Hybrid AI Systems Grounded on Just-in-time Qualitative Spatio-Temporal Reasoning

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Outline

1. Bio
2. Hybrid AI: Overview
3. Hybrid AI with a Spatio-Temporal Flavor
4. Fundamentals of Spatio-Temporal Formalisms
5. Research Topics on Hybrid Spatio-Temporal AI
6. Discussion
Personal Details

- Greek, born in Wickede, Germany

- Languages: Greek > English > German > Spanish > French

- Research fellow (Wissenschaftlicher Mitarbeiter) with 5h/week teaching load at Otto-Friedrich-University Bamberg (Germany)
Education

- Ph.D. in Computer Science in 2017 from Université d’Artois (France); brief stay in University of Technology Sydney (Australia)

- M.Sc. in Advanced Information Systems and B.Sc. in Computer Science in 2012 and 2009 respectively from the National and Kapodistrian University of Athens (Greece)
Short Bio: Zhiguo Long

- Born in Chengdu, Sichuan, China (Hometown of Pandas!)
- Ph.D. in Software Engineering in 2017 from University of Technology Sydney (Australia), supervised by Prof. Sanjiang Li
- Half-year visit in 2015 at Cardiff University (UK), supervised by Prof. Steven Schockaert.
- Assistant Professor with School of Computing and Artificial Intelligence, Southwest Jiaotong University, Chengdu, China
- Homepage: https://zhiguolong.github.io/
Hybrid AI: An Overview

Part I
Neuro-Symbolic AI

Neural-symbolic AI seeks to bring together robust learning in neural networks with reasoning and explainability via symbolic representations for network models

A. d’Avila Garcez and L. C. Lamb

Neuro-Symbolic AI Architectures

- Neural architectures for logical reasoning\(^2\)

- Logical specification of neural networks\(^3\)

- *Architectures integrating learning and reasoning*\(^4\)

  - *Our main focus here!*


Figure: Cyclical interaction in Neuro-Symbolic AI; a symbolic system feeds symbolic (partial) knowledge to a neural network system, which can be trained on raw data, and knowledge acquired through machine learning can then be extracted back to the symbolic system, and made available for further processing in symbolic form.\(^5\)

Neuro-Symbolic AI Components

Symbolic AI module

- A knowledge base (KB), which stores facts and rules
- A symbolic model, viz., the KB’s logic (e.g., modal logic, first-order logic, deductive reasoning, and so on)

Machine learning module

- Any kind of neural network architecture or other connectionist model

Raw data

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Alternative Terms for Neuro-Symbolic AI

- Data-driven vs knowledge-driven
- Subsymbolic vs symbolic
- Learners vs solvers
- Thinking fast vs thinking slow (Daniel Kahneman)
- Statistical learning vs symbolic reasoning
- Perception vs logical reasoning
- Connectionism vs computationalism
- Scruffy vs neat
Why Neuro-Symbolic AI?

- High explainability and high accuracy performance
  - Explainability stems from Symbolic AI
  - Accuracy\(^7\) stems from ML model
- Mimics human problem-solving
  - Perception, mostly accurate and fast, can be seen as a data-driven process
  - Reasoning, mostly complex and slow, can be realized by logical reasoning
- Hot research topic and major AI challenge\(^8\)

\(^7\)ML models can be designed and trained with relatively much less effort compared to their accuracy performance
\(^8\)https://ai100.stanford.edu/2021-report/gathering-strength-gathering-storms-one-hundred-year-study-artificial-intelligence
Ok, but Why Not End-to-end Learning?

