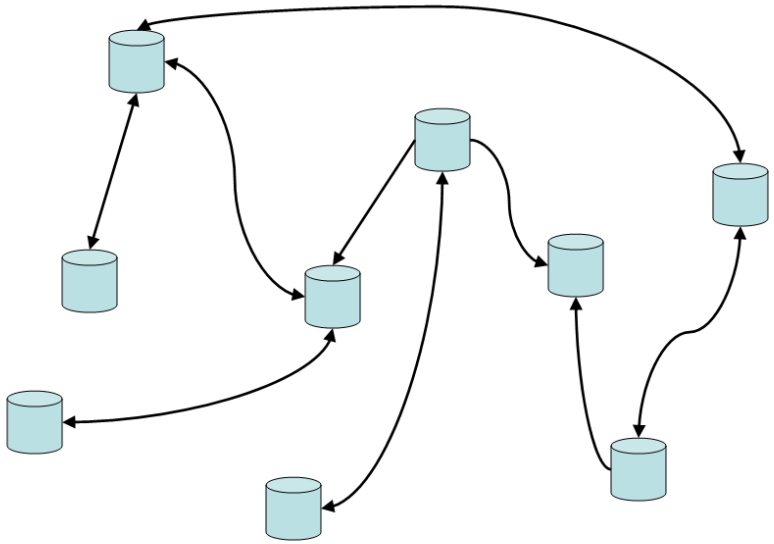
The Semantics of Consistency and Trust in Peer Data Exchange Systems

Leopoldo Bertossi*
Carleton University
Ottawa, Canada
bertossi@scs.carleton.ca

Loreto Bravo
University of Edinburgh
Edinburgh, UK
lbravo@inf.ed.ac.uk

Peer-to-Peer Data Exchange Systems



Each peer has a local and autonomous database

Data at two different peers may be related by data exchange constraints (DECs) (or data mappings)

Local queries are posed to individual peers

Peers exchange data when they answer their queries

How data is exchanged depends on the query, the DECs, the data at the relevant peers, and also on trust relationships between peers

A peer does not update its physical instance according to its DECs and other peers' instances

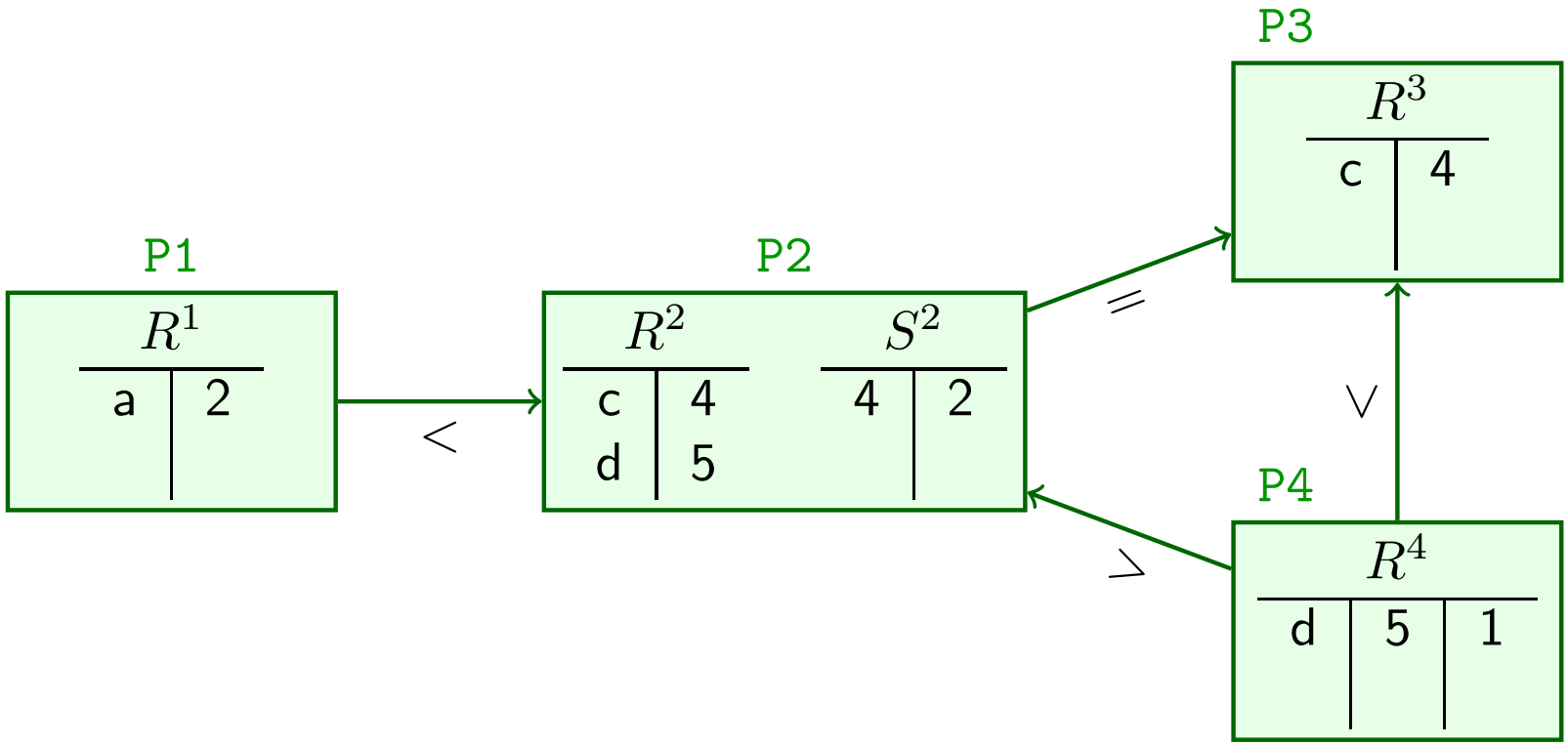
However, if a peer P is answering a (local) query $Q_{\mathtt{P}}$, it may, at query time:

- Import data from other peers to complement its data
- Ignore part of its own data

All this depending upon its own DECs and the peers' instances

But also upon the trust relationships that P has with other peers

Example: Peers, their schemas, instances, DECs, trust relationships:



DECs:

$\Sigma(\mathsf{P1},\mathsf{P2}) = \{\forall x \forall y (R^2(x,y) \rightarrow R^1(x,y))\}$

$\Sigma(\mathsf{P2},\mathsf{P3}) = \{\forall x \forall y (R^2(x,y) \wedge R^3(x,y) \rightarrow \mathbf{false})\}$

$\Sigma(\mathsf{P4},\mathsf{P2}) = \{\forall x \forall y \forall z (R^2(x,y) \wedge S^2(y,z) \rightarrow R^4(x,y,z))\}$

$\Sigma(\mathsf{P4},\mathsf{P3}) = \{\forall x \forall y (R^3(x,y) \rightarrow \exists z R^4(x,y,z))\}$

We consider data exchange constraints (DECs) of the following kinds:

- *Universal data exchange constraint* (UDEC) between peers P1, P1:

$$\forall \bar{x}(\bigwedge_{i=1}^{n} R_i(\bar{x}_i) \longrightarrow (\bigvee_{j=1}^{m} Q_j(\bar{y}_j) \vee \varphi)) \tag{1}$$

  $R_i, Q_j \in \mathcal{R}(\mathtt{P1}) \cup \mathcal{R}(\mathtt{P2})$, and φ is a disjunction of built-in atoms

- *Referential data exchange constraint* (RDEC) between peers P1, P1:

$$\forall \bar{x}(R(\bar{x}) \longrightarrow \exists \bar{y}\ Q(\bar{x}', \bar{y})) \tag{2}$$

  $R, Q \in \mathcal{R}(\mathtt{P1}) \cup \mathcal{R}(\mathtt{P2})$, and $\bar{x}' \subseteq \bar{x}$

