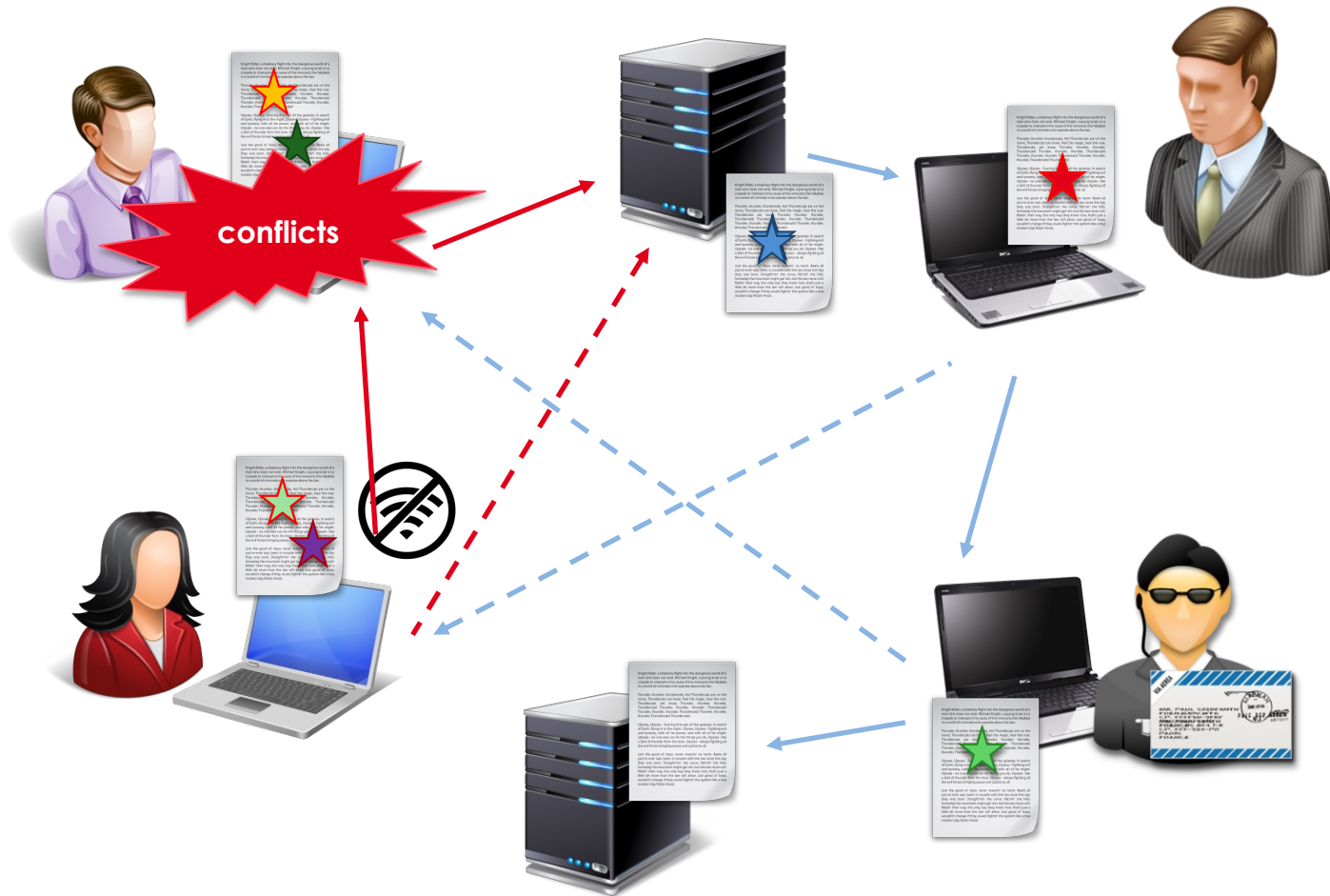
# Vision: Peer-to-Peer Collaborative Systems



# 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**?

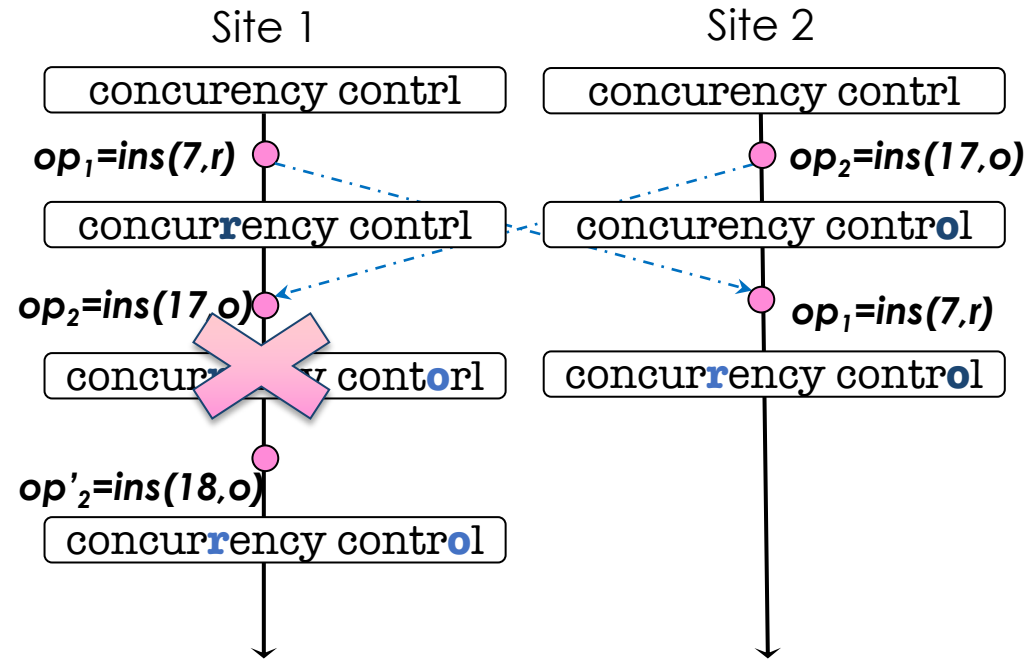
# Research issues

- 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: $O(H.c)$	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**

