

# A Flexible DL-based Architecture for Deductive Information Systems

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## Background and Motivation

- Description logics (DLs) provide widely accepted standards for decidable knowledge representation
- Benefits: Scalability of expressivity, foundations for ontology languages (Semantic Web), impressive theory, performant DL systems (DLS)
- Question: A basis for ontology-based information systems (IS)?
- Evaluation: How to use and extend a DL system for building an ontology-based query answering system for city maps?
- Contribution: Pragmatic solutions to tackle the design, representation and query answering problem in domains for which standard DLs are not well-suited

## Drawbacks of Today's DLS for IS Building

- Scalability for ABoxes not easy to achieve (see LUBM with NRQL + RACERPRO)
- Few have expressive and practical ABox QL
- Persistency for large ABoxes? Use a DB, but:
  - Query answering requires inference – DB access during reasoning? Pre-loading of (which portions of the) ABox into memory?
  - Thesis: as long as RPC is much slower, representation layer should include query answering engine and reasoning engine
- ABoxes not good for “data representation” (Strings, Polygons), Concrete Domains: overkill in many cases

## Underlying Thesis

- Pragmatic solutions needed for today's IS designers
  - Existing DLS must be reused (cannot be reimplemented in a short period of time)
  - Pragmatic ways to extend DLS in case representational deficiencies are encountered should be identified → this paper
  - Extensions must / should be easier to implement than DLS
  - Longtime perspective: DLS with “open architecture”? Plug in mechanism?
  - Even if this is achieved, extensibility is hard due to inherent intellectual complexity

## Contributions

- “Road map for a difficult terrain”
- Three pragmatic settings for city maps IS
  - Setting 1: What can be done with RACERPRO ABox left alone
  - Setting 2: (RACERPRO external) spatial representation (“spatial DB”) + ABox
  - Setting 3: (RACERPRO internal) spatial representation + ABox
- Base the IS on software abstractions
  - Abstract from remote vs. local procedure call
  - Abstract from ABox representation of the DLs
  - Provide more flexible means for data / information representation than ABoxes

## Contributions (2)

- Base the IS on software abstractions
  - Allow for hybrid representations (layering of representations)
  - Use one internal data model for the IS which allows all this: “substrate data model”
  - flexible, extensible query language needed: “substrate query language framework”
- ⇒ “Semantic Middleware”
  - Thesis: flexible way to build DL-based IS
  - Example: NRQL was first external to RACERPRO; since it was implemented on top of “substrate” middleware, it could be migrated easily into RACERPRO

## Digitale Stadtkarte (DISK)

- © “Amt für Geoinformation und Vermessung”
- Two digital vector maps in SQD format
- Objects are “classified” according to a fixed list of categories (“Objektschlüssel-Katalog”):
  - 5164 ⇒ lake, navigable, 4128 ⇒ meadow, 2224 ⇒ park, 2119 ⇒ living area, ...
  - Taxonomic relationships (“is-a”) implicitly present, but not explicitly modeled ⇒ needs remodeling
  - Very specific categories, no generalizing categories: *cemetery\_for\_non\_christians*, but *cemetery* is missing



# Digitale Stadtkarte (DISK)

- Map 1: 2694 geo objects, 361 primary

Map Viewer
- □ ×

File Map Key Control Spatial Querying

Autotracking  
  Map Text  
  Nodes  
  Sensitive Objects  
  Only Bound  
  Solid Areas  
  Highlight Bindings  
  Show Bindings  
  Stored Relations

Current Range

GemeindeName (auch Name einer Samtgemeinde) TEXT  
 Gewaechshaus FLAECHE  
 Gewaesser TEXT  
 Gewaessernamen TEXT  
 Gitterpunkte fuer das Einpassen von Vorlagen PUNKT  
 GK-Gitterlinie 1 km LINIE  
 GK-Gitterlinie 2 km LINIE  
 Grenze statistisches Gebiet LINIE  
 Grenze statistisches Gebiet, gleichz. Ortsteilgr. LINIE  
 Grenze statistisches Gebiet, im Gewaesser LINIE  
 Grenzen einer Mitglieds-gemeinde einer Samtgemeinde LINIE  
 Haefen FLAECHE  
 Haefen unter Eb 6 und 7 FLAECHE  
 Haefengebiete-grenze (Zustaendigkeit Strom- und Haefenbau) L  
**Hauptverkehrsstrasse LINIE**  
 Hauptverkehrsstrasse unter Eb 6 und 7 LINIE  
 Hauptverkehrsstrasse, Tunnel LINIE  
 Hausnummer TEXT  
 Heide FLAECHE  
 Heide SYMBOL  
 Hoefflinlinie LINIE  
 Hochspannungsleitung LINIE  
 Hochspannungsleitung TEXT  
 Hochspannungsmast SYMBOL  
 Hochspannungspfeil SYMBOL  
 Hochwasserschutzanlage (nicht Deich 4011/181) LINIE  
**Industrie/Gewerbe FLAECHE**  
 Kanal, nicht schiffbar FLAECHE  
 Kanal, nicht schiffbar, unter Eb 6 und 7 FLAECHE  
 Kanal, schiffbar FLAECHE  
 Kanal, schiffbar, unter Eb 6 und 7 FLAECHE  
**Kapelle SYMBOL**  
**Kilometrierung BAB, BAB-aehnlich SYMBOL**  
 Kilometrierung BAB, BAB-aehnlich TEXT  
**Kirche SYMBOL**  
 Kirche SYMBOL  
**Kleingarten FLAECHE**  
**Kleingarten SYMBOL**  
 Kleingartennummer(-name) TEXT  
**Kreisgrenze offentliches Gebaeude LINIE**  
 Krankenhaus SYMBOL  
 Kreisgrenze LINIE  
 Kreisname TEXT  
 Kuestenbereich FLAECHE  
 Kuestenbereich SYMBOL-AN-LINIE  
 Landesgrenzband, Abgrenzung aussen (100 m) LINIE  
 Landesgrenzband, Abgrenzung Mitte (50 m) LINIE  
 Landesgrenze LINIE  
 Landesgrenze, Grenzband 1 FLAECHE  
 Landesgrenze, Grenzband 2 FLAECHE  
 Landschaftsname TEXT

