Leveraging Qualitative Spatio-Temporal Reasoning for Dependable AI/ML

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Qualitative Spatial & Temporal Reasoning

- QSTR is a major field of study in Knowledge Representation & Reasoning, and Symbolic AI in general [Lig11].
- QSTR abstracts from numerical quantities of space and time by using qualitative descriptions instead (e.g., *precedes*, *contains*, *is left of*).

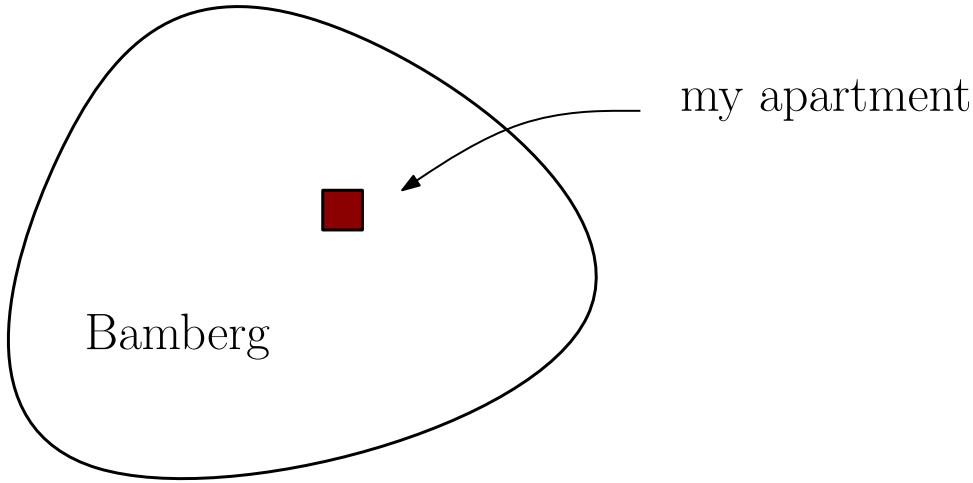


Figure: My apartment is located in the city of Bamberg, Germany

Qualitative Constraint Language

A binary qualitative constraint language is based on a finite set B of base relations such that:

- its base relations are defined on an infinite domain D

  for example, D *can be the real line*;

- its base relations are *jointly exhaustive and pairwise disjoint*

  for example, $X\ b\ Y$*, where* $b \in \{<, >, =\}$;

- B contains the identity relation Id

  for example, if $\mathrm{B} = \{<, >, =\}$*, then* Id *is* $=$;

- B is closed under the converse operation $(^{-1})$

  for example, $<^{-1}$ *is* $>$;

2^{B} expresses all relations (definite and indefinite knowledge).

The RCC8 Constraint Language

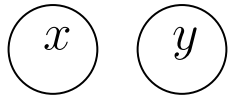
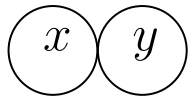
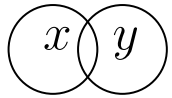
disconnected	DC	
externally connected	EC	
partially overlapping	PO	
tangential proper part	$TPP \quad TPPi$	
non-tangential proper part	$NTPP \quad NTPPi$	
equal	EQ	

