Meaningful Datatypes: Ontologically-Sound Dependent Type Systems for Data Science

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The Role of Data Science

- Data Science is increasingly important and valuable
- It drives important decisions
- Understanding data is critical

What’s in a (Data) Type?

- All data is representative of real-world phenomena
- Important decisions are made based on data scientists’ results
- The nuances of the real world are reduced to integers, strings, etc

Outline

1. Why are datatypes problematic for data science?

2. What are my contributions to solving this problem?

3. What is the significance of these contributions?

4. What are the directions for future work?

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   I. **Datatype Problem Classes**
   II. **The gaps in current work**

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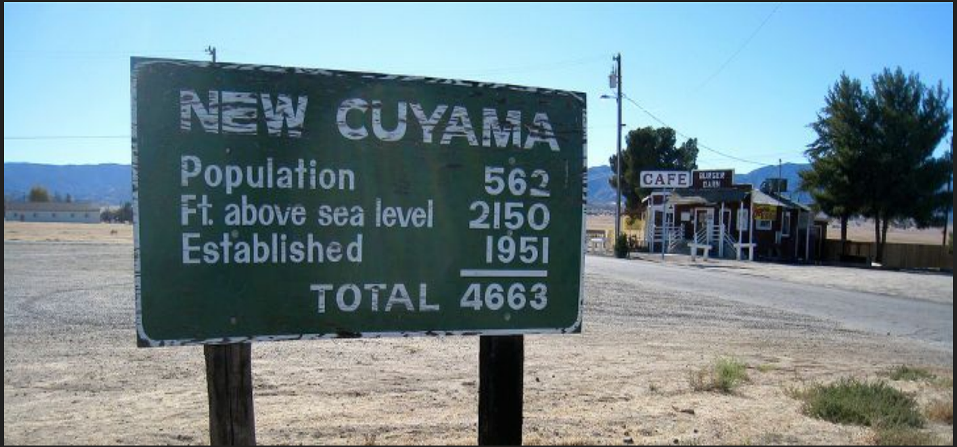
Datatype Problems

The Real World

- Implicit rules
- Complex concepts and relationships

Simple Datatypes

- Numbers are numbers*
- String OR Integer OR Float OR …
- Same datatype represents many different concepts



Datatype Problem Classes

1. Time

2. Mereology

3. Provenance

Datatype Problem Classes

1. **Time**
2. Mereology
3. Provenance

Datatype Issues: Time

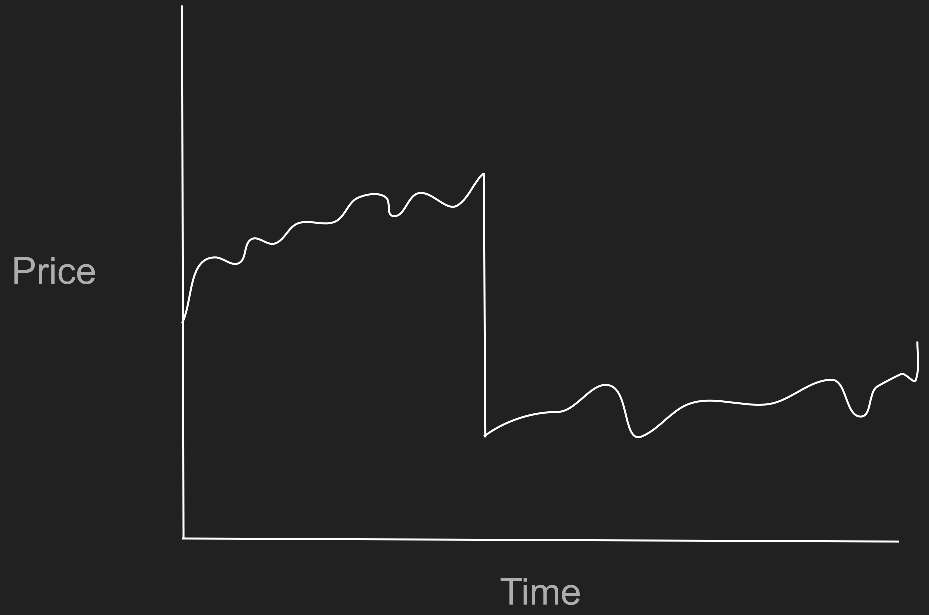
- Time is common and important in most data

- Ex: House Prices

Date	Average House Price
1960-05-20	12 000
…	…
2022-01-01	850 000

Datatype Issues: Time

- Ex: Frankfurt Stock Exchange Quote



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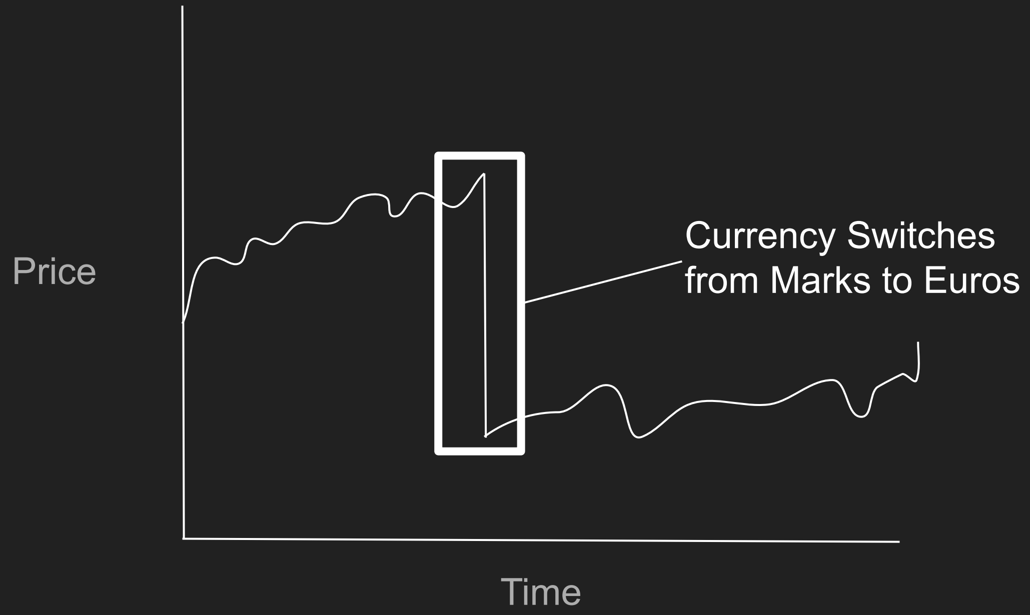

Datatype Problem Classes

1. Time
2. **Mereology**
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Datatype Issues: Mereology

- Mereology in data exists in many different forms

- Ex: COVID-19 Vaccination Data

Date	**Fully Vaccinated**	**% of Eligible Population Fully Vaccinated**
2021-06-22	1 200 000	3.5%
…	…	…
2021-07-29	1 335 000	2.6%
…	…	…
2022-05-28	1 086 100	2.2%

Datatype Issues: Mereology

- Mereology in data exists in many different forms

- Ex: COVID-19 Vaccination Data

Date	Fully Vaccinated	% of Eligible Population Fully Vaccinated
2021-06-22	1 200 000	3.5%
Children Become Part of Eligible Population		…
2021-07-29	1 335 000	2.6%
…	…	…
2022-05-28	1 086 100	2.2%

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…	…	…
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“Fully Vaccinated” definition changes to 3+ doses		…
2022-05-28	1 086 100	2.2%

