

Ontologies in Quantum

Modeling Relationships That Are Resilient and Fast

Version 1.2.2-SNAPSHOT, 2025-10-29T14:03:58Z

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Chapter 1. Ontologies in Quantum: Modeling Relationships That Are Resilient and Fast



Looking for the short implementation plan? See [PROPOSAL.md](#) at the repository root for a concise module-by-module checklist.

This section explains what an ontology is, how it differs from a traditional object model, and how the Quantum Ontology modules make it practical to apply ontology ideas to your domain models and queries. It also contrasts ontology-driven relationships with direct object references (for example, using `@Reference` or `EntityReference`).

1.1. What is an Ontology?

In software terms, an ontology is a formal, explicit specification of concepts and their relationships.

- **Concepts (Classes):** Named categories/types in your domain. Concepts can form taxonomies (is-a hierarchies), be declared disjoint, or be equivalent.
- **Relationships (Properties):** Named relationships between entities. Properties can have a domain (applies to X) and a range (points to Y). They may be inverse or transitive.
- **Axioms (Rules):** Constraints and entailment rules, including property chains such as: if (A \rightarrow p \rightarrow B) and (B \rightarrow q \rightarrow C) then we infer (A \rightarrow r \rightarrow C).
- **Inference:** The process of deriving new facts (types, labels, edges) that were not explicitly stored but follow from axioms and known facts.

An ontology is not the data; it is the schema plus logic that gives your data additional meaning and enables consistent, automated inferences.

1.2. Ontology vs. Object Model

A conventional object model focuses on concrete classes, fields, and direct references between objects at implementation time. An ontology focuses on semantic types and relationships, with explicit rules that can derive new knowledge independent of how objects are instantiated.

Key differences:

- **Purpose** - Object model: Encapsulate data and behavior for application code generation and persistence. - Ontology: Encode shared meaning, constraints, and inference rules that remain stable as implementation details change.
- **Relationship handling** - Object model: Typically uses direct references or foreign keys; traversals are hard-coded and fragile to change. - Ontology: Uses named predicates (properties) and can infer additional relationships by rules (property chains, inverses, transitivity).
- **Polymorphism and evolution** - Object model: Polymorphism requires class inheritance in code; cross-cutting categories are awkward to add later. - Ontology: Entities can have multiple types/labels at once. New concepts and properties can be introduced without breaking existing data.
- **Querying** - Object model: Queries couple to concrete classes and field paths; changes force query rewrites. - Ontology: Queries target semantic relationships; reasoners can materialize edges that queries reuse, decoupling queries from implementation details.

1.3. Why prefer Ontology-driven relationships over @Reference/EntityReference

Direct references (@Reference or custom EntityReference) are simple to start but become restrictive as domains grow: - Tight coupling: Code and queries couple to concrete field paths (customer.primaryAddress.id), making refactors risky. - Limited expressivity: Hard to encode and reuse higher-order relationships (e.g., "partners of my supplier's parent org"). - Poor polymorphism: References point to one collection/type; accommodating multiple target types requires extra code. - Performance pitfalls: Deep traversals cause extra queries, N+1 selects, or complex \$lookup joins.

Ontology-driven edges address these issues: - Decoupling via predicates: Use named predicates (e.g., hasAddress, memberOf, supplies) that remain stable while internal object fields change. - Inference for reachability: Property chains can materialize implied links ($A \xrightarrow{-p} B \ \& \ B \xrightarrow{-q} C \Rightarrow A \xrightarrow{-r} C$), avoiding runtime multi-hop traversals. - Polymorphism-first: A predicate can connect heterogeneous types; type inferences (domain/range) remain consistent. - Query performance: Pre-materialized edges allow single-hop, index-friendly queries (in or eq filters) instead of ad-hoc multi-collection traversals. - Resilience to change: You can add or modify rules without rewriting data structures or touching referencing fields across models.

1.4. How Quantum supports Ontologies

Quantum provides three cooperating modules that make ontology modeling practical and fast:

- quantum-ontology-core (package com.e2eq.ontology.core)
- OntologyRegistry: Holds the TBox (terminology) of your ontology.
- ClassDef: Concept names and relationships (parents, disjointWith, sameAs).
- PropertyDef: Property names with optional domain, range, inverse flags, and transitivity.
- PropertyChainDef: Rules that define multi-hop implications (chains \rightarrow implied property).
- TBox: Container for classes, properties, and property chains.
- Reasoner interface and ForwardChainingReasoner: Given an entity snapshot and the registry, computes inferences:
- New types/labels to assert on entities.
- New edges to add (implied by property chains, inverses, or other rules).
- quantum-ontology-mongo (package com.e2eq.ontology.mongo)
- EdgeDao: A thin DAO around an edges collection in Mongo. Each edge contains tenantId, src, predicate p, dst, inferred flag, provenance, and timestamp.
- OntologyMaterializer: Runs the Reasoner for an entity snapshot and upserts the inferred edges, so queries can be rewritten to simple in/in eq filters.
- quantum-ontology-policy-bridge (package com.e2eq.ontology.policy)
- ListQueryRewriter: Takes a base query and rewrites it using the EdgeDao to filter by the set of source entity ids that have a specific predicate to a given destination.
- This integrates ontology edges with RuleContext or policy decisions: policy asks for entities

related by a predicate; the rewriter converts that into an efficient Mongo query.

These modules let you define your ontology (core), materialize derived relations (mongo), and leverage them in access and list queries (policy bridge).



In Quarkus, all ontology components are CDI-managed. Inject `EdgeDao` and services via `@Inject`; indexes are ensured automatically at startup by `OntologyMongoProducers`. Configure collection/database with properties `ontology.mongo.database` and `ontology.mongo.collection.edges`.