Figure: The base relations of RCC8; $\cdot i$ denotes the inverse of $\cdot$

The Interval Algebra (IA) Constraint Language

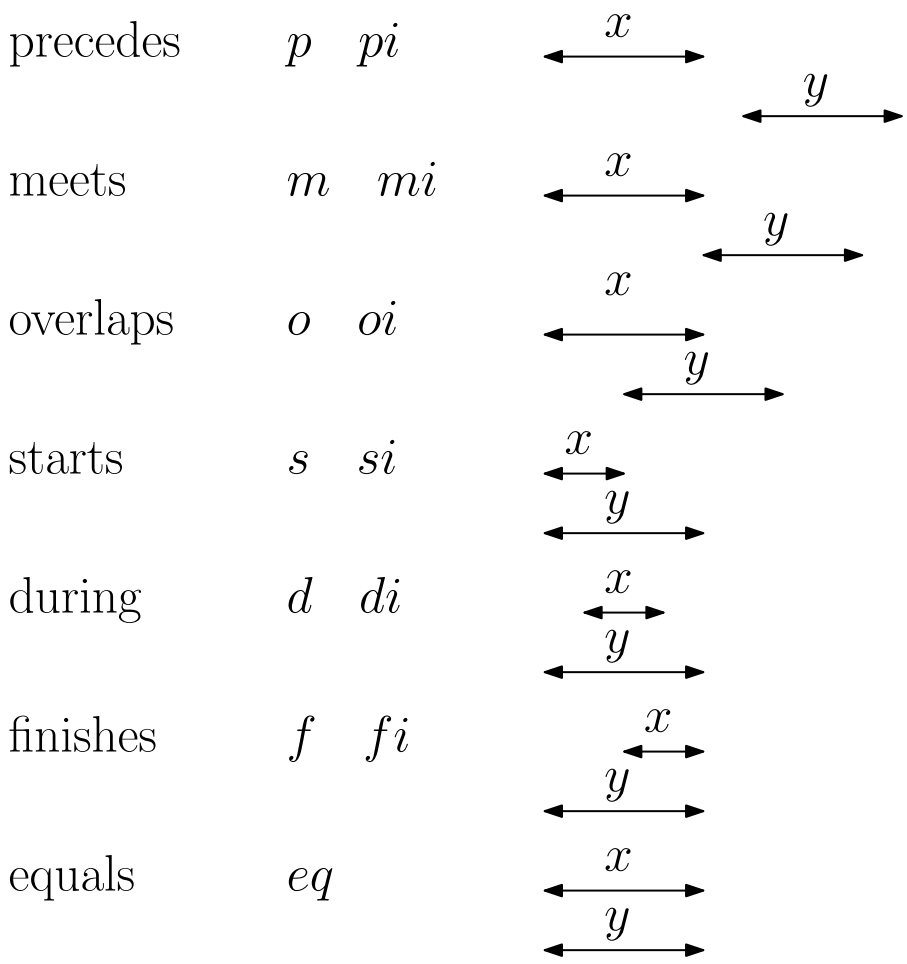


Figure: The base relations of IA; $\cdot i$ denotes the inverse of $\cdot$

Applications of QSTR

- Natural language processing
- Mobile robot navigation
- Image processing
- Geographical information systems (GIS)
- Qualitative spatio-temporal reasoning
- Querying linked geospatial data (e.g., GeoSPARQL)
- Neuro-symbolic reasoning