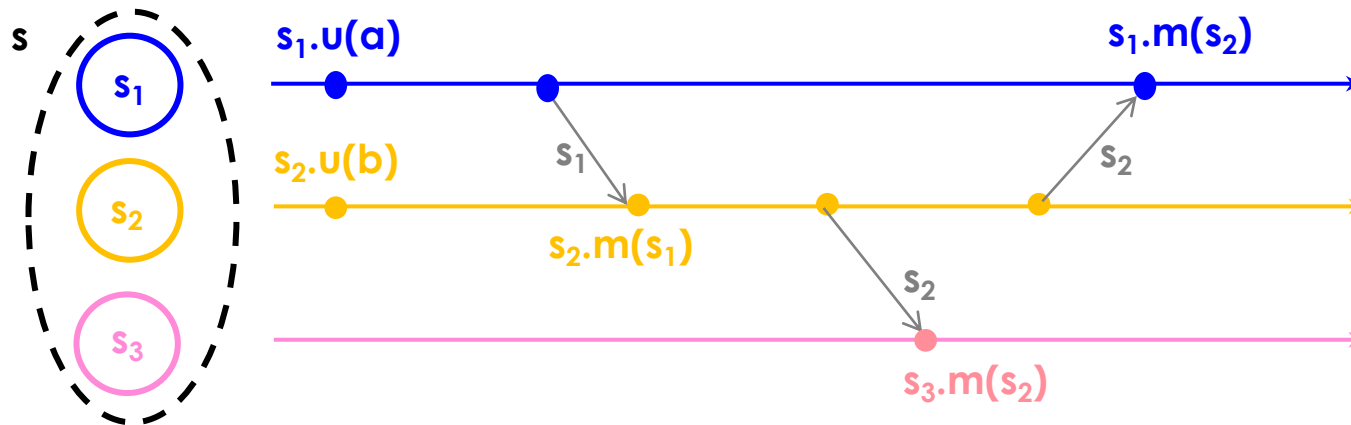
# Conflict-free Replicated Data Types (CRDT) [SPBZ11]

- 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

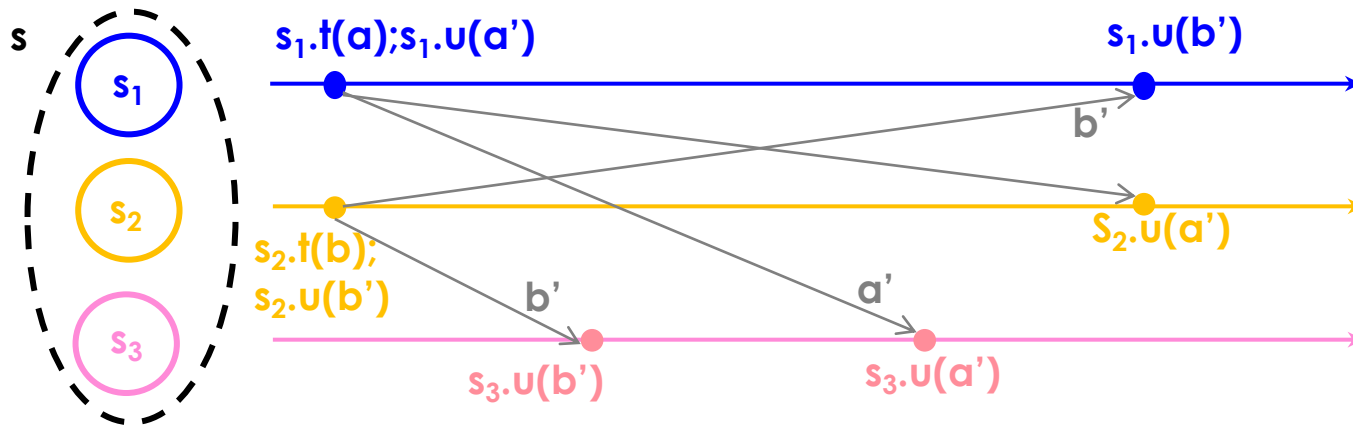
# Conflict-free Replicated Data Types (CRDT)

## 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><math>\langle 1, 2, 1 \rangle</math></b>	<b>c</b>
$\langle 1, 2, 2 \rangle$	o
$\langle 2, 1, 2 \rangle$	n
$\langle 3, 1, 3 \rangle$	c
$\langle 3, 1, 3 \rangle \langle 8, 4, 5 \rangle$	u
$\langle 3, 2, 5 \rangle$	r
$\langle 4, 1, 7 \rangle$	e
$\langle 4, 1, 7 \rangle \langle 9, 2, 6 \rangle$	n
$\langle 7, 2, 8 \rangle$	c
$\langle 9, 1, 7 \rangle$	y
$\langle 10, 2, 8 \rangle$	
$\langle 12, 3, 1 \rangle$	c
$\langle 12, 3, 1 \rangle \langle 6, 5, 1 \rangle$	o
$\langle 12, 3, 1 \rangle \langle 7, 8, 2 \rangle$	n
$\langle 12, 3, 1 \rangle \langle 7, 8, 2 \rangle \langle 12, 3, 5 \rangle$	t
$\langle 12, 3, 1 \rangle \langle 7, 8, 2 \rangle \langle 13, 3, 6 \rangle$	r
$\langle 12, 3, 1 \rangle \langle 7, 8, 2 \rangle \langle 14, 3, 7 \rangle$	l

ins( $\langle 3, 2, 5 \rangle \langle 13, 1, 7 \rangle$ , r)

ins( $\langle 12, 3, 1 \rangle \langle 7, 8, 2 \rangle \langle 13, 3, 6 \rangle \langle 7, 2, 9 \rangle$ , o)

