Semantic data integration in P2P systems

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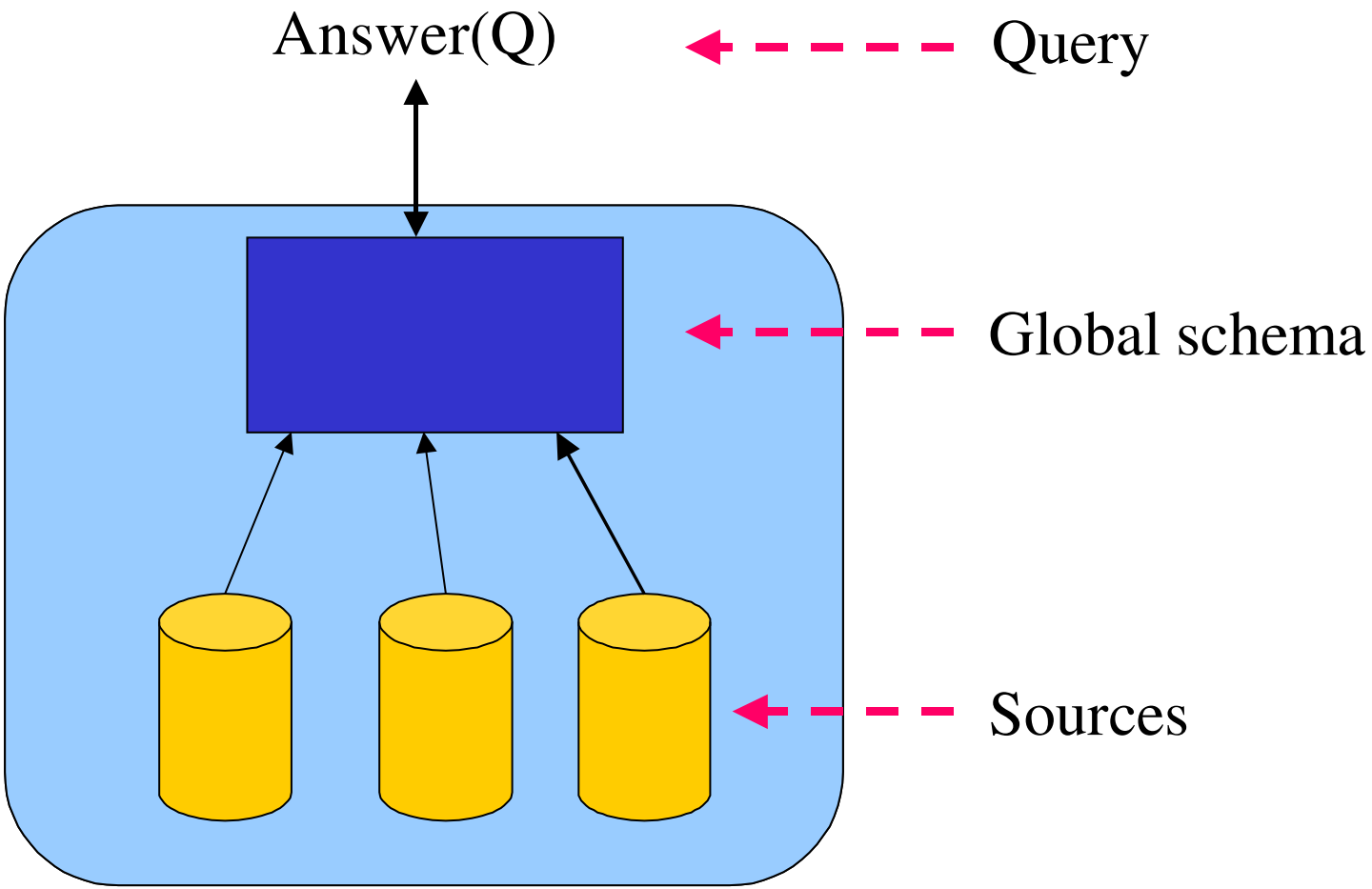
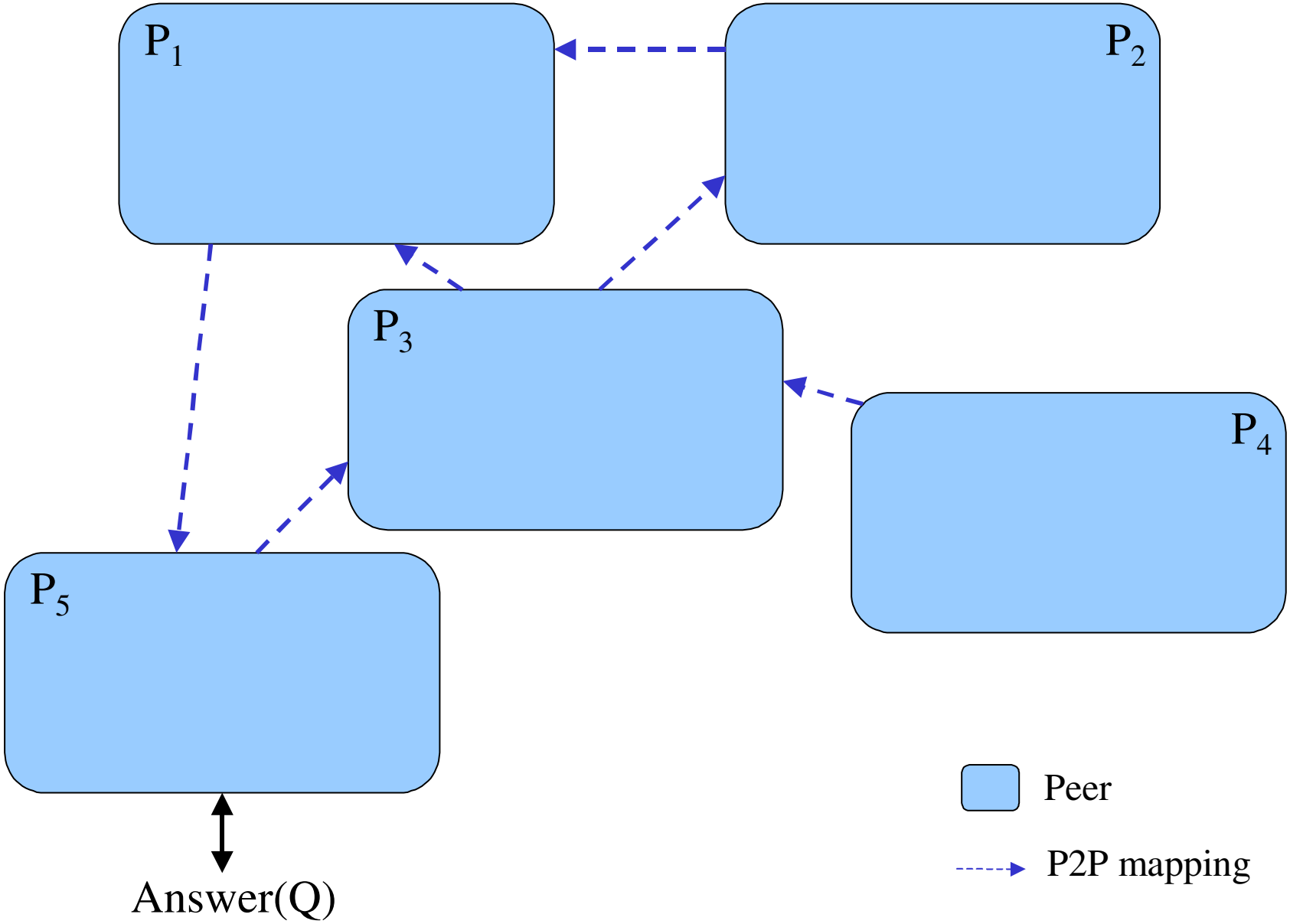
Mediator-based data integration



