The Landform Reference Ontology (LFRO): A Foundation for Exploring Linguistic and Geospatial Conceptualization of Landforms

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Abstract

The landform reference ontology (LFRO) formalizes ontological distinctions underlying naïve geographic cognition and reasoning about landforms. The LFRO taxonomy is currently based only on form-based distinctions. In this significantly revised version, several new categories have been added to explicate ontological distinctions related to material-spatial dependence and physical support. Nuances of common natural language landform terms and implications for their mapping are discussed.

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1 Motivation and background

The Landform Reference Ontology (LFRO) is being developed as a domain reference ontology for knowledge representation and reasoning about landforms. Its immediate purpose is to guide automated landform mapping from imagery data, but it is carefully being designed as a more generally applicable reference ontology, independent of any specific culture, language, or scientific discipline. LFRO is *not* being proposed as a universal ontology. Landforms have been previously argued to be mind-dependent or fiat [7] or quasi-objects [1] because their demarcation and categorization is not independent of human cognition. Ethnophysiographic research clearly shows there are many alternative ways of describing the domain of landforms.[9] As one extreme case, in the Lokono language, there is only one scale and size independent general term *horhorho* for landforms, and all distinctions are made through a complex vocabulary of lexical phrases that classify landforms as networks of connected places.[11]

While LFRO clearly cannot cover every possible conceptualization of landforms, there are still many consistent patterns in how people from diverse backgrounds conceptualize landforms. This makes LFRO a worthy, albeit ambitious, ontology engineering initiative to unify, through linguistic and formal ontological approaches, those fundamental categories and relationships that typically and generally (but not necessarily) seem to underlie most people's common sense (naïve geographic) conceptualization and reasoning about landforms.[8] The expectation is that, others can use this as a foundation to represent and compare more specialized linguistic, cultural and geo-scientific concepts.

In the current phase, only the most important criterion of (three-dimensional) form is relied upon, because, landforms are apprehended as unitary entities primarily (but not exclusively) based on their characteristic form. Partitioning of the surface arbitrarily based on non-morphological criteria will yield regions with other unifying characteristics, but not landforms with a coherent, characteristic shape. An initial, simpler version of LFRO based on form considerations was introduced in a short paper.[12] In this substantially revised version, several new categories are introduced to explicate critical ontological notions of material-spatial dependence and support.[4]

Many scientific, administrative, and folk landform classification systems and vocabularies have obviously informed the conceptual development of LFRO. Here, for lack of space, only a few directly relevant ontology design efforts are acknowledged. The *surface network* ontology [13], which formalizes the well-established theory of surface networks, was the first step in identifying the critical shape elements of the terrain surface. When further aligned and integrated with the ontology of spatial regions [2] and contours [6], it will also complement LFRO as an automated terrain feature extraction and reasoning ontology (the primary inspiration for designing LFRO). The *surface water features* ontology pattern provided insights about depressions [14], while work on hydro domain formal ontology (HyFO) provided essential insights about holes and physical containment, which strongly influenced how concave landforms should be represented in LFRO.[2],[3],[5]

2 Design and rationale for the Landform Reference Ontology

2.1 The ontology of landforms

Figure 1 presents all the categories and relationships recognized in LFRO. Grounding of LFRO in the DOLCE upper level ontology [10] is now used to explicitly declare that all landforms are of type *Physical Endurant*, which are physical entities that wholly (i.e., with

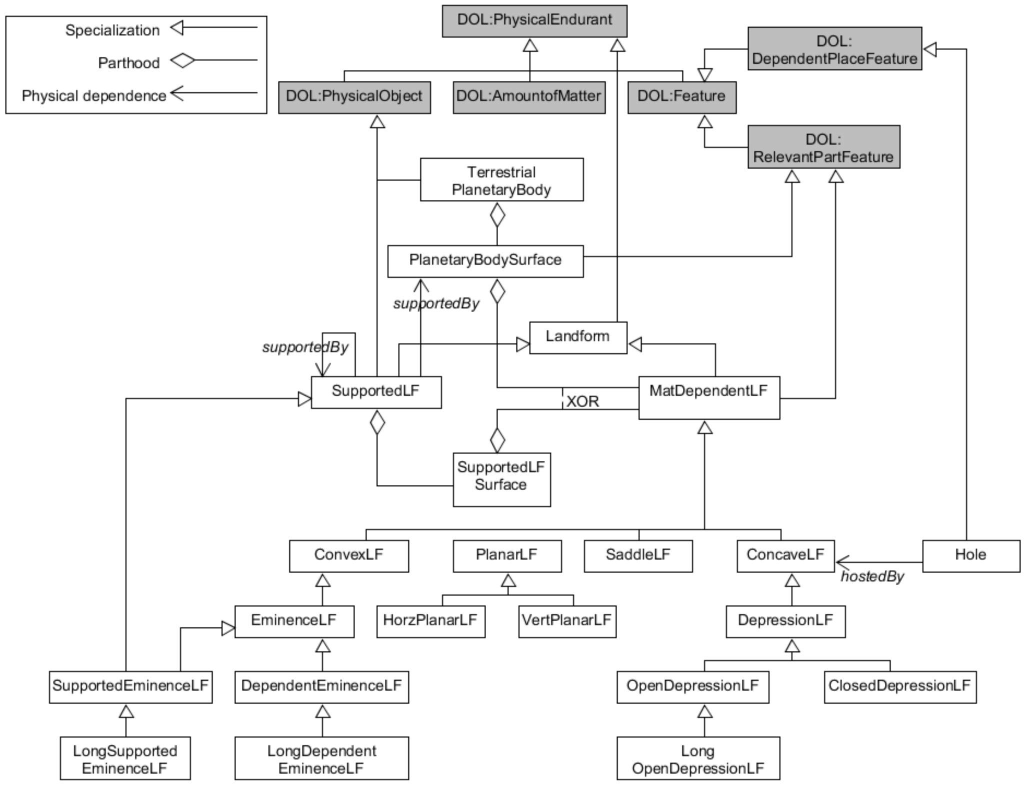

Figure 1 The categories and primary relationships of the Landform Reference Ontology (LFRO), with top level categories grounded in DOLCE categories (prefixed with DOL:).

all their proper parts) exist (typically as three-dimensional entities) in physical space at any time they exist. DOLCE specializes physical endurants into *physical objects*, *features* and *amount of matter*. Features depend on (are hosted by) other physical endurants and are of two types: relevant parts (materially constituted bumps, edges, surfaces) or dependent places (immaterial holes, shadows, etc.).

While LFRO is designed primarily for landforms on Earth, it can also be applied to any other terrestrial/telluric planetary body – i.e., whose surface region is materially constituted of rocky (silicate) or metallic material (like the bedrock and regolith composing the Earth's surface). LFRO is also intentionally designed to remain neutral regarding what qualifies as the surface of a planetary body – whether it is only the bedrock or also includes all or some of the overlying regolith material (e.g., sand, soil, alluvium, glacial till).

Intuitively, a *landform* is a physical endurant that is physically dependent on the solid surface of a terrestrial planetary body (*TerrestrialPlanetaryBody*) in two ways: it is either part of the surface (*MatDependentLF*) or physically supported by/on the surface (*SupportedLF*). The *MatDependentLF* category includes landforms that are *materially* and *spatially* dependent on either the solid surface of a planetary body or the surface of a *SupportedLF* landform. As explained in [4], material-spatial interdependence (*mat-dep*) is a type of physical dependence that requires the physical extents of two entities to be necessarily and mutually contingent (e.g. an object and a material part thereof or its matter, or a hole and its host). Thus, *MatDependentLF* landforms are (DOLCE) relevant part features of the surface. The location and identity of *MatDependentLF* landforms are also intrinsically tied to their location on the host surface. Most commonly known landform categories will be categorized under the *MatDependentLF* category.

In contrast to *MatDependentLF* landforms, *SupportedLF* landforms are not features of the host surface, but independent, physical object landforms supported on/by the surface. While the formalization of a support is still being worked out, intuitively, support is the relation between two material, physical endurants (objects or features) where one significantly contributes to maintaining the other one in one (or more) specific location(s). *SupportedLF* landforms can be supported directly on the planetary body surface, or another *SupportedLF* landform surface. *SupportedLF* landform surfaces can support both dependent and supported landforms. A special challenge in formalizing *SupportedLF* semantics arises because some surface entities (e.g., covered landfill and burial mounds) can be treated as landforms in some contexts, but other artificial structures (e.g., bridges, buildings), even if formed by naturally occurring rocks and soil, can never be.

2.2 Shape based categorization of landforms

In the first version of LFRO, *Landform* was the direct parent category for all shape-based subcategories. However, now, it can be said more specifically that all material landforms inherit their shape from certain characteristically shaped parts of the host surface. Based on generic landform shape-based categories proposed in [8], five, mutually exclusive shape-specific landform subcategories are specialized from the *MatDependentLF* category: *ConvexLF*, *ConcaveLF*, *HorzPlanarLF*, *VertPlanarLF* and *SaddleLF*. Convex and concave landforms comprise an overwhelming number of commonsense landform categories. While a convex landform protrudes out from the host surface, a concave landform is an indentation in the host surface, and necessarily hosts a hole feature. Planar surfaces are now further subcategorized as vertical or horizontal because such surfaces are experienced and lexicalized quite differently. The saddle subcategory was added to model passes, notches and gaps.

The semantics of concave landforms requires modeling of multiple possible perspectives of the negative spaces (holes) associated with such landforms. While any concave surface part necessarily encloses some hole, when people think of a concave-shaped *landform*, they may associate it variously with i) *only* the immaterial hole hosted by the concave part of the surface; ii) *only* the material concave part *ConcaveLF* of the surface, or iii) *both* the immaterial hole and the enclosing concave part of the surface. Every *ConcaveLF* landform must host some hole – regardless of whether the hole itself is viewed as a landform or not. Examples and implications of these three choices are discussed briefly in section 3.

An topographic eminence is a convex landform that stands completely above its surroundings. The coresponding *EminenceLF* category in LFRO is now split into two subcategories. *DependentEminenceLF* eminences (e.g., mountain, plateau, hill) inherit their characteristic convex shape from a host part of the planetary surface while *SupportedEminenceLF* eminences (e.g. landfills, mounds) are independent physical objects. Both these eminence categories are further specialized as *LongDependentEminenceLF* or *LongDependentSupportedLF* subcategories to explicitly cover elongated eminences such as ridge forms.

The subcategories for concave landforms and their various specializations remain unchanged from the previous version.[12] *ConcaveLF* landforms that are surrounded completely by higher land are specialized as *DepressionLF*, which is further specialized as *closed* and *open*. *ClosedDepressionLF* landforms have a rim marking the upper edge, the constant elevation of which is determined by the location of the closed depression's pour-point. *ClosedDepressionLF* landforms are special because they can store water for prolonged periods, thereby acting as containers for water bodies (e.g., puddle, lake, sea), provided enough water is available. In contrast, *OpenDepressionLF* landforms are "open" because they lack a unique enclosing rim, and/or have holes and openings such that they cannot be store water, but only allow it to flow through. Open and closed depression landforms can also be specialized based on planimetric shape (of their spatial region) to distinguish elongated depressions. Only the *LongOpenDepressionLF* category is currently recognized because elongated open depressions (e.g., stream channel, valley, canyon, ravine, canal, and trench) are quite frequently recognized across the world. Such landforms are commonly perceived as a concave part of the surface with a primary, sloping longitudinal axis, sloping sides, and generally open at both ends of the longitudinal section to allow water to flow through.

3 Exploring semantics and mapping of linguistic landform categories using LFRO

While some linguistic categories are easier to associate with one LFRO category, many others can be interpreted in multiple ways. For instance, a mountain landform will be a surface-dependent eminence for most people, but the terms hill or ridge can be used for both surface-supported and dependent eminences. If the surface is defined as the bedrock only, cinder cones, drumlins, and sand dunes will all be categorized as *SupportedEminenceLF*. However, if the earth's surface is not bedrock, but the exposed land surface (ground) that is directly accessible to us, the above-mentioned landforms should be modeled as (*DependentEminenceLF*) landforms. Similarly, people often assume craters to be like lake basins, which are closed depressions, but if any part of the rim is eroded to base level, the crater transforms into an open depression, that cannot contain water bodies. Considering a language other than English, the Yindjibardi term *marnda* can be applied to a variety of eminences including mountains, hills, ridges, and ranges.[9] Marnda is, therefore, almost (but not perfectly) synonymous with *EminenceLF*. Another Yindjibardi language term *bantha* refers to artificial or piled up eminences [9], and, will, therefore, be a subcategory of *SupportedEminenceLF*.

LFRO also helps illustrate practical reasoning implications of different conceptualizations of landforms. For example, if valley (or any other term) refers to just the immaterial *Hole* in the surface, then it can contain a water body, but it must be the concave part of the adjacent host surface that provides the material support for the water body and all other things that are "in" the valley. Alternatively, if the valley is just the material *ConcaveLF* part of the surface, it can only support, but not contain water bodies (which can only be contained in the hosted hole). Also, unlike the immaterial valley, a material concave valley can also share a part with the bordering mountain or hill. Finally, if a valley is conceived as a landform that has both *ConcaveLF* and *Hole* as necessary constituent parts, then people holding such a view would consider a valley to have all the above-mentioned properties. Note that it is not even necessary that people use the same interpretation for all concave landforms – for valley, they might choose the compound landform interpretation, while sink holes may be treated as holes, ignoring the materiality of their bottoms and sides.

LFRO can also be used to construct decision trees to choose appropriate mapping algorithms and construct semantic queries. For example, a semantic search for "*landforms that can store water*" would return all closed depression landforms, while searching for "*landforms where streams can flow*" would return all open longitudinal depression landforms. Analysis of linguistic terms and their alignment with LFRO also suggests that automated systems might be better off starting with methods to make generalized categorical distinctions. So, differences between mountain/hill/plateau/butte or valley/canyon/gorge or gully/gulch/rill are probably quite difficult to tease out. It might be better to first define methods to delineate eminences, elongated eminences, closed depressions, and open longitudinal depressions.

While LFRO is still, primarily, a taxonomy, a comprehensive axiomatic formalization will be undertaken only after some existing limitations are resolved by adding new LFRO form categories. Then LFRO will be integrated with the hydro-domain ontology HyFO and the (suitably enhanced) surface network ontology to support semantic reasoning and guide automated mapping methods. For example, a request for mapping a valley floor can be recast as a query to find the area within a certain distance and/or height of a *surface network courseline*.[13] A search for lake boundaries can be automatically inferred to require delineation of a closed depression landform, which in turn can be linked to finding pits and their basins from surface network theory.[13] Finally, LFRO needs to be expanded to support reasoning with other non-morphological commonsense criteria such as size, material, color, geomorphological origin, and culturally significant factors.

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