1.5. Modeling guidance: from object fields to predicates

- Name relationships explicitly
- Define clear predicate names (`hasAddress`, `memberOf`, `supplies`, `owns`, `assignedTo`). Avoid encoding relationship semantics in field names only.
- Keep object model minimal and flexible
- Store lightweight identifiers (ids) as needed, but avoid deeply nested reference graphs that encode traversals in code.
- Model polymorphic relationships
- Prefer predicates that naturally connect multiple possible types (e.g., `assignedTo` can target `User`, `Team`, `Bot`) and rely on ontology type assertions to constrain where needed.
- Use property chains for common paths
- If business logic often traverses $A \rightarrow B \rightarrow C$, define a chain $p \sqcap q \Rightarrow r$ and materialize r for faster queries and simpler policies.
- Capture inverses and transitivity
- For natural inverses (`parentOf` \sqcap `childOf`) or transitive relations (`partOf`, `locatedIn`), define them in the ontology so edges and queries stay consistent.
- Keep provenance
- Record why an edge exists (`prov.rule`, `prov.inputs`) so you can recompute, audit, or retract when inputs change.

1.6. Querying with ontology edges vs direct references

- Direct reference example (fragile/slow)
- Query: "Find Orders whose buyer belongs to Org X or its parents."
- With `@Reference`: requires joining `Order` \rightarrow `User` \rightarrow `Org` and recursing `org.parent`; costly and tightly coupled to fields.
- Ontology edge example (resilient/fast)
- Define predicates: `placedBy(order, user)`, `memberOf(user, org)`, `ancestorOf(org, org)`. Define chain `placedBy` \sqcap `memberOf` \Rightarrow `placedInOrg`.

- Materialize edges: (order --placedInOrg→ org). Also make ancestorOf transitive.
- Query becomes: where order._id in EdgeDao.srcIdsByDst(tenantId, "placedInOrg", orgX).
- With transitivity, you can precompute ancestor closure or add a chain placedInOrg □ ancestorOf ⇒ placedInOrg to include parents automatically.

1.7. Migration: from @Reference to ontology edges

- Start by introducing predicates alongside existing references; do not remove references immediately.
- Materialize edges for hot read paths; keep provenance so you can reconstruct.
- Gradually update queries (list screens, policy filters) to use ListQueryRewriter with EdgeDao instead of deep traversals or \$lookup.
- Once stable, you can simplify models by removing rigid reference fields where unnecessary and rely on edges for read-side composition.

1.8. Performance and operational notes

- Indexing: Create compound indexes on edges: (tenantId, p, dst) and (tenantId, src, p) to support both reverse and forward lookups.
- Write amplification vs read wins: Materialization adds write work, but dramatically improves read latency and simplifies queries.
- Consistency: Re-materialize edges on relevant entity changes (source, destination, or intermediate) using OntologyMaterializer.
- Multi-tenancy: Keep tenantId in the edge key and filters; the provided EdgeDao methods include tenant scoping.

1.9. How this integrates with Functional Areas/Domains

- Functional domains often map to concept clusters in the ontology. Use @FunctionalMapping to aid discovery and apply policies per area/domain.
- Policies can refer to relationships semantically ("hasEdge placedInOrg OrgX") and rely on the policy bridge to turn this into efficient data filters.

1.10. Summary

- Ontology-powered relationships provide a stable, semantic layer over your object model.
- The Quantum Ontology modules let you define, infer, and query these relationships efficiently on MongoDB.
- Compared with direct @Reference/EntityReference, ontology edges are more expressive, resilient to change, and typically faster for complex list/policy queries once materialized.

Chapter 2. Concrete example: Sales Orders, Shipments, and evolving to Fulfillment/Returns

This example shows how to use an ontology to model relationships around Orders, Customers, and Shipments, and how the model can evolve to include Fulfillment and Returns without breaking existing queries. We will:

- Define core concepts and predicates.
- Add property chains that materialize implied relationships for fast queries.
- Show how queries are rewritten using edges instead of deep object traversals.
- Evolve the model to support Fulfillment and Returns with minimal changes.

Core concepts (classes)

- Order, Customer, Organization, Shipment, Address, Region
- Later evolution: FulfillmentTask, FulfillmentUnit, ReturnRequest, ReturnItem, RMA

Key predicates (relationships)

- `placedBy(order, customer)`: who placed the order
- `memberOf(customer, org)`: a customer belongs to an organization (or account)
- `orderHasShipment(order, shipment)`: outbound shipment for the order
- `shipsTo(shipment, address)`: shipment destination
- `locatedIn(address, region)`: address is located in a Region
- `ancestorOf(org, org)`: organizational ancestry (transitive)

Property chains (implied relationships)

- `placedBy` \square `memberOf` \Rightarrow `placedInOrg`
- If `(order --placedBy-> customer)` and `(customer --memberOf-> org)`, then infer `(order --placedInOrg-> org)`
- `orderHasShipment` \square `shipsTo` \Rightarrow `orderShipsTo`
- If `(order --orderHasShipment-> shipment)` and `(shipment --shipsTo-> address)`, infer `(order --orderShipsTo-> address)`
- `orderShipsTo` \square `locatedIn` \Rightarrow `orderShipsToRegion`
- If `(order --orderShipsTo-> address)` and `(address --locatedIn-> region)`, infer `(order --orderShipsToRegion-> region)`
- `placedInOrg` \square `ancestorOf` \Rightarrow `placedInOrg`
- Makes `placedInOrg` resilient to org hierarchy changes (`ancestorOf` is transitive). This is a common “closure” trick: re-assert the same predicate via chain to absorb hierarchy.