$\mathcal{R}(\mathtt{P})$ is the relational schema of peer P

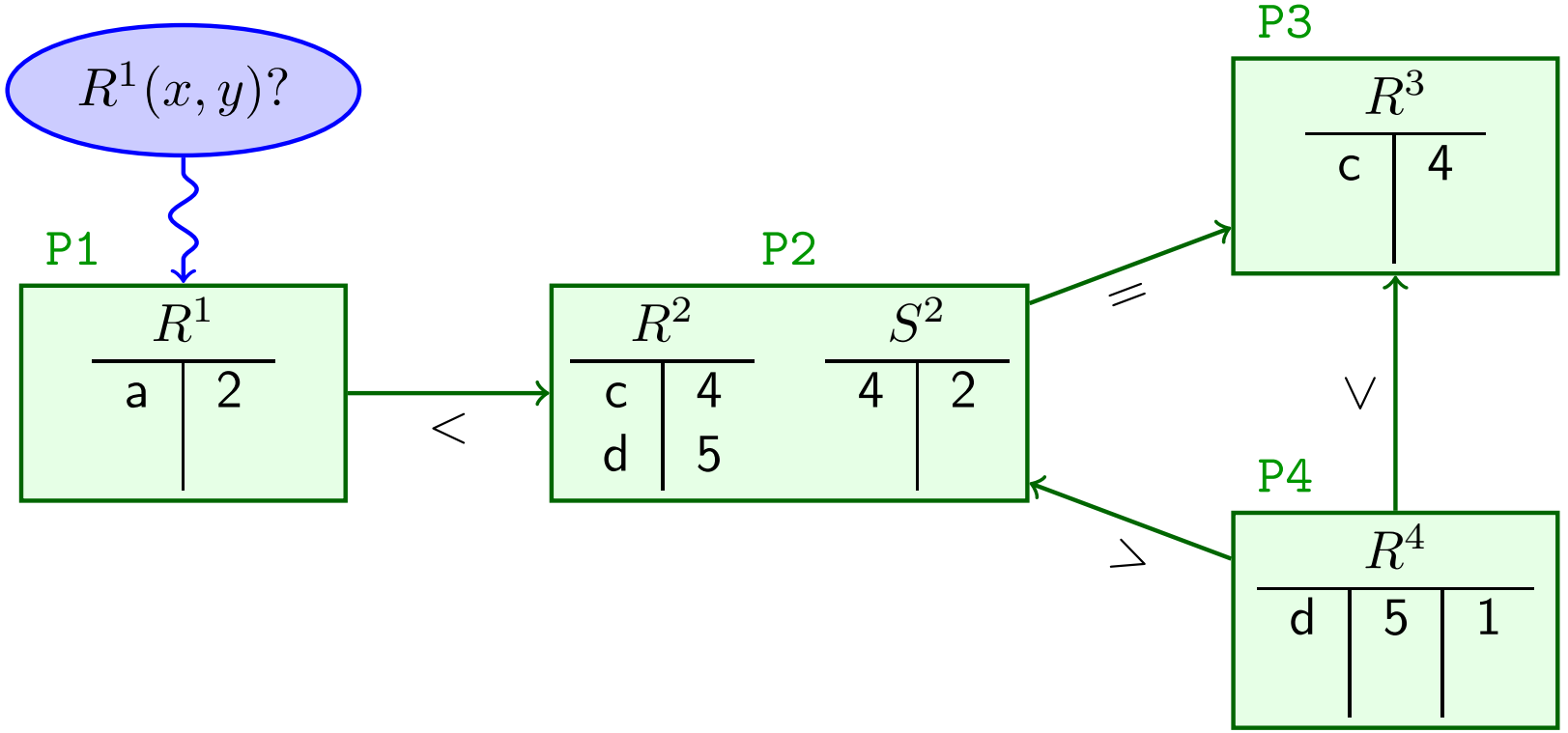
When a peer P receives a query:

- P sends queries to its neighbors to check the satisfaction of its DECs
- If they are not satisfied, P tries to restore satisfaction of (consistency wrt) its DECs
  - ▷ A repair, that satisfies the DECs, respects the trust relationships and is "as close as possible" to P's original data is called a Solution for P
- There might be many solutions
  - ▷ Peer P will only return the data or query answers that are certain, i.e. that are true in all of P's solutions
  - ▷ These are the peer consistent answers (PCAs) from P

The answers to its queries to a neighbor P' are also true in all solutions for P'

The same idea/process has to be applied to P's neighbors, and so on ...

Idea, intuitions, "operational" semantics



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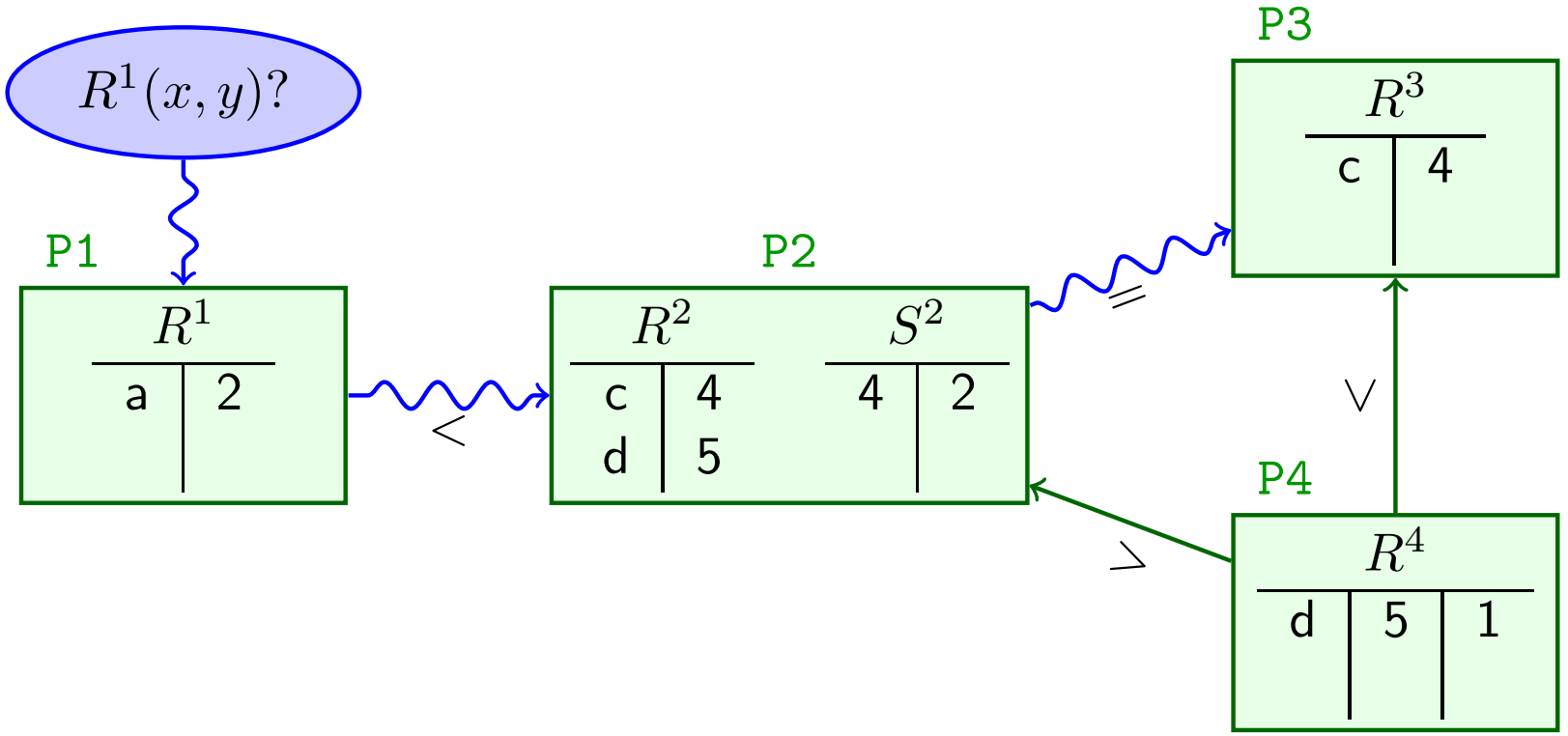
$$\left.\begin{array}{ll}\Sigma(\mathsf{P4},\mathsf{P3}) = & \{\forall x\forall y(R^3(x,y) \rightarrow \exists z R^4(x,y,z))\}\end{array}\right\} \text{RDEC}$$



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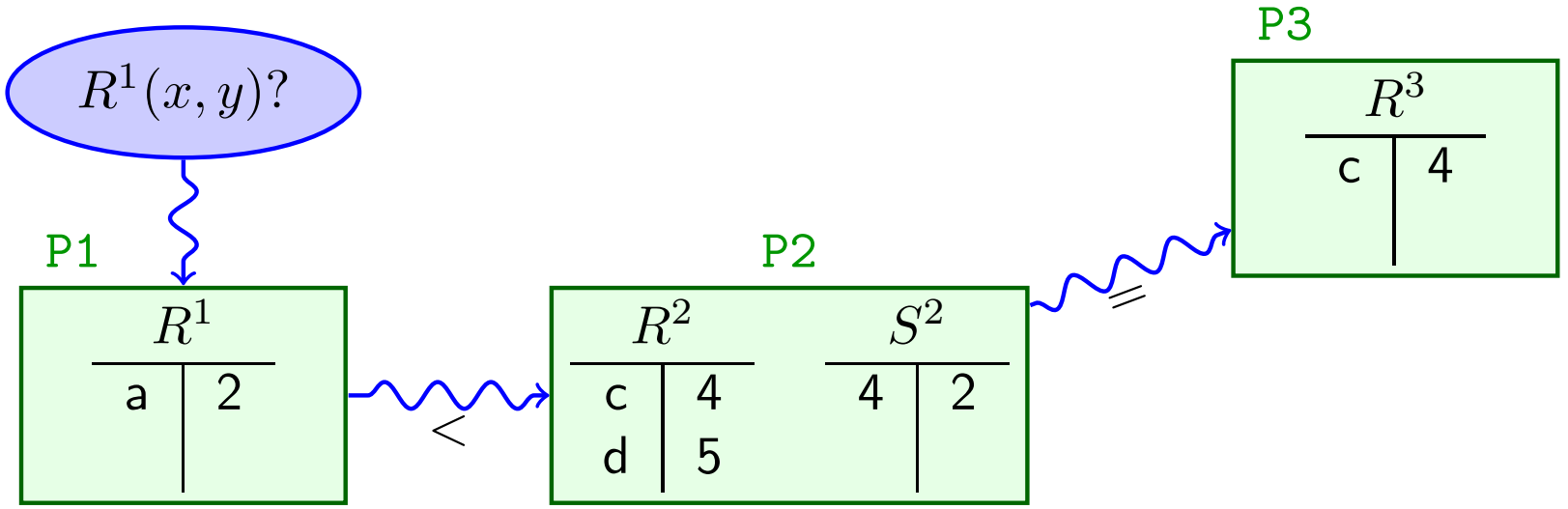
Peer P4 will have no effect on the query!



