Logical Aspects of Massively Parallel and Distributed Systems

Frank Neven
Hasselt University
PODS Tutorial

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Logical aspects of massively parallel and distributed systems

Topics	Setting
Complexity of query evaluation Foundations of query optimization	*synchronized parallel systems*
Monotone recursive queries	*asynchronous distributed systems*

Topic #1: complexity of query evaluation

synchronous setting

Question

How can we understand the complexity of query processing on shared-nothing parallel architectures?

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  - Large numbers of servers
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- Focus: *join queries* and *Shares/HyperCube algorithm*

Topic #2: foundations of query optimization

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- Framework for reasoning on data partitioning
- Parallel-correctness and transferability
- Focus: *join queries and single-round parallel algorithms*

Topic #3: Datalog and monotone queries

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- Coordination-freeness
- CALM: consistency and logical monotonicity
- Focus: *monotone and Datalog queries (and extensions)*

Outline

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Massively Parallel Communication Model (MPC)

Aim of MPC [Koutris, Suciu, PODS 2011]
Understand the complexity of parallel query processing on shared-nothing architectures

Examples
MapReduce, Spark, Pig, Hive, Dremel, . . .

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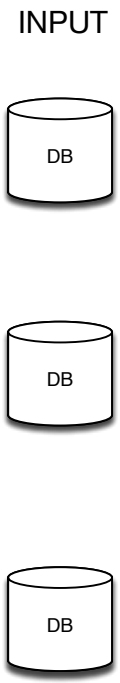
Understand the complexity of parallel query processing on shared-nothing architectures

Examples
MapReduce, Spark, Pig, Hive, Dremel, ...

Characteristics

- Computation is performed by p servers connected by a complete network of private channels
- Computation proceeds in rounds:
  - *Communication phase:* servers exchange data
  - *Computation phase:* each server performs only local computation

Massively Parallel Communication Model



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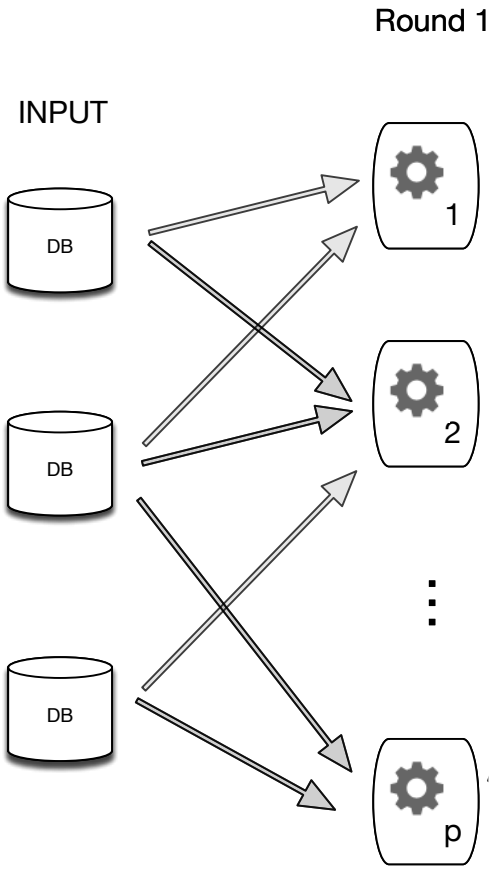

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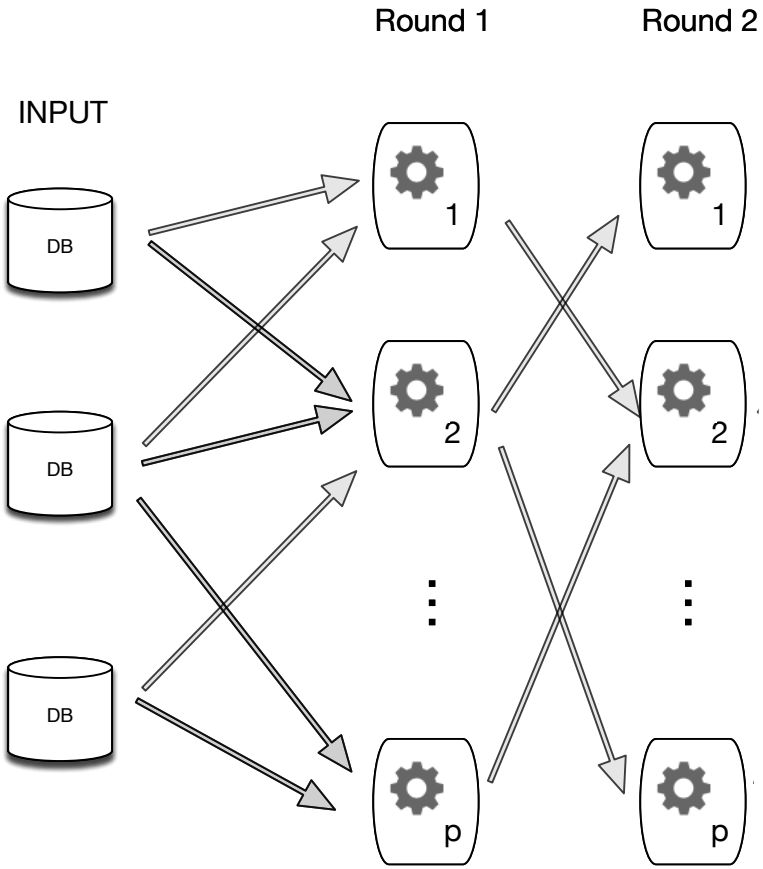

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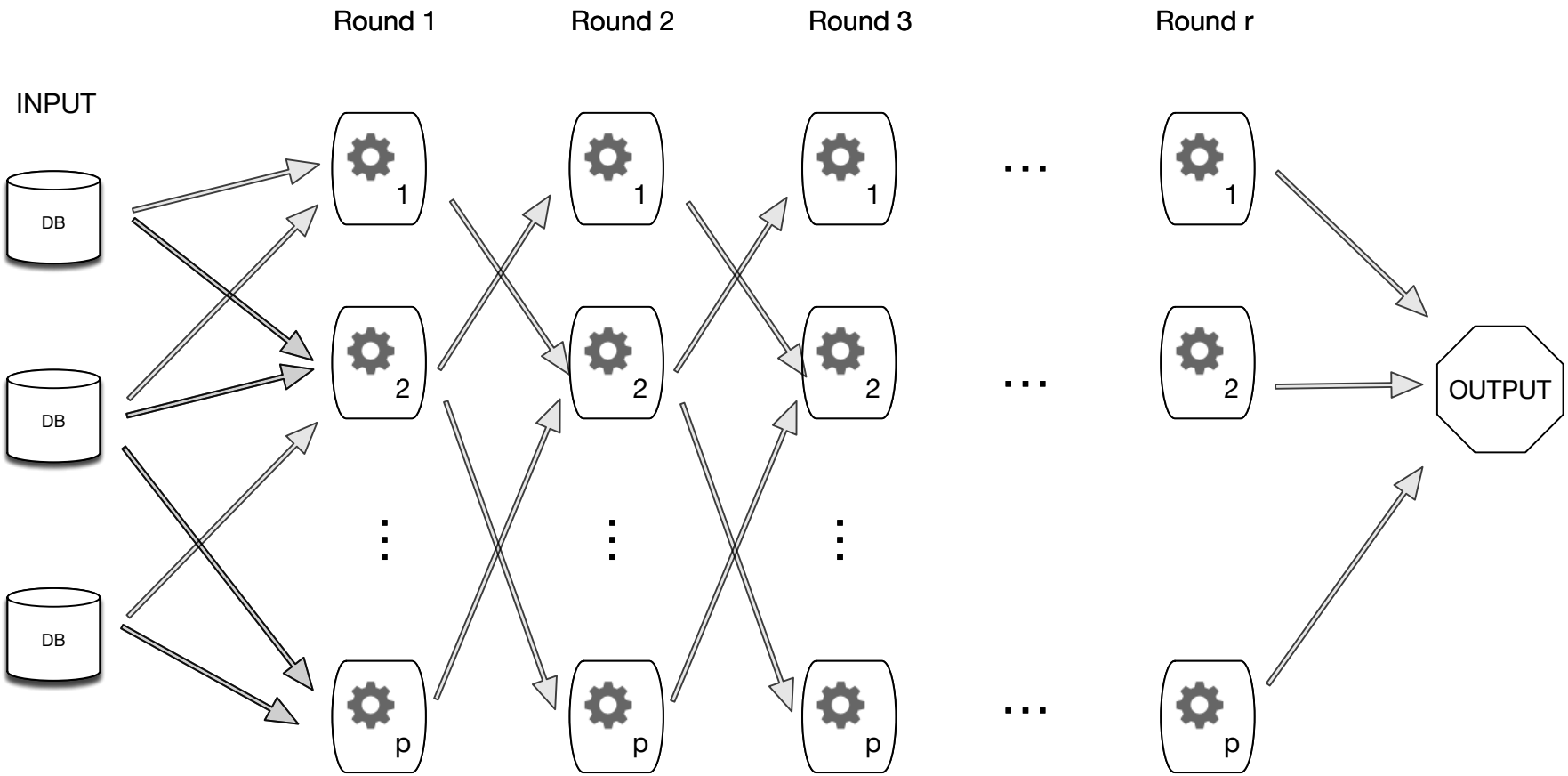

How do we measure complexity?

Possible measures

1. Load:
   - The load at each server is the amount of data received by a server during a particular round.
   - Minimization targets:
     - Total load (communication cost)
     - Maximal load (load balancedness)
2. Number of rounds

Typically ignoring the complexity of local computations.

Outline

Shares/HyperCube algorithm: single-round multi-join evaluation [Afrati, Ullman, EDBT 2010], [Beame, Koutris, Suciu, PODS 2013]

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- Triangle Query $H(x, y, z) \leftarrow R(x, y), S(y, z), T(z, x)$ (3-ary query)
- Identify every server with a coordinate in the 3-dimensional hypercube

$$[1, \alpha_x] \times [1, \alpha_y] \times [1, \alpha_z].$$

- α_x is the share of variable x
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- hash function h_x mapping domain values to $[1, \alpha_x]$
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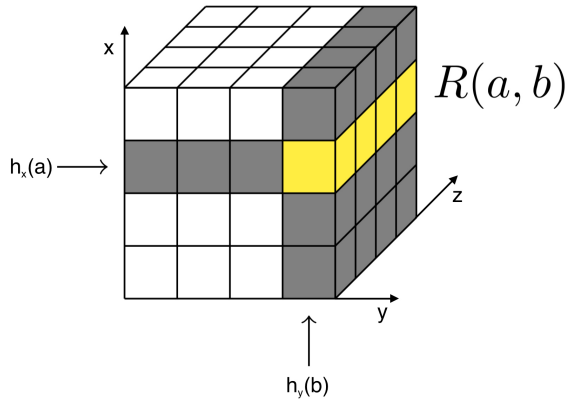

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- $R(a, b)$ is sent to every server $(h_x(a), h_y(b), \star)$ (replicating every tuple α_z times)

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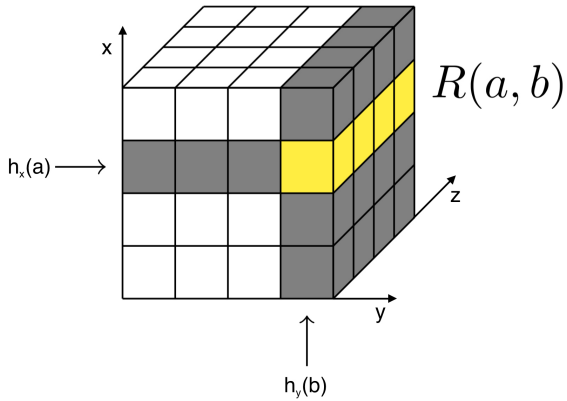

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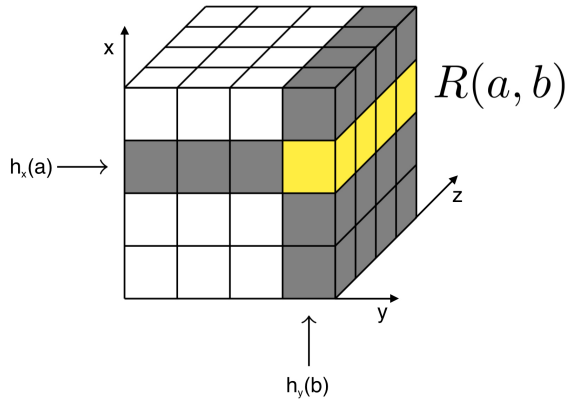

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Computation phase: All servers evaluate the triangle query.