A minimal Java-style snippet to define this TBox

```
import java.util.*;
import com.e2eq.ontology.core.OntologyRegistry;
import com.e2eq.ontology.core.OntologyRegistry.*;

Map<String, ClassDef> classes = Map.of(
    "Order", new ClassDef("Order", Set.of(), Set.of(), Set.of()),
    "Customer", new ClassDef("Customer", Set.of(), Set.of(), Set.of()),
    "Organization", new ClassDef("Organization", Set.of(), Set.of(), Set.of()),
    "Shipment", new ClassDef("Shipment", Set.of(), Set.of(), Set.of()),
    "Address", new ClassDef("Address", Set.of(), Set.of(), Set.of()),
    "Region", new ClassDef("Region", Set.of(), Set.of(), Set.of())
);

Map<String, PropertyDef> props = Map.of(
    "placedBy", new PropertyDef("placedBy", Optional.of("Order"), Optional.of("Customer"), false, Optional.empty(), false),
    "memberOf", new PropertyDef("memberOf", Optional.of("Customer"), Optional.of("Organization"), false, Optional.empty(), false),
    "orderHasShipment", new PropertyDef("orderHasShipment", Optional.of("Order"), Optional.of("Shipment"), false, Optional.empty(), false),
    "shipsTo", new PropertyDef("shipsTo", Optional.of("Shipment"), Optional.of("Address"), false, Optional.empty(), false),
    "locatedIn", new PropertyDef("locatedIn", Optional.of("Address"), Optional.of("Region"), false, Optional.empty(), false),
    "ancestorOf", new PropertyDef("ancestorOf", Optional.of("Organization"), Optional.of("Organization"), false, Optional.empty(), true), // transitive
    // implied predicates (no domain/range required, but you may add them for validation)
    "placedInOrg", new PropertyDef("placedInOrg", Optional.of("Order"), Optional.of("Organization"), false, Optional.empty(), false),
    "orderShipsTo", new PropertyDef("orderShipsTo", Optional.of("Order"), Optional.of("Address"), false, Optional.empty(), false),
    "orderShipsToRegion", new PropertyDef("orderShipsToRegion", Optional.of("Order"), Optional.of("Region"), false, Optional.empty(), false)
);

List<PropertyChainDef> chains = List.of(
    new PropertyChainDef(List.of("placedBy", "memberOf"), "placedInOrg"),
    new PropertyChainDef(List.of("orderHasShipment", "shipsTo"), "orderShipsTo"),
    new PropertyChainDef(List.of("orderShipsTo", "locatedIn"), "orderShipsToRegion"),
    new PropertyChainDef(List.of("placedInOrg", "ancestorOf"), "placedInOrg")
);

OntologyRegistry.TBox tbox = new OntologyRegistry.TBox(classes, props, chains);
OntologyRegistry registry = OntologyRegistry.inMemory(tbox);
```

Materializing edges for an Order

- Explicit facts for order O1:
- O1 placedBy C9
- C9 memberOf OrgA
- O1 orderHasShipment S17
- S17 shipsTo Addr42
- Addr42 locatedIn RegionWest
- OrgA ancestorOf OrgParent
- Inferred edges after running the reasoner for O1's snapshot:
- O1 placedInOrg OrgA
- O1 placedInOrg OrgParent (via closure with ancestorOf)
- O1 orderShipsTo Addr42
- O1 orderShipsToRegion RegionWest

How queries become simple and fast

- List Orders for Organization OrgParent (including children):
- Instead of joining Order → Customer → Org and recursing org.parent, run a single filter using materialized edges.

```
import com.mongodb.client.model.Filters;
import org.bson.conversions.Bson;
import com.e2eq.ontology.policy.ListQueryRewriter;

Bson base = Filters.eq("status", "OPEN");
Bson rewritten = rewriter.rewriteForHasEdge(base, tenantId, "placedInOrg", "OrgParent");
// Use rewritten in your Mongo find
```

- List Orders shipping to RegionWest:

```
Bson rewritten2 = rewriter.rewriteForHasEdge(Filters.empty(), tenantId,
"orderShipsToRegion", "RegionWest");
```

Why this is resilient

- If tomorrow Customer becomes AccountContact and the organization model gains Divisions and multi-parent org graphs, you only adjust predicates and chains.
- Queries that rely on placedInOrg or orderShipsToRegion remain unchanged and fast, because edges are re-materialized by OntologyMaterializer.

Evolving the model: add Fulfillment

New concepts

- FulfillmentTask: a unit of work to pick/pack/ship order lines
- FulfillmentUnit: a logical grouping (e.g., wave, tote, parcel)

New predicates

- fulfills(task, order)
- realizedBy(order, fulfillmentUnit)
- taskProduces(task, shipment)

New chains (implied)

- fulfills \Rightarrow derived edge from task to order; combine with taskProduces to connect order to shipment without touching Order fields:
- fulfills \square taskProduces \Rightarrow orderHasShipment
- realizedBy \square orderHasShipment \Rightarrow fulfilledByUnit
- If (order --realizedBy- \rightarrow fu) and (order --orderHasShipment- \rightarrow s) \Rightarrow (fu --fulfillsShipment- \rightarrow s) or simply (order --fulfilledByUnit- \rightarrow fu)

These chains let you introduce warehouse concepts without changing how UI filters orders by organization or ship-to region. Existing queries still operate via placedInOrg and orderShipsToRegion.

Evolving further: add Returns

New concepts

- ReturnRequest, ReturnItem, RMA

New predicates

- hasReturn(order, returnRequest)
- returnFor(returnItem, order)
- returnRma(returnRequest, rma)

New chains (implied)

- hasReturn \Rightarrow openReturnOnOrg via placedInOrg:
- hasReturn \square placedInOrg \Rightarrow returnPlacedInOrg
- returnFor \square orderShipsToRegion \Rightarrow returnShipsToRegion

Example queries with new capabilities

- List Orders with open returns in OrgParent:

```
Bson r = rewriter.rewriteForHasEdge(Filters.empty(), tenantId, "returnPlacedInOrg",
"OrgParent");
```

- List Returns associated to Orders shipping to RegionWest:

```
Bson r2 = rewriter.rewriteForHasEdge(Filters.empty(), tenantId, "returnShipsToRegion",  
"RegionWest");
```

Comparison with direct references (@Reference/EntityReference)

- With direct references you would encode fields like Order.customer, Order.shipments, Shipment.address, Address.region and then implement multi-hop traversals in code or \$lookup pipelines, rewriting them whenever you add Fulfillment or Returns.
- With ontology edges, you keep predicates stable and add property chains. Existing list and policy queries keep working and typically become faster due to single-hop filters on an indexed edges collection.

Operational tips for this scenario

- Ensure EdgeDao has indexes on (tenantId, p, dst) and (tenantId, src, p).
- Use OntologyMaterializer when Order, Shipment, Customer, Address, or org hierarchy changes to keep edges fresh.
- Keep provenance in edge.prov (rule, inputs) so you can recompute or retract edges when source data changes.