An Example of Neuro-Symbolic Reasoning

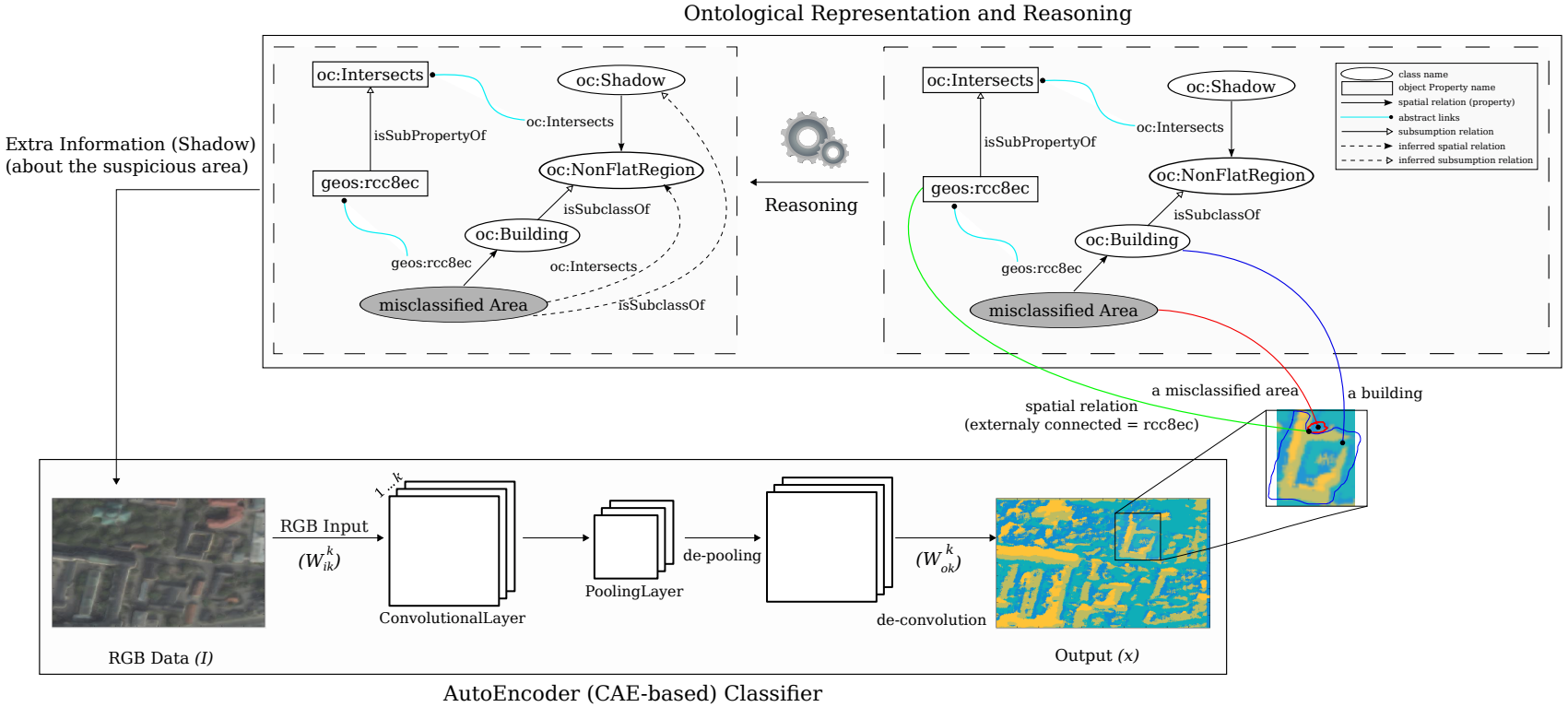


Figure: A neuro-symbolic framework for enhancing geospatial semantic segmentation

An Example of Qualitative Spatio-Temporal Reasoning

$$\phi = EC(x, y) \wedge NTPPi(x, \bigcirc x) \wedge \\ \bigcirc\Box(DC(x, y) \wedge DC(x, \bigcirc y) \wedge NTPPi(y, \bigcirc y))$$