Datatype Problem Classes

1. Time
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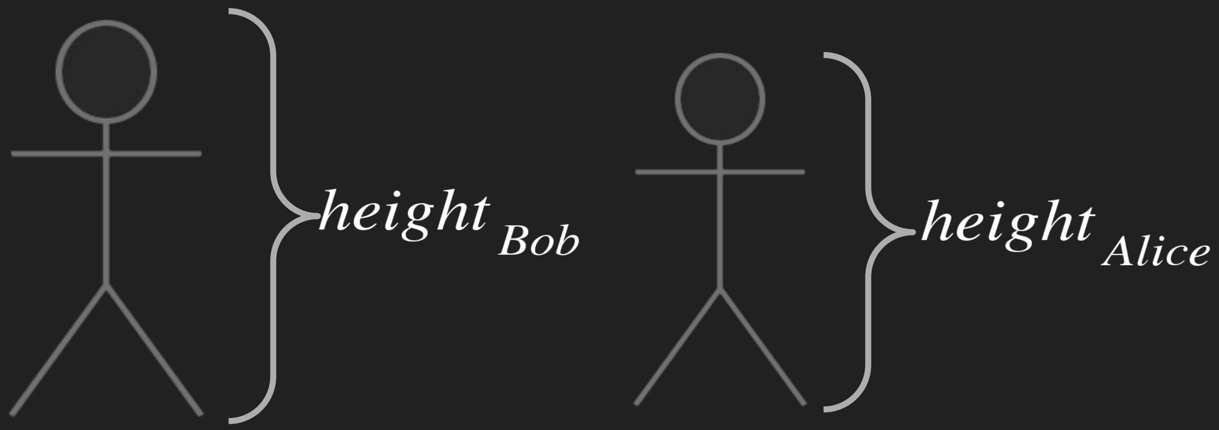
3. **Provenance**

Datatype Issues: Provenance

- Data science operations transform real-world interpretations

- Ex: Height Measurements



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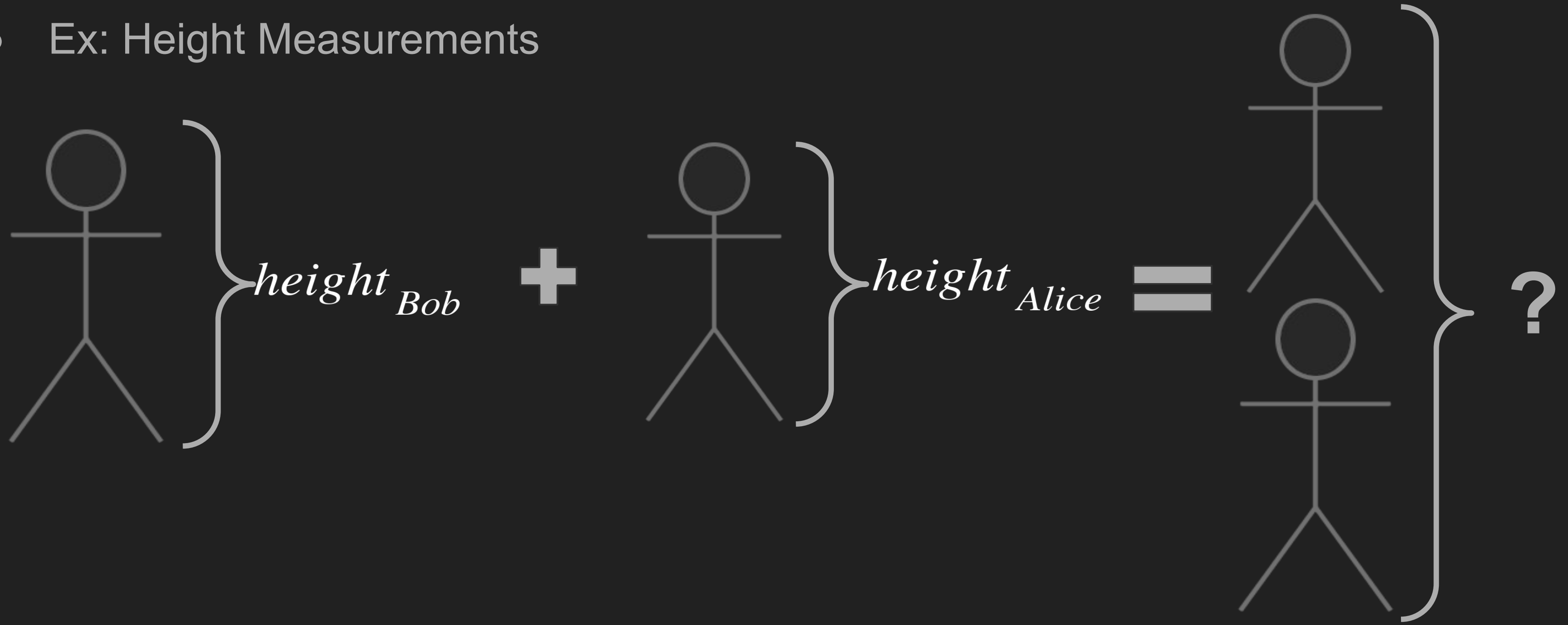

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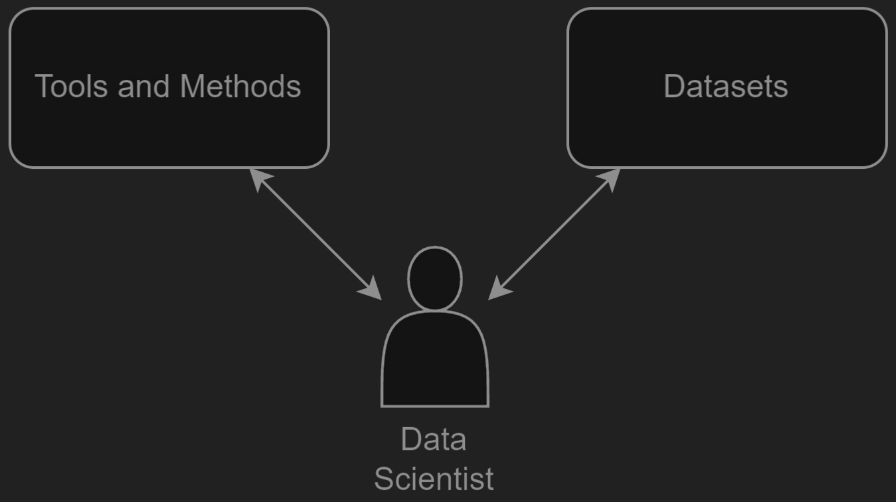
Datatype Issues: Current Solutions

- These approaches supplement datatypes with external knowledge and tools

- Applied in informal, ad-hoc, opaque, laborious ways



Datatype Issues: Current Solutions

1. Documentation

2. Provenance Tracking

3. Knowledge Representation

Datatype Issues: Current Solutions

1. **Documentation**

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3. Knowledge Representation

Documentation Standards

- Understand data through documentation standards
  - Provide list of important questions to be answered about the dataset

Motivation	Composition	Collection Process	Maintenance
...?	…?	…?	…?

Documentation Standards

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Motivation	Composition	Collection Process	Maintenance
...?	…?	…?	…?

- We have a more complete picture of the dataset, however:
  - Description is still in natural language
  - Description is static
  - Description is not machine readable

Datatype Issues: Current Solutions

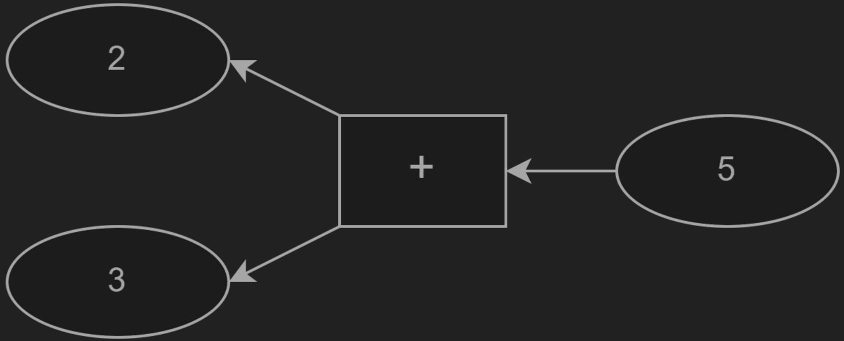
1. Documentation

2. **Provenance Tracking**

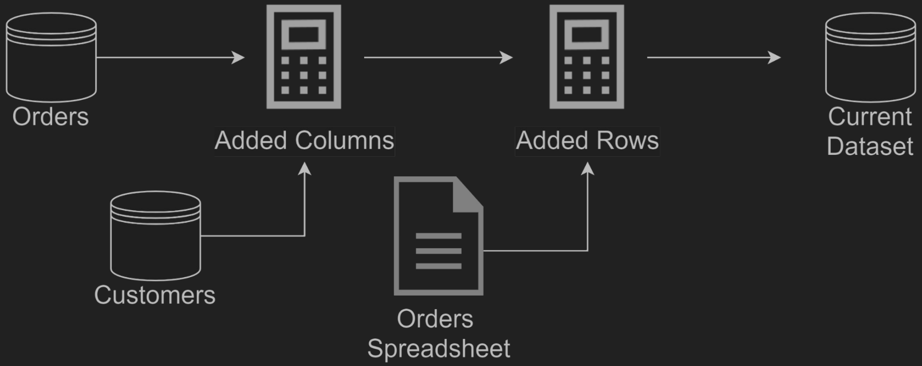
3. Knowledge Representation

Provenance Tracking

- Lineage-Provenance (What, How?)



- Where-Provenance (Where From?)



Provenance Tracking

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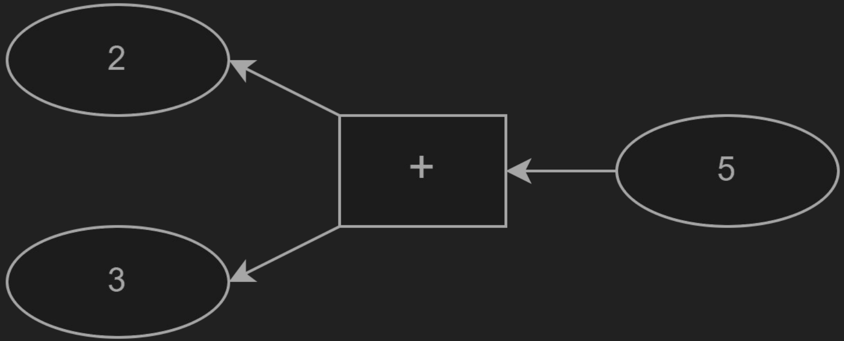

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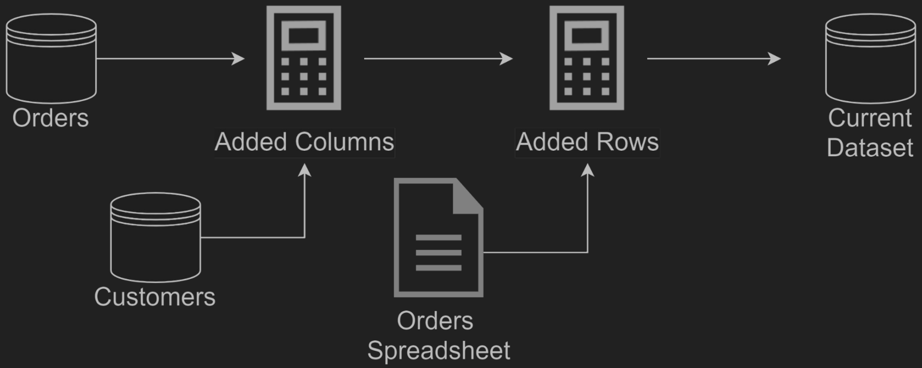

- No automatic error detection
- Does not encode real-world semantics
- Human verification still necessary

Datatype Issues: Current Solutions

1. Documentation

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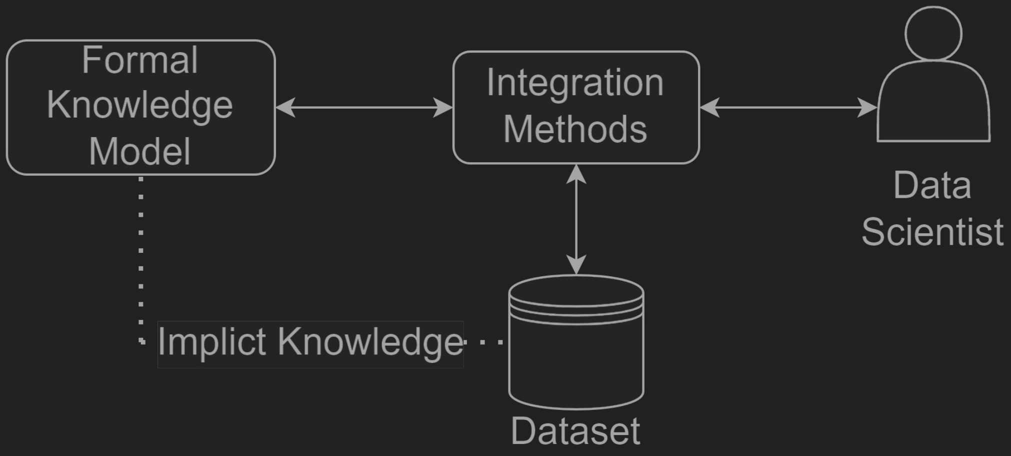
3. **Knowledge Representation**