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Triangle Query $H(x, y, z) \leftarrow R(x, y), S(y, z), T(z, x)$

Property

For every valuation

$$V = \{x \mapsto a, y \mapsto b, z \mapsto c\}$$

the required facts

$$\{R(a, b), S(b, c), T(c, a)\}$$

meet at server with coordinate

$$(h_x(a), h_y(b), h_z(c))$$

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$$M/p^{1/\tau^*(Q)}$$

    per server ($\tau^*(Q)$ is optimal fractional vertex cover number of Q)
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  - HyperCube provides matching upper bound
- Practical? [Chu, Balazinska, Suciu, SIGMOD 2015] [Afrati, Ullman, TKDE 2011]
  - rounding issues
  - *strong* for queries with large intermediate results
  - *weak* on queries with small output

Intermediate wrap-up:

Summary:

- MPC as a model to study parallel query evaluation
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Research opportunities:

- Skew [Beame, Koutris, Suciu, PODS 2014] [Afrati, Stasinopoulos, Ullman, Vassilakopoulos, 2015]
- Multi-round
  - GYM [Afrati, Joglekar, R, Salihoglu, Ullman, 2014]
  - lower-bound: any multi-round algorithm requires at least load

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per server ($\rho^*(Q)$ is optimal fractional edge cover number of Q) [Beame, Koutris, Suciu, ICDT 2016]
  - matching upper bound for binary relations [Ketsman, Suciu, 2016]

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Distribution policies

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Generic one-round algorithm
(relative to a distribution policy **P** and a query Q)

1. Reshuffle all data according to **P**
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3. Output then is the union of all local results

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Potential for query optimization

Can we avoid the reshuffle step in the generic one-round algorithm?

Reasoning on data distribution

First scenario. The data is already distributed over the servers.
Can we use the generic one-round algorithm to evaluate a given query using the current distribution?

- *if yes:* no data reshuffling needed
- *if no:* choose another distribution policy that works

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Decision problem: parallel-correctness

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Decision problem: parallel-correctness transfer

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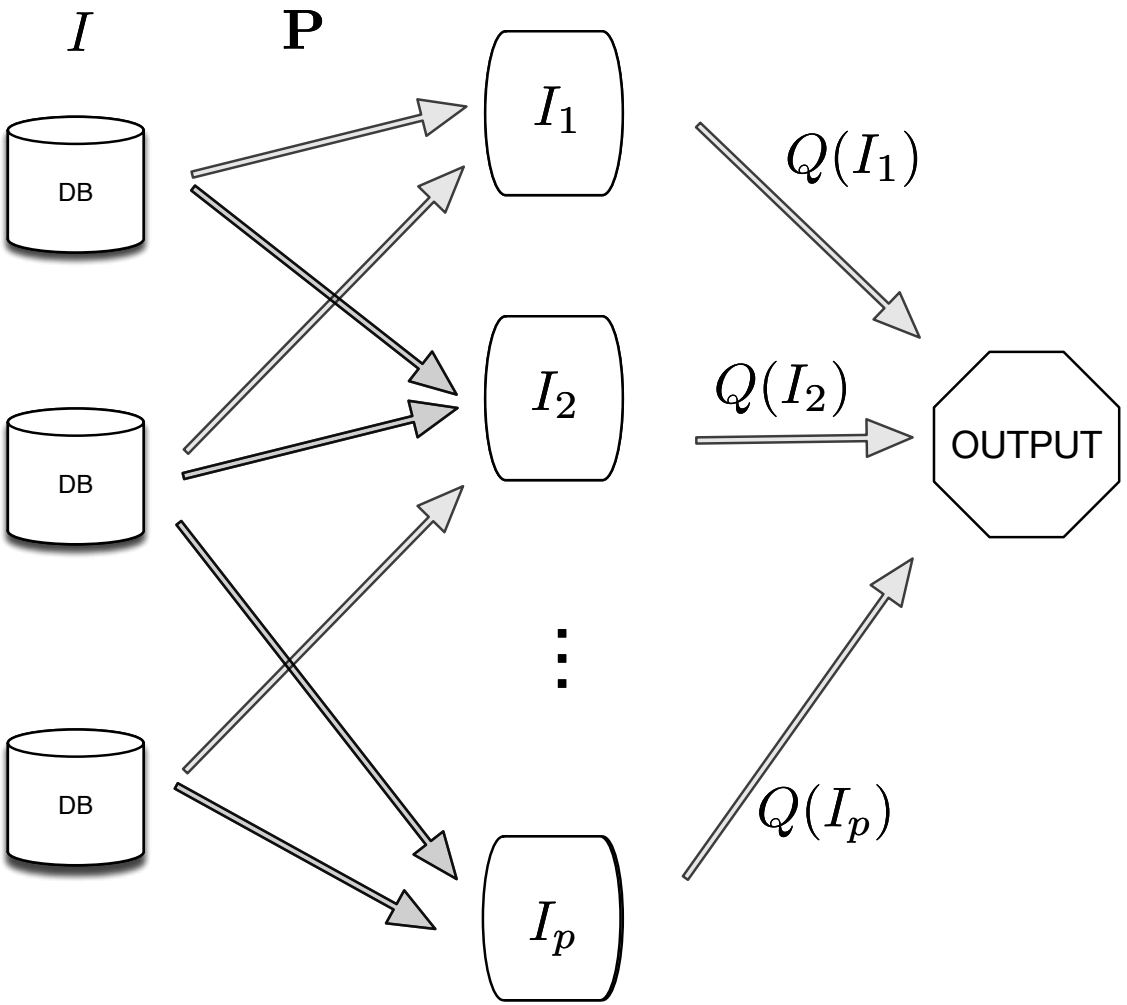
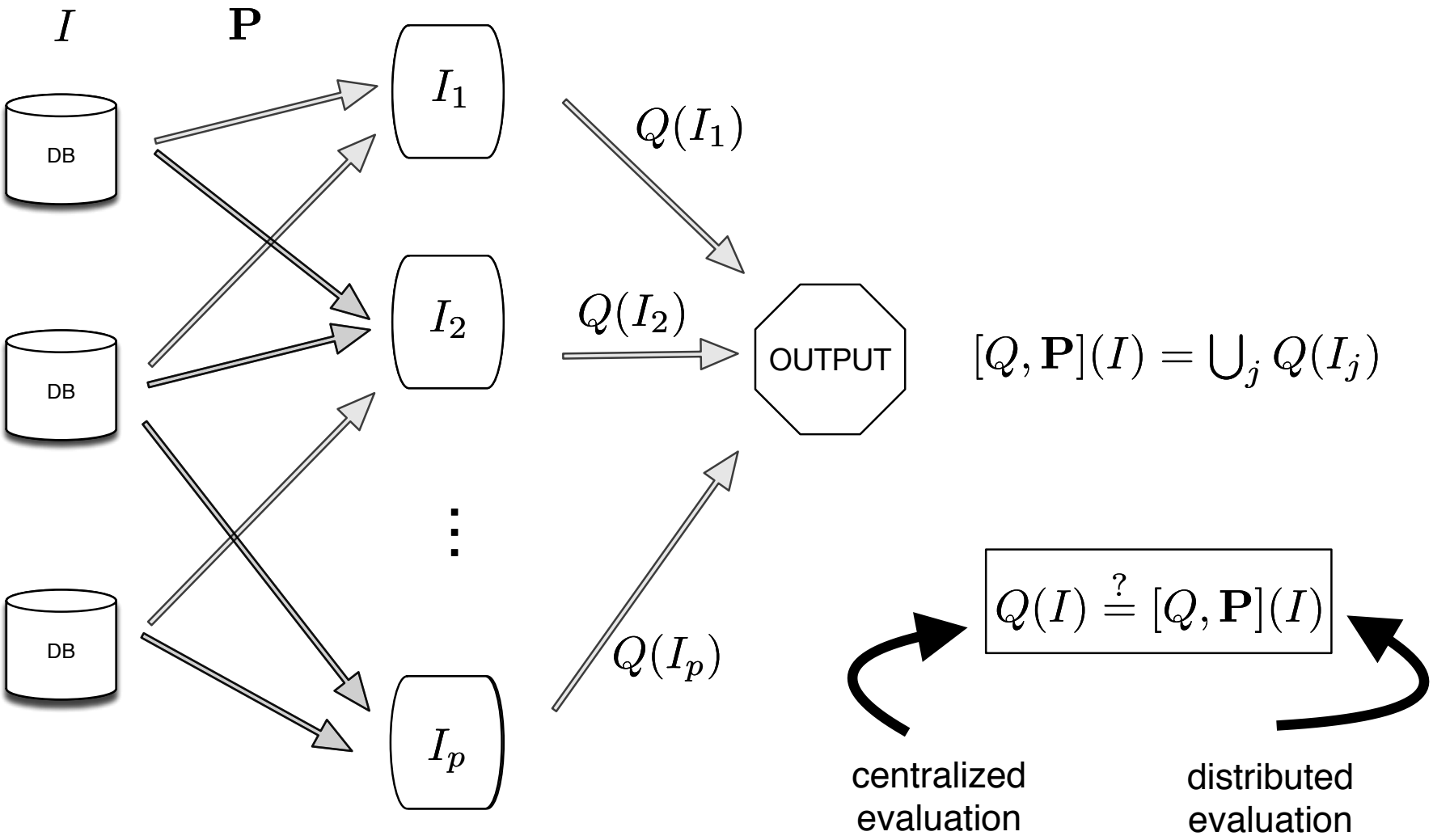
Parallel-correctness



$$[Q, \mathbf{P}](I) = \bigcup_j Q(I_j)$$

Parallel-correctness



Parallel-correctness: a bit more formal

Definition

A query Q is parallel-correct on I w.r.t. $\mathbf{P}$ iff $Q(I) = [Q, \mathbf{P}](I)$.

If Q is monotone, then always $Q(I) \supseteq [Q, \mathbf{P}](I)$

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A valuation V for a conjunctive query

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If for every valuation V for Q, there is a node κ in the network for which

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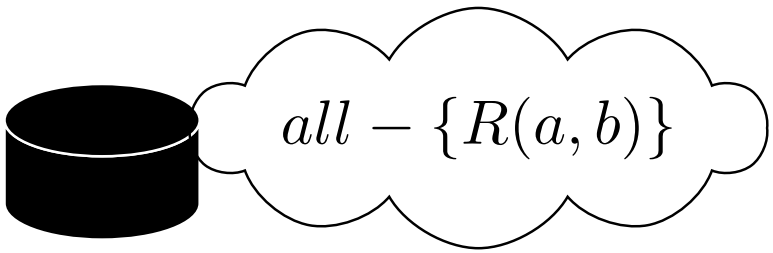
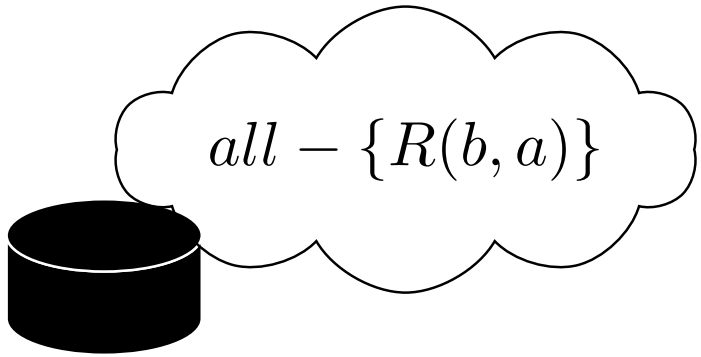
- $Q(I) \supseteq [Q, \mathbf{P}](I)$ follows by monotonicity
- Every CQ is parallel-correct w.r.t. its HyperCube distribution

Sufficient but not a necessary condition: counterexample

Distribution policy $\boldsymbol{P}$





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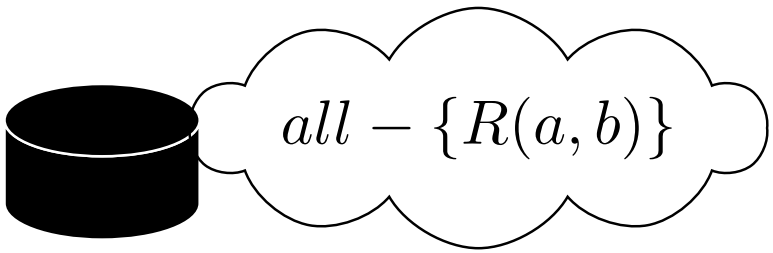

