# Structuring GIS information with types of granularity: a case study
# *Estructuración de información SIG con tipos de granularidad: un estudio de caso*

C. Maria Keet
Faculty of Computer Science
Free University of Bozen-Bolzano, Italy
tel: +39 0471 016127 – fax: +39 0471 016009 – keet@inf.unibz.it

***Abstract*— Dealing with granularity in the GIS domain is a well-known issue, and multiple data-centric engineering solutions have been developed to deal with finer- and coarser-grained data and information within one information system. These are, however, difficult to maintain and cumbersome for interoperability. To address these issues, we propose eight types of granularity and a facilitating basic theory of granularity to structure granulation hierarchies in the GIS domain. Several common hierarchies will be re-assessed and refined. It illustrates a methodology of first representing *what* one desires to consider for a GIS application, i.e., at the semantic layer, so as to enable reaping benefits of flexibility, reusability, transparency, and interoperability at the implementation layer.**

**Keywords: Granularity, conceptual analysis, modeling for GIS, semantics and Ontology for geography**

**Resumen—*La granularidad en el dominio de SIG es un tema conocido, y múltiples soluciones centradas en datos e implementaciónes se han desarrollado para manejar datos e informaciónes más finas y más gruesas dentro un sistema de información. Éstos son, sin embargo, difíciles de mantener y engorrosos para la interoperabilidad. Para abordar estos problemas, proponemos ocho tipos de granularidad y una teoría de granularidad básica para facilitar la estructuración de granulación en las jerarquías en el dominio SIG. Varios jerarquías comunes serán re-evaluadas y perfeccionadas. Se ilustra una metodología para representar lo que uno desea considerar para un aplicación SIG, es decir, a la capa semántica, a fin de que puedan cosechar los beneficios de la flexibilidad, reutilización, la transparencia y la interoperabilidad en la capa de aplicación.***

***Palabras claves: Granularidad, analisis conceptual, modelación para SIG, Semántica y ontología geoespacial***

## I. INTRODUCTION

While most GIS and closely related applications for environmental sciences still have a data-centric application focus, there are several attempts to take it to a higher level of abstraction by first representing the subject domain semantics. The latter comprises both the conceptual modelling-oriented approach and ontologies [1], [4], [8], [15], [23], the notion of contextual modelling [9], [25], [27], and the wider scope of Semantic Web Technologies enhanced software as exemplified by conferences such as GeoWEB and GeoSW. However, as [1] notes, “A comprehensive ontology for the geo-spatial domain is still indiscernible. ... none of the methods reviewed ...have indicated an integrated framework that can be used across the geographic domain in *different contexts* for managing *different kinds of information*” (p. 515, emphasis added). The first gap is under active investigation in, e.g., the SEEK project [23] and the W3C incubator group [22]; the second, managing contexts and different kinds of information, is an open issue. Contexts in the sense of *different points of view* are being addressed piecemeal at the semantic layer [9], [27], but this ignores context *at different levels of granularity* or ‘contexts with additional constraints’. Granularity at the modelling layer, be it in an ontology or expressive conceptual data model, enjoys some theoretical foundations [7], [14], [18] and many ad-hoc implementation options that range from basic extensions of conceptual modeling languages [25], [27], [11] to the hard-coded implementations in multi-resolution and multi-representation databases [40], [39]. These implementation options, however, do not yet deal *explicitly* with different kinds of information. To manage instance data, type-level information and knowledge, scale-based granularity, and non-scale-based, semantic, granularity, one requires a foundational and comprehensive approach to address them in one system—and preferably in such a way so as to be usable, reusable, interoperable, and scalable.

With as ultimate aim such a comprehensive system, we propose foundational semantics of *types of granularity* to identify better the nuances in different kinds of information and a basic, formal, *theory of granularity* to model granularity unambiguously and to serve as a first step toward a comprehensive ontology for granularity. The more precisely represented semantics makes granularity hierarchies with their levels implementation-independent at the modelling layer and, hence, are in principle reusable, interoperable, and scalable. That it is also usable will be demonstrated with several examples of typical GIS hierarchies. In addition, having the types of granularity separated but linked to a modelling framework for granularity, it makes querying the data transparent, for we have only a determined set of principal functions to retrieve data, aggregate, and so forth, which can be explicitly represented at the conceptual layer and which follow from the type of granularity chosen for each particular granulation hierarchy. The granularity framework that we will introduce—a basic version of a theory of granularity [18]—effectively lifts the data-centrism up to the conceptual layer and thereby makes it possible to structure the perspectives and levels consistently across implementations and, consequently, offer a new, simpler, way of querying the data in the granular levels. Further, it leaves open the option to system developers to integrate the theory either in the database or in application software; hence, the basic theory of granularity with the types of granularity serves both multi-resolution and multi-representation spatial databases (pre-computed versus dynamically calculated population of granular levels with instances) and it does not matter if the contents in the framework are instances in the database or types/classes in an ontology.

The remainder of the article is organised as follows. Related works are discussed in section II. Subsequently, preliminaries for the GIS granulation case study are given (section III) with the types of granularity and a basic framework (first order logical theory) for representing a granulated system. This enables us to reassess several hierarchies and GIS usage scenarios is section IV. We close with conclusions and future works in section V.

## II. RELATED WORKS AND PROBLEM SPECIFICATION

Geography and ecology have a relatively long history in information systems development, including dealing with granularity; see [33] and references therein[1]. Most of the proposals on representation and usage of spatial granularity have a data-centric focus [7], [10], [33], [38], [39], [40], except for minor adornments for granular spatial and/or temporal entity types in conceptual data modelling languages, such as the Oracle Cartridge, Granular GeoGraph [11], MADS [27], DISTIL [30], and the application of MultiDimER to geography [24], [25]. The OpenGeospatial Consortium (OGC) has produced several standards to aid implementations using, among others, GML [29] and application objects [31], which are data- and application-centric but do not address their semantics other than depicting summaries in UML class diagrams that is officially an informal modeling language [26]; a consensus approach for management of granularity is yet to be addressed. In addition, these solutions lack any kind of *framework* for dealing with granularity and therefore have to use elaborate functions and queries to fill this gap and they have to find a way to deal with a variety of oftentimes inconsistent hierarchies that are incompatible across implementations. In the remainder of this section, we analyse in detail proposals within GIS and ecology research, respectively, with respect to their treatment of granularity.

### A. Modelling granularity for GIS

Core notions that GISs deal with are resolution, (cartographic) generalisation and simplification, and multiple perspectives. Resolution refers to a minimum geometric measure that the focal object must have to be relevant and be included in the map. Definitions of generalisation and simplification are not consistent across the literature [40], [39], [38], but a distinction is made between plain reduction in resolution and hiding attributes or whole objects; that is, going from, e.g., a detailed spatial shape to a simpler spatial shape on a map to represent some object (from $Polygon$ to $Point$) versus going up in a taxonomy of types (from $Wheat$ to $Cereal$). So, one has either a particular object $x$ (say, the Louvre in Paris) that is represented as polygon at resolution $r1$ and as point at resolution $r2$, with $r1$ being finer-grained than $r2$, or, e.g., a land parcel that has plants of type $Y$ (say, wheat) at $r1$, and $Z$ (cereal) at $r2$, with $r1$ finer-grained than $r2$ and, importantly, $Y \subset Z$, which does not hold for the point and polygon. Thus, we are actually using different *mechanisms* for describing the different hierarchies (this will be elaborated upon and structured in section III-A, below). While for the former type, as well as commonly used others such as different ranges of altitude represented on a cartographic map, the emphasis is on scale-dependent granularity, non-scale-dependent granularity—also referred to as *semantic granularity* or *qualitative granularity*—has been well noted [7], [10], [12], [27], [33], [38] but not widely investigated. [7] and [33] seek to tackle the latter through the notion of partitions using mereology and set theory, respectively, and [38] propose a "granularity lattice" as a set of levels of detail. This granularity lattice is made up of pairs $\langle \sigma, \tau \rangle$, where each pair is denoted with a granularity $g_i$, $\sigma$ denotes the spatial level of detail, and $\tau$ a given depth in a taxonomy to which an order is applied ($\langle \sigma_1, \tau_1 \rangle \leq \langle \sigma_2, \tau_2 \rangle$ iff $\sigma_1 \leq \sigma_2$ and $\tau_1 \leq \tau_2$, hence, then also $g_1 \leq g_2$) and a set of maps is associated to each pair $\langle \sigma_i, \tau_i \rangle$. The only use of level $g_i$ is to go from a particular map at

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[1] GISs offer additional functionality, such as approximations and vagueness, performance optimizations, and time, which are beyond the scope of this article.

$g_i$ to its adjacent coarser map at $g_j$ or vice versa using the "Lift" or "Gen" functions, respectively. However, it does not go further than this rudimentary notion of granular levels in a lattice at the logical level, thereby is of limited use for more sophisticated data analysis and information retrieval. The object-centred formal approaches of [7] and [33], on the other hand, do not deal with levels of granularity, but focus on constraints on the objects, such as pairwise disjointness, covering constraints, and behaviour of geometric attributes. A different approach to non-scale-dependent granularity is the introduction of ontologies in Fonseca et al.'s Ontology-Driven Geographic Information System ODGIS [12]; in addition to the taxonomic "vertical" granularity ($Lake$ is finer-grained than $Body\ of\ Water$), they add a "horizontal" component at the same level of detail where another property of the type is highlighted, e.g., $Lake$ in the *role* of $Protected\ Area$. Likewise, [10] and [39] add the implicit notion of criterion to emphasise a particular property within a hierarchy, which is in contrast to the unrestricted levels in DISTIL that are defined on the fly by an end user [30]. What [10], [12], [39] have in common, is that they provide a basic idea to *highlight one or more properties of an entity (/type)*. This has been investigated in detail in [18], where the ontologically motivated analysis has resulted in the unambiguous granularity components *criterion* for granulation and *granular perspective* for a chosen viewpoint in order to enable explicit, consistent representation throughout and between applications.

The notion of 'horizontal' navigation—or: the same entity or entity type viewed from different perspectives at the same level of granularity—to accommodate for different types of use and user perspectives, is addressed most comprehensively by the MADS conceptual data modelling language [27], [28]. Each entity type and relation in a MADS conceptual data model can have extra tabs for each perspective on the type so that upon clicking it, one sees only those attributes that are relevant to the chosen perspective. Such a multi-viewpoint entity type suggests a unified approach to the entity types but in the formal representation underneath, there are actually as much types as there are tabs, such as $AvalancheEventE$ and $AvalancheEventM$ for the $E$ngineer's and $M$anager's viewpoints (see Figure 1 in [28]). In contradistinction to this formalisation decision, one can also take the ontological commitment that there is *one* entity type ($Avalanche\ Event$) and for each perspective a *subset of the attributes* (properties) is considered to make different domain expert views. Furthermore, the main focus of MADS is conceptual data modelling for spatio-temporal databases and GIS applications in particular, hence, granularity aspects, such as indistinguishability and relations between entity types at different levels of granularity, do not receive explicit attention, although MADS does support the standard ISO spatial data types for spatial entities and the ISO temporal aspects[2] at different levels of granularity. While this is useful for the scenarios it was developed, in a slightly different setting, one may want to use also other spatial and temporal data type categorisations. Then, it is an imperative to have a common underlying principle for granulation hierarchies so as to be able to both distinguish between the two and relate them to enhance interoperability. In addition to the modelling language, MADS has a comprehensive data manipulation language with algebra and conceptual query builder tool. The algebra and its use demonstrate elaborate formulations of queries (including granular queries), which is at least in part due to the fact that there is no explicit framework or modeling constructs to declare that something is of a particular level of granularity and how that relates to entities in a level in another granulation hierarchy. Including such declarative knowledge at the conceptual layer could simplify the data manipulation, and increase the prospects of use and reuse.

### *B. A more comprehensive GIS domain with environmental science and ecology*

Information systems for ecology and climatology complicate GISs. They require the geographic information, temporally indexed, and then add other pieces of information and dimensions. One comparatively straight-forward extension are ecosystem hierarchies such as the "National hierarchical framework of ecological units" used by the US Department of Agriculture's Forest Service [5], which has been analysed in detail by [8], [37]. Their rigour to distinguish within that classification between a partonomy of individuals for particular regions to be part of a larger region, a taxonomy of classes for types of ecological units, and distinction between type and instance help disambiguation, but does not solve the core problem with the granular levels and their contents. To see what is principally wrong with such a hierarchy, we start with Appendix 1 of [5], which describes the mapping from the USDA ecological units to the widely used Köppen climate classification equivalent; see Table I. For the third layer, no Köppen equivalent is given, because the USDA's Provinces are actually *instances*, i.e., particular regions, whereas the Köppen's system is based on a *combination of properties independent of a particular area and time*, i.e., *types* of regions, so that each particular area that satisfies those properties is classified accordingly (see also [21]). In addition, the USDA system orders along the line of 'the kind of weather common for the Mediterranean countries',

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[2] ISO TC 211, Geographic Information—Spatial Schema, ISO 19107:2003 and ISO TC 211, Geographic Information—Temporal Schema, ISO 19108:2002.

TABLE I

COMPARISON OF THE USDA'S "ECOREGION EQUIVALENTS" WITH THE RELEVANT SECTION OF THE KÖPPEN CLIMATE CLASSIFICATION.

| **Köppen** | | **USDA's "Ecoregion equivalents"** |
|---|---|---|
| Warm temperate climate (C) | $\equiv$ | Humid Temperate Domain (200) |
| ↑ | | ↑ |
| Warm temperate climate, dry summer (Cs) | $\equiv$ | Mediterranean Division (260) |
| ↑ | | ↑ |
| *no equivalent given in [5]*<br>(Warm temperate climate, dry, hot summer (Csa) [21]) | $\not\equiv$ | California coastal steppe, Mixed forest, and Redwood forest Province (263) |

which changes over time and does not indicate any particular characteristic. This makes either the top two layers of the USDA classification prone to manual updates or the bottom "province" layer liable to manual reclassifications, which in both cases results in time-inconsistent data that complicates data analysis. Compare this with the ease of updating the world map using the Köppen system where only measurement data have to be fed into the database and (re-)classification occurs automatically [21]. Moreover, if we indeed look at even finer-grained *ecological* units and not just the physical geography (temperature and humidity) for climate, then $Steppe$, $Mixed\ forest$, $and\ Redwood\ forest$ are rather distinct units for they have different vegetation. This is not addressed in [5], but one has to resort to, e.g., the finer-grained WWF ecological land classification with its 14 biomes and 825 terrestrial ecoregions and, e.g., the proposed refinement of the typology of forest types that is based on 35 forest indicators, such as age structure/diameter distribution, deadwood, and tree species composition [6]. This situation indicates one needs the ability to relate these various small hierarchies in a consistent way so as to use them in integrated GISs. In addition, relatively new sub-disciplines, such as molecular ecology and metagenomics, add additional levels of granularity.

A different issue is the *interplay* between qualitative and quantitative granularity. There is a wide range of mostly quantitative properties (parameters or indices) that are taken into the equation in ecology [32], where choosing the wrong scale can lead to false conclusions. For instance, presumed niche-overlap of co-existing species at coarse-grained land plots at larger time intervals compared to effective spatio-temporal niche differentiation when observed at finer-grained values; e.g., grassland ants that have dawn, afternoon or nocturnal foraging habits—hence, also at slightly different temperatures—and whose routes are apart if observed in, say, 5 m$^2$ plots as opposed to 100 m$^2$ [2]. Let us take the classification levels based on similar spatial scales, as shown in Table II, where each named level contains instances, such as Palearctic and Afrotropic in the $Ecozone$-level. Although they are well-structured in the sense of *which* dimensions we consider, why there are gaps is left unanswered: do $Ecodistrict$, $Ecosection$, and $Ecosite$ really make sense and if so, then one can observe the flora and fauna at that scale, hence the current empty cells in the zoogeography should be completed (or justified why not). Structuring quantitative and qualitative information in more detail, both ontologically in the sense of developing even simple taxonomies [15] and more clearly structured than informal granularity hierarchies [34], requires considerable effort to achieve.

Thus, we are faced with the problem of not having an explicit, declarative way for representing granular levels and hierarchies, which, in turn, leads to the situation of having to deal with cumbersome queries to retrieve the granulated information. In addition, even if we would have a way to represent the granulation hierarchies in an unambiguous manner with a formal semantics, then simply formalising informal hierarchies—of which it is ambiguous what the criteria and mechanism for granulation are—still leaves unclear the issue of computation to automatically move between levels, cross-linking different hierarchies and/or integrating them and therefore is prone to complicated software code that hampers its usability and reusability, and, hence, maintainability, due to the lack of transparency.

## III. ONTOLOGICAL NOTIONS FOR GRANULATION OF THE GIS DOMAIN

In order to address at least some of the issues discussed in the previous section, we take a two-pronged approach to provide and test a methodology for granulating the GIS domain. First, foundational semantics of types of granularity, i.e. differences in ways of devising granulation hierarchies, are considered. Second, these foundational notions are integrated with a basic, formal, theory of for granularity that makes explicit and precise in a logical theory the hitherto informally used 'levels', 'hierarchies' and so forth. This will be used to reassess typical granularities in GIS, such as cartographic maps, conditional hierarchies, and scale-based categorisations, in section IV.

### *A. Types of granularity*

One can extract 'patterns' from extant granulation hierarchies, that is, grouping types of hierarchies with their levels by the way how the levels are identified and specify such *mechanisms of granulation*. Being able to distinguish between the different types of granularity,

TABLE II

Typical classification levels in ecosystems based on similar spatial scales (based on [3]).

| | **Biotic** | | | **Abiotic** | | |
|---|---|---|---|---|---|---|
| **Ecosystem** | **Biogeography** | **Zoogeography** | **Phytogeography** | **Physiography** | **Geology** | **Pedology** |
| Ecozone | Biome | | Floral kingdom | | | |
| Ecoprovince | | Zoogeographic province | Floral province | | Geoprovince | |
| Ecoregion | Bioregion | | Floral region | Physioregion | Georegion | Pedoregion |
| Ecodistrict | | | | | | |
| Ecosection | | | | | | |
| Ecosite | | | | | | |
| Ecotope | Biotope | Zootope | Phytotope | Physiotope | Geotope | Pedotope |
| Ecoelement | Bioelement | | Geoelement | | | |

then, avoids comparing apples and oranges in the implementation: on the one hand, traversing levels in one hierarchy may be achieved by, e.g., simple aggregation operations in a database whereas others are primarily based on the relation between the entities so that a traversal along a partonomy is more appropriate, and, on the other hand, at a higher level of abstraction, the semantics of certain hierarchies are the same regardless if one implements it as a multi-resolution or multi-representation database. The precisely defined meaning could then be reused for interoperability. The first step for dealing with such foundational semantics of granularity is the disambiguation of types of granularity, which have been structured in a taxonomy elsewhere [18], [16]. Here we summarise the eight identified ‘leaf’ types of the taxonomy of types of granularity, which comprise the main mechanisms of granulation, and illustrate each type with an example.

**nrG**: levels of **n**on-scale-dependent **G**ranularity are ordered according to one type of relation in a perspective; e.g., (structural-)$part\_of$, (spatially-)$contained\_in$. The primary types of granulation relations [18] include, at least, $is\_a$, $participates\_in$, $member\_of$, and $proper\_part\_of$ with its subtypes $contained\_in$ and $involved\_in$ as defined in [20], e.g., for $located\_in$ we have the definition:

$$\begin{aligned}\forall x,y(located\_in(x,y) \triangleq part\_of(x,y) \wedge R(x) \wedge \\ R(y) \wedge \exists z,w(has\_2D(z,x) \wedge \\ has\_2D(w,y) \wedge ED(z) \wedge ED(w)))\end{aligned} \tag{1}$$

where $part\_of$ is standard part of as in Ground Mereology, $ED$ endurant (‘object’) and $R$ spatial region as defined in the foundational ontology DOLCE, and $has\_2D$ to relate the entity to the region it occupies.

**nfG**: levels of **n**on-scale dependent **G**ranularity are ordered by simultaneous **f**olding $\geq 2$ different (types of) entities, such as folding events and states, and folding relations between those entities upon going to a coarser-grained level; e.g., the ‘black boxes’ in biology [36] such as the $Second\ messenger\ system$, and ER clustering.

**nasG**: **n**on-scale-dependency using **a**ggregation of the **s**ame collection of instances of one type that subsequently can be granulated using semantic criteria. The class at a lower level is a subtype of the class at the coarser-grained level; e.g., a collection of $Phone\ point$s and at the finer-grained level we have $Landline$s and $Mobile\ phone\ point$s.

**nacG**: **n**on-scale dependency using **a**ggregation attributed to the notion of an entity generally labelled with a **c**ollective noun that has an existing semantics, and the instances of the aggregate are different from instances of its members, and a change in its members does not affect the meaning of the whole; e.g., $Population$ with $Organisms\ of\ type\ x$, or $Team$ as aggregate of its $Player$s.

**sgrG**: **s**cale dependency, taking into account **g**rain size with respect to **r**esolution; e.g., $Cell\ wall$ represented as line, as lipid bi-layer, and as three-dimensional structure, or $the\ Louvre$ on cartographic maps as polygon or as point depending on the resolution of the map.

**sgpG**: **s**cale dependency, with **g**rain size and **p**hysical size of the entities where the differences in physical size of the entities (/types) is *the* property for granulation. The zooming factor is like a grain size when relating levels of granularity, where *within one* level one can distinguish instances of, *e.g.*, $\geq 1$mm but instances smaller than 1 mm fall through the sieve and are indistinguishable from each other, but they are distinguishable at lower levels of granularity; e.g., sieves with different pore sizes that retains the entities or lets them through, a Euro coins separator, or two objects touching each other, e.g., wallpaper and the wall where, when zoomed in, we also observe the glue that connects the wallpaper to the wall.

**samG**: **s**cale dependency using **a**ggregation of the **s**ame collection of instances of the same Urelement that subsequently can be granulated in various ways at lower levels of detail using a mathematical function; e.g., $Second$, $Minute$, and $Hour$, with 60 seconds in a minute and so forth.

**saoG**: also exhibits **s**cale-dependency, but now with the carving up of the same entity at each level according to a coarser or finer grid of which the cells can be **a**ggregated and lay **o**ver the representation of a material entity; note it is a *material* entity, because one cannot put a grid over the representation of a non-material entity like an organisation, but one can do this with e.g. a lake—that is, with GIS objects such as representations of entities on cartographic maps. For instance, the earth with its isotherms, where the isotherms are in steps of 10 degrees, 5 degrees, 1 degree detail (this does not consider roughness or fuzziness of the measurement, which is an orthogonal issue). Possibly, one could decide to create subtypes for standard GIS square raster and other types (shapes) of raster.

### *B. Basic theory of granularity*

We introduce a simplified, yet effective, theory of granularity in first order predicate logic[3]. A comprehensive theory of granularity (TOG) with model-theoretic semantics (and containing all definitions, constraints, and proofs) is presented in [18], but abridged here due to space limitations. The principal entities with their axiomatization are given in the following definition.

DEFINITION *1 (Granularity theory $\mathcal{G}$):* A granularity framework is a tuple
$\Sigma = \{\Delta, \Pi, \Lambda, \Upsilon, \Theta, \Gamma, R_E, R_L, R_C, R_G, uses_\gamma, conv, \mathcal{F}, has\_permitted_\gamma\}$ where

1) $\Delta$ is the domain, that can be divided up into a particular subject domain $\delta^s$ and the encompassing granularity frame $\delta^f$ that contains the other elements of the granularity framework;
2) $\Pi$ denotes granular perspective (granulation hierarchy), where its instances are denoted with $\pi_1, \ldots, \pi_n$ (the other symbols are defined below, except for $DF$, which is DOLCE's notion of definition):
   $\forall x(\Pi(x) \triangleq \exists w, y, z, \phi(DF(x, y) \wedge R_C(x, z) \wedge \Upsilon(z) \wedge R_E(x, w) \wedge R_G(x, \phi)))$;
3) $\Lambda$ denotes granular level, where its instances are denoted with $\lambda_1, \ldots, \lambda_n$:
   $\forall x(\Lambda(x) \triangleq \exists! v, w, y, z(DF(x, y) \wedge \Pi(w) \wedge R_E(x, w) \wedge \Upsilon(z) \wedge R_C(w, z) \wedge V(v) \wedge has\_value(z, v)))$, where $V$ stands for DOLCE's region and $\forall x, y(has\_value(x, y) \rightarrow Prop(x) \wedge V(y)$ where $Prop$ is a property (which may be a measurable quality property);
4) $\Upsilon$ is the granulation criterion (a combination of at least two properties $prop$, of which one may be a quality property $Q$) by which one granulates a particular perspective, where its instances are denoted with $\upsilon_1, \ldots, \upsilon_m$:

   Each criterion $\Upsilon$ is a combination of either (1) $\exists^{\geq 2} y(Prop(y) \wedge \neg Q(y))$, i.e., at least two properties $Prop$ but not a quality property $Q$, or (2) $\exists y \exists! z(Prop(y) \wedge Q(z) \wedge \neg(y = z))$, i.e., at least one $Prop$ and exactly one $Q$, which are related to $\Upsilon$ through the $C_P$ relation (where $\forall x, y(C_P(x, y) \rightarrow \Upsilon(x) \wedge Prop(y)))$;
5) $\Theta$ is a type of granularity from the taxonomy of types of granularity [16];
6) $\Gamma$ is a granulation relation between entities residing in adjacent levels, being one of $is\_a$, $participates\_in$, $member\_of$, $ppart\_of$, $involved\_in$, or $contained\_in$ (as defined in [20]);
7) $\mathcal{F}$ is a set of conversion functions
8) $R_E$ (and its inverse $R_E^-$) is a binary proper parthood relation (*sensu* Ground Mereology) constrained to relating two framework components, being either a level and a perspective or a perspective and a domain:
   $\forall x, y(R_E(x, y) \rightarrow \Lambda(x) \wedge \Pi(y))$ or $\forall x, y(R_E(x, y) \rightarrow \Pi(x) \wedge \delta(y))$ and $\forall x, y(R_E^-(x, y) \rightarrow \delta(x) \wedge \Pi(y))$ or $\forall x, y(R_E^-(x, y) \rightarrow \Pi(x) \wedge \Lambda(y))$, and $R_E(x, y) \rightarrow ppart\_of(x, y)$ and $R_E^-(x, y) \rightarrow has\_ppart(x, y)$;
9) $R_L$ is a binary parthood relation constrained to relating two adjacent fine and coarser-grained levels that reside in the same perspective:
   $\forall x, y(R_L(x, y) \triangleq s\_ppart\_of(x, y) \wedge \Lambda(x) \wedge \Lambda(y) \wedge \neg(x = y))$;
10) $R_C$ is a binary relation associating a granulation criterion to a perspective:
    $\forall x, y(R_C(x, y) \rightarrow \Pi(x) \wedge \Upsilon(y))$;
11) $R_G$ is a binary relation relating a perspective or level to the type of granularity it adheres to:
    $\forall x, y(R_G(x, y) \rightarrow (\Pi(x) \vee \Lambda(x)) \wedge \Theta(y))$;
12) $uses_\gamma$ is a binary relation between $\Theta$ and $\Gamma$:
    $\forall x, y(uses_\gamma(x, y) \rightarrow \Theta(x) \wedge \Gamma(y))$;
13) $has\_permitted_\gamma$ is a binary relation between one type of $\Theta$, **nrG**, and $\Gamma$:
    $\forall x, y(has\_permitted_\gamma(x, y) \rightarrow \Theta(x) \wedge (x \rightarrow nrG) \wedge \Gamma(y))$;
14) The conversion relation, $conv(x, \phi, \vartheta)$, relates a granular level $\Lambda(x)$ that adheres to a (subtype of) **sG** type of granularity $\phi$ to function $\vartheta \in \mathcal{F}$ :
    $\forall x, \phi, \vartheta(conv(x, \phi, \vartheta) \rightarrow GL(x) \wedge (\phi \rightarrow sG) \wedge F(\vartheta))$;
15) The following constraints hold:
    i. For each $\pi_i$ there must be exactly one criterion $\upsilon_i$: $\forall x(\Pi(x) \rightarrow \exists! y\, R_C(x, y))$;
    ii. For each $\pi_i$ there must be exactly one type of granularity $\theta_i$: $\forall x(\Pi(x) \rightarrow \exists! \phi\, R_G(x, \phi))$;
    iii. Each criterion must be related to at least two properties: $\forall x(\Upsilon(x) \rightarrow \exists^{\geq 2} y\, C_P(x, y))$;
    iv. Each perspective can be identified by the combination of the criterion and type of granularity it adheres to: $\forall x(\Pi(x) \rightarrow \exists! y, \phi(R_C(x, y) \wedge$

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[3] The universal quantification $\forall$ can be verbalised as "for each" or "for all", the existential quantification $\exists$ as "there exists" or "at least one" (with $\exists!$ as exactly one), $\wedge$ as "and", $\vee$ as "or", $\neg$ as "not", the implication $\rightarrow$ as "implies" or "if ... then", and $\triangleq$ for definition. See, e.g., [13] for definitions of formula, sentence, *theory* $\mathcal{T}$ as a consistent set of sentences, and the notion of satisfiability of a theory (i.e., then there is an interpretation $\mathcal{I}$ that is a model of $\mathcal{T}$).

$R_G(x, \phi)))$, where $\phi$ is a shorthand for any of the eight types of granularity;

v. Each perspective must contain at least two levels: $\forall x(\Pi(x) \rightarrow \exists^{\geq 2} y R_E^-(x, y))$, where $R_E^-$ is the inverse of $R_E$;

vi. Each level must be contained in exactly one perspective: $\forall x(\Lambda(x) \rightarrow \exists! y R_E(x, y))$;

vii. The multiplicity (cardinality) for $R_L$ is 1:1, i.e., $\forall x \exists! y(R_L(x, y))$;

viii. Each usage of **nrG** is related to exactly one $\Gamma$: $\forall x(nrG(x) \rightarrow \exists! y(has\_permitted_\gamma(x, y))$;

ix. If $\Gamma(x)$ adheres to **sG** type of granularity, then it does have a relation to a function $\vartheta$ related to it through the $conv$ relation: $\forall x, \phi(R_G(x, \phi) \wedge (\phi \rightarrow sG) \rightarrow \exists \vartheta\, conv(x, \phi, \vartheta))$;

x. For each $\Gamma(x)$, there are $\leq$ 2 functions $\vartheta$: $\forall x(\Gamma(x) \rightarrow \exists \phi \exists^{\leq 2} \vartheta\, conv(x, \phi, \vartheta))$.

To move toward implementations, we need to have three principal components for a granulated information system: the types of granularity (summarized in section III-A) that link to the basic theory of granularity through $\Theta$ as defined in Definition 1, an instantiation (model) of this theory—a granularity framework $\delta^f$ for a specific subject domain $\delta^s$ for ecosystems, with entities such as the $\lambda_i = Biotope$ and $\pi_i = Biogeography$ that are contained in the overall frame $\delta_i^f$ (with $r_e(\lambda_i, \pi_i)$ and $r_e(\pi_i, \delta_i^f)$) if one follows the information in Table II—and the data sources that are granulated, such as the Michelin database of the European road network and the Google Earth database. Then, with Definition 1 and such a $\pi_i$, we have to have at least one more level other than $\lambda_i$ (constraint 15-v, see [17] for the proofs), a criterion for granulation $\upsilon_i$ (constraint 15-i), e.g., scale-delimited biogeography, and a type of granularity $\theta_i$ that that hierarchy adheres to (constraint 15-ii), such as **samG**. How the types of granularity, $\mathcal{G}$ and an instantiation (model) of $\mathcal{G}$ with specific granular perspective, levels, criteria and so forth interact will be demonstrated with the case study in the next section.

## IV. PARTICULAR GRANULAR PERSPECTIVES IN GIS

Let us now take four different granular perspectives (granulation hierarchies), two on spatial data representation and two that are conditionally linked; see Table III. For the granular perspectives $\pi_1$, $\pi_2$, $\pi_3$, and $\pi_4$ we have criteria and types of granularity as summarised in Table IV; that is, we have an instantiation of $\mathcal{G}$ with relations such as $r_g(\pi_1, \theta_1)$ and $r_c(\pi_1, \upsilon_1)$ for each perspective to ensure constraint 15-iv from Definition 1 is satisfied (and thus also 15-i and 15-ii), and a required $has\_permitted_\gamma(nrG, contained\_in)$ for $\pi_3$ (constraint 15-viii); note that for $\pi_3$ the recording of a $\Gamma$ is necessary because it is of granularity type **nrG**, whereas it is optional for $\pi_1$ and $\pi_2$ for which we have a $uses_\gamma(\theta_2, ppart\_of)$. In addition, taking the names of the levels, then we can describe the basic framework components with $r_e(Point, \pi_1)$, $r_e(Line, \pi_1)$, $r_e(Polygon, \pi_1)$, and $r_e(Polyhedron, \pi_1)$—i.e., relating levels to a perspective—as well as $r_l(Polyhedron, Polygon)$, $r_l(Polygon, Line)$, and $r_l(Line, Point)$ to relate the levels in that perspective; this satisfies 15-iv, 15-v, and 15-vi. The other granular perspectives are described analogously (where no level names are available, one can use a numbering scheme $\lambda_1, ..., \lambda_n$).

Looking at $\pi_2$, it is clear that many more such type of granular perspectives can be described with a varying amount of levels; the underlying principle to do so, however, is the same for each one: an overlay grid with cells of some shape and a conversion function for how to aggregate the cells, i.e., adhering to **saoG**-type of granulation. To distinguish between the different types of rasters and their raster size, we use the properties the criterion is made up of; e.g., $\pi_2$ can represent a section of the Irish Transverse Mercator (see the Irish National Grid, http://www.osi.ie), where the quality property $Q$ is the size of the side of the square and the second property the raster shape. The conversion function $\vartheta_2 \in \mathcal{F}$ is a multiplication (division) by $10$, hence we relate this to the levels with the $conv$ relation as, $conv(\lambda_{2\text{-}4}, \theta_2, \vartheta_2)$ with $\theta_2 =$ **saoG** and $\vartheta_2 = \times 10$ and so forth; this is likewise for the other perspectives with scale-dependent type of granularity, hence, also 15-ix holds. 15-x holds too, as e.g., $\lambda_{2\text{-}4}$ can have only one function to the adjacent coarser-grained level whereas the levels in $\pi_3$ do not have a conversion function to calculate the values. The granularity framework thus provides an approach to record such information explicitly instead of burying it in the software code or to describe it only informally.

The perspectives $\pi_3$ and $\pi_4$ are clearly of a different type of granularity both compared to each other and to $\pi_1$ and $\pi_2$. For instance, whereas $\pi_3$ explicitly has a granulation relation $\Gamma$, $\pi_4$ explicitly does not have one, because the instances in the levels are rivers that do not bear any 'water throughput relation' to each other; some rivers flow into others and are therefore physically related, but that is another theme compared to assessing river sizes. Nevertheless, $\pi_3$ and $\pi_4$ are closely related for they easily can be used in tandem. The intuition of this relatedness was highlighted by [10], which we have limited here for two granular perspectives, being "administrative boundaries" with four levels and a "hydrographic" one that classifies rivers on their water flow, also with four levels; see Table III. Irrespective if the levels make sense ontologically and if the given values in $\pi_4$ are indeed the values used for map-making, the intention is to represent constraints such as *if one makes a map with granularity at the* $Province$*-level then only rivers with a flow* $\geq$*10 000*

TABLE III

SAMPLE GRANULAR PERSPECTIVES FOR GIS/CARTOGRAPHY WITH (LEFT) STANDARD SPATIAL DATA REPRESENTATION OPTIONS AND (RIGHT) WITH CONDITIONAL LEVELS ACROSS PERSPECTIVES (BASED ON [10]) THAT LINK HUMAN GEOGRAPHY WITH PHYSICAL GEOGRAPHY, E.G., FOR MAP MAKING OR AS STEP TO FIND CORRELATIONS BETWEEN THE BUILT ENVIRONMENT AND FRESHWATER AVAILABILITY.

| **Spatial data representation** | | **Conditional perspectives** | | |
|---|---|---|---|---|
| **Shape** ($\pi_1$) | **Raster** ($\pi_2$) (Size in m) | **Admin** ($\pi_3$) | | **Hydro** ($\pi_4$) (river with flow $\geq$) |
| Point | 1000 | Country | ⇔ | 100 000 litres/min |
| ↑ | ↑ | ↑ | | ↑ |
| Line | 100 | Province | ⇔ | 10 000 litres/min |
| ↑ | ↑ | ↑ | | ↑ |
| Polygon | 10 | Region | ⇔ | 2500 litres/min |
| ↑ | ↑ | ↑ | | ↑ |
| Polyhedron | 1 | Municipality | ⇔ | 1000 litres/min |
| | | ↑ | | ↑ |
| | | Municipality district | ⇔ | 250 litres/min |

TABLE IV

PROPERTIES OF THE GRANULAR PERSPECTIVES IN TABLES III AND V; SEE DEFINITION 1 AND TEXT FOR DETAILS.

| $\Pi$ | $\Theta$ | $\Upsilon$ | $\Gamma$ | **Comments on additional modeling entities** |
|---|---|---|---|---|
| $\pi_1$ | $\theta_1 =$ sgrG | $\upsilon_1 =$ GIS vector-based spatial data representation | $\gamma_1 = has\_ppart$ | relation to the granulated entity, relation to resolution and how to convert between these resolutions |
| $\pi_2$ | $\theta_2 =$ saoG | $\upsilon_2 =$ GIS raster-based spatial data representation | $\gamma_2 = ppart\_of$ | additional conversion function to aggregate the squares into the next coarser level, relation to the granulated entity |
| $\pi_3$ | $\theta_3 =$ nrG | $\upsilon_3 =$ Administrative region | $\gamma_3 = contained\_in$ | |
| $\pi_4$ | $\theta_4 =$ sgpG | $\upsilon_4 =$ River water throughput | – | |
| $\pi_5$ | $\theta_5 =$ saoG | $\upsilon_5 =$ July isotherm, average | | optional aggregation function to move from finer-to coarser-grained level, linked to an administrative region entity |
| $\pi_6$ | $\theta_6 =$ saoG | $\upsilon_6 =$ Yearly precipitation, average | | optional aggregation function to move from finer-to coarser-grained level, linked to an administrative region entity |

TABLE V

VARYING SCALES AT DIFFERENT LEVELS OF REGIONS AS WELL AS WITHIN-SCALE VARIATIONS; VALUES POPULATING THE LEVELS ARE TAKEN FROM MAPS IN THE DUTCH "GROTE BOS ATLAS".

| | **Avg. July temperature** ($\pi_5$) (°C) | **Avg. Yearly Precipitation** ($\pi_6$) (in mm) |
|---|---|---|
| $\lambda_1$ World | 0 – 10 – 20 – 30 | <250 – 250-500 – 500-1000 – 1000-2000 – $\geq$2000 |
| | ↑ | ↑ |
| $\lambda_2$ Europe (EU) | <10 – 10-15 – 15-17.5 – 17.5-20 – 20-25 – $\geq$25 | <200 – 200-400 – 400-600 – 600-800 – 800-1200 – 1200-2000 – $\geq$2000 |
| | ↑ | ↑ |
| $\lambda_3$ Netherlands (country) | 16 – 16.5 – 17 – 17.5 | <750 – 750-800 – 800-850 – 850-900 – $\geq$900 |

*litres/min should be included in the map*. That is, in a GIS application we have a *conditional selection* across perspectives. With $\mathcal{G}$ and two functions to select a level ($selectL : \mathcal{L} \mapsto \mathcal{L}$, with $\mathcal{L}$ the set of all levels $\lambda_1 ... \lambda_n$) and retrieve the contents of a level ($getC : \mathcal{L} \mapsto \mathcal{E}$, and $\mathcal{E}$ the collection of universals or particulars residing in a level $\lambda_i$), we can generalise this into a constraint pattern for conditional selection and retrieval (where $i \neq j$):

*if* $selectL(\lambda_i)$ *and* $getC(\lambda_i)$ *where* $r_e(\lambda_i, \pi_i)$, *then* $selectL(\lambda_j)$ *and* $getC(\lambda_j)$, *where* $r_e(\lambda_j, \pi_j)$, *as well*

Although it may seem a peculiarity for GIS, we could apply such a constraint equally in, say, medicine, such as for cancer growth of colorectal cancer where "*if the medical doctor needs a day-by-day view of the growth of the cancer in patient1, then deliver the tissue samples*" as opposed to delivering cell cultures or microarrays. This type of constraint is not in the definition of $\mathcal{G}$ (nor added as compound function in the dynamic components of the TOG [18][4]), because such constraints can be declared in an instantiation of $\mathcal{G}$ only and, as shown with the generic constraint, can be dealt with adequately. A software developer, however, might prefer to add the pattern to make it easier for

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[4] With the more comprehensive logical apparatus of the TOG, relating levels and perspectives can be done either through various parthood relations or chaining levels (through $R_L$ and its inverse) and perspectives ($R_P$).

the domain expert to declare these type of conditional selections, but this is within the scope of user-friendliness. Last, a brief analysis on the status of $\pi_3$ is in order. The sample levels serve as illustration and suffice to convey the intuition, but they deserve closer ontological investigation. Due to historical reasons or multi-linguality, the hierarchy could be different, hence, a semantic mapping may need to be carried out. In particular, in some countries $Region$ is a proper part of ($ppart\_of$) $Province$, whereas in other countries it is exactly the opposite; this can be addressed with declaring full definitions of the intension of the concept. The case is different for alternative administrative categorisations, as in, e.g., the UK one has $Parish$ as proper part of $QuasiUnitaryAuthority$, which are aggregations based on *church*-based administrative areas as opposed to *state*-based administrative areas. Given that these are two distinct criteria, one will have two granular perspectives. Both systems have been formally defined in the AdministrativeGeography ontology by the UK Ordnance Survey[5]; thus, declaring granular perspectives can be informed by ontologies and, conversely, can facilitate ontology development.

Let us now assess a third aspect. We took six maps on temperature and precipitation in the Dutch "Grote Bosatlas" (51$^{st}$ ed.) over three regions, which is shown in Table V. We are facing several issues with these hierarchies. One is the time duration taken for the two perspectives—1 year vs. 0.5 year—and the other one is the high flexibility of the scales. The former can be harmonised by a particular granular perspective for time, such as a calendar hierarchy, and subsequently link it conditionally to the other two perspectives, whereas the latter could involve a more elaborate rework. Consider the differences of degrees of the isotherms, which are $x = 10$, ($x = 2.5$ or $x = 5$), and $x = 0.5$°C, respectively, and ($x = 250$ or $x = 500$ or $x = 1000$), ($x = 200$ or $x = 400$ or $x = 800$), and $x = 50$, respectively, for the levels for yearly precipitation. This is human readable, but computationally cumbersome, inflexible, and hampers transparency of a software application that has to compute aggregations or make abstractions. There is a granularity in the different cut-off values within three of the six levels, being that the middle of the scale has smaller differences between the values (e.g., 200mm) than the outer parts (800mm). Given the repeated use of such scales in multiple maps and an apparent perceived requirement to do so, one could choose to make this explicit in a separate granular perspective that serves as declarative knowledge and subsequently use it to create the maps. One also could decide to change these scales, with, e.g., 15 – 15.5 – 16 – 16.5 – 17 – 17.5 for $\lambda_3$ in $\pi_5$; it is, however, beyond the scope to assess which is the 'better' option according to domain experts or software developers. The major advantage in any case, is that with the explicit (basic) theory of granularity $\mathcal{G}$ at the conceptual layer and an instantiation as its model, it is irrelevant if at the back-end this is implemented as a multi-resolution database and the map computed on the fly, by a multi-representation database, or some object-oriented application software. Put differently, the *conceptualization is the same* throughout, but the implementation can vary, just like we have a difference in principle between a conceptual data model (in ER, UML etc.) and the final SQL/Java/etc. code in the physical database or software application. With the types of granularity and $\mathcal{G}$, we now have a means of declaring explicit, formally, and precisely the subject domain knowledge about granularity, which has as benefits the transparency, usability, reusability, and interoperability of GISs. This, in turn, has the major knock-on advantages that both rules, such as the conditional selections, and queries in general are much simpler to carry out for we can easily select a level, i.e., the *what* we want to know, without having to take into account *how* it is implemented in the particular application.

Finally, we can use the same principle for linking geo-ontologies that cover different perspectives and/or levels, analogous to the OBO Foundry approach for biomedical ontologies [35], [19], and, as a next step or a merging, extend it further to, say, geographic healthcare information systems.

## V. CONCLUSION

To structure granular perspectives (granularity hierarchies) not only in the GIS subject domain, but, in principle, also other, related, subject domains, we introduced eight types of granularity and a facilitating basic theory of granularity to structure granular perspectives in the GIS domain. Several common GIS hierarchies have been assessed and refined, which demonstrated, among others, the advantage of declarative knowledge for conditional hierarchies and orthogonal granularities that can be split up so as to increase transparency and reuse. It illustrates a modelling approach of first representing *what* one desires to consider concerning granularity for a GIS application at the semantic layer (rather than the *how* to implement it), so as to have a formal foundation to enable reaping benefits of flexibility, reusability, transparency, and interoperability at the implementation layer.

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