Knowledge Representation

- Diverse knowledge can be represented at many levels of detail

- Integration method and role of data science operations is problematic



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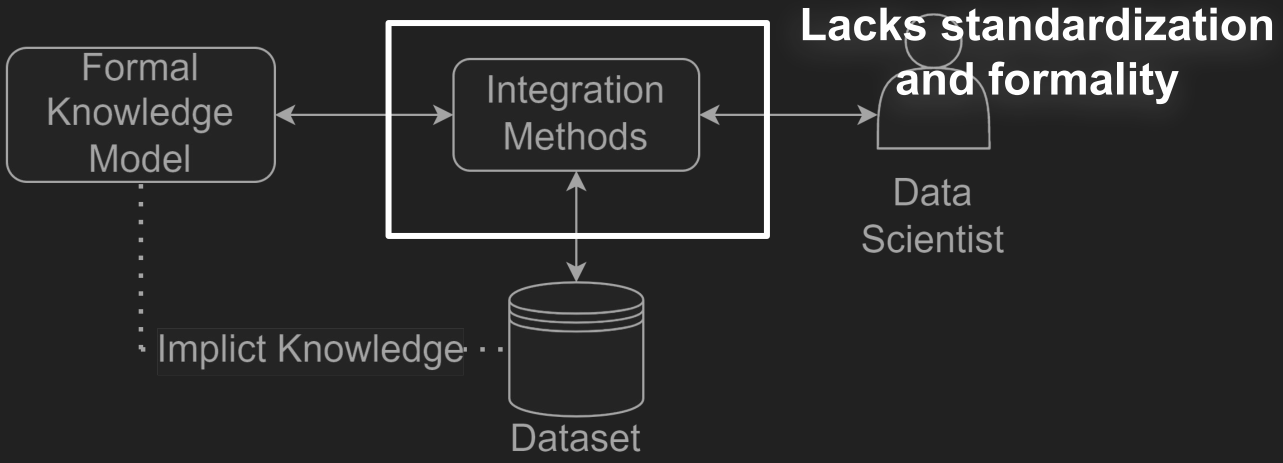

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Ontologically-Sound Dependent Type Systems for Data Science

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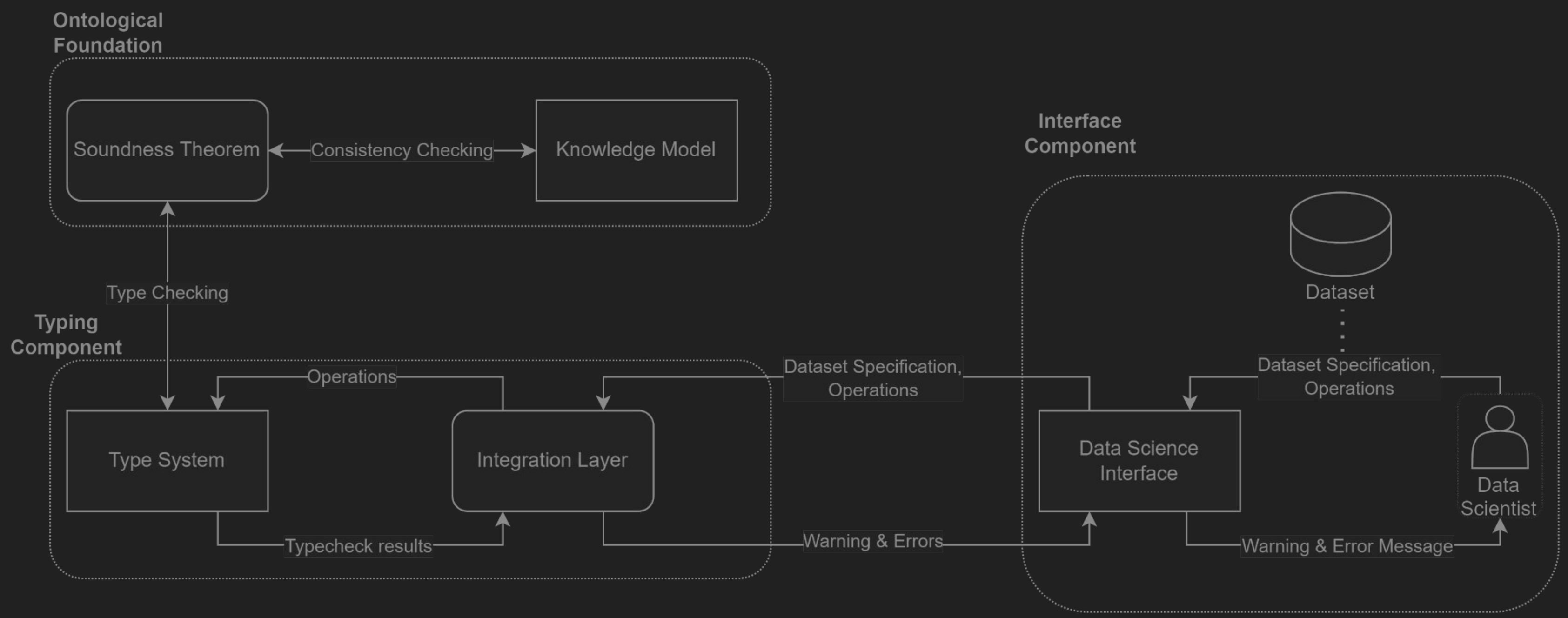

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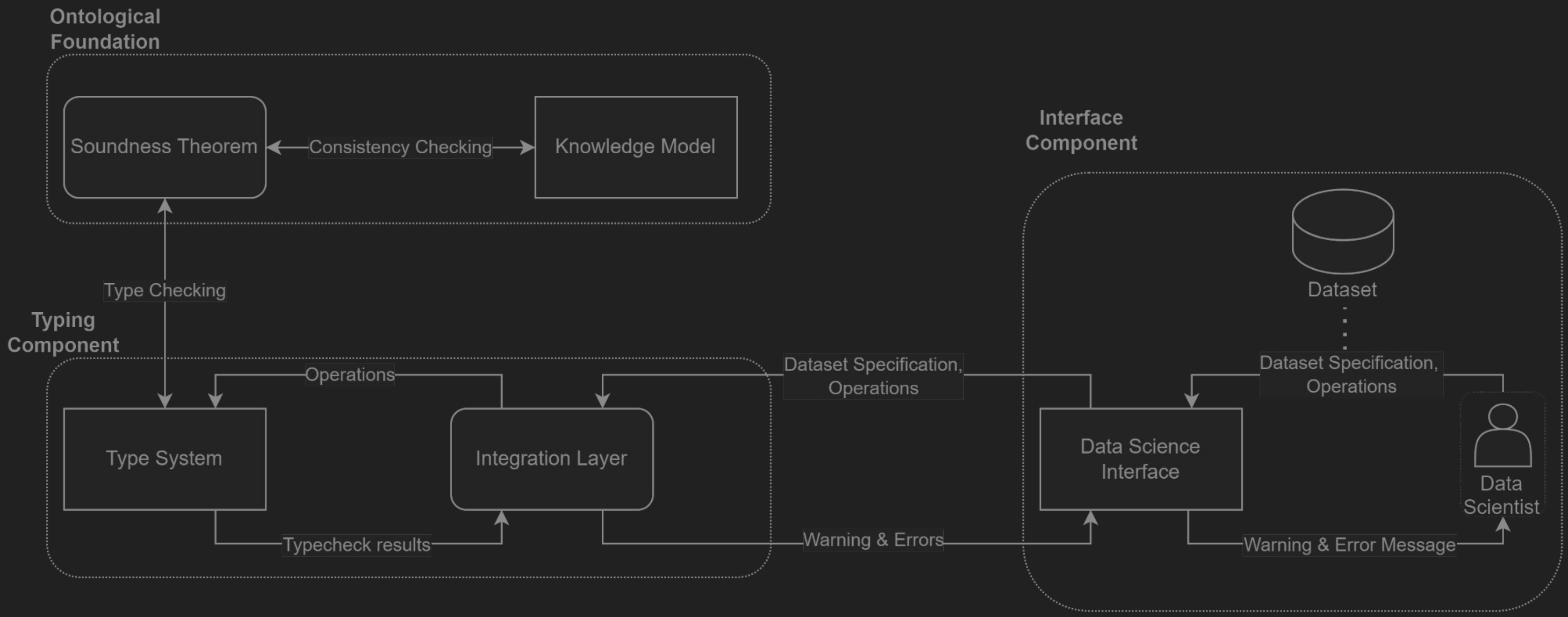

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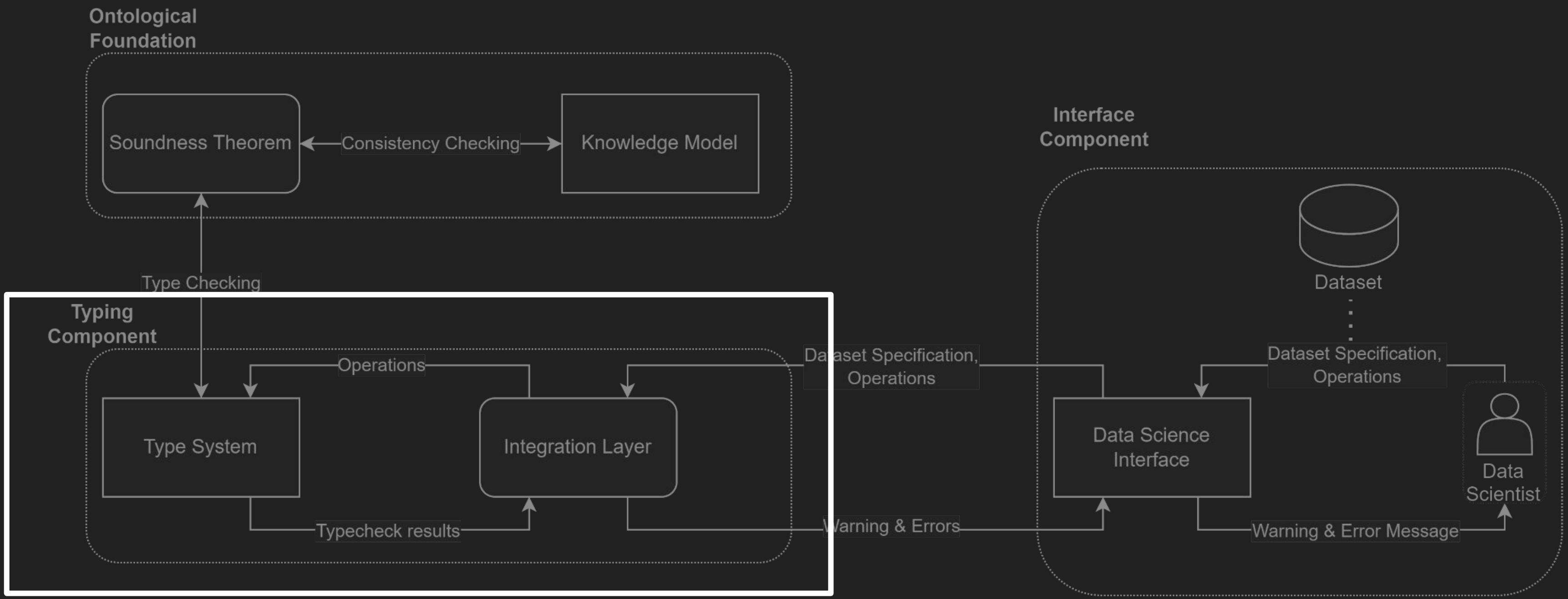

