The Void in Hydro Ontology

Torsten Hahmann
Boyan Brodaric

Dept. of Computer Science, University of Toronto

Geological Survey of Canada, Natural Resources Canada

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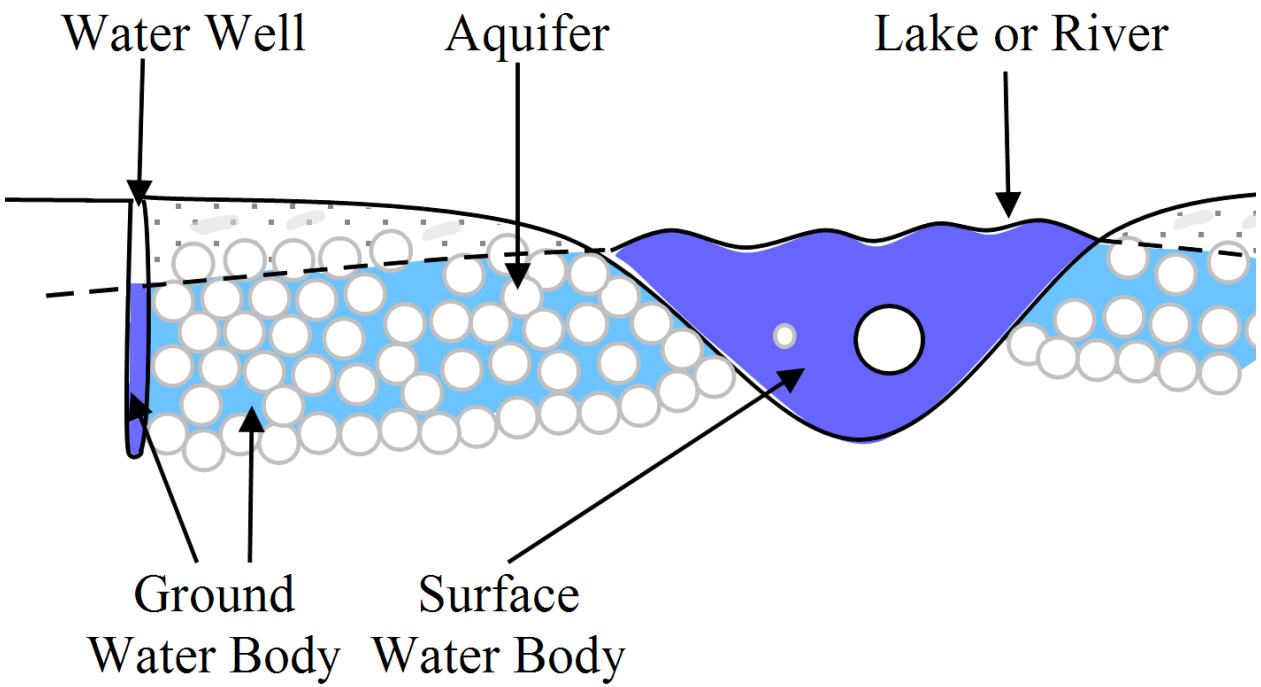
Outline

1. The Essence
   - What, Why, and How?
   - A Flavour of The Result
2. The Ingredients
3. Our Contributions
4. Some Concluding Remarks

The Essence

Objective

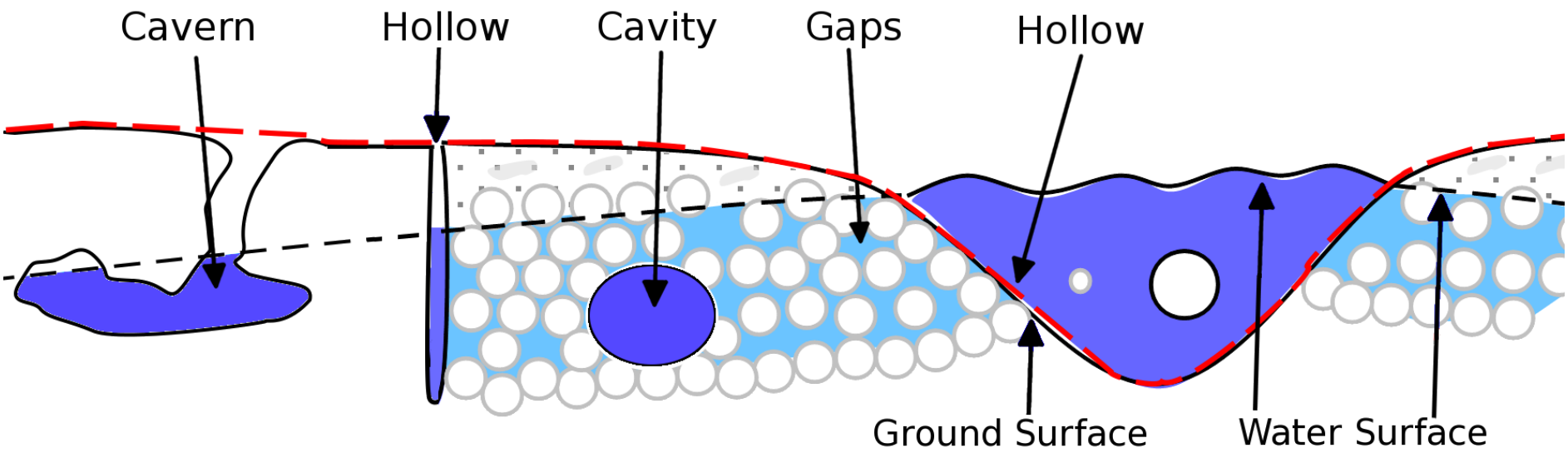
- Develop a rigorous formalization for hydro entities such as:
  - water bodies (surface and subsurface) and
  - spaces containing water bodies
- as they occur in hydrogeology and hydrology, and
- extend the DOLCE ontology with hydro entities.



