Converting Spatiotemporal Data Among Multiple Granularity Systems

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Motivation

Spatiotemporal data are often expressed in terms of granularities to indicate measurement units. If data from multiple granularity systems needs to be used in a unified application, we have to extend the data conversion and comparison to inter-system.

Challenges:

- Heterogeneity in *granularity relations*: Incongruous conversion semantics
- Heterogeneity in *granularities*: Existence of common refined granularity (CRG) to ensure correct granular comparison
- Uncertainty

Objective: a **theoretical framework** solving the problem.

1. A model that accepts heterogeneity
2. Preconditions for inter-system conversions
3. Combination of heterogeneous granularity systems
4. Quantification of uncertainty
5. Optimal CRG for granular comparison

Modeling Granularity Systems

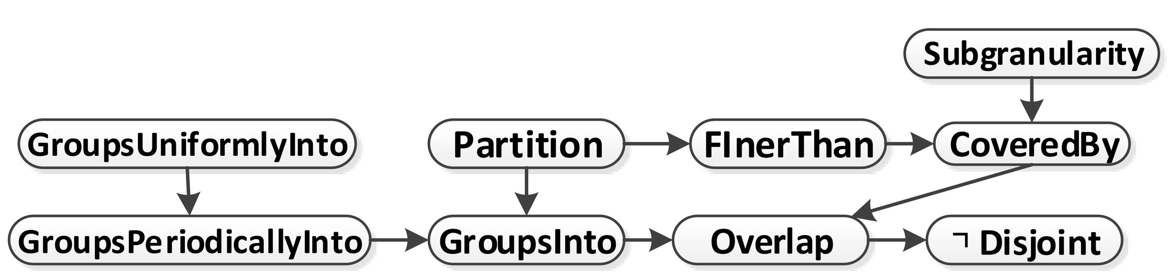
A Granularity divides a domain into **granules**:

- Spatial Granularity G_S: $N \rightarrow 2^S$ ($S \subseteq R^2$)
- Temporal Granularity G_T: $N \rightarrow 2^T$ ($T \subseteq R$)

Granularity relations:

Partial-order (and coresponding inverse)	
Groups Into (Grouped By)	Finer Than(Coarser Than)
Partition (Partitioned By)	Sub-granularity
Covered By (Covers)	
Groups Periodically Into	Groups Uniformly Into
Symmetric	
Disjoint	Overlap

Logical inferences of partial-order relations



Granularity order: Given any G,H on *D* s.t. $G \unlhd H$:

- Refine-order $(G \prec H)_{\leq}$ means $\leq$ always splits H into more granules
- Merge-order $(G \succ H)_{\leq}$ means $\leq$ always merge H into less granules

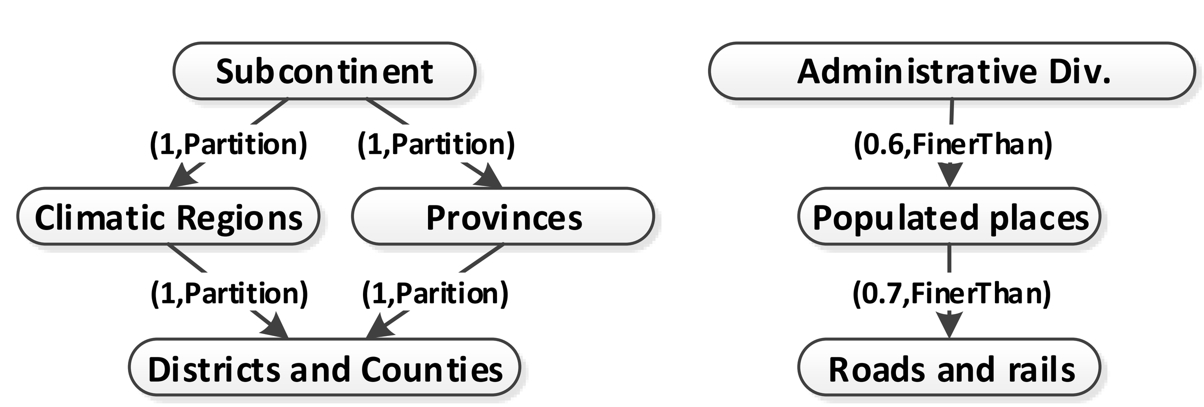
Granularity system GS(D, {G}, $\leq$, G_0, G_1):

- *D: The definition domain of the granularities in GS.*
- *{G}: The set of granularities in GS.*
- *$\leq$: The partial-order linking relation that manages the {G}. ({G}, $\unlhd$) forms a partial-order lattice.*
- *$G_0 \in \{G\}$: the zero element, i.e. $\forall G \in \{G\}$, $G_0 \unlhd G$.*
- *$G_1 \in \{G\}$: the identity element, i.e. $\forall G \in \{G\}$, $G \unlhd G_1$*

***D*-system group:** *A D-system group $\mathcal{E}_D$ is a group of granularity systems defined on the domain D.*

Weighted Granularity Graph (WG)

- An acyclic digraph where edges are labeled with linking relations, and weights between (0, 1] to represent uncertainty of conversions.
- Transitive reduction.



