Causal-Consistent Reversibility in a Tuple-Based Distributed Language

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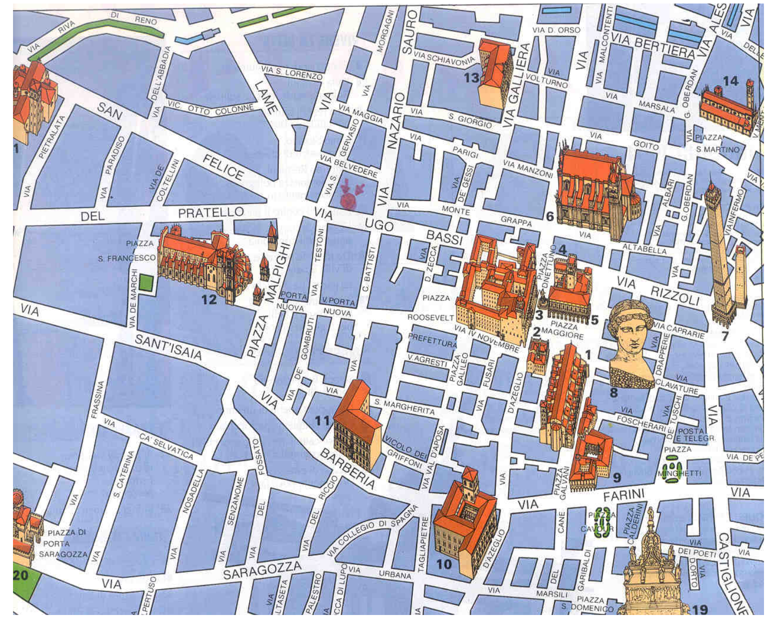
Joint work with Elena Giachino, Ivan Lanese and Claudio Mezzina

Map of the talk

- Reversibility
- Klaim
- Uncontrolled reversibility in Klaim
- Controlling reversibility: **roll** operator
- Conclusions



What is reversibility?

The possibility of executing a computation both in the standard, forward direction, and in the backward direction, going back to a past state

- Reversibility everywhere
  - chemistry/biology
  - quantum computing
  - state space exploration
  - …

Our aim

- We want to exploit reversibility for programming reliable concurrent/distributed systems
  - To make a system reliable we want to avoid "bad" states
  - If a bad state is reached, reversibility allows to go back to some past state
- Understanding reversibility is the key to
  - Understand existing patterns for programming reliable systems, e.g. checkpointing, rollback-recovery, transactions, …
  - Combine and improve them
  - Develop new patterns

Reverse execution of a sequential program

- Recursively undo the last step
  - Computations are undone in reverse order
  - To reverse A;B reverse B, then reverse A

- We want the Loop Lemma to hold
  - From state S, doing A and then undoing A should lead back to S
  - From state S, undoing A (if A is in the past) and then redoing A should lead back to S

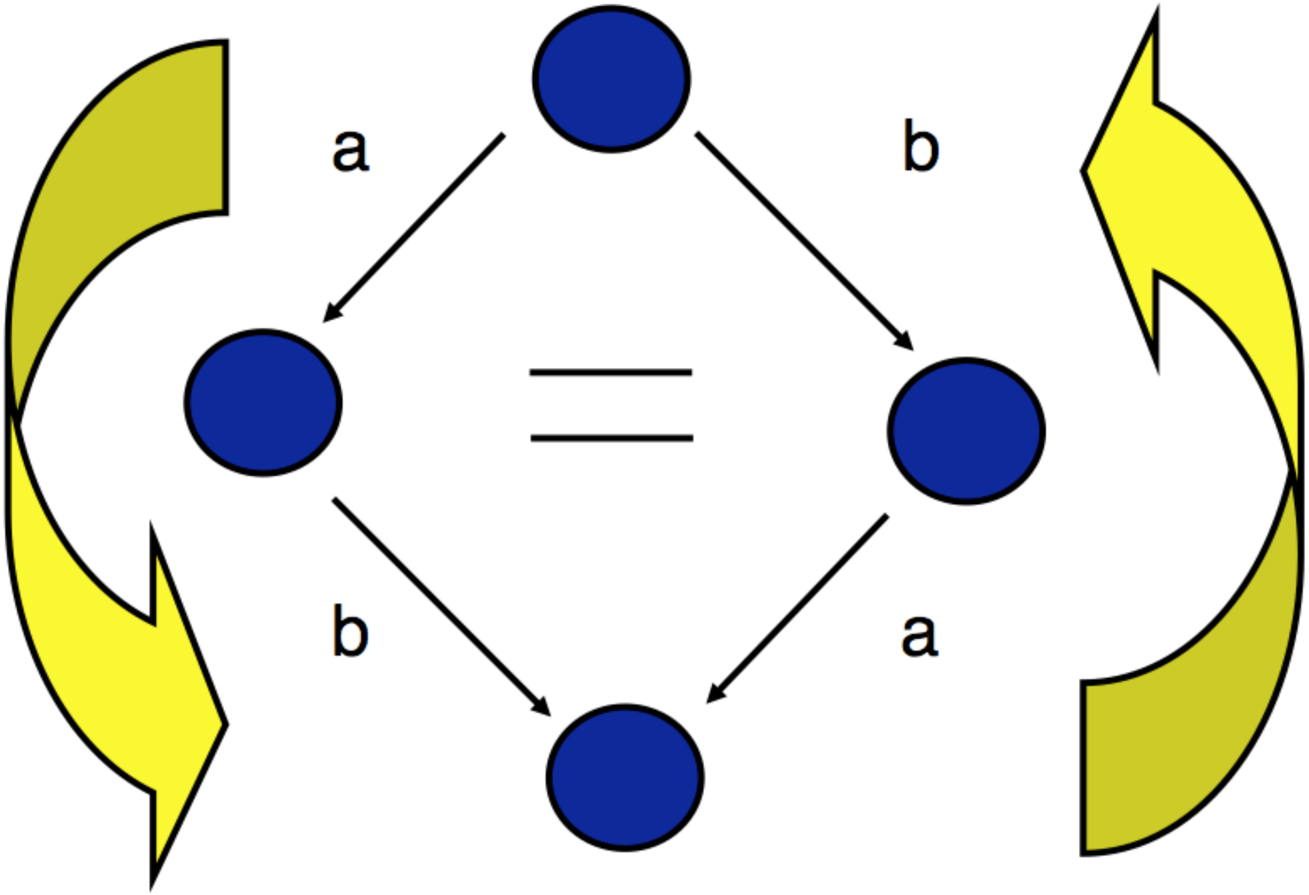
Different approaches to reversibility

- Undoing computational steps, not necessarily easy
  - Computation steps may cause loss of information
  - X=5 causes the loss of the past value of X
- Considering languages which are reversible
  - Featuring only actions that cause no loss of information
- Taking a language which is not reversible and make it reversible
  - One should save information on the past configurations
  - X=5 becomes reversible by recording the old value of X

Reversibility and concurrency

- In a sequential setting, recursively undo the last action
- Which is the last action in a concurrent setting?
  - Many possibilities
  - For sure, if an action A caused an action B, A could not be the last one
- Causal-consistent reversibility: recursively undo any action whose consequences (if any) have already been undone

Causal-consistent reversibility



Reversibility and concurrency

- Causal-consistent reversibility allows one to distinguish non-determinism from concurrency

- Two sequential actions whose order is chosen nondeterminstically should be reversed in reverse order

- Two concurrent actions can be reversed in any order
  – Choosing an interleaving for them is an arbitrary choice
  – It should have no impact on the possible reverse behaviors