Chapter 3. Integrating Ontology with Morphia, Permissions, and Multi-tenancy

This section focuses on integration and developer experience: how ontology edges flow into Morphia-based repositories and the permission rule language, while remaining fully multi-tenant and secure.

3.1. Big picture: where ontology fits

- Write path (materialization):
- Your domain code persists entities with minimal direct references.
- An `OntologyMaterializer` runs when entities change to derive and upsert edges into the edges collection (per tenant).
- Policy path (authorization and list filters):
- The permission rule language evaluates the caller's `SecurityContext/RuleContext` and produces logical filters.
- When a rule asks for a semantic relationship (`hasEdge`), we use `ListQueryRewriter` + `EdgeDao` to translate that into efficient Mongo filters over ids.
- Read path (queries):
- Morphia repos apply the base data-domain filters and the rewritten ontology constraint to queries, producing fast lists without deep joins.

3.2. Rule language: add `hasEdge()`

We introduce a policy function/operator to reference ontology edges directly from rules:

- Signature: `hasEdge(predicate, dstIdOrVar)`
- predicate: String name of the ontology predicate (e.g., `"placedInOrg"`, `"orderShipsToRegion"`).
- dstIdOrVar: Either a concrete id/refName or a variable resolved from `RuleContext` (e.g., `principal.orgRefName`, `request.region`).
- Semantics: The rule grants/filters entities for which an edge (`tenantId`, `src = entity._id`, `p = predicate`, `dst = resolvedDst`) exists.
- Composition: `hasEdge` can be combined with existing rule clauses (and/or/not) and other filters (states, tags, `ownerId`, etc.).

Example rule snippets (illustrative):

- Allow viewing Orders in the caller's org (including ancestors via ontology closure):
- `allow VIEW Order when hasEdge("placedInOrg", principal.orgRefName)`
- Restrict list to Orders shipping to a region chosen in request:
- `allow LIST Order when hasEdge("orderShipsToRegion", request.region)`

Under the hood, policy evaluation uses `ListQueryRewriter.hasEdge(...)`, which converts `hasEdge` into a Morphia Filter limiting `_id` to the allowed source ids; compose it with your base filter via `Filters.and(...)`.

3.3. Passing tenantId correctly

- Always resolve `tenantId` from `RuleContext/SecurityContext` (the same source your repos use for realm/database selection).
- `EdgeDao` and `ListQueryRewriter` already accept `tenantId`; never cross tenant boundaries when reading edges.
- Index recommendation (per tenant):
 - `(tenantId, p, dst)`
 - `(tenantId, src, p)`

3.4. Morphia repository integration patterns

The goal is zero-friction usage in existing repos without invasive changes.

Option A: Apply ontology constraints in code paths that already construct BSON filters.

- If your repo method builds a Bson filter before calling `find()`, wrap it through `rewriter`:

```
Bson base = Filters.and(existingFilters...);
Bson rewritten = hasEdgeRequested
    ? rewriter.rewriteForHasEdge(base, tenantId, predicate, dst)
    : base;
var cursor = datastore.getDatabase().getCollection(coll).find(rewritten);
```

Option B: Apply ontology constraints to Morphia Filter/Query via ids.

- When the repo uses Morphia's typed query API instead of BSON, pre-compute the id set and constrain by `_id`:

```
Set<String> ids = edgeDao.srcIdsByDst(tenantId, predicate, dst);
if (ids.isEmpty()) {
    return List.of(); // short-circuit
}
query.filter(Filters.in("_id", ids));
```

Option C: Centralize in a tiny helper for developer ergonomics.

- Provide one helper in your application layer, invoked wherever policies inject additional constraints:

```
public final class OntologyFilterHelper {
```

```
private final ListQueryRewriter rewriter;
public OntologyFilterHelper(ListQueryRewriter r) { this.rewriter = r; }

public Bson ensureHasEdge(Bson base, String tenantId, String predicate, String dst)
{
    return rewriter.rewriteForHasEdge(base, tenantId, predicate, dst);
}
}
```

3.5. Where ontology materialization happens

- Automatic on write via repository hook:
- When you save or update an entity, the framework runs an internal PostPersistHook (OntologyWriteHook) that:
 - extracts explicit edges from fields/getters annotated with @OntologyProperty using a startup-built metadata cache (no per-call reflection), and
 - calls OntologyMaterializer to infer inverse, transitive, symmetric, and super-property edges and upsert them to the edges collection.
- This is enabled by default. To disable temporarily (e.g., for bulk loads), set: ontology.auto-materialize=false
- Intermediates and re-materialization:
 - If you change entities that are not the source but affect chains (e.g., Address.region, Customer.memberOf), those sources will get updated the next time they are saved. For immediate consistency across a tenant, run the re-materialization job (see below).
 - Provide nightly/backfill jobs for recomputing edges across a tenant when ontology rules evolve.

3.5.1. Configuration

```
# default is true
ontology.auto-materialize=true
```

3.5.2. Example: annotate and save — edges are materialized automatically

```
@OntologyClass(id = "Order")
public class Order {
    private String refName;

    @OntologyProperty(id = "placedBy", functional = true)
    public Customer getCustomer() { return customer; }
}

@OntologyClass(id = "Customer")
public class Customer {
```

```
private String refName;

@OntologyProperty(id = "memberOf")
public Organization getOrg() { return org; }
}
```

- Saving an Order will automatically create explicit placedBy and, via chains/inference, placedInOrg and inverse edges as defined in your ontology registry. No manual calls to `OntologyMaterializer.apply(...)` are required.

3.6. Security and multi-tenant considerations

- Edge rows include `tenantId` and should be validated/filtered by tenant on every operation.
- Never trust a client-supplied predicate or destination id blindly; combine with rule evaluation and whitelist allowed predicates per domain if needed.
- For shared resources across tenants (rare), model cross-tenant permissions at the policy layer; don't reuse edges across tenants unless explicitly designed.