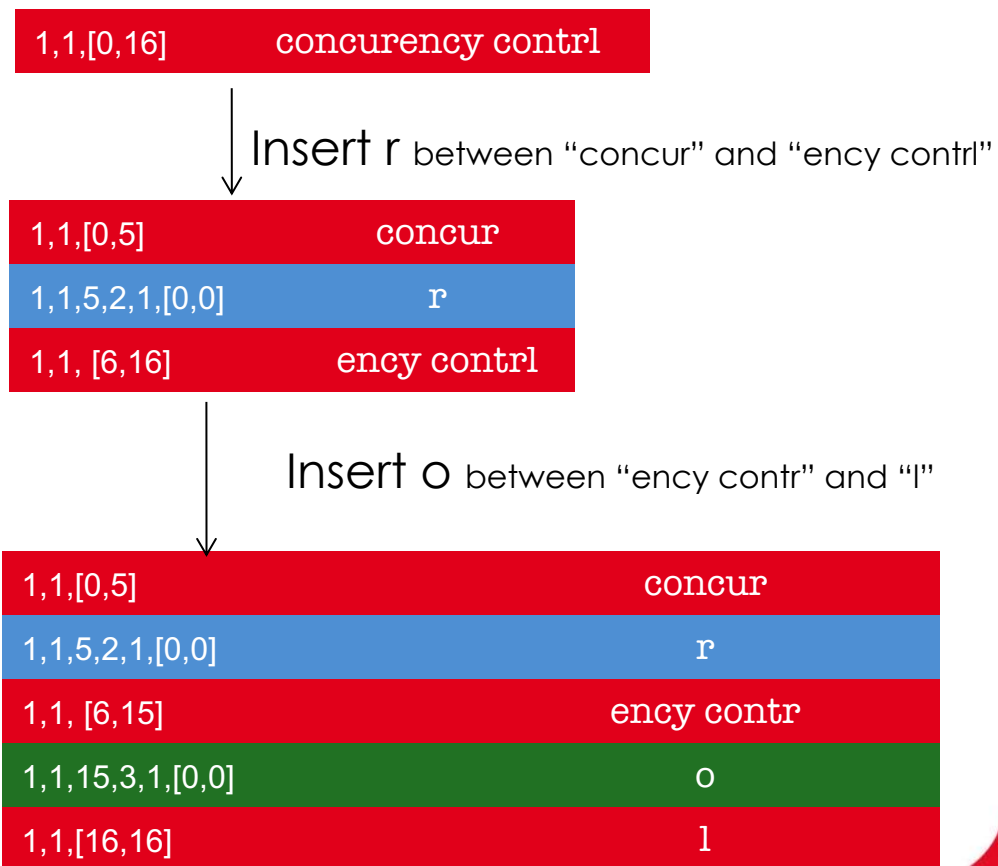
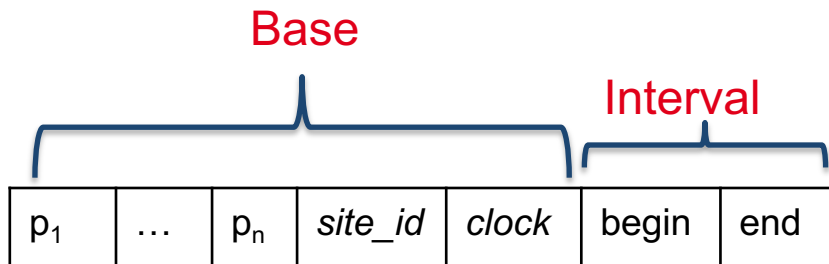
- Time complexity
  - Average:  $O(k \log(n))$
  - Worst case:  $O(H * \log(H))$
  - H: #ops
  - n: doc. size (non deleted chars.)
  - k: avg. size of Logoot identifier
- No need for concurrency detection
- Identifiers storage cost
- New design for each data type
- Suitable for large-scale collaboration**

# Conflict-free Replicated Data Types (CRDT)

## LogootSplit [AM0113]

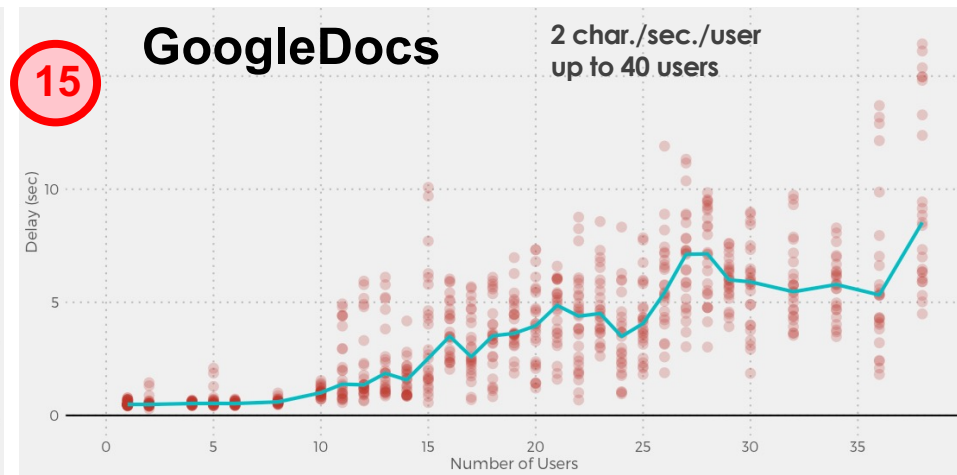
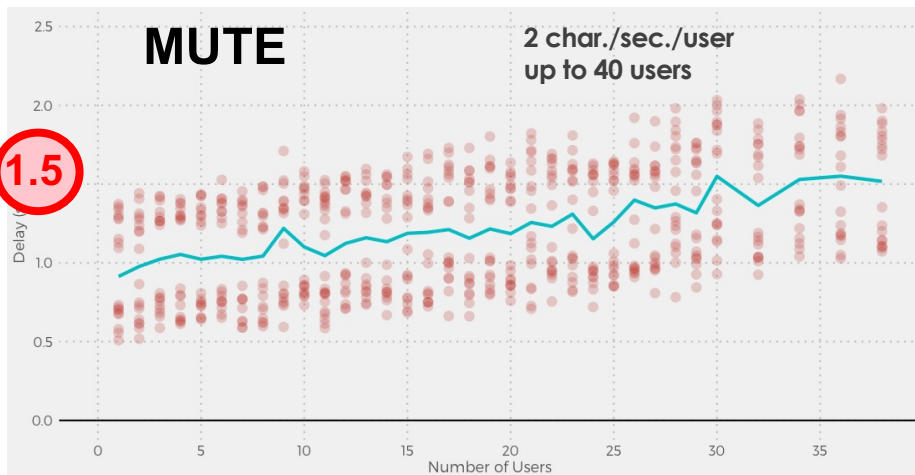
**Aggregation of elements** to limit metadata

LogootSplit identifiers



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

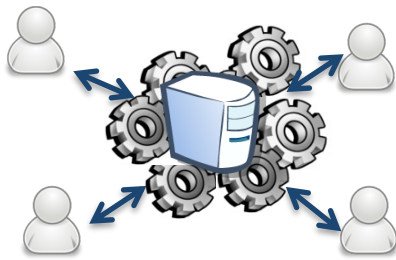
- Implemented in MUTE P2P collaborative editor [[NEOIC17](#)] [[github.com/coast-team/mute](#), OpenPaaS::NG, ADT MUTE]
- Better performances than GoogleDocs [[DI16a](#)]