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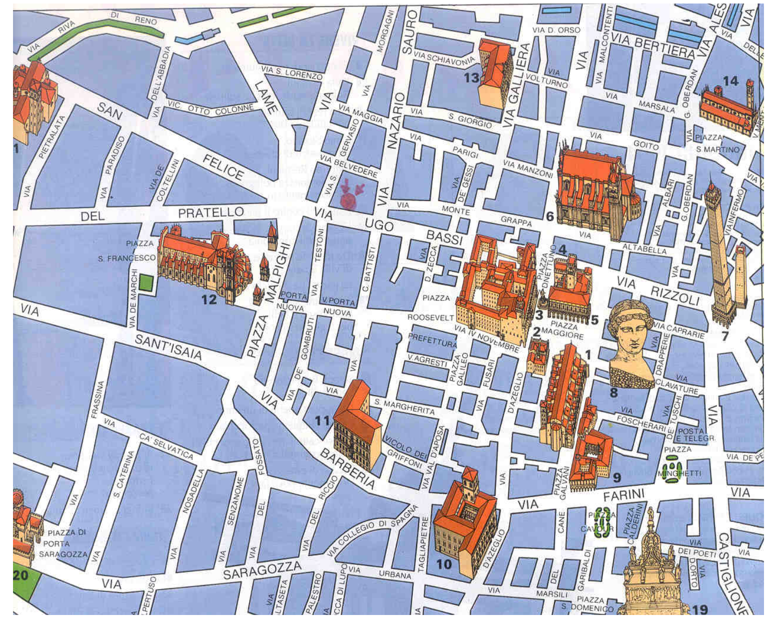

Klaim

- Coordination language based on distributed tuple spaces
  - Linda operations for creating and accessing tuples
  - Tuples accessed via pattern-matching
- Klaim nets composed by distributed nodes containing processes and data (tuples)
- We consider a subset of Klaim called μKlaim

μKlaim syntax

$$
\begin{array}{rlllllllll}
\text{(Nets)} & N & ::= & \mathbf{0} & \mid & l :: C & \mid & N_1 \parallel N_2 & \mid & (\nu l)N \\
\text{(Components)} & C & ::= & \langle et \rangle & \mid & P & \mid & C_1 \mid C_2 & & \\
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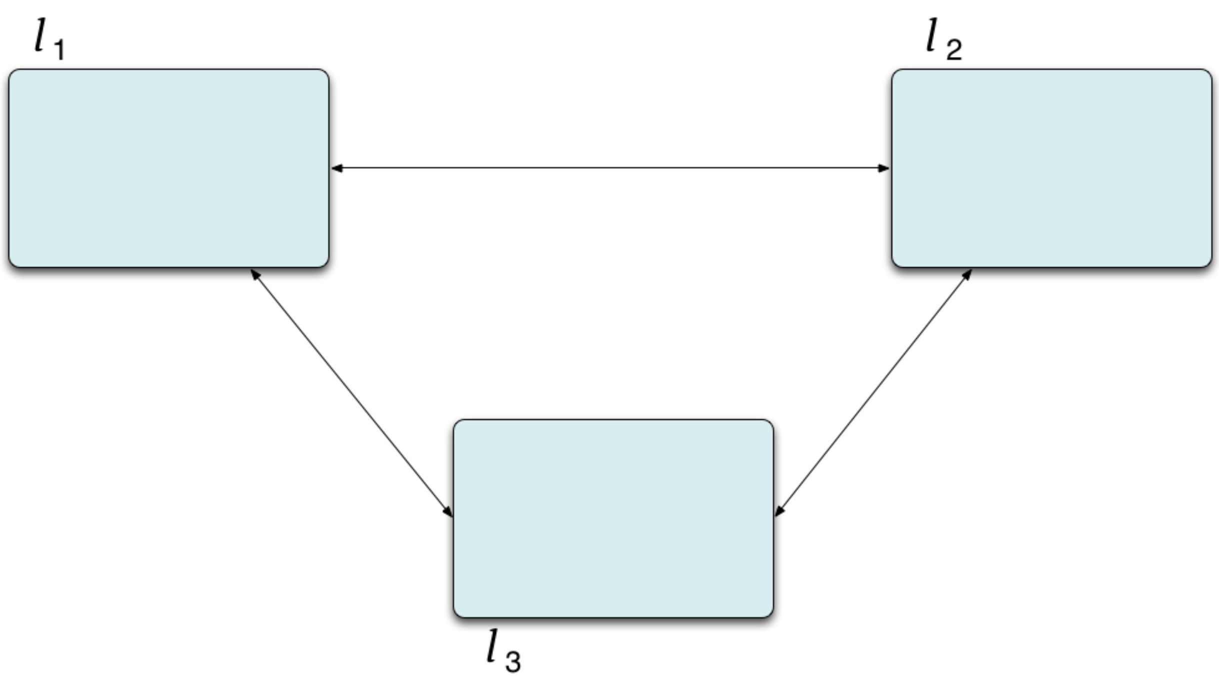

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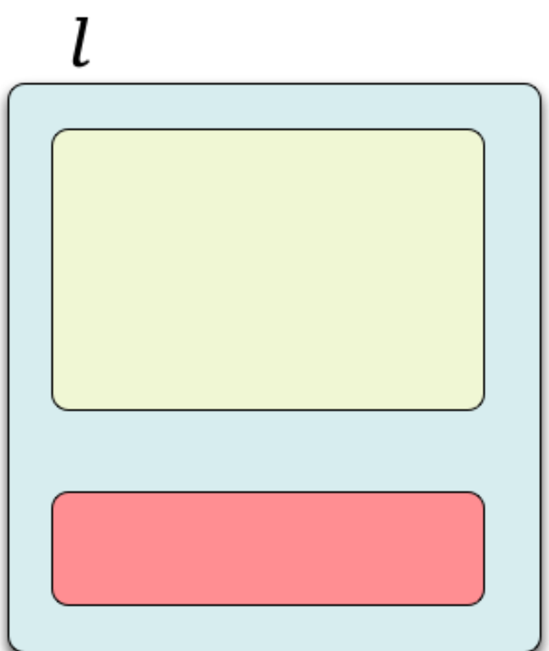

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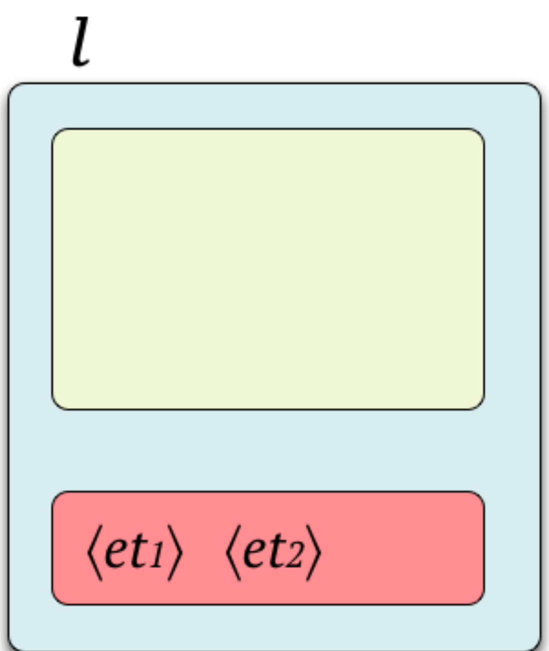