**Racer-Explicit-Relations-Map**

Map Coordinates

Full Map: (73845,33755) - (76417,36327)  
 Map Range: (73865,33775) - (76397,36307)  
 Range: 2532 \* 2532 meters

Map Overview

Map Infos

```

THEMATIC-SUBSTRATE:EXCLUDE-PERMUTATIONS-P
THEMATIC-SUBSTRATE:HOW-MANY &ALLOW-OTHER-
(BLOCK NIL
(LET ((THEMATIC-SUBSTRATE:TRUE-P NIL)
      (THEMATIC-SUBSTRATE:COUNTER 0)
      (THEMATIC-SUBSTRATE:ENDINGS NIL)
      (THEMATIC-SUBSTRATE:"CANDIDATES" NIL)
      (THEMATIC-SUBSTRATE:ABOX
        (WHEN (TYPEP SUBSTRATE 'RACER-SUBSTRATE)
          (THEMATIC-SUBSTRATE:ABOX SUBSTRATE)))
      (THEMATIC-SUBSTRATE:TBOX
        (WHEN (TYPEP SUBSTRATE 'RACER-SUBSTRATE)
          (THEMATIC-SUBSTRATE:TBOX SUBSTRATE)))
      (APPLY #'QUERYING-STARTED SUBSTRATE THEMATIC-
        (PROGN
          (GRAPH-VISUALIZER-WITH-NEW-MARKING-CONTEX-
            (LET ((THEMATIC-SUBSTRATE:CAND
                  (GRAPH-VISUALIZER-FIND-NODE SUBSTRATE '
            
```

Undo Unhighlight Clear Reset Redraw Delete Infos

Command: Highlight Touching Objects  
 Enter a SI-GEOM-THING: #<RACER-MAP-POLYGON 10973>  
 Command: □

R: Menu of completions.



# Digitale Stadtkarte (DISK)

- Map 2: 18.039 geo objects, 5.418 primary

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Landesgrenze, Grenzband 2 FLAECHE  
Landschaftsname TEXT  
Landungsbruecke, Anlegestelle LINIE

**Basic-Implicit-Relations-Map**

Map Coordinates

Full Map: (69778,32000) - (78073,39458)  
Map Range: (70528,32453) - (77624,39549)  
Range: 7096 \* 7096 meters

Map Overview

Map Infos

Infos For Map /HOME/MWESSEL/MAPS/OBJENDORF.SQ  
18039 Objects in Map,  
50713 Objects in Spatial Index,  
0 Unknown Object OS Keys,  
63 Known Object OS Keys.

Undo Unhighlight Clear Reset Redraw Delete Infos

Command: Adjust Map Extent #=<BOUNDING-BOX 23C07FB4>  
Command: Adjust Map Center #=<BOUNDING-BOX 23C07FB4>  
Command: █

L: Adjust Map Center; M: Full Map Extent; R: Menu.

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# Aspects of Geographic Data

- Two groups of aspects
  - Thematic: Geographic Category (Semantics)
  - Spatial: Area, Shape, Relationships, ...
- Space has specific properties
- Instances of spatial data types (polygons etc.) automatically preserve many important spatial aspects of the represented geo object (a polygon represents both shape and area)
- A map intrinsically represents spatial relationships  $\Rightarrow$  rich, “analogical” representation
- In an ABox, everything must be represented symbolically  $\Rightarrow$  “symbolic bottleneck”

## Spatio-Thematic Querying

- DISK ontology in a TBox
- Remodelling of thematic DISK categories:  
 $cemetery\_for\_non\_christians \sqsubseteq cemetery$
- Additional spatio-thematic vocabulary:  
 $park\_with\_lake \equiv park \sqcap \exists contains.lake$
- Use **spatio-thematic** vocabulary in queries:

$ans(?lake, ?park, ?creek, ?industrial\_area, ?chemical\_plant) \leftarrow$   
 $lake(?lake), chemically\_contaminated(?lake), park(?park),$   
 $contains(?park, ?lake), creek(?creek),$   
 $flows\_in(?creek, ?lake), crosses(?creek, ?industrial\_area),$   
 $contains(?industrial\_area, ?chemical\_plant),$   
 $unreliable(?chemical\_plant).$

## Representing DISK: Setting 1

- What can be done with RacerPro left alone?
- Remodeling of thematic categories in a TBox
  - $\text{concept\_for\_key}(2224) =_{def} \textit{park}$

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- Representation of the map as an ABox  $\mathcal{A}$ 
  - For each map object  $i$  with key  $n$ , add  $i : \text{concept\_for\_key}(n)$  to  $\mathcal{A}$
  - Represent dedicated metric aspects in the CD  
 $(i : \exists(\textit{area}). =_{123456})$



