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Qualitative Spatial Reasoning using Answer Set Programming

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About UoH

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  - 5 Research Centres

- Centre for Planning, Autonomy and Representation of Knowledge
  - Led by Profs Lee McCluskey and Grigoris Antoniou
  - 14 members

Outline

- Motivation
- Qualitative Spatial Reasoning
- Answer Set Programming
- Trajectory Calculus
- Generalised Encoding
- Current and Future Steps

Reasoning with Trajectories

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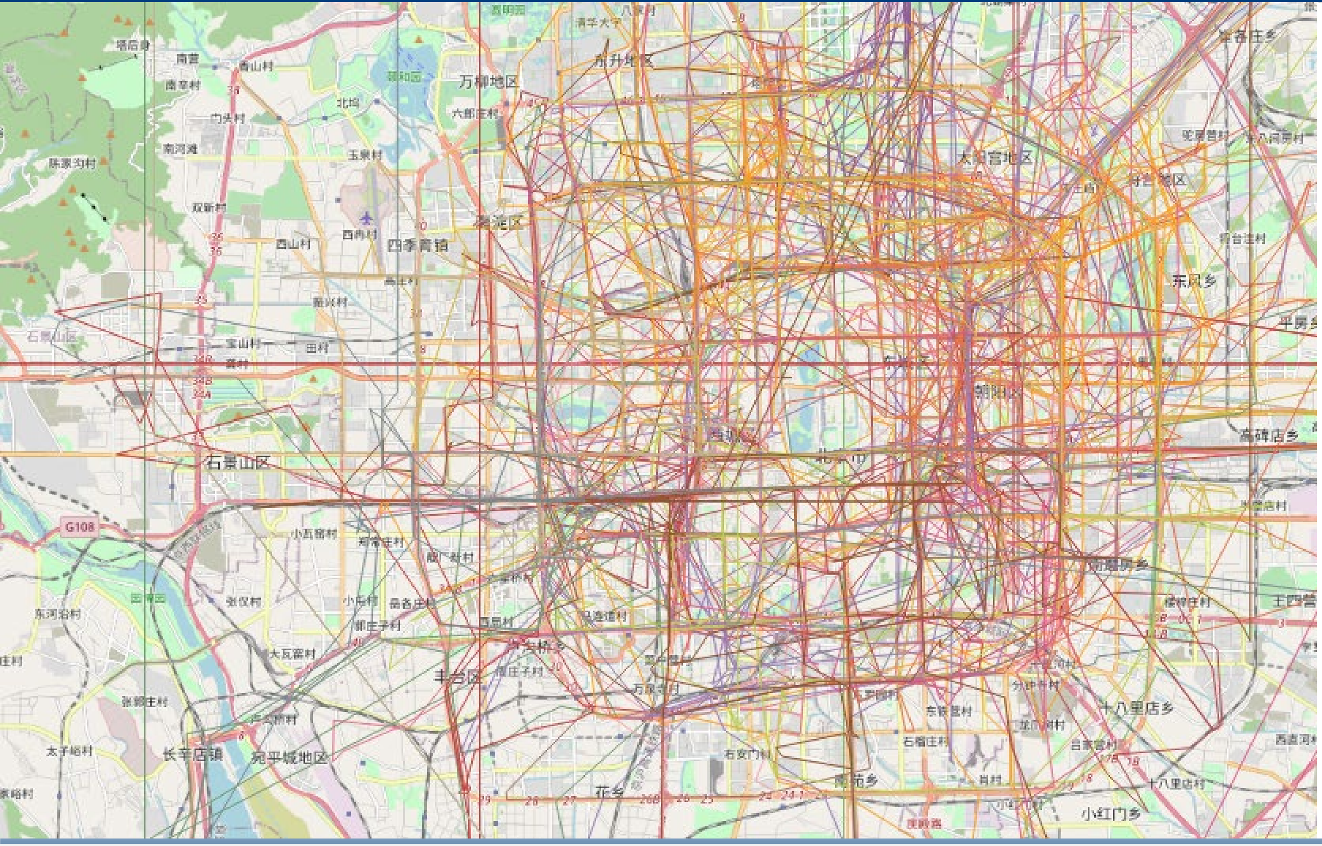