Inter-system Conversion

Granularity conversion is a function $Conv_{H \rightarrow G}(H')_{\leq}$ to convert a subgranularity *H'* (i.e. subset) of granularity *H* to granularity *G* s.t. $G \unlhd H$

- Refine-conversion: if $(G \prec H)_{\leq}$
- Merge-conversion: if $(G \succ H)_{\leq}$

Semantic preservation: *Given two linking relations $\leq$, $\leq^*$, we denote $\forall G, G^*: G \unlhd G^* \nvdash G \leq^* G$ as $\leq \rightarrow \leq^*$. Given granularities G,H,I s.t. $G \unlhd H \leq^* I$, then $Conv_{H \rightarrow G}(Conv_{I \rightarrow H}(I')_{\leq^*}, G)_{\leq} = Conv_{I \rightarrow G}(I')_{\leq^*}$ iff $\leq \rightarrow \leq^*$.*

- The semantics grows monotonically stronger.

Semantic consistency: *Given two linking relations $\leq$, $\leq^*$. Given granularities G,H,I s.t. $G \unlhd H \leq^* I$, composed conversion from I to G is semantic consistent iff any of $\leq = \leq^*$, $\leq \rightarrow \leq^*$ or $\leq^* \rightarrow \leq$ holds.*

- There's a weakest relation to decide a consistent semantics

Semantic preservation ⊢ Semantic consistency

Multi-system Combination

Objective:

- Combine multiple systems into one lattice
- Inter-system conversions and granular comparison can be handled just like in-system.

Precondition: Combinability

Two granularity systems can be combined iff

1. Any refine-conversion in the granularity system is semantic preserved and/or semantic consistent.
2. For any pair of granularities from different systems, a CRG exists in the combined system.

Semantic preserved combinability (SPC)

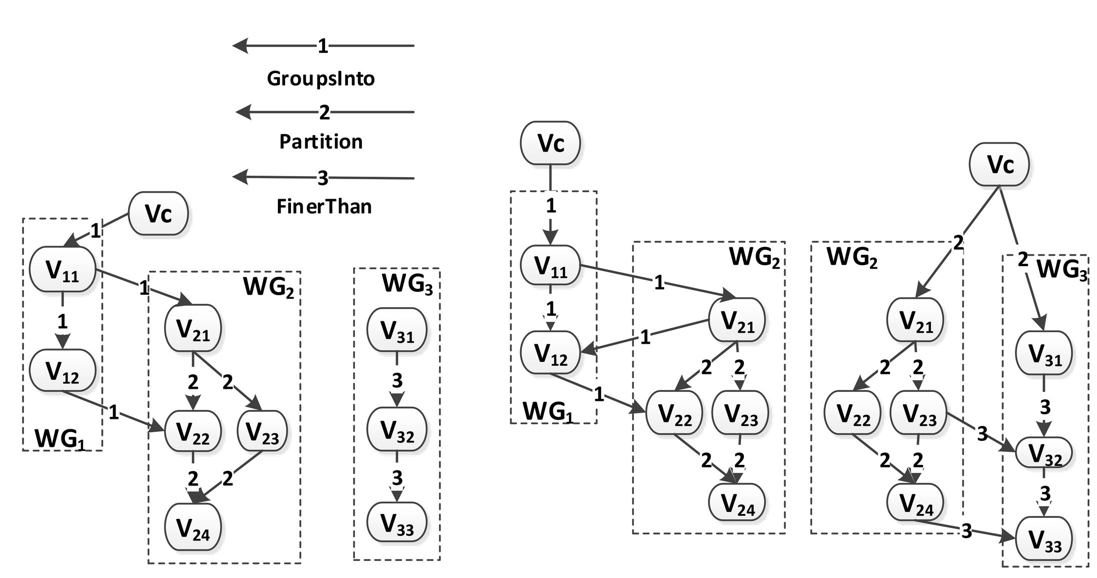
Semantic preservation is ensured in above 1. Therefore conversions in original systems can be inherited to the combined system

Semantic consistent combinability (SCC)

Semantic consistency is ensured in above 1. At least correctness of inter-system conversions and granular comparison is ensured.

Sufficient-necessary Conditions

- S-N conditions are proved for SPC and SCC
- Verification reduced to an **O(1)** procedure based on zero-elements G_0 of two systems logical inference of their linking relations $\leq$.