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  - Compute qualitative RCC8 relationships:  
 $(i, j) : EC, (i, k) : TPPI, \dots$



A,B

EQ

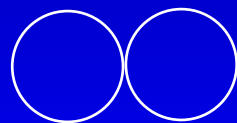


A

DC



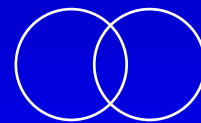
B



A

B

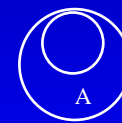
EC



A

B

PQ



B

TPP



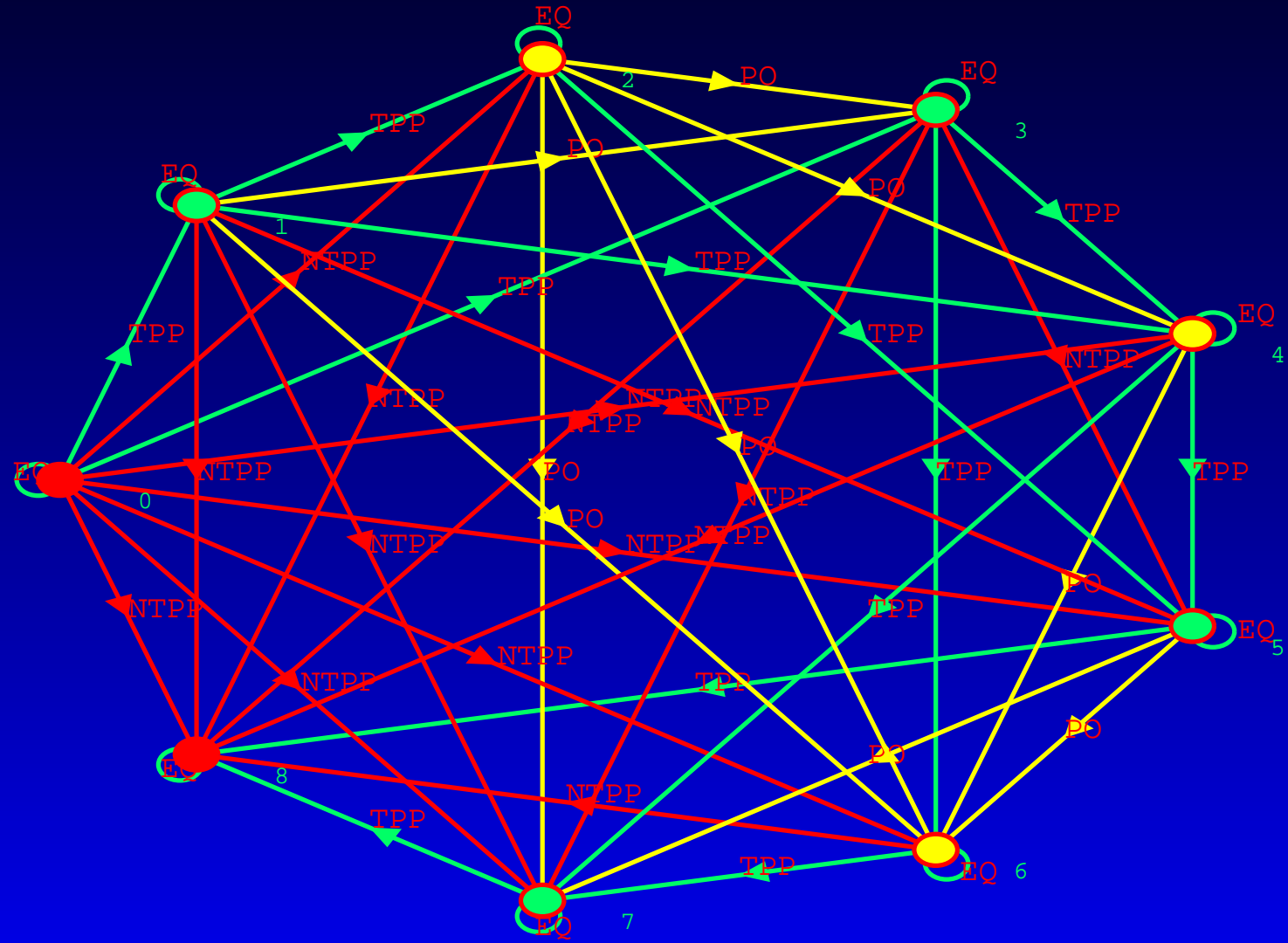
A

NTPP

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    - Compute qualitative RCC8 relationships:  $(i, j) : EC, (i, k) : TPPI, \dots$
- $\Rightarrow$  RCC8 network in the ABox (network is always consistent)

# Illustration: DISK ABox



## Querying the DISK (Setting 1)

- Simple spatio-thematic QL: instance retrieval queries
- $\text{concept\_instances}(\textit{park\_with\_lake}) = \{i, \dots\}$
- $i \in \text{concept\_instances}(\textit{park} \sqcap (\exists NTPPI.\textit{lake} \sqcup \exists TPPI.\textit{lake}))$
- If  $\{ i : \textit{park}, k : \textit{lake}, j : \textit{meadow}, (i, j) : TPPI, (j, k) : NTPPI \} \subseteq \mathcal{A}$ ,  
then also  $(i, k) : NTPPI \in \mathcal{A}$  (due to map)
- RCC roles in ABox must be closed: for each  $i$ ,  
add  $i : (\leq n R) \sqcap (\geq n R)$
- $n =_{def} |\{ j \mid (i, j) : R \in \mathcal{A} \}|$