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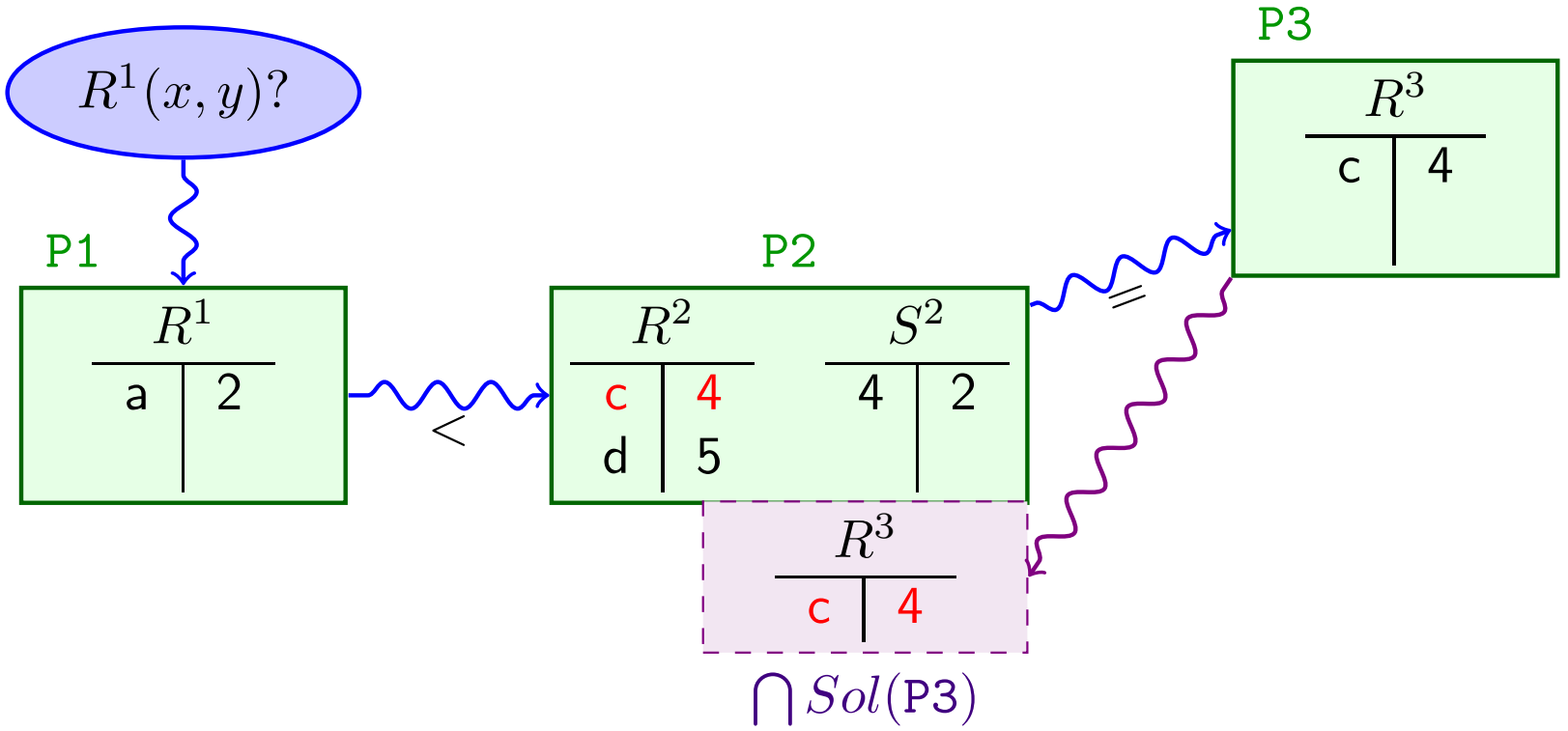

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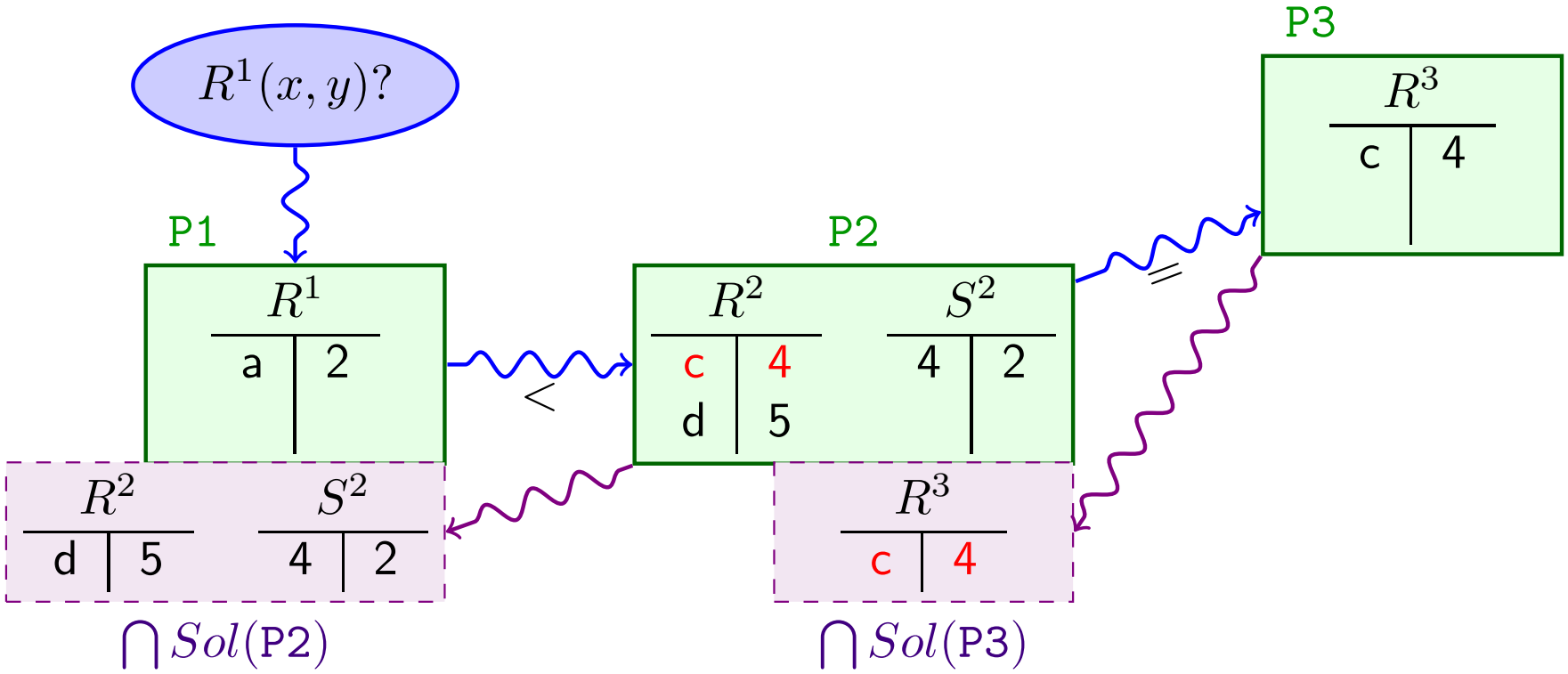