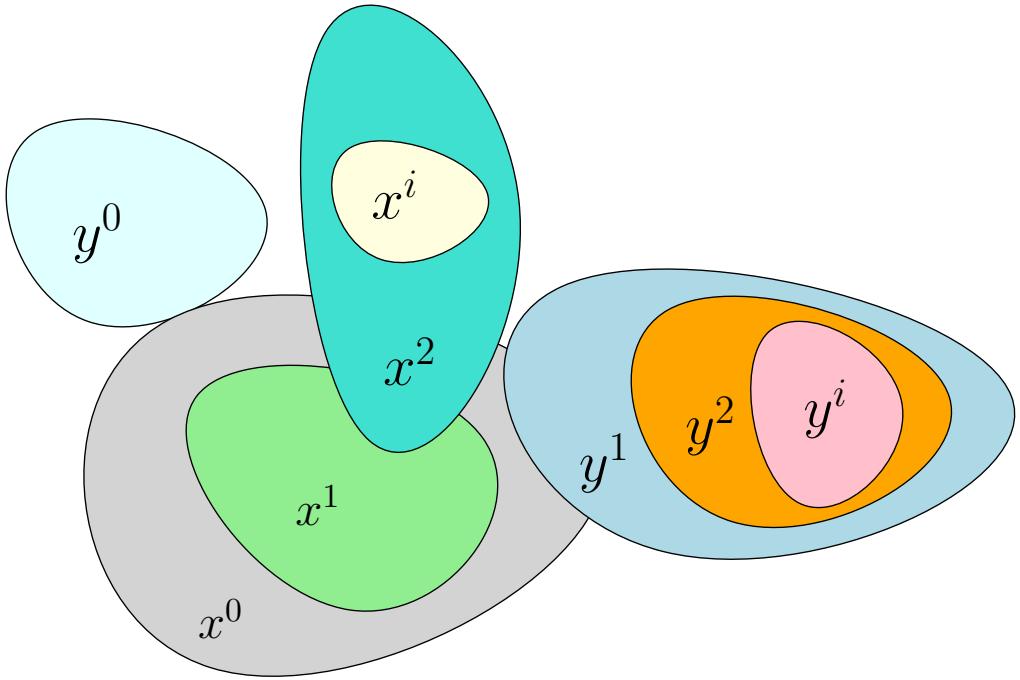


Figure: A model of the formula ϕ

An Example of Image Processing

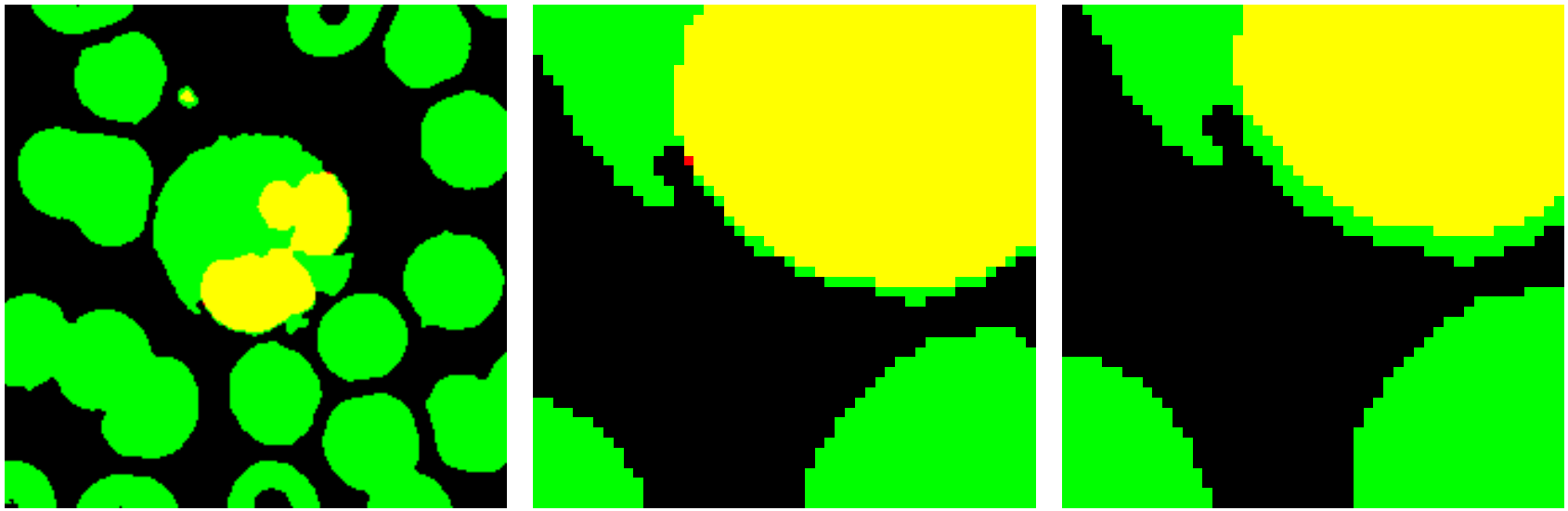


Figure: Left: segmented cell bodies (green), lobulated cell nuclei (yellow and red) and background (black), Middle: segmented cell nucleus extending outside border of host cell (red pixels), Right: the result of applying a morphological erosion operator; in this case the original *partially overlaps* relation changes to *proper part*

Qualitative Constraint Network

Spatial or temporal information for a set of entities can be represented by a qualitative constraint network (QCN).