3.7. Developer workflow and DX checklist

- When writing a rule: use `hasEdge("<predicate>", <rhs>)` and rely on `RuleContext` variables for the destination when possible.
- When writing a list endpoint: read optional ontology filter hints from the policy layer; if present, apply `ensureHasEdge(...)` before `find()`.
- When changing domain relationships: update predicates/chains and re-materialize; list/policy code stays unchanged.
- When indexing a new tenant: include the edges indexes early and validate via a smoke test query using `ListQueryRewriter`.

3.8. Cookbook: end-to-end example with Orders + Org

- Policy: allow LIST Order when `hasEdge("placedInOrg", principal.orgRefName)`
- Request lifecycle: 1) Security filter builds `SecurityContext` and `RuleContext` with `tenantId` and `principal`. 2) Policy evaluation returns a directive to constrain by `hasEdge("placedInOrg", orgRefName)`. 3) Repo builds base filter (`state != ARCHIVED`, etc.). 4) Repo calls `OntologyFilterHelper.ensureHasEdge(base, tenantId, "placedInOrg", orgRefName)`. 5) Mongo executes a single-hop query using materialized edges; results respect both policy and multi-tenancy.

3.9. Migration notes for teams using @Reference

- Keep existing references for write-side integrity and local joins where simple.
- Introduce ontology edges on hot read paths first; update policy rules to `hasEdge` and verify results.

- Gradually replace deep \$lookup traversals with hasEdge-based rewrites.
- Ensure materialization hooks are deployed before removing data fields used as inputs to the ontology.

Chapter 4. Primer: First-time guide to core relationship semantics

If you are new to ontology terms, the following quick explanations will help you build intuition. Each concept explains what it means, a tiny example, and how it affects queries using `hasEdge`.

- **Functional property**
 - What it means: For a given source entity, there is at most one target for this property. Think “single-valued.”
 - Example: `placedBy(Order, Customer)` is functional because an `Order` is placed by exactly one `Customer`.
 - Why it matters: On writes, the latest value replaces any previous one. In storage, you can enforce uniqueness for `(tenantId, src, p)`. Queries are simpler because there’s at most one matching edge per source.
 - In practice: When you save an `Order` with a different `placedBy`, the old edge is replaced so `hasEdge("placedBy", customerX)` reflects the latest truth.
- **Transitive property**
 - What it means: The relationship “chains through” intermediates. If `A` relates-to `B` and `B` relates-to `C` with the same property `p`, then `A` relates-to `C` by `p` as well.
 - Example: `ancestorOf(Org, Org)` is transitive: `OrgA ancestorOf OrgB` and `OrgB ancestorOf OrgC` implies `OrgA ancestorOf OrgC`.
 - Why it matters: You can answer reachability questions without specifying every hop. The system can materialize or compute the closure so queries like `hasEdge("ancestorOf", OrgC)` return `OrgA` even if the path is multiple hops.
 - In practice: Use transitive for hierarchies like `parent/ancestor`, `partOf`, `locatedIn`, `reportsTo`.
- **subPropertyOf (property hierarchy)**
 - What it means: One property is a more specific form of another. If `p ⊆ q` (“`p` is a sub-property of `q`”), then every `(s, p, o)` also counts as `(s, q, o)`.
 - Example: `placedInOrg ⊆ inOrg`. If an `Order` is `placedInOrg ACME`, then it is also `inOrg ACME`.
 - Why it matters: Queries written against the broader property (`q`) automatically include results from all its specializations (`p`). The system may materialize the super-property edges for performance.
 - In practice: You can write policies/queries once for `inOrg` and still match edges stored as `placedInOrg`.
- **inverseOf (inverse properties)**
 - What it means: Two properties point in opposite directions. If `p` is the inverse of `q`, then `(s, p, o)` implies `(o, q, s)`.
 - Example: `parentOf ⊆ childOf`. If `OrgA parentOf OrgB`, then `OrgB childOf OrgA`.
 - Why it matters: You only need to assert one direction; the system can infer the other. Queries

can use whichever direction is natural.

- In practice: If you stored `parentOf`, you can still query with `hasEdge("childOf", OrgA)` and find `OrgB` once inverses are materialized.

Putting it together - These traits combine. For example, `placedInOrg` can be declared a `subPropertyOf inOrg`; `ancestorOf` can be transitive; `parentOf` and `childOf` can be inverses. The reasoner uses these facts to materialize convenient edges so your queries remain simple and fast. - Your application code typically continues to use the same three query helpers: `hasEdge`, `hasEdgeAny`, `notHasEdge`. The richer semantics affect which edges exist, not how you call them.

Chapter 5. New ontology features in this release

This release expands the ontology engine and query integration to support a richer, OWL-RL-inspired subset while keeping the developer experience simple and backward compatible. The following capabilities are now available and used transparently by the materializer and query rewriter:

5.1. Feature overview

- `subClassOf` (class hierarchy)
- Model taxonomies (e.g., `Order` \sqsubset `Entity`, `Employee` \sqsubset `Person`). Used for validation and optional type filters.
- `subPropertyOf` (property hierarchy)
- If $p \sqsubset q$ and you assert (s, p, o) , the system materializes (s, q, o) . Queries on q will match p 's edges as well.
- inverse properties
- If p is the inverse of q , asserting (s, p, o) will materialize (o, q, s) . Example: `parentOf` \sqsubset `childOf`.
- symmetric properties
- For symmetric p , asserting (s, p, o) materializes (o, p, s) . Example: `peerOf` between organizations.
- transitive properties
- For transitive p , if (s, p, m) and (m, p, o) then (s, p, o) is inferred. Typical for `ancestorOf`, `partOf`, `locatedIn`, `memberOf` within hierarchical contexts.
- functional properties
- For functional p , each source s has at most one destination o . Upserts replace the prior value. Useful for single-valued relations like `placedBy` on `Order`.

All inferred edges carry `inferred=true` and provenance containing the rule used (e.g., transitive, inverse, `subPropertyOf`). These edges live in the same collection and are fully queryable.