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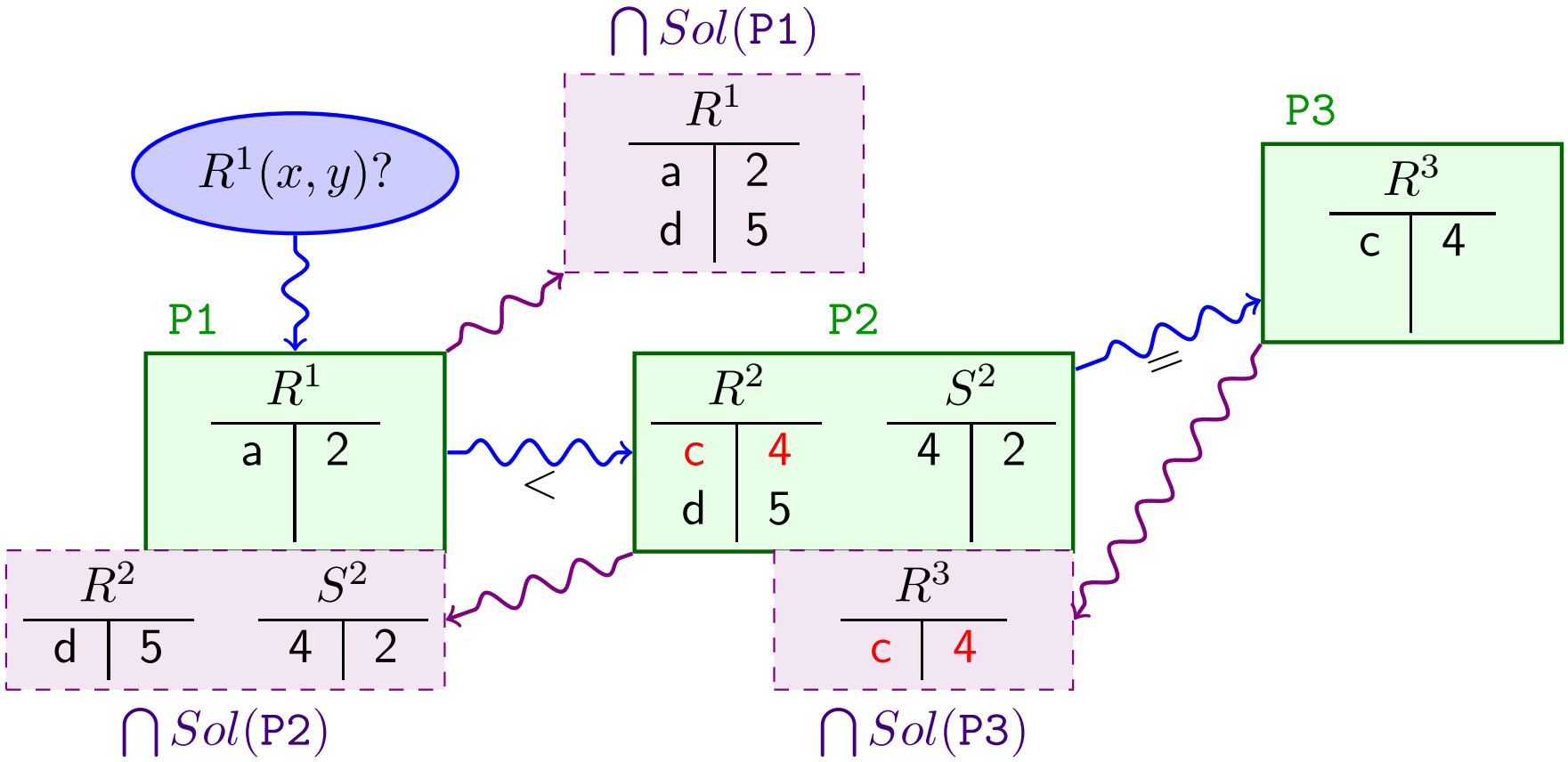

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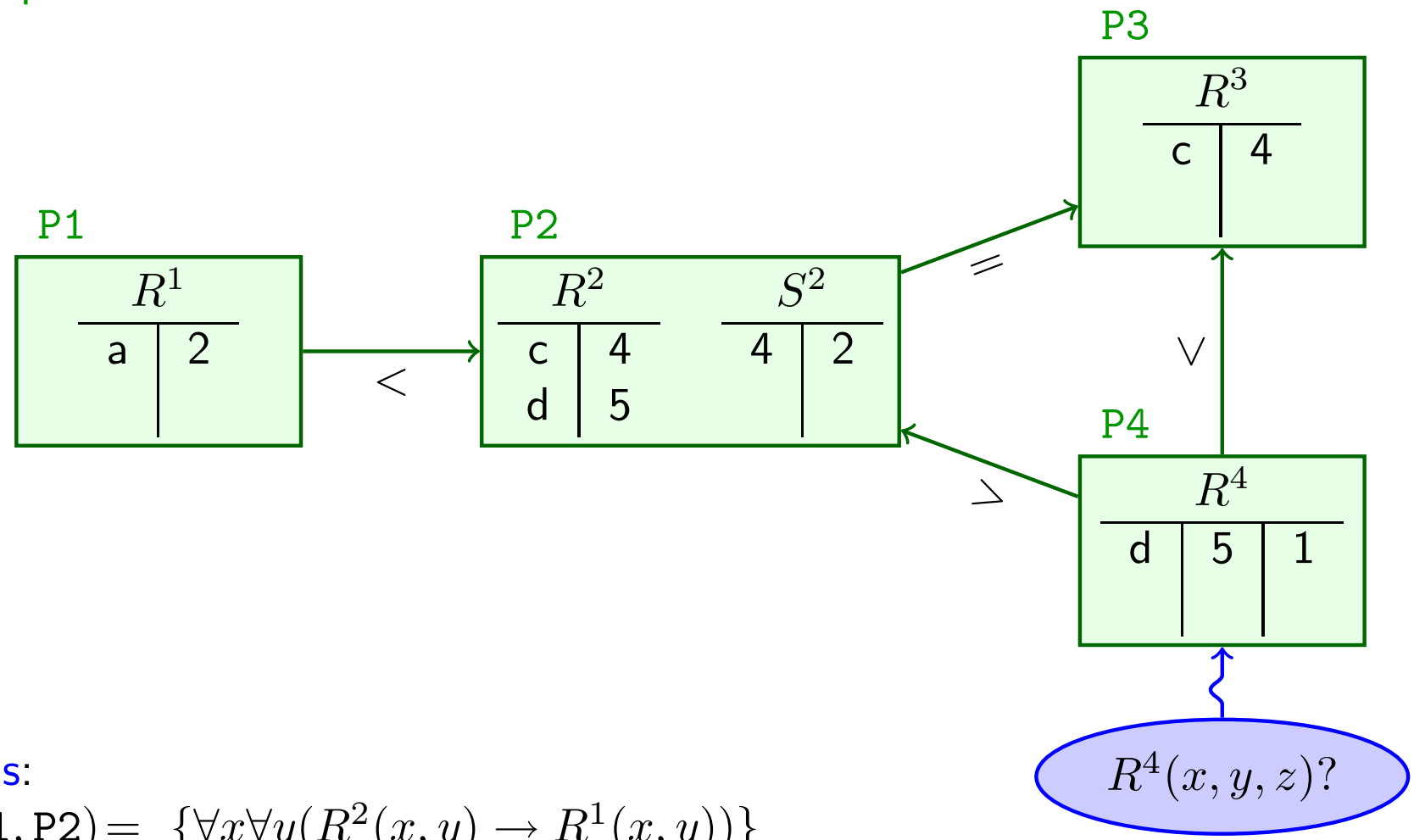
Peer consistent answers from P1: $(a,2)$ and $(d,5)$

Example:



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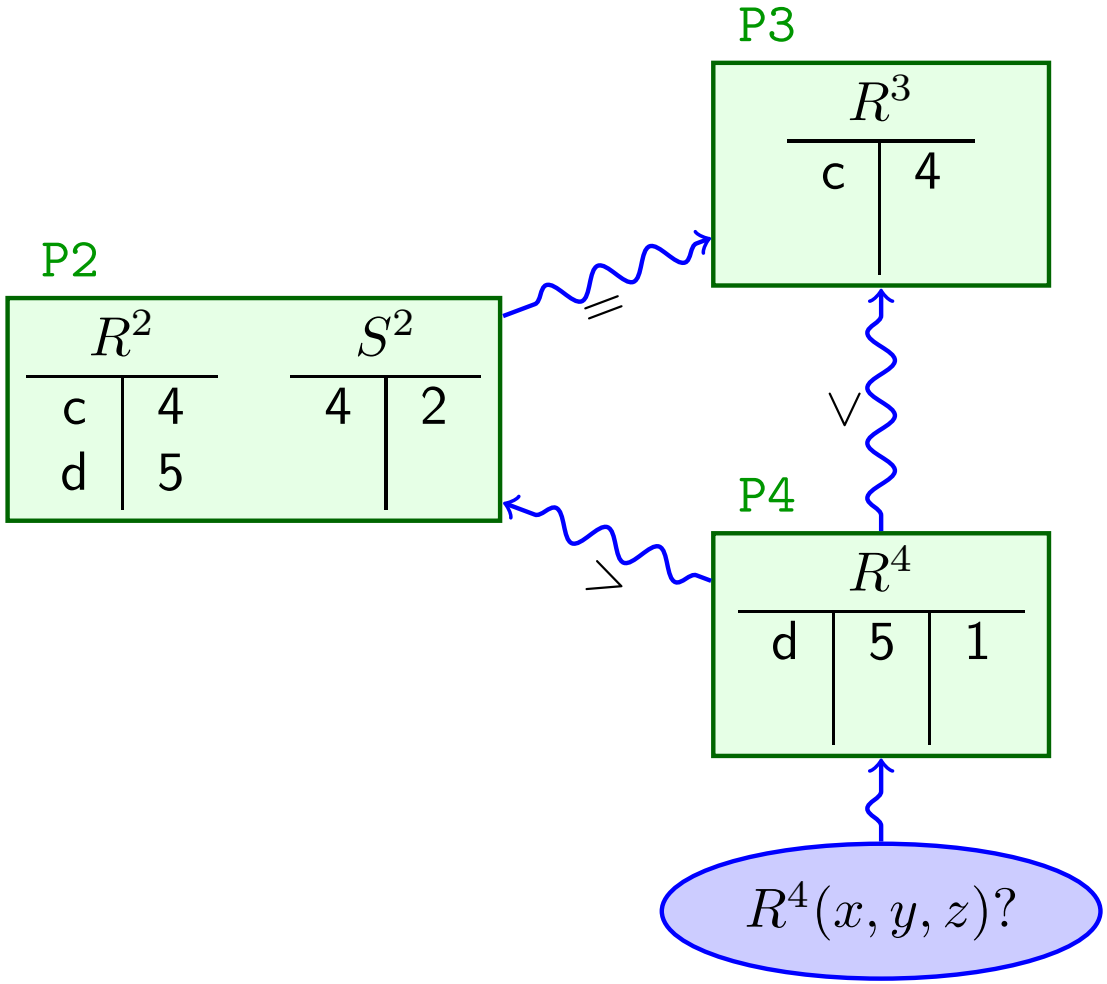

