Converting Spatiotemporal Data Among Multiple Granularity Systems

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ABSTRACT
Spatiotemporal data are often expressed in terms of granularities to indicate the measurement units of the data. A granularity system usually consists of a set of granularities that share a "common refined granularity" (CRG) to enable granular comparison and data conversion within the system. However, if data from multiple granularity systems needs to be used in a unified application, it is necessary to extend the data conversion and comparison within a granularity system to those for multiple granularity systems. This paper proposes a formal framework to enable such an extension. The framework involves essentially some preconditions and properties for verifying the existence of a CRG and unifying conversions of incongruous semantics, and supports the approach to integrate multiple systems into one so as to process granular data interoperation across systems just like in a single system.

CCS Concepts
• **Information systems → Spatial-temporal systems**

Keywords
Spatiotemporal data, multiple granularity systems, granularity conversion, granular comparison, system combination

1. INTRODUCTION
In this decade where over 80% datasets have spatial and temporal components [1], the notion of multi-granularity has become significant for expressing and exchanging spatiotemporal data under specific units of measurement.

It's a common practice in literatures to organize a group of granularities in a partial-order set or a lattice [1-4, 6, 7], where granularities are linked with a partial-order topological relation (hereafter *linking relation*) into a hierarchy set. Two major functions are normally associated with such a set, namely *granularity conversion* and *granular comparison* [2, 6]. The former enables the expression of data in different measurement units, while the latter supports the topological or statistical analysis on spatially or temporally qualified information. We may term a specific set of granularities as a *granularity system*.

The relevant literatures have implicitly assumed that a single granularity system is sufficient for data in an application. However, when multiple applications need to be integrated or mashed up into one, we may have a scenario where several granularity systems are simultaneously used for the data in the same spatial or temporal domain. Such coexistence usually results from different representation standards as well as separate data maintenance realms, causing *heterogeneity in granularities*. Besides, *heterogeneity in linking relations* is reflected by instances in the literature [1, 4, 6, 7].

Technically, realizing the interoperation of data across multiple granularity systems unifies current models from independent representation schemas to form a single global schema, essentially enabling reasoning and exchanging of spatiotemporal data of multiple granularity systems. This will make it possible to reconstitute existing applications for new purposes, e.g., to support spatiotemporal queries and extraction of knowledge from various data sources or spatiotemporal-dependent resources regardless of how they are expressed in their original granularity systems.

However, this is a non-trivial problem which brings several new challenges to multi-granular modeling. Besides adapting the heterogeneity in a model, interoperation of data across systems inevitably requires extending the original in-system granularity conversion and granular comparison [1, 4] to their inter-system equivalents. Heterogeneity of granularity systems often implies incongruous semantics of conversion, and indeterminacy of the existence of a Common Refined Granularity (CRG) to support correct granular comparison. These challenges are currently without sufficient theoretical foundation to tackle.

In this work, we propose a formal framework to extend the granularity conversion and granular comparison of spatiotemporal data across multiple granularity systems. This framework defines two constraints for composing inter-system granularity conversions, namely *semantic preservation* and *semantic consistency*. We show that granularity systems can be combined, or they have *combinabiliy*, only if they are semantically preserved or semantically consistent and globally having a CRG. A novel approach is proposed to combine multi-systems to a single lattice, where inter-system conversion and comparison can be processed transparently just like in a single system.

The rest of the paper is organized as follows. In section 2, we state the background. In section 3, we introduce the approach to combine multiple granularity systems and derive its prerequisites. In section 4, we conclude with final remarks. Due to the space limitation, this paper gives only brief introduction to our contributions. Readers are referred to the extended technical report [10] for detailed definitions, examples, proofs, and remarks.

2. BACK GROUND
The spatial and temporal granularities are defined respectively with mappings $G_S: N \rightarrow 2^S$ and $G_T: N \rightarrow 2^T$ where S and T are respectively spatial and temporal domain. Within each granularity, all granules' extents are disjoint (i.e. non-overlapping).