P2P data integration



Objectives of our work

- Definition of a **general framework** for P2P data integration
  - Structure of one peer
  - Structure of the whole systems
- Definition of **semantics** for P2P data integration
  - Semantics of one peer
  - Semantics of the whole system
    - based on first order logic
    - new proposal based on **epistemic logic**
- Techniques for **query answering** in the epistemic semantics

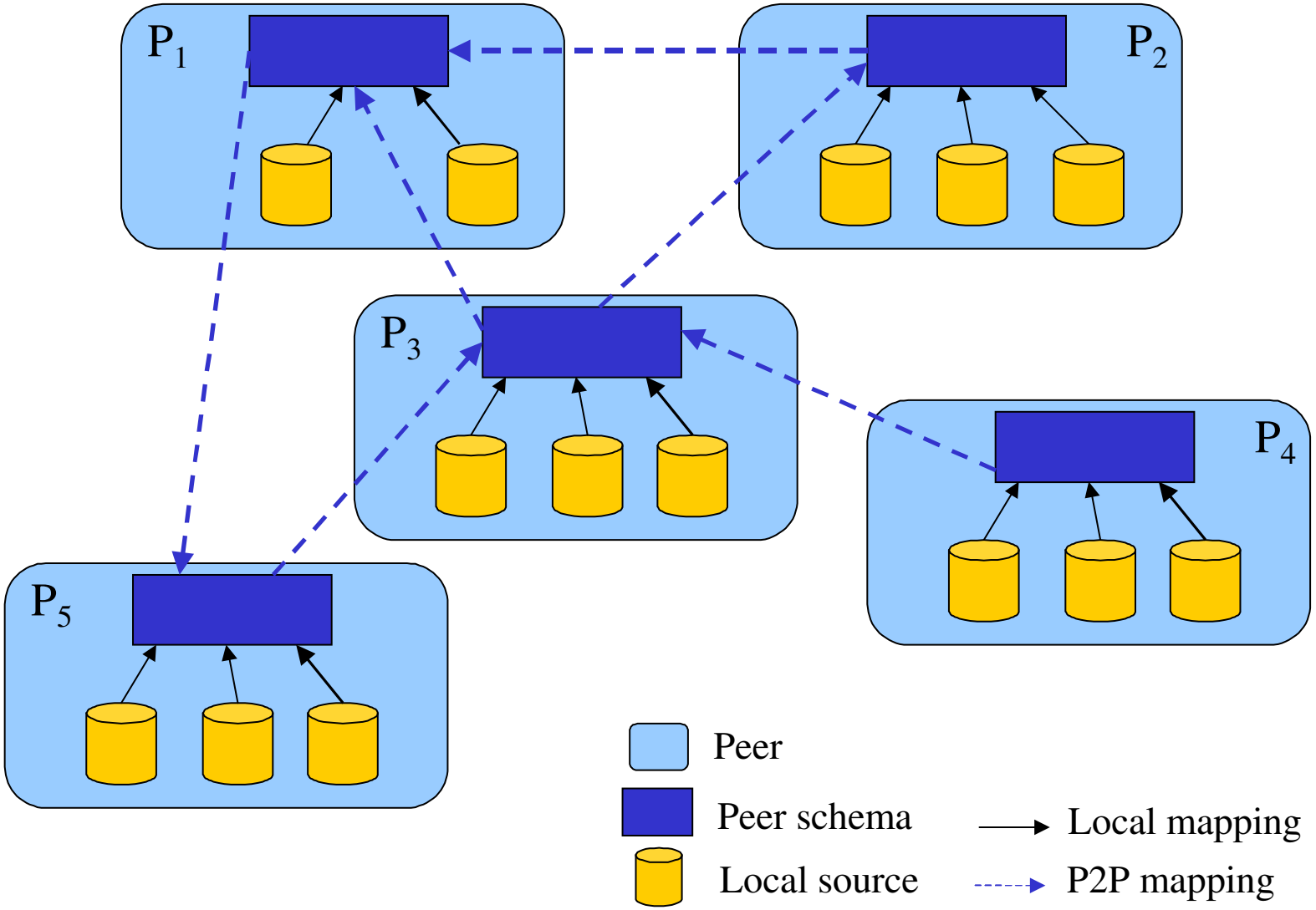
P2P data integration: general framework

A **P2P system** $\Pi = (\mathcal{P}, \mathcal{M})$ is constituted by

- a **set $\mathcal{P}$ of peers** $\{P_1, \ldots, P_n\}$,
  where each peer P_i models an autonomous information site, that
  - exports its information content in terms of a schema, and
  - stores actual data in a set of local sources
- a **set $\mathcal{M}$ of P2P mappings**,
  where each P2P mapping is a schema level assertion relating information between n peers (on one side) and one peer (on the other side)

Inspired by [Catarci&Lenzerini COOPIS '92], Halevy&al. ICDE'03]. Other related work: [Ghidini&Serafini FCS '98], [Bernstein&al. WebDB '02].

P2P data integration: general framework



Logic-based formal framework for P2P data integration

- Each peer P_i of Π is a triple (G_i, S_i, L_i) constituted by
  - a schema G_i, i.e., a set of FOL formulas over the peer alphabet A_{G_i}
  - a set S_i of local sources (finite relational alphabet)
  - a set L_i of local GLAV mappings from the sources S_i to the peer schema, each one of the form (ϕ_S and ϕ_G are conjunctions of atoms):

$$\exists \vec{\mathbf{z}} \phi_S(\vec{\mathbf{x}}, \vec{\mathbf{z}}) \rightsquigarrow \exists \vec{\mathbf{y}} \phi_G(\vec{\mathbf{x}}, \vec{\mathbf{y}})$$

- Each P2P mapping is an assertion of the form

$$q_1(\vec{\mathbf{x}}) \rightsquigarrow q_2(\vec{\mathbf{x}})$$

  where
  - q_1 is a FOL query over the union of the alphabets of the peers in $\mathcal{P}$,
  - q_2 is a FOL query over the alphabet of a single peer, and
  - q_1 and q_2 are of the same arity