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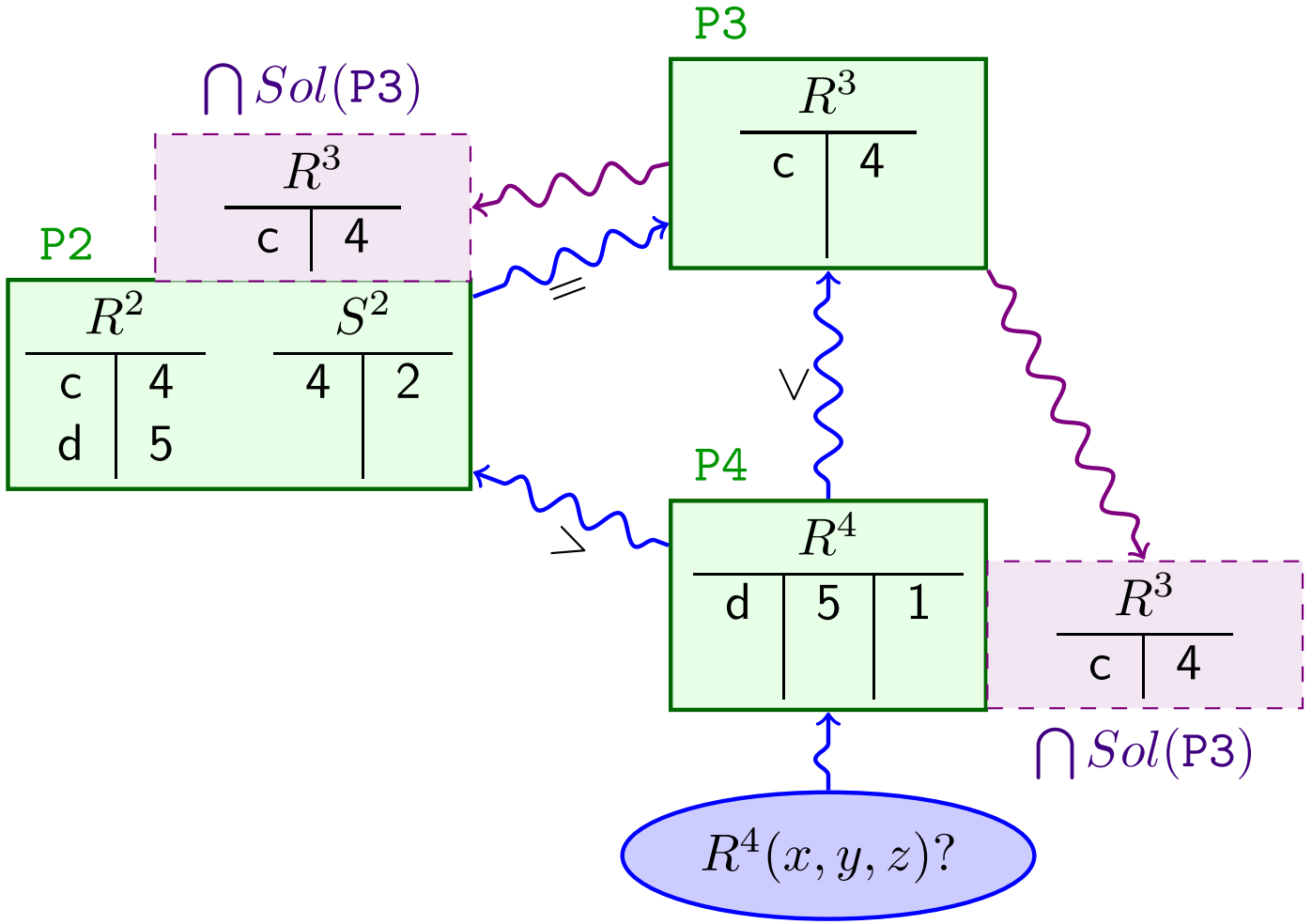

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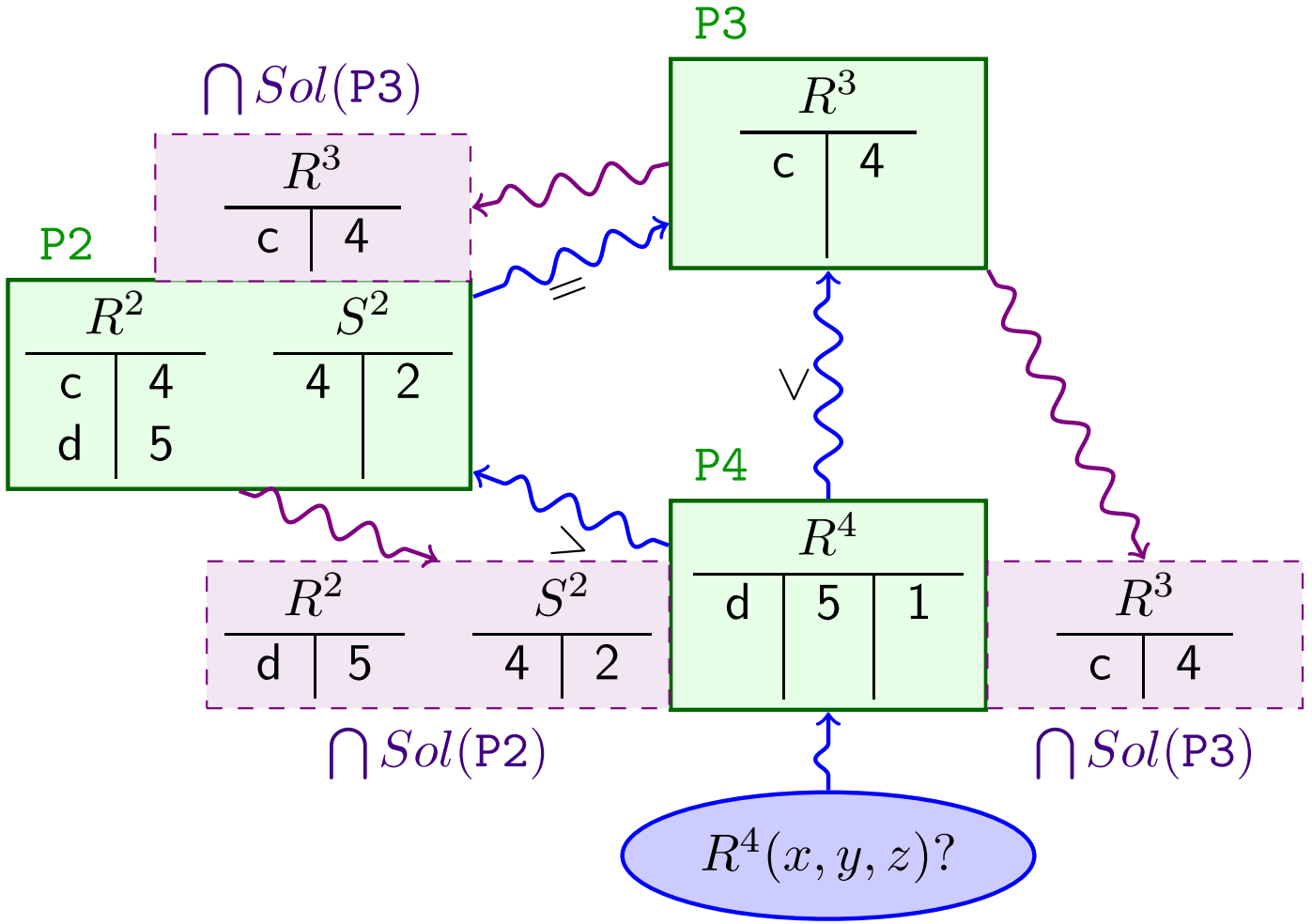