## Querying the DISK (Setting 1) (2)

- $\text{concept\_instances}(\textit{bird\_sanctuary}) = \{i, \dots\}$
- $\textit{bird\_sanctuary} \doteq \textit{park} \sqcap$   
 $\forall NTPPI. \neg \textit{building} \sqcap \forall TPPI. \neg \textit{building}$

$\mathcal{A} \cup \{(i, k) : NTPPI\} \cup$

$\{i : (\leq_1 TPPI) \sqcap (\geq_1 TPPI), i : (\leq_1 NTPPI) \sqcap (\geq_1 NTPPI), \dots\} \cup$

$\{i : (\neg \textit{park} \sqcup ((\exists TPPI. \textit{building}) \sqcap (\exists NTPPI. \textit{building})))\}$

- is unsatisfiable, if  $\{\textit{building}, \textit{park}, \textit{meadow}\}$  are mutually disjoint
- Problems in the TBox: incomplete subsumption relationships (not a problem for query answering)
- Moreover, NRQL can be used

## Querying the DISK with NRQL

- NRQL offers classical negation and NAF
- For which living areas can it be proven that there are no adjacent freeways?

$$\begin{aligned} \text{ans}(?living\_area) \leftarrow & \text{living\_area}(?living\_area), \\ & \forall \text{adjacent} . \neg \text{freeway}(?living\_area) \end{aligned}$$

- Requires RCC closed ABox and disjointness axioms, as just discussed (not so good ...)
- Living areas with no known adjacent freeways?

$$\begin{aligned} \text{ans}(?living\_area) \leftarrow & \\ & \text{living\_area}(?living\_area), \\ & \setminus (\pi(?living\_area) \text{ adjacent}(?living\_area, ?freeway), \\ & \text{freeway}(?freeway)) \end{aligned}$$



# NRQL Concrete Syntax

Q1:

```
(retrieve (?x)
  (and (?x living-area)
    (?x (all adjacent
      (not freeway))))))
```

Q2:

```
(retrieve (?x)
  (and (?x living-area)
    (not (project-to (?x)
      (and (?x ?y adjacent)
        (?y freeway))))))
```

# Extensible Substrate QL Framework

- NRQL is a specialized “Substrate QL” for substrates  $S$  of type ABox
- Two kinds of atoms: unary  $C(x)$ , binary  $R(x, y)$
- $x, y$ : Individuals, variables (with act. dom. sem.)
- Extensions of atoms on substrate  $S$ :  
$$C(x)^{\mathcal{E}} =_{def} \{ i \mid S \models C(i) \},$$
$$R(x, y)^{\mathcal{E}} =_{def} \{ (i, j) \mid S \models R(i, j) \}.$$
- Due to NAF:  $\models_{NAF}$  instead of  $\models$
- Complex queries: Relational operators AND (“ $\times$ ”), UNION ( $\cup$ ), NEG ( $\setminus$ ), PROJECT-TO ( $\pi$ )
- New atoms can be added:  $\models$  must be defined for  $S \times atom$ ,  $\Rightarrow$  very flexible!

## Problems with Setting 1

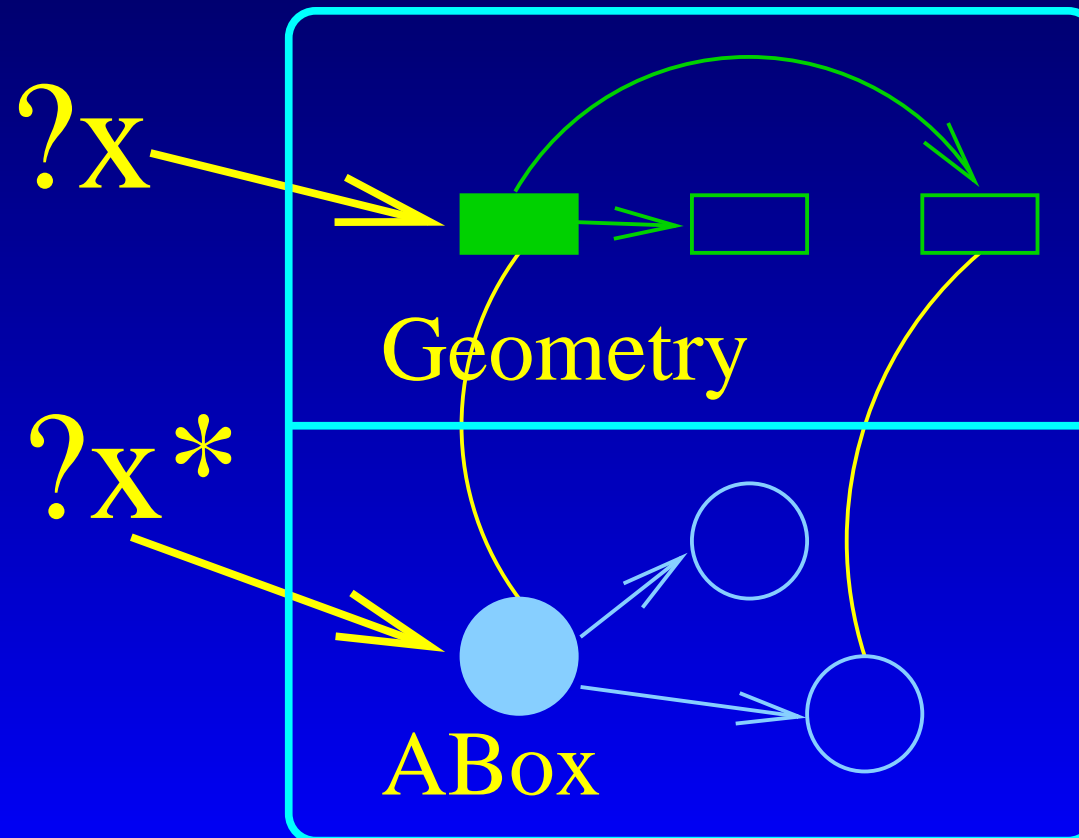
- $n^2$  size of generated ABoxes (29 million role assertions with *DC*, 19.880 without DC)
- Missing practically relevant query atoms (e.g., distance queries)
- Qualitative representation of “spatial data” in an ABox
- “Closed domain reasoning” required  $\Rightarrow$  misuse of the DL system (open domain reasoning)
- Geometry needed anyway, at least for presentation purposes
- $\Rightarrow$  Motivates hybrid representation and query language