General Idea

Define Water Bodies by their Containers' Physical Voids

- Lake or River WB: in a hollow of the ground surface
- Water Well WB: in a hollow below the ground surface
- Aquifer WB: in gaps in the rock matter and in holes below the ground surface



Motivation

Existing Groundwater Data Standards, such as

- INSPIRE (Infrastructure for Spatial Information in Europe) Data Specification for Geology and
- Groundwater Markup Language (GWML),

. . . Have Various Ontological Issues, such as

- Semantic ambiguity
  - INSPIRE/GWML GroundwaterBody: not clear if one is an object and the other a changing amount of matter
- Semantic incompleteness
  - Aquifer is a RockBody in INSPIRE/GWML, but not modeled with voids
- Semantic granularity: no differentiation of voids
- Groundwater and surface water schemas largely disconnected

Approach

Engineering Effort that Brings Together Elements of Spatial Ontology

- DOLCE (Masolo et al., 2003) as upper ontology providing a coarse classification of physical endurants into physical objects, features, and matter
- Layered Mereotopology (Donnelly, 2003) for grounding physical endurants in abstract space
- Multidimensional Mereotopology (Hahmann & Gruninger, 2011) as qualitative axiomatization of abstract space
- Classifying Holes (Casati & Varzi, 1994)
- Axiomatization of Convex Hulls (Cohn et al., 1997)

Contributions

General Contributions:

- Adapts spatial ontology elements to work together (engineering)
- Demonstrates the potential of state-of-the-art spatial ontologies

Specific Contributions:

- Extends the classification of holes to voids
- Distinguishes microscopic from macroscopic voids
- Refines the DOLCE category 'feature' and adds hydrogeology domain entities

Example

A WaterBody may only be constituted by water if it has constituents:

$$WB(x) \rightarrow NAPO(x) \wedge \forall y[DK_1(y,x) \rightarrow Water(y)]$$

A RockBody is constituted by rock matter and only by rock matter:

$$RB(x) \equiv NAPO(x) \wedge \exists y[DK_1(y,x)] \wedge \forall y[DK_1(y,x) \rightarrow RockMatter(y)]$$

GS denotes a ground surface (not fully defined):

$$GS(gs) \rightarrow RPF(gs) \wedge \exists o[NAPO(o) \wedge hosts(o,gs)]$$

$WB, RB, GS, Water, RockMatter$ ..... Domain theory (Hydrogeology)

$NAPO, RPF, DK_1, hosts$ ..... DOLCE concepts/relations

Example (contd.)

Surface- vs. Ground-WaterBody:

$$\mathit{SurfaceWB}(wb) \rightarrow \mathit{WB}(wb) \wedge \exists gs[\mathbf{hol_e}(wb, gs) \wedge \mathit{GS}(gs)]$$

$$\mathit{GroundWB}(wb) \rightarrow \mathit{WB}(wb) \wedge \exists rb, gs\big[\mathit{RB}(rb) \wedge \mathit{hosts}(rb, gs) \wedge \mathit{GS}(gs) \wedge r(wb) \subseteq \mathbf{voidspace}(rb) \wedge \forall v[\mathbf{hol_e}(rb, v) \rightarrow \neg \mathit{PO}(wb, v)]\big]$$

A HydroRockBody consists of a RockBody and a GroundWaterBody with the GroundWaterBody located in Voids of the RockBody:

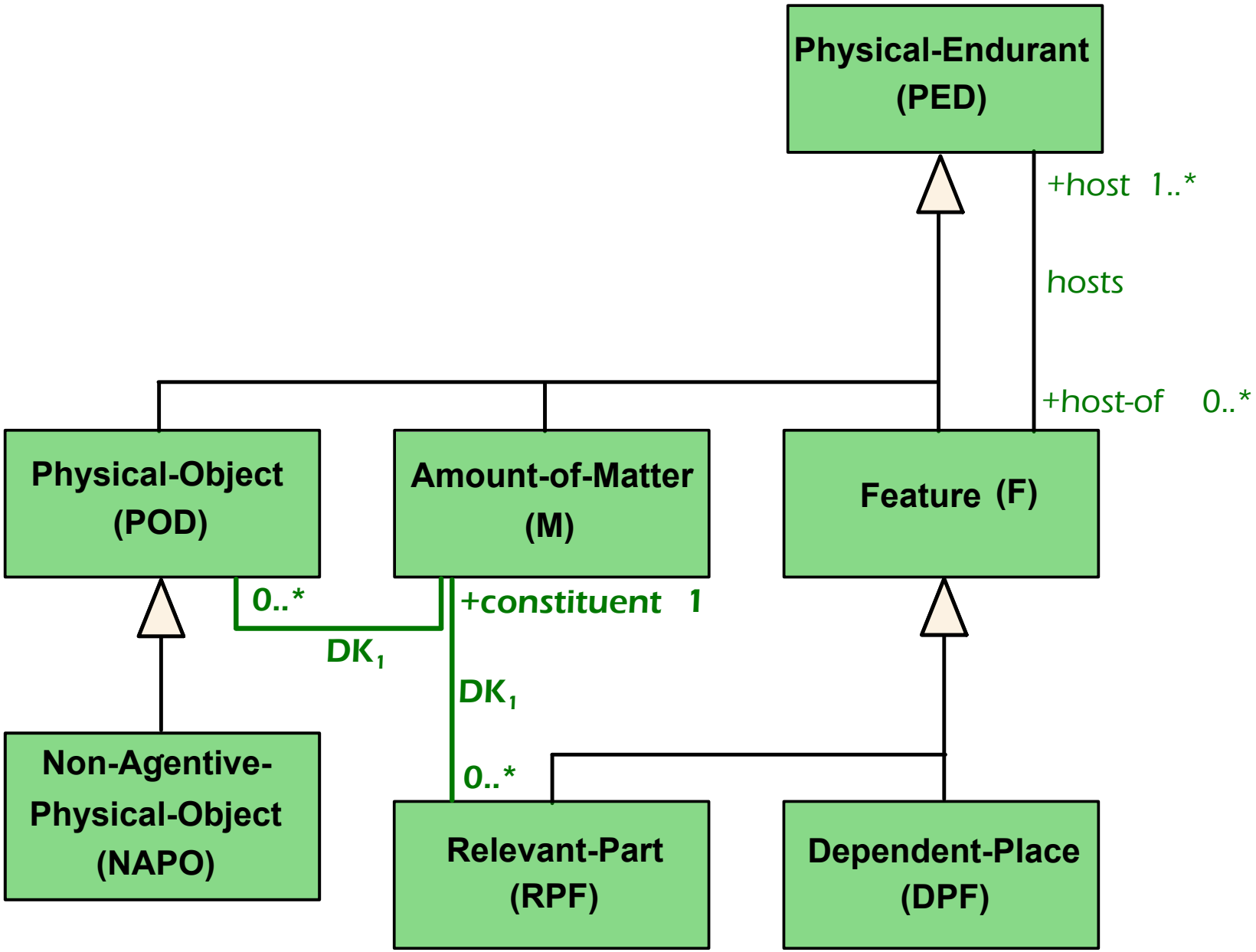
$$\mathit{HydroRockBody}(aq) \rightarrow \mathit{NAPO}(aq) \wedge \exists rb, wb\big[r(aq) = r(rb) + r(wb) \wedge \mathit{RB}(rb) \wedge \mathit{GroundWB}(wb) \wedge r(wb) \subseteq \mathbf{con\text{-}voidspace}(rb)\big]$$

A Reservoir is the voidspace of some RockBody:

$$\mathit{Reservoir}(wr) \equiv \mathbf{V}(wr) \wedge \exists rb[\mathit{RB}(rb) \wedge r(wr) = \mathbf{voidspace}(rb)]$$

The Ingredients

DOLCE: Classification of Physical Endurants



Grounding Physical Space in Abstract Space

Region function $r(x) = y$ to relate a physical endurant x to the spatial region y it occupies (called 'Layered Mereotopology' in Donnelly, 2003)

- Physical Space
  - Small number of identifiable physical endurants of interest
  - Identity criteria is important, cf. (Bennett, 2002)
  - May be physical objects (with matter); could also be virtual objects (with a certain shared property)
- Abstract Space
  - Mathematical abstraction: points, lines, curves, line and curve segments, 2D regions (curved or flat), volumes, etc.
  - Many spatial entities with no counterpart in physical space

Multidimensional Mereotopology

Theory of abstract space that generalizes traditional mereotopology (only regions of a single dimension) to a setting in which points, curves, areas, bodies, etc. can coexist (Hahmann & Gruninger 2011)

- Primitive 1: Spatial containment $r(x) \subseteq r(y)$
- Primitive 2: Relative dimension $x \leq_{\dim} y$
- Primitive 3: Empty region $ZEX(x)$

Defined functions and relations:

- Functions: intersection $(\cdot)$, difference $(-)$, sum $(+)$, universal (S_{u})
- Function: relative complement $(')$ for regions of maximal dimension
- Relations: Next-lowest dimension $(\prec_{\dim})$, Contact (C), Part (P), Proper Part (PP), Overlap (PO), ...