MeTS Type System

- Dependent pair types enforce operation preconditions

```
RegionSum : List Disjoint Region -> Region
```

- Values change after each operation : Provenance-Integrated

```
PopAvg(operands) = Avg Over operands
```

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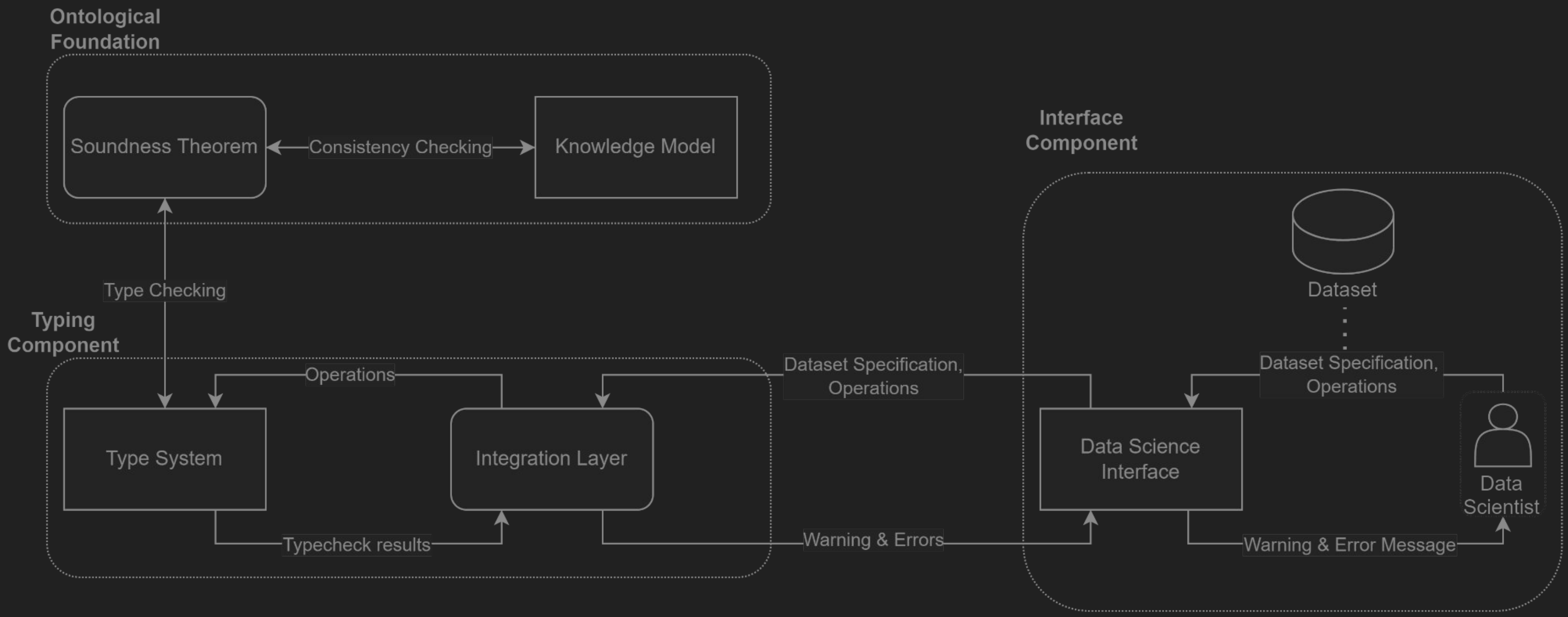

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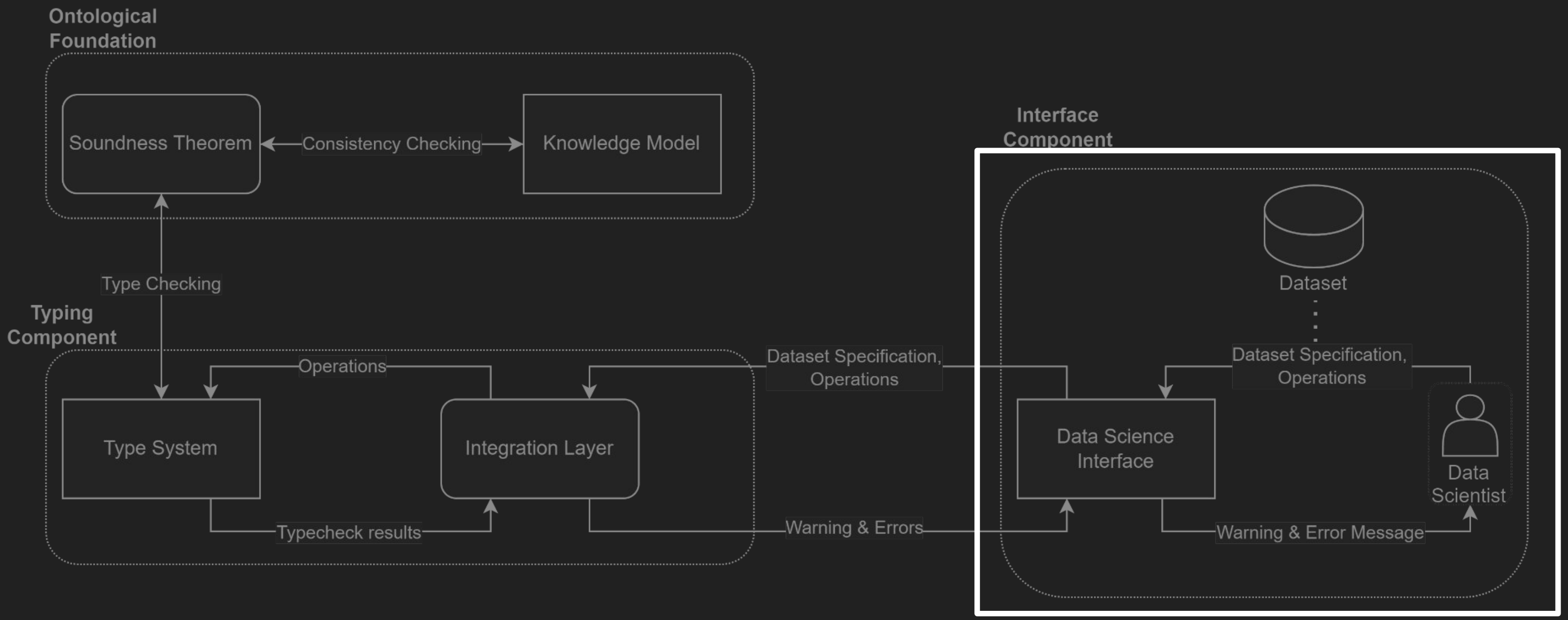

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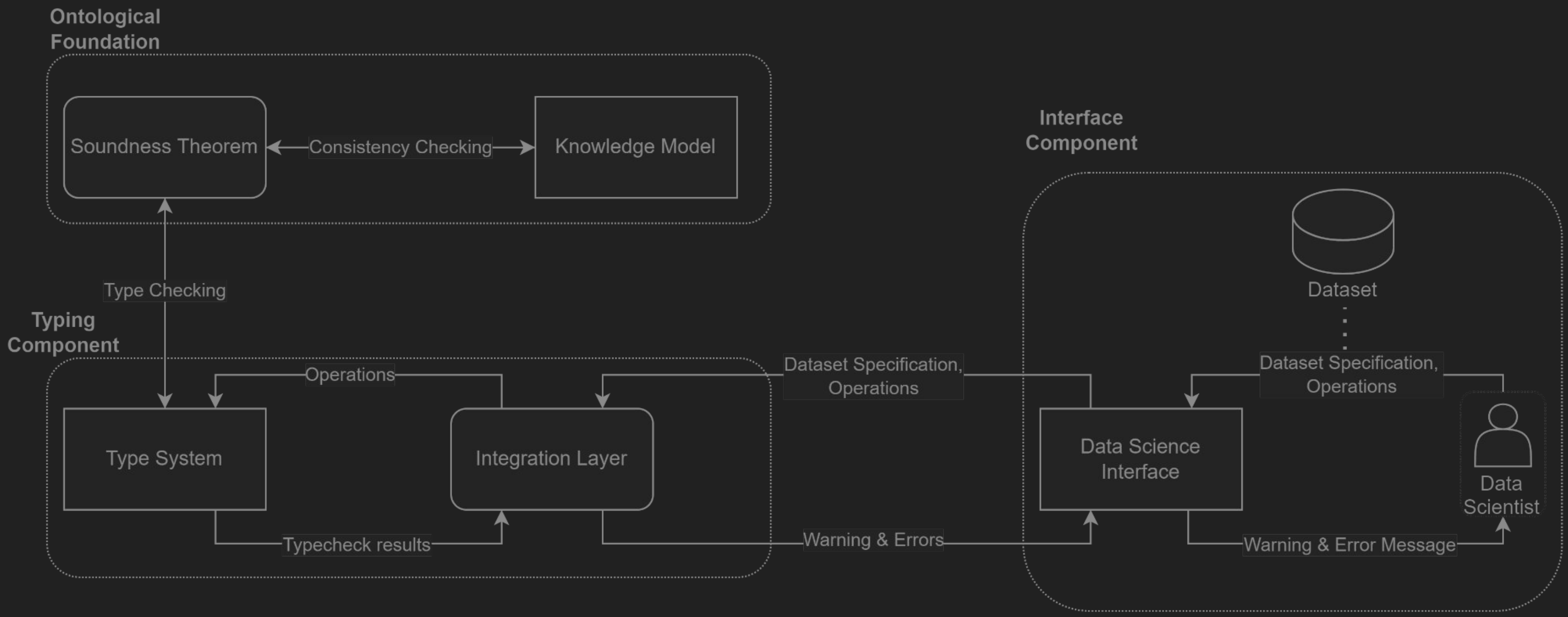