Representation learning only includes statistical information—it does not capture perturbations (interventions), reasoning, planning

ML models should be tied to assumptions that align with **physics** and **human cognition** to allow for generalization

Modular approach: decompose knowledge into independent and recomposable pieces

B. Schölkopf et al.⁹

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https://arxiv.org/abs/2102.11107
Number of people who drowned by falling into a pool correlates with Films Nicolas Cage appeared in

**Figure:** Nicolas Cage causing deaths?\(^{10}\)

\(^{10}\)http://www.tylervigen.com/spurious-correlations
ML Caveats: Perturbations/Interventions (2/4)

Relation to causality: conditional probabilities cannot reliably predict the outcome of an intervention

- “Seeing people with open umbrellas suggests that it is raining” → “Closing umbrellas does not stop the rain”

Figure: An adversarial example

https://gradientscience.org/intro_adversarial/
Counterfactual problems involve:

- reasoning about why things happened;
- imagining the consequences of different actions in hindsight;
- and determining which actions would have achieved a desired outcome

“Would a given patient have suffered heart failure if they had started exercising a year earlier?”
Data diversity is an untestable condition a priori.

Figure: Thanks to machine learning models the robot apocalypse was short lived\textsuperscript{12}

\textsuperscript{12}https://www.smbc-comics.com/comic/rise-of-the-machines
Ok, but Why Not Just Symbolic AI Then?

- Knowledge acquisition bottleneck
  - Never-ending need for carefully crafted rules
  - Too much data vs too few domain experts to classify and structure it
  - Semantic alignment issues
- Symbols can be largely used when the input is definite and falls under certainty
Neuro-Symbolic AI Sum-up So Far

- Better than standalone Machine Learning or Symbolic AI
- Statistics (correlations) + logic $\approx$ causality
- Raises many open questions / opportunities for research
- Resembles human reasoning, with respect to some rationale
- Still far away from dealing with “insight problems”\(^\text{13}\)

Useful Links

- Browse the following Neuro-Symbolic AI website
  http://www.neural-symbolic.org/

- Watch the latest Neural-Symbolic AI tutorials
  https://dtai.cs.kuleuven.be/tutorials/nesytutorial/

- Watch the lecture by Prof. Bernhard Schölkopf on Symbolic, Statistical, and Causal Representations
  https://youtu.be/gSfntg5vpUUx
Hybrid AI with a Spatio-Temporal Flavor

Part II
We recall the previous quote

*ML models should be tied to assumptions that align with physics and human cognition to allow for generalization*

*B. Schölkopf et al.*

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*B. Schölkopf et al.: Towards Causal Representation Learning. (2021)*

https://arxiv.org/abs/2102.11107
Two Logical Rules: Which is Better? Why?

- “if I accelerate faster than the vehicle directly in front of me, then I will overtake it”

- “if I accelerate faster than the vehicle directly in front of me, then I will crush it”
Injecting Causality via Spatio-Temporal Calculi

- Qualitative Spatial & Temporal Reasoning (QSTR) is a major field of study in KR, and Symbolic AI in general\(^\text{15}\).

- QSTR abstracts from numerical quantities of space and time by using natural descriptions instead (e.g., *precedes*, *contains*, *is left of*), grounded on *physics* and *human cognition*.

![Diagram](image)

**Figure:** Left: Qualitative abstraction of a spatial configuration, Right: Temporal constraint network of 3 variables (tasks); \(\) denotes complete uncertainty.

\(^{15}\) G. Ligozat.: *Qualitative Spatial and Temporal Reasoning*. ISTE Series. Wiley, 2011
An abundance of calculi exist for many types of spatial and temporal information (e.g., trajectories, occlusion, intervals)\textsuperscript{16}

Example Calculus: Allen’s Interval Algebra

Figure: The base relations of Interval Algebra; $\cdot i$ denotes the inverse of $\cdot$. 
Applications: Geospatial Semantic Segmentation

**Ontological Representation and Reasoning**

Extra Information (Shadow) (about the suspicious area)

**Figure:** A semantic referee reasons about the mistakes made by the classifier based on ontological concepts and provides additional information back to the classifier that prevents the classifier from making the same misclassifications.