## Representing the DISK: Setting 2

- Map Substrate:  $(ABox, SBox, *)$ 
  - Substrate 1: ABox - thematic aspects
  - Substrate 2: SBox - map geometry
  - \*: part. inject. mapping from nodes in  $S_1$  to  $S_2$

## Representing the DISK: Setting 2

- Map Substrate:  $(ABox, SBox, *)$ 
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  - Substrate 2: SBox - map geometry
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## Representing the DISK: Setting 2

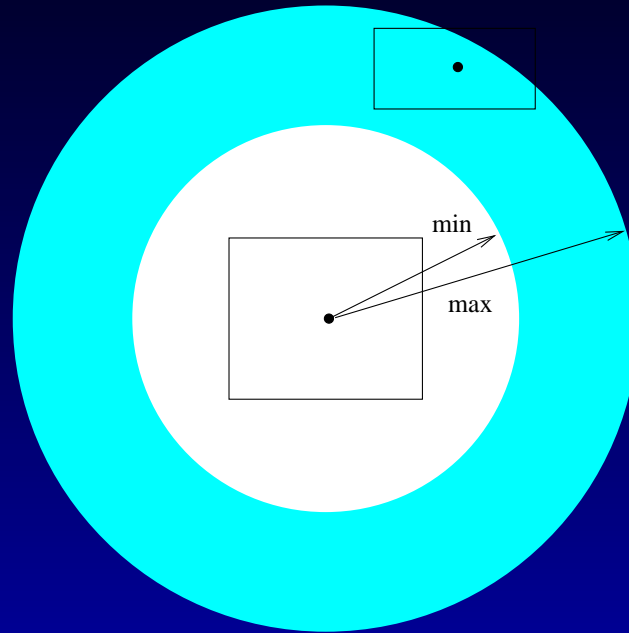
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  - Substrate 2: SBox - map geometry
  - $*$ : part. inject. mapping from nodes in  $S_1$  to  $S_2$
- ⊕ Non-symbolic spatial binary query atoms
- ⊕ On-demand computation and inspection of spatial aspects
- ⊕ Dedicated index structures
- ⊕ Closed world reasoning in  $SBox$
- ⊕ Simple model checking
- ⊖ No more “reasoning” on spatial aspects



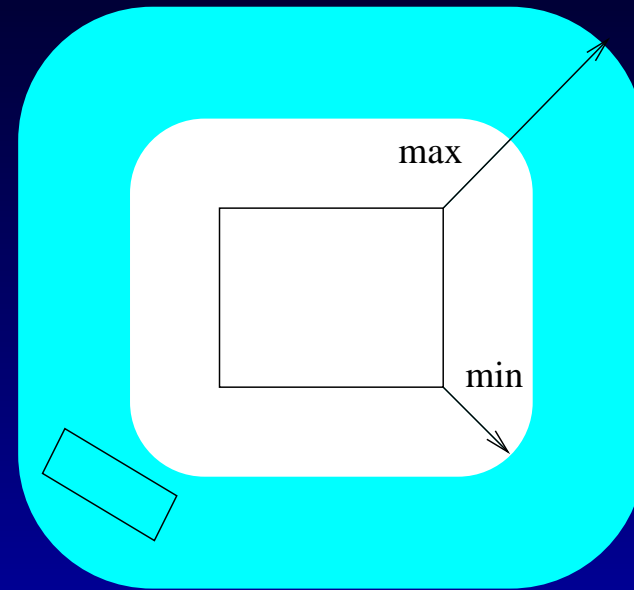
## Spatial NRQL- SNRQL

- Two sorts of atoms in SNRQL
- ABox atoms:
  - Variables range over ABox individuals
  - Atoms as in NRQL (concept, role, constraint query atoms)
- Spatial atoms:
  - Variables range over SBox individuals
  - RCC atoms
  - Geometric attributes: area, length, ...
  - Metric relationships: range queries, epsilon queries, ...
- Variables are bound in parallel, bindings reflect the “\*” mapping

# Spatial NRQL- SNRQL



Range Query



Epsilon Query

# SNRQL Concrete Syntax

```

(retrieve (?*x ?*y)
  (and (?*x
    (and living-area
      (all living-quality
        first-class-area)))
    (?y ?x (:inside-distance 750))
    (?*y subway-station)
    (?x ?y :adjacent)
    (?*y golf-club)
    (?y (:area 10000000 nil))))
  