Formal framework for P2P data integration: semantics

- We refer to a fixed infinite interpretation domain Δ, common to all peers. We also refer to a fixed, infinite, denumerable, set Γ of constants, that act as *standard names*, i.e., Γ is isomorphic to the interpretation domain
- A local source database $\mathcal{D}$ for Π is a database over Γ for the set L of all local source predicates in the various peers of Π
- A global database for Π is a database over Γ for the symbols in $\mathcal{A}_\Pi$, the alphabet of the union G of all peer schemas of Π (which are assumed to be pairwise disjoint)
- A global database for Π is said to be legal wrt G if it satisfies all peer schemas

Formal framework for P2P data integration: semantics

Given a local source database $\mathcal{D}$ for Π, the set of models of Π relative to $\mathcal{D}$ is:

$sem^{\mathcal{D}}(\mathbf{\Pi}) = \{\ \mathcal{B}$ | $\mathcal{B}$ is a global database for Π that is legal wrt G, and satisfies all local mapping assertions wrt $\mathcal{D}$, and satisfies all P2P mapping assertions $\}$

- $\mathcal{B}$ satisfies a local mapping assertion $\exists\vec{\mathbf{z}}\phi_S(\vec{\mathbf{x}},\vec{\mathbf{z}}) \rightsquigarrow \exists\vec{\mathbf{y}}\phi_i(\vec{\mathbf{x}},\vec{\mathbf{y}})$ wrt $\mathcal{D}$ if $(\exists\vec{\mathbf{z}}\phi_S(\vec{\mathbf{x}},\vec{\mathbf{z}}))^{\mathcal{D}} \subseteq (\exists\vec{\mathbf{y}}\phi_i(\vec{\mathbf{x}},\vec{\mathbf{y}}))^{\mathcal{B}}$
- the meaning of $\mathcal{B}$ satisfying a P2P mapping assertion may vary in the various approaches

The set of certain answers to a query Q of arity n posed to a peer P of Π wrt the source database $\mathcal{D}$ is the set

$$ans(Q^P, \Pi, \mathcal{D}) = \{\ \vec{\mathbf{t}} \in \Gamma^n \mid \forall \mathcal{B} \in sem^{\mathcal{D}}(\Pi) :\ \vec{\mathbf{t}} \in Q^{\mathcal{B}}\}$$

Formalization of one peer

From the above definition, it follows that we are modeling each peer $P = (G, S, L)$ as a GLAV data integration system, in turn modeled as a FOL theory T_P:

- The alphabet of T_P is obtained as union of the alphabet of G and the alphabet of the local sources S of P,
- The formulas of T_P are obtained as follows:
  - there is one formula of the form

$$\forall \vec{\mathbf{x}} \, (\exists \vec{\mathbf{z}} \phi_S(\vec{\mathbf{x}}, \vec{\mathbf{z}}) \rightarrow \exists \vec{\mathbf{y}} \phi_S(\vec{\mathbf{x}}, \vec{\mathbf{y}}))$$

    for each local mapping assertion $\exists \vec{\mathbf{z}} \phi_S(\vec{\mathbf{x}}, \vec{\mathbf{z}}) \rightsquigarrow \exists \vec{\mathbf{y}} \phi_i(\vec{\mathbf{x}}, \vec{\mathbf{y}})$
  - T_P includes all the FOL formulas expressing the schema G.

Possible formalizations of P2P mapping

We consider two alternatives for specifying the semantics of P2P mappings:

- Based on First Order Logic

  P2P mappings are considered as material logical implication

- New proposal based on Epistemic Logic

  P2P mappings are considered as specifications of exchange of certain answers

First order logic semantics of P2P mappings

According to most approaches (see [Halevy&al. ICDE'03], [Bernstein&al. WebDB '02]), the semantics of P2P mapping assertions in a P2P system Π is given in terms of first order logic (FOL), where satisfaction of a P2P mapping assertion

$$q_1(\vec{\mathbf{x}}) \rightsquigarrow q_2(\vec{\mathbf{x}})$$

of Π by a global database $\mathcal{B}$ means

- satisfaction of the FOL formula

$$\forall \vec{\mathbf{x}}\, q_1(\vec{\mathbf{x}}) \rightarrow q_2(\vec{\mathbf{x}})$$

- which is equivalent to the condition

$$q_1^{\mathcal{B}} \subseteq q_2^{\mathcal{B}}$$

First order logic semantics of P2P mappings

We claim that the FOL semantics is not adequate for P2P data integration, because

- The system is modeled by a flat FOL theory, with no formal separation between the various peers
- The modular structure of the system is not reflected in the semantics
- Bad computational properties: computing the set of certain answers to a conjunctive query Q posed to a peer is undecidable (see [Halevy&al. ICDE'03], [Koch FOIKS'02]), even for simple P2P systems, (i.e., when all peer schemas are empty, and P2P mappings are conjunctive, see later)
- In order to recover decidability, one has to limit the expressive power of P2P mappings (e.g., acyclicity of P2P mappings is assumed in [Halevy&al. ICDE'03])

Epistemic semantics for P2P mappings: objectives

We propose a new semantics for P2P mappings, with the following aims:

- We want to take into account that peers in our context are to be considered autonomous sites, that exchange information
- We do not want to limit a-priori the topology of the mapping assertions among the peers in the system
- We seek for a semantic characterization that leads to a setting where query answering is decidable, and possibly, polynomially tractable

Epistemic semantics for P2P mappings: basic idea

The new semantics is based on epistemic logic [Reiter TARK '88]

- A P2P mapping $q_1(\vec{\mathbf{x}}) \rightsquigarrow q_2(\vec{\mathbf{x}})$ is interpreted as an epistemic formula which imposes that only the certain answers to $q_1(\vec{\mathbf{x}})$ in the peers $i_1, \ldots, i_m$ are transferred to peer j as facts satisfying q_2 (peers $i_1, \ldots, i_m$ communicate to peer j only facts that are certain, i.e., true in every model of the P2P system)
- The modular structure of the system is now reflected in the semantics (by virtue of the modal semantics of epistemic logics)
- Good computational properties: for simple P2P systems, computing the set of certain answers to a conjunctive query Q wrt a local source database $\mathcal{D}$ is not only decidable, but also polynomial time in the size of $\mathcal{D}$, even for cyclic mappings

Epistemic logic: basic notions

In epistemic logic, we have a new form of atoms, namely (α is again a formula):