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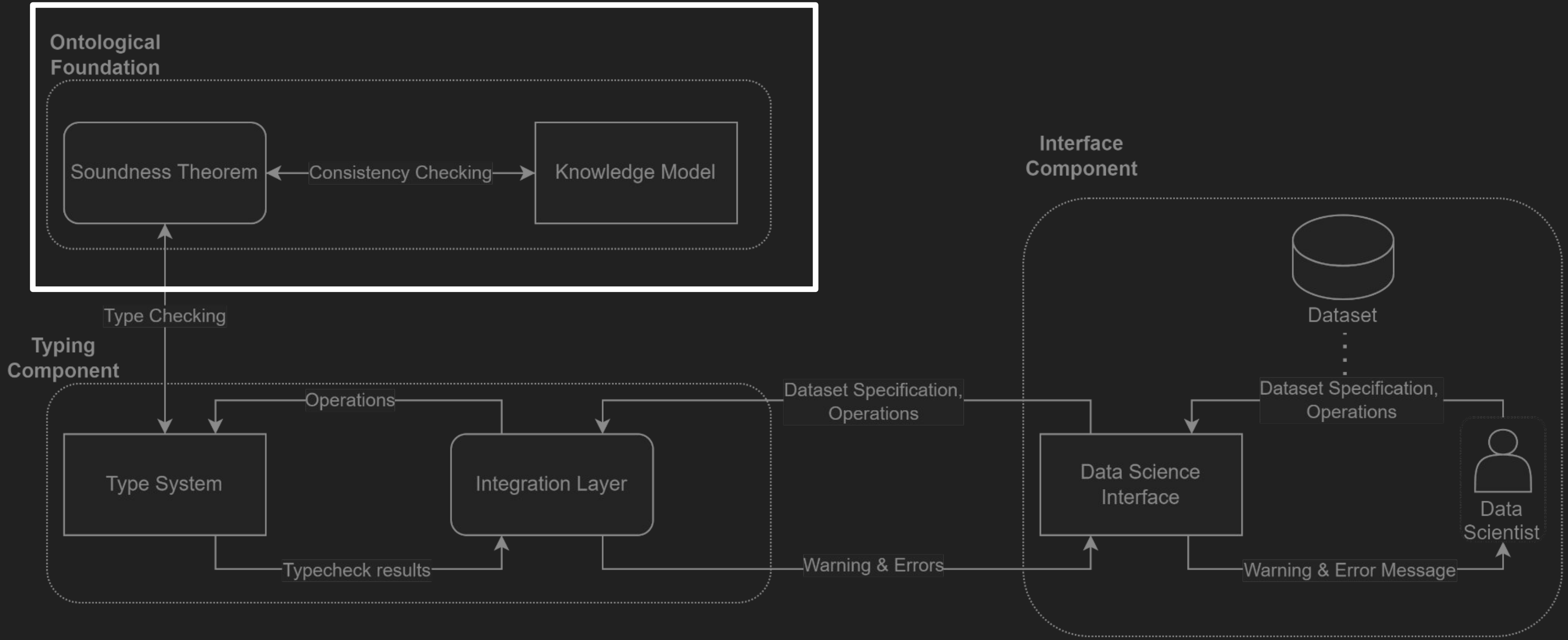

Census Data Ontology

- Represents the fundamental factors of census data
    - Movement of People
    - Crowd mereology
    - Geopolitical occupation
    - Geospatial mereology

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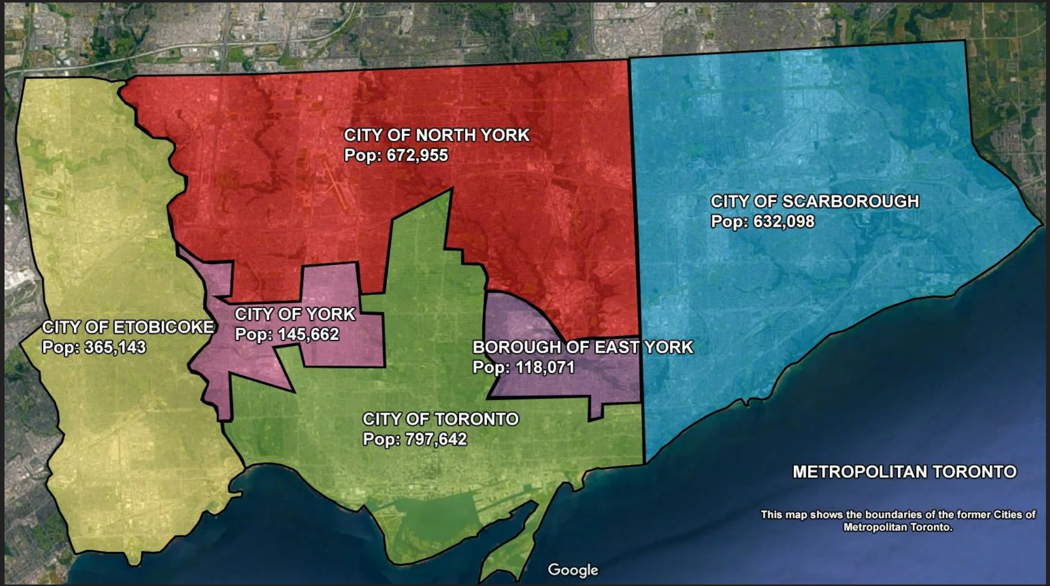
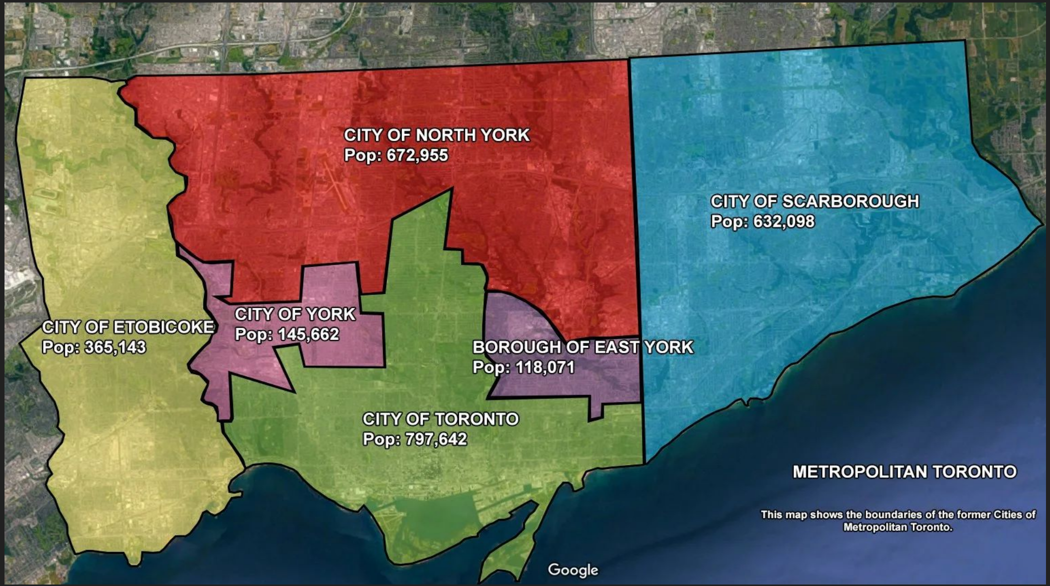