5.2. Business problems solved

- E-commerce organizational access
- Problem: “Show me all orders placed in ACME (including subsidiaries).”
- Solution: Define `placedBy`, `memberOf`, `placedInOrg` with chain `placedBy` \sqsubset `memberOf` \Rightarrow `placedInOrg`, and make `ancestorOf` transitive. Either materialize closure with a chain `placedInOrg` \sqsubset `ancestorOf` \Rightarrow `placedInOrg` or use p being transitive. Queries use `hasEdge("placedInOrg", orgId)`.
- HR management

- Problem: “List employees who report to VP_X directly or indirectly.”
- Solution: Define reportsTo as transitive. Query hasEdge("reportsTo", "VP_X").
- Third-party and data lineage
- Problem: “Which datasets are derived from Source S?”
- Solution: Define derivedFrom as transitive and inverse derivedInto. Record symmetric peerOf for bidirectional partnerships where relevant.
- Supplier networks (supply chain)
- Problem: “Find parts supplied by a vendor’s parent company’s peers.”
- Solution: Use subPropertyOf to roll up specialized edges into a common supplies predicate, define parentOf/childOf inverses, and peerOf symmetric at the org level.

5.3. How to code it with current APIs

Below are concise examples showing how to define the ontology, materialize inferences, and query with existing components. These mirror the types already present in this repository and require no grammar changes.

5.3.1. 1) Define ontology (programmatic TBox)

Java (at startup, e.g., in a CDI producer):

```
@Produces @Singleton
public OntologyRegistry ontologyRegistry() {
    Map<String, OntologyRegistry.ClassDef> classes = Map.of(
        "Order",      new OntologyRegistry.ClassDef("Order", Set.of(), Set.of(), Set.
of()),
        "Customer",   new OntologyRegistry.ClassDef("Customer", Set.of(), Set.of(),
Set.of()),
        "Organization", new OntologyRegistry.ClassDef("Organization", Set.of(), Set.of(),
Set.of())
    );

    Map<String, OntologyRegistry.PropertyDef> props = new HashMap<>();
    // Single-valued ⇒ functional
    props.put("placedBy", new OntologyRegistry.PropertyDef(
        "placedBy", Optional.of("Order"), Optional.of("Customer"), false, Optional.
empty(),
        false, /*transitive*/ false, /*symmetric*/ true /*functional*/, Set.of()
    ));
    props.put("memberOf", new OntologyRegistry.PropertyDef(
        "memberOf", Optional.of("Customer"), Optional.of("Organization"), false,
Optional.empty(),
        false, false, false, Set.of()
    ));
    props.put("placedInOrg", new OntologyRegistry.PropertyDef(
        "placedInOrg", Optional.of("Order"), Optional.of("Organization"), false,
```

```

Optional.empty(),
    false, false, false, Set.of("inOrg") // subPropertyOf example
));
props.put("inOrg", new OntologyRegistry.PropertyDef(
    "inOrg", Optional.of("Order"), Optional.of("Organization"), false, Optional
.empty(),
    false, false, false, Set.of()
));
// Transitive ancestor relation
props.put("ancestorOf", new OntologyRegistry.PropertyDef(
    "ancestorOf", Optional.of("Organization"), Optional.of("Organization"), false,
Optional.empty(),
    true, /*transitive*/ false, false, Set.of()
));
// Inverses and symmetric
props.put("parentOf", new OntologyRegistry.PropertyDef(
    "parentOf", Optional.of("Organization"), Optional.of("Organization"), false,
Optional.of("childOf"),
    false, false, false, Set.of()
));
props.put("childOf", new OntologyRegistry.PropertyDef(
    "childOf", Optional.of("Organization"), Optional.of("Organization"), true,
Optional.empty(),
    false, false, false, Set.of()
));
props.put("peerOf", new OntologyRegistry.PropertyDef(
    "peerOf", Optional.of("Organization"), Optional.of("Organization"), false,
Optional.empty(),
    false, /*transitive*/ true, /*symmetric*/ false, /*functional*/ Set.of()
));

List<OntologyRegistry.PropertyChainDef> chains = List.of(
    // Order --placedBy--> Customer --memberOf--> Org ⇒ Order --placedInOrg--> Org
    new OntologyRegistry.PropertyChainDef(List.of("placedBy", "memberOf"),
    "placedInOrg"),
    // Include ancestor closure for placedInOrg results
    new OntologyRegistry.PropertyChainDef(List.of("placedInOrg", "ancestorOf"),
    "placedInOrg")
);

return OntologyRegistry.inMemory(new OntologyRegistry.TBox(classes, props, chains));
}

```

Notes: - subPropertyOf is modeled via the PropertyDef.subPropertyOf set. - Inverse and symmetric are encoded in PropertyDef.inverseOf and PropertyDef.symmetric. - Transitivity is toggled via PropertyDef.transitive.

5.3.2. 2) Materialize inferences when data changes

Use OntologyMaterializer or call the Reasoner directly and upsert edges via OntologyEdgeRepo.

```

@Inject ForwardChainingReasoner reasoner;
@Inject OntologyRegistry ontologyRegistry;
@Inject OntologyEdgeRepo edgeRepo;

public void onOrderSaved(String tenant, String orderId, String customerId, String
orgId) {
    List<Reasoner.Edge> explicit = List.of(
        new Reasoner.Edge(orderId, "placedBy", customerId, false, Optional.empty()),
        new Reasoner.Edge(customerId, "memberOf", orgId, false, Optional.empty())
    );
    Reasoner.EntitySnapshot snap = new Reasoner.EntitySnapshot(tenant, orderId, "Order",
explicit);
    Reasoner.InferenceResult out = reasoner.infer(snap, ontologyRegistry);
    for (Reasoner.Edge e : out.addEdges()) {
        Map<String, Object> prov = e.prov().map(p -> Map.<String, Object>of("rule", p.rule(
), "inputs", p.inputs())).orElse(Map.of());
        edgeRepo.upsert(tenant, e.srcId(), e.p(), e.dstId(), true, prov);
    }
}

```

The materializer computes and persists: - subPropertyOf roll-ups (e.g., placedInOrg \sqsubseteq inOrg \Rightarrow write inOrg) - inverse/symmetric counterparts - transitive closures (bounded to the snapshot inputs; you can also chain for closures)

5.3.3. 3) Query with ListQueryRewriter (Quarkus/Morphia)