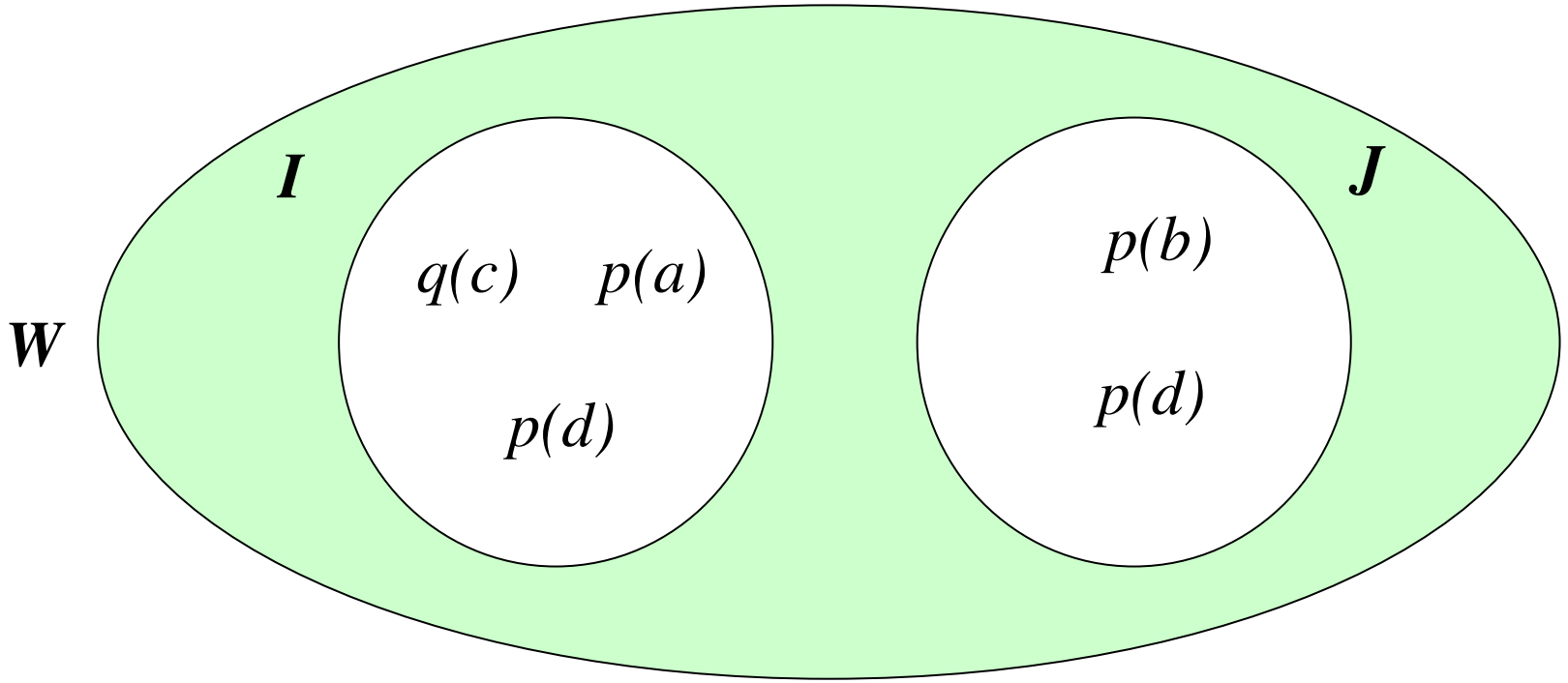
$$\mathbf{K}\,\alpha$$

An epistemic interpretation $\mathcal{E}$ is a pair $(\mathcal{I}, \mathcal{W})$, where $\mathcal{I}$ is a FOL interpretation, $\mathcal{W}$ is a set of FOL interpretations, and $\mathcal{I} \in \mathcal{W}$.

- a FOL formula constituted by an atom $f(\vec{\mathbf{x}})$ is satisfied in $(\mathcal{I}, \mathcal{W})$ by the tuples $\vec{\mathbf{t}}$ of constants such that $f(\vec{\mathbf{t}})$ is true in $\mathcal{I}$
- an atom of the form $\mathbf{K}\alpha(\vec{\mathbf{x}})$ is satisfied in $(\mathcal{I}, \mathcal{W})$ by the tuples $\vec{\mathbf{t}}$ of constants such that $\alpha(\vec{\mathbf{t}})$ is satisfied in all the pairs $(\mathcal{J}, \mathcal{W})$ such that $\mathcal{J} \in \mathcal{W}$

An epistemic model of an epistemic logic theory $\{\phi_1, \ldots, \phi_t\}$ (finite set of global axioms) is an epistemic interpretation $(\mathcal{I}, \mathcal{W})$ that satisfies every axiom of the theory, i.e., such that for every $\mathcal{J} \in W$, each ϕ_i is satisfied by $(\mathcal{J}, \mathcal{W})$.

