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A Semantic Approach to Battery Digital Twins

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Overview

1. **What** is a **digital twin**?
2. **Why** is a **semantic approach** needed?
3. **How** can a semantic digital twin be **implemented**?
4. **What** are the **challenges**?
5. **What** is the **outlook**?

What is a digital twin?

What is a Battery Digital Twin?

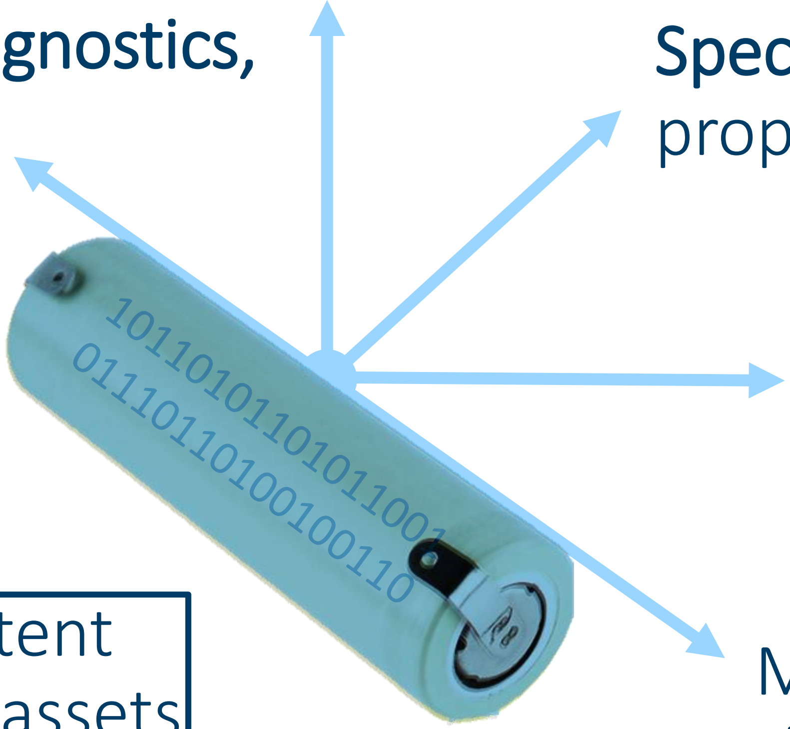
A digital representation of a physical asset

A coherent and persistent framework for linking assets

Access **current state**

Analysis, diagnostics, prognostics

Specification for properties



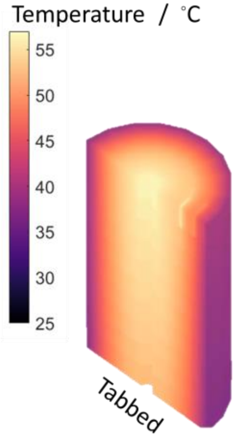
Access **historical data**

Model-based **state simulation**

What is a Battery Digital Twin?

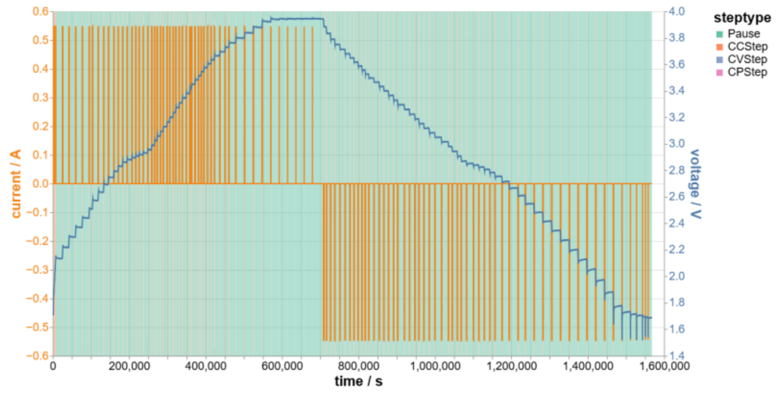
The pieces necessary to implement a battery digital twin **exist**, and they **work great on their own, but** they **do not work well together**.