Use hasEdge/hasEdgeAny/notHasEdge to turn ontology constraints into Morphia filters over your entity collection. The rewriter internally fetches the set of source ids from the edge store and builds an in("refName", ...) filter that composes with your attribute predicates.

```

@Inject ListQueryRewriter queryRewriter;
@Inject MorphiaDatastore datastore;

public List<TestOrder> openOrdersIn(String tenant, String orgId) {
    var status = dev.morphia.query.filters.Filters.eq("status", "OPEN");
    var inOrg = queryRewriter.hasEdge(tenant, "placedInOrg", orgId);
    var combined = dev.morphia.query.filters.Filters.and(status, inOrg);
    return datastore.find(TestOrder.class).filter(combined).iterator().toList();
}

```

To include multiple orgs:

```

var f = queryRewriter.hasEdgeAny(tenant, "placedInOrg", List.of("ORG-ACME", "ORG-
GLOBEX"));

```

To exclude restricted orgs:

```
var f = queryRewriter.notHasEdge(tenant, "placedInOrg", "ORG-RESTRICTED");
```

5.3.4. Functional properties at write time

For single-valued relationships declared functional, configure a unique index over (tenantId, src, p) in your edge store (or rely on repo semantics) and treat upserts as replacements.

Practical guidance: - Mark naturally single-valued links functional (placedBy, primaryOwner). - On write, remove or overwrite any prior dst for the same (tenant, src, p).

5.4. Backward compatibility and migration

- Grammar/API: No changes needed. The same hasEdge/hasEdgeAny/notHasEdge functions work; results simply become more expressive as ontology features are enabled.
- Feature flags: You may enable features per property (e.g., transitive) gradually. Queries remain stable.
- Provenance: Keep prov so you can re-compute or retract inferred edges when inputs or rules change.

5.5. Troubleshooting and tips

- Empty result from hasEdge: Means no matching edges exist; check whether inferences are being materialized for the predicate you expect.
- Tenant scoping: All repo calls include tenantId; ensure you pass the correct tenant in both write and read paths.
- Indexes: For heavy reads, ensure compound indexes on (tenantId, p, dst) and (tenantId, src, p). For functional, consider a unique (tenantId, src, p).
- Testing: Use Quarkus @QuarkusTest to wire CDI and a test OntologyRegistry producer. Populate explicit edges, run the reasoner, then assert with the repo and query rewriter as shown in the integration tests included with the repository.

Chapter 6. Model-first ontology with annotations and MorphiaOntologyLoader

This section shows how to use your Morphia model classes as the source of truth for the ontology. You annotate model classes/fields to declare ontology concepts and property traits; at startup, MorphiaOntologyLoader scans MorphiaDatastore.getMapper() to build the OntologyRegistry automatically.

6.1. Why model-first?

- Single source of truth: semantics live next to the data model; less drift between code and config.
- Safer refactors: renames/types evolve in code and the ontology follows.
- No separate YAML/JSON needed for most use cases; optional overrides remain possible later if needed.

6.2. Annotations overview

Two lightweight annotations are used on model classes and fields. They are provided by quantum-ontology-core and can be added to any Morphia-mapped entity (deriving from UnversionedBaseModel).

- @OntologyClass
 - id: optional explicit class id (defaults to the simple class name)
 - subClassOf: optional extra parents (in addition to Java inheritance)
- @OntologyProperty
 - id: optional explicit property id (defaults to the field name)
 - subPropertyOf: property hierarchy roll-up targets
 - inverseOf: name of the inverse property (declare on one side)
 - transitive: whether the property is transitive
 - symmetric: whether the property is symmetric
 - functional: at most one target per source (defaults to true for single-valued fields)
 - domain: override inferred domain (defaults to declaring @OntologyClass)
 - range: override inferred range (defaults to the field/element type)



functional is inferred true for single-valued fields and false for collections/maps unless you override it.

6.3. Example: Orders placed in an Organization (e-commerce)

Below we implement the same business example covered earlier using model annotations.

```
@OntologyClass(id = "Order")
@Entity(value = "orders")
public class Order extends UnversionedBaseModel {
    private String status;

    // Order --placedBy--> Customer (single-valued => functional)
    @OntologyProperty(id = "placedBy", inverseOf = "placed", functional = true)
    private Customer placedBy;
}

@OntologyClass(id = "Customer")
@Entity(value = "customers")
public class Customer extends UnversionedBaseModel {
    // Customer --memberOf--> Org (transitive across org tree)
    @OntologyProperty(id = "memberOf", transitive = true)
    private Org memberOf;
}

@OntologyClass(id = "Organization")
@Entity(value = "orgs")
public class Org extends UnversionedBaseModel {
    // Org --parentOf--> Org, with inverse childOf
    @OntologyProperty(id = "parentOf", inverseOf = "childOf")
    private Org parent;

    // Optional symmetric relationship between peers
    @OntologyProperty(id = "peerOf", symmetric = true)
    private Set<Org> peers;
}
```

Optionally, model a super-property to roll up specialized edges:

```
@OntologyClass(id = "Order")
public class Order extends UnversionedBaseModel {
    @OntologyProperty(id = "placedBy", inverseOf = "placed", functional = true)
    private Customer placedBy;

    // Roll-up predicate for org membership of orders; placedInOrg ⊑ inOrg
    @OntologyProperty(id = "placedInOrg", subPropertyOf = {"inOrg"})
    private Org inOrgDirect;
}
```

With these annotations in place, the loader will infer: - Classes: Order, Customer, Organization (+ hierarchy from Java inheritance) - Properties: placedBy (functional), memberOf (transitive), parentOf ↔ childOf (inverse), peerOf (symmetric) - subPropertyOf: placedInOrg ↔ inOrg (if declared)

6.4. How the registry is produced (Quarkus CDI)

OntologyCoreProducers wires MorphiaOntologyLoader by default. On startup it scans your models and produces a singleton OntologyRegistry.

```
@ApplicationScoped
public class OntologyCoreProducers {
    @Inject MorphiaDatastore morphiaDatastore;

    @Produces @Singleton
    public OntologyRegistry ontologyRegistry() {
        try {
            MorphiaOntologyLoader loader = new MorphiaOntologyLoader(morphiaDatastore);
            OntologyRegistry reg = loader.load();
            return isEmpty(reg) ? emptyRegistry() : reg;
        } catch (Throwable t) {
            return emptyRegistry();
        }
    }
}
```

If you need manual control (tests, migrations), you can call the loader directly:

```
MorphiaOntologyLoader loader = new MorphiaOntologyLoader(datastore);
OntologyRegistry registry = loader.load();
```



Keep annotations minimal. Only add traits that aren't obvious from the Java type system (e.g., transitive, symmetric, inverse, subPropertyOf).

