VQPy: An Object-Oriented Approach to Modern Video Analytics

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The Surge of Video Data

Surveillance Cameras

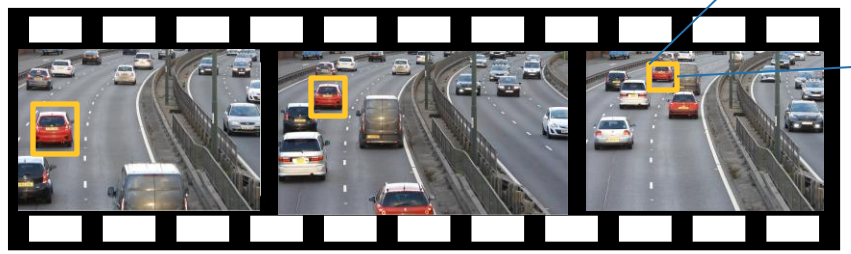
1 billion installed in the world in 2021

Autonomous Driving

A self-driving test vehicle generates **20 to 40 TB** of data per day.

Video Query

Amber alert: The license plate of a red Honda heading north.



Response: “FX66 UUW”

Intersection incident type: A turning right vehicle collides with a going straight vehicle.

Video queries center on video objects and their spatial/temporal relationships.

Response: “frame [i, i + k]”

Complexity of Video Queries: Multiple CV Tasks Required

AMBER alert: The license plate of a red Honda heading north.

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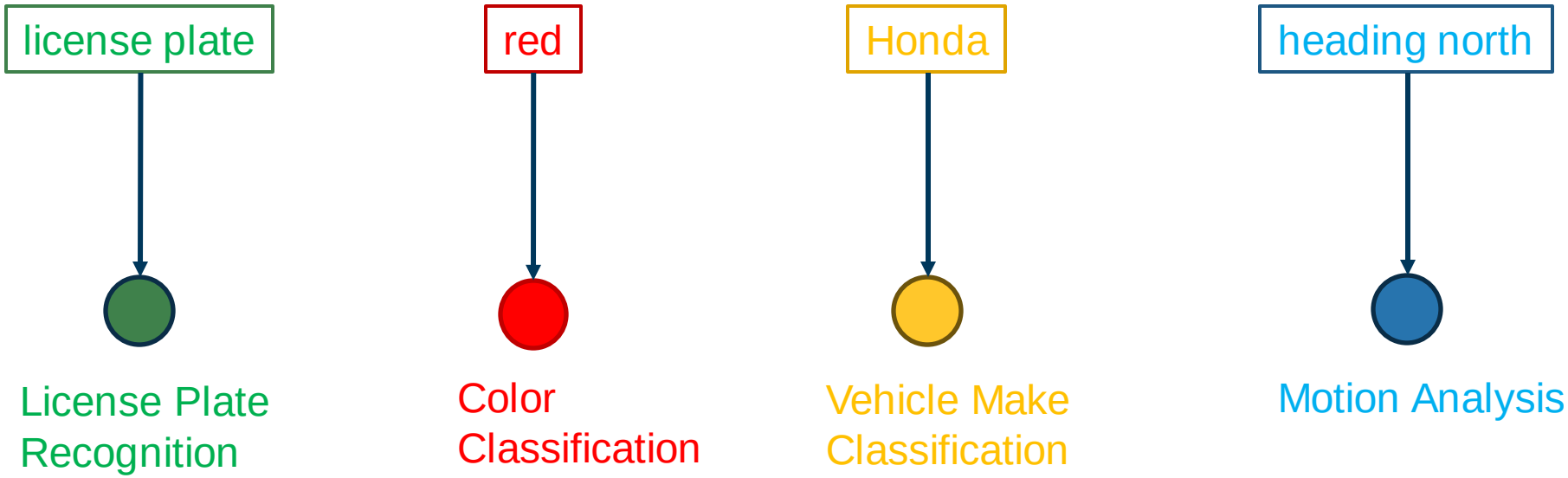
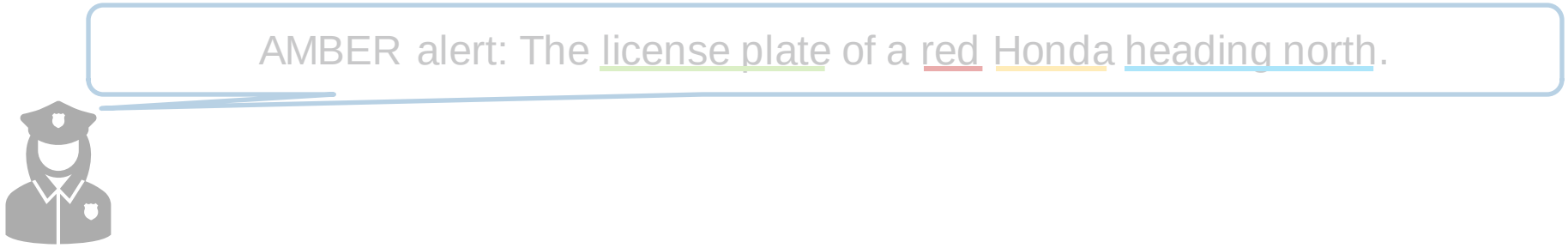