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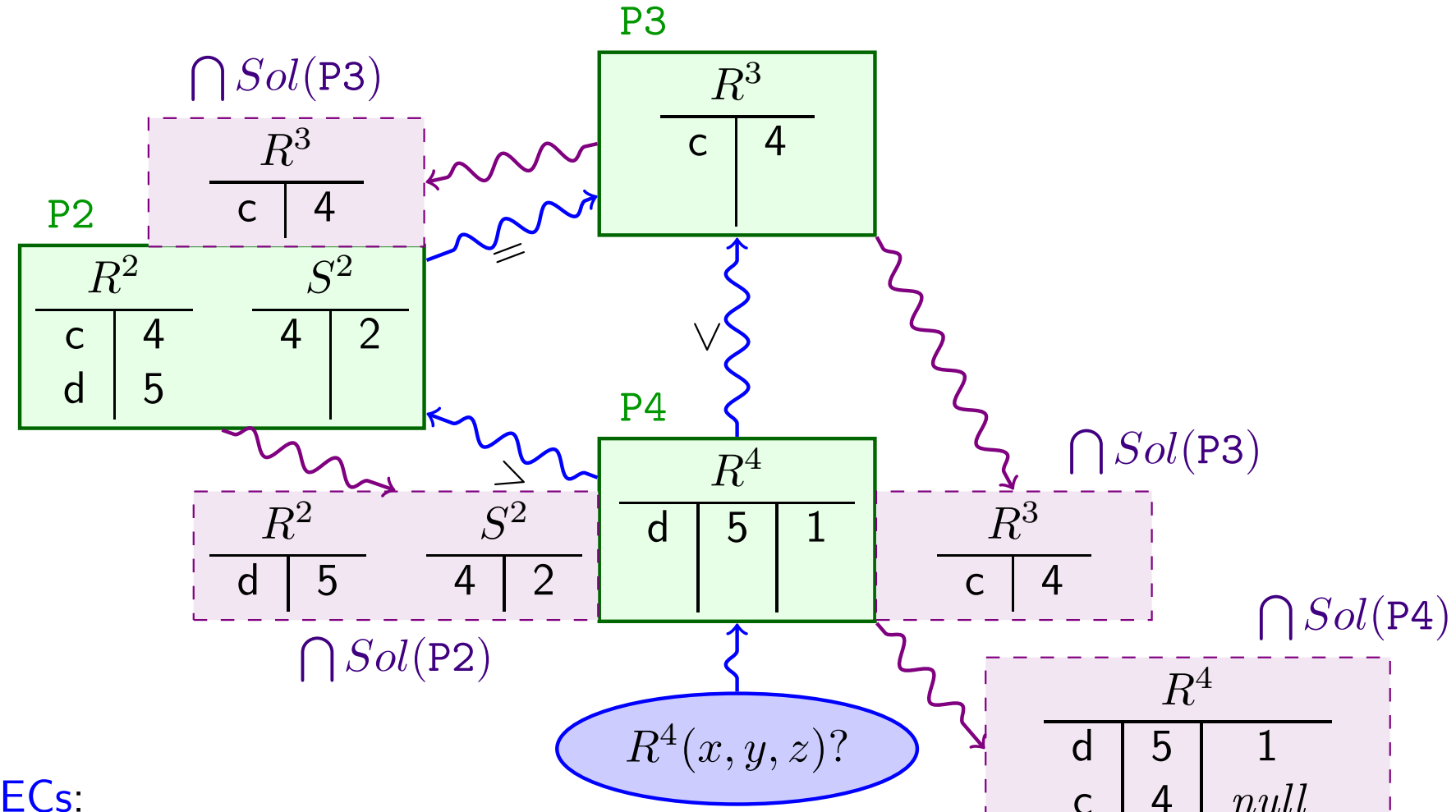

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PCAs from P4: $(d,5,1)$ and $(c,4,null)$

Incomplete information is represented by means of null values

This is important

Actually, they follow a FO semantics that is a reconstruction of null values in SQL

This is why we do not accept DECs that generate tuples via joins

It is also possible to impose local ICs on peers' instances

They can be uniformly handled as before by means of DECs of the form $\Sigma(\mathtt{P}, \mathtt{P})$ and an $=$-trust relationship

What follows?

1. A logic-based semantics

2. Capturing peers' solutions as models of logic programs

Formal semantics

Given a peer P and instances D, D' for the union schema of P and its neighbors, D' is a *neighborhood solution for P and D*:

1. [satisfaction] D' satisfies the DECs and local constraints of P

2. [trust] The data in D' associated to the peers that P trusts more than itself is the same as the one in D

3. [minimality] There is no instance D'' that satisfies 1. and 2., and such that D'' is "closer" to D than D'

   Closeness is defined in such a way that: changes are minimal under set inclusion of sets of tuples [Arenas, Bertossi, Chomicki, PODS99], and referential DECs are repaired by insertions of $null$

   The semantics of satisfaction of constraints in the presence of $null$ values is the same as in commercial DBMS, and is formalized in FOL in [Bravo, Bertossi, EDBT'06]

Now we have to consider transitive relationships

Let $D(\mathtt{P})$ be the database instance for peer $\mathtt{P}$

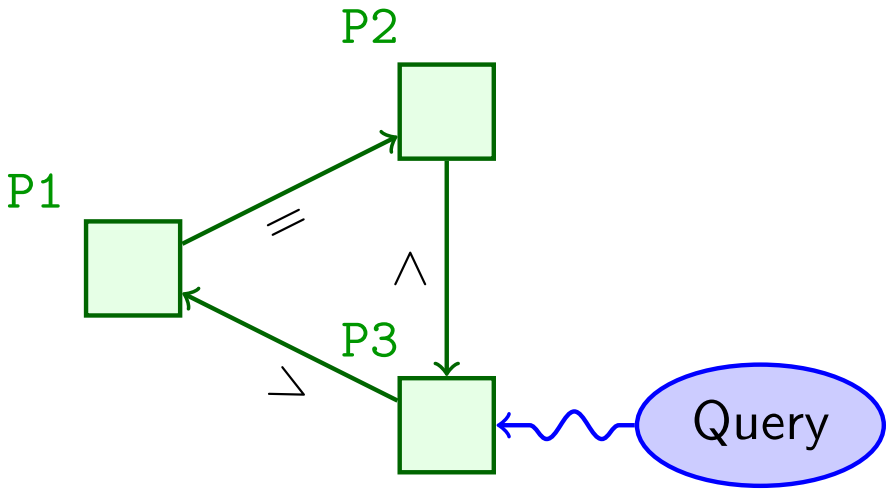
A solution for $\mathtt{P}$ can be recursively defined as:

- If $\mathtt{P}$ has no DECs, then the solution is $D(\mathtt{P})$
- Otherwise:

  1. Let D be a database instance containing the union of
     - $D(\mathtt{P})$
     - for each neighboring peer, the intersection of its solutions
  2. Let D' be a neighborhood solution for $\mathtt{P}$ and D

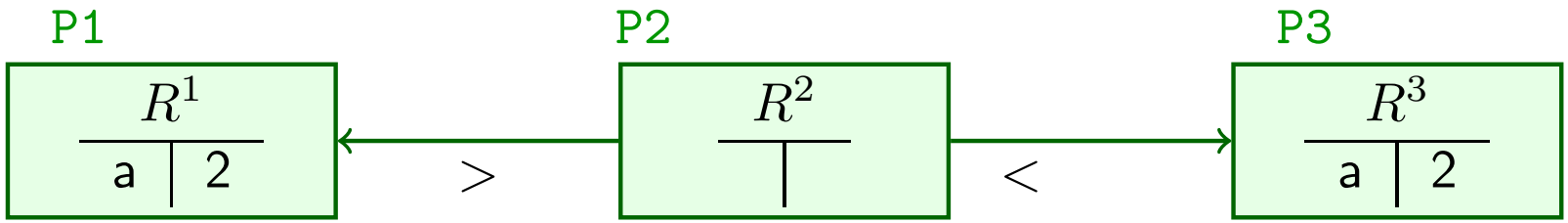
  Then, D' restricted to the schema of $\mathtt{P}$ is a the solution for $\mathtt{P}$

We restrict to acyclic peer data exchange systems to avoid the following:



- P3 needs the intersection of P1's solutions $\Rightarrow$ P1 needs the intersection of P2's solutions $\Rightarrow$ P2 needs the intersection of P3's solutions $\Rightarrow \cdots$
- Cycles can be detected by using a query identifier that is propagated as an annotation and detected

It might be the case that a peer has no solution:



DECs:

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$\Sigma(\mathsf{P2}, \mathsf{P3}) = \{\forall x \forall y (R^2(x, y) \wedge R^3(x, y) \rightarrow \mathbf{false})\}$

Peer P2 trusts P1 and P3 more than itself, but both provide contradictory information

Given a first-order query $\mathcal{Q}$ posed to peer P:

ground tuple $\bar{t}$ is a *peer consistent answer* to $\mathcal{Q}$ from P iff $D' \models \mathcal{Q}(\bar{t})$ for every solution instance D' for P

Theorem: Deciding if a tuple is a peer consistent answer to a query is Π_2^P−complete

Logic programs for peers' solutions

- Answer set programs have been used to specify and compute repairs of databases that are inconsistent wrt ICs
  [Barcelo, Bertossi, PADL'03] [Barcelo, Bertossi, Bravo, LNCS 2582]
- Those programs can be adjusted so that there is a one-to-one correspondence between their answer sets and the solutions of peer
  - ▷ The trust relationships, DECs and local ICs have to be taken into consideration
- The program uses annotation constants to indicate the atoms that may virtually inserted or deleted in order to restore consistency:

Annotation	Atom	The tuple $P(\bar{a})$ is ...
$\mathbf{t_a}$	$P\_(\bar{a}, \mathbf{t_a})$	advised to be made true
$\mathbf{f_a}$	$P\_(\bar{a}, \mathbf{f_a})$	advised to be made false
$\mathbf{t}^\star$	$P'(\bar{a}, \mathbf{t}^\star)$	true or becomes true
$\mathbf{f}^\star$	$P\_(\bar{a}, \mathbf{f}^\star)$	false or becomes false
$\mathbf{t}^{\star\star}$	$P\_(\bar{a}, \mathbf{t}^{\star\star})$	true in the solution

All of them needed if there are interacting DECs for a peer; and several repair steps become necessary