Given two granularities G and H, research in this area [1, 2] has

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defined a set of topological granularity relations for spatial granularities, which are partial-order relations: *GroupsInto*, *FinerThan*, *Partition*, *Subgranularity*, *CoveredBy*, *CoarserThan*, *PartitionedBy*, *Covers*; and symmetric relations: *Disjoint*, *Overlap*. These relations can be adopted for temporal granularities, followed by two time-dedicated partial-order relations given in [2, 3], i.e., *GroupsPeriodicallyInto* and *GroupsUniformlyInto*. Definitions of these granularity topological relations can be found in [10]

Literatures organize multiple granularities in a hierarchical structure [1-4, 6, 7] where granularities are associated with one partial-order topological relation and hold a communal finest unit of representation. Formally a granularity system is defined as a quintuple $GS(D, \{G\}, \leq, G_0, G_1)$, where $\{G\}$ is the set of granularities whose definition domain is D. G_0 and G_1 are respectively zero-elements and identity elements, and $\leq$ is the linking relation. We use the notion *D-system group* $\mathcal{E}_D$ to denote the universal set of granularity systems on domain D. Multiple heterogeneous granularity systems are allowed to coexist in $\mathcal{E}_D$

Camossi et al has highlighted *granularity conversion* and *granular comparison* as the fundamental challenges in current spatio-temporal multi-granularity research [2]. A 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, where G,H satisfy $G \leq H$, and $\leq$ is a linking relation. Meanwhile, we say a conversion is a *refine-conversion* if it always splits granules in H', otherwise it's a *merge-conversion* as it merges H' to less granules [10]. Current literatures consider conversions only inside one system [2, 6, 8], while conversion among different systems with heterogeneous linking relations brings along issues to be solved in our work, such as inconsistency of conversion semantics and incorrectness of conversion. In [10] we provide a complete logical inference among the granularity relations, which is a premise to discuss semantic constraints of granularity conversion later. Besides conversion, in order to perform meaningful comparison, inter-granularity data should be converted to a CRG [2, 6]. Thus we must verify the existence of CRG for any pair of granularities in multiple systems.

3. COMBINING GRANULARITY SYSTEMS

The purpose of multi-system combination is to merge multiple lattice-based systems from $\mathcal{E}_D$ into one lattice, so as to extend original in-system functionalities among multiple systems. However, due to the heterogeneity of granularity systems, combination is restricted by the semantics of granularity conversion and feasibility of granular comparison across original systems.

We hereby discuss the property *combinability*, which guarantees essential pre-conditions of inter-system granularity conversion, i.e. semantic preservation and semantic consistency, as well as the support of granular comparison. Then, we propose the approach of multi-system combination.

3.1 Semantic Preservation and Consistency

The semantic preservation and semantic consistency of composed atom conversions are defined as follows.

Definition 3.1 (*Semantic Preservation*): *Let $G_1..G_n$ be n (n>2) granularities, and $\leq_k$ be the linking relations s.t. $\forall k \in [1,n-1]$, $G_k \leq_k G_{k+1}$. Let G' be a subgranularity of G_1, the composed conversion from G_1 to G_n is semantic preserved if $Conv^{n-1}_{G1\rightarrow\ldots\rightarrow Gn}(G')_{\leq 1} = Conv_{G1\rightarrow Gn}(G')_{\leq 1}$. I.e., the semantics of the first atom conversion is preserved in the rest atom conversions.*

Definition 3.2 (*Semantic Consistency*): *Let $G_1..G_n$ be n (n>2) granularities, and $\leq_k$ be the linking relations s.t. $\forall k \in [1,n-1]$, $G_k \leq_k G_{k+1}$. Let G' be a subgranularity of G_1, the composed conversion from G_1 to G_n is semantic consistent if $\exists j \in [1,n-1]$ s.t. $Conv^{n-1}_{G1\rightarrow\ldots\rightarrow Gn}(G')_{\leq j} = Conv_{G1\rightarrow Gn}(G')_{\leq j}$. I.e., the uniform semantics is given based on one atom conversion in the composed conversions.*

Across multiple systems, semantic preservation directly extends the conversion from a granularity in the original system to another one in the second system within its reach with the same semantics. While semantic consistency decides a uniform semantic for a composed conversion, although it may lose the semantics of the original system. E.g., if we regard a refine-conversion of granule {g} in a GroupsInto system as fetching all granules in a certain refined granularity that groups into {g}, such illustration still applies to a semantic preserved conversion for {g}, but may not apply to a semantic consistent one for {g} as the semantics can be weaker.

In scenes where granularities are used for precise multi-resolution representation, we have to preserve the conversion semantics in original systems so as not to lose certain properties (such as geometric congruity, periodicity, etc.), by following Property 3.1.

Property 3.1 (*Semantic Preserved Compositionality*): *Given two linking relations $\leq$, $\leq^*$, we denote $\forall G,G^*: G \leq G^* \vdash G \leq^* G$ as $\leq \rightarrow \leq^*$. Given granularities G,H,I s.t. $G \leq H \leq^* I$, then $Conv_{H\rightarrow G}(Conv_{I\rightarrow H}(I')_{\leq^*}, G)_{\leq} = Conv_{I\rightarrow G}(I')_{\leq^*}$ iff $\leq \rightarrow \leq^*$.*

While other scenes may require only semantic consistency among conversions so as to guarantee their compositionality, by following the condition in the next property.