Epistemic logic: examples

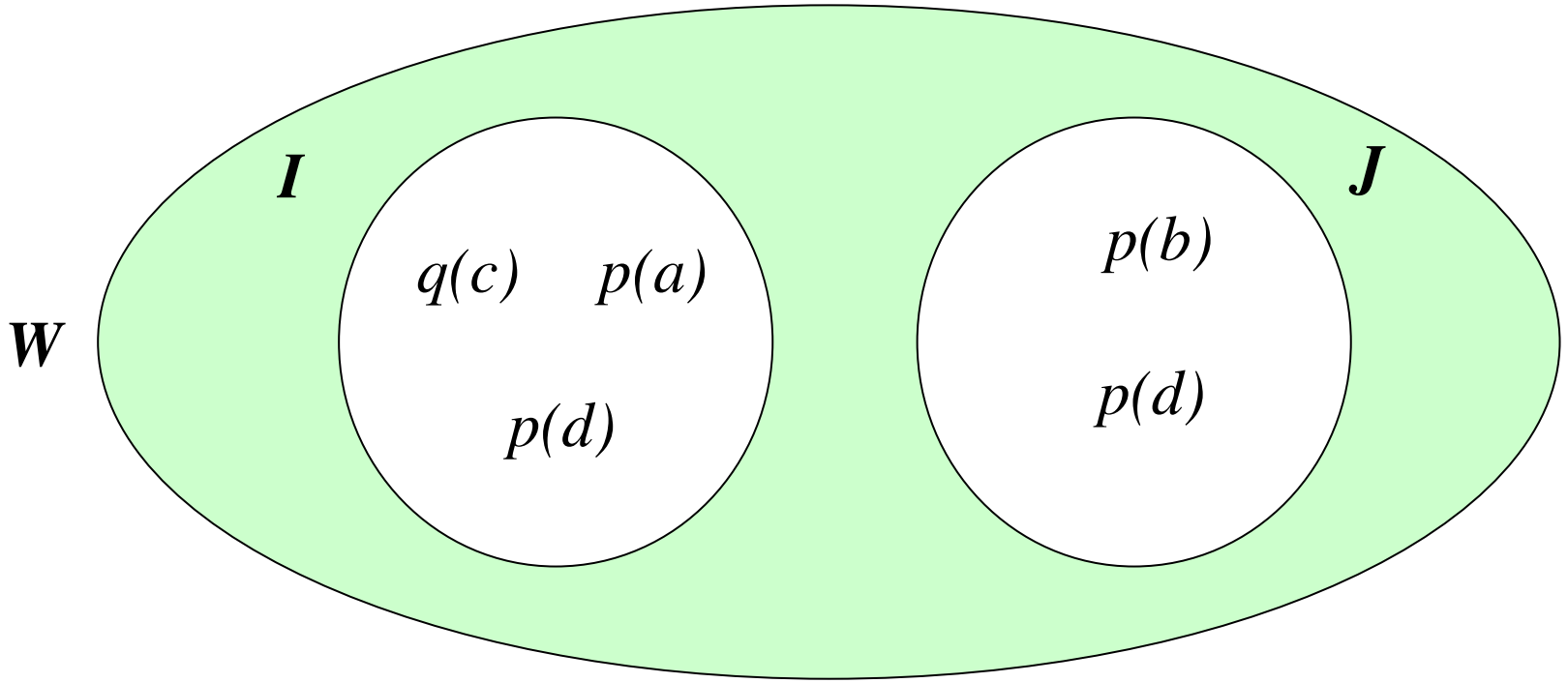


$$(\mathcal{I}, \mathcal{W}) \models q(c)$$

$$(\mathcal{J}, \mathcal{W}) \not\models q(c)$$

$$(\mathcal{I}, \mathcal{W}) \not\models \mathbf{K}\, q(c)$$

Epistemic logic: examples



$$(\mathcal{I}, \mathcal{W}) \models \mathbf{K}\,(p(a) \vee p(b))$$

$$(\mathcal{I}, \mathcal{W}) \not\models (\mathbf{K}\,p(a)) \vee (\mathbf{K}\,p(b))$$

$$(\mathcal{J}, \mathcal{W}) \models \mathbf{K}\,p(d)$$

Epistemic semantics for P2P mappings: basic idea

We formalize a P2P system $\Pi = (\mathcal{P}, \mathcal{M})$ in terms of the epistemic logic theory E_Π:

- the alphabet $\mathcal{A}_\Pi$ is the disjoint union of the alphabets of the various peer theories, one corresponding to one peer in $\mathcal{P}$
- all the formulas of the various theories T_P are axioms in E_Π,
- there is one axiom in E_Π of the form

$$\forall \vec{\mathbf{x}} \ ((\mathbf{K}\, q_1(\vec{\mathbf{x}})) \rightarrow q_2(\vec{\mathbf{x}}))$$

for each P2P mapping assertion $q_1(\vec{\mathbf{x}}) \rightsquigarrow q_2(\vec{\mathbf{x}})$ in $\mathcal{M}$.

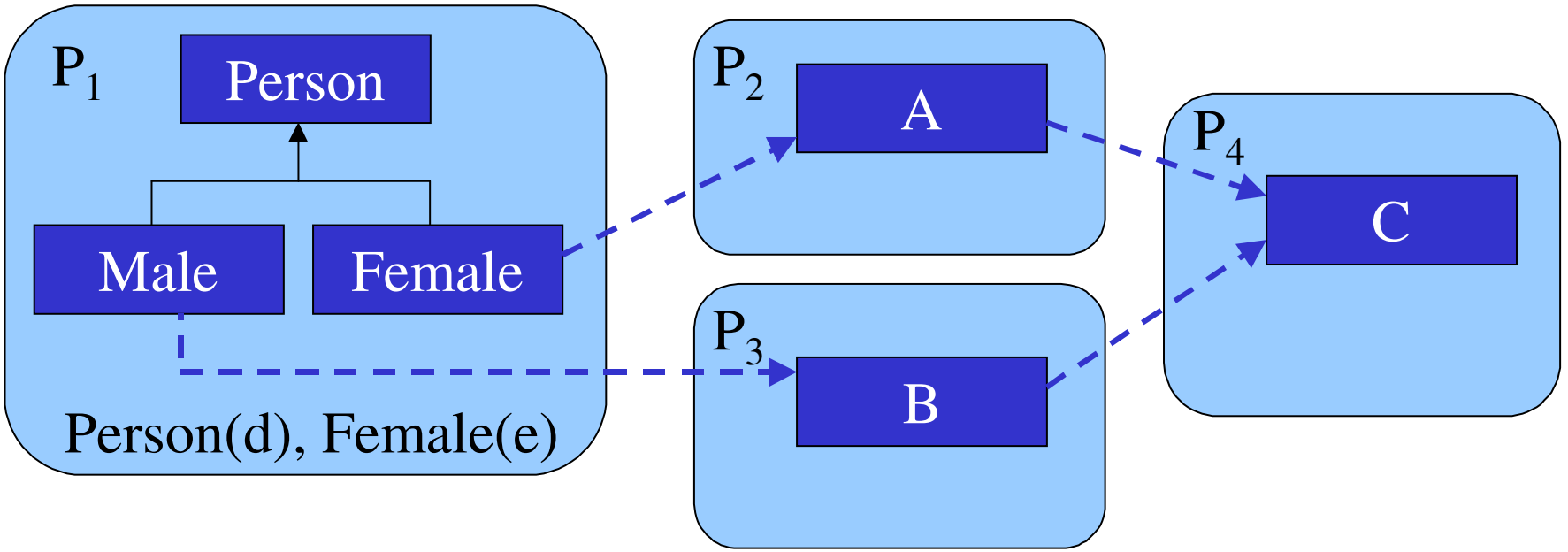
Epistemic semantics for P2P mappings: basic idea

An epistemic interpretation $(\mathcal{I}, \mathcal{W})$ for Π based on $\mathcal{D}$ satisfies the P2P mapping assertion $q_1(\vec{\mathbf{x}}) \rightsquigarrow q_2(\vec{\mathbf{x}})$ if, for every $(\mathcal{J}, \mathcal{W})$ such that $\mathcal{J} \in \mathcal{W}$, for every tuple $\vec{\mathbf{t}}$ of objects in Γ, the fact that $q_1(\vec{\mathbf{t}})$ is satisfied in every FOL models in $\mathcal{W}$ implies that $q_2(\vec{\mathbf{t}})$ is satisfied in $\mathcal{J}$.