6.5. Materializing inferences from annotated models

Materialization is automatic on save/update through the repository hook; you do not need to assemble explicit edge lists or call OntologyMaterializer manually.

- What happens:
- The framework inspects fields/getters annotated with @OntologyProperty and extracts explicit edges.
- The reasoner applies inverse, symmetric, transitive, and subPropertyOf traits from the registry and upserts inferred edges.
- When to trigger re-materialization manually:

- After ontology rule changes (e.g., you mark a property transitive or add an inverse), run your re-materialization job to recompute edges for existing entities in a tenant.
- During bulk imports, you can disable auto-materialize and run the job afterward.

Example: disable auto-materialize for a batch, then rebuild

```
ontology.auto-materialize=false
```

```
@Inject OntologyRebuilder rebuilder; // your maintenance utility

public void runBackfill(String tenantId) {
    rebuilder.recomputeTenant(tenantId);
}
```

6.6. Querying using ListQueryRewriter (unchanged)

Your query code does not change. It benefits from materialized edges that now carry richer semantics from annotations.

```
@Inject ListQueryRewriter queryRewriter;
@Inject MorphiaDatastore datastore;

public List<Order> openOrdersIn(String tenant, String orgId) {
    var status = dev.morphia.query.filters.Filters.eq("status", "OPEN");
    var inOrg = queryRewriter.hasEdge(tenant, "placedInOrg", orgId);
    var combined = dev.morphia.query.filters.Filters.and(status, inOrg);
    return datastore.find(Order.class).filter(combined).iterator().toList();
}
```

To include subsidiaries via ancestor/parent relationships, either: - Declare ancestorOf as transitive in the model and materialize a closure, or - Add a property chain placedInOrg \square ancestorOf \Rightarrow placedInOrg in your registry initialization.

6.7. Business case recipes with annotations

- E-commerce org access
- Annotate placedBy (functional), memberOf (transitive), and optionally parentOf (inverse childOf). Materialize placedInOrg via a property chain. Query hasEdge("placedInOrg", org).
- HR reporting lines
- Annotate reportsTo as transitive on Employee; query hasEdge("reportsTo", managerId).
- Supplier networks
- Annotate supplies as a base property; use subPropertyOf to roll up specialized suppliesDirect and suppliesViaSubsidiary to supplies; annotate peerOf on Org as symmetric.

6.8. Troubleshooting

- The registry is empty at runtime
- Ensure your models are discovered by Morphia (annotated with `@Entity`) and that the Quarkus application initializes `MorphiaDatastore` before the ontology producer.
- Inverse not applied
- Declare `inverseOf` on one side only; the loader will wire both directions.
- Functional not enforced
- For functional properties, ensure your edge repository enforces unique (`tenantId`, `src`, `p`) or that your write path overwrites prior values.

6.9. Migration strategy

- Start by adding `@OntologyProperty` to the most important relationships; don't attempt to annotate everything at once.
- Keep existing `@Reference` fields if you have them; use edges for query-time semantics and policy integration first.
- Add tests that verify the loader discovered your properties (including inverses/subPropertyOf) and that queries via `hasEdge` behave as expected.

6.10. Modeling guidance: annotate existing id/reference getters (keep API and DB clean)

- Prefer annotating getters that already exist in your schema (String ids or existing `@Reference` fields). Avoid adding embedded objects solely to drive ontology.
- If you do need a synthetic accessor purely for ontology, hide it from API docs and persistence using `@JsonIgnore`, `@Schema(hidden = true)`, and `@dev.morphia.annotations.Transient`.

Recommended pattern: annotate an existing id getter (Swagger unchanged)

```
import com.e2eq.ontology.annotations.OntologyClass;
import com.e2eq.ontology.annotations.OntologyProperty;
import dev.morphia.annotations.Entity;

@Entity
@OntologyClass(id = "Order")
public class Order extends UnversionedBaseModel {
    // Existing field that is already part of your API/DB contract
    private String customerRefName;

    public String getCustomerRefName() { return customerRefName; }
    public void setCustomerRefName(String v) { this.customerRefName = v; }

    // Drives ontology edges without changing Swagger: the getter already exists and
```

```

returns a String id
@OntologyProperty(id = "placedBy", functional = true)
public String customerIdForEdges() { return getCustomerRefName(); }
}

```

Because AnnotatedEdgeExtractor treats CharSequence targets as ids, annotating a String-returning getter produces edges without introducing new embedded objects. Your Swagger/OpenAPI and persisted shape remain unchanged.

Optional: use an existing @Reference instead of an id

```

@Entity
@OntologyClass(id = "Order")
public class Order extends UnversionedBaseModel {
    @dev.morphia.annotations.Reference
    private Customer customer; // already in your schema

    @OntologyProperty(id = "placedBy", inverseOf = "placed", functional = true)
    public Customer getCustomer() { return customer; }
}

```

If you must add an ontology-only accessor, hide it

```

import com.fasterxml.jackson.annotation.JsonIgnore;
import io.swagger.v3.oas.annotations.media.Schema;
import dev.morphia.annotations.Transient;

@Entity
@OntologyClass(id = "Order")
public class Order extends UnversionedBaseModel {
    private String orgRefName; // real field

    // Hidden from API docs and persistence, used only to emit an ontology edge
    @JsonIgnore
    @Schema(hidden = true)
    @Transient
    @OntologyProperty(id = "placedInOrg", subPropertyOf = {"inOrg"})
    public String placedInOrgEdge() { return orgRefName; }
}

```

These patterns keep your REST and database contracts clear while allowing ontology materialization to happen automatically on writes.