(a) (b)

Multi-system Combination Algorithms

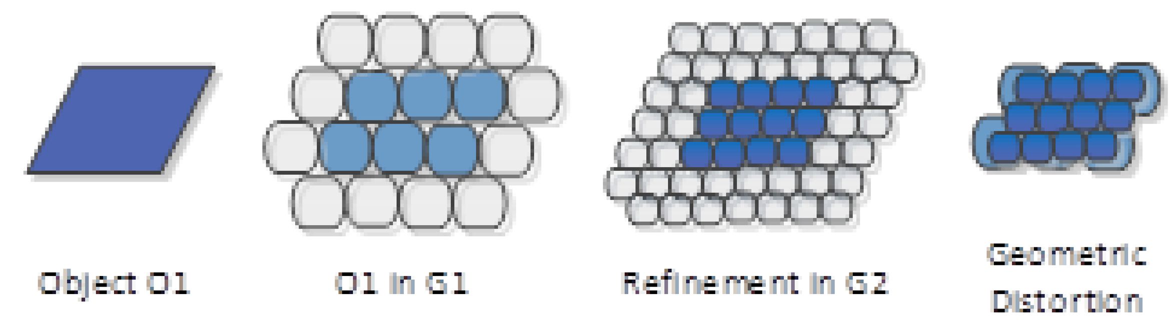
We provide two algorithms to combine combinable systems from $\mathcal{E}_D$ to a target system into the *transitive reduction* of a *lattice*.

- *SPCombine*(*GS*, $\{GS\}_D$): one that perform a semantic preserved combination.
- *SCCombine*(*GS*, $\{GS\}_D$): one that perform a semantic consistent combination.

Both are O(n^3) algorithms.

Uncertainty Quantification

Each linking relation varies in geometric properties, granularity conversion unavoidably contains distortion that causes imprecise representation and statistical analysis of granular data.



Granular and Granularity Geometric Precision

- $u(g,H) = \frac{g^{o} \cap (Conv_{G \rightarrow H}(\{g\})_{\leq})^{o}}{g^{o} \cup (Conv_{G \rightarrow H}(\{g\})_{\leq})^{o}}$.
- $U(G,H) = E(u_{\rho}(G(i),H)) = \frac{(\bigcup_{i \in N} G(i)^{o}) \cap (\bigcup_{i \in N} H(i)^{o})}{(\bigcup_{i \in N} G(i)^{o}) \cup (\bigcup_{i \in N} H(i)^{o})}$

Data density

Give a dataset E, and an extent C, the data density in C is defined as: $\rho(C) = \frac{|\{e \mid e \in E \wedge coveredBy(e,C)\}|}{C^{o}}$

ρ-granular and ρ-granularity Precision

Precision measurement that considers data density.

- $u_{\rho}(g,H) = \rho\left(\frac{g^{o} \cap (Conv_{G \rightarrow H}(\{g\})_{\leq})^{o}}{g^{o} \cup (Conv_{G \rightarrow H}(\{g\})_{\leq})^{o}}\right)$
- $U_{\rho}(G,H) = E(u_{\rho}(G(i),H)) = \frac{\rho\left((\bigcup_{i \in N} G(i)^{o}) \cap (\bigcup_{i \in N} H(i)^{o})\right)}{\rho\left((\bigcup_{i \in N} G(i)^{o}) \cup (\bigcup_{i \in N} H(i)^{o})\right)}$

Inter-system Granular Comparison

For two granularities, multiple CRGs can coexist. Any of them can be the measurement unit we compare granules on.

Use uncertainty quantification as weights on WG

- ***Transitivity*** *$G \unlhd H \unlhd I$, $U(I,H) \cdot U(H,G) = U(I,G)$ and $U_{\rho}(I,H) \cdot U_{\rho}(H,G) = U_{\rho}(I,G)$ always hold.*
- ***Path-independence*** *$G \unlhd H \unlhd I$, $G \unlhd H' \unlhd I$ and $H \neq H'$. Then $U(I,H) \cdot U(H,G) = U(I,H') \cdot U(H',G)$ and $U_{\rho}(I,H) \cdot U_{\rho}(H,G) = U_{\rho}(I, H') \cdot U_{\rho}(H',G)$ always hold.*

Optimal CRG

Find the CRG whose *geometric mean* of *U* or U_{ρ} is minimal.

- Least Common Ancestor (LCA) on WG
- Easy O(n) solution

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Application Aspects

Spatial Knowledge Integration

- Automatic integration given spatial granules

High-divergent Time Conversion

- Conversion across high divergent time systems

Integrated Data Analysis

- Non-blocking analysis among data of different representation standard.

Querying Linked Data

- Mutable query condition expressions

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