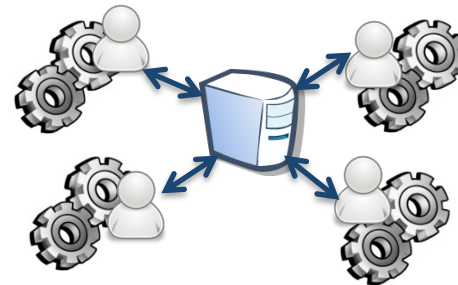
- Related approach on wikis transferred to XWiki [[IA021](#)]

# 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

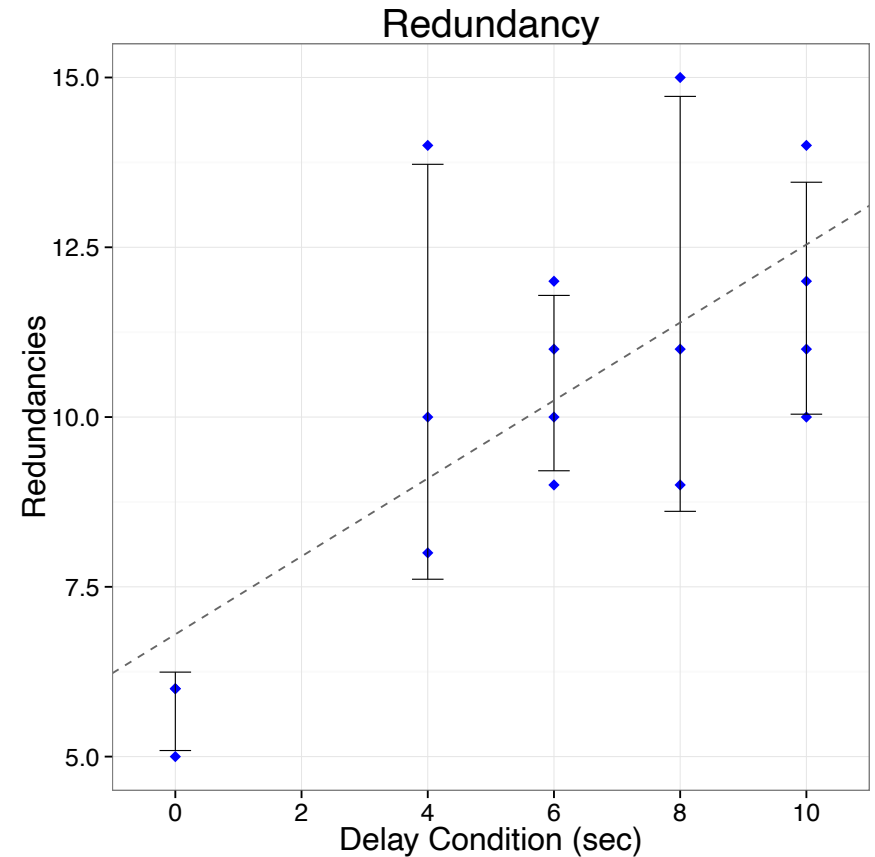
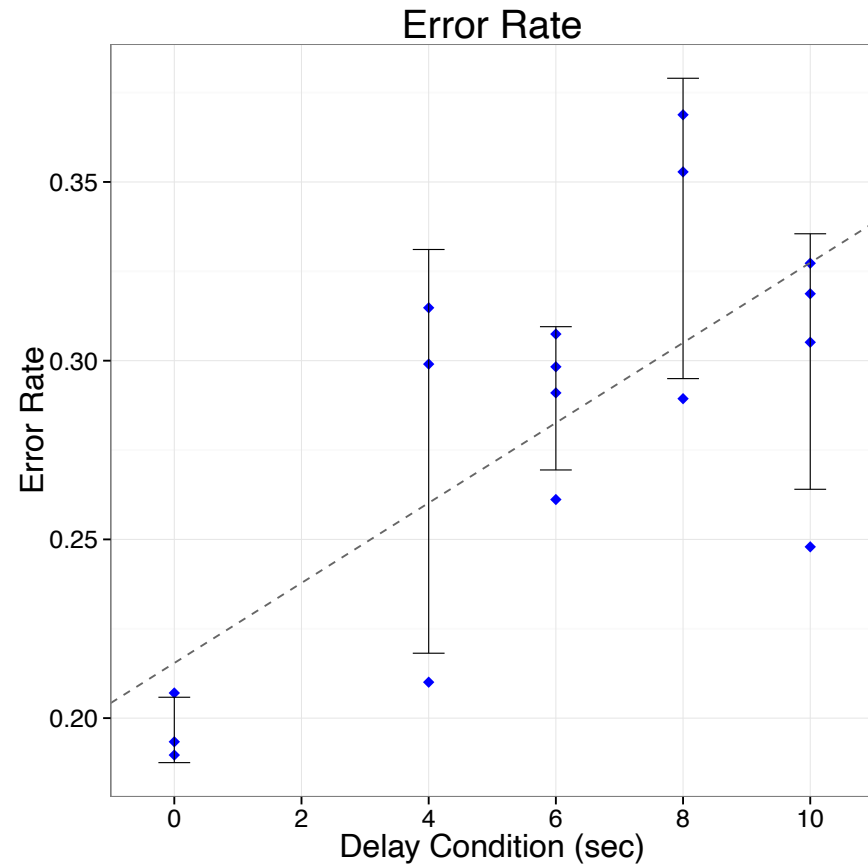
# Note-taking [IOFSC15]

The image shows a screenshot of a web browser window displaying a note-taking application. The browser's address bar shows the URL `ec2-184-72-75-76.compute-1.amazonaws.com/p/notes005`. The browser's toolbar includes a search icon, a home icon, and a user profile icon. The note-taking application's toolbar contains various editing tools such as bold, italic, underline, strikethrough, bulleted list, numbered list, indent, outdent, undo, and redo. The main content area shows a list of notes with line numbers on the left. A black box with the text "Editing zone" is overlaid on the top part of the notes. Three circular callouts are drawn around specific text in the notes, with lines connecting them to a larger black box labeled "Chat dialogue". The chat dialogue box is located in the bottom right corner and contains a list of messages:

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

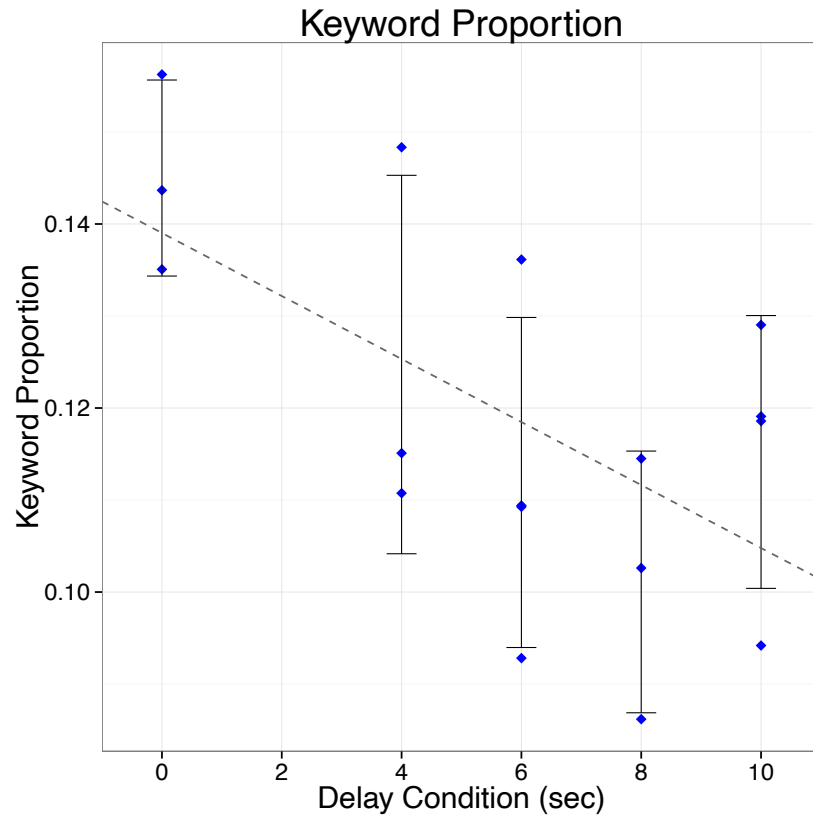


# Delay reduces Group Performance



- 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**?

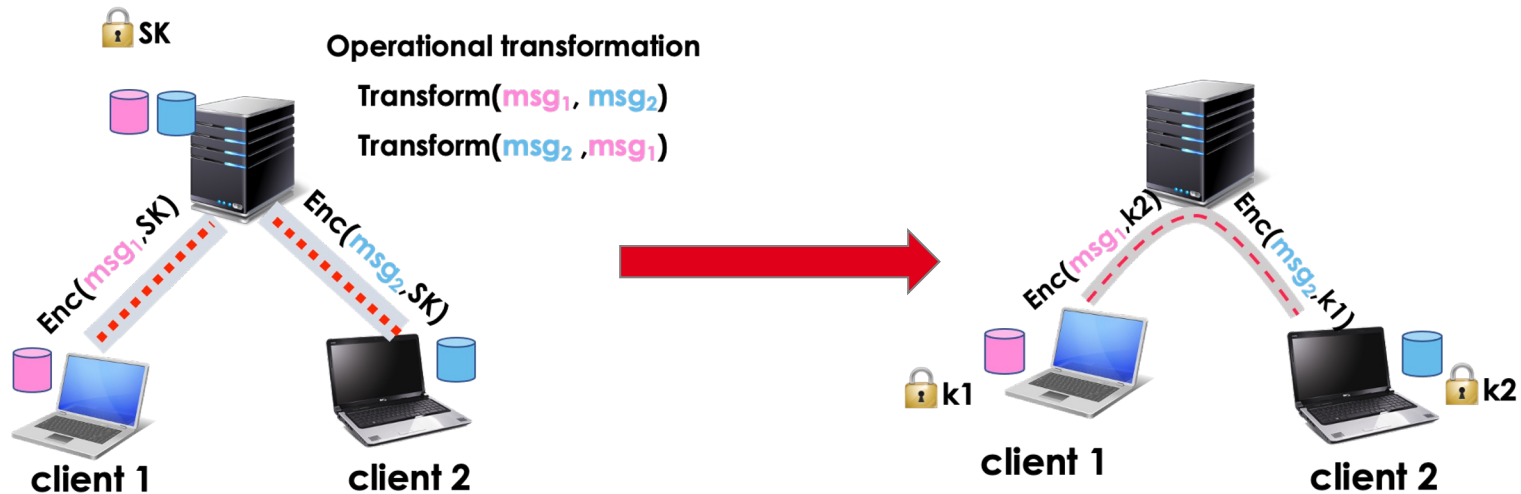
# Security in peer-to-peer collaboration



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

# Encryption for mutable data by means of CRDTs

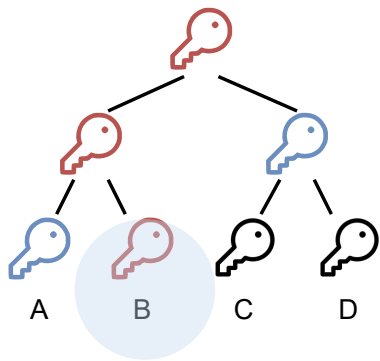
- CRDTs suitable for client-side E2E encryption