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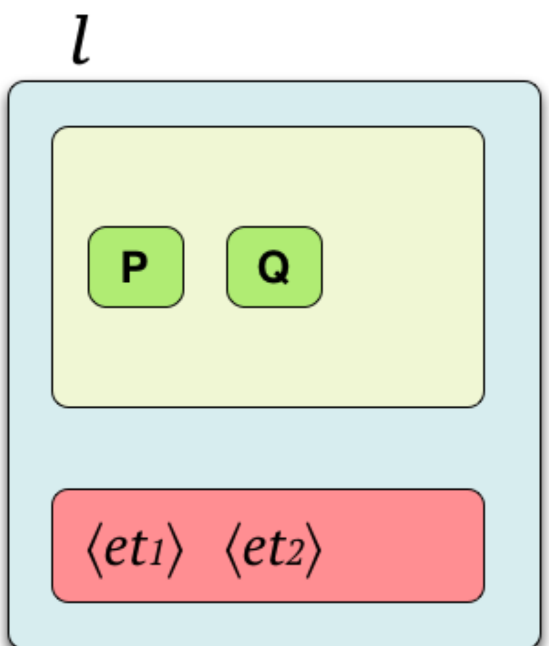

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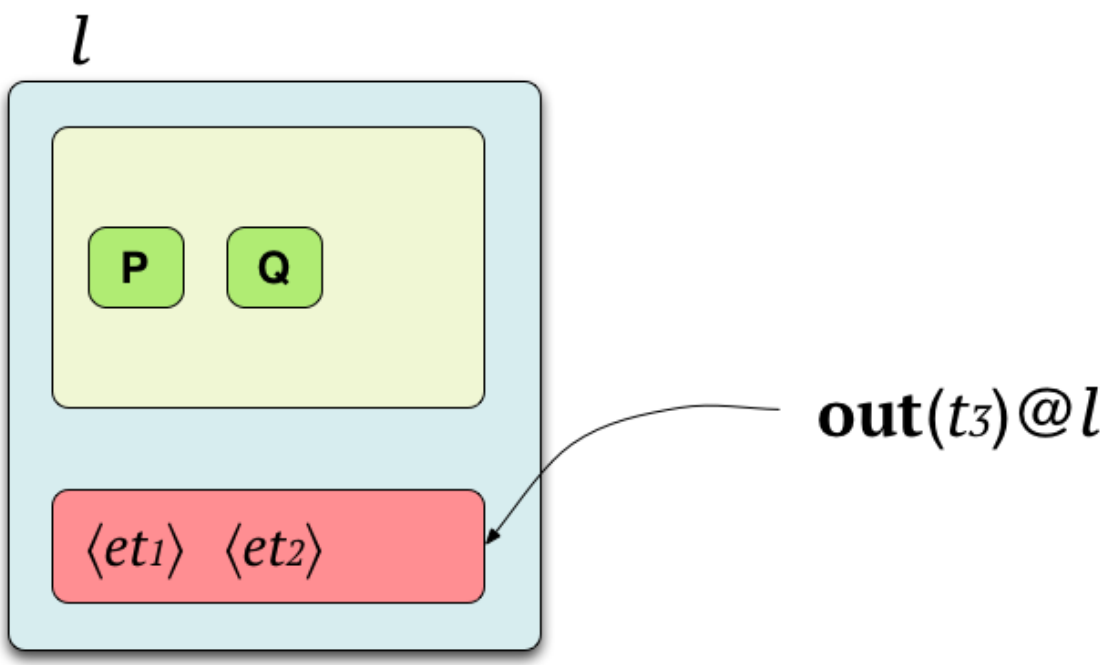

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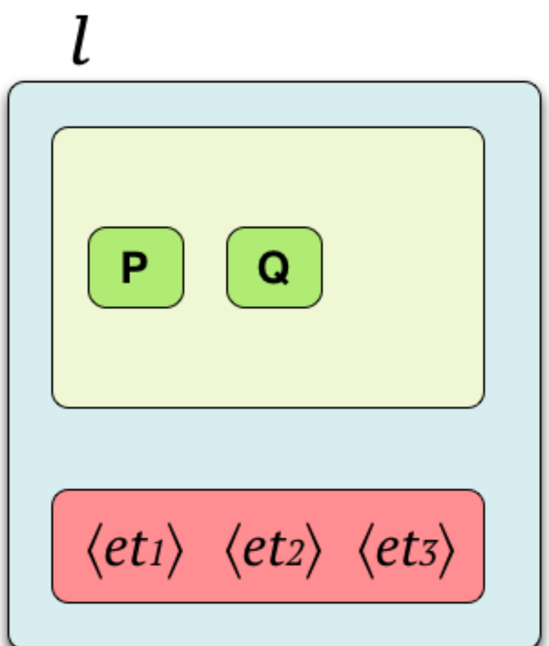

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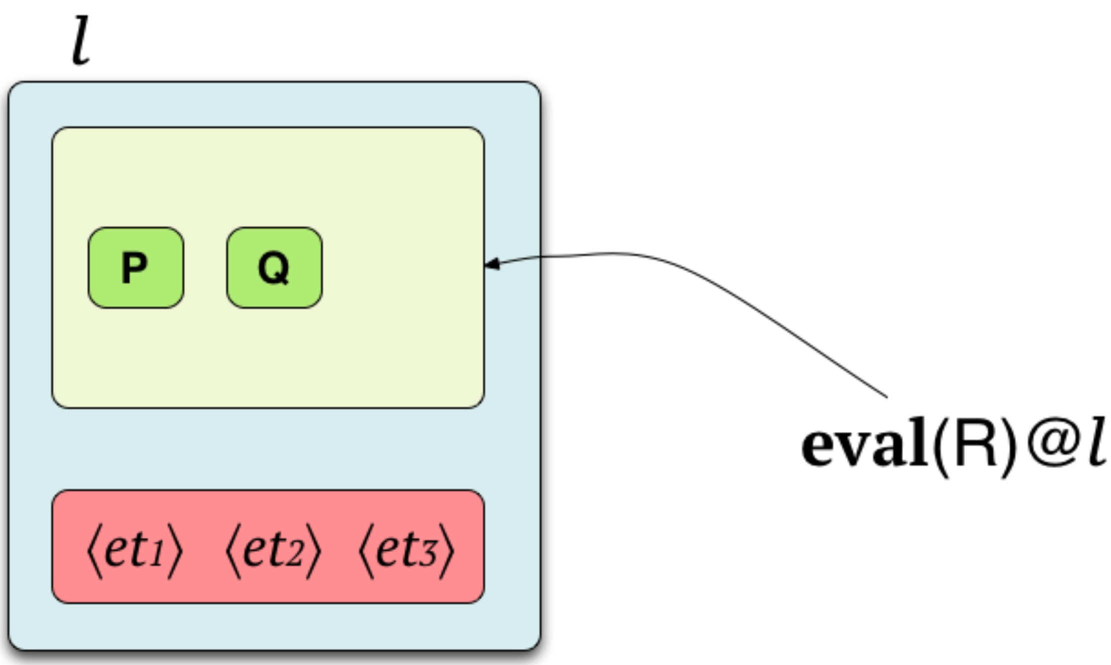

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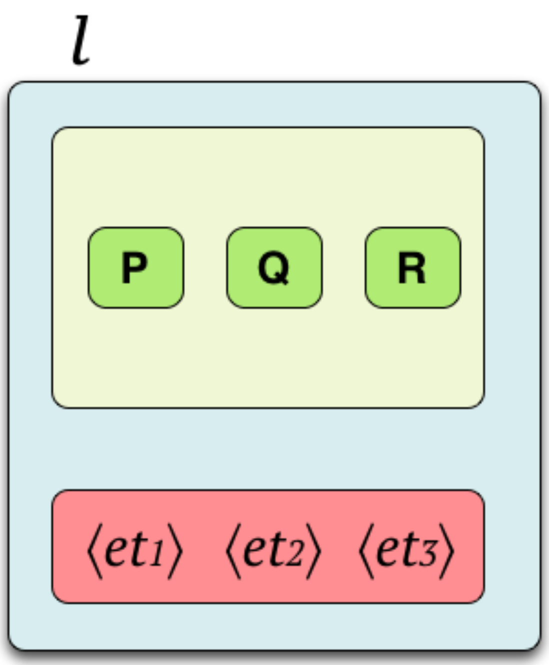