Definition

A QCN *is a pair* $\mathcal{N} = (V, C)$ *where* V *is a non-empty finite set of variables, and* C *a mapping* $C : V \times V \to 2^{\mathsf{B}}$.

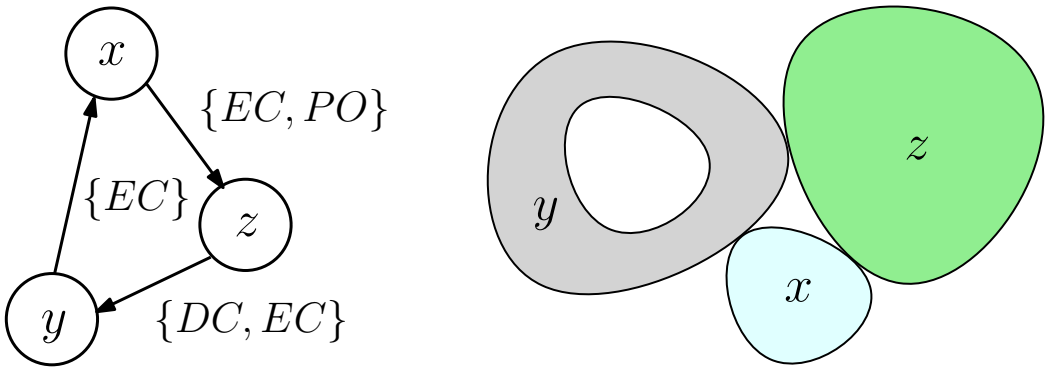


Figure: A QCN of RCC8 along with a solution

Fundamental Reasoning Problems of QCNs (1/3)

Definition

The satisfiability checking problem of a QCN $\mathcal{N}$ *is deciding whether* $\mathcal{N}$ *admits a solution.*

- The satisfiability checking problem is NP-hard in general.

Fundamental Reasoning Problems of QCNs (2/3)

Definition

*The minimal labeling problem (*MLP*) of a* QCN $\mathcal{N}$ *is finding the strongest implied constraints of* $\mathcal{N}$*.*

- The MLP is polynomial-time Turing reducible to the satisfiability checking problem [GS93].

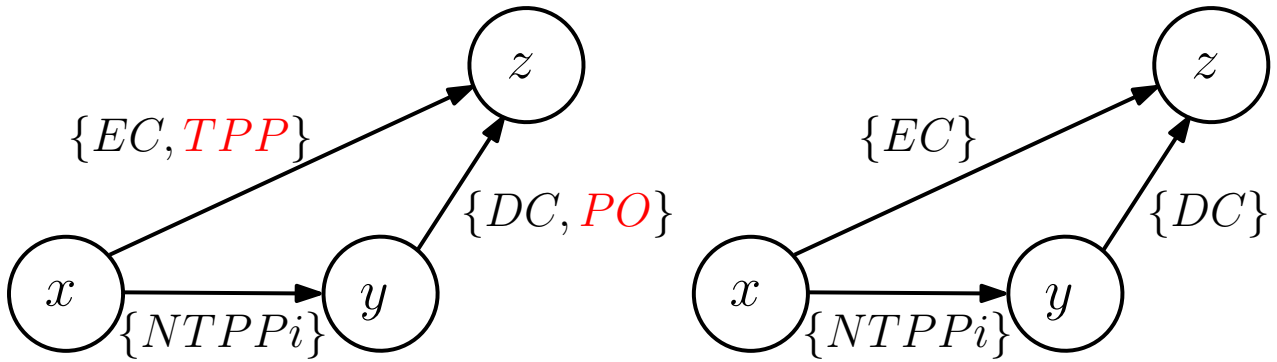


Figure: A RCC8 network (left) and its minimal network (right)

