VectraFlow

An AI-Augmented Data-Flow System

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VectraFlow

A **data-flow engine**

that natively supports modern **ML models** with

an **extended relational model** for **unstructured** and **multi-modal** data processing

Supports **stream** and **batch** processing

Lighthouse Domain: Medical Data Lakes
(collaboration with the RI Hospital)

Example apps:

- Medical data summarization
- Early warning system
- Compliance monitoring
- Automatic report generation

Key requirements:

- Integrate ML models (including LLMs)
- Support stream and batch oriented processing
- Ensure high reliability and scalability

Data and Query Model

Classical **data-flow** architecture with an **extended** relational model:

- **Data types**
  - Vector (sparse and dense)
  - Unstructured (e.g., free-form text, images)
- **Manipulation operators**
  - E.g., convert data to vectors, cluster vectors
- **Semantic relational operators**
  - Based on vectors, LLM prompts, and general ML models
  - Retain general semantics of relational operators

Example Semantic Operators

iV-Filter(): applies **embedding similarity** to **select** incoming tuples (Lu et al., 2025)

E.g., **identify** incoming patient records that are similar to historical patient records

P-Agg(): prompts an **LLM** to **aggregate** over a window of tuples (Patel et al., 2024)

E.g., **summarize** over multiple medical documents

M-Filter(): invokes a **classifier** to **select** tuples based on their attributes (Lu et al., 2025)

E.g., **identify** abnormalities in medical imaging

…

Outline

Novel semantic operators + optimizations (iV-Filter)

Reliability features (integrity constraints)

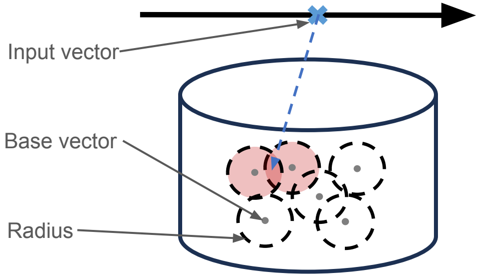
Working prototype

iV-Filter (Lu et al., 2025)

Motivation: **continuously filter** incoming vectors on the stream

In-memory table stores **base vectors** (i.e., base queries)

Each base vector has a **radius** (i.e., similarity threshold)



iV-Filter: selects **input vectors** that fall within the **radii** of **base vectors**

and returns the corresponding base vector IDs

Use case: early warning systems

identify incoming patient records that are similar to historical patient records

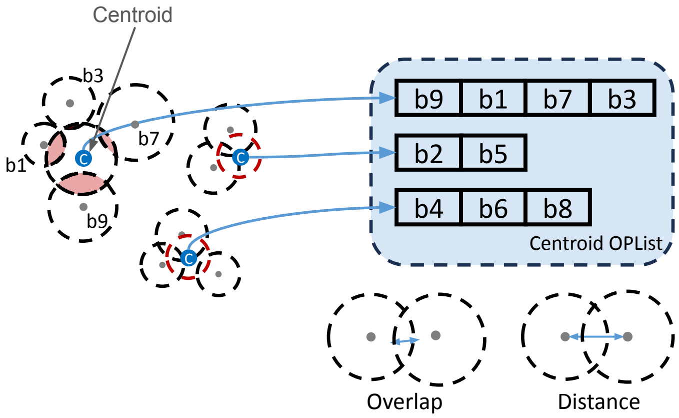
iV-Filter Optimizations

Centroid OPList (Overlapped Partition List):

- Insight: base vectors containing the incoming vector must **overlap**
- OPList: **list** of base vectors that **overlap** with the given base vector
- Centroid OPList**: cluster** base vectors and assign a **radius** + **OPList** to each **centroid**

Search: assign input vector to the nearest centroid and **scan** its **OPList** for base vectors that contain the input vector

Other optimizations: batching, sorting, bucketing, early stopping



b9 b1 b7 b3

b2 b5

b4 b6 b8

Semantic Integrity Constraints

Problem: semantic operators may yield **erroneous** results

Solution: **guardrails** around semantic operators to enforce **data consistency**

- User-specified **predicates** on output tuples
- Can apply **constrained decoding** for certain predicates
- Otherwise,
    - if tuple violates predicates, **retry** operator
    - if specified retry threshold is reached, **drop** tuple