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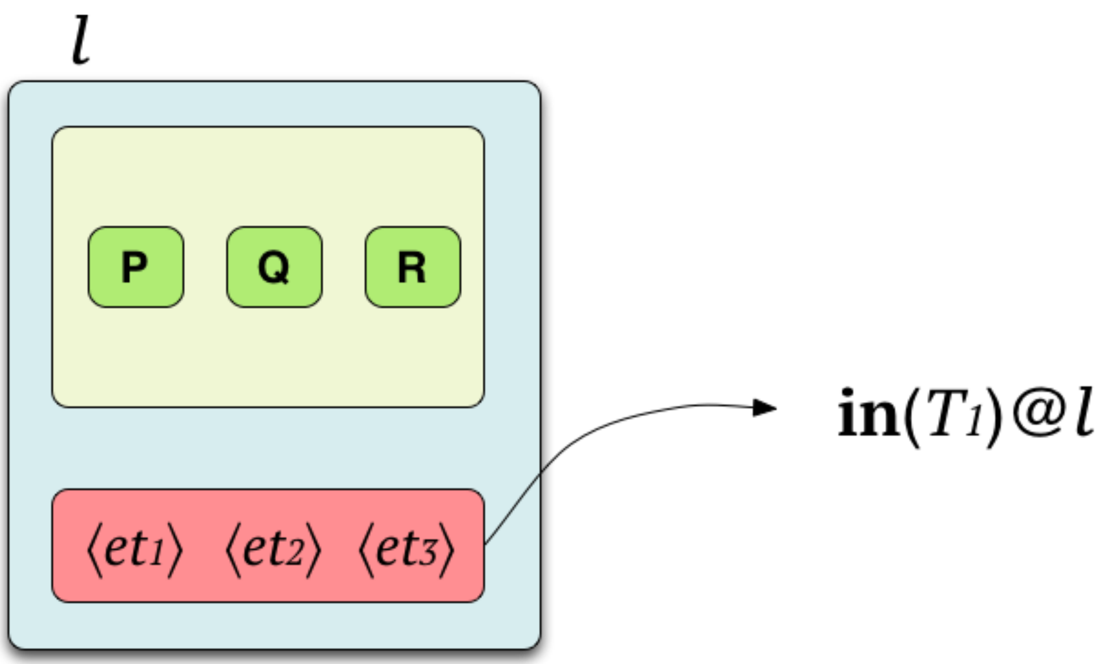

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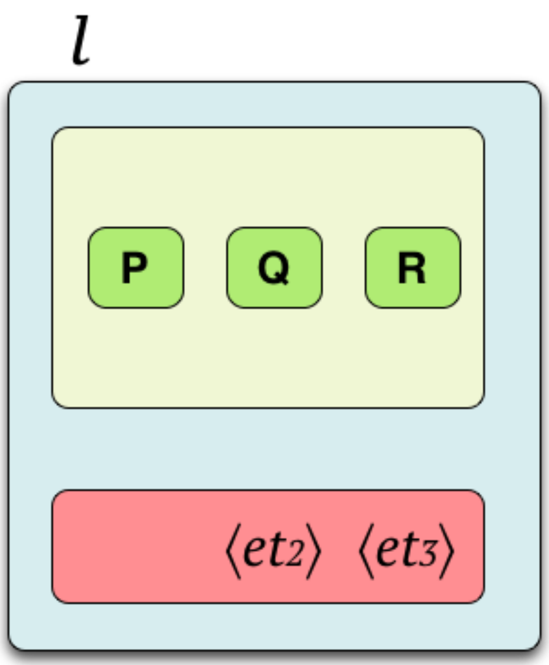

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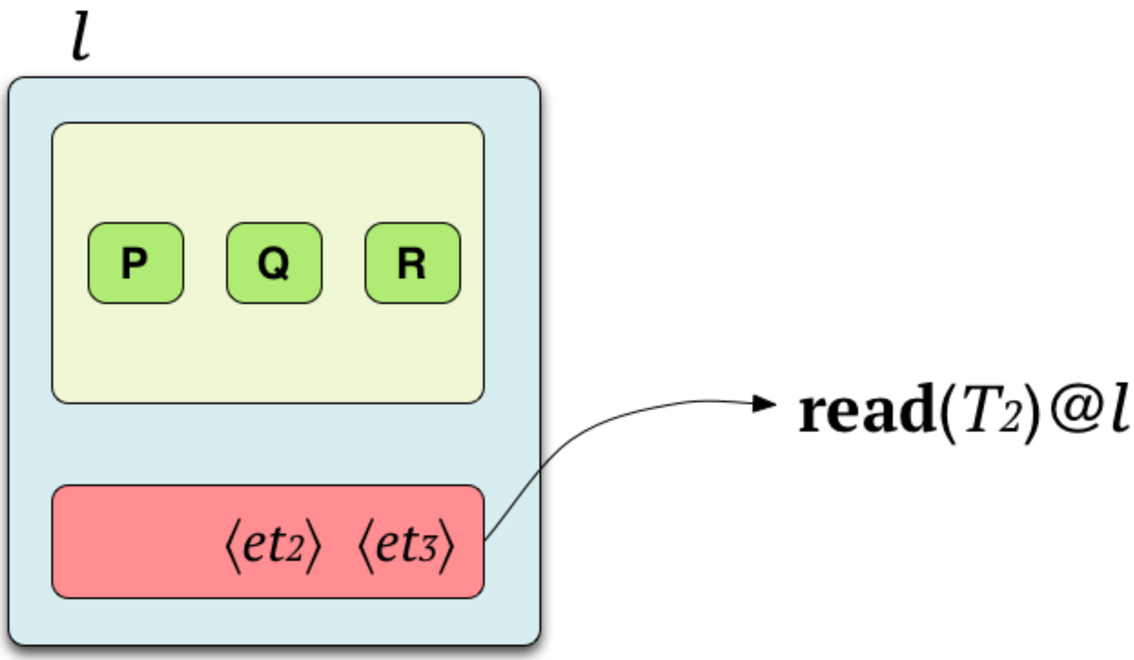

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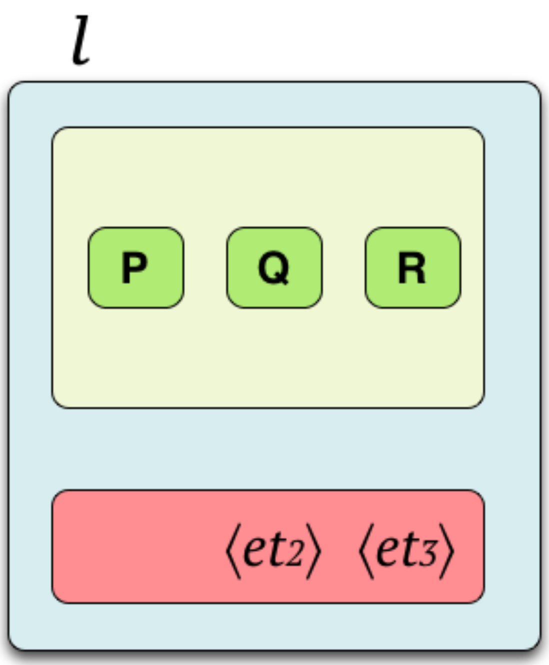