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**Figure Notes:**

Applications: Medicine / 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$^{18}$

Applications: Region Approximation / Emergency Response

Figure: Illustration of locating a region by natural language descriptions, e.g., “Bushfire burning about 5km northwest of Yallourn North” and “I saw fire about 10km northeast from Moe”, with the help of a region approximation method.\(^\text{19}\)

\(^{19}\) Ongoing work with Southwest Jiaotong University (China) (submitted to a journal)
Applications: Drone Monitoring

Figure: “Never fly over an urban area for more than 3 minutes”: \( \forall r \in \text{UrbanRegion}, \Box (PO \lor TPP \lor NTPP(Drone, r) \rightarrow \Diamond_{[0,180]} DC(Drone, r))^{20} \)

\( ^{20} \)F. Heintz and D. de Leng: *Spatio-Temporal Stream Reasoning with Incomplete Spatial Information*. In: ECAI. 2014
Fundamentals of Spatio-Temporal Formalisms

Part III
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 $B = \{<, >, =\},$ then $Id$ is $=$ ;*

- $B$ is closed under the converse operation $(-1)$
  
  *for example, $<^{-1}$ is $>$;*

$2^B$ expresses all relations (definite and indefinite knowledge).
Example Calculus (Reminder): RCC8

\[ X \quad DC \quad X \]
\[ X \quad EC \quad Y \]
\[ X \quad PO \quad Y \]
\[ X \quad EQ \quad X \]
\[ X \quad TPP \quad Y \]
\[ Y \quad TPPi \quad X \]
\[ X \quad NTPP \quad Y \]
\[ Y \quad NTPPi \quad X \]

**Figure:** The base relations of RCC8; \( \cdot i \) denotes the inverse of \( \cdot \)

An abundance of calculi exist for many types of spatial and temporal information (e.g., trajectories, occlusion, intervals)\(^{21}\)

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 \( C : V \times V \rightarrow 2^B \).

Figure: A QCN of RCC8 along with a solution

An atomic satisfiable sub-QCN of the original QCN is a *scenario* of it.
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.
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.

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

The redundancy problem of a QCN $N$ is determining if a particular constraint of $N$ is entailed by the rest of the constraints of $N$.

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

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**Figure:** A RCC8 network (left) and its prime network (right).
Local Consistencies

- Approximate satisfiability
- Simplify a QCN / prune search space
- Realize forward-checking in a backtracking algorithm
The weak composition \( EC \diamond NTPP \) yields the set of base relations \( \{NTPP, TPP, PO\} \).

\[
\begin{align*}
NTPP(x, z) & \quad TPP(x, z) & \quad PO(x, z)
\end{align*}
\]

**Figure:** Three possible configurations for regions \( x, y, z \) when we have \( EC(x, y) \diamond NTPP(y, z) \)

We can precompute and store all weak composition outputs in a table in memory.
Given a QCN $\mathcal{N} = (V, C)$ and a graph $G = (V, E)$, $\Diamond_G$-consistency enforces consistency on all triples of variables in $\mathcal{N}$ that correspond to triangles in $G$.\footnote{M. Sioutis et al.: An Efficient Approach for Tackling Large Real World Qualitative Spatial Networks. Int. J. Artif. Intell. Tools 25 (2016)}

**Definition**

Given a QCN $\mathcal{N} = (V, C)$ and a graph $G = (V, E)$, $\mathcal{N}$ is $\Diamond_G$-consistent if and only if $\forall \{v_i, v_j\}, \{v_i, v_k\}, \{v_k, v_j\} \in E$, we have that $C(v_i, v_j) \subseteq C(v_i, v_k) \Diamond C(v_k, v_j)$.

**Figure:** A QCN of RCC8 that is not $\Diamond$-consistent
**\( \diamond G \)-Consistency: Results**

**Proposition**

Let \( \mathcal{N} = (V, C) \) be a QCN defined over a subclass of relations that has patchwork for \( \diamond \)-consistent QCNs, and \( G = (V, E) \) a chordal graph such that \( G(\mathcal{N}) \subseteq G \). If \( \mathcal{N} \) is not trivially inconsistent and \( \diamond G \)-consistent, then \( \mathcal{N} \) is satisfiable.