Census Data Ontology

- “I live in Toronto” - different interpretations over time

- Toronto as a region of land vs the geopolitical entity



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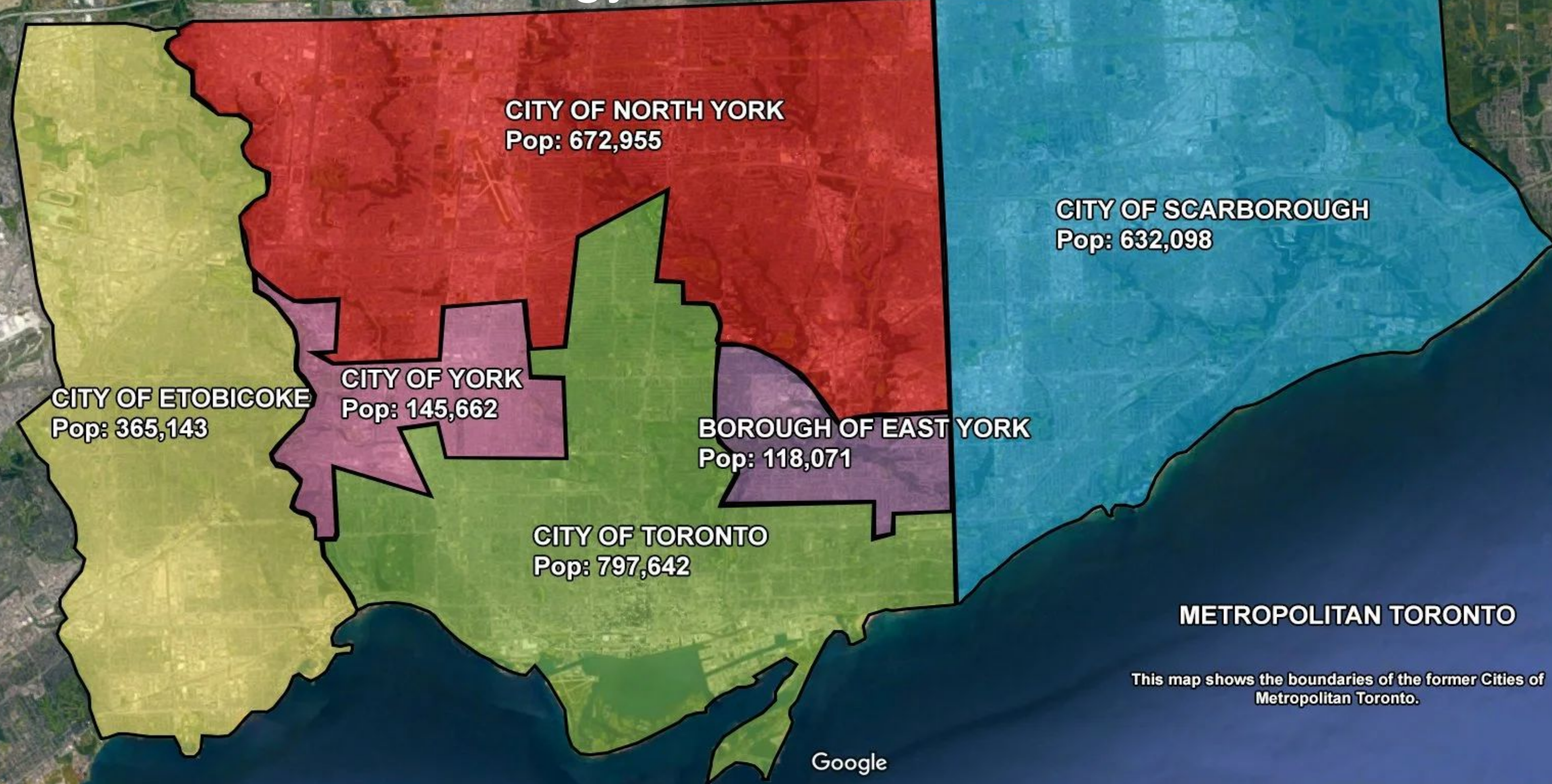

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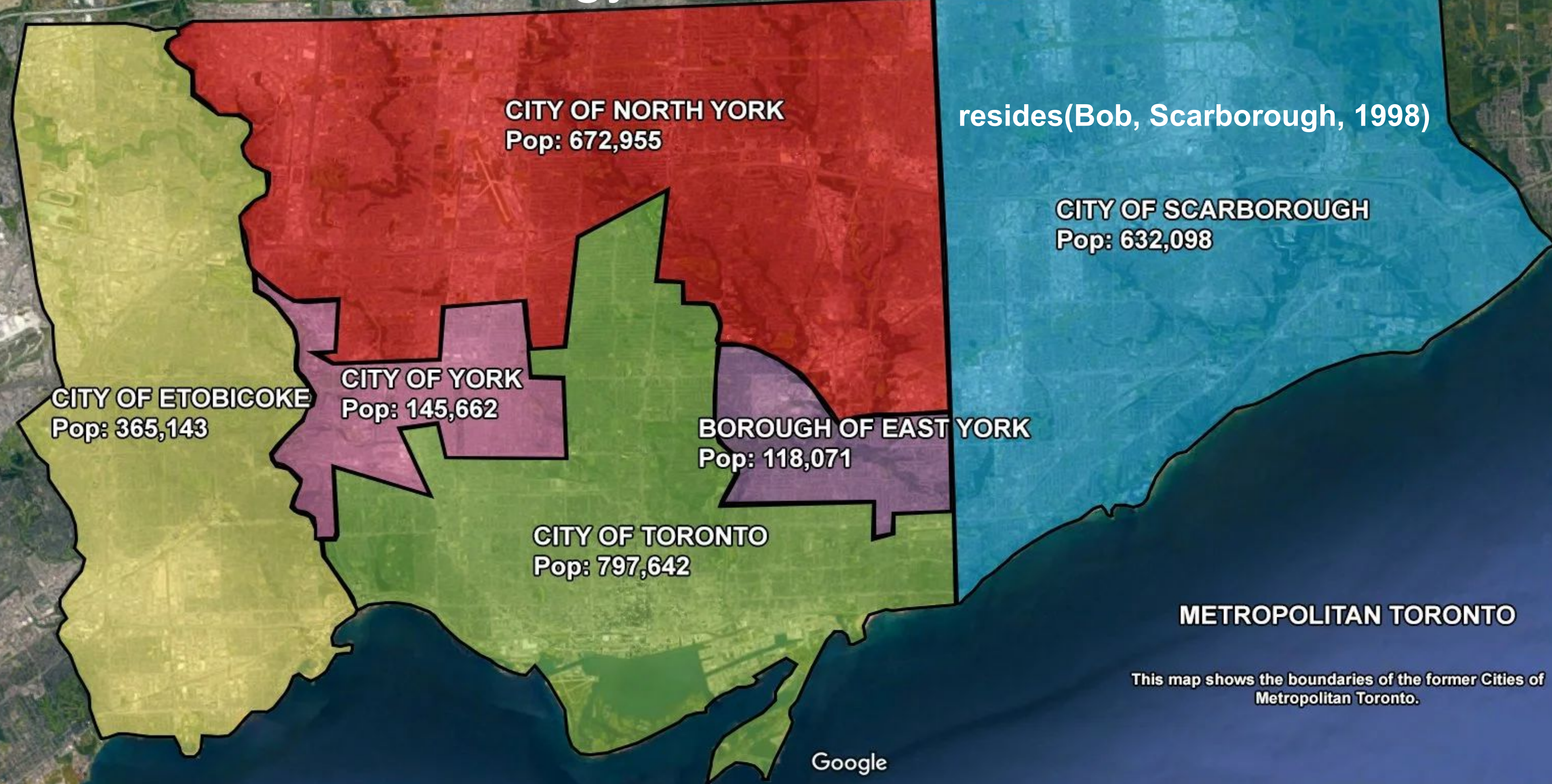

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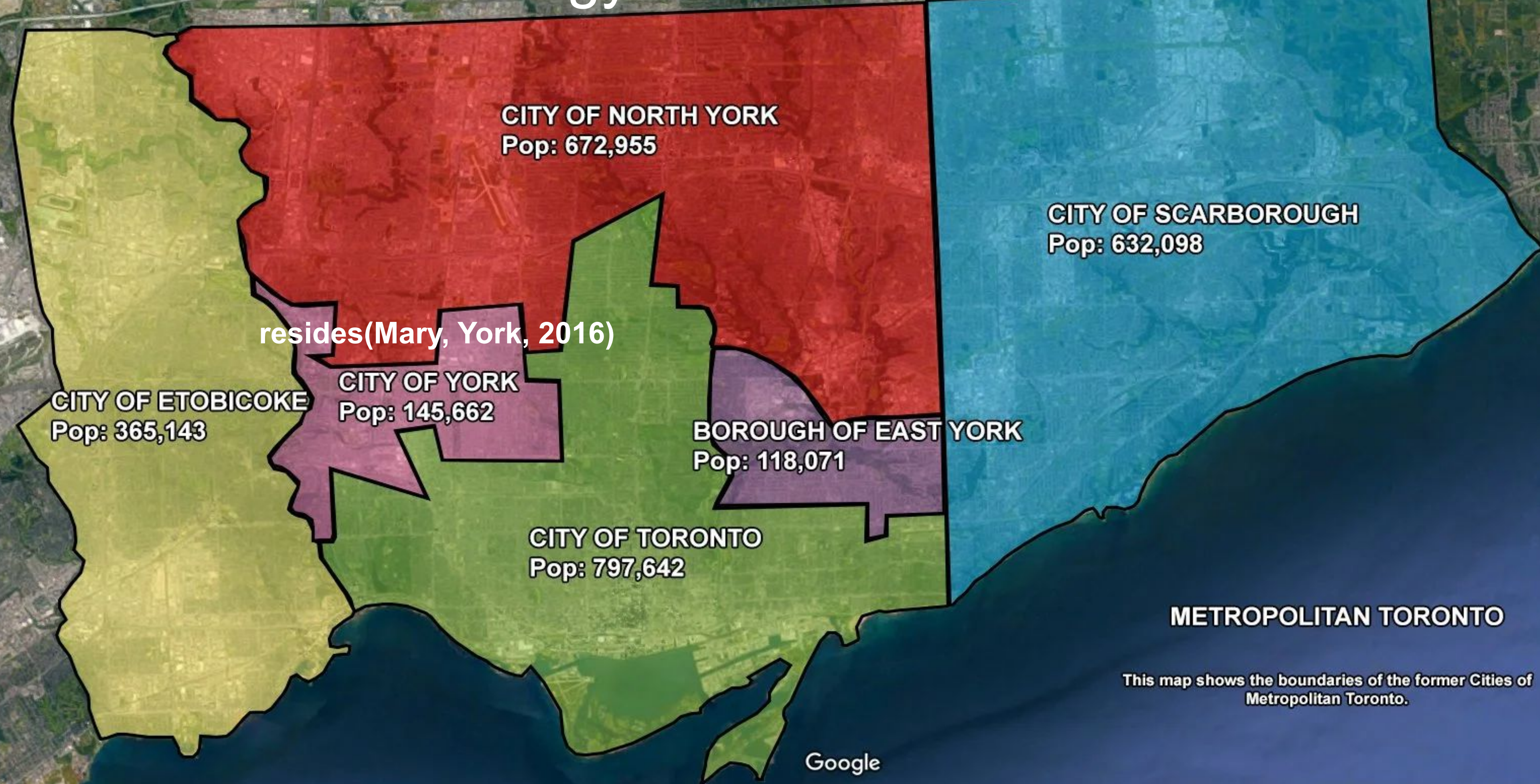