Example: $\Sigma(\mathtt{P1}, \mathtt{P2}) = \{\forall x \forall y (R^2(x,y) \rightarrow R^1(x,y))\}$
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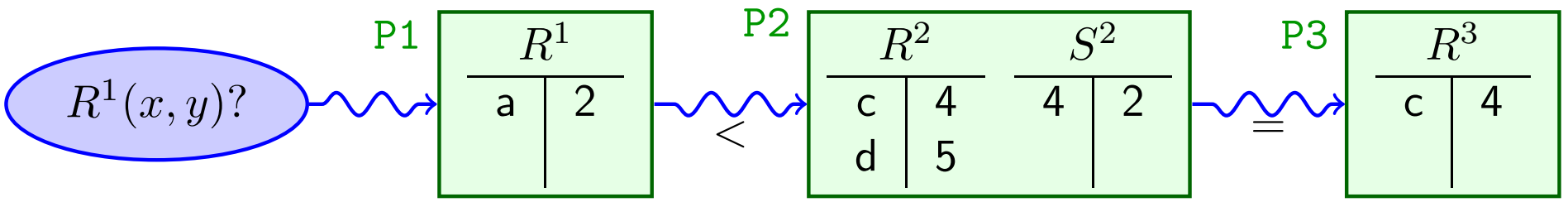

- Peer P3 has no DECs, therefore its only solution is $D(\mathtt{P3})$

DECs: $\Sigma(\mathtt{P1},\mathtt{P2}) = \{\forall x \forall y(R^2(x,y) \rightarrow R^1(x,y))\}$
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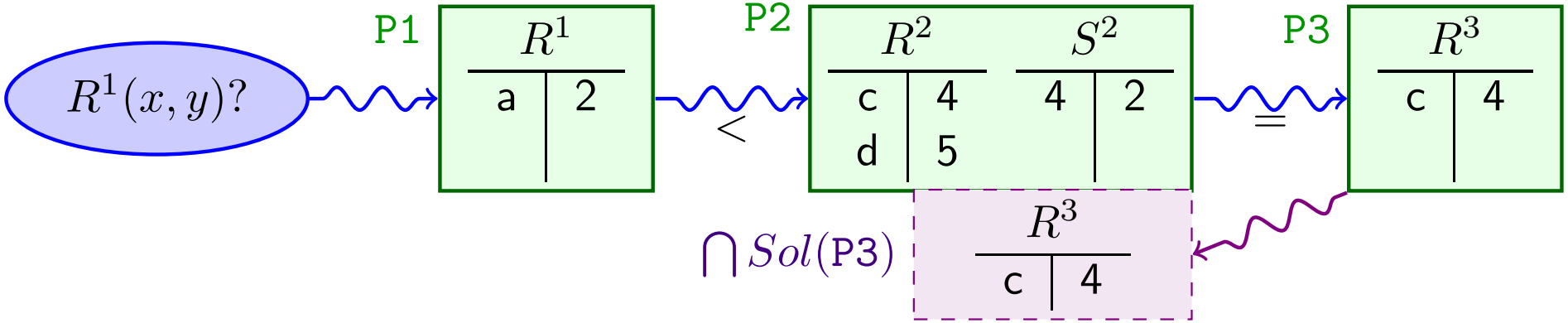

- To find the solution of peer P2 we can use its solution program!

$dom(a).\quad dom(c).\quad \ldots$
$R^3(c,4)\quad R^2(c,4)\quad R^2(d,5)\quad S^2(4,2)$
$R^3\_(x,y,\mathbf{f_a}) \vee R^2\_(x,y,\mathbf{f_a}) \leftarrow R^2\_(x,y,\mathbf{t}^\star),\ R^3\_(x,y,\mathbf{t}^\star), x \neq null, y \neq null.$
$R^3\_(x,y,\mathbf{t}^\star) \leftarrow R^3\_(x,y,\mathbf{t_a}).$
$R^3\_(x,y,\mathbf{t}^\star) \leftarrow R^3(x,y).$
$R^3\_(x,y,\mathbf{f}^\star) \leftarrow R^3\_(x,y,\mathbf{f_a}).$
$R^3\_(x,y,\mathbf{f}^\star) \leftarrow dom(x), dom(y),\ not\ R^3(x,y).$
$R^2\_(x,y,\mathbf{t}^{\star\star}) \leftarrow R^2\_(x,y,\mathbf{t}^\star),\ not\ R^2\_(x,y,\mathbf{f_a}).$
$\leftarrow R^3\_(x,y,\mathbf{t_a}), R^3\_(x,y,\mathbf{f_a}).$

} (Similarly for R^2)

$dom(a).\quad dom(c).\quad \ldots$
$R^3(c,4)\quad R^2(c,4)\quad R^2(d,5)\quad S^2(4,2)$
$R^3_{\_}(x,y,\mathbf{f_a}) \vee R^2_{\_}(x,y,\mathbf{f_a}) \leftarrow R^2_{\_}(x,y,\mathbf{t}^\star),\ R^3_{\_}(x,y,\mathbf{t}^\star), x \neq null, y \neq null.$
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} (Similarly for R^2)

- This program has two answer sets
- By collecting the atoms with annotation constant $\mathbf{t}^{\star\star}$ we get (neighborhood) solutions:

D_1 :

R^2	
d	5

S^2	
4	2

R^3	
c	4

D_2 :

R^2	
c	4
d	5

S^2	
4	2

R^3

⋂?: Just skeptical query answering, no materialization: $Ans(x,y) \leftarrow R^2(x,y,\mathbf{t}^{\star\star})$

DECs: $\Sigma(\mathtt{P1},\mathtt{P2}) = \{\forall x\forall y(R^2(x,y) \rightarrow R^1(x,y))\}$
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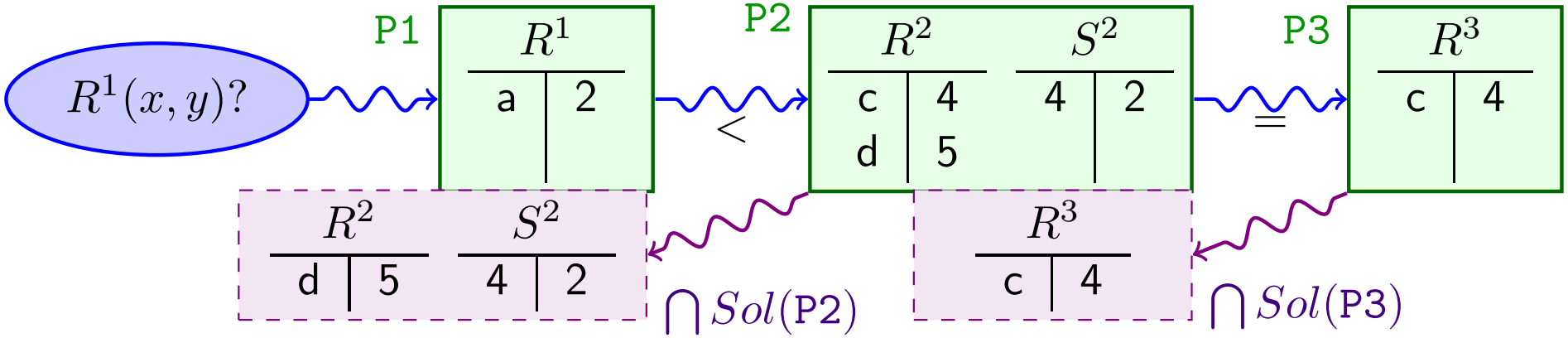

- To find the solution of peer P1 we can use its solution program!

$dom(a).\quad dom(c).\quad \ldots$
$R^1(a,2)\quad R^2(d,5)\quad S^2(4,2)$
$R^1_{\_}(x,y,\mathbf{t_a}) \leftarrow R^2_{\_}(x,y,\mathbf{t}^\star),\ R^1_{\_}(x,y,\mathbf{f}^\star), x \neq null, y \neq null.$
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$\leftarrow R^1\_(x,y,\mathbf{t_a}), R^1\_(x,y,\mathbf{f_a}).$

} (Similarly for R^2)

- This program has one answer set; then one neighbor solution
- By collecting from it the atoms with annotation constant $\mathbf{t}^{\star\star}$ we get this (neighborhood) solution:

D_1 :

R^1	
a	2
d	5

R^2	
d	5

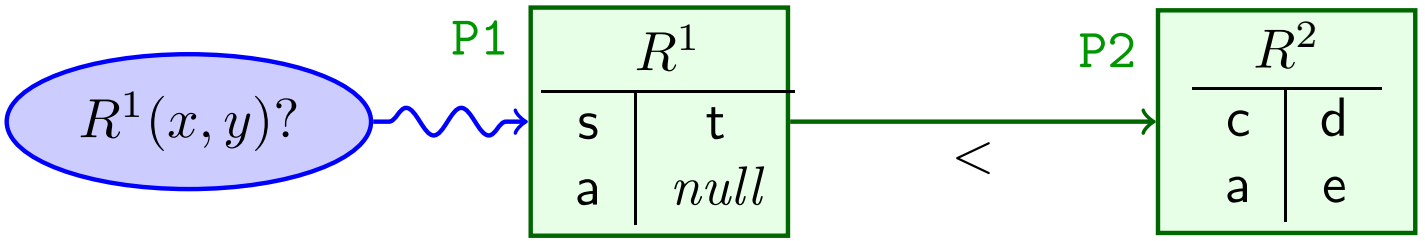
S^2	
4	2

- The query $R^1(x,y)?$ can also be added to the answer set program:

$$Ans(x,y) \leftarrow R^1(x,y,\mathbf{t}^{\star\star})$$

- The query answer is then obtained from the result $\{Ans(a,2), Ans(d,5)\}$

Example: $\Sigma(\mathtt{P1}, \mathtt{P2}) = \{\forall xy\ (R^2(x,y) \rightarrow \exists z\ R^1(x,z))\}$
$IC(\mathtt{P1}) = \{\forall xyz\ (R^1(x,y) \wedge R^1(x,z) \rightarrow y = z)\}$