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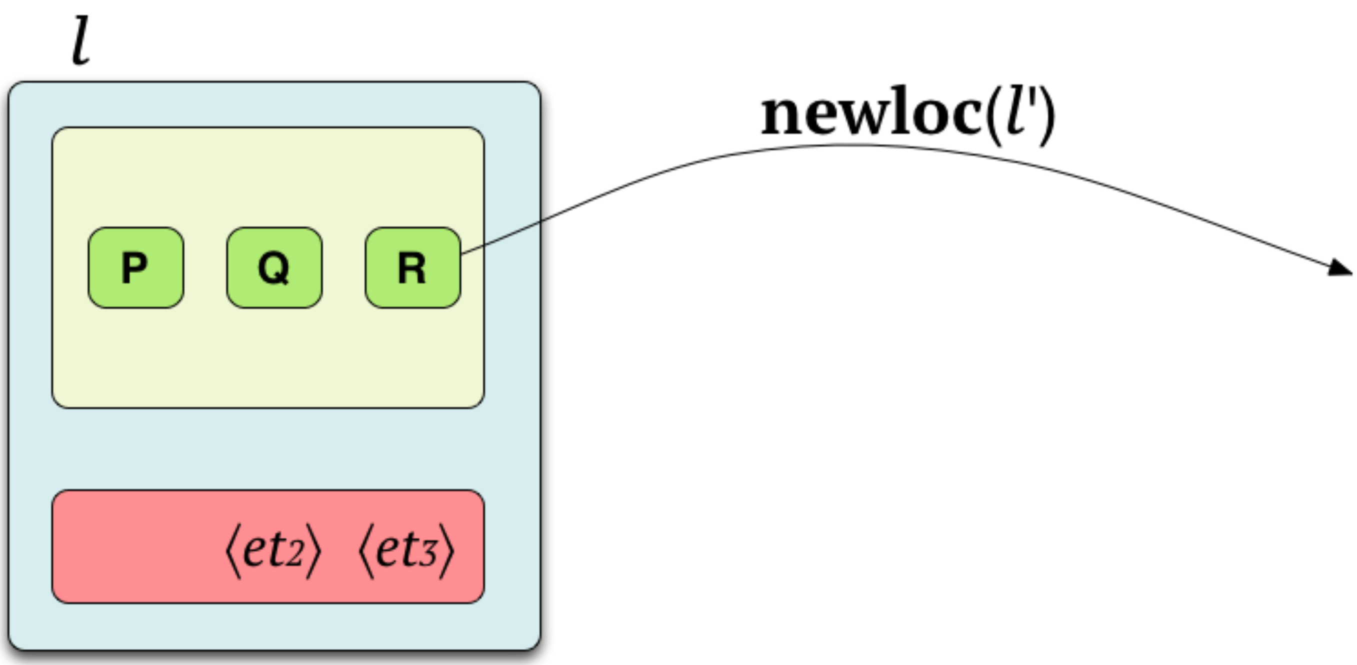

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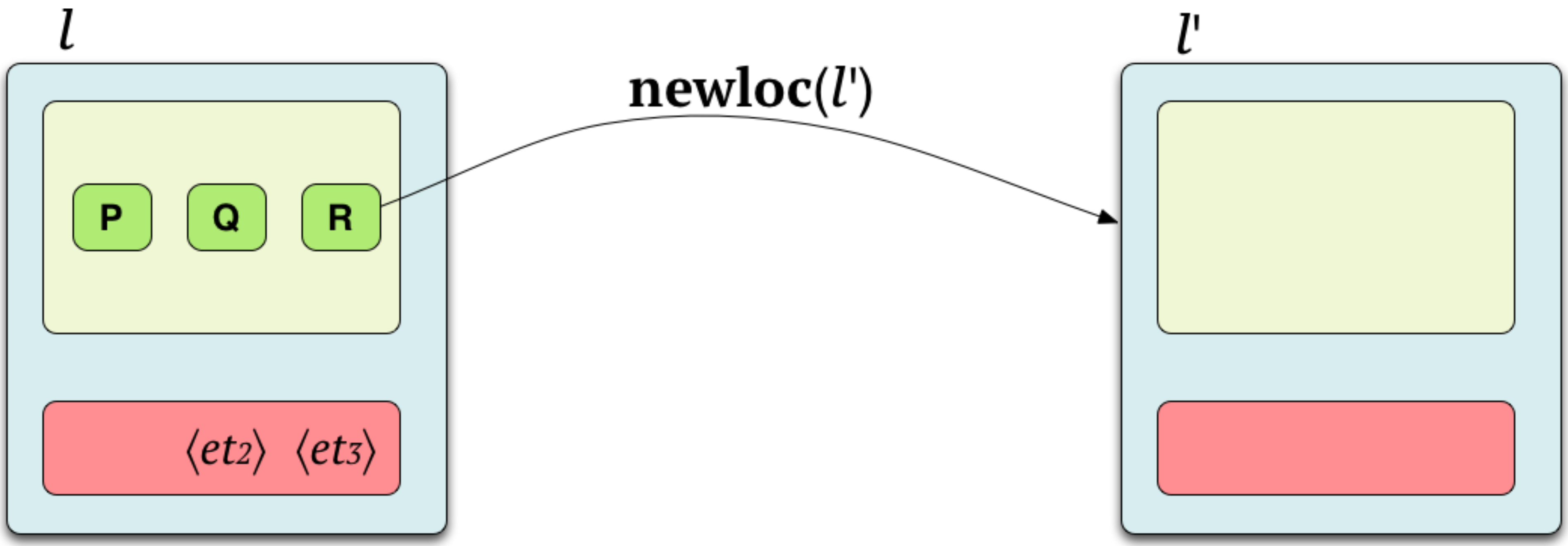

μKlaim semantics

$$\frac{[\![t]\!] = et}{l :: \mathbf{out}(t)@l'.P \;\; \| \;\; l' :: \mathbf{nil} \;\mapsto\; l :: P \parallel l' :: \langle et \rangle} \; (Out)$$

μKlaim semantics

$$\frac{[\![t]\!] = et}{l :: \mathbf{out}(t)@l'.P \;\|\; l' :: \mathbf{nil} \;\mapsto\; l :: P \,\|\, l' :: \langle et \rangle} \;(Out)$$

$$\frac{match([\![T]\!], et) = \sigma}{l :: \mathbf{in}(T)@l'.P \;\|\; l' :: \langle et \rangle \;\mapsto\; l :: P\sigma \,\|\, l' :: \mathbf{nil}} \;(In)$$

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$$\frac{match([\![T]\!], et) = \sigma}{l :: \mathbf{read}(T)@l'.P \;\|\; l' :: \langle et \rangle \;\mapsto\; l :: P\sigma \,\|\, l' :: \langle et \rangle} \; (Read)$$

$$l :: \mathbf{newloc}(l').P \;\mapsto\; (\nu l')(l :: P \,\|\, l' :: \mathbf{nil}) \;\; (New)$$

$$l :: \mathbf{eval}(Q)@l'.P \;\|\; l' :: \mathbf{nil} \;\mapsto\; l :: P \,\|\, l' :: Q \;\; (Eval)$$

μKlaim semantics

Evaluation-closed relation

A relation is evaluation closed if it is closed under active contexts

$$N1 \longmapsto N1' \text{ implies } N1 \parallel N2 \longmapsto N1' \parallel N2 \text{ and } (\nu l)\, N1 \longmapsto (\nu l) N1'$$

and under structural congruence

$$N \equiv M \longmapsto M' \equiv N' \text{ implies } N \longmapsto N'$$

μKlaim semantics

The μKlaim reduction relation $\longmapsto$ is the smallest evaluation-closed relation satisfying the rules in previous slide