- T-Drive dataset: trajectories generated by 10,357 taxis in Beijing
- Motivating Query MQ1: Find areas with maximum concentration of intersecting trajectories, with trajectories also passing through one of the roads surrounding the Forbidden City

Reasoning with Regions

- ASR dataset: locations of more than 125,000 registered antenna structures across the USA
- Motivating Query MQ2: Find the minimum number of antennas required to cover a particular area, avoiding interference by ensuring that overlapping regions do not use the same frequencies

Motivation

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- Common features of motivating queries
  - **Qualitative** aspects
    - Intersecting trajectories
    - Overlapping regions
  - Other, **non-qualitative** reasoning
    - Maximum concentration, pass through particular location
    - Antenna coverage and minimum number of frequencies
- Need for an approach to represent and reason with such knowledge that **integrates** both qualitative and non-qualitative aspects

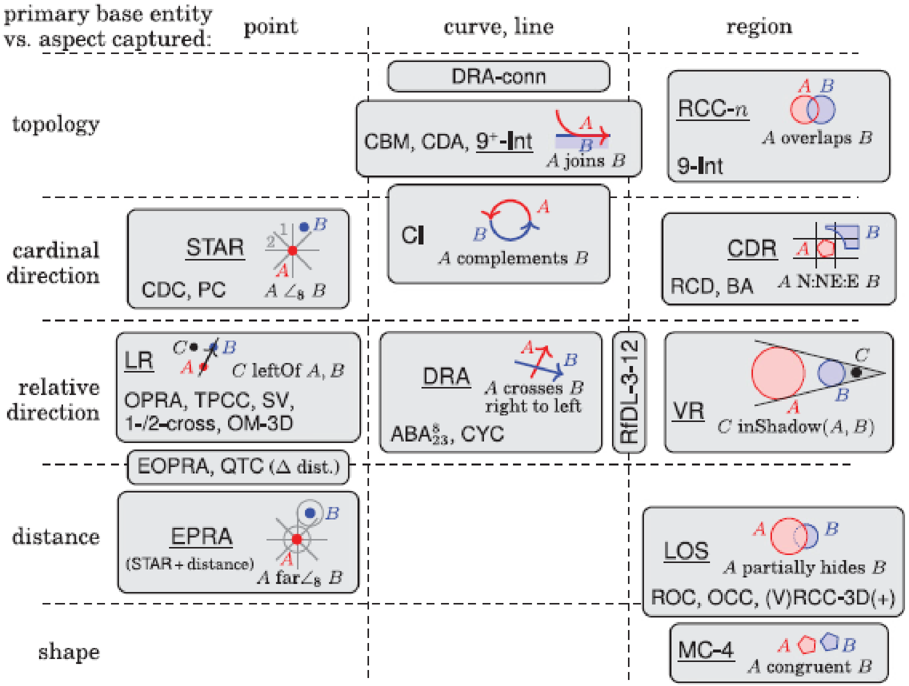
Qualitative Reasoning

- Less precise but more comprehensible
  - Compare rather than measure
- Motivated by human cognition
  - Humans rarely think using precise quantities
  - Bring human and machine thinking closer
  - Increase interpretability of reasoning results
- More suitable than quantitative reasoning when
  - Knowledge about the environment is **incomplete** or **imprecise**
  - Understandable interactions and acceptable **explanations** are more important than high precision

Qualitative Spatial Reasoning

- Focus on spatial (and temporal) domains
  - Rich structures to exploit
  - Quite important for many applications
    - naval traffic monitoring
    - warehouse process optimisation
    - robot manipulation
- Probably the most well-researched domains for qualitative reasoning
  - Well over 40 different formalisms, called **qualitative (spatial) calculi**

Qualitative Spatial Calculi



Dylla et al. (2017)

Region Connection Calculus (RCC)

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- Recall MQ2: Find the minimum number of antennas [...] by ensuring that **overlapping regions** do not use the same frequencies
- RCC allows reasoning about qualitative relations between regions on space
  - RCC-5 has 5 **jointly exhaustive** and **pairwise disjoint** base relations