open-source models



BattMo

data management & analysis



digital product passport

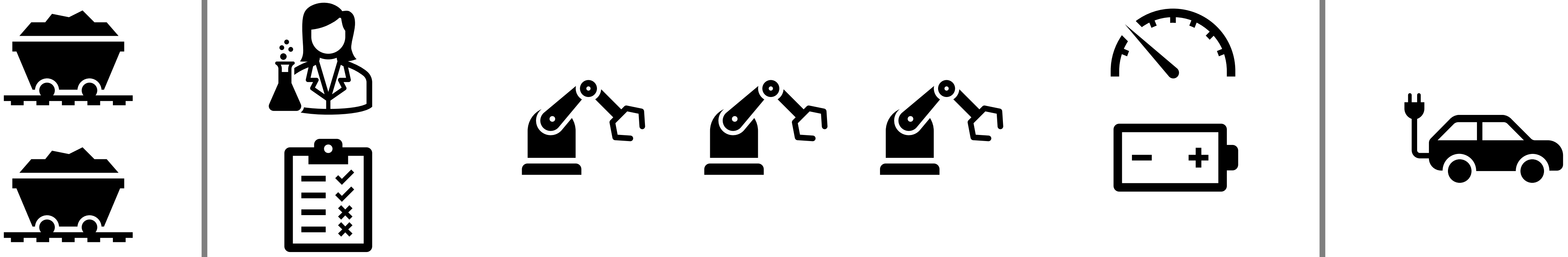
Varying API specifications, JSON I/O schemas, plain text documentation

Why is a semantic approach needed?

Why is a semantic approach needed?

Battery design, manufacturing, and operation **is an "everything problem"** and we need to **link knowledge across many domains** to solve it.

Raw Materials	Quality Checks	Manufacturing Steps	Testing	Integration
Specs	Lab Reports	Equipment Settings & In-Line Measurements	Electrical Data	BMS Data



Why is a semantic approach needed?

Battery design, manufacturing, and operation **is an "everything problem"** and we need to **link knowledge across many domains** to solve it.

A semantic approach is necessary to **support data interoperability, knowledge management, and provide a foundation for AI activities**

How can a semantic digital twin be implemented?

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Implementation: EMMO Battery Domain Ontology

The **EMMO Battery Domain Ontology** offers an extensive collection of concepts describing **battery knowledge**, building on existing resources like **IEC and IUPAC recommendations**.

- Supports descriptions of **battery materials, components, cells, systems, processes, models, and datasets**
- **Re-uses and extends** other **EMMO domains** including **chemical-substance, characterisation, and electrochemistry**
- Adheres to **EMMO community guidelines** and **W3C best practices**
- Designed with **Semantic Web integration** in mind

Implementation: Battery Metadata

```
{
  "@context": "https://w3id.org/emmo/domain/battery/context",
  "@type": "Battery",
  "hasPositiveElectrode": {
    "@type": "Electrode",
    "hasActiveMaterial": {
      "@type": "LithiumIronPhosphate"
    }
  },
  "hasProperty": [
    {
      "@type": "NominalVoltage",
      "hasNumericalPart": {
        "@type": "RealData",
        "hasNumberValue": 3.6
      },
      "hasMeasurementUnit": "emmo:Volt"
    }
  ]
}
```

JSON-LD Playground

- **Ontology** contains everything necessary to provide a **holistic description of batteries** and **their properties.**
- **Terms contain mappings to other prominent sources**, e.g. Wikidata, DBpedia, PubChem, etc.