Example

$$\begin{tikzcd}[column sep=small]
& l_1 :: \langle \mathit{foo} \rangle \parallel l_2 :: \mathbf{read}(\mathit{foo})@l_1.P \parallel l_3 :: \mathbf{read}(\mathit{foo})@l_1.P' \arrow[dl] \arrow[dr] & \\
l_1 :: \langle \mathit{foo} \rangle \parallel l_2 :: \mathbf{read}(\mathit{foo})@l_1.P \parallel l_3 :: P' \arrow[dr] & & l_1 :: \langle \mathit{foo} \rangle \parallel l_2 :: P \parallel l_3 :: \mathbf{read}(\mathit{foo})@l_1.P' \arrow[dl] \\
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\end{tikzcd}$$

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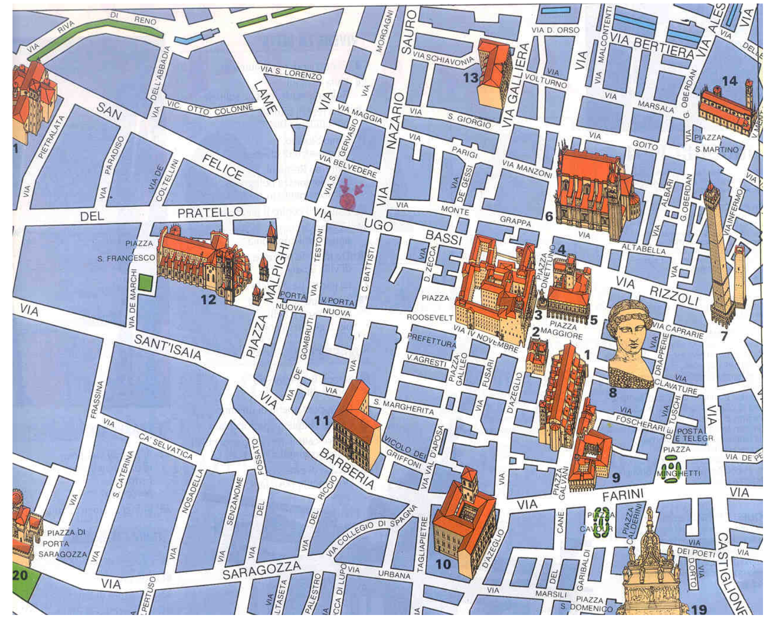

Making μKlaim reversible

- We define RμKlaim, an extension of μKlaim allowing:
  - *forward* actions, modeling μKlaim actions
  - *backward* actions, undoing them
- Some new problems arise
- Read dependencies
  - Two **read**s on the same tuple should not create dependences
  - If the **out** creating the tuple is undone then **read**s on the tuple should be undone too
- Localities
  - Localities are now resources and establish dependences
  - To undo a **newloc** one has to undo all the operations on the created locality

RμKlaim syntax

$$
\begin{array}{rcl}
\text{(Nets)}\ N & ::= & \mathbf{0} \quad | \quad l :: C \quad | \quad l :: \mathbf{empty} \quad | \quad N_1 \parallel N_2 \quad | \quad (\nu z)N \\
\text{(Components)}\ C & ::= & k : \langle et \rangle \quad | \quad k : P \quad | \quad C_1 \mid C_2 \quad | \quad \mu \quad | \quad k_1 \prec (k_2, k_3) \\
\text{(Processes)}\ P & ::= & \mathbf{nil} \quad | \quad a.P \quad | \quad P_1 \mid P_2 \quad | \quad A \\
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 & | & \mathbf{in}(T)@\ell \quad | \quad \mathbf{read}(T)@\ell \quad | \quad \mathbf{newloc}(l) \\
\text{(Memories)}\ \mu & ::= & [k : \mathbf{out}(t)@l; k''; k'] \quad | \quad [k : \mathbf{in}(T)@l.P; h : \langle et \rangle; k'] \\
 & | & [k : \mathbf{read}(T)@l.P; h; k'] \quad | \quad [k : \mathbf{newloc}(l); k'] \\
 & | & [k : \mathbf{eval}(Q)@l; k''; k']
\end{array}
$$

RμKlaim semantics – tuple operators

$$\frac{[\![t]\!] = et}{\begin{array}{l} l :: k : \mathbf{out}(t)@l'.P \;\; \| \;\; l' :: \mathbf{empty} \\ \;\mapsto_r \;\; (\nu k', k'')\,(\,l :: k' : P \mid [k : \mathbf{out}(t)@l'; k''; k'] \;\; \| \;\; l' :: k'' : \langle et \rangle\,) \end{array}} \; (Out)$$

RμKlaim semantics – tuple operators

$$\frac{[\![t]\!] = et}{\begin{array}{l} l :: k : \mathbf{out}(t)@l'.P \ \parallel \ l' :: \mathbf{empty} \\ \mapsto_r \ (\nu k', k'')\,(\, l :: k' : P \mid [k : \mathbf{out}(t)@l'; k''; k'] \ \parallel \ l' :: k'' : \langle et \rangle\,) \end{array}} \quad \textit{(Out)}$$

$$\begin{array}{l} (\nu k'')\,(\, l :: k' : P \mid [k : \mathbf{out}(t)@l'; k''; k'] \ \parallel \ l' :: k'' : \langle et \rangle\,) \\ \rightsquigarrow_r \ l :: k : \mathbf{out}(t)@l'.P \ \parallel \ l' :: \mathbf{empty} \end{array} \quad \textit{(OutRev)}$$

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$$\begin{array}{l} (\nu k'')\,(\, l :: k' : P \mid [k : \mathbf{out}(t)@l'; k''; k'] \;\parallel\; l' :: k'' : \langle et \rangle\,) \\ \rightsquigarrow_r \; l :: k : \mathbf{out}(t)@l'.P \;\parallel\; l' :: \mathbf{empty} \end{array} \quad (OutRev)$$

$$\frac{match([\![T]\!], et) = \sigma}{\begin{array}{l} l :: k : \mathbf{in}(T)@l'.P \;\parallel\; l' :: h : \langle et \rangle \\ \mapsto_r \; (\nu k')\, l :: k' : P\sigma \mid [k : \mathbf{in}(T)@l'.P; h : \langle et \rangle; k'] \;\parallel\; l' :: \mathbf{empty} \end{array}} \quad (In)$$

$$\begin{array}{l} l :: k' : Q \mid [k : \mathbf{in}(T)@l'.P; h : \langle et \rangle; k'] \;\parallel\; l' :: \mathbf{empty} \\ \rightsquigarrow_r \; l :: k : \mathbf{in}(T)@l'.P \;\parallel\; l' :: h : \langle et \rangle \end{array} \quad (InRev)$$

$$\frac{match([\![T]\!], et) = \sigma}{\begin{array}{l} l :: k : \mathbf{read}(T)@l'.P \;\parallel\; l' :: h : \langle et \rangle \\ \mapsto_r \; (\nu k')\, l :: k' : P\sigma \mid [k : \mathbf{read}(T)@l'.P; h; k'] \;\parallel\; l' :: h : \langle et \rangle \end{array}} \quad (Read)$$

$$\begin{array}{l} l :: k' : Q \mid [k : \mathbf{read}(T)@l'.P; h; k'] \;\parallel\; l' :: h : \langle et \rangle \\ \rightsquigarrow_r \; l :: k : \mathbf{read}(T)@l'.P \;\parallel\; l' :: h : \langle et \rangle \end{array} \quad (ReadRev)$$