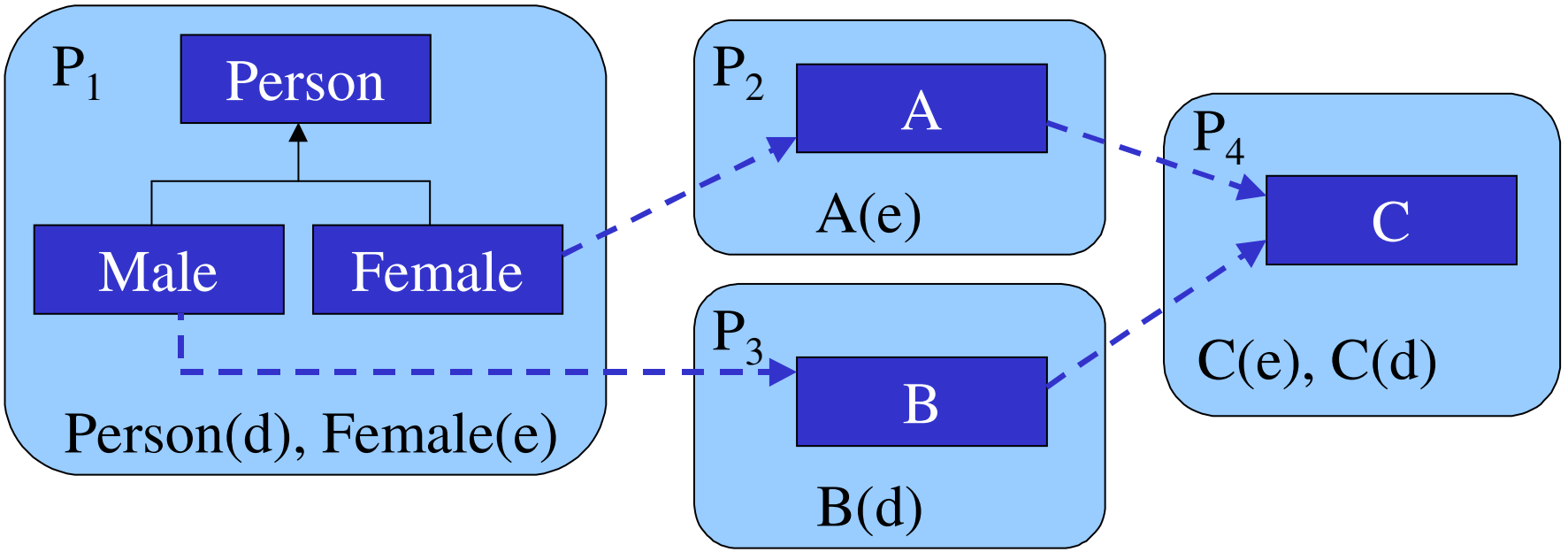
An epistemic model for $\Pi = (\mathcal{P}, \mathcal{M})$ based on $\mathcal{D}$ is any epistemic interpretation for Π based on $\mathcal{D}$ that satisfies all the axioms corresponding to the P2P mapping assertions in $\mathcal{M}$.

Let q be a query over one peer of Π. The certain answer $ans_{\mathbf{k}}(q, \Pi, \mathcal{D})$ to q in Π based on $\mathcal{D}$ is the set of tuples $\vec{\mathbf{t}}$ of objects in Γ such that $q(\vec{\mathbf{t}})$ is satisfied in every epistemic model $(\mathcal{I}, \mathcal{W})$ of Π based on $\mathcal{D}$.

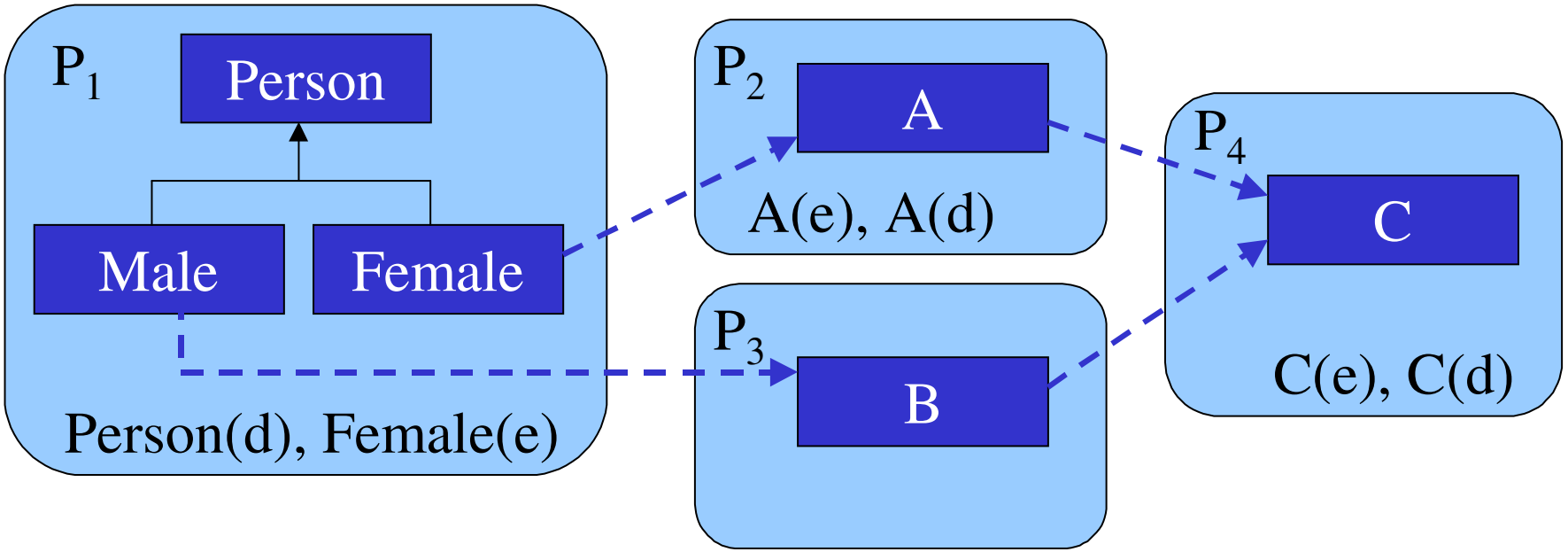
Semantics of P2P mappings: example



FOL Semantics of P2P mappings: model 1

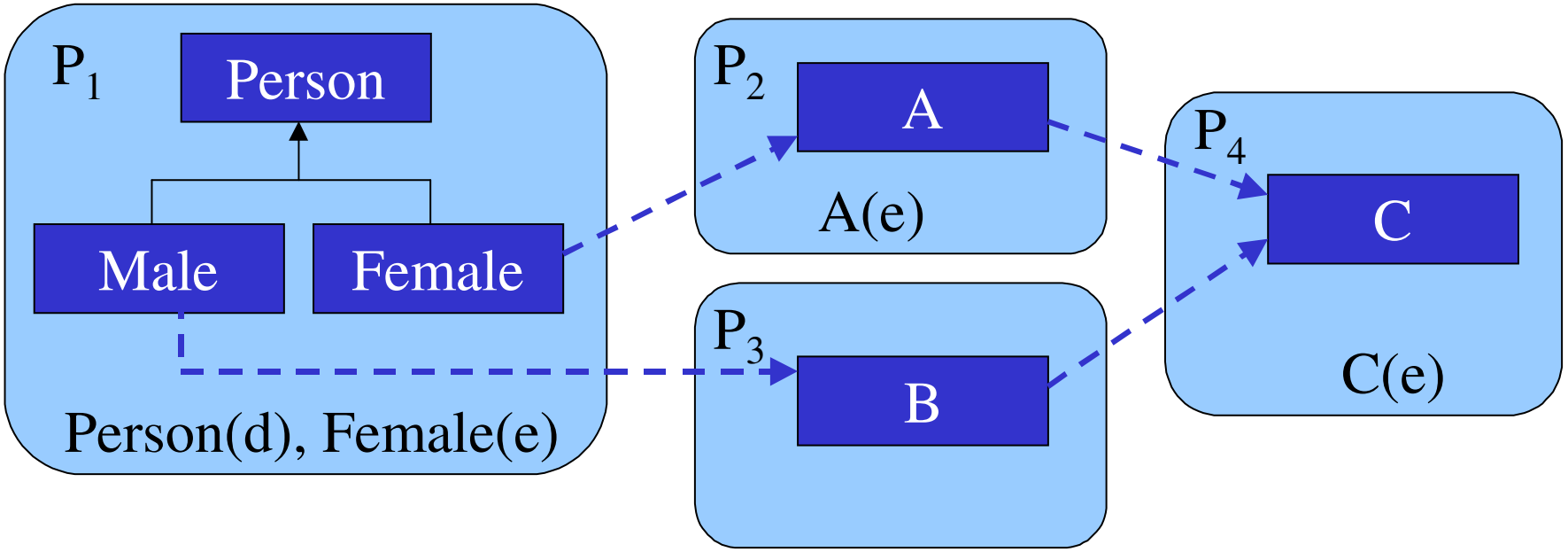


FOL Semantics of P2P mappings: model 2



According to the FOL semantics, $C(d)$ is a true in all cases, and therefore is a certain answer.