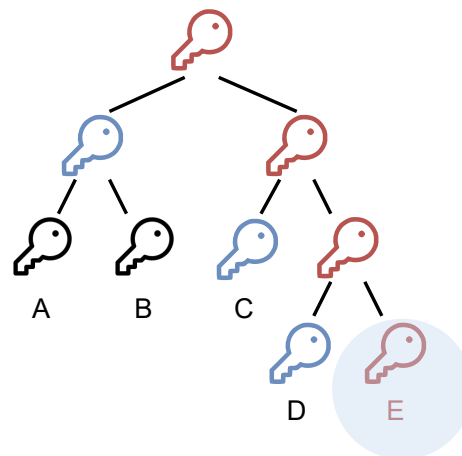


# Group key management for large and dynamic groups

- 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

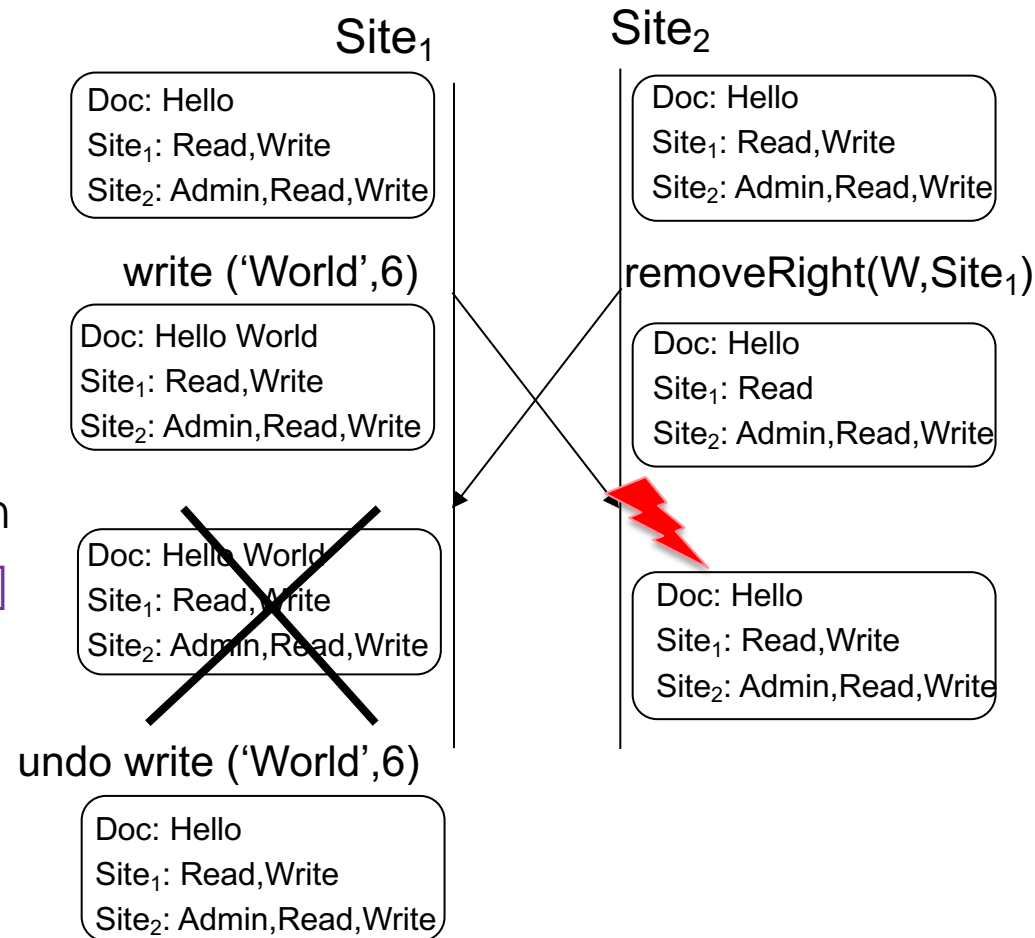
# Access control for peer-to-peer systems without central authority