Composition (⋄) table: $x\ \boldsymbol{r}\ y$ and $y\ \boldsymbol{s}\ z$ then $x\ \boldsymbol{r} \diamond \boldsymbol{s}\ z$

r \ s	**DR**	**PO**	**PP**	**PPI**	**EQ**
DR	All	DR, PO, PP	DR, PO, PP	DR	DR
PO	DR, PO, PPI	All	PO, PP	DR, PO, PPI	PO
PP	DR	DR, PO, PP	PP	All	PP
PPI	DR, PO, PPI	PO, PPI	EQ, PO, PP, PPI	PPI	PPI
EQ	DR	PO	PP	PPI	EQ

Reasoning Tool Support

- Two toolkits support multiple qualitative spatial calculi
  - GQR
  - SparQ
- Both support standard qualitative reasoning tasks
  - Such as deciding whether a set of qualitative constraints (relations) over a domain are consistent
- Both are dedicated qualitative reasoning tools
  - Neither supports reasoning beyond qualitative calculi

Answer Set Programming (ASP)

- ASP is an approach to problem solving that is
  - **Declarative**: describe the problem, not how to solve it
  - **Logic**-based: knowledge is represented in the form of logic formulas
  - **Rule**-based: logic formulas are arranged as rules with premises and conclusions
- ASP allows for solving hard search and optimisation problems
  - Reasoning with qualitative relations is one such problem

ASP Logic Programs

- An ASP logic program is a set of rules of the form

$$\underbrace{A}_{\text{head}} \leftarrow \underbrace{B_1, \ldots, B_m, not\ C_1, \ldots, not\ C_n}_{\text{body}}$$

  - $A, B_1, \ldots, B_m$ and $C_1, \ldots, not\ C_n$ are atoms (logic formulas that cannot be split further)
  - "$\leftarrow$" denotes "if" and "," denotes "and"
  - "not" denotes "negation-as-failure" (false due to failing to prove true)
  - Semantics: A is true if $B_1, \ldots, B_m$ are true and $C_1, \ldots, C_n$ cannot be proven to be true
    - If A is missing, semantics: it is not possible for $B_1, \ldots, B_m$ to be true and for $C_1, \ldots, C_n$ to not be provable to be true

ASP Reasoning

$$A \leftarrow B_1, \ldots, B_m, not\ C_1, \ldots, not\ C_n$$

- Reasoning in ASP follows these steps:
  1. Assign true or false to atoms one after the other
  2. Propagate values from bodies to heads
  3. If contradicting results, negate the assignment(s) that led to this
  4. Repeat Steps 1-3 until all atoms have been assigned value
  5. An **answer set** is the set of all atoms assigned to true

Qualitative Reasoning with Trajectories

- Recall MQ1: Find areas with maximum concentration of **intersecting trajectories** […]
- We need a qualitative calculus capable of (efficiently) reasoning about relations between trajectories
- QTC (Weghe et al. 2016) focuses on detailed representation at the expense of efficient reasoning
  - Up to 81 relations to account for location, velocity, acceleration and motion azimuth of moving point objects
- Proposed solution: **simplify trajectory** model, viewing trajectories as complete **paths**

Proposed Simplifications

- Trajectories modelled as sequences of *regions* on a *partitioned* map
  - Given a map M, a partitioning R of M is defined as a set of non-overlapping regions r_i, such that $M = \bigcup_{r_i \in R} r_i$
- Trajectories are treated as **whole** paths and not on the basis of individual points
- Individual features of moving objects such as velocity and acceleration are not taken into account