RμKlaim semantics – distribution operators

$$\begin{array}{ll} l :: k : \mathbf{newloc}(l').P & \\ \mapsto_r \ (\nu l')\,(\,(\nu k')\,l :: k' : P \mid [k : \mathbf{newloc}(l'); k'] \ \ \| \ \ l' :: \mathbf{empty}\,) & \textit{(New)} \end{array}$$

$$\begin{array}{ll} (\nu l')\,(\,l :: k' : P \mid [k : \mathbf{newloc}(l'); k'] \ \ \| \ \ l' :: \mathbf{empty}\,) & \\ \rightsquigarrow_r \ l :: k : \mathbf{newloc}(l').P & \textit{(NewRev)} \end{array}$$

$$\begin{array}{ll} l :: k : \mathbf{eval}(Q)@l'.P \ \ \| \ \ l' :: \mathbf{empty} & \\ \mapsto_r \ (\nu k', k'')\,(\,l :: k' : P \mid [k : \mathbf{eval}(Q)@l'; k''; k'] \ \ \| \ \ l' :: k'' : Q\,) & \textit{(Eval)} \end{array}$$

$$\begin{array}{ll} l :: k' : P \mid [k : \mathbf{eval}(Q)@l'; k''; k'] \ \ \| \ \ l' :: k'' : Q & \\ \rightsquigarrow_r \ l :: k : \mathbf{eval}(Q)@l'.P \ \ \| \ \ l' :: \mathbf{empty} & \textit{(EvalRev)} \end{array}$$

Example

$$l_1 :: k_1 : \langle foo \rangle \parallel l_2 :: k_2 : \mathbf{read}(foo)@l_1.P \\ \parallel l_3 :: k_3 : \mathbf{read}(foo)@l_1.P'$$

$$(\nu k_3')\ (l_1 :: k_1 : \langle foo \rangle \parallel l_2 :: k_2 : \mathbf{read}(foo)@l_1.P \\ \parallel l_3 :: k_3' : P' \mid [k_3 : \mathbf{read}(foo)@l_1.P'; k_1; k_3']\ )$$

$$(\nu k_2')\ (l_1 :: k_1 : \langle foo \rangle \\ \parallel l_2 :: k_2' : P \mid [k_2 : \mathbf{read}(foo)@l_1.P; k_1; k_2'] \\ \parallel l_3 :: k_3 : \mathbf{read}(foo)@l_1.P'\ )$$

$$(\nu k_2', k_3')\ (l_1 :: k_1 : \langle foo \rangle \\ \parallel l_2 :: k_2' : P \mid [k_2 : \mathbf{read}(foo)@l_1.P; k_1; k_2'] \\ \parallel l_3 :: k_3' : P' \mid [k_3 : \mathbf{read}(foo)@l_1.P'; k_1; k_3']\ )$$

Example

$$\begin{aligned} l_1 \ :: \ k_1 : \langle \mathit{foo} \rangle \ \| \ & l_2 \ :: \ k_2 : \mathbf{in}(\mathit{foo})@l_1.\mathbf{out}(\mathit{foo})@l_1.P \\ \| \ & l_3 \ :: \ k_3 : \mathbf{in}(\mathit{foo})@l_1.\mathbf{out}(\mathit{foo})@l_1.P' \end{aligned}$$

$$\Big\downarrow \text{execute } \mathbf{in} \text{ in } l_2$$

$$\Big\downarrow \text{execute } \mathbf{out} \text{ in } l_2$$

$$\Big\downarrow \text{execute } \mathbf{in} \text{ in } l_3$$

$$\Big\downarrow \text{execute } \mathbf{out} \text{ in } l_3$$

$$\begin{aligned} & (\nu k_2', k_2'', k_2''', k_3', k_3'', k_3''')(l_1 \ :: \ k_3''' : \langle \mathit{foo} \rangle \\ & \ \| \ l_2 \ :: \ k_2'' : P \ | \ [k_2 : \mathbf{in}(\mathit{foo})@l_1.\mathbf{out}(\mathit{foo})@l_1.P; k_1 : \langle \mathit{foo} \rangle; k_2'] \\ & \qquad\qquad\qquad | \ [k_2' : \mathbf{out}(\mathit{foo})@l_1; k_2'''; k_2''] \\ & \ \| \ l_3 \ :: \ k_3'' : P' \ | \ [k_3 : \mathbf{in}(\mathit{foo})@l_1.\mathbf{out}(\mathit{foo})@l_1.P'; k_2''' : \langle \mathit{foo} \rangle; k_3'] \\ & \qquad\qquad\qquad | \ [k_3' : \mathbf{out}(\mathit{foo})@l_1; k_3'''; k_3''] \ ) \end{aligned}$$

Example

$$l_1 :: k_1 : \langle foo \rangle \parallel l_2 :: k_2 : \mathbf{in}(foo)@l_1.\mathbf{out}(foo)@l_1.P$$
$$\parallel l_3 :: k_3 : \mathbf{in}(foo)@l_1.\mathbf{out}(foo)@l_1.P'$$

execute **in** in l_2

execute **out** in l_2

execute **in** in l_3

execute **out** in l_3

it needs $k_2''' : \langle foo \rangle$ in l_1 to perform a backward step

$$(\nu k_2', k_2'', k_2''', k_3', k_3'', k_3''')(l_1 :: k_3''' : \langle foo \rangle$$
$$\parallel l_2 :: k_2'' : P \mid [k_2 : \mathbf{in}(foo)@l_1.\mathbf{out}(foo)@l_1.P; k_1 : \langle foo \rangle; k_2']$$
$$\mid [k_2' : \mathbf{out}(foo)@l_1; k_2'''; k_2'']$$
$$\parallel l_3 :: k_3'' : P' \mid [k_3 : \mathbf{in}(foo)@l_1.\mathbf{out}(foo)@l_1.P'; k_2''' : \langle foo \rangle; k_3']$$
$$\mid [k_3' : \mathbf{out}(foo)@l_1; k_3'''; k_3''])$$

Properties

- The forward semantics of RμKlaim follows the semantics of μKlaim
- The Loop Lemma holds
  - i.e., each reduction in RμKlaim has an inverse
- RμKlaim is causally consistent
  - same approach of previous works
  - different technicalities (due to more complex causality structure)

Concurrency in RμKlaim

- Two transitions are concurrent unless
  - They use the same resource
  - At least one transition does not use it in read-only modality
- Resources defined by function λ on memories

$$
\begin{array}{rcl}
\lambda([k : \mathbf{out}(t)@l; k''; k']) & = & \{k, k', k'', \mathtt{r}(l)\} \\
\lambda([k : \mathbf{in}(T)@l.P; k'' : \langle et \rangle; k']) & = & \{k, k', k'', \mathtt{r}(l)\} \\
\lambda([k : \mathbf{read}(T)@l.P; k''; k']) & = & \{k, \mathtt{r}(k''), k', \mathtt{r}(l)\} \\
\lambda([k : \mathbf{eval}(Q)@l; k''; k']) & = & \{k, k', k'', \mathtt{r}(l)\} \\
\lambda([k : \mathbf{newloc}(l); k']) & = & \{k, k', l\}
\end{array}
$$

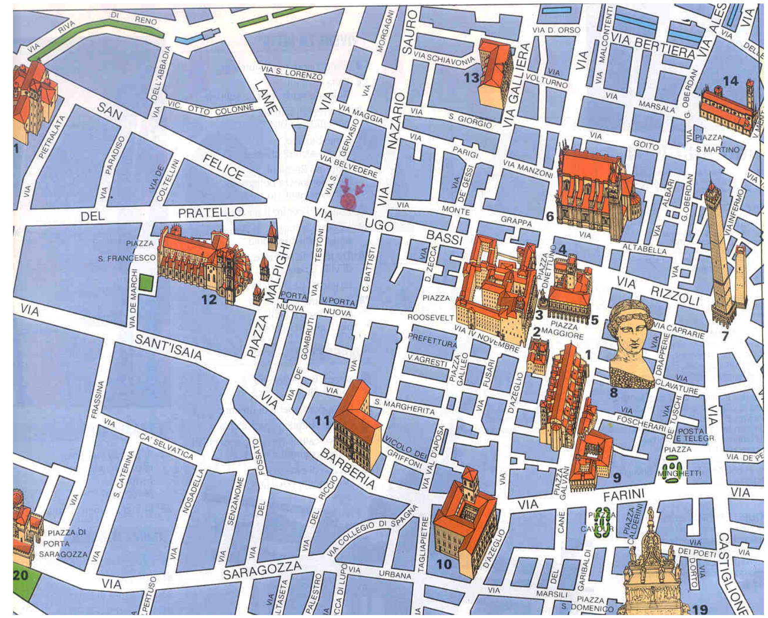
- **Read** uses the tuple in read-only modality
- All primitives but **newloc** use the locality name in read-only modality