## 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?



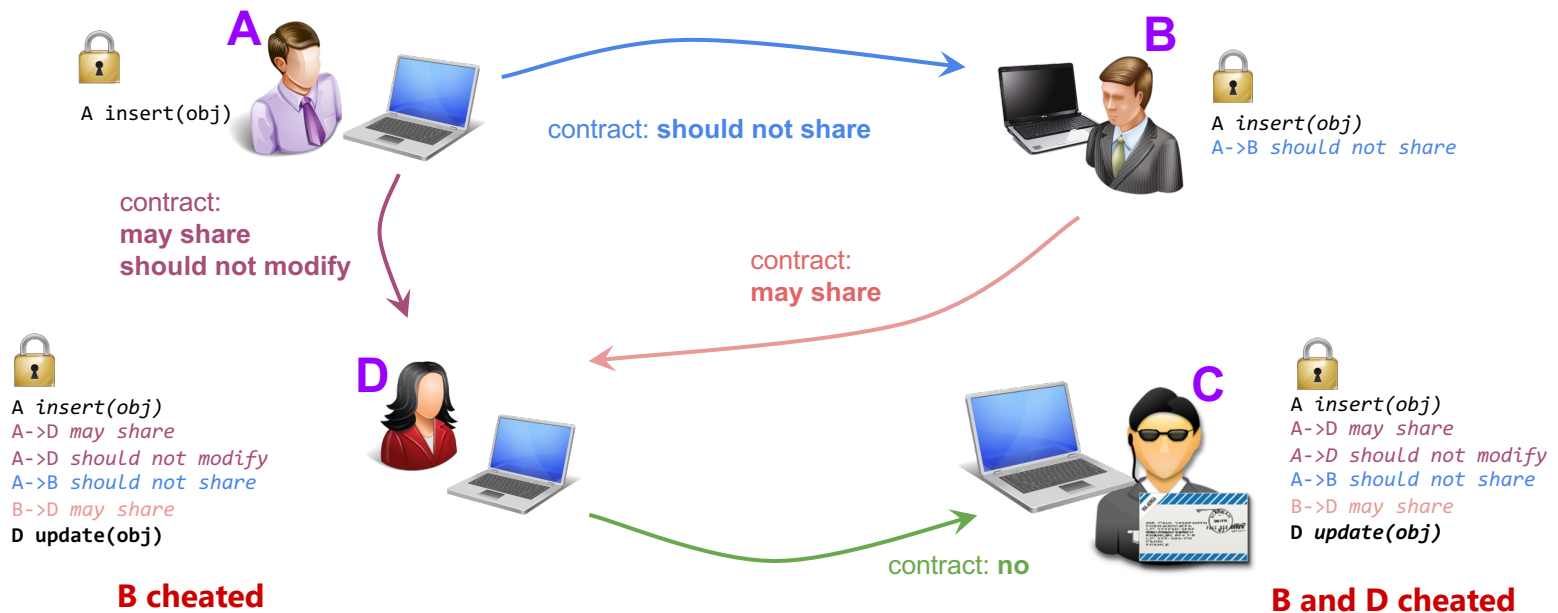


# Trust computation - contribution

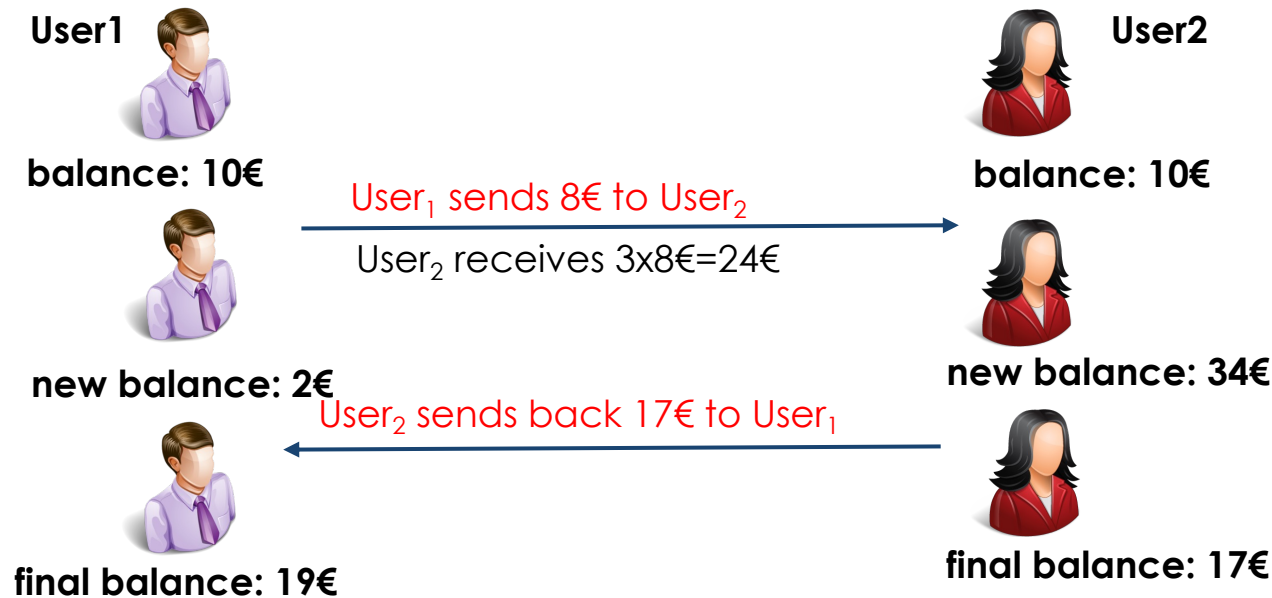
- Evaluate collaborators trust based on their past behavior
  - Contract-based collaborative editing
  - Trust game

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

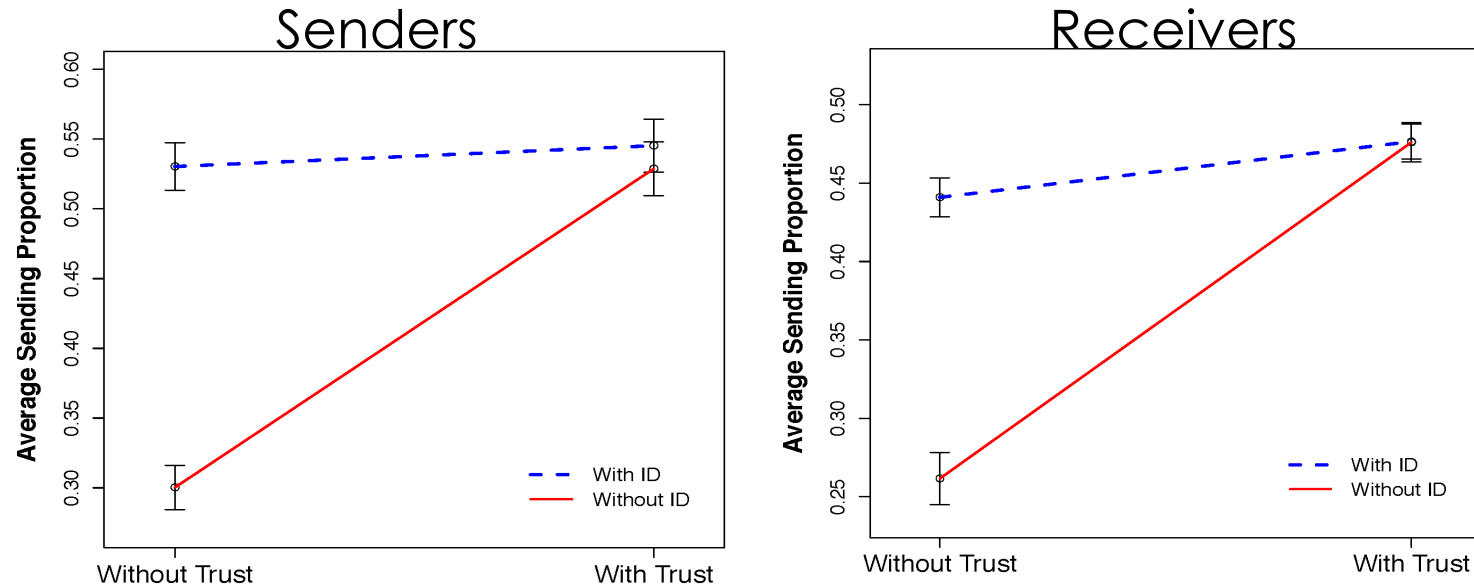
$$send\_proportion_t = \frac{sending\_amount_t}{max\_sending\_amount}$$

- 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/>)

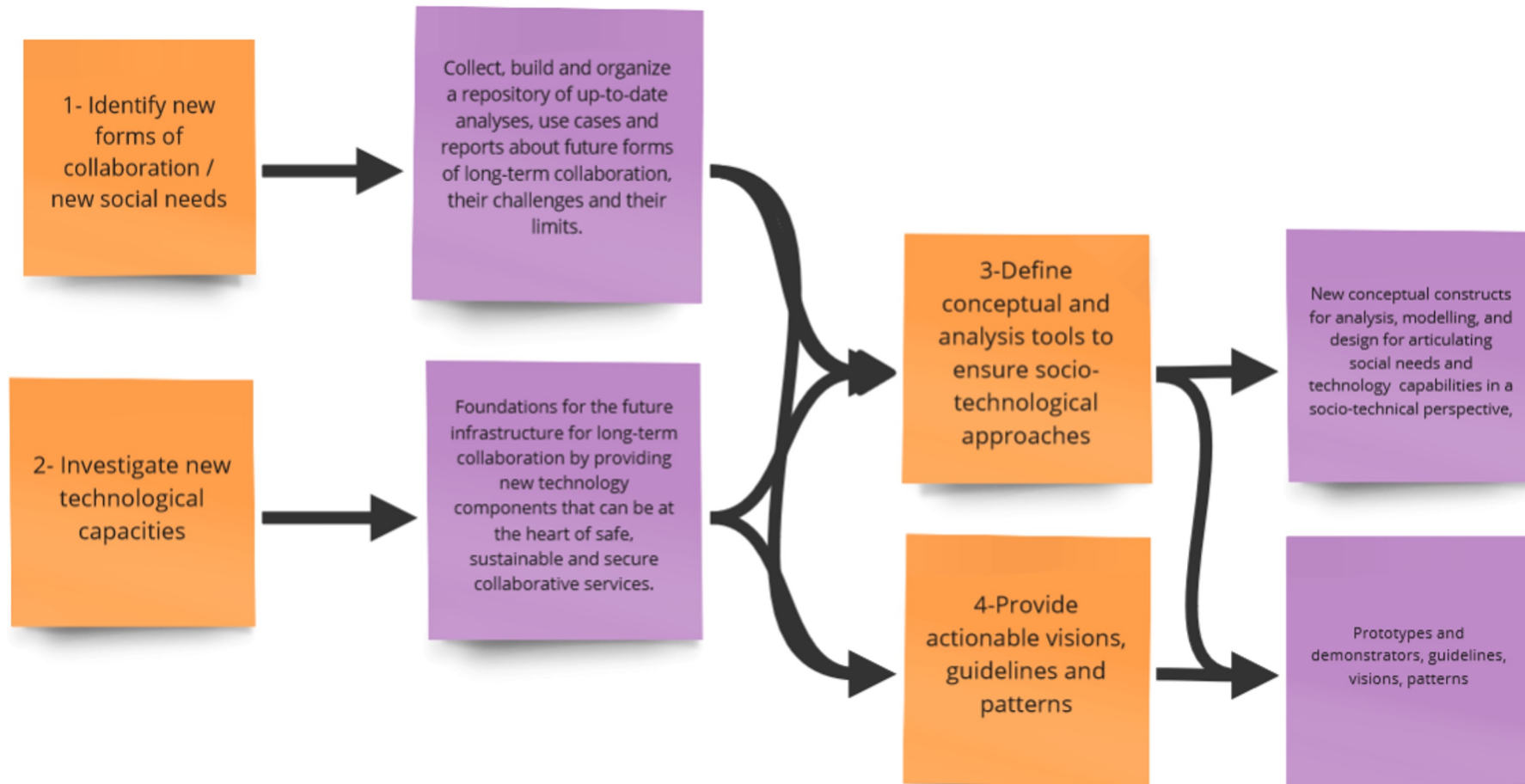
## PILOT – Practices and infrastructure for long term collaboration