Epistemic Semantics of P2P mappings



According to the epistemic semantics, $C(d)$ is not a certain answer.

Query answering for simple P2P systems

We call a P2P system $\Pi = (\mathcal{P}, \mathcal{M})$ simple if it satisfies the following restrictions:

1. peer theories are empty, i.e., each peer schema of Π simply consists of a relational alphabet

2. P2P mapping assertions in $\mathcal{M}$ are expressed using conjunctive queries, i.e., a P2P mapping assertion is an expression of the form $q_1(\vec{\mathbf{x}}) \rightsquigarrow q_2(\vec{\mathbf{x}})$, where q_1 and q_2 are conjunctive queries of the same arity, q_1 is expressed over the union of the alphabets of the peers, and q_2 is expressed over the alphabet of a single peer

3. the language for querying the P2P system is union of conjunctive queries (UCQ), i.e., a query over a P2P system is a UCQ over the alphabet of a single peer

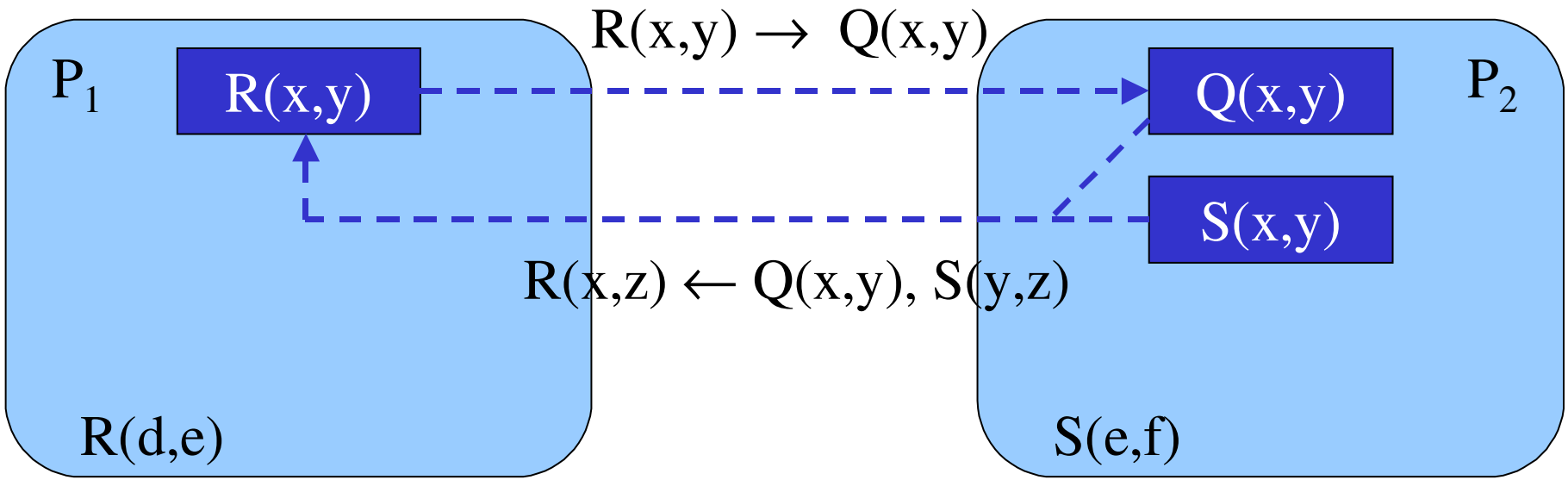
Query answering for simple P2P systems

We have proved that, given an UCQ q posed to a simple P2P system S, and given a source database $\mathcal{D}$ for Π, one can construct a finite database *RDB* on the alphabet $\mathcal{A}_\Pi$ that is the union of the alphabet of the peer schemas in Π, such that for each tuple $\vec{\mathbf{t}}$ of constants in Γ, $\vec{\mathbf{t}} \in \mathit{ans}_{\mathbf{k}}(q, \Pi, \mathcal{D})$ if and only if $\vec{\mathbf{t}} \in q^{\mathit{RDB}}$.

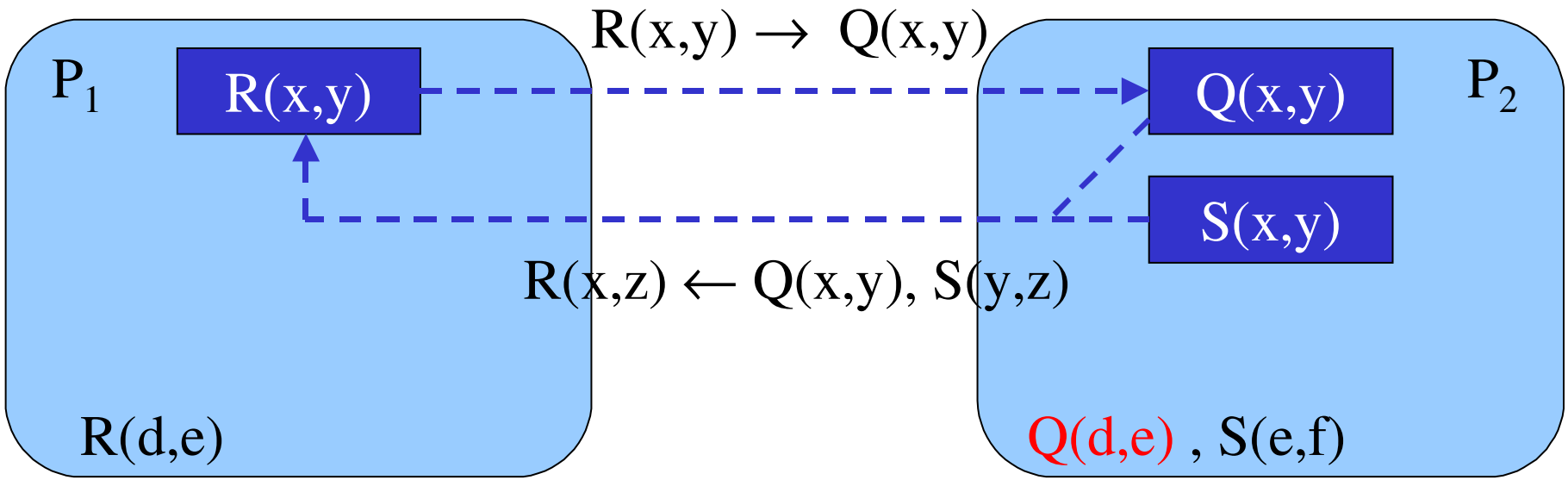
Intuitively, such a finite database *RDB* constitutes a "representative" of all the epistemic models for Π based on $\mathcal{D}$ with respect to the query q.