Integrity Constraint Classes

IC Class	Use Case
Domain	Medication dose stays within clinically safe **boundary**
Inclusion/exclusion	Generated business report doesn’t **contain** undesirable language
Grounding	Extracted test records are **present** in the original medical document
Check <predicate>	Evaluate **arbitrary** predicates (e.g., simple statements, UDFs)

Grounding Constraints

Output values from attribute-generating semantic operators are derived from:

- Knowledge **internal** to the LLM (i.e., **parametric** knowledge)
- Knowledge **external** to the LLM (i.e., **non-parametric** knowledge)
  - Input tuples to the system
  - Returned tuples from in-memory tables

} **source tuples**

Verification use cases:

- Extractive (e.g., medical test result extraction)
- Abstractive (e.g., medical data summarization)

Want: attribute value is **grounded** in its **source tuple(s)**

Enforcing Grounding Constraints

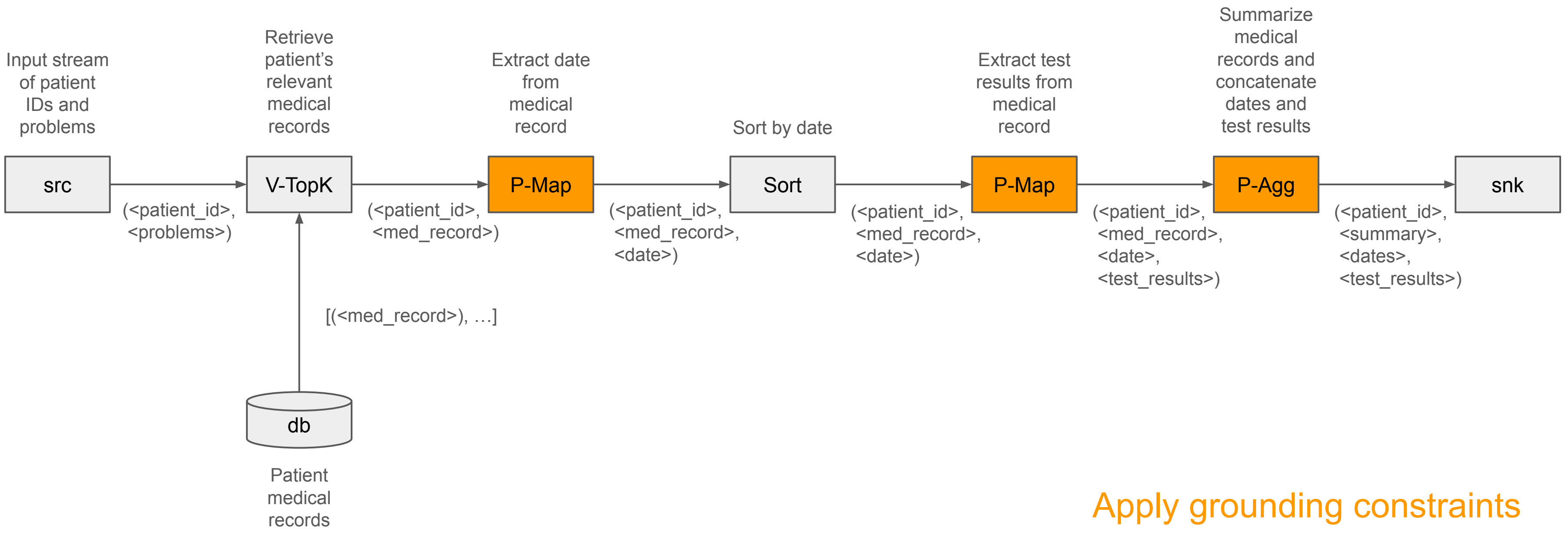
Want: attribute value is **grounded** in its **source tuple(s)**

- Recursively apply **checks** to all attributes in the attribute’s **lineage**
- **Check**: output value is **grounded** in input value(s)
- Require different **grounding semantics** depending on the **use case**

Semantics	Verification Mechanism	Use Case
Match	Exact keyword match	Extractive
Similarity	Similarity score	Abstractive
Model	LLM evaluator	Extractive + abstractive

Demo!