```

## Hybridness can be made transparent

- Add end-user syntax for DLMAPS system: user must not be aware of the details of the map representation
- $ans(?x, ?y) \leftarrow$   
 $park(?x), contains(?x, ?y), lake\_or\_pond(?y)$
- $lake\_or\_pond(?y) \rightarrow$   
 $(lake \sqcup pond)(? * y)$
- $contains(?x, ?y) \rightarrow$   
 $NTPPI(?x, ?y) \vee TPPI(?x, ?y)$

## Problems with the Approach

- Theoretical problems: No spatial reasoning
  - Practical problems (perspective: IS designer)
    - ABox / SBox separated, communication overhead (caches required)
    - Hybrid QL required
    - IS designers probably do not want to implement a query answering engine, thus:
      - Split hybrid query into subqueries, send to different sources, combine sub-results
      - Probably bad performance (no overall query optimization, communication overhead, combination of results, ...)
- ⇒ Shows a way, but too hard to realize

## Hybrid Substrates in RACERPRO

- Thus, in order to avoid these problems, this functionality should be put into the DL system

⇒ Hybrid substrates for RACERPRO

- Makes functionality available for other IS designers
- Compensate for representational deficiencies of the ABox
  - Data substrate: stores told value data (from CD of ABox or OWL documents, enabled retrieval facilities)
  - RCC substrate: associate an RCC network with an ABox (next) ⇒ limited form of spatial reasoning



# The Data Substrate

```
(retrieve (?x ?*name ?*age)
  (and (?x (and |http://...#person|
              (an |http://...#age|)))
    (?*x ?*name |http://...#name|)
    (?*name ( (:predicate (search "wessel"))
              ((:predicate (search "michael"))
               (:predicate (search "achim"))))))
    (?*x ?*age |http://...#age|)
    (?*age ((:predicate (< 40))))))
```

- New sort of variables:  $*?x$  ( $*\$?x$ ), ranging over data nodes
- Data nodes can also be data values in OWL documents
- Data nodes/edges have descriptive labels: kind, role, property, ...
- Notion of entailment for labels of nodes/edges
- Data query atoms are in pos. CNF & contain literals and predicates.

## The RCC Substrate

- Substrate QL based on notion of logical consequence: a binding to a variable is only established if this binding holds in all models (“certain answer”)

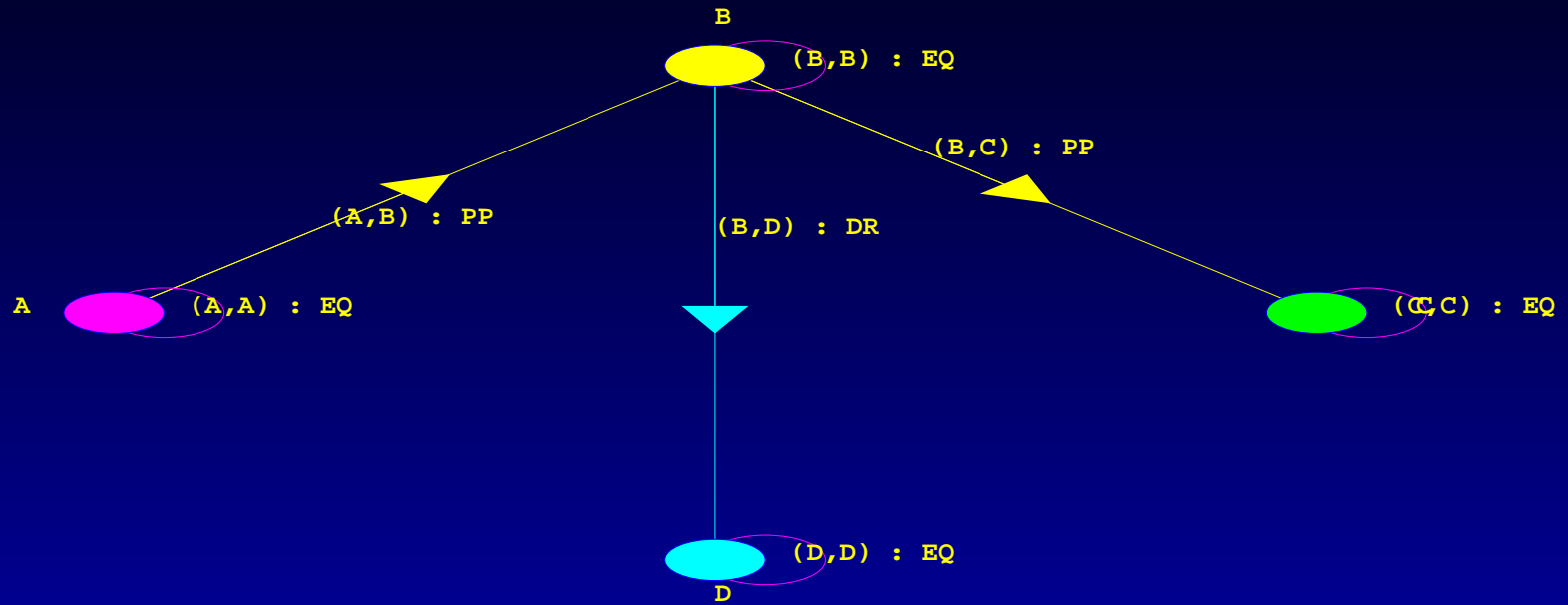
## The RCC Substrate

- Substrate QL based on notion of logical consequence: a binding to a variable is only established if this binding holds in all models (“certain answer”)
- Question: Holds  $R(x, y)$  in all models of the RCC network  $\mathcal{R}$ ?