The size of *RDB* is polynomial in the size of source database $\mathcal{D}$, and the whole process of query answering has polynomial time complexity in the size of source database $\mathcal{D}$.

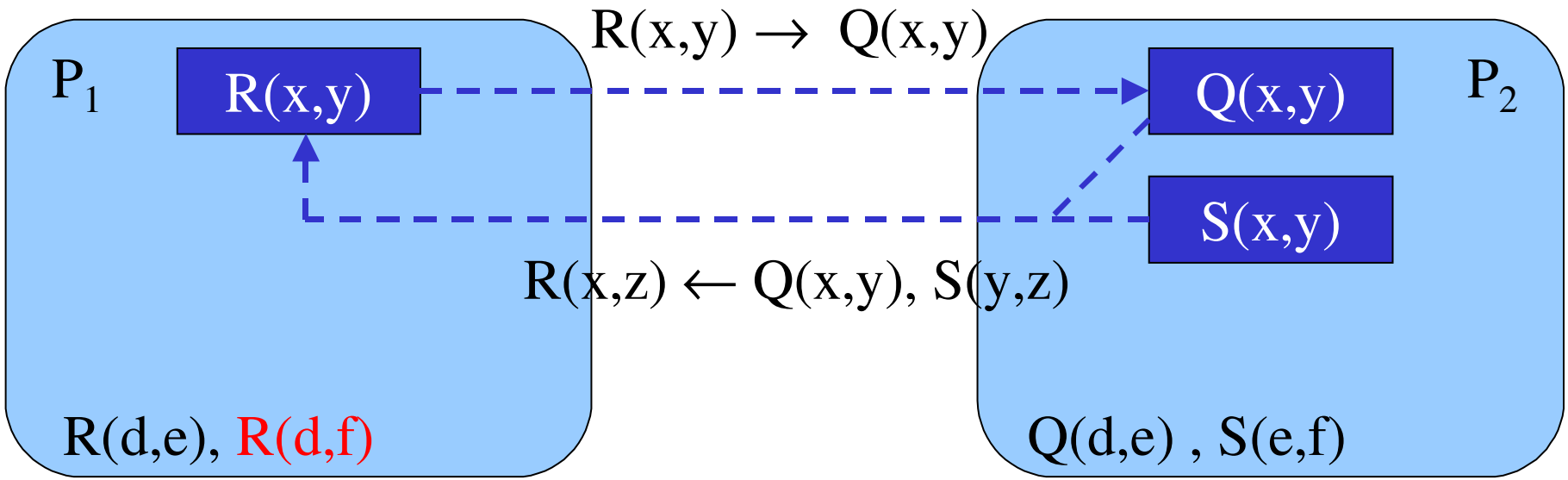
Query answering for simple P2P systems: example



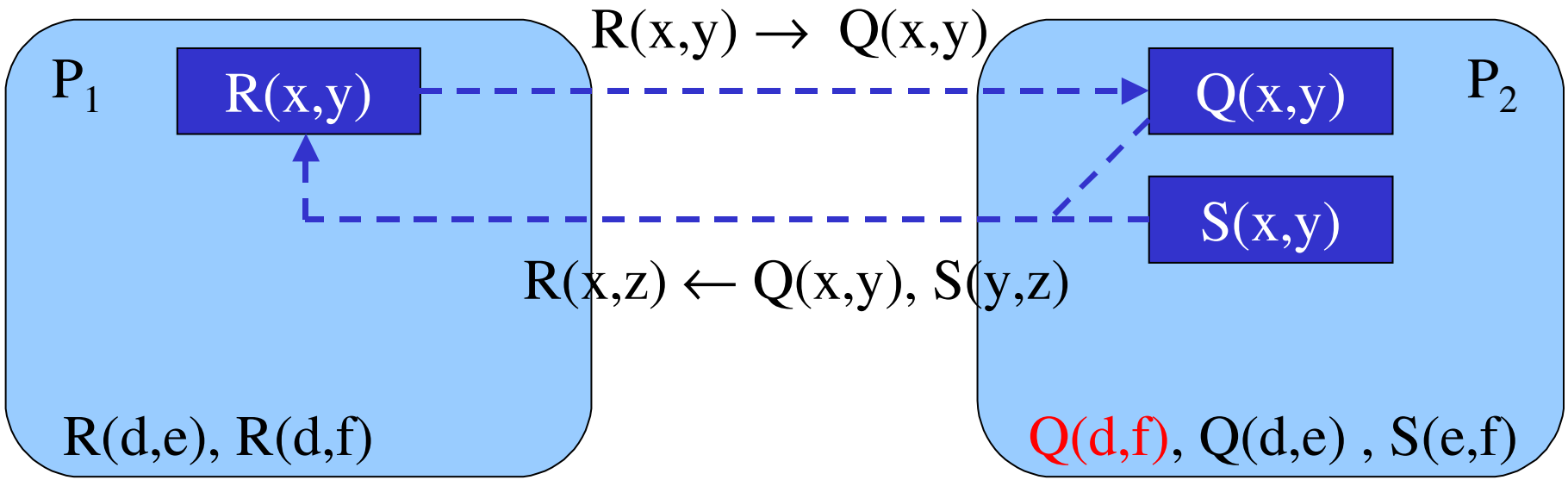
Query answering for simple P2P systems: example



Query answering for simple P2P systems: example



Query answering for simple P2P systems: example



Query answering for simple P2P systems

Algorithm answer($\Pi, \mathcal{D}, q$)

Input simple P2P system $\Pi = (\mathcal{P}, \mathcal{M})$, with $\mathcal{P} = \{P_1, \ldots, P_n\}$,
source database $\mathcal{D}$ for Π, UCQ q over one peer P_i

Output set of tuples of objects in Γ

begin

RDB $\leftarrow \emptyset$;

for $i = 1, \ldots, n$ **do** *RDB* $\leftarrow$ retrieve-data-by-local-mapping$(\Pi, P_i, D,$ *RDB*$)$;

repeat

RDB' $\leftarrow$ *RDB*;

RDB $\leftarrow$ retrieve-data-by-P2P-mapping$(\mathcal{M},$ *RDB*$)$

until *RDB'* $=$ *RDB*;

return q^{RDB}

end

Current work

- A new algorithm driven by the query and the structure of mappings
- More expressive peer schemas, by adding integrity constraints to simple P2P systems, in the line of [Calì&al. Information Systems ’03]
- Dealing with inconsistencies between peers, in the line of [Calì&al. PODS’03]
- Dealing with peers with limited query capabilities
- Dealing with different vocabularies of constants in different peers in the line of [Bernstein&al. WebDB ’02]
- Experiments within the Infomix European project, and the Sewasie European project