Demo: Medical History Summarization



Input stream of patient IDs and problems

Retrieve patient's relevant medical records

Extract date from medical record

Sort by date

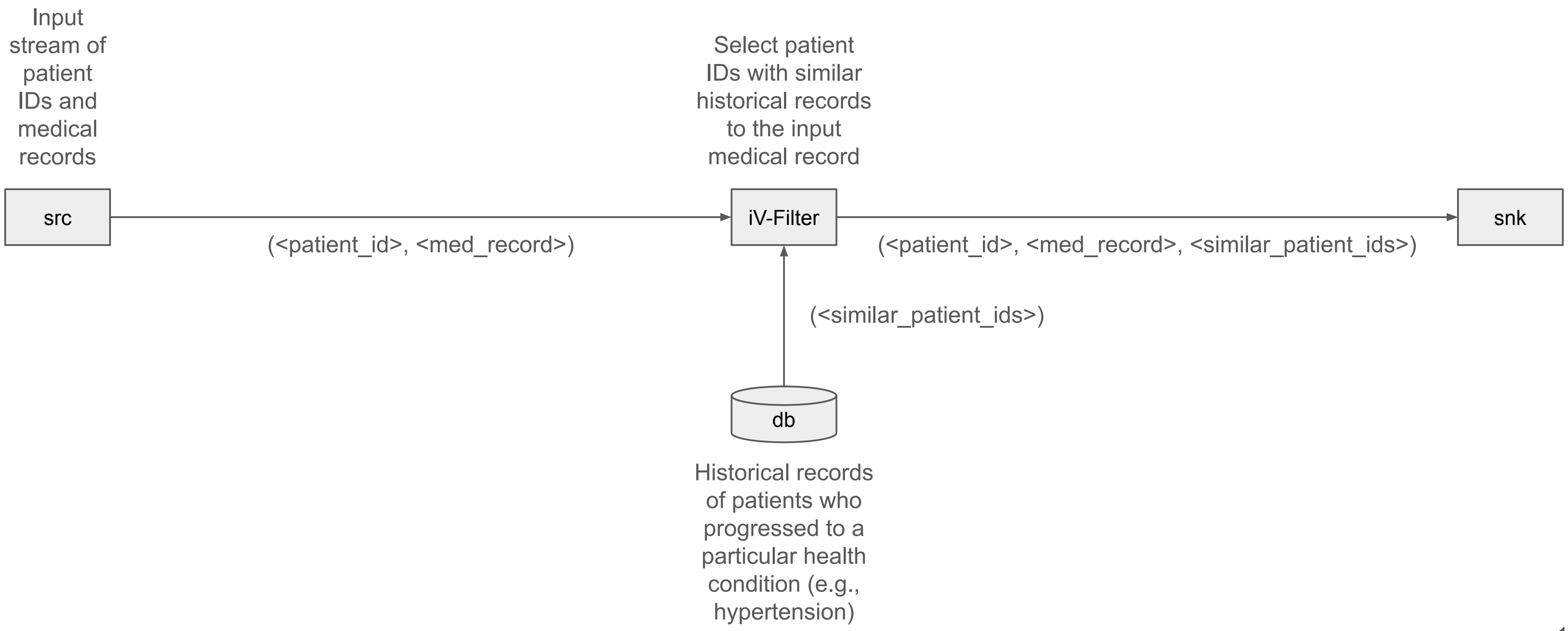
Extract test results from medical record

Summarize medical records and concatenate dates and test results

src
(<patient_id>, <problems>)
V-TopK
[(<med_record>), …]
db
Patient medical records
(<patient_id>, <med_record>)
P-Map
(<patient_id>, <med_record>, <date>)
Sort
(<patient_id>, <med_record>, <date>)
P-Map
(<patient_id>, <med_record>, <date>, <test_results>)
P-Agg
(<patient_id>, <summary>, <dates>, <test_results>)
snk

Apply grounding constraints

Demo: Early Warning System



Input stream of patient IDs and medical records

Select patient IDs with similar historical records to the input medical record

src

iV-Filter

snk

(<patient_id>, <med_record>)

(<patient_id>, <med_record>, <similar_patient_ids>)

(<similar_patient_ids>)

db

Historical records of patients who progressed to a particular health condition (e.g., hypertension)

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