\( \diamond \)-consistency is \( \diamond G \)-consistency where \( G \) is a complete graph

![Triangulation of the underlying constraint graph of a QCN](image-url)
Algorithm 1: PWC(\(\mathcal{N}, G\))

in: A QCN \(\mathcal{N} = (V, C)\) and a graph \(G = (V, E)\).
output: \(\hat{G}(\mathcal{N})\).

begin

\(Q \leftarrow E;\)

while \(Q \neq \emptyset\) do

\(\{v, v'\} \leftarrow Q.pop();\)

foreach \(v'' \in V | \{v, v''\}, \{v', v''\} \in E\) do

\(r \leftarrow C(v, v'') \cap (C(v, v') \diamond C(v', v''));\)

if \(r \subseteq C(v, v'')\) then

\(C(v, v'') \leftarrow r;\)

\(C(v'', v) \leftarrow r^{-1};\)

\(Q \leftarrow Q \cup \{\{v, v''\}\};\)

\(r \leftarrow C(v'', v') \cap (C(v'', v) \diamond C(v, v'));\)

if \(r \subseteq C(v'', v')\) then

\(C(v'', v') \leftarrow r;\)

\(C(v', v'') \leftarrow r^{-1};\)

\(Q \leftarrow Q \cup \{\{v'', v'\}\};\)

return \(\mathcal{N}\);

end

Runtime: \(O(\Delta(G)|E||B|)\)
◮-Consistency: Definition

Given a QCN $\mathcal{N} = (V, C)$ and some ordering of its variables, $\bowtie$-consistency entails consistency on all triples of variables in $\mathcal{N}$ along that ordering.\footnote{M. Sioutis et al.: Leveraging Variable Elimination for Efficiently Reasoning about Qualitative Constraints. Int. J. Artif. Intell. Tools 27 (2018)}

\begin{definition}
Given a QCN $\mathcal{N} = (V = \{v_0, v_1, \ldots, v_{n-1}\}, C)$, $\mathcal{N}$ is $\bowtie$-consistent iff for all $v_i, v_k, v_j \in V$ with $i, j < k$ we have that $C(v_i, v_j) \subseteq C(v_i, v_k) \bowtie C(v_k, v_j)$.
\end{definition}

\begin{figure}
\centering
\begin{tikzpicture}
  \node (x) at (0,2) {$x$};
  \node (y) at (0,0) {$y$};
  \node (z) at (1,1) {$z$};
  \path[->, thick]
    (x) edge node [above] {$\{TPP\}$} (z)
    (y) edge node [left] {$\{EQ\}$} (z)
    (x) edge node [right] {$\{TPPI, PO\}$} (y);
\end{tikzpicture}
\caption{A QCN of RCC8 that is not $\bowtie$-consistent w.r.t. the ordering $(z, y, x)$}
\end{figure}
Proposition

Let $\mathcal{N} = (V = \{v_0, v_1, \ldots, v_{n-1}\}, C)$ be a QCN defined over a distributive subclass of relations over which every $\blacklozenge$-consistent atomic QCN is satisfiable. If $\mathcal{N}$ is $\blacktriangleleft$-consistent and not trivially inconsistent, then $\mathcal{N}$ is satisfiable.

Figure: Eliminating variables one by one and propagating constraints
Proposition

Let $\mathcal{N} = (V = \{v_0, v_1, \ldots, v_{n-1}\}, C)$ be a $\triangleleft$-consistent and not trivially inconsistent QCN defined over a distributive subclass of relations over which every $\triangleleft$-consistent atomic QCN is satisfiable. To refine $\mathcal{N}$ to a scenario $S$, for each $k$ from $1$ to $n-1$ and for each $i \in \{0, \ldots, k-1\}$ do:

- $C(v_k, v_i) \leftarrow \bigcap_{j=0}^{k-1} C(v_k, v_j) \circ C(v_j, v_i)$;
- $C(v_k, v_i) \leftarrow \{b\}$ for some $b \in C(v_k, v_i)$;
- $C(v_i, v_k) \leftarrow (C(v_k, v_i))^{-1}$.