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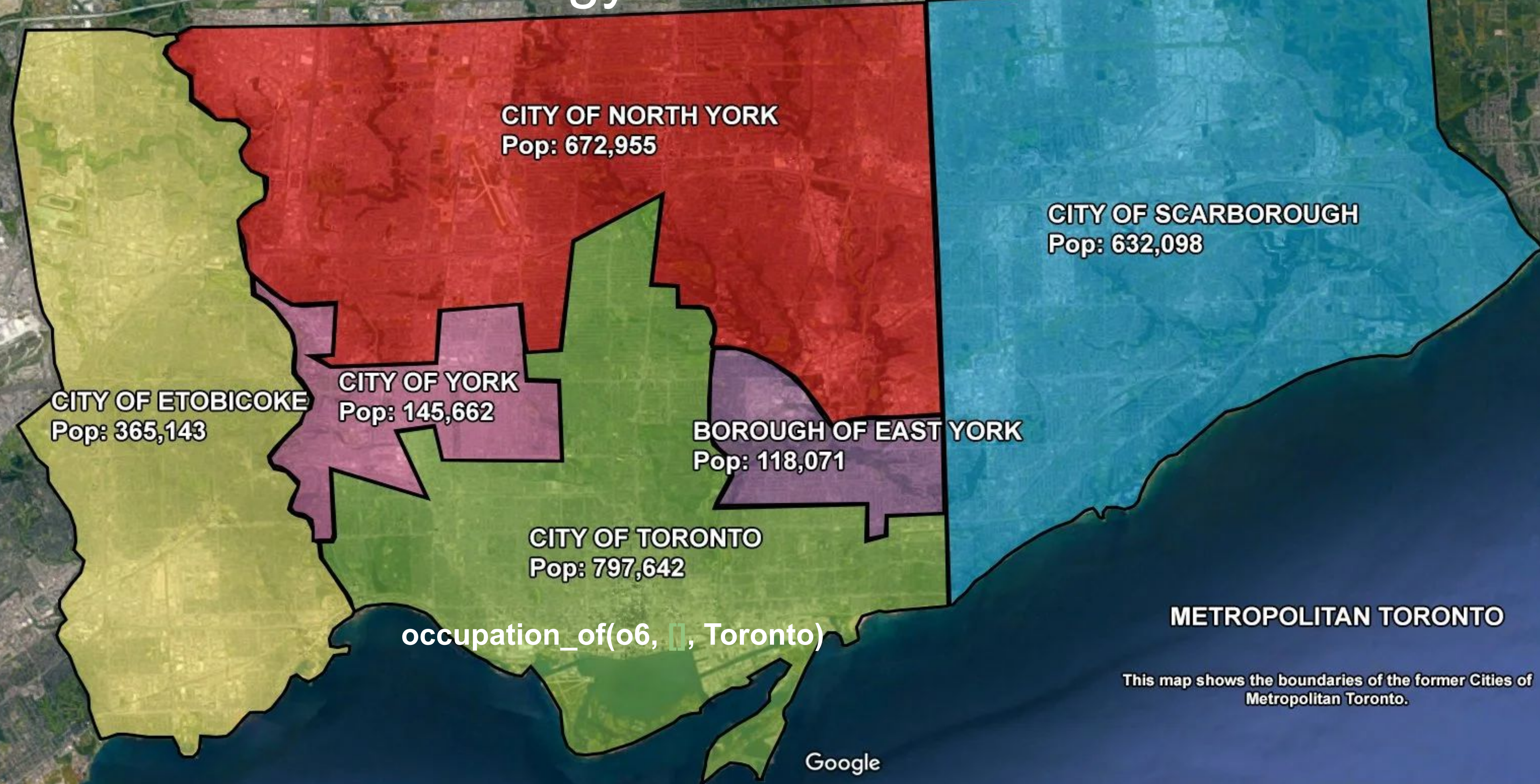

occupation_of(o6, [], Toronto)

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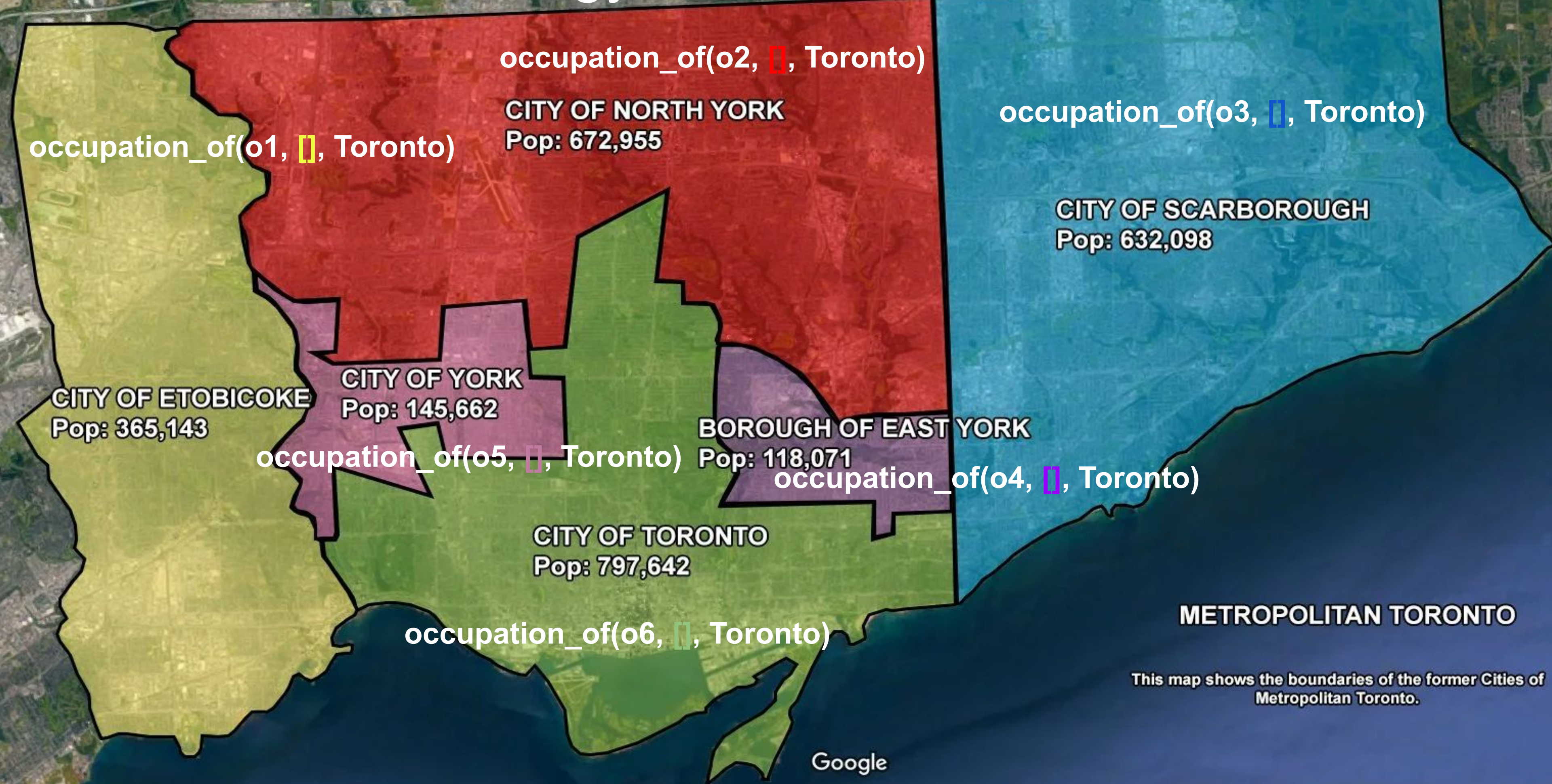

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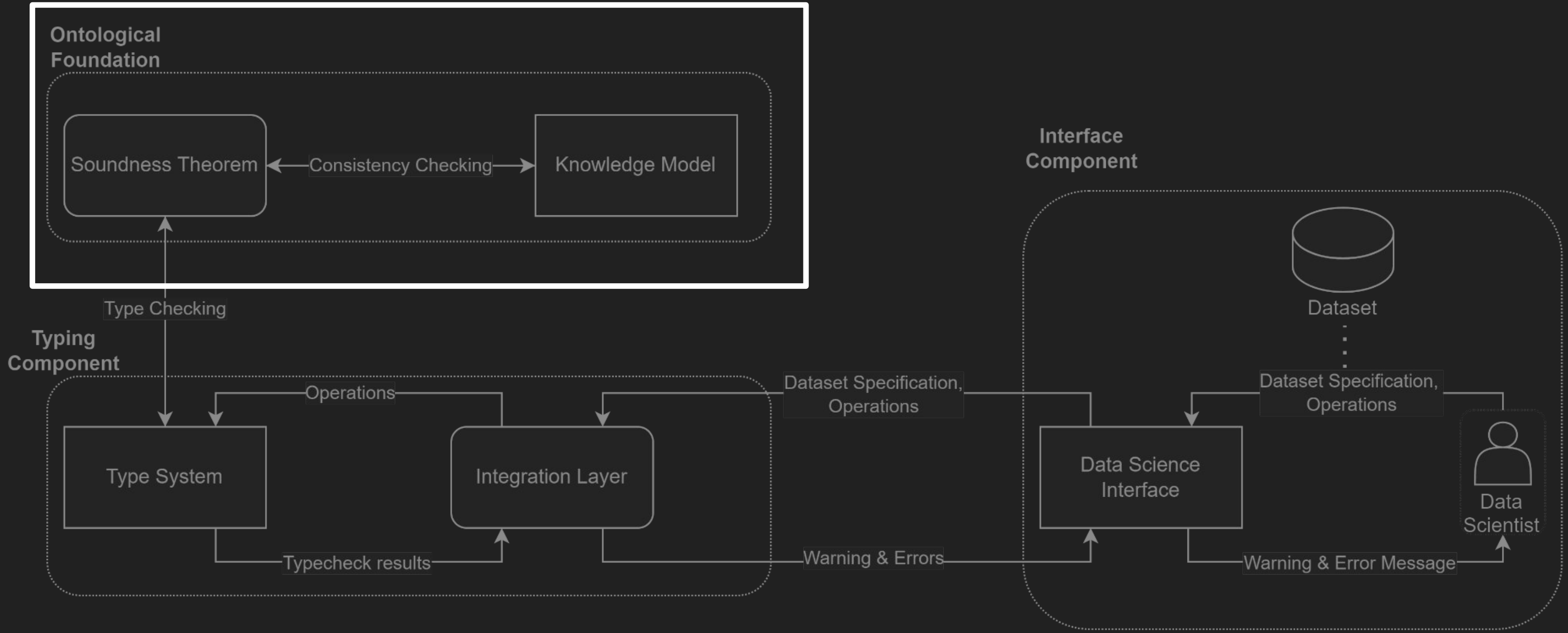