Trajectory Calculus TC-6

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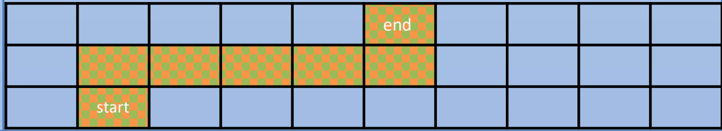
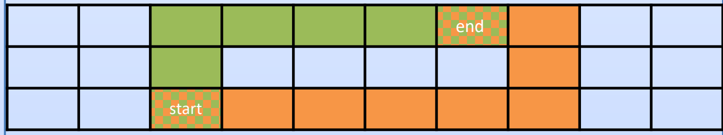
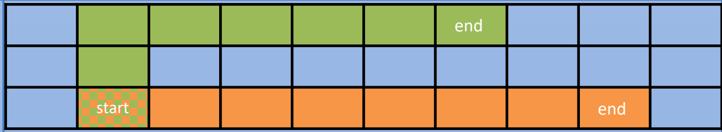
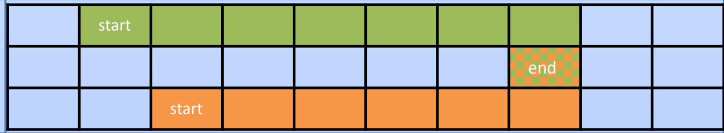
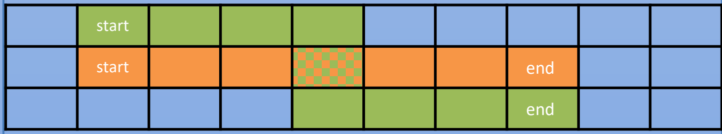
- Simplest case: trajectories are arbitrary, but consecutive regions within them must be different
- A trajectory is allowed to start and end at the same region
  - Given a partitioning R, a trajectory T is defined as a sequence of regions $(t_1, t_2, \dots, t_n), n \geq 2$, where $t_i \neq t_{i+1}, 1 \leq i < n$
- Possible associations between two trajectories are captured by 6 base relations
  - Jointly exhaustive, pairwise disjoint and symmetric

TC-6 Base Relations

Relation	Interpretation	Illustration
Equal (Eq)	T_1 and T_2 are equal (identical trajectories)	
Alternative (Alt)	T_1 and T_2 are alternative (different trajectories for the same start and end regions)	
Start (S)	T_1 and T_2 start at the same region (but end at different regions)	
Finish (F)	T_1 and T_2 end at the same region (but start at different regions)	
Intersect (I)	T_1 and T_2 intersect (different start and end regions but at least one common region)	
Disjoint (Dis)	T_1 and T_2 are disjoint (no common regions)	

TC-6 Composition Table

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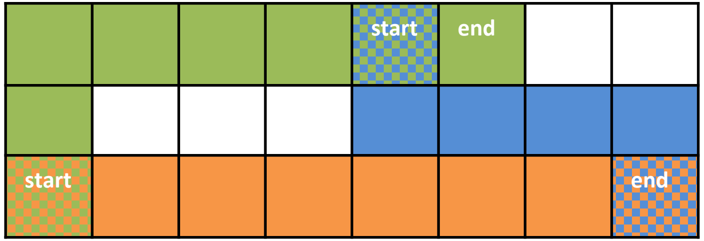
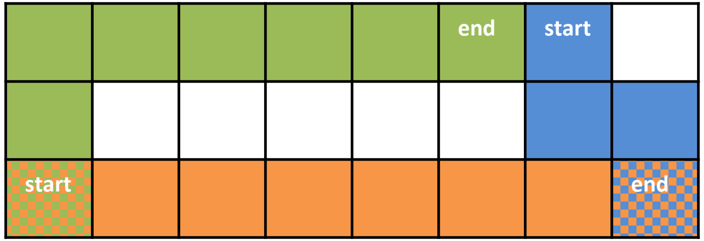
T_1 S T_2

T_2 F T_3



T_1 I T_3

T_1 Dis T_3



Relations	Eq	Alt	S	F	I	Dis
Eq	Eq	Alt	S	F	I	Dis
Alt	Alt	Eq, Alt	S	F	I, Dis	I, Dis
S	S	S	Eq, Alt, S	I, Dis	F, I, Dis	F, I, Dis
…	…	…	…	…	…	…

Encoding TC-6 in ASP

- Trajectories as **predicates** $traj(1), \ldots traj(n)$
- Base **relations** as predicates $eq(X,Y), alt(X,Y), s(X,Y), f(X,Y), i(X,Y), dis(X,Y)$
- Ensure **only one** relation per pair of trajectories using a choice rule: $\{eq(X,Y); \ldots; dis(X,Y)\} = 1 \leftarrow traj(X), traj(Y), X < Y$
  - ; denotes disjunction
- For each **composition table entry**, one integrity constraint rule of the form $\leftarrow r_a(X,Y), r_b(Y,Z), not\ r_i(X,Z), \ldots, not\ r_n(X,Z)$
  - Read as: it is not possible for relation r_a to hold between trajectories X and Y and r_b to hold between Y and Z and for none of the relations $r_i \ldots r_n$ in the corresponding cell in the composition table
  - e.g. $\leftarrow s(X,Y), f(Y,Z), not\ i(X,Z), not\ dis(X,Z)$