Figure: Adding variables one by one and propagating constraints
Algorithm 2: DWC(\(\mathcal{N}, \alpha\))

\[
\text{in : A QCN } \mathcal{N} = (V, C) \text{ with } |V| = n, \text{ and a bijection } \alpha \text{ of } V \text{ onto } \\
\{0, 1, \ldots, n - 1\}.
\]

\[
\text{output : } \overset{\triangle}{\mathcal{N}}.
\]

\[
1 \begin{align*}
G & \leftarrow (V, E = E(G(\mathcal{N}))); \\
\text{for } x \text{ from } n - 1 \text{ to } 1 \text{ do} & \\
\nu & \leftarrow \alpha^{-1}(x); \\
\text{adj} & \leftarrow \{v' \mid \{v', v\} \in E \wedge \alpha(v') < \alpha(v)\}; \\
\text{foreach } v', v'' \in \text{adj} \text{ do} & \\
\text{if } \alpha(v') < \alpha(v'') \text{ then} & \\
\text{if } \{v', v''\} \notin E \text{ then} & \\
E & \leftarrow E \cup \{\{v', v''\}\}; \\
\tau & \leftarrow C(v', v'') \cap (C(v', v) \odot C(v, v'')); \\
\text{if } \tau \neq C(v', v'') \text{ then} & \\
C(v', v'') & \leftarrow \tau; \\
C(v'', v') & \leftarrow \tau^{-1};
\end{align*}
\]

\[
\text{return } \mathcal{N};
\]

Runtime: \(O(\Delta(G)^2 |V|)\)
Given a QCN $\mathcal{N} = (V, C)$, a chordal graph $G = (V, E) \supseteq G(\mathcal{N})$, and a subclass $\mathcal{A}$ for which $\hat{G}$-consistency is complete, we aim to characterize a QCN $\mathcal{N}'$ such that:

$$\mathcal{N}' \subseteq \mathcal{N} \text{ and } \mathcal{N}' = \hat{G}(\mathcal{A}(\mathcal{N}'))$$
Solving via backtracking search

Let us consider a QCN $\mathcal{N}$, we tackle it as follows.

- Every relation $r$ forming a constraint in $\mathcal{N}$ is split into subrelations $r' \subseteq r$.

- These subrelations $r'$ belong to a set of relations $\mathcal{A}$ over which the QCN becomes tractable.

- After every refinement of a relation $r$ into one of its subrelations $r'$, a validity check is performed:
  - if the refinement is valid, we proceed with the next one;
  - if the refinement is not valid, we backtrack to the previous one.

- When $\mathcal{N}$ has been refined into relations of $\mathcal{A}$, we stop.
Algorithm 3: Consistency($\mathcal{N}$, $G$, $\mathcal{A}$)

**in** : A QCN $\mathcal{N} = (V, C)$, a graph $G = (V, E)$, and a subclass $\mathcal{A}$ of $2^B$.

**output** : Null, or a refinement of network $\mathcal{N}$ over $\mathcal{A}$.

1. **begin**
2. $\mathcal{N} \leftarrow \text{PWC}(\mathcal{N}, G)$;
3. if $\exists \{v_i, v_j\} \in E$ such that $C(v_i, v_j) = \emptyset$ then
   4. return Null;
5. if $\forall \{v_i, v_j\} \in E$ we have that $C(v_i, v_j) \in \mathcal{A}$ then
   6. return $\mathcal{N}$;
7. choose a constraint $C(v_i, v_j)$ with $\{v_i, v_j\} \in E$ such that $C(v_i, v_j) \notin \mathcal{A}$;
8. split $C(v_i, v_j)$ into $r_1, \ldots, r_k \in \mathcal{A}$: $r_1 \cup \ldots \cup r_k = C(v_i, v_j)$;
9. foreach $r \in \{r_l \mid 1 \leq l \leq k\}$ do
   10. $\mathcal{N}[v_i, v_j] \leftarrow r$; $\mathcal{N}[v_j, v_i] \leftarrow r^{-1}$;
   11. result $\leftarrow \text{Consistency}(\mathcal{N}, G, \mathcal{A})$;
   12. if result $\neq$ Null then
      13. return result;
14. return Null;
A QCN as a SAT instance