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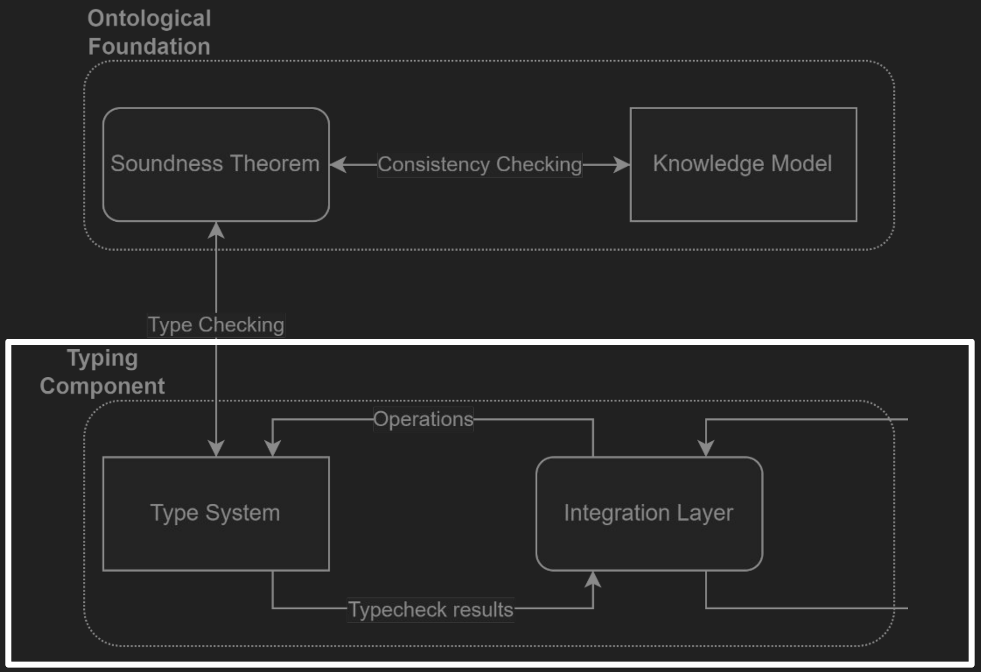

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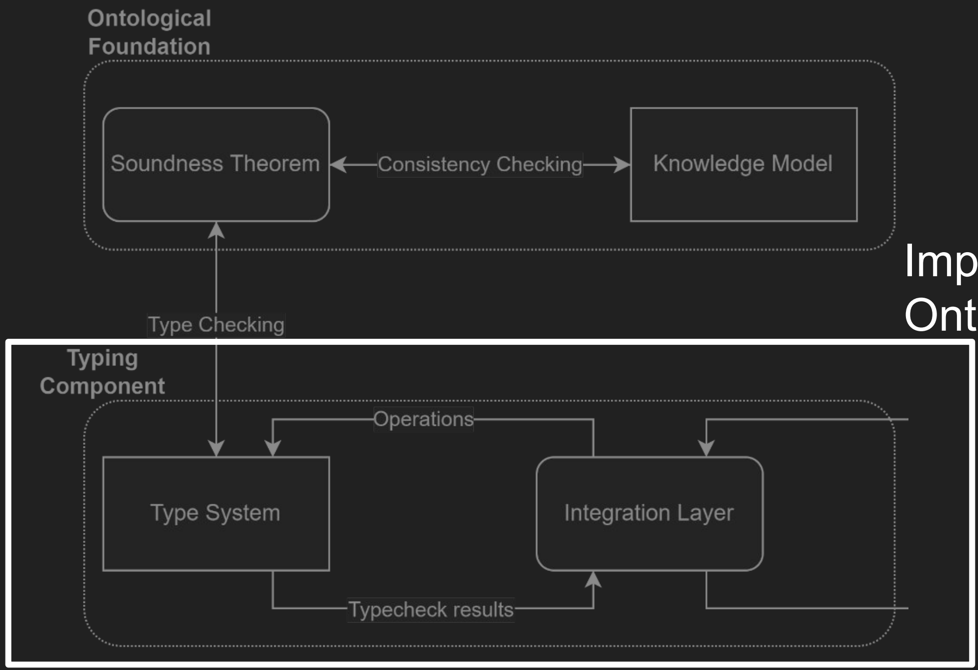

Implicit
Ontological Commitments

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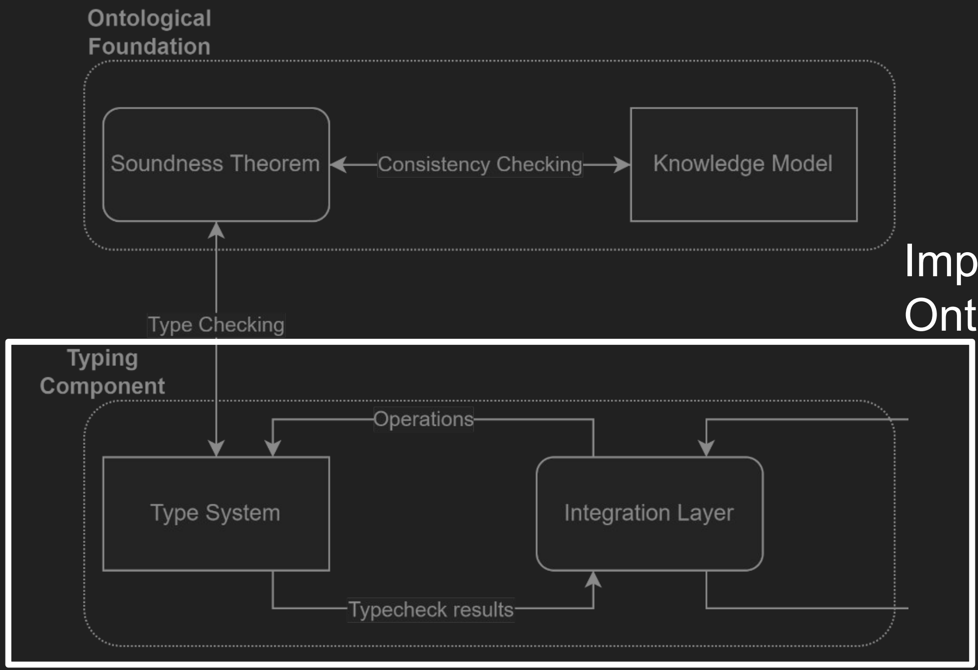

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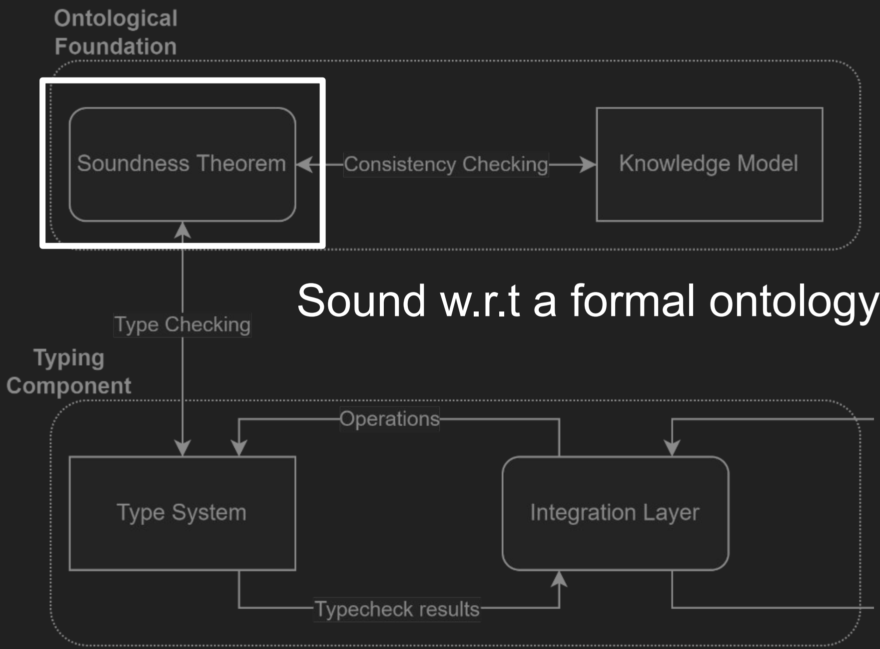

Sound w.r.t a formal ontology

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Contributions & Significance

1. MeTS Framework

2. Census Data Ontology

3. MeTS Soundness Theorem

Contributions & Significance

1. **MeTS Framework**

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Contributions & Significance

1. **MeTS Framework**
   I. Applies dependent types to model real-world knowledge for data science
   II. Elevates type safety to a meaningful result
   III. Ensures real-world interpretation is upheld throughout the data science pipeline

2. Census Data Ontology

3. MeTS Soundness Theorem

Contributions & Significance

1. MeTS Framework

2. **Census Data Ontology**

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Contributions & Significance

1. MeTS Framework

2. **Census Data Ontology**
   I. Models fundamental factors of census data
   II. Provides exceptional expressiveness
   III. Models census data operations

3. MeTS Soundness Theorem

Contributions & Significance

1. MeTS Framework

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3. **MeTS Soundness Theorem**

Contributions & Significance

1. MeTS Framework

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3. **MeTS Soundness Theorem**
    I. **Decouples ontological commitments from type system implementation**
    II. **Enables increased knowledge sharing**
    III. **Creates opportunities for efficient alternative reasoning**

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Future Work

1. **Correspondence Theorem**

2. Ontology for Data Quantities

3. Tractability

Future Work

1. **Correspondence Theorem**
   I. **Soundness AND completeness**
   II. **Requires detailed specification for logic and type systems**
   III. **New methods of collaboration**

2. Ontology for Data Quantities

3. Tractability

Future Work

1. Correspondence Theorem

2. **Ontology for Data Quantities**

3. Tractability

Future Work

1. Correspondence Theorem

2. **Ontology for Data Quantities**
   I. **Meta-model of existing ontologies**
   II. **Provenance and operation-centric**
   III. **Guides development of future ontologies and MeTS**

3. Tractability

Future Work

1. Correspondence Theorem

2. Ontology for Data Quantities

3. **Tractability**

Future Work

1. Correspondence Theorem

2. Ontology for Data Quantities

3. **Tractability**
   I. **Minimal change to data scientists workflow**
   II. **Integrate MeTS into existing data science tools**
   III. **Enable increased adoption**

Thank you!

Questions?

References

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