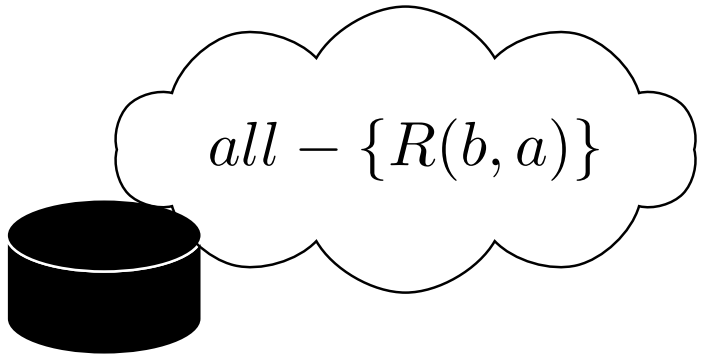

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Derives:

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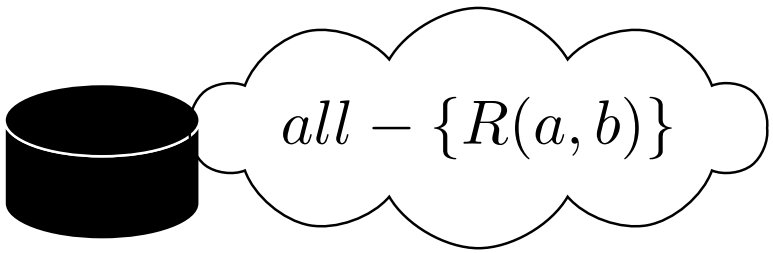

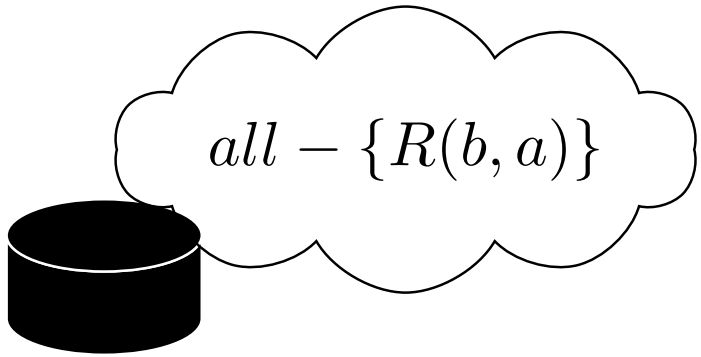

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Derives:

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Parallel-correctness for CQs: characterization

Lemma

Q is parallel-correct w.r.t. $\mathbf{P}$ *iff*

for every minimal valuation V *for* Q,

there is a node κ *in the network for which*

$$V(body_Q) \subseteq \mathbf{P}^{-1}(\kappa).$$

Definition

V is minimal if no V' exists, where

- $V'(\text{head}_Q) = V(\text{head}_Q)$; and,
- $V'(\text{body}_Q) \subsetneq V(\text{body}_Q)$.

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- bound on the size of representations of nodes κ
- bound on the complexity of the test $V(\text{body}_Q) \subseteq \mathbf{P}^{-1}(\kappa)$.

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Theorem (Ameloot, Geck, Ketsman, N., Schwentick, 2015)

Deciding whether a CQ is parallel-correct w.r.t. **P** *is Π_2^P-complete.*

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Reduces to reasoning on properties of minimal valuations.

Parallel-correctness beyond CQs: adding unions, inequalities, negation

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- Non-monotone: parallel-soundness, parallel-completeness

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Parallel-correctness beyond CQs: adding unions, inequalities, negation

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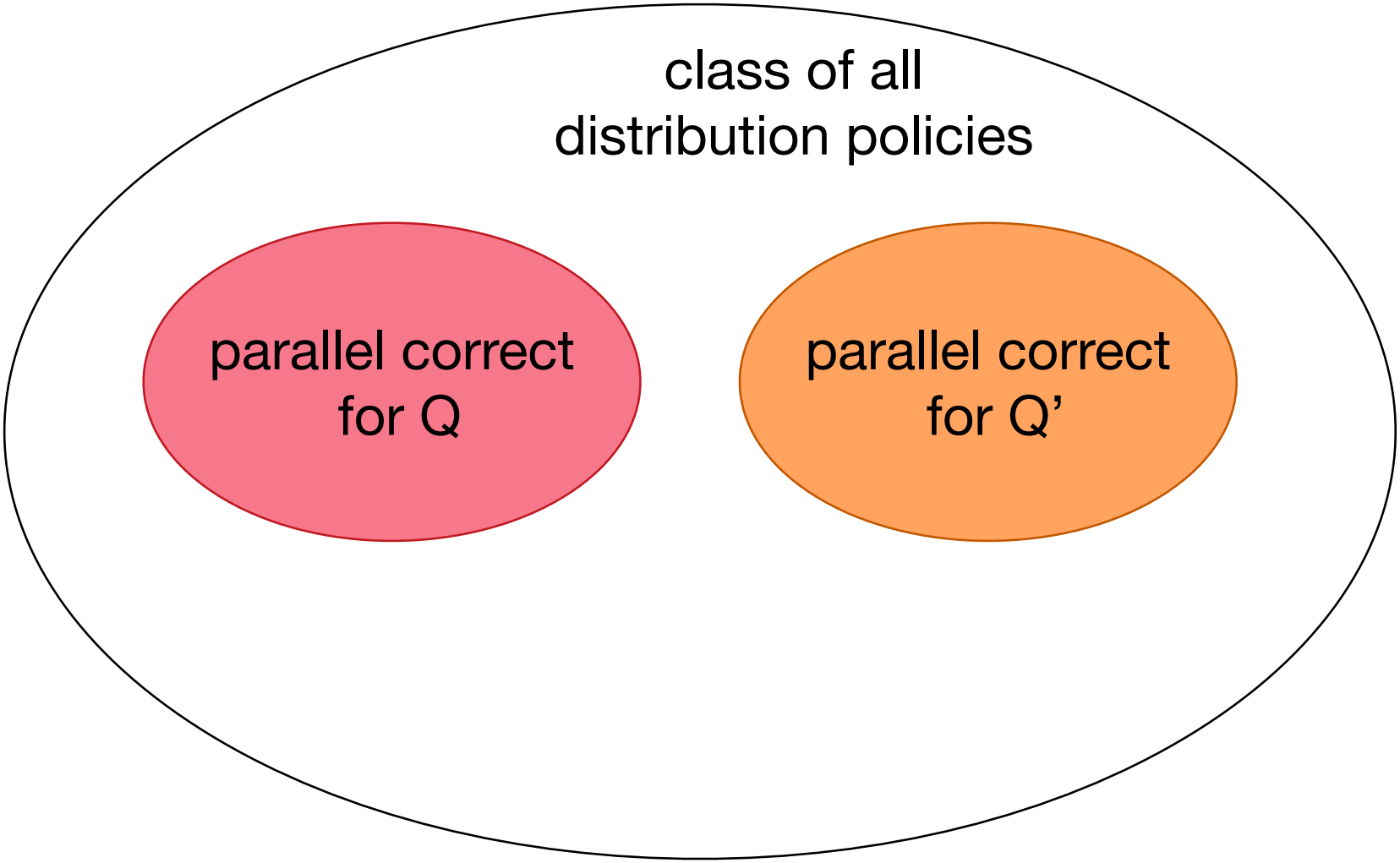
Outline

Evaluating Q' after Q (for free)



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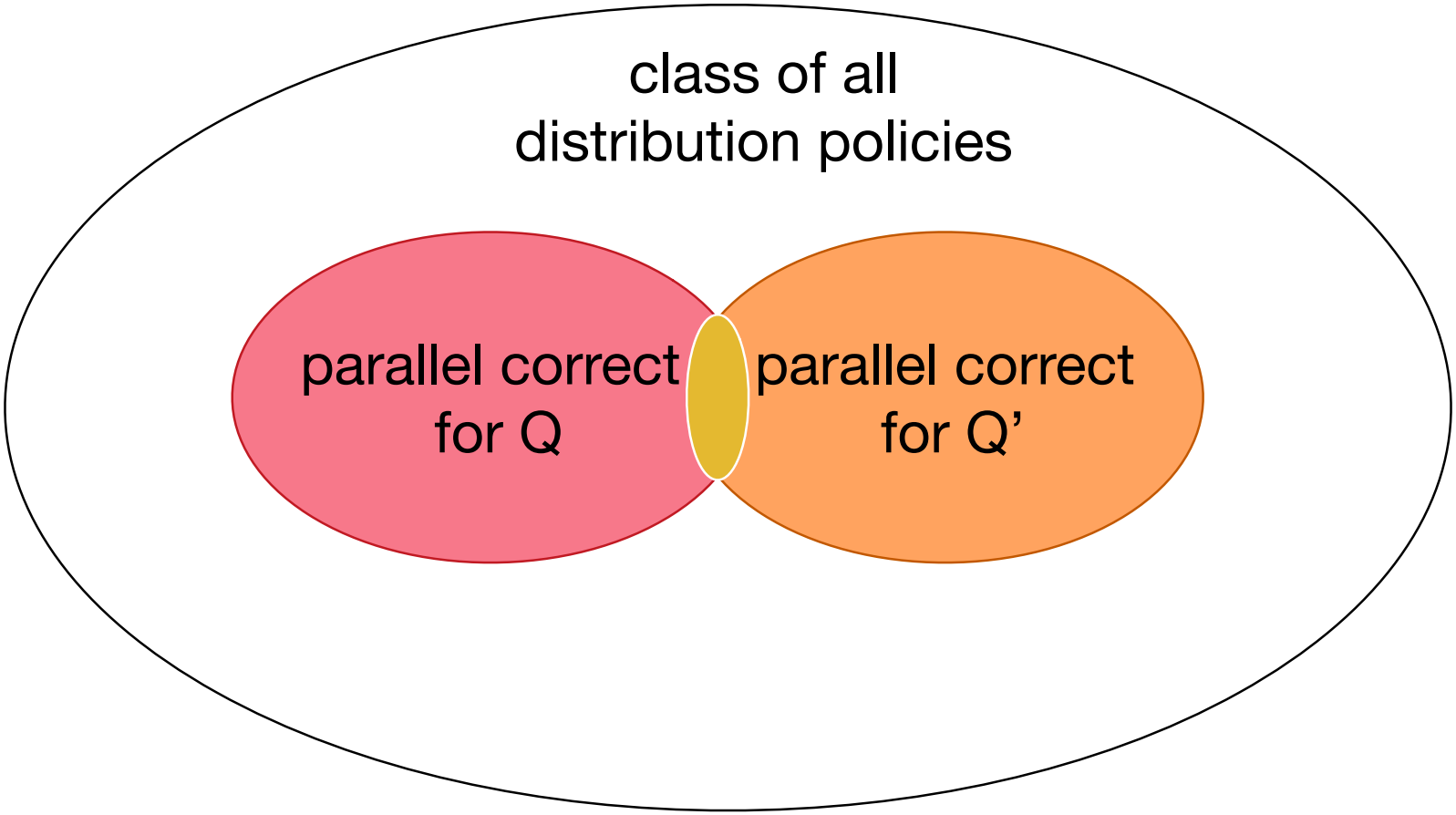

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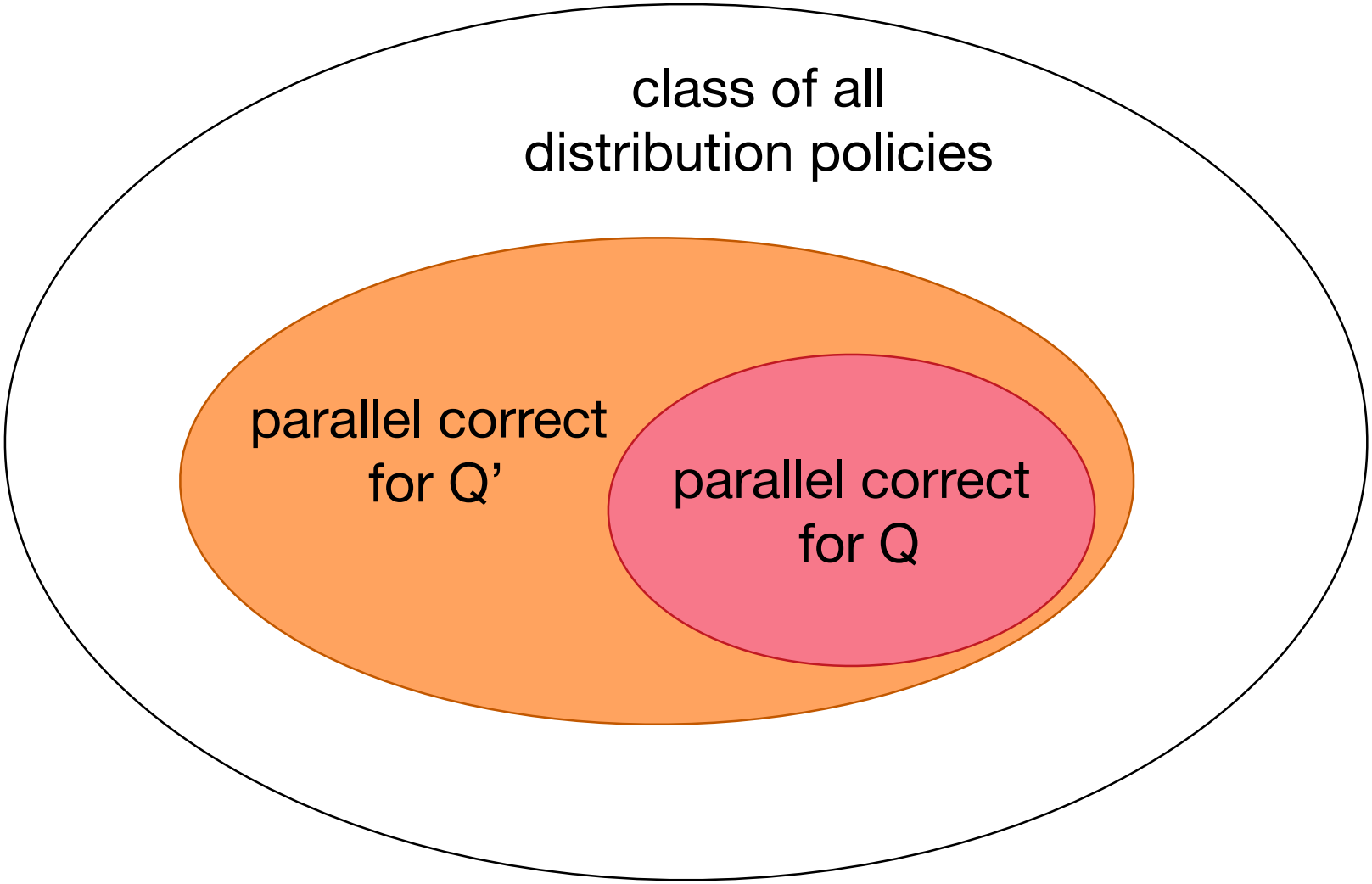