Let $\mathcal{N} = (V, C)$ be a QCN instance, make variable $x_{ij}^b$ for every $v_i, v_j \in V$ and $b \in C(v_i, v_j)$, then make encoding as follows\(^{24}\)

at least one constraint: $x_{ij}^{b_1} \lor x_{ij}^{b_2} \ldots \lor x_{ij}^{b_{|C(v_i, v_j)|}}$

at most one constraint: $\neg (x_{ij}^{b_k} \land x_{ij}^{b_l})$, $\forall$ distinct $b_k, b_l \in C(v_i, v_j)$

weak composition: $(x_{ij}^{b_m} \land x_{ij}^{b_n}) \rightarrow (x_{ij}^{b_1} \lor x_{ij}^{b_2} \ldots \lor x_{ij}^{b_w})$

\(^{24}\)D. N. Pham et al.: *Towards an efficient SAT encoding for temporal reasoning*. In: CP. 2006
A QCN as an ASP instance

Let $\mathcal{N} = (V, C)$ be a QCN instance over the set of base relation $B$, then make encoding as follows\(^{25}\)

**base relation declaration:** \{\textit{rel}\(R\).\}, $\forall R \in B$

**choice rule:** $1\{\textit{label}(U, V, L) : \textit{rel}(L)\}1 : -$ \textit{variable}1\((U)\), \textit{variable}2\((V)\), $U < V$.

**QCN size:** \textit{variable}1\((0..|V| - 1)\). \textit{variable}2\((0..|V| - 1)\).

**weak composition:** \{\textit{:- label}\(X, Y, R_1\), \textit{label}\(Y, Z, R_2\), \textit{label}\(X, Z, R_3\).\}\}

**integrity constraint:** \{\textit{:- label}\(X, Y, R\).\}  
\(/ / R \notin C(X, Y)\)

\(^{25}\)J. J. Li: *Qualitative Spatial and Temporal Reasoning with Answer Set Programming*. In: ICTAI. 2012
A Case of Robustness in AI

- We want to have some measure of the quality of a spatial or temporal configuration, viz., scenario.\textsuperscript{26}

- We focus on scenarios that can withstand perturbations, i.e., that limit as much as possible the need for successive repairs.

\begin{figure}
\centering
\begin{tikzpicture}
\node[shape=circle,draw] (A) at (0,0) {Task A};
\node[shape=circle,draw] (B) at (1,1) {Task B};
\node[shape=circle,draw] (C) at (2,0) {Task C};
\draw[-stealth] (A) -- node[above] {\texttt{follows}} (B);
\draw[-stealth] (B) -- node[above] {\texttt{precedes}} (C);
\draw[-stealth] (C) -- node[below] {\texttt{precedes}} (A);
\end{tikzpicture}
\caption{Tasks scheduled in a factory; as there might be unpredictable incidents concerning resource availability (e.g., power outage), how should the factory schedule production so that it may be least disturbed?}
\end{figure}

\textsuperscript{26} M. Sioutis et al.: \textit{On Robustness in Qualitative Constraint Networks}. In: IJCAI. 2020
Robust Scenario

Definition

Given a network \( N \), a scenario \( S \) of \( N \) is robust iff:

\[
S \in \arg \max_{S' \in [\[N\]]} \text{similarity}(S', [\[N\]])
\]

where

\[
\text{similarity}(N, M) = \frac{\sum_{N' \in M} \#\text{sameConstraints}(N, N')/|N'|}{|M|}
\]

Intuitively, a robust scenario of a network \( N \) has the largest number of common constraints on average with each scenario of \( N \), i.e., with each satisfiable atomic network in \([\[N\]]\).
Revisiting the Task Scheduling Example

Choosing *follows* over *precedes* between Tasks A and B, maintains the whole range of possibilities between Tasks A and C.