Property 3.2 (*Semantic Consistent Compositionality*): *Given two linking relations $\leq$, $\leq^*$. Given granularities G,H,I s.t. $G \leq H \leq^* I$, composed conversion from I to G is semantic consistent iff any of $\leq = \leq^*$, $\leq \rightarrow \leq^*$ or $\leq^* \rightarrow \leq$ holds.*

Above properties can be easily extended for conditions of three or more atom conversions via inductive method. They clarify the requisite to extend granularity conversion to inter-system regardless of the heterogeneity in $\mathcal{E}_D$.

3.2 Combinability

Definition 3.3 (*Combinability*): *Two granularity systems from $\mathcal{E}_D$ can be combined to a single system 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.*

Requirement 1 enables granularity conversions in a combined system. Thereof, if we guarantee semantic preservation to any conversion, we say these systems satisfy *semantic preserved combinability*. Otherwise, inter-system conversions should be guaranteed semantic consistency. Such systems satisfy *semantic consistent combinability*. If requirement 1 is fulfilled, then requirement 2 enables granular comparison for all granules in a combined system.

For a pair of granularity systems GS, GS' from $\mathcal{E}_D$, the sufficient-necessary (SN) conditions for semantic preserved combinability or semantic consistent combinability are given as below

Theorem 3.1 (*Semantic Preserved Combinability*): *Given a pair of refining granularity systems $GS(D, \{G\}, \leq, G_0, G_1)$ and $GS'(D, \{G\}', \leq', G'_0, G'_1)$ from $\mathcal{E}_D$, semantic preserved combinability holds between iff one of the follows holds.*

1. *$G_0 = G'_0$ ($\leq = \leq'$, C1; or $\leq \neq \leq'$, C2).*
2. *$\leq = \leq'$, while $G_0 \leq G'_0$ or $G'_0 \leq G_0$ (C3); or $\leq = \leq'$ and exists a third (intermediate) granularity system GS^* from $\mathcal{E}_D$ with zero element G^*_0 s.t. $G^*_0 \leq G_0$ and $G^*_0 \leq G'_0$ (C4).*
3. *$\leq \rightarrow \leq'$ and $G_0 \leq' G'_0$; or $\leq' \rightarrow \leq$ and $G'_0 \leq G_0$; (C5) or exists a third*

(intermediate) system $GS^* \in \mathcal{E}_D$ *having linking relation* $\leq^*$, *s.t.* $\leq^* \rightarrow \leq$ *and* $\leq^* \rightarrow \leq'$, *and zero element* G^*_0 *s.t.* $G^*_0 \leq G_0$ *and* $G^*_0 \leq' G'_0$ *(C6).*

Theorem 3.2 (*Semantic Consistent Combinability*): *Given a pair of refining granularity systems* $GS(D, \{G\}, \leq, G_0, G_1)$ *and* $GS'(D, \{G\}', \leq', G'_0, G'_1)$ *from* $\mathcal{E}_D$*, semantic consistent combinability holds between them iff one of the follows holds.*

1. $G_0 = G'_0$ ($\leq = \leq'$, *C1; or* $\leq \neq \leq'$, *C2).*
2. *Any of* $\leq = \leq'$, $\leq \rightarrow \leq^*$ *or* $\leq^* \rightarrow \leq$ *holds and either of these relation applies between* G_0 *or* G'_0 *(C3); or exists a third (intermediate) system* GS^* *from* $\mathcal{E}_D$ *having linking relation* $\leq^*$, *s.t. any of* ($\leq = \leq^*$, $\leq^* \rightarrow \leq$ *or* $\leq \rightarrow \leq^*$) *and any of* ($\leq = \leq^*$, $\leq^* \rightarrow \leq'$ *or* $\leq' \rightarrow \leq^*$) *hold, and zero element* G^*_0 *s.t. either of* $\leq$, $\leq^*$ *applies from* G^*_0 *to* G_0 *and either of* $\leq'$, $\leq^*$ *applies from* G^*_0 *to* G'_0*(C4).*

Algorithms to verify either of the combinability conditions can be created as sequential procedures to verify the satisfaction of C1~C6 in Theorem 3.1 or C1~C4 in Theorem 3.2. They require O(1) time complexity with the aid of the logic inferences of granularity relations and the global granularity relation matrix introduced in [10].