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Transferability of parallel-correctness

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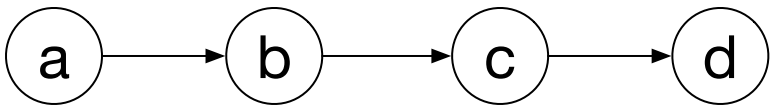

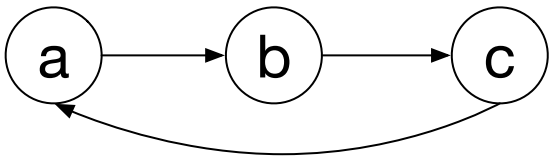

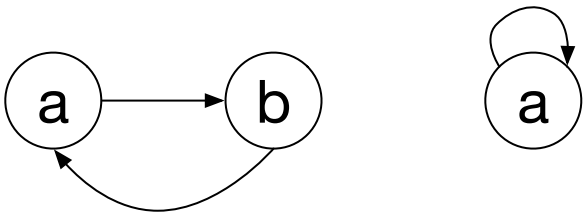

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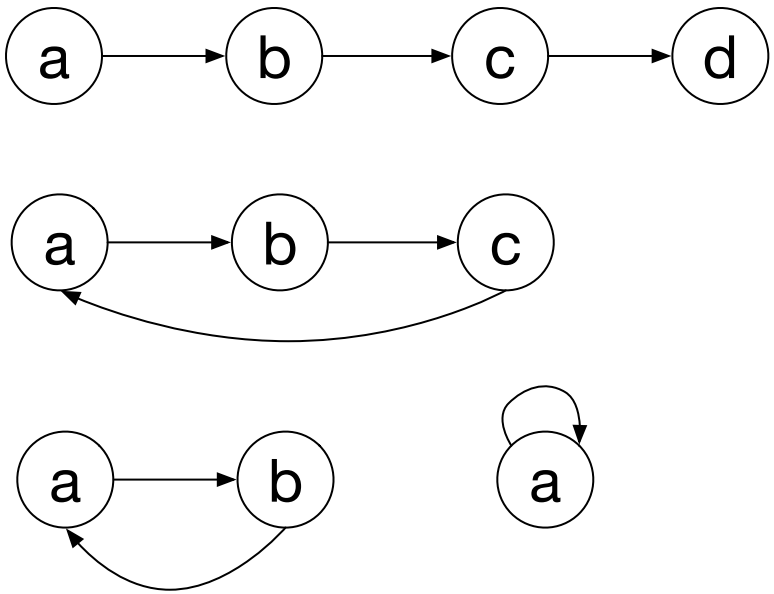

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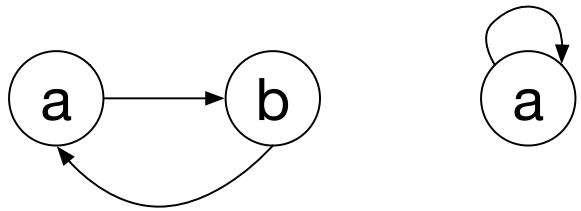

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Transferability for CQs: characterization and complexity

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For conjunctive queries Q and Q', $Q \rightarrow_T Q'$ iff
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Deciding $Q \rightarrow_T Q'$ is Π_3^P-complete.

Only depends on the size of queries! Independent on representation of distribution policies.

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Theorem

Let Q be a strongly minimal CQ and Q' be a CQ.

- *Deciding $Q \rightarrow_T Q'$ is NP-complete.*
- *Deciding parallel-correctness of Q w.r.t. a distribution policy $\mathbf{P}$ is in coNP.*

Intermediate wrap-up: parallel-correctness and transferability

Summary:

- Framework for reasoning about correctness of *arbitrary* distribution policies
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- Practical considerations
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Outline

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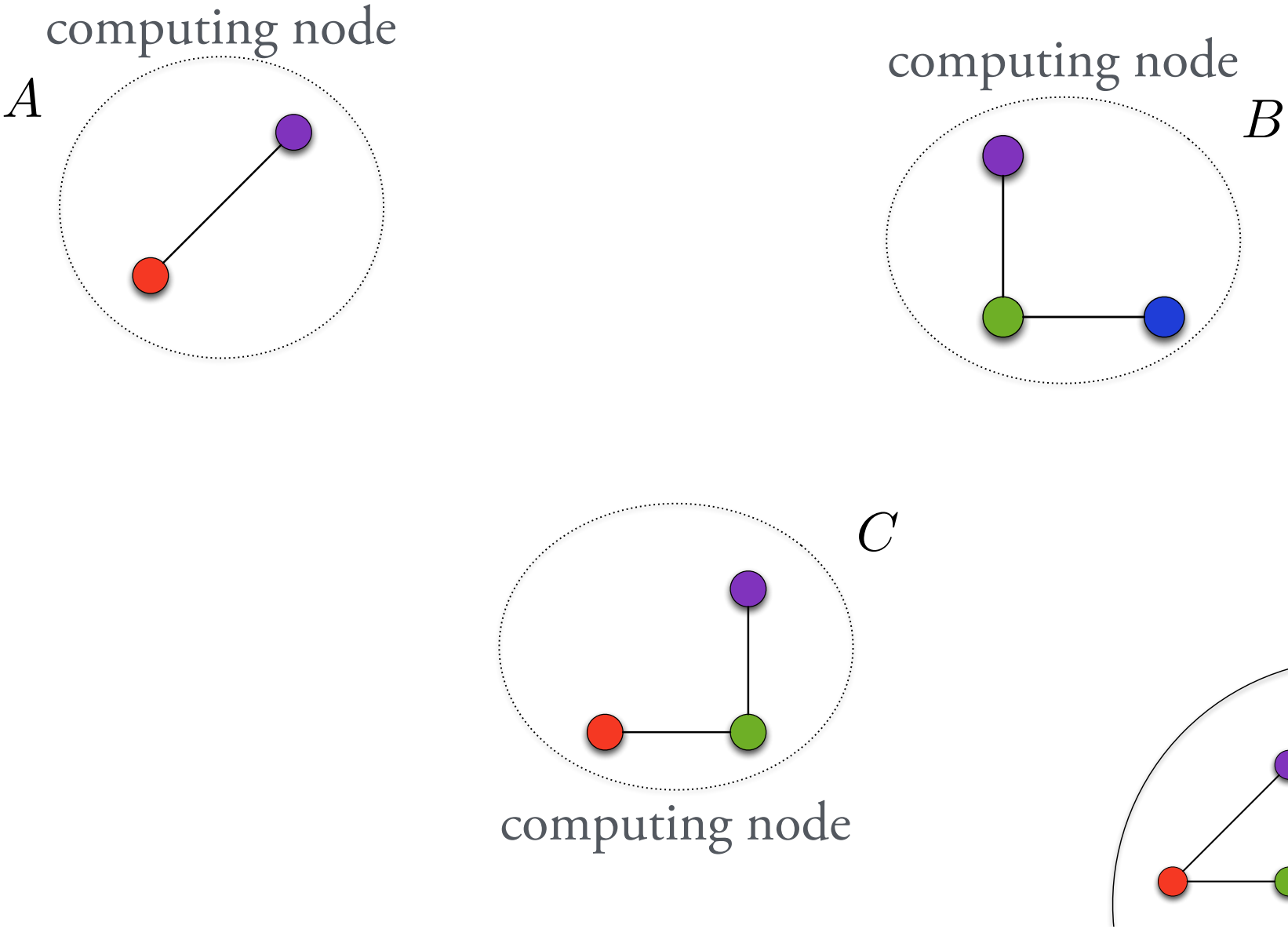
- Our focus:
  - Which fragments/extensions of Datalog can be asynchronously evaluated in a coordination-free manner?
  - *Setting:* messages can never be lost but can be arbitrarily delayed.
  - *Requirement:* output can never be retracted, should eventually be complete

Outline

Example

Query: select all triangles



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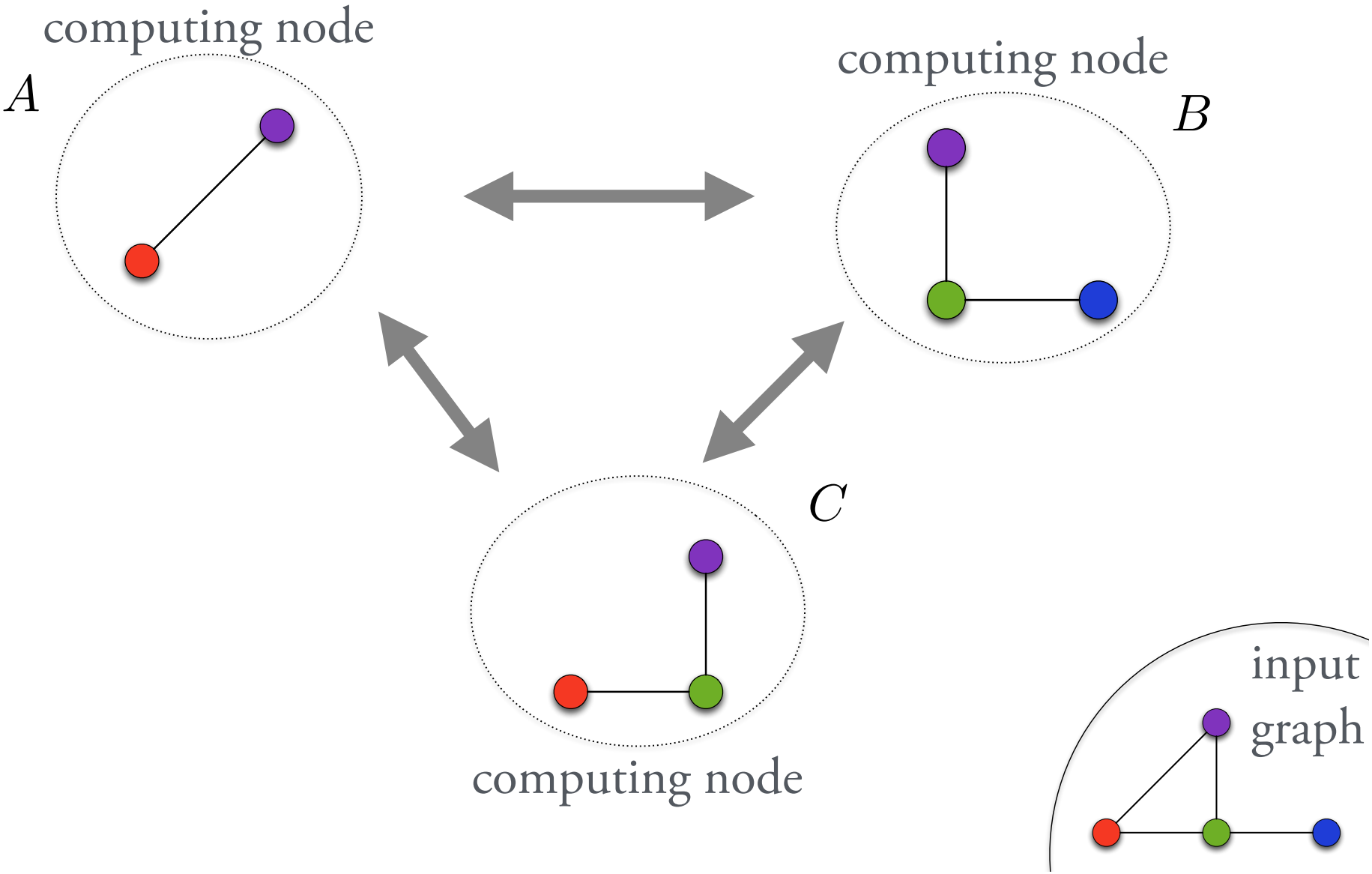