Causal consistency

- *Causal equivalence* identifies traces that differ only for
  - swaps of concurrent transitions
  - simplifications of inverse transitions

- *Casual consistency*: there is a unique way to go from one state to another one up to causal equivalence
  - causal equivalent traces can be reversed in the same ways
  - traces which are not causal equivalent lead to distinct nets

Map of the talk



- Reversibility
- Klaim
- Uncontrolled reversibility in Klaim
- Controlling reversibility: **roll** operator
- Conclusions

Controlling reversibility

- Uncontrolled reversibility is not suitable for programming

- We use reversibility to define a **roll** operator
  - To undo a given past action
  - And all its consequences

- We call CRμKlaim the extension of μKlaim with **roll**

CRμKlaim syntax

$$
\begin{array}{rlcl}
\text{(Nets)} & N & ::= & \mathbf{0} \quad | \quad l :: C \quad | \quad l :: \mathbf{empty} \quad | \quad N_1 \parallel N_2 \quad | \quad (\nu z)N \\
\text{(Components)} & C & ::= & k : \langle et \rangle \quad | \quad k : P \quad | \quad C_1 \mid C_2 \quad | \quad \mu \quad | \quad k_1 \prec (k_2, k_3) \\
\text{(Processes)} & P & ::= & \mathbf{nil} \quad | \quad a.P \quad | \quad P_1 \mid P_2 \quad | \quad A \quad | \quad \mathbf{roll}(\iota) \\
\text{(Actions)} & a & ::= & \mathbf{out}_\gamma(t)@\ell \quad | \quad \mathbf{eval}_\gamma(P)@\ell \quad | \quad \mathbf{in}_\gamma(T)@\ell \quad | \\
 & & & \mathbf{read}_\gamma(T)@\ell \quad | \quad \mathbf{newloc}_\gamma(l) \\
\text{(Memories)} & \mu & ::= & [k : \mathbf{out}_\gamma(t)@l.P; k''; k'] \quad | \quad [k : \mathbf{in}_\gamma(T)@l.P; h : \langle t \rangle; k'] \\
 & & | & [k : \mathbf{read}_\gamma(T)@l.P; h; k'] \quad | \quad [k : \mathbf{newloc}_\gamma(l).P; k'] \\
 & & | & [k : \mathbf{eval}_\gamma(Q)@l.P; k''; k']
\end{array}
$$

Example

- From

$$l :: k : \mathbf{out}_\gamma(foo)@l.\mathbf{roll}(\gamma) \parallel l' :: k' : \mathbf{in}(foo)@l.\mathbf{nil}$$

- We get

$$(\nu k'', k''', k'''')$$
$$(l :: k'' : \mathbf{roll}(k) \mid [k : \mathbf{out}_\gamma(foo)@l.\mathbf{roll}(\gamma); k'''; k'']$$
$$\parallel l' :: k'''' : \mathbf{nil} \mid [k' : \mathbf{in}(foo)@l.\mathbf{nil}; k''' : \langle foo \rangle; k''''])$$

- When we undo the **out** we need to restore the **in**

CRμKlaim semantics

$$
\begin{array}{l}
l :: k : \mathbf{eval}_\gamma(Q)@l'.P \ \ \| \ \ l' :: \mathbf{empty} \\
\mapsto_c \ (\nu k', k'')\,(\, l :: k' : P[k/\gamma] \mid [k : \mathbf{eval}_\gamma(Q)@l'.P; k''; k'] \ \| \ l' :: k'' : Q\,)
\end{array}
\quad (Eval)
$$

$$
\frac{\begin{array}{c}
M = (\nu\tilde{z})l :: k' : \mathbf{roll}(k) \parallel l' :: [k : a.P; \xi] \parallel N \quad k <: M \quad \texttt{complete}(M) \\
N_t = l'' :: h : \langle t\rangle \text{ if } a = \mathbf{in}_\gamma(T)@l'' \wedge \xi = h : \langle t\rangle; k'', \text{ otherwise } N_t = \mathbf{0} \\
N_l = \mathbf{0} \text{ if } k <:_M l, \text{ otherwise } N_l = l :: \mathbf{empty}
\end{array}}{(\nu\tilde{z})l :: k' : \mathbf{roll}(k) \parallel l' :: [k : a.P; \xi] \parallel N \ \rightsquigarrow_c \ l' :: k : a.P \parallel N_t \parallel N_l \parallel N \lightning_k}
\quad (Roll)
$$

- M is complete and depends on k
- N_t: if the undone action is an **in**, we should release the tuple
- N_l: we should not consume the **roll** locality, unless created by the undone computation
- $N \lightning_k$: resources consumed by the computation should be released

Results

- CRμKlaim is a controlled version of RμKlaim

- It inherits all its properties

Map of the talk

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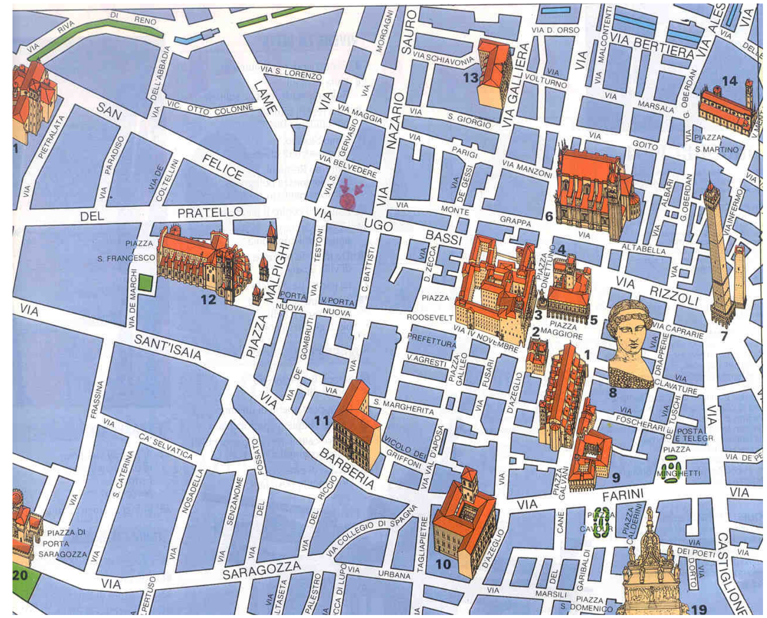

Summary

- We defined uncontrolled and controlled causal-consistent reversibility for μKlaim

- Two main features taken into account
  - Read dependences
  - Localities

Future work

- Part of HOπ theory not yet transported to μKlaim
  - Encoding of the reversible language in the basic one
    - Would allow to exploit Klaim implementations
  - Low-level controlled semantics
  - Alternatives

- The killer application may be in the field of STM

Thanks!

Questions?

5th International Workshop on Modeling and Simulation of Peer-to-Peer and Autonomic Systems (MOSPAS 2014)

July 21-25, 2014 - Bologna, Italy

Submission Deadline:

March 11, 2014