$dom(a).\ dom(b).\ \ldots\ R^1(a, null).\ R^1(s,t).\ R^2(c,d).\ R^2(a,e).$
$R^1_{\_}(x, null, \mathbf{t_a}) \leftarrow R^2_{\_}(x, \mathbf{t}^\star),\ not\ aux(x), x \neq null.$
$aux(x) \leftarrow R^1(x, null),\ not\ R^1_{\_}(x, null, \mathbf{f_a}).$
$aux(x) \leftarrow R^1(x, y, \mathbf{t}^\star),\ not\ R^1_{\_}(x, y, \mathbf{f_a}), x \neq null, y \neq null.$
$R^1(x, y, \mathbf{f_a}) \vee R^1(x, z, \mathbf{f_a}) \leftarrow R^1(x, y, \mathbf{t}^\star), R^1(x, z, \mathbf{t}^\star),\ x \neq null,\ y \neq z.$

The solution obtained from the answer set is:

R^1	
s	t
a	*null*
c	*null*

- A set of DECs and ICs is Ref-acyclic if there is no cycles through referential DECs or ICs

- For example:
  - ▷ Ref-acyclic

$$\begin{aligned}\Sigma(\mathtt{P1},\mathtt{P2}) = \{&\forall xy\ (R^1(x,y) \rightarrow R^2(x,y)),\\ &\forall xy\ (R^2(x,y) \rightarrow R^1(x,y))\}\\ \Sigma(\mathtt{P2},\mathtt{P1}) = \{&\forall x(S^2(x) \rightarrow \exists y S^1(x,y))\}\end{aligned}$$

  - ▷ Not ref-acyclic

$$\begin{aligned}\Sigma(\mathtt{P1},\mathtt{P2}) = \{&\forall xy\ (R^1(x,y) \rightarrow \exists z\ R^2(x,z)),\\ &\forall xy\ (R^2(x,y) \rightarrow R^1(x,y))\}\end{aligned}$$

Theorem: for a ref-acyclic set of DECs and ICs, there is a one-to-one correspondence between answer sets and solutions of a peer

Special case

- Unrestricted Import Case:
  - ▷ The DECs are such that data is only imported to the peer (nothing is deleted)
  - ▷ All peers trust other peers more than themselves

- Nice properties:
  - ▷ A solution always exist
  - ▷ The solution program can be replaced by a non-disjunctive program:
    - ∗ The problem of determining if a tuple is a peer consistent answer of a query is in NP

Optimizations and relaxing conditions

- It is possible to relax the conditions of ref-acyclicity and of acyclicity of the graph and:
  - A sensible semantics can be provided
  - Correct and complete solution-programs can be given

- For example:
  - The cycles in the graph might not be relevant to the query
  - Even if the DECs and ICs are not ref-acyclic, depending on the interaction with the trust relationships, the solution-program can provide exactly the set of solutions

- Instead of requesting all the data of the neighboring sources:
  - restrict to the data that is relevant to check the DECs that have an impact on a query

Final remarks

We have provided:

1. A semantics for a peer data exchange system which
   - Respects the modularity and independence of the different peers
   - Takes trust relationships into consideration
   - Uses $null$ to repair referential DECs and ICs considering the same semantics of satisfaction of constraints as commercial DBMSs
2. A solution program with answer set programming which can be used to obtain the peer consistent answers

The Semantics of Consistency and Trust in Peer Data Exchange Systems

Leopoldo Bertossi*
Carleton University, Canada
bertossi@scs.carleton.ca

Loreto Bravo
University of Edinburgh, UK
lbravo@inf.ed.ac.uk

Related work

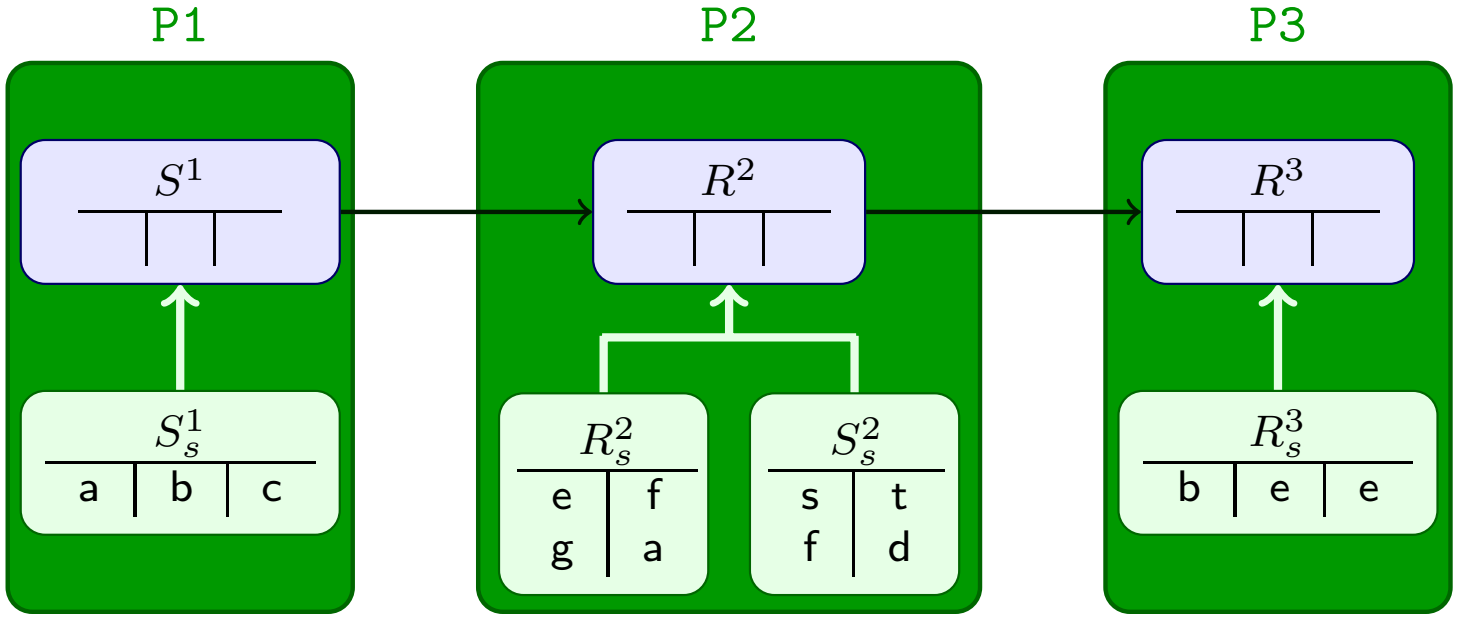
(Calvanese et al.;DBISP2P'03,DBPL'05,PODS'04)
(Franconi et al.; P2P&DB'04)

- Based on epistemic logic
- DECs are of the form:

$$cq_i \rightarrow cq_j$$

  where cq_i and cq_j are conjunctive queries over `Pi` and `Pj`'s schemas, resp.

- No trust relationships
  - ▷ Implicitly: peers trust themselves less than other peers
- Local ICs violations are avoided
  - ▷ A peer that is inconsistent wrt its local ICs is ignored
  - ▷ New atoms are added into a peer by interaction with other peers only if this does not produce a local IC violation.



- GAV Local Mappings:
  $\forall xyz(S^1_s(x,y,z) \rightarrow S^1(x,y,z))$
  $\forall xyz(R^2_s(x,y) \wedge R^2_s(y,z) \rightarrow R^2(x,y,z))$
  $\forall xyz(R^3_s(x,y,z) \rightarrow R^3(x,y,z))$
- DECs:
  $\forall xy(R^2(x,y,z) \rightarrow \exists w R^1(x,y,w))$
  $\forall xy(R^3(x,y,y) \rightarrow \exists uv R^3(u,x,v))$

If peer P1 receives a query, it will need the following theory in epistemic logic:

$$\left.\begin{array}{l}\mathbf{K_1}(\forall xyz(S^1_s(x,y,z) \rightarrow S^1(x,y,z))) \\ \forall xy(\mathbf{K_2}(R^2(x,y,z)) \rightarrow \mathbf{K_1}(\exists w R^1(x,y,w)))\end{array}\right\} \text{Specification of P1}$$

$$\left.\begin{array}{l}\mathbf{K_2}(\forall xyz(R^2_s(x,y) \wedge R^2_s(y,z) \rightarrow R^2(x,y,z))) \\ \forall xy(\mathbf{K_3}(R^3(x,y,y)) \rightarrow \mathbf{K_2}(\exists uv R^3(u,x,v)))\}\end{array}\right\} \text{Specification of P2}$$

$$\left.\begin{array}{l}\mathbf{K_3}(\forall xyz(R^3_s(x,y,z) \rightarrow R^3(x,y,z)))\end{array}\right\} \text{Specification of P3}$$

- $\mathbf{K_i}\phi$ can be interpreted as ϕ is known by peer Pi
- A tuple $\bar{t}$ is a peer consistent answer to a query Q posed to peer Pi if $\mathbf{K_i}Q(\bar{t})$ is a logical consequence of the epistemic theory

- Pros: semantics can be applied in the presence of cycles
- Cons: the program has to be run in peer P1
  - ▷ Requires data, mappings and DECs not only of neighbors, but of all accessible peers

Our approach can be easily adapted so that each peer is a data integration system