Choosing *precedes* over any other relation between Tasks A and C, can resist the change of *follows* switching back to *precedes* between Tasks A and B.
Evaluation: Perturbation Tolerance Comparison

Figure: Perturbation tolerance comparison with job-shop dataset
Useful Links

- **Python Qualitative Constraint-based Tools**
  https://msioutis.gitlab.io/software/

- **GQR: C++ Qualitative Constraint-based Reasoner**
  https://www.sfbtr8.spatial-cognition.de/en/project/reasoning/r4-logospace/research-tools/gqr/index.html

- **SparQ: A Toolbox for Qualitative Spatial and Temporal Reasoning**
  https://www.uni-bamberg.de/en/sme/research/sparq/
Future Research Topics

Part IV
Enabling Abductive Learning

Figure: Abductive Learning framework\textsuperscript{27}

Enabling Abductive Learning: Underlying Challenges (1/2)

- Adaptive and dynamic algorithms for runtime verification of neural network-based components

- Parsimonious local consistencies (e.g., restricted to neighbourhood\textsuperscript{28})

- Dynamic algorithms for repair (revision), inconsistency minimization

Enabling Abductive Learning: Underlying Challenges (2/2)

- Relation-aware and/or lazy tree decompositions

- Backbone-based decoupling and backdoor-based search space splitting approaches\(^{29}\) (reasoning shortcuts)

- Exploitation of AI hardware (e.g., GPUs)

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\(^{29}\) M. Sioutis and T. Janhunen. *Towards Leveraging Backdoors in Qualitative Constraint Networks*. In: KI. Short paper. 2019
Neuro-symbolic AI

- Neuro-symbolic formulae:

\[
X^{(95\% \text{ yolk})} \text{ is contained in } (45\% \text{ true}) \text{ or overlaps } (55\% \text{ true}) \ Y^{(90\% \text{ egg})}
\]

\[
\left( \text{Train } X \{\text{canUse}\} \left( \text{Track } A \oplus \text{Track } B \right) \right) \land \left( \text{Train } Y \{\text{canUse}\} \text{ Track } B \right) \land
\left( \text{departInt}(\text{Train } X) \{\text{precedes } 10\% , \text{meets } 30\% , \text{overlaps } 60\% \} \text{ departInt}(\text{Train } Y) \right)
\]

\[\square \left( \neg \text{blocked}(\text{Track } A) \land \neg \text{blocked}(\text{Track } B) \right)\]

Update: \(\Diamond \text{blocked}(\text{Track } A)^{90\%}\)

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Hierarchical portfolio of solvers

- QSTR information can be encoded/tackled in different ways (aside from native QSTR approaches), e.g.:
  - as SAT or even traditional CSP instances\textsuperscript{31};
  - and as Answer Set Programming (ASP) instances too\textsuperscript{32,33}

- Automate choice/combination of tools for a given task

\textsuperscript{33} T. Janhunen and M. Sioutis.: Allen’s Interval Algebra Makes the Difference. In: DECLARE. 2019
Data mining

- Knowledge discovery in spatio-temporal data

- Removal of redundancy from spatio-temporal KBs

- Pattern discovery / identification at run-time
Final Remarks

- QSTR, within Neuro-Symbolic AI especially, 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 modular architectures for AI that are grounded on *physics* and *human cognition*
Thank you for your interest and attention!

http://msioutis.gitlab.io

The purpose of abstraction is not to be vague, but to create a new semantic level in which one can be absolutely precise

Dijkstra