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Implementation: Battery Metadata

```
{
  "@context": "https://w3id.org/emmo/domain/battery/context",
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JSON-LD Playground

- **Ontology** contains everything necessary to provide a **holistic description of batteries** and **their properties.**
- **Terms contain mappings to other prominent sources**, e.g. Wikidata, DBpedia, PubChem, etc.
- **Pre-built classes** for common battery types under **IEC standards.**

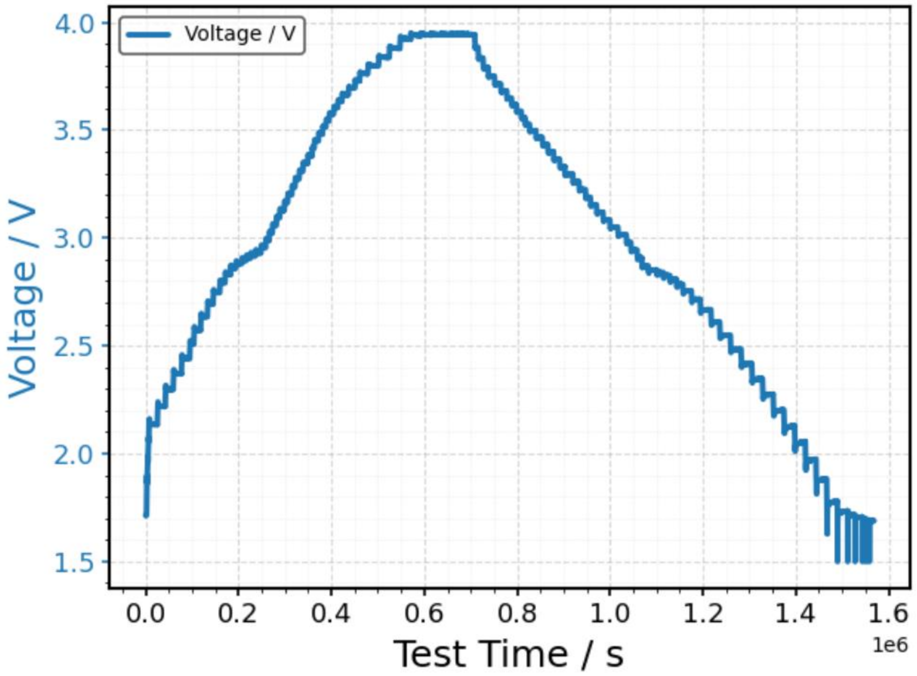
Implementation: Timeseries Data

Establishing interoperability of test data among different equipment providers is a stubborn and persistent challenge.

- Many **battery testing equipment** manufacturers **serialize data using a variety of formats and content.**