- 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  
annotation  
concurrent  
trust

real-time  
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  
performance  
inter-document  
co-authoring

# References

- **[AI123]** Quantifying the Performance of Conflict-free Replicated Data Types in InterPlanetary File System. Q. Acher, C.-L. Ignat, S. Ibrahim. DICG@Middleware 2023
- **[AMO113]** Supporting Adaptable Granularity of Changes for Massive Scale Collaborative Editing. L. André, S. Martin, G. Oster, C.-L. Ignat. CollaborateCom 2013.
- **[ASB18]** Delta state replicated data types. P. S. Almeida, A. Shoker, C. Baquero. Journal of Parallel and Distributed Computing, 2018
- **[B00]** Brewer, E.A. “Towards robust distributed systems”. In Proc. of PODC, 2000.
- **[BDM95]** Trust, social history, and reciprocity. J. Berg, J. Dickhaut, and K. McCabe, Games and Econ. Behav.1995.
- **[DI16a]** Performance of real-time collaborative editors at large scale: User perspective. Q. V. Dang, C.-L. Ignat. Networking 2016
- **[DI16b]** Computational Trust Model for Repeated Trust Games. Q. V. Dang, C.-L. Ignat. Trustcom 2016
- **[EG89]** Concurrency Control in GroupWare Systems, C.A. Ellis and S.J. Gibbs. ACM SIGMOD Record 18(2), 1989.
- **[EGR91]** Groupware: Some issues and experiences, C.A. Ellis, S. J. Gibbs and G. Rein, Communications of the ACM,1991

# References

- **[IAO21]** Enhancing rich content wikis with real-time collaboration. C.-L. Ignat, L. André, G. Oster. *Concurr. Comput. Pract. Exp.* 2021
- **[ID21]** Users trust assessment based on their past behavior in large scale collaboration. C.-L. Ignat, Q.-V. Dang. *ICCP* 2021
- **[IDS19]** The influence of trust score on cooperative behavior. C.-L. Ignat, Q.-V. Dang, and V. L. Shalin. *ACM Trans. Internet Technol.* 2019
- **[IEB24]** Synql: A CRDT-based Approach for Replicated Relational Databases with Integrity Constraints. C.-L. Ignat, V. Elvinger, H. Ba. *DAIS* 2024
- **[IOFSC15]** How Do User Groups Cope with Delay in Real-Time Collaborative Note Taking. C.-L. Ignat, G. Oster, O. Fox, V. L. Shalin, F. Charoy. *ECSCW* 2015
- **[J88]** GroupWare: Computer Support for Business Teams. R. Johansen. The Free Press, New York, NY, USA, 1988.
- **[L21]** Confiance dans les situations de travail collaboratifs médiatisés par des environnements numériques. B. Linot. Thèse de doctorat, Univ. de Lorraine, 2021
- **[NEOIC17]** MUTE: A Peer-to-Peer Web-based Real-time Collaborative Editor. M. Nicolas, V. Elvinger, G. Oster, C.-L. Ignat, F. Charoy. *ECSCW*, 2017

# References

- **[NI18]** An Analysis of Merge Conflicts and Resolutions in Git-Based Open Source Projects. H. L. Nguyen, C.-L. Ignat. Journal of CSCW, 2018
- **[PIFTI23]** Design of an Efficient Distributed Delivery Service for Group Key Agreement Protocols. L. Paillat, C.-L. Ignat, D. Frey, M. Turuani, A. Ismail. FPS 2023
- **[PMSL09]** A commutative replicated data type for cooperative editing, N. Preguica, M. Joan, M. Shapiro, and M. Letia. ICDCS 2009.
- **[RIP23]** Access control based on CRDTs for Collaborative Distributed Applications. P.-A. Rault, C.-L. Ignat, O. Perrin. TrustCom 2023
- **[SPBZ11]** Conflict-free Replicated Data Types, M. Shapiro, N. Preguica, C. Baquero, M. Zawirski. Research Report, RR-7687, INRIA, 2011
- **[TI11]** H. T. T. Truong, C.-L. Ignat. Log Auditing for Trust Assessment in Peer-to-Peer Collaboration. ISPDC 2011
- **[TIBM11]** A contract-extended push-pull-clone model. H. T. T. Truong, C.-L. Ignat, M.-R. Bouguelia, P. Molli. CollaborateCom 2011
- **[TIM12]** Authenticating operation-based history in collaborative systems. H. T. T. Truong, C.-L. Ignat, P. Molli. GROUP 2012
- **[WUM09]** Logoot : a Scalable Optimistic Replication Algorithm for Collaborative Editing on P2P Networks, S. Weiss, P. Urso and P. Molli. ICDCS 2009.