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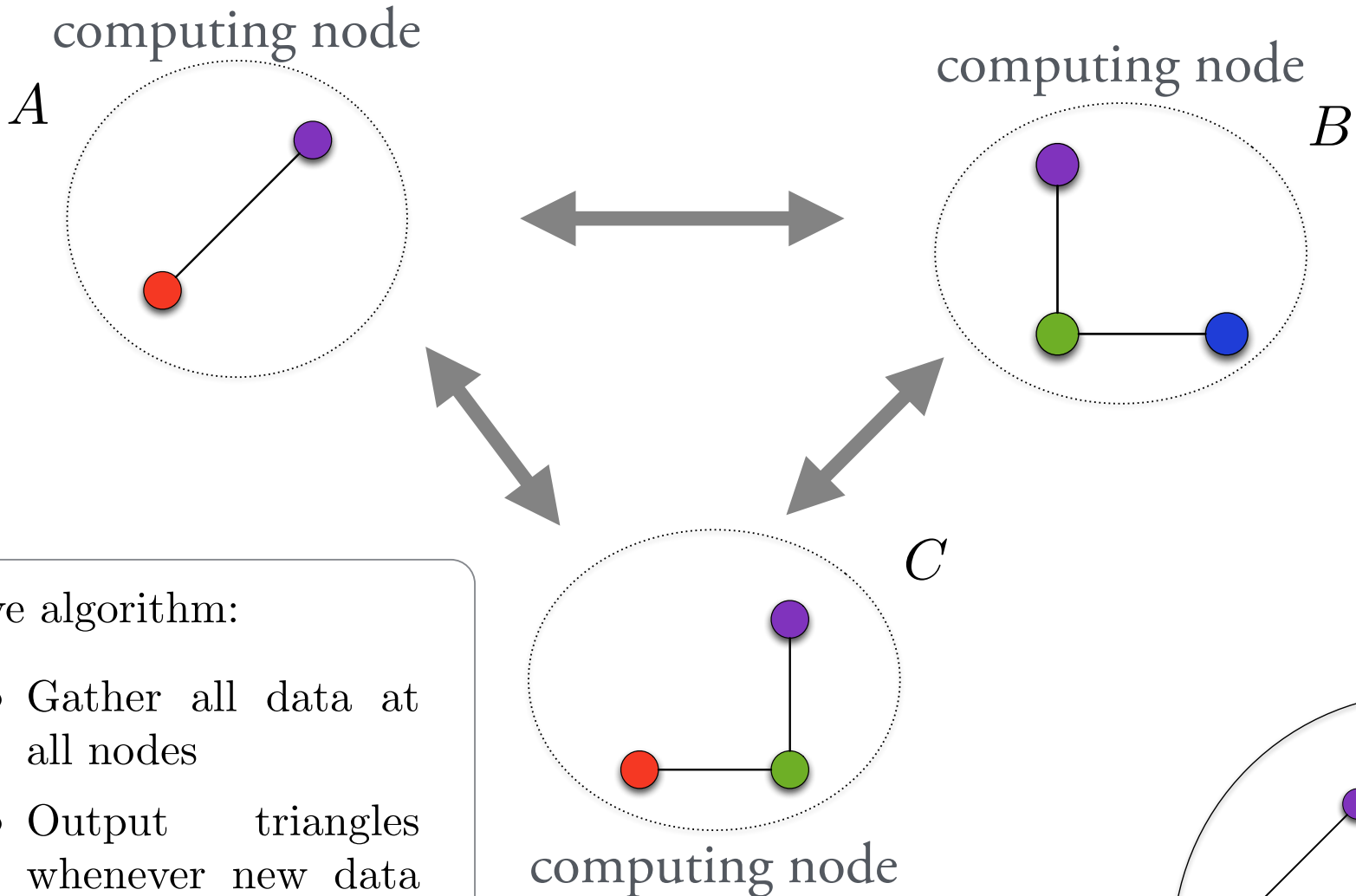

Naive algorithm:

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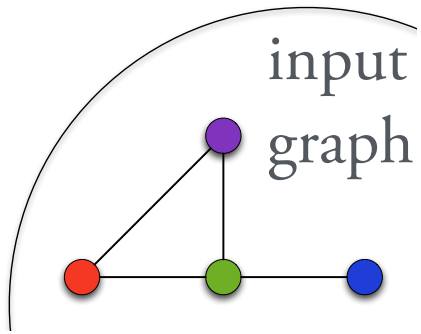

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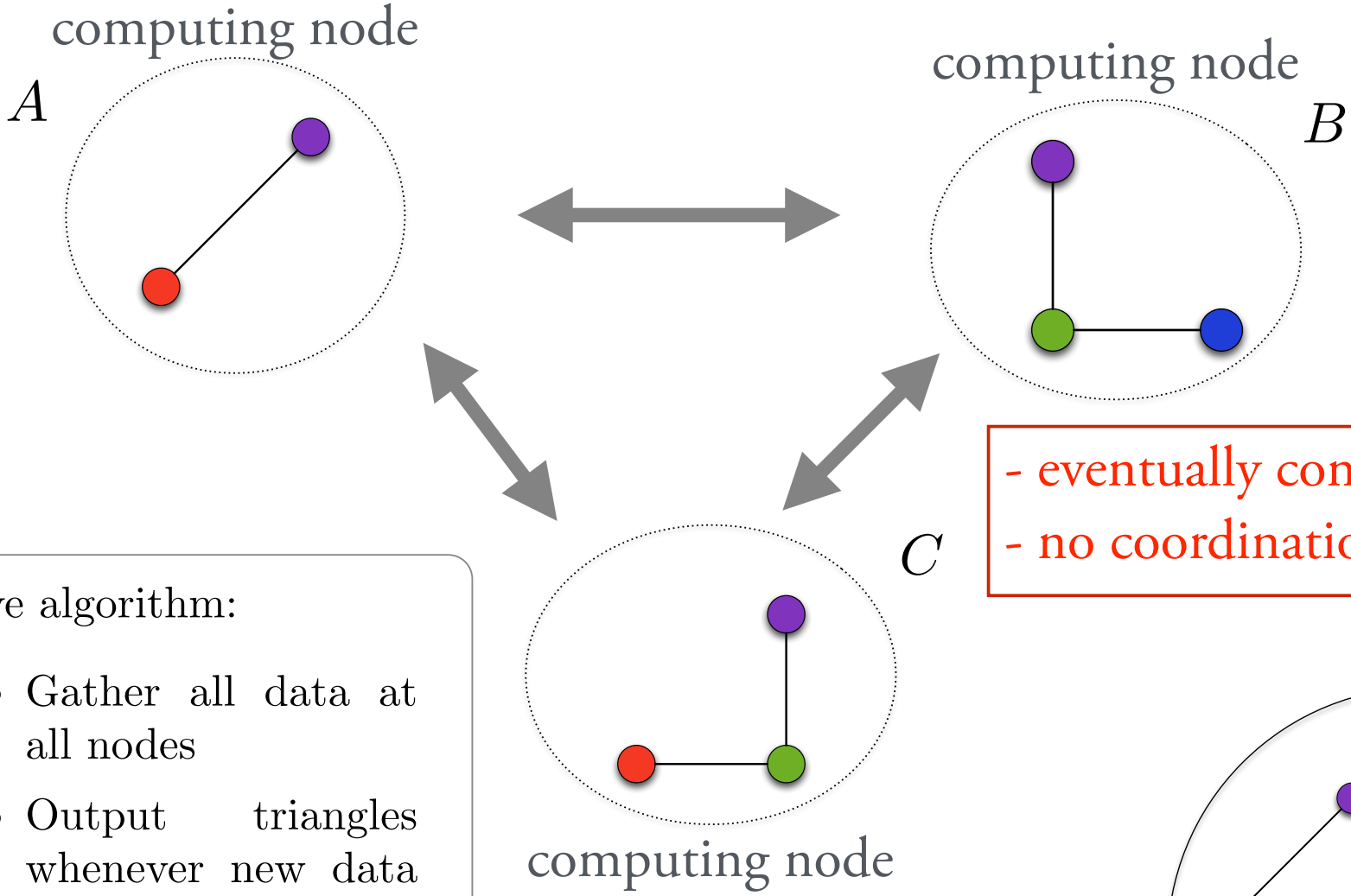

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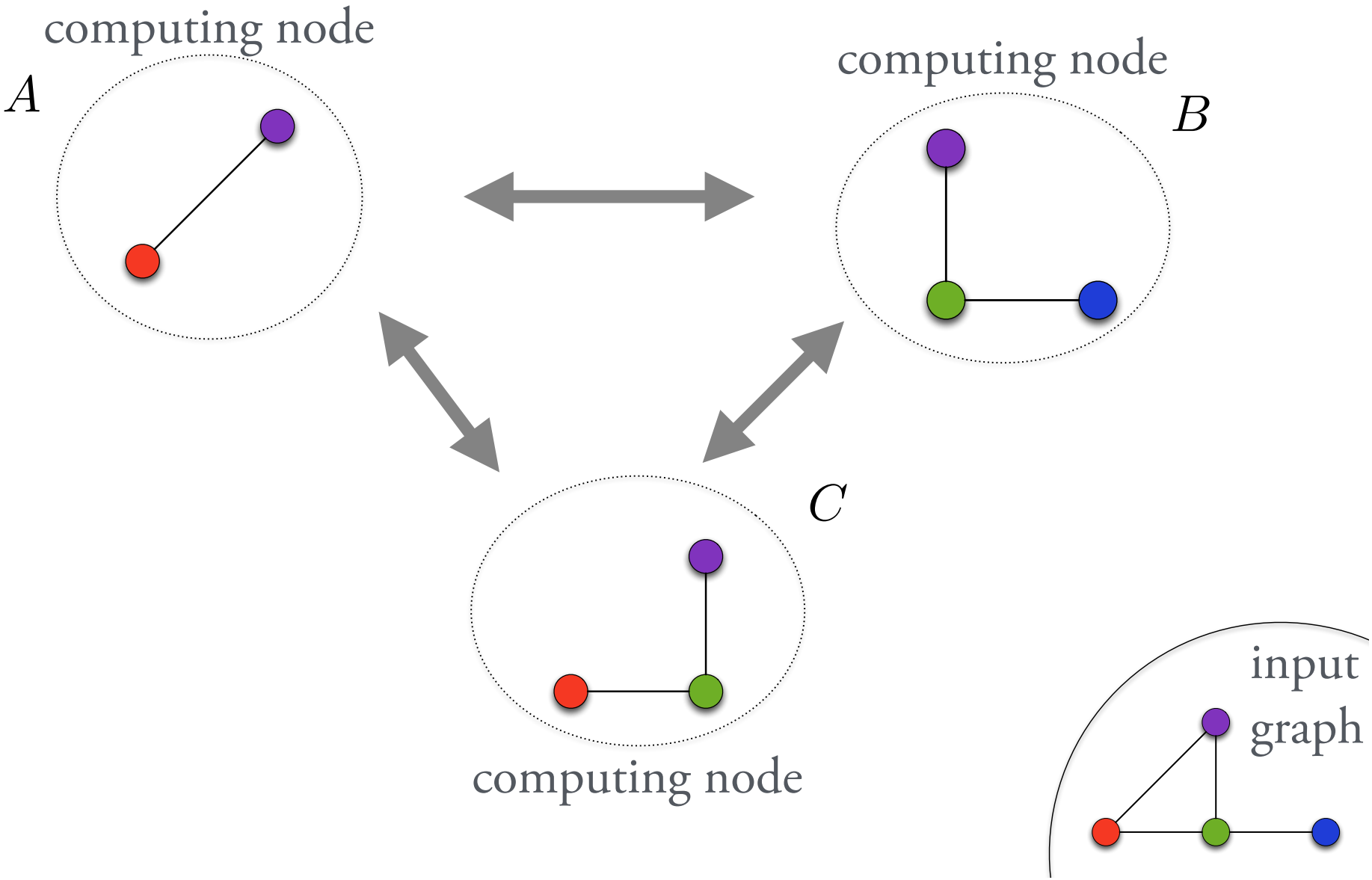