- **Proprietary binary files**, csv, txt, xlsx – tables containing columns with very **similar but distinct headers and meanings.**
- **Battery2030+ CSA** is partnering with **DigiBatt** and the **Linux Foundation** to create a **semantic standard for timeseries battery data**
- **Recommended terms and units** formalized in an **application ontology**, used to create **CSVW table schema**, and supported with a **python package**.

Implementation: Timeseries Data

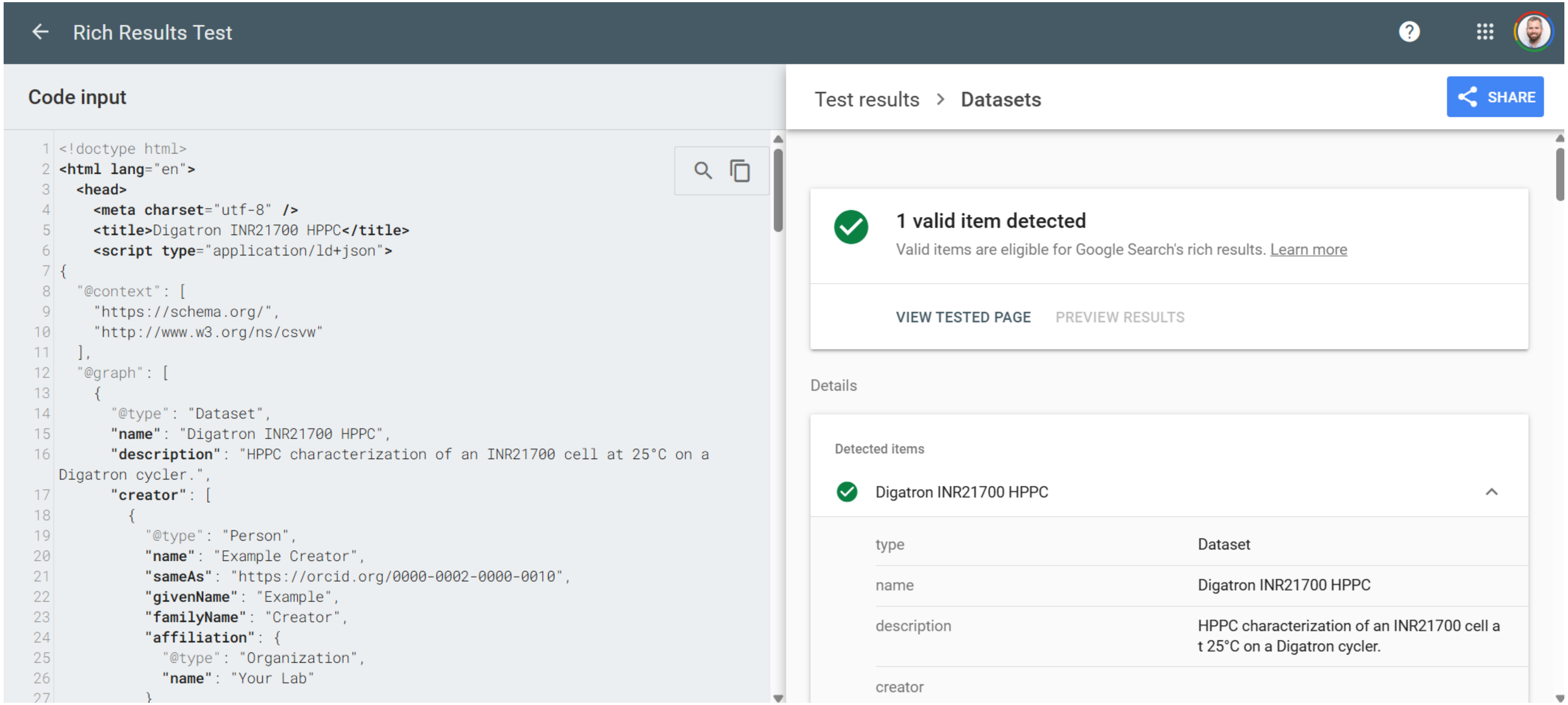
```
df = bdf.read("https://zenodo.org/records/17289383/files/SINTEF__NaCR32140-MP10-04__2025-08-25__GITT_0p05C_25degC__BioLogic.mpt")
bdf.plot(df)
```



	Test Time / s	Voltage / V	Current / A	Ambient Temperature / degC	Cycle Count / 1
0	0.0	1.71423	0.0	23.509834	0.0
1	10.0	1.714152	0.0	23.162155	0.0