Fundamental Reasoning Problems of QCNs (3/3)

Definition

The redundancy problem of a QCN $\mathcal{N}$ *is determining if a particular constraint of* $\mathcal{N}$ *is entailed by the rest of the constraints of* $\mathcal{N}$

- Like the MLP, the redundancy problem is polynomial-time Turing reducible to the satisfiability checking problem [GS93].

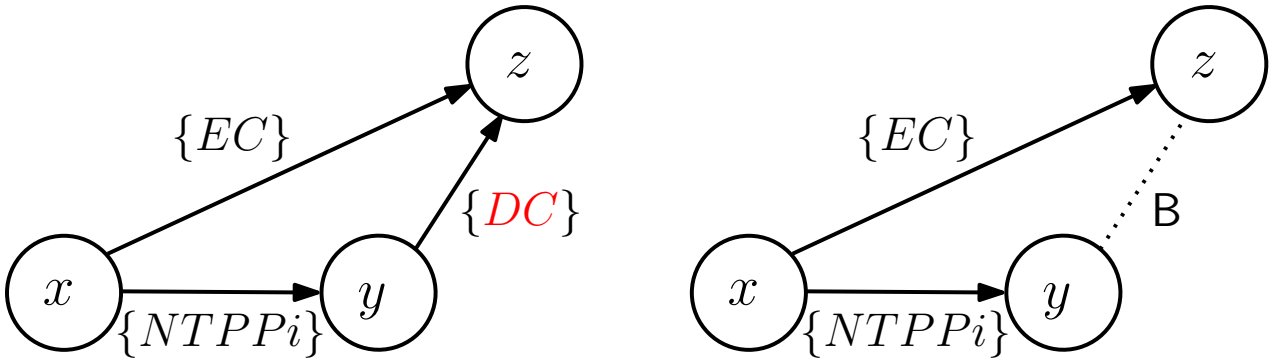


Figure: A RCC8 network (left) and its prime network (right)

Research Roadmap: Long-term Ambition

- Push the envelope in QSTR by defining tools for efficiently reasoning about dynamic spatio-temporal data.
- Integrate the developed tools into the larger context of highly active areas such as:
  - neuro-symbolic reasoning;
  - planning;
  - data mining.
- Study combinations of QSTR with other paradigms (e.g., CP, ASP, CBR).
- Encode QSTR in SMT approaches.

Research Roadmap: Neuro-Symbolic Reasoning

- Verification of the output of a classifier
- Explanation of ML-based decisions (interpretability problem)
- Trustable AI

Research Roadmap: Planning

- Learning of dynamic spatio-temporal representations of an environment
- Applications of spatio-temporal models in motion planning and control under complex spatio-temporal tasks
- Handling of uncertain environments and collaborative mobile autonomous systems

Research Roadmap: Data Mining

- Facilitation of spatio-temporal pattern recognition algorithms
- Pattern discovery / identification at run-time
- Removal of redundancy from spatio-temporal KBs

Final Remarks

- QSTR is a research area relevant for many AI application domains (e.g., in defence or medicine).
- It extends from Theoretical Computer Science to Practical Applications, and vice versa.
- Important to consider hybrid architectures for AI/ML that involve also symbolic computation.

Thank you for your interest and attention!
Please visit my homepage at: `http://msioutis.gitlab.io`

References

Martin Charles Golumbic and Ron Shamir. "Complexity and Algorithms for Reasoning about Time: A Graph-Theoretic Approach". In: *J. ACM* 40 (1993), pp. 1108–1133 (cit. on pp. 12, 13).

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