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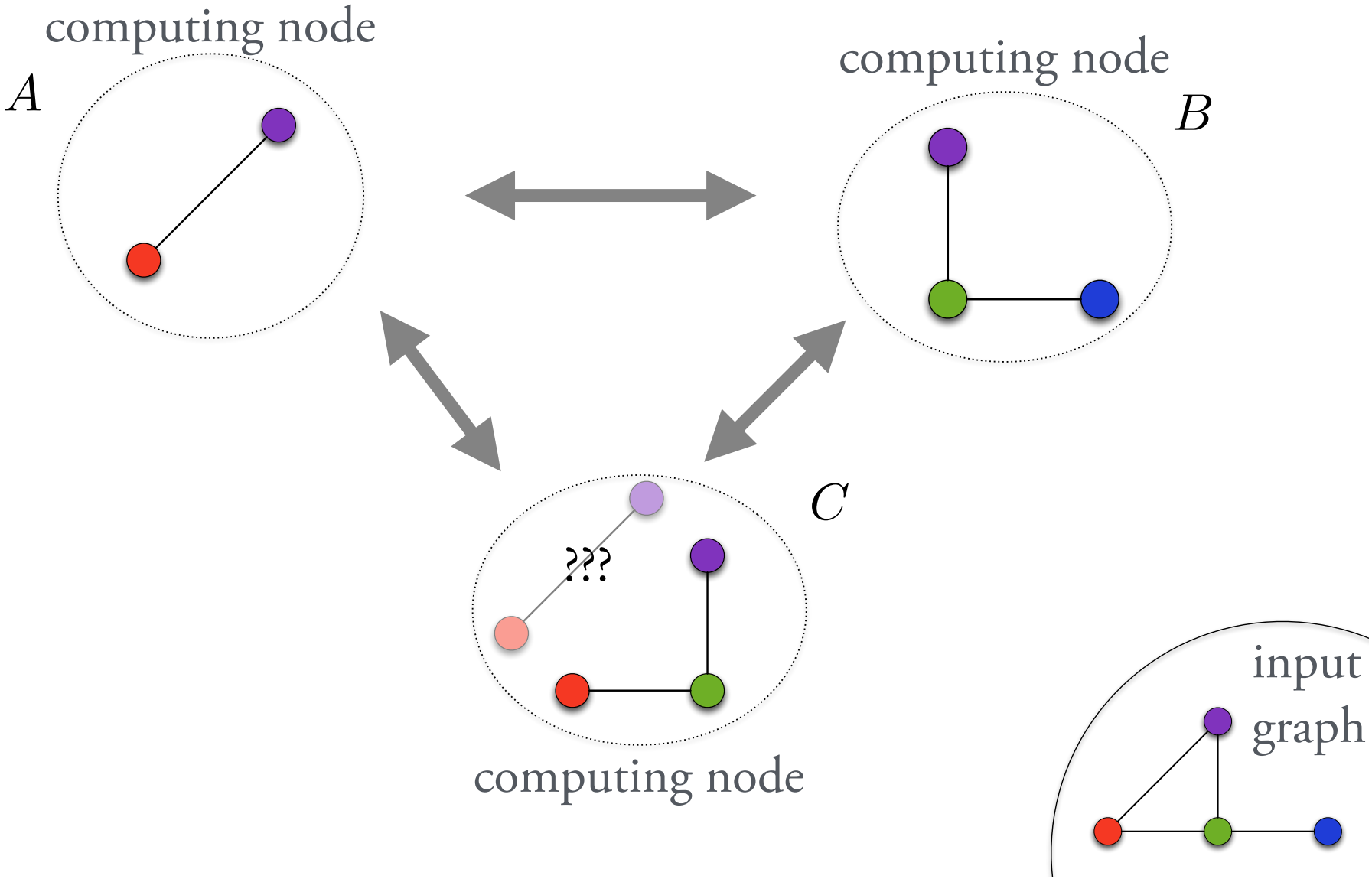

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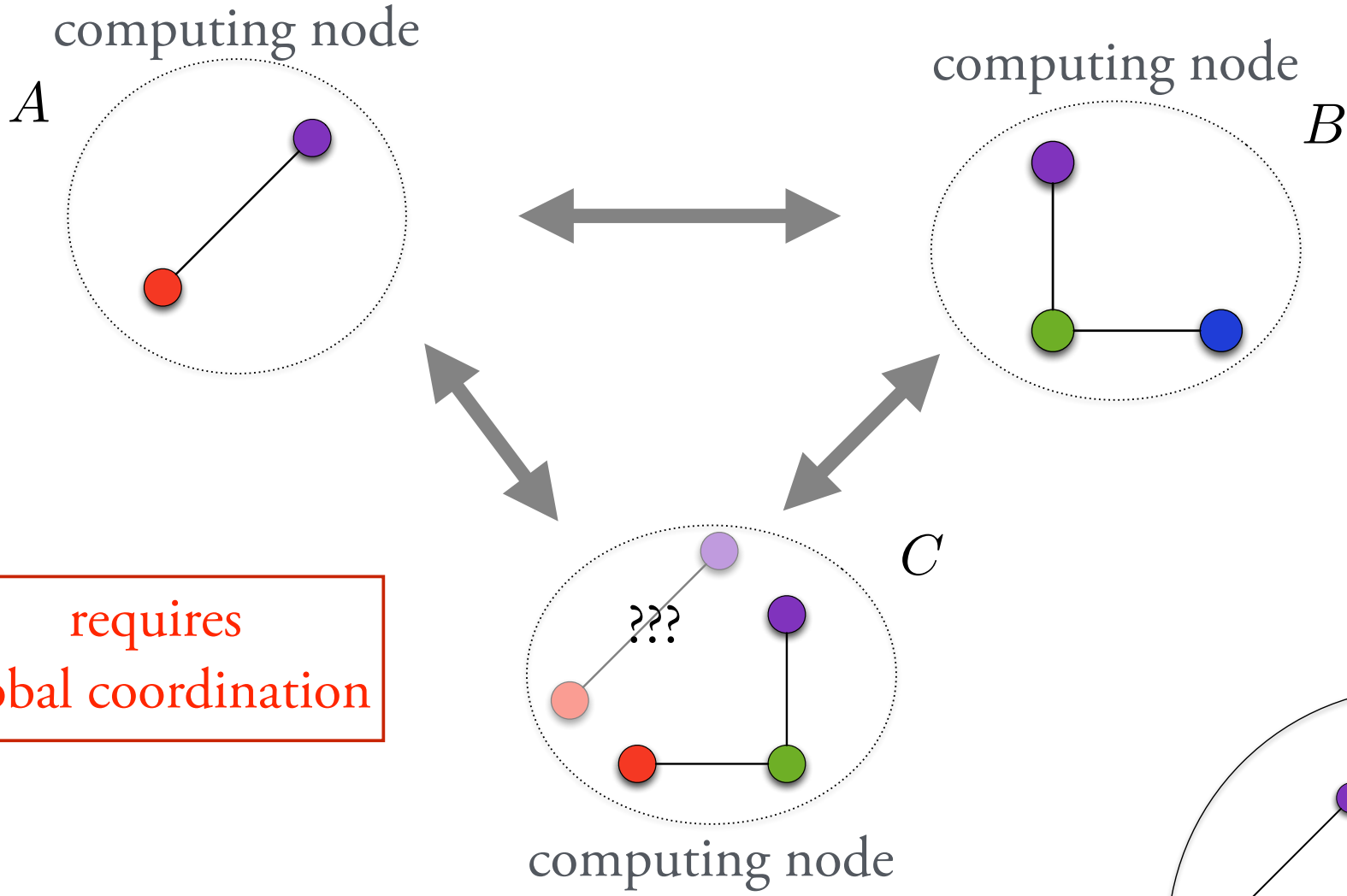

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CALM-conjecture [Hellerstein, PODS 2010]

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Outline

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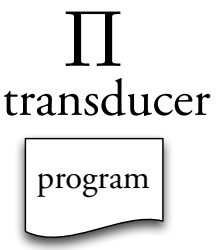

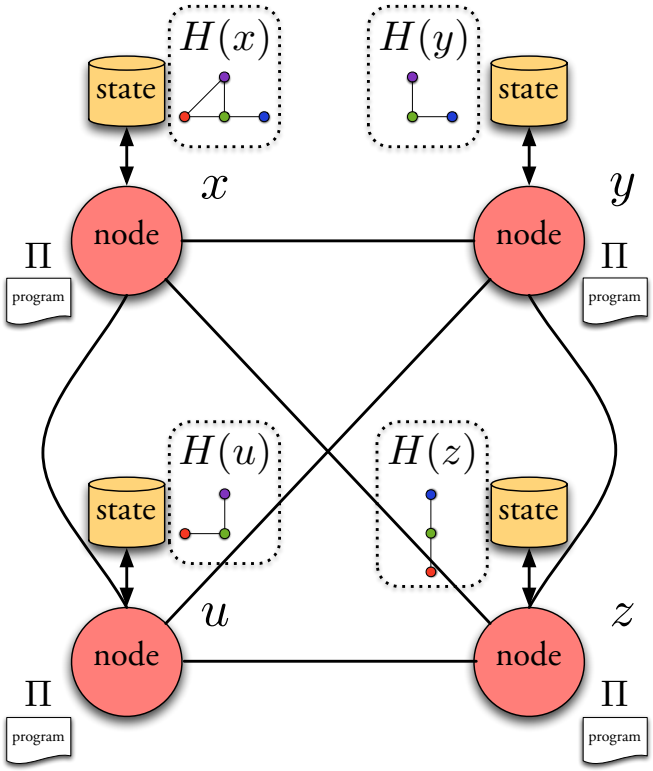

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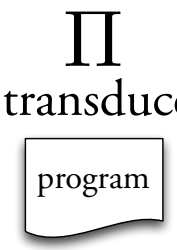

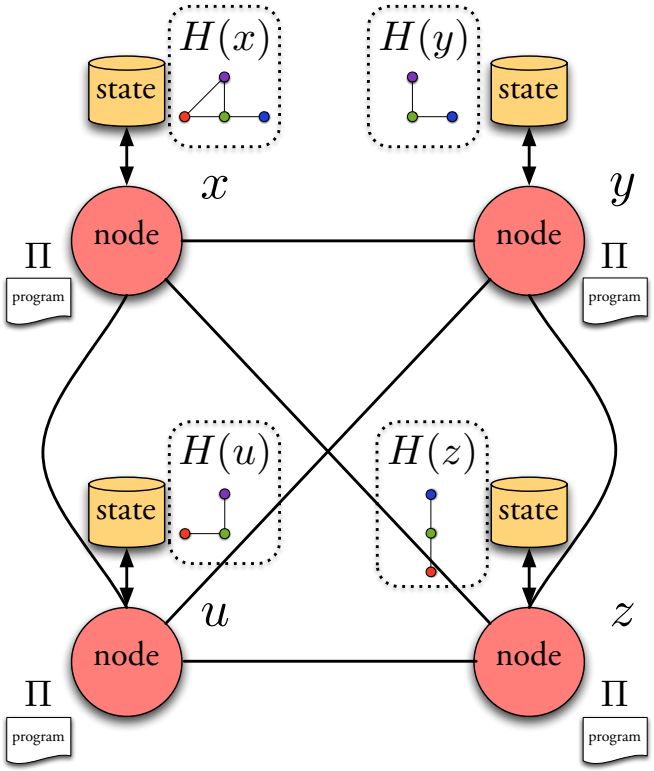

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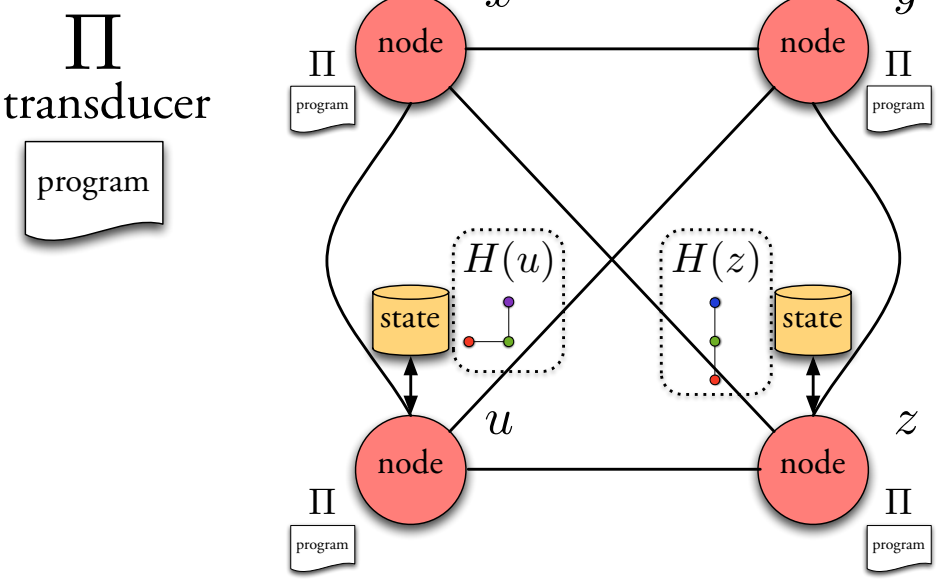