2	20.000001	1.714152	0.0	23.383406	0.0
3	30.000001	1.71423	0.0	23.328093	0.0
4	40.000002	1.714191	0.0	23.375504	0.0

https://w3id.org/battery-data-alliance/ontology/battery-data-format/schema

Implementation: Timeseries Data



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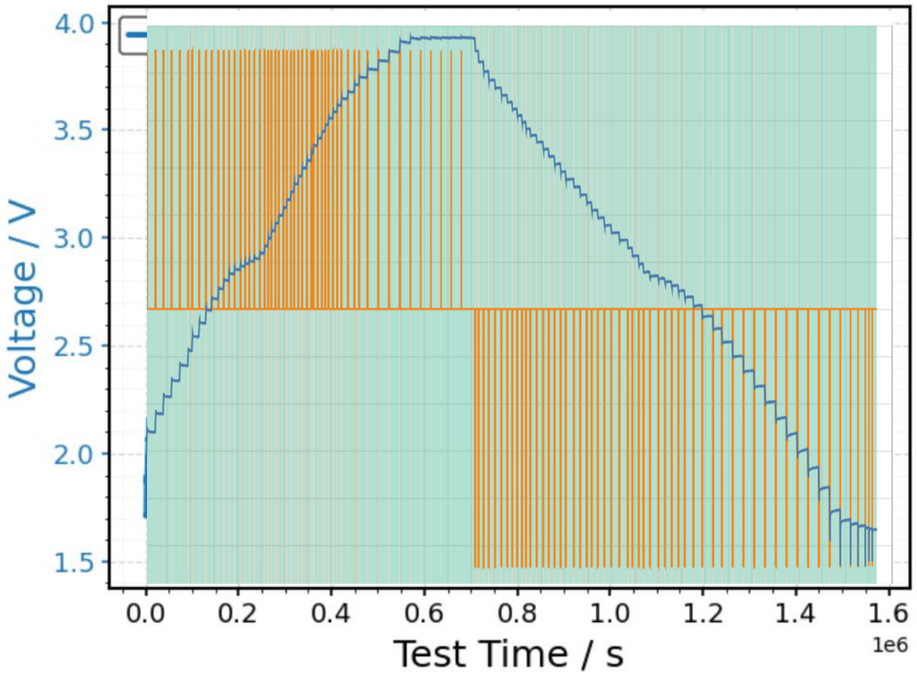

	Test Time / s	Voltage / V	Current / A	Ambient Temperature / degC	Cycle Count / 1
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Implementation: Model Parameters

There are a variety of **open-source battery simulation** packages available, but **sharing parameters across platforms and partners creates semantic challenges.**

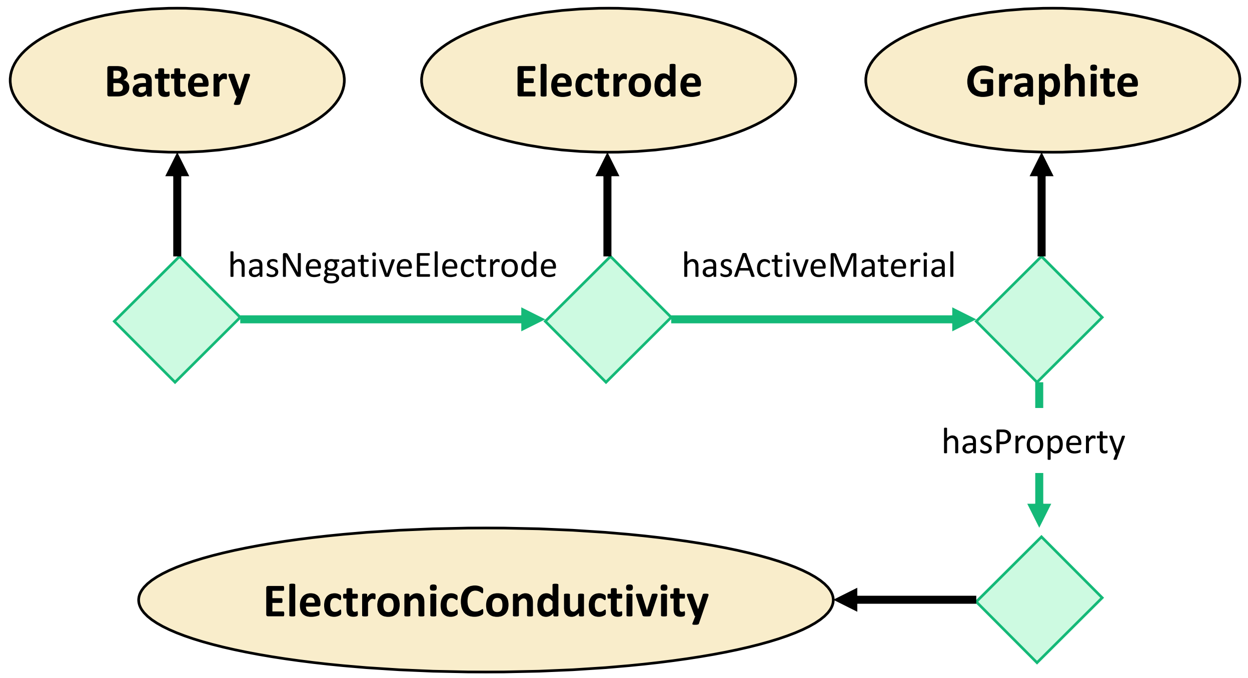
- **Battery Parameter Exchange (BPX)** is an activity at the Faraday Institution to create a **standardized exchange format for Li-ion battery model parameters**.