Reasoning with the ASP encoding

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- The ASP encoding can determine whether a set of relations between trajectories is consistent
  - e.g. $s(1,2), f(2,3), eq(1,3)$ is inconsistent, since it violates the constraint $\leftarrow s(X,Y), f(Y,Z), not\ i(X,Z), not\ dis(X,Z)$
  - e.g. $s(1,2), f(2,3)$ is consistent and there are two answer sets, one with $i(1,3)$ and one with $dis(1,3)$
- Additional **non-qualitative** rules can be added
  - e.g. for MQ1, add a rule

$$crosses(X, Lat, Long) \leftarrow traj(X), point(Lat, Long)$$

checking whether a trajectory passes through a particular point

Generalised Encoding

- The previous encoding is only good for TC-6
  - What about other qualitative calculi, like RCC-5 for MQ2?
- Need for a generalised encoding that can be used for any standard qualitative calculus
  - This encoding can then be improved based on particular properties of each calculus

Domain and Base Relations

- **Domain elements** as predicates $element(1), \ldots element(n)$
  - e.g. one such predicate for each known region for RCC-5

- Base **relations** as predicates $relation(name)$
  - e.g. for RCC-5
    $relation(dr), relation(po), relation(pp), relation(ppi), relation(eq)$
  - This can also be written using **term pooling** as

$$relation(dr; po; pp; ppi; eq)$$

Composition Table

- One predicate for each cell in the table with three arguments
  - Row relation
  - Column relation
  - Valid relation for the composition of the latter two
  - e.g. $table(pp, eq, (pp))$
    $table(pp, dr, (dr))$
    $table(pp, po, (dr; po; pp))$
    $table(pp, pp, (pp))$
    $table(pp, ppc, (eq; dr; po; pp; ppc))$

Search Space

- Predicate $true(X, R, Y)$ denoting that relation R holds for the ordered pair of elements (X, Y)
- Choice rule

  $\{true(X, R, Y) : relation(R)\} = 1 \leftarrow element(X), element(Y), X! = Y$
  - Rule head means that if $true(X, R, Y)$ holds, there is exactly one R that makes $relation(R)$ hold
  - $X! = Y$ instead of $X < Y$ because there are calculi where if $true(X, R_1, Y)$ and $true(Y, R_2, X), R_1 \neq R_2$
- To enforce the composition table:

$\leftarrow true(X, R_1, Y), true(Y, R_2, Z), not\ true(X, R_{out}, Z) : table(R_1, R_2, R_{out})$
  - Meaning that it is not possible for R_1 and R_2 to hold for (X, Y) and (Y, Z) and for none of the R_{out} in the corresponding table predicates to hold

Input Constraints

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- Predicate $constraint(X, R, Y)$ denoting that the pair (X, Y) is involved in a constraint, with R as a possible relation for the pair
- The generalised encoding can perform consistency checks as before
  - e.g. $constraint(1, pp, 2)$,$constraint(2, pp, 3), constraint(1, dr, 3)$ is inconsistent, since $table(pp, pp, (pp))$
- Additional **non-qualitative** rules can be added
  - e.g. for MQ2, add a rule

$$\leftarrow true(X, overlaps, Y), frequency(X, F_1), frequency(Y, F_2), F_1 = F_2$$

ensuring that overlapping regions don't share the same frequency

Current Steps

- Ensuring that the generalised encoding is indeed capable of modelling all qualitative calculi
  - Also considering calculus-specific improvements
- Experiments to compare efficiency of ASP implementations against GQR and SparQ

Future Steps

- Implement converter from GQR and SparQ to ASP
- Develop a toolkit that guides the user through
  - encoding a problem instance in ASP
  - solving the problem
  - explaining the solution
- Explore additional case studies requiring a combination of qualitative and non-qualitative reasoning

Questions?

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