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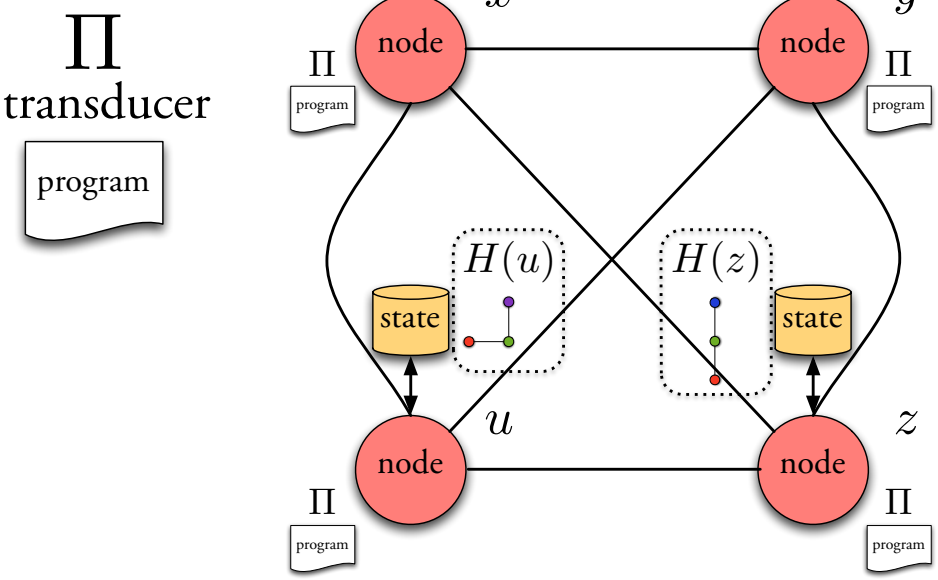

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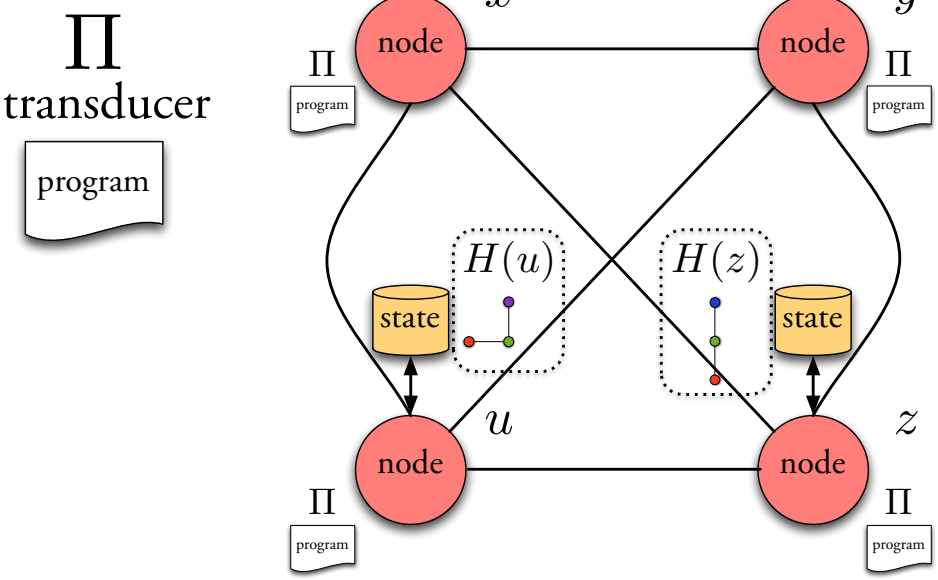

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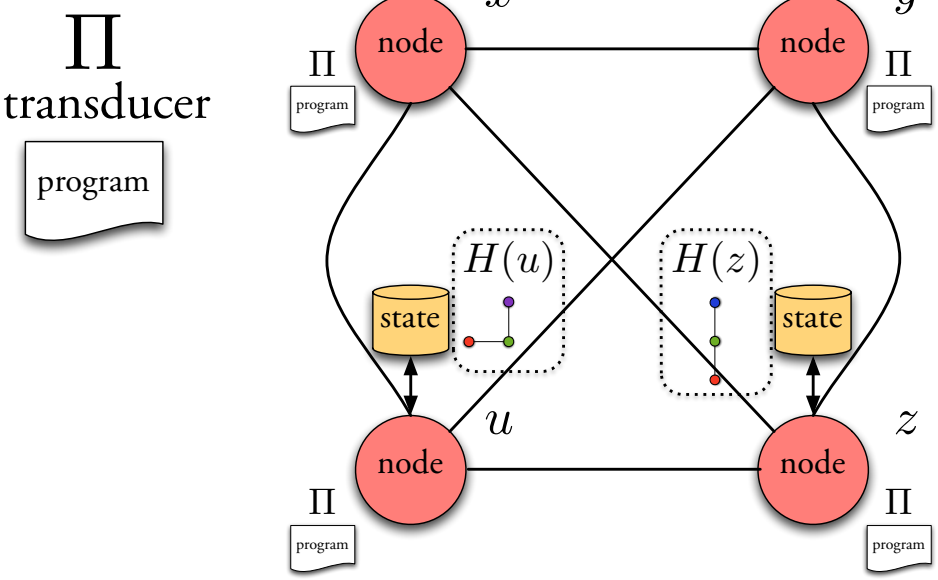

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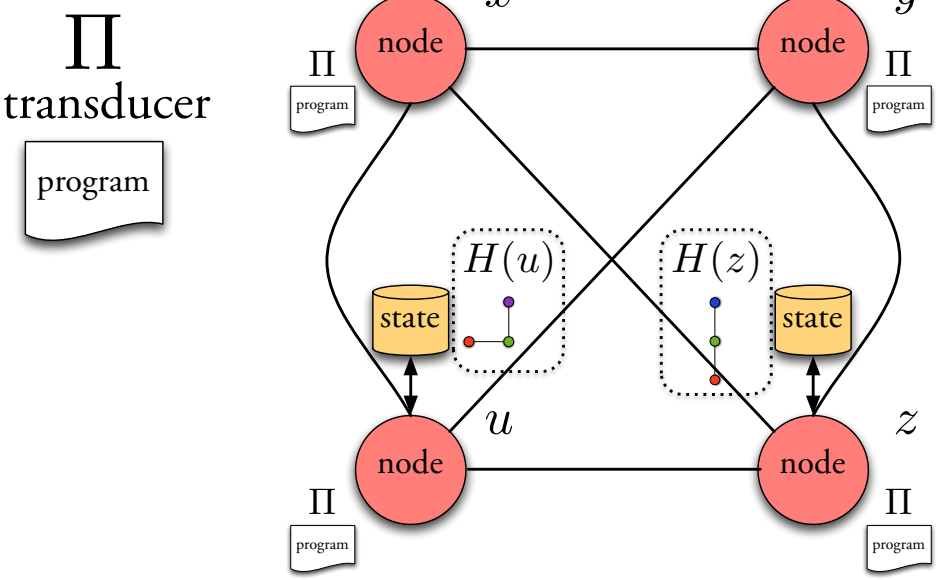

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  - computes queries: inflationary and eventually consistent semantics

Computing all queries

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Relational transducer networks compute every query

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Idea.

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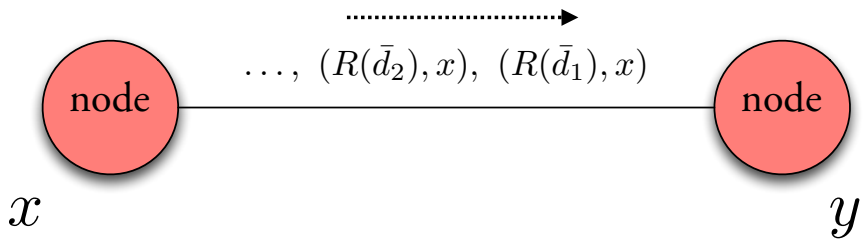

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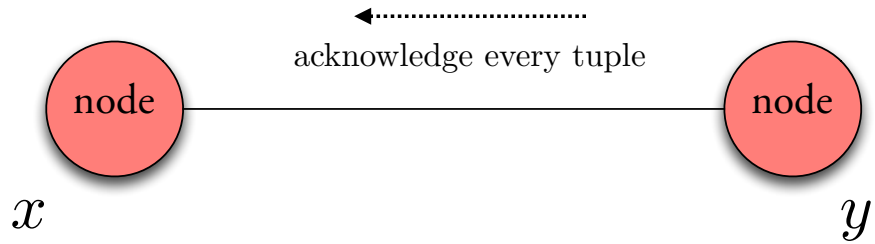

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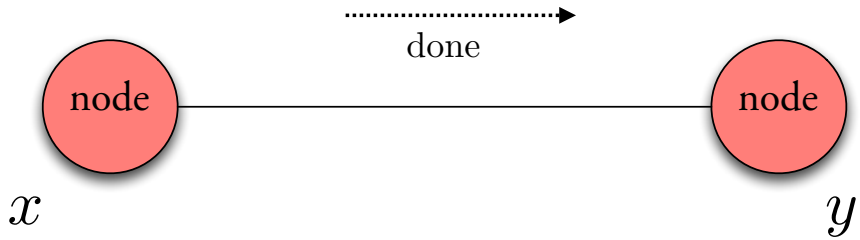

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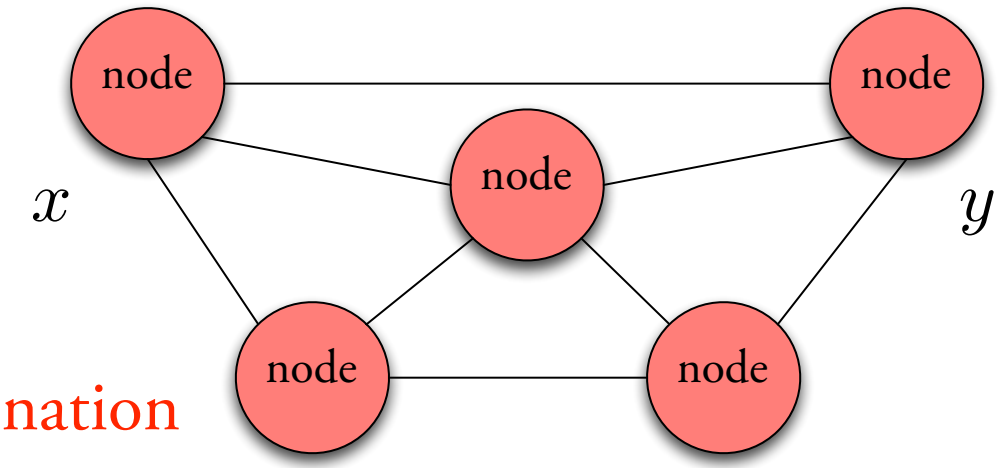

global coordination

need to know every node in the network

Coordination: intuition

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- Reduces parallellism

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Goal

Separate *data*-communication from *coordination*-communication

Coordination-freeness

Informal Definition

A relational transducer network Π is coordination-free if
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Intuition:

- On ideal distribution: communication but no coordination
- On non-ideal distribution: only communication for data transfer, not for coordination

Example of coordination-freeness: output all triangles

Transducer program

- Broadcast local edges
- Output a triangle when one can be derived

Coordination-free:

- Ideal distribution: whole database on one node
- Query is computed by only heartbeat transitions

Outline

CALM-Theorem (0)

Theorem (Ameloot, N., Van den Bussche, PODS 2011)

The following are equivalent. Query Q is

- *computable by a coordination-free relational transducer network;*
- *computable by an oblivious relational transducer network; and,*
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Corollary:

- coordination-free computations can only define monotone queries

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oblivious: not knowing the identities of all other nodes in the network

Corollary:

- coordination-free computations can only define monotone queries
- Complete language for coordination-free computation: language defining all monotone queries
  - e.g., Datalog with inequalities and value invention [Hull, Yoshikawa, 1990] [Cabibbo, 1998]

Weaker forms of monotonicity

Definition

A query Q is monotone if $Q(I) \subseteq Q(I \cup J)$ for all instances I and J.

Observation

If Q is monotone then $Q(I_s) \subseteq Q(I)$ for any $I_s \subseteq I$.