- Formalized in an **application ontology** to provide **semantic interoperability** of parameter sets between **open-source simulation tools** PyBaMM, BattMo, cideMOD, etc.
- Also integrated into **commercial software** like **AVL Cruise M**, **ANSYS Fluent**, and **GT-AutoLion**

What are the challenges?

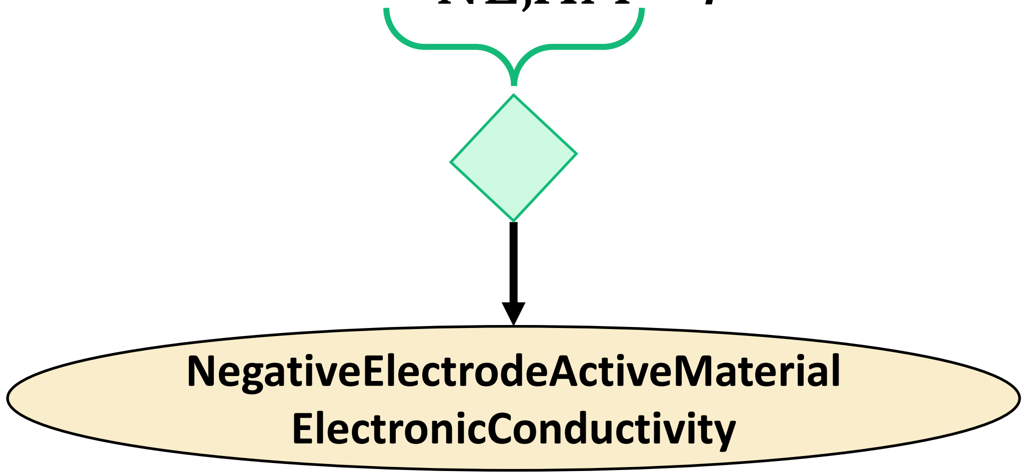
Challenge: Model Parameter Extraction

A battery is often described as a **holistic arrangement**, creating a **hierarchy of parts with properties. But simulation software** is designed around **parameters** with **very specific meaning and usually flattened**.

In the passport metadata	In the model

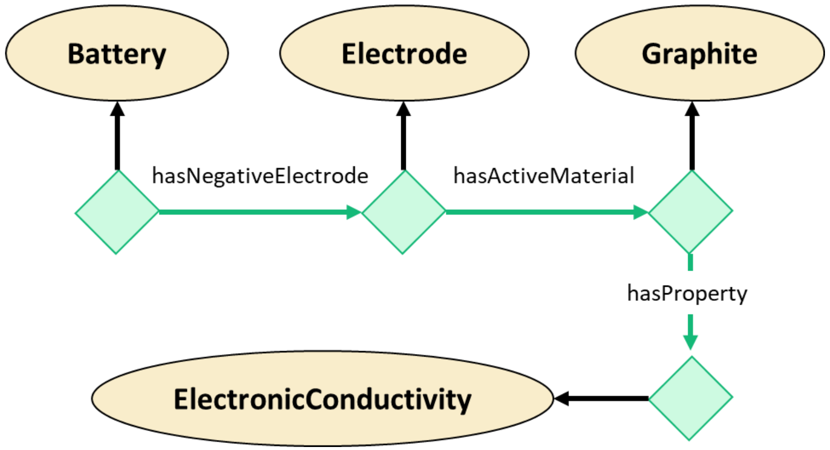


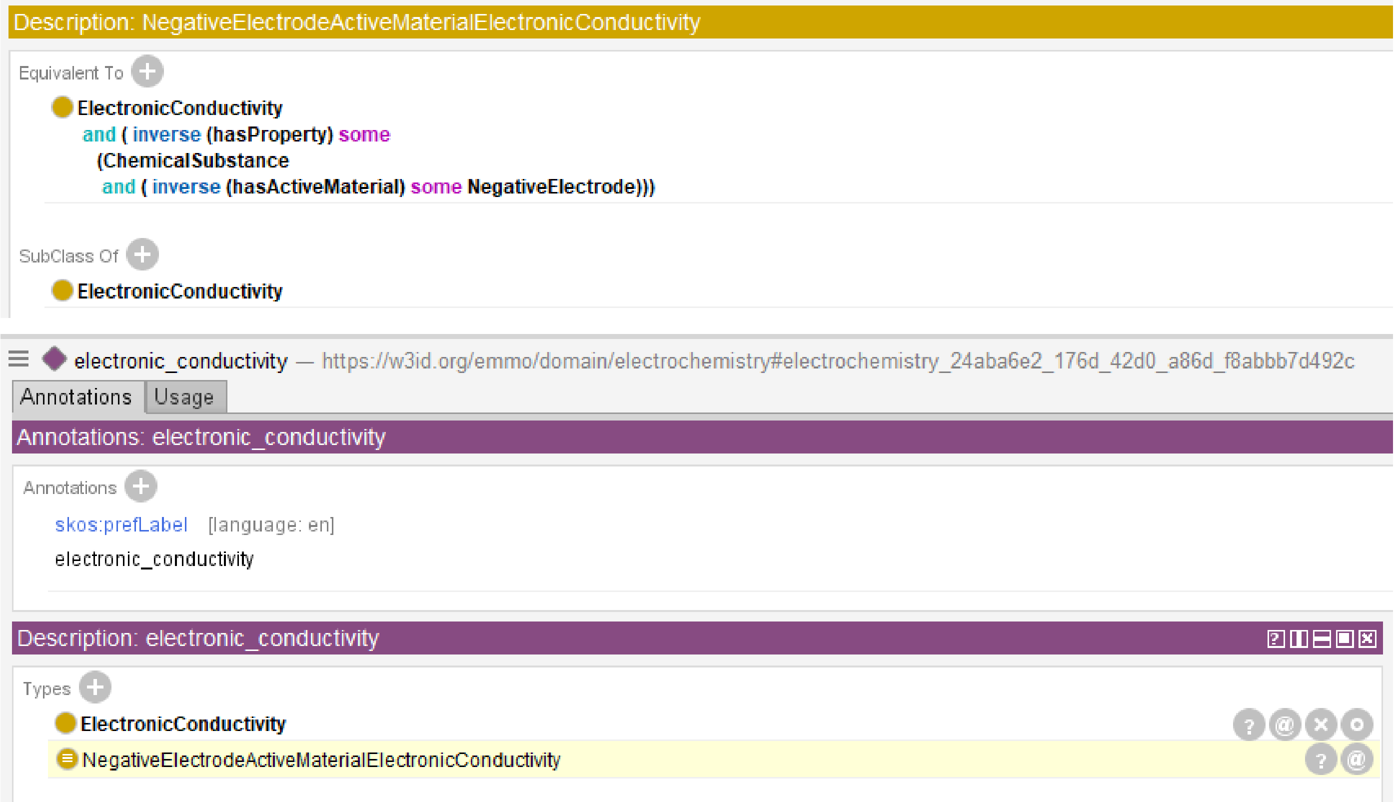
$$i = -\sigma_{\mathrm{NE,AM}} \nabla \phi$$