3.3 Multi-system Combination

We can now combine multi-systems from $\mathcal{E}_D$ to a uniform system that guarantees correct inter-system granular comparison and granularity conversions.

Given a group of systems in $\mathcal{E}_D$, denoted as $\{GS\}_D$, the combination algorithms combine elements from that to a target $GS \in \{GS\}_D$ as long as they satisfy corresponding combinability. The algorithms are referred as *SPCombine(GS,* $\{GS\}_D$*)* (semantic preserved combination) and *SCCombine(GS,* $\{GS\}_D$*)* (semantic consistent combination), which are both processed in the form of granularity graphs [2]. In fact, the two algorithms are logically similar (only being different in creating edges between two systems according to their semantic constraints). Exemplarily, we give *SPCombine* as below.

Algorithm 3.1 *SPCombine***(***GS*, $\{GS\}_D$**)**

```
let Gc be the extent of GS.D          'a communal G1 for {GS}D
CreateDirectedEdge(Gc, GS.G1)  'from Gc to G1
GS.G1←Gc
for each GS'∊{GS}D do
  if GS'≠GS and SPCombinability(GS, GS',{GS}D) then
     {GS}D←{GS}D\GS'
     ClearTags(checked)
     if R(GS)=R(GS') then        'R(GS) is the linking relation of GS
        DFSCreateEdges(GS.G1, GS'.G1,R(GS),checked,false)
        DFSCreateEdges(GS'.G1, GS.G1,R(GS),checked,false)
     else if R(GS')→R(GS) then
        DFSCreateEdges(GS.G1, GS'.G1,R(GS),checked,false)
        R(GS)←R(GS')
     else if R(GS)→R(GS') then
        DFSCreateEdges(GS'.G1, GS.G1,R(GS'),checked,false)
     else for each GS*∊{GS}D do
        if R(GS*)→R(GS) and R(GS*)→R(GS') then
           {GS}D←{GS}D\GS*
           DFSCreateEdges(GS.G1,GS*.G1,R(GS),checked,false)
           DFSCreateEdges(GS'.G1,GS*.G1,R(GS'),checked,false)
           R(GS)←R(GS*)
           continue
for each GS'∊{GS}D do
  if GS.G0=GS'.G0 do
     {GS}D←{GS}D\GS'
     MergeVertex(GS.G0, GS'.G0)
     CreateDirectedEdge(GS.G1,GS'.G1)
return GS.G1
```

Thereof, DFSCreateEdges (Algorithm 3.2) links the granularities of one system to those of the other to mark atom relations, while provides transitive reduction as the definition of granularity graphs.

Algorithm 3.2 *DFSCreateEdges***(***v, u,* $\leq$*, checked[,], foundabove***)**

```
found←foundbelow←created←false
checked[v,u]←true
if foundabove=false and u ≤ v then
   found←true
if (found∨foundabove=true) and Succ(v)≠∅ then
  for each v'∊Succ(v) do
     if checked[v,u]=false and u≤ v' then
        foundbelow←true
        DFSCreateEdges(v', u, ≤, true)
     else for each u' ∊Succ(u)
           if checked[v',u']=false then
              DFSCreateEdges(v', u', ≤, checked,false)
  if foundbelow=false then 'an atom relation is found
     CreateDirectedEdge(v,u) 'from v to u
     created←true
if created=true and Succ(v)≠∅ and Succ(u)≠∅ then
   for each v'∊Succ(v) do
      for each u' ∊Succ(u)
         if checked[v',u']=false then
            DFSCreateEdges(v', u', ≤, checked,false)
else if found∨foundabove=false and Succ(u)≠∅ then
    for each u'∊Succ(v) do
       if checked[v,u']=false then
          DFSCreateEdges(v', u, ≤, checked,false)
else return
```

Remarks and examples for the algorithm are given in [10].

4. CONCLUSION

In this paper, we proposed a formal framework to extend spatio-temporal data conversion and comparison among multiple granularity systems. We have dealt with the heterogeneity of granularity systems reflected in literatures, and introduced the rules of semantic preservation and consistency to enable the correctness and inheritability of granularity conversions across heterogeneous systems. By studying the binary relationships of granularity systems w.r.t. linking relations and zero elements, we have derived SN conditions for two types of combinability, and given corresponding combination algorithms. Meanwhile, we're studying the quantification of the uncertainty in such interoperations, as well as how our framework will benefit the application aspects of knowledge bases. In [10], we have discussed them along with other open challenges.

5. ACKNOWLEDGEMENT

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