Weaker forms of monotonicity

Definition

A query Q is domain-distinct-monotone if

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for all instances I and J for which J is domain distinct from I.

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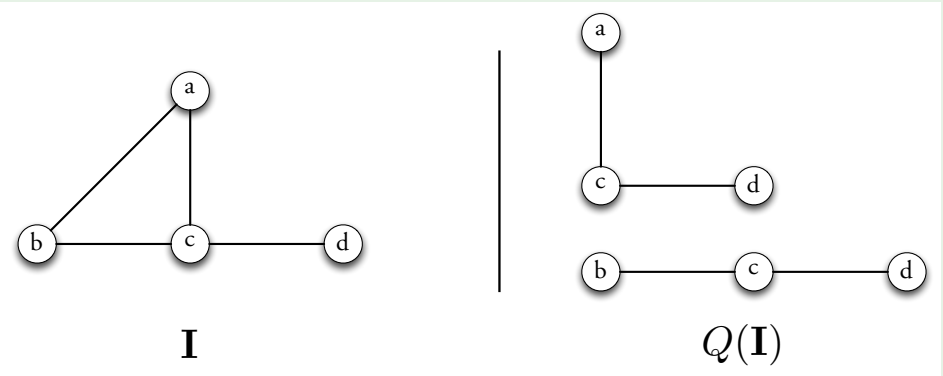
Selecting open triangles in a graph is domain-distinct-monotone.



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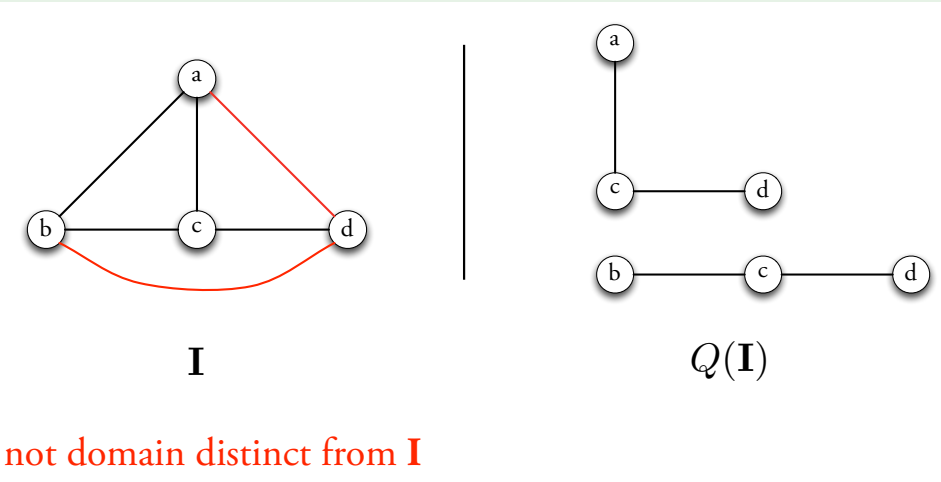

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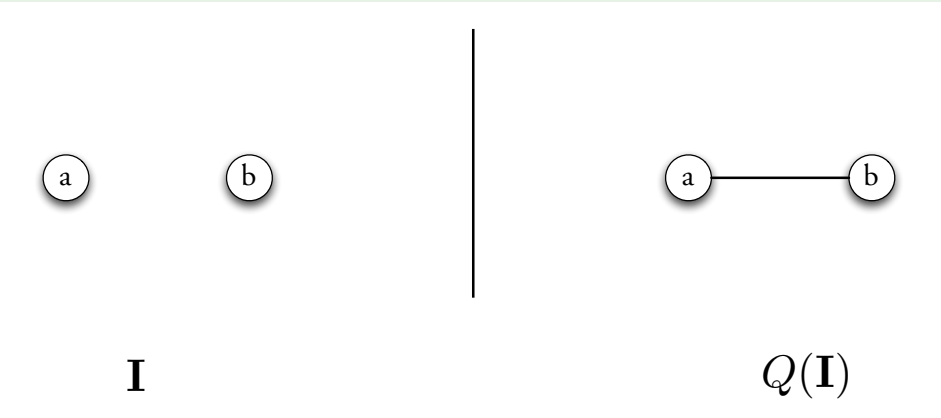

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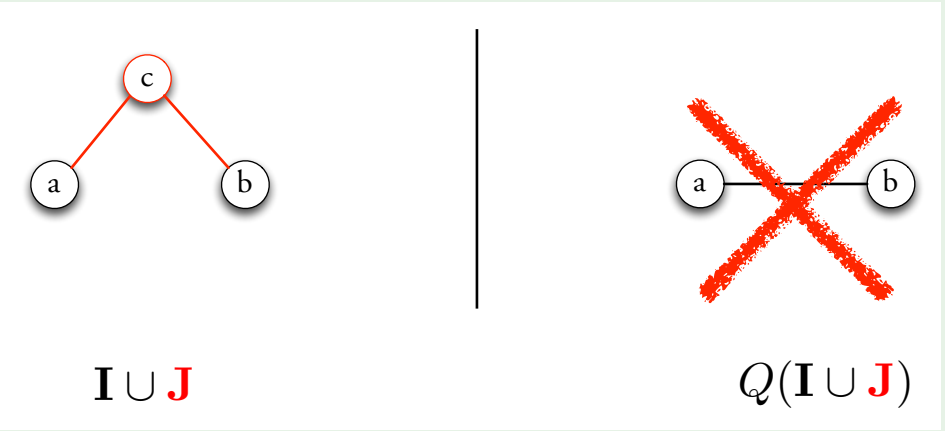

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Observation (preserved under extensions)

When Q is domain-distinct-monotone, then

$$Q(I_{|C}) \subseteq Q(I)$$

for all subsets of the domain C.

Induced subinstance: $I_C = \{\mathbf{f} \in I \mid \text{adom}(\mathbf{f}) \subseteq C\}$

CALM-Theorem (1)

Theorem (Ameloot, Ketsman, N., Zinn, PODS 2014)

The following are equivalent. Query Q is

1. *computable by a coordination-free relational transducer network that has access to the initial distribution;*
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Crux (2)→(1): (very rough)

- every transducer has access to the initial distribution:
  - broadcast both occurring and missing facts
- transducer outputs $Q(J_{|C})$ for every set C on which they have complete knowledge

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Corollary:

- Every language defining all domain-disjoint-monotone queries is a complete language for coordination-free computation
- Semi-positive datalog with value invention [Cabibbo, 1998]

Even weaker forms of monotonicity

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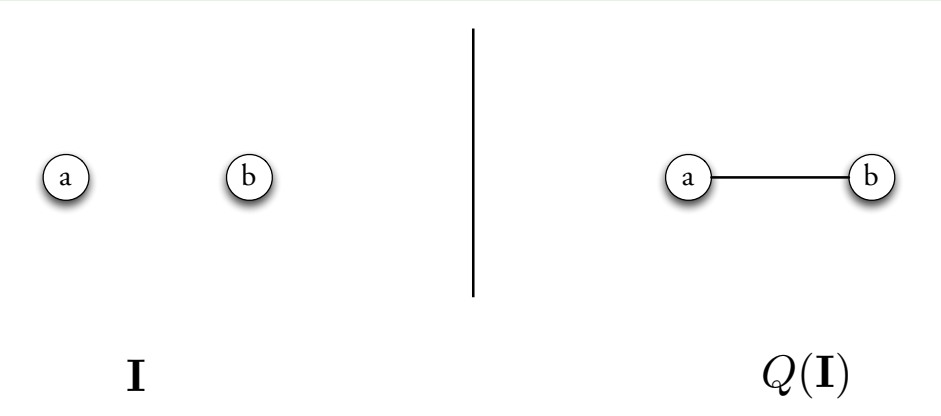

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Observation (preserved under disjoint extension)

When Q is domain-disjoint-monotone, then

$$Q(C) \subseteq Q(I)$$

for all instances I and connected components C of I.

CALM-Theorem (2)

Theorem (Ameloot, Ketsman, N., Zinn, PODS 2014)

The following are equivalent. Query Q is

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- Semi-connected Datalog with value invention [Ameloot, Ketsman, N., Zinn, PODS 2014]

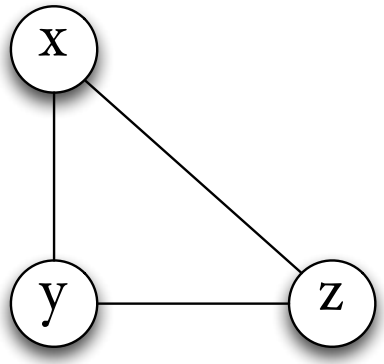
Connected Datalog rule

Definition

A Datalog¬ rule is connected when the graph formed by the positive atoms is connected.

Example

$\varphi \equiv O(x, y, z) \leftarrow E(x, y), E(y, z), E(z, x)$ is connected

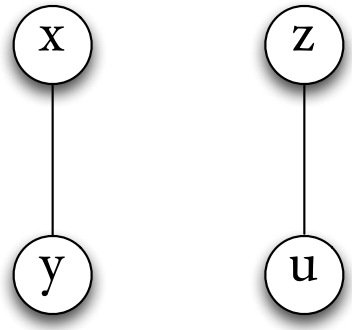


$graph^{+}(\varphi)$

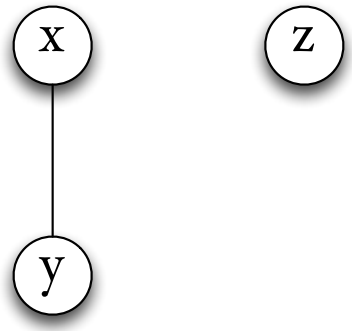
Connected Datalog rule

Example

$O(x, y, z) \leftarrow E(x, y), E(z, u)$ is not connected



$O(x, y, z) \leftarrow E(x, y), \neg E(y, z)$ is not connected



Semi-connected Datalog

Definition

A Datalog$^\neg$ program is semi-connected if all rules are connected except (possibly) those of the last stratum.

Example

$$\begin{array}{lcl} TC(x,y) & \leftarrow & E(x,y) \\ TC(x,y) & \leftarrow & E(x,z), TC(z,y) \\ \hline O(x,y) & \leftarrow & \neg TC(x,y), x \neq y \end{array}$$

- Semi-positive Datalog is strictly included in semi-connected Datalog$^\neg$
- Semi-connected Datalog$^\neg$ defines only domain-distinct-monotone queries

Connected Datalog

Win-move: $\mathsf{win}(x) \leftarrow \mathsf{move}(x, y), \neg\mathsf{win}(y)$

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The query computing the won positions of the win-move game is in $\mathcal{F}_2$

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Proof. Simulation in semi-monotone fragment of Datalog$_\forall^{\neg\neg}$ with a novel disorderly semantics [Abiteboul, Vianu, 1991].

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Theorem (Ameloot, Ketsman, N., Zinn, ICDT 2015)

Queries expressed in connected Datalog under the well-founded semantics are in $\mathcal{F}_2$.

CALM overview

$$
\begin{array}{ccccccccc}
\text{Datalog}(\neq) & \subsetneq & \text{wILOG}(\neq) & = & \mathcal{M} & = & \mathcal{F}_0 & = & \mathcal{A}_0 \\
\not\cap & & \not\cap & & \not\cap & & \not\cap & & \not\cap \\
\text{SP-Datalog} & \subsetneq & \text{SP-wILOG} & = & \mathcal{M}_{distinct} & = & \mathcal{F}_1 & = & \mathcal{A}_1 \\
\not\cap & & \not\cap & & \not\cap & & \not\cap & & \not\cap \\
\text{semicon-Datalog}^{\neg} & \subsetneq & \text{semicon-wILOG}^{\neg} & = & \mathcal{M}_{disjoint} & = & \mathcal{F}_2 & = & \mathcal{A}_2
\end{array}
$$

Intermediate wrap-up

Summary:

- CALM-theorems link Datalog, monotonicity, and coordination-freeness on different levels
- Connected Datalog

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- CALM-theorems link Datalog, monotonicity, and coordination-freeness on different levels
- Connected Datalog

Research issues:

- Broadcast algorithms are not efficient (initial steps in [Ketsman, N., ICDT 2015])
- Quantify coordination [Alvaro et al., CIDR 2011, ICDE 2014]
- General theory of asynchronous query evaluation to capture efficient evaluation

Outline

Discussion

- Overview
  - MPC & Shares/HyperCube
  - Parallel-correctness and transferability




  - Coordination-freeness and degrees of monotonicity




- Fascinating research area:
  - exciting new machinery
    - e.g., optimal fractional node/edge coverings
  - old wine in new bottles
    - e.g., decision problems relating to CQs
    - e.g., Datalog and monotonicity

Thank you for your attention

Questions?