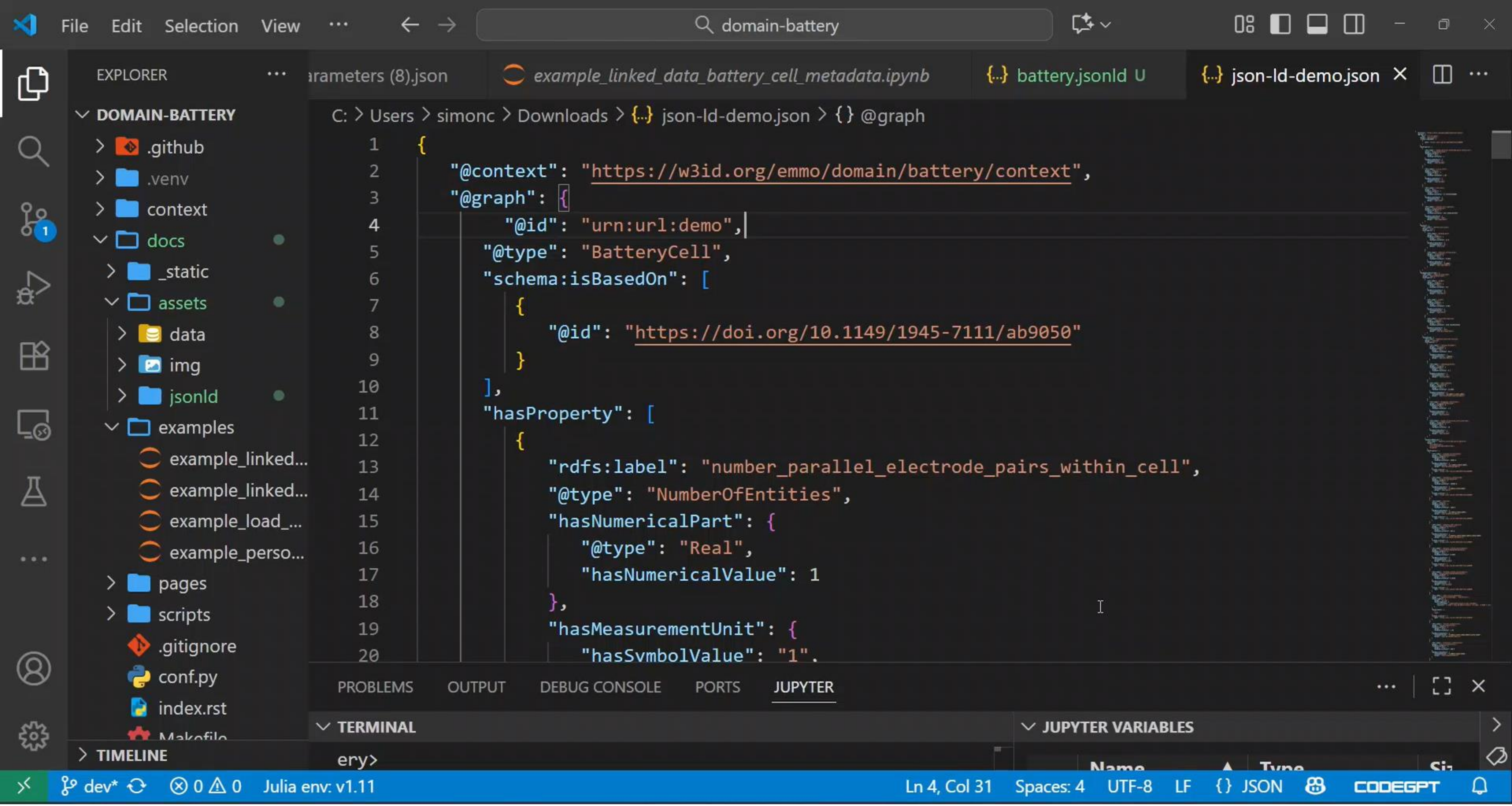


Solution: Equivalence-Based Inference

Using **equivalence statements in the ontology**, we can use the **reasoner to infer relationships** between **cell metadata and model parameters** to **accelerate and automate their extraction.**



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DOMAIN-BATTERY
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json-ld-demo.json
C: > Users > simonc > Downloads > json-ld-demo.json > @graph
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"@graph": {
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"@type": "BatteryCell",
"schema:isBasedOn": [
{
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}
],
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{
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"hasNumericalPart": {
"@type": "Real",
"hasNumericalValue": 1
},
"hasMeasurementUnit": {
"hasSymbolValue": "1",
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What is the outlook?

What is the outlook

- The battery domain is diverse and complex – spanning a broad base of domain knowledge
- Semantic technology has allowed us to start to bridge the gaps and create a coherent and persistent description of battery resources
- The individual components have been addressed
- We are working to bring this together into an open-source orchestration layer to allow for agents to make complex decisions using information from across the battery domain.

Thank You

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BATTERY 2030+

BIG-MAP

digibatt

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