Can express, e.g., that physical endurants occupy regions of maximal dimension and can capture abstract boundaries of next-lowest dimension

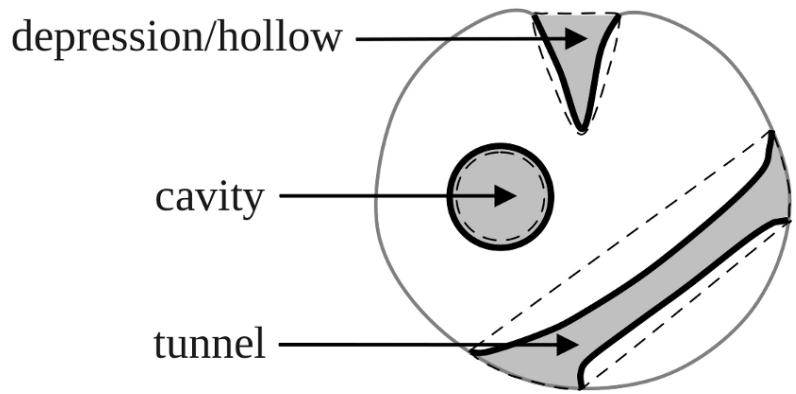
Holes (Casati & Varzi "Holes and Other Superficialities", 1994)

- A Hole must be hosted by a host that is not a Hole
- Dependent on the existence of concavities: a Hole occupies a region in the convex hull of its host that is not occupied by the host itself, i.e.,

$$ch(x) \subsetneq r(x) \text{ and } r(y) \subseteq ch(x) - r(x)$$

  - Convex hull operation *ch* plays a key role; (Cohn et al., 1997) provide the most complete axiomatization to date

- Basic classification: hollows, depressions, tunnels, cavities



- Holes and their hosts are self-connected pieces

Our Contributions

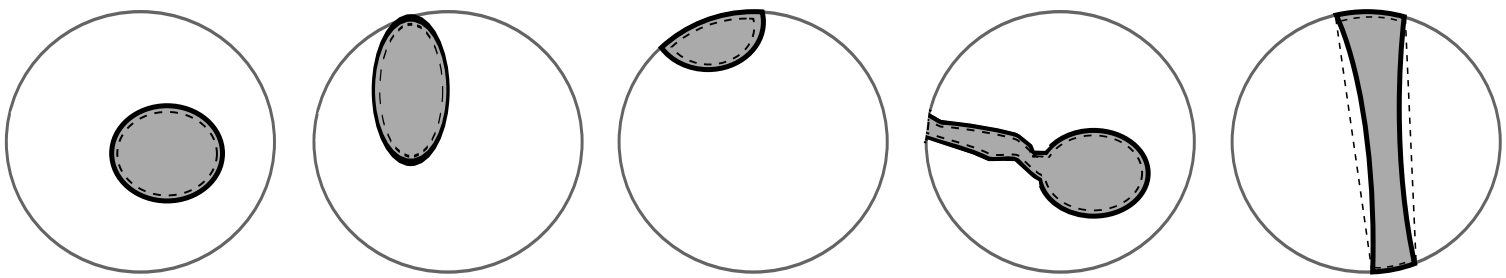
Generalizing to Voids: Holes vs. Gaps

- Void: physical space in the host's convex hull not overlapping the host
- Classifying physical voids based on the host's self-connectedness

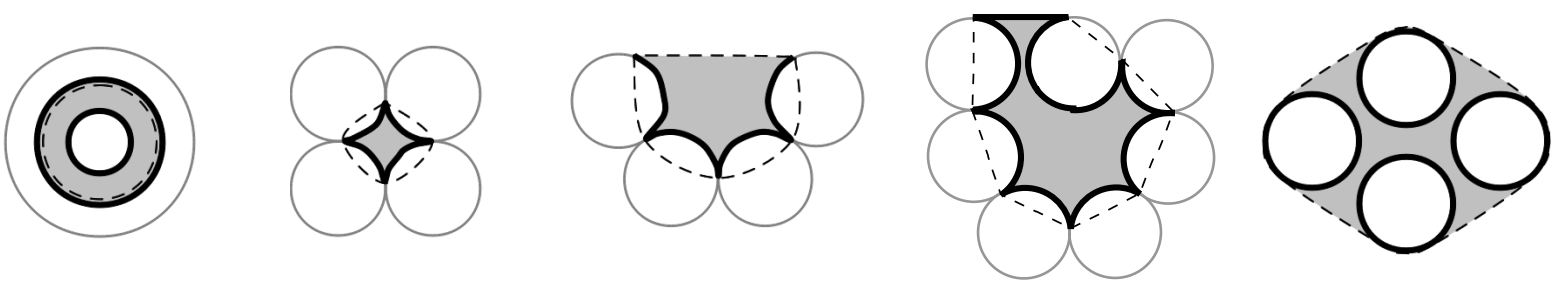
$C_{\mathrm{S}}(x, y) \equiv C(x, y) \wedge x =_{\dim} y \wedge r(x) \cdot r(y) \prec_{\dim} x$ (strongly connected)