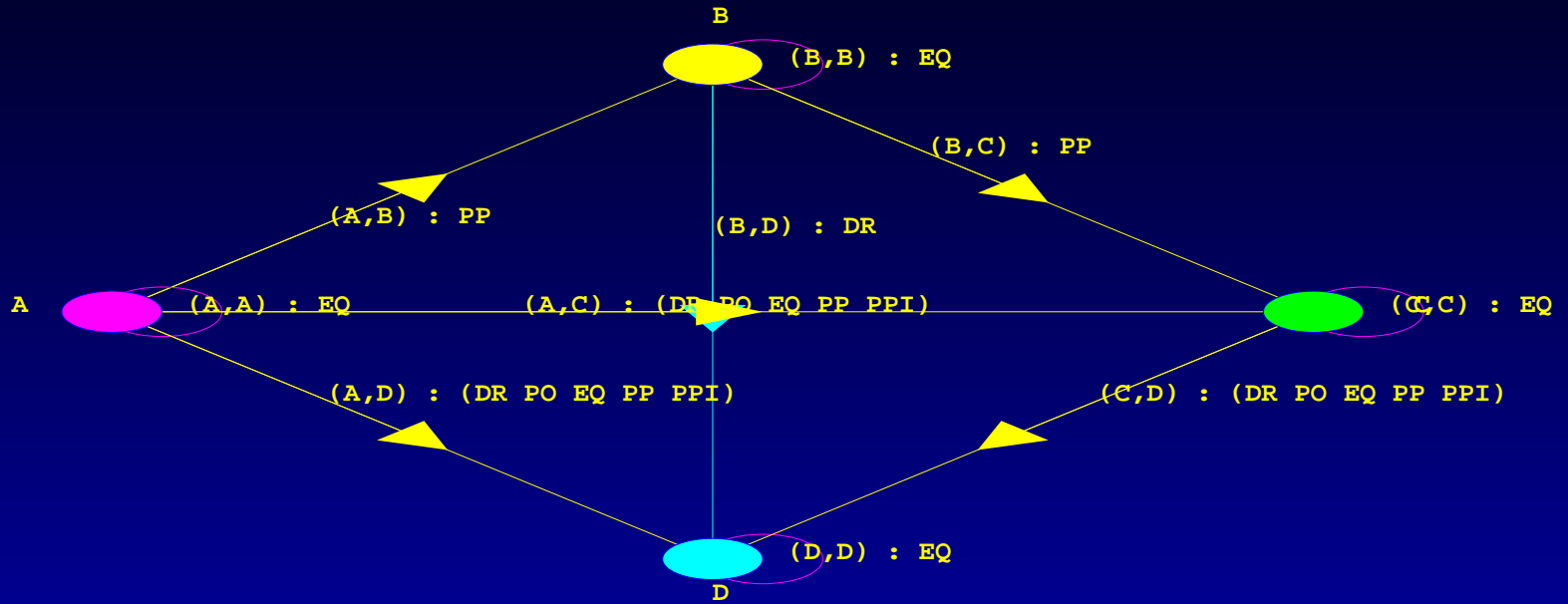
## The RCC Substrate

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- Question: Holds  $R(x, y)$  in all models of the RCC network  $\mathcal{R}$ ?
- Not so easy, since  $\mathcal{R}$  (or  $R$ ) can contain non-base relations

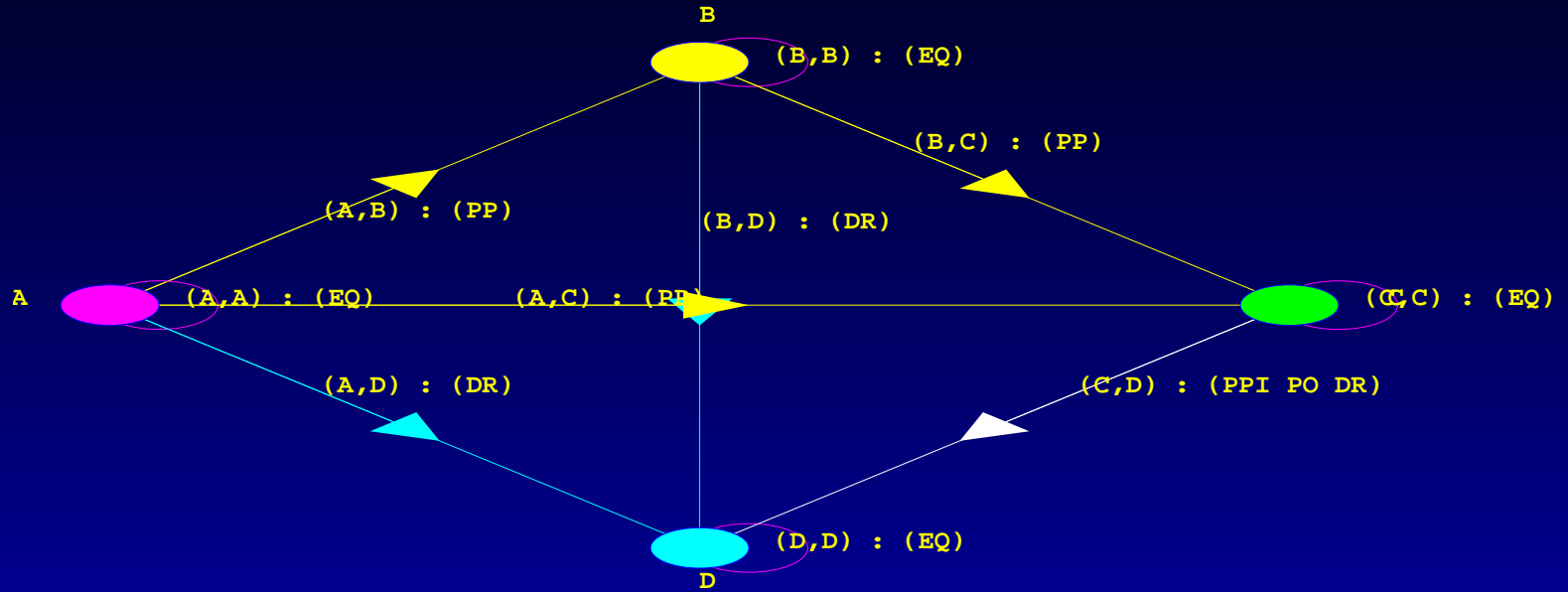
# The RCC Substrate



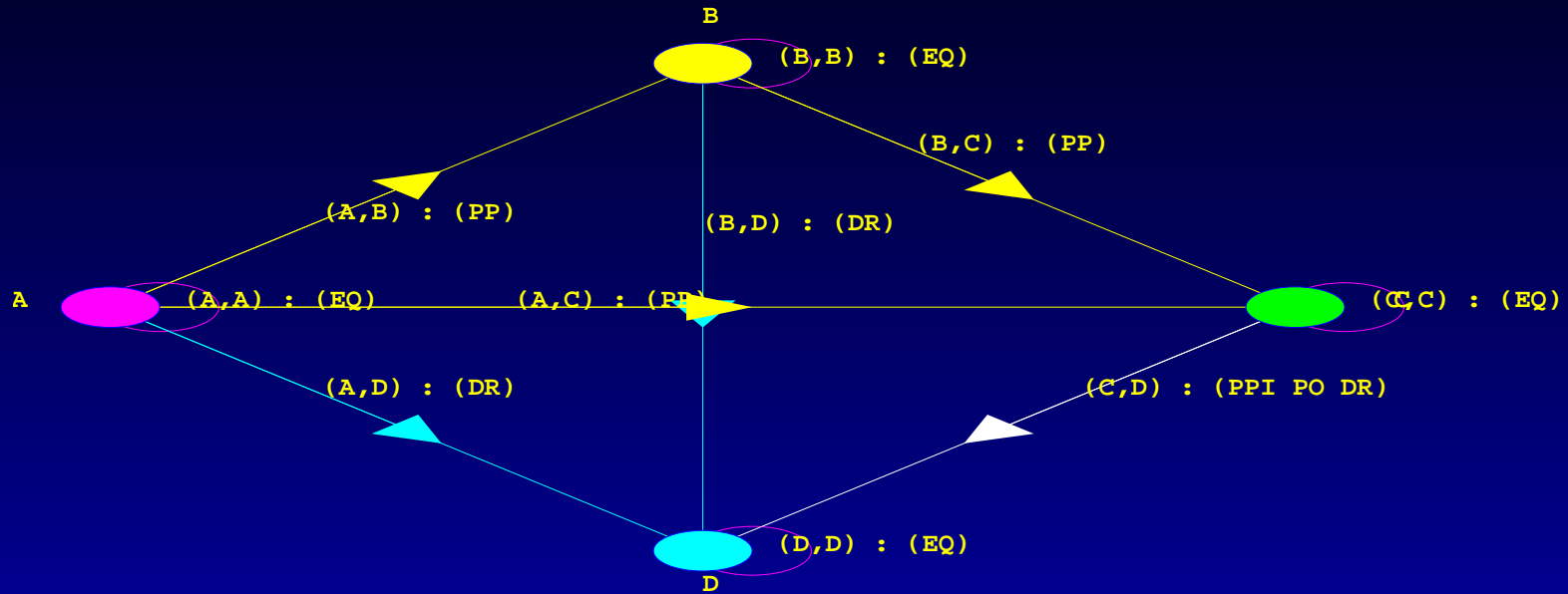
# The RCC Substrate



# The RCC Substrate



# The RCC Substrate



$$\begin{aligned} &\models DR(A, D) \\ &\models PP(A, C) \\ &\models \{PPI, PO, DR\}(C, D) \\ &\models \dots \end{aligned}$$



## The RCC Substrate

- Substrate QL based on notion of logical consequence: a binding to a variable is only established if this binding holds in all models (“certain answer”)
- Question: Holds  $R(x, y)$  in all models of the RCC network  $\mathcal{R}$ ?
- Not so easy, since  $\mathcal{R}$  (or  $R$ ) can contain non-base relations
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# Conclusion

- Spatial parts from spatio-thematic concepts removed from the TBox
- Instead, spatially aware query answering instead of TBox / concept reasoning
- Simple layering of representations can be of great value in practice
- (Possibly) Hybrid substrate QL framework allows for extensibility
- Base the IS on abstractions so that the representation can be changed easily
- (Theoretically) simple techniques can be successful in practice

Thanks  
for your  
attention!