$ICon(x) \equiv \forall y[PP(y, x) \rightarrow C_{\mathrm{S}}(y, r(x) - r(y))]$ (interior-connectedness)

- **Hole**: the host is interior self-connected ($ICon$)



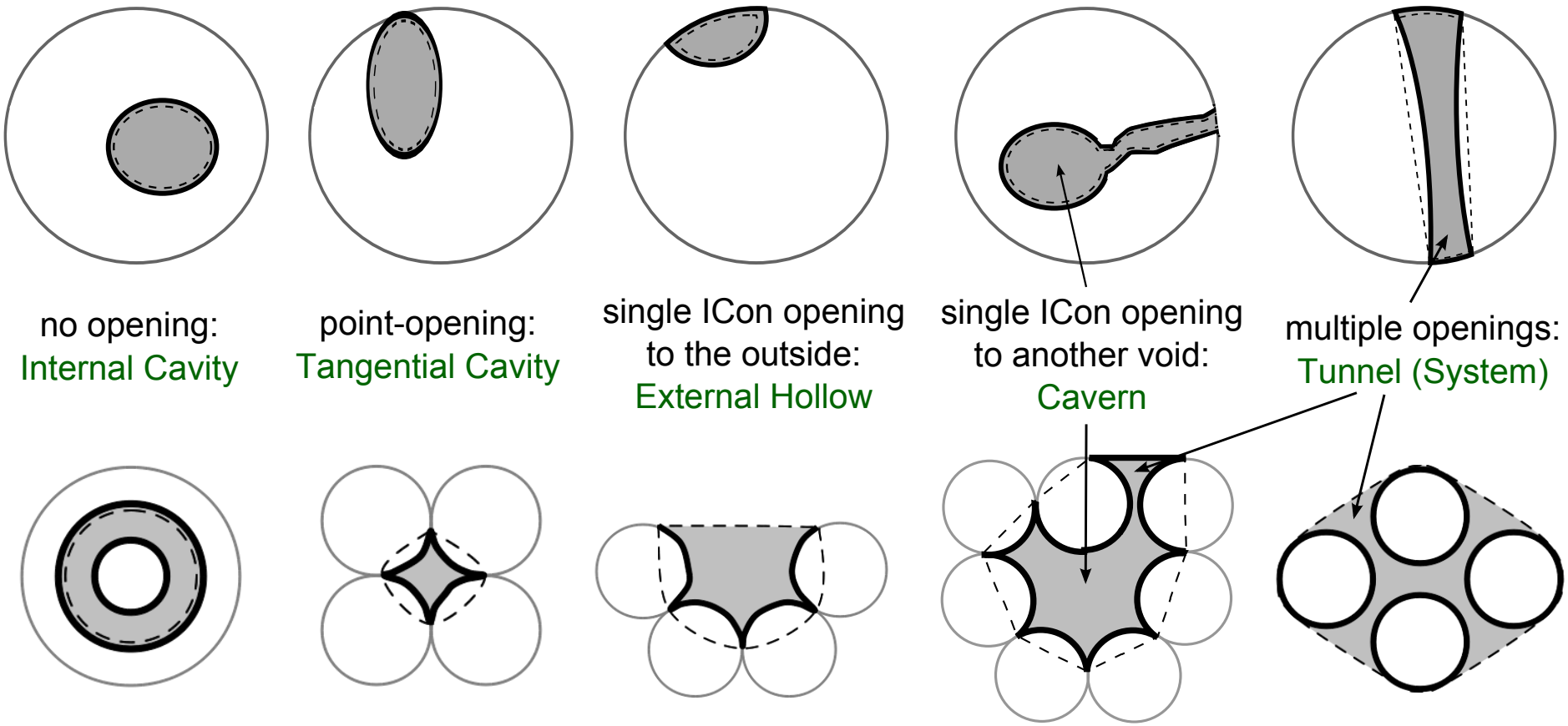
- **Gap**: the host is not interior self-connected ($\neg ICon$)



Generalizing to Voids: Cavities vs. Hollows vs. Tunnels

Classifying physical voids based on their opening

- Works equally for holes and gaps
- Opening to the outside or to other voids



Macroscopic vs. Microscopic Voids

Assumption: an object's matter *may* occupy only a **subregion** of the object's region (departure from DOLCE axiomatization)

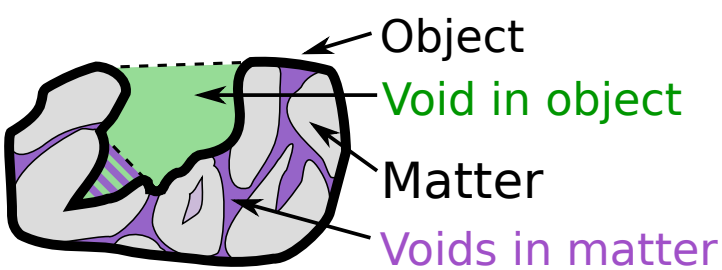
$\Rightarrow$ there may be holes in the matter of a solid object

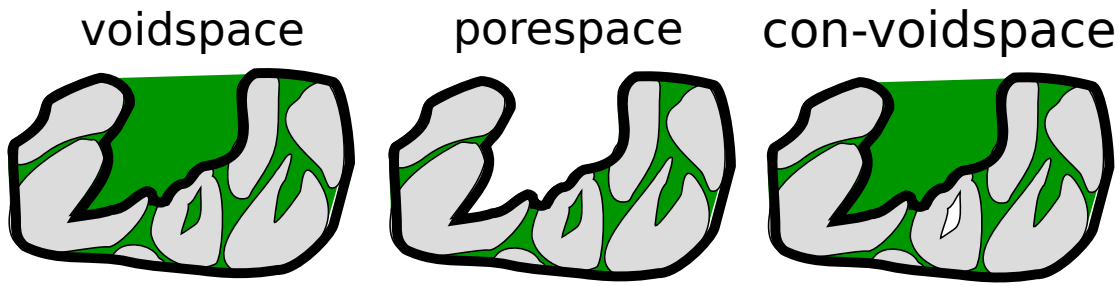
Macroscopic Void: a void in the object

Microscopic Void: a void in the matter that is not a void in the object

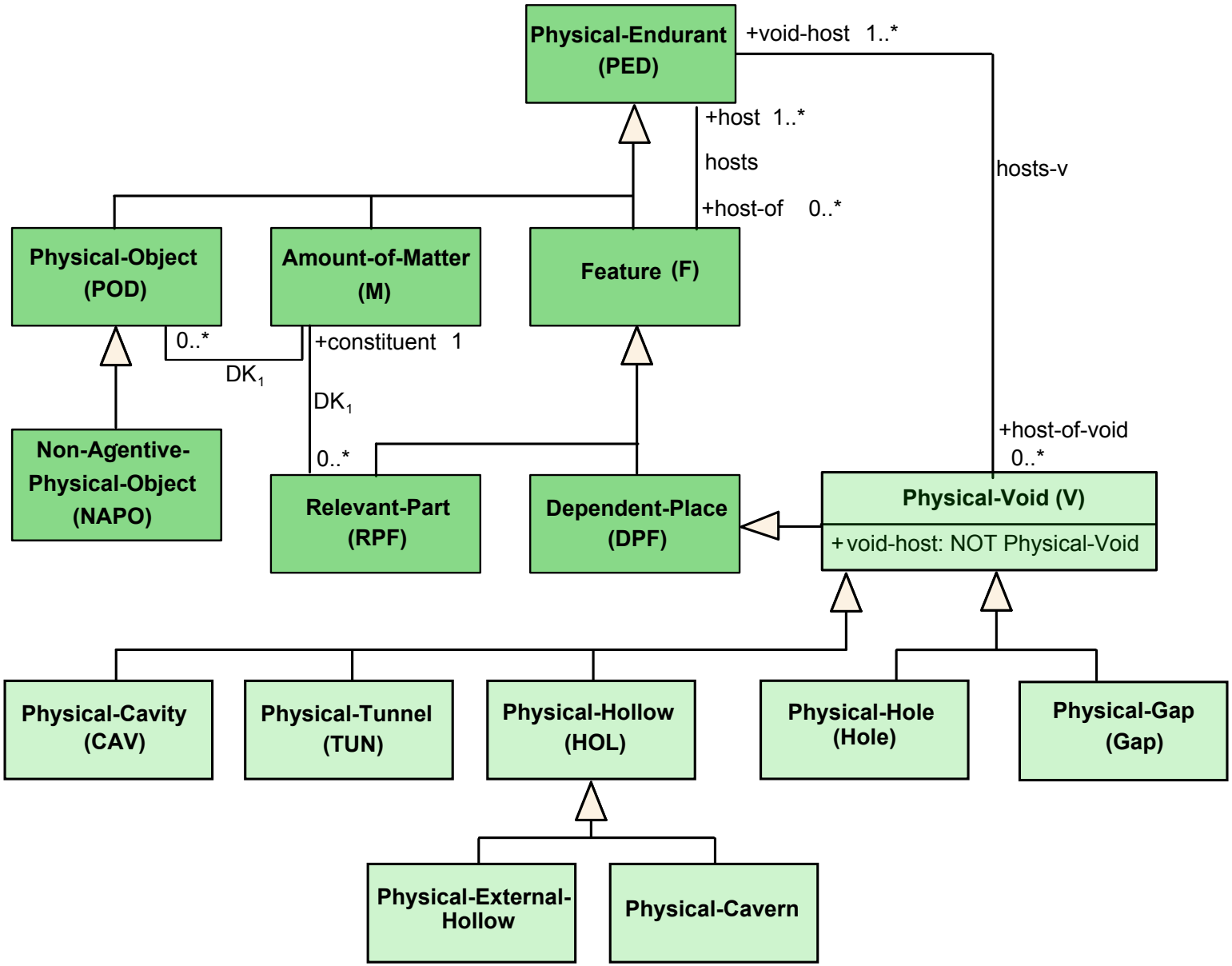
Definable concepts:

- Voidspace of an object: all voids (micro- and macroscopic)
- Porespace of an object: voidspace not occupied by macroscopic voids
- Connected Voidspace: voidspace connected to the outside





Refining DOLCE: Physical Voids



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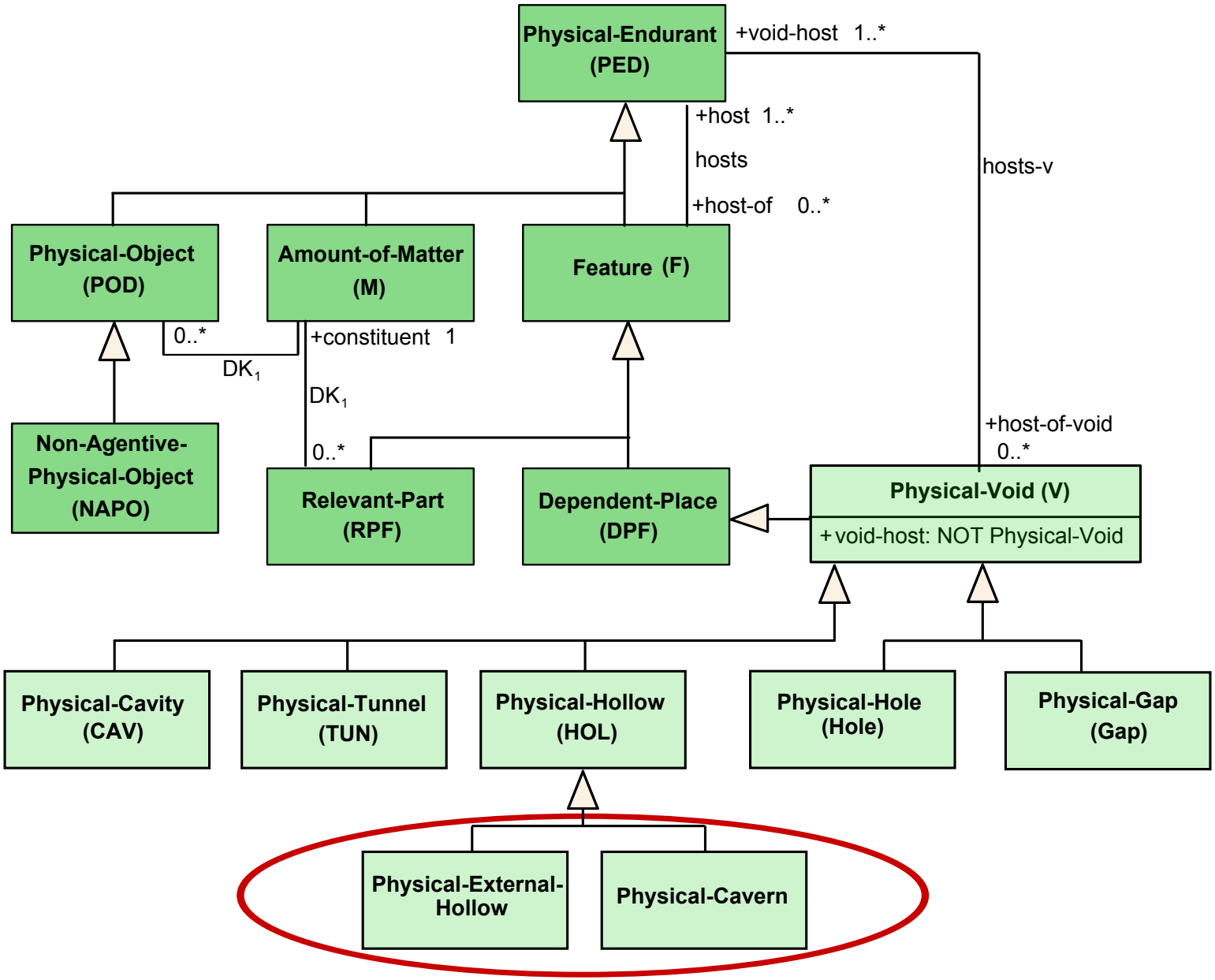
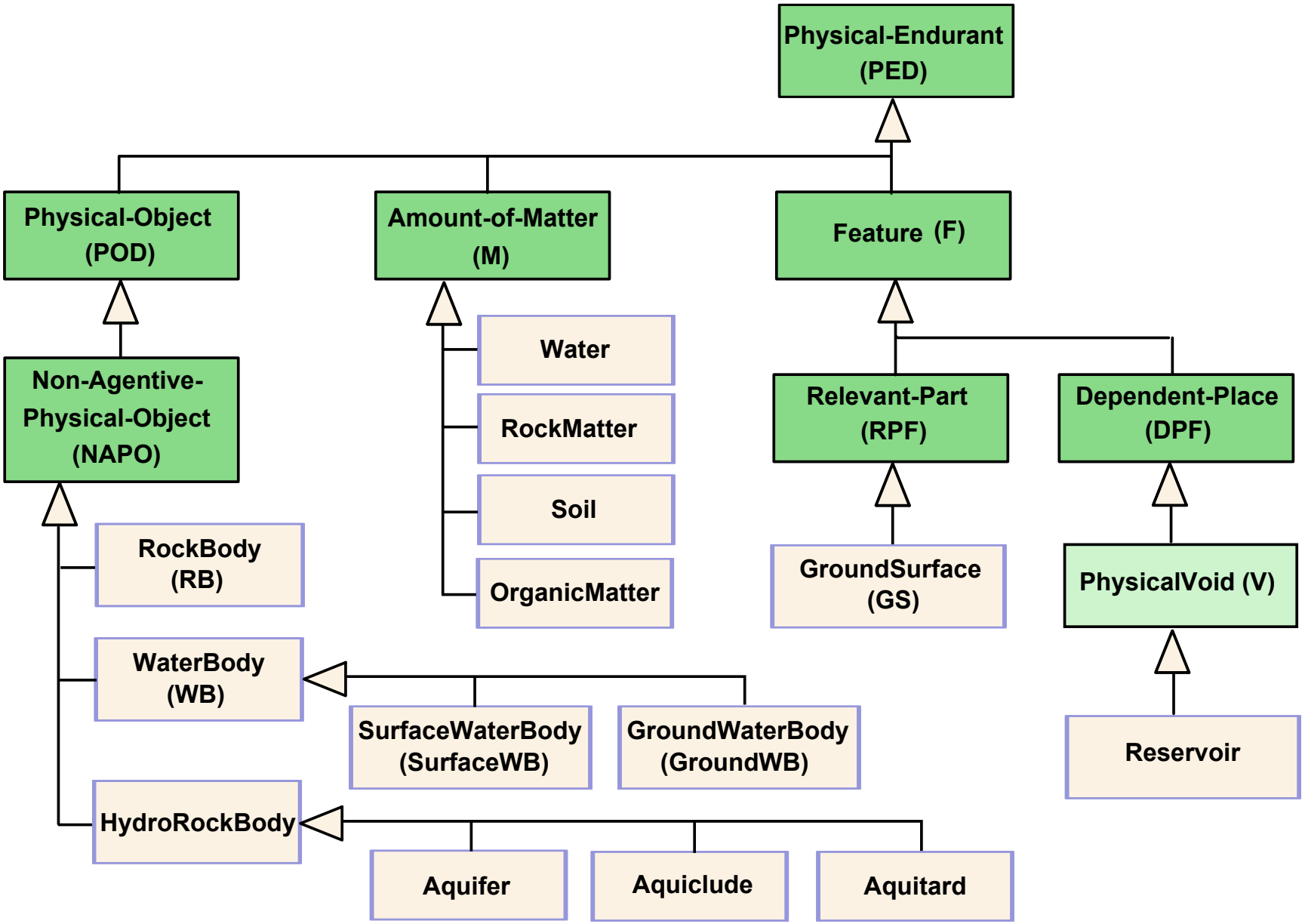


Refining DOLCE: Physical Endurants from Hydrogeology



Concluding Remarks

- Limitations: A coarse delineation of water bodies into surface and subsurface water bodies, but no finer specialization yet:
  - E.g. Lake and River are not defined, and cannot model differences between Aquifer, Aquitard, and Aquiclude defined by degree of permeability (water flow capability)
- Many Open Questions:
  - Is a Lake, River, or Well a WaterBody, Container, or Void?
  - Identifying relevant voids (e.g. caverns, tunnels)
  - Extending caverns ('interior void' with openings only to other voids)
  - How to best define the 'GroundSurface'?
- Future Work: Classification of containment and constitution relations between voids and physical objects (or matter)
- **Many thanks to the reviewers, especially to the first reviewer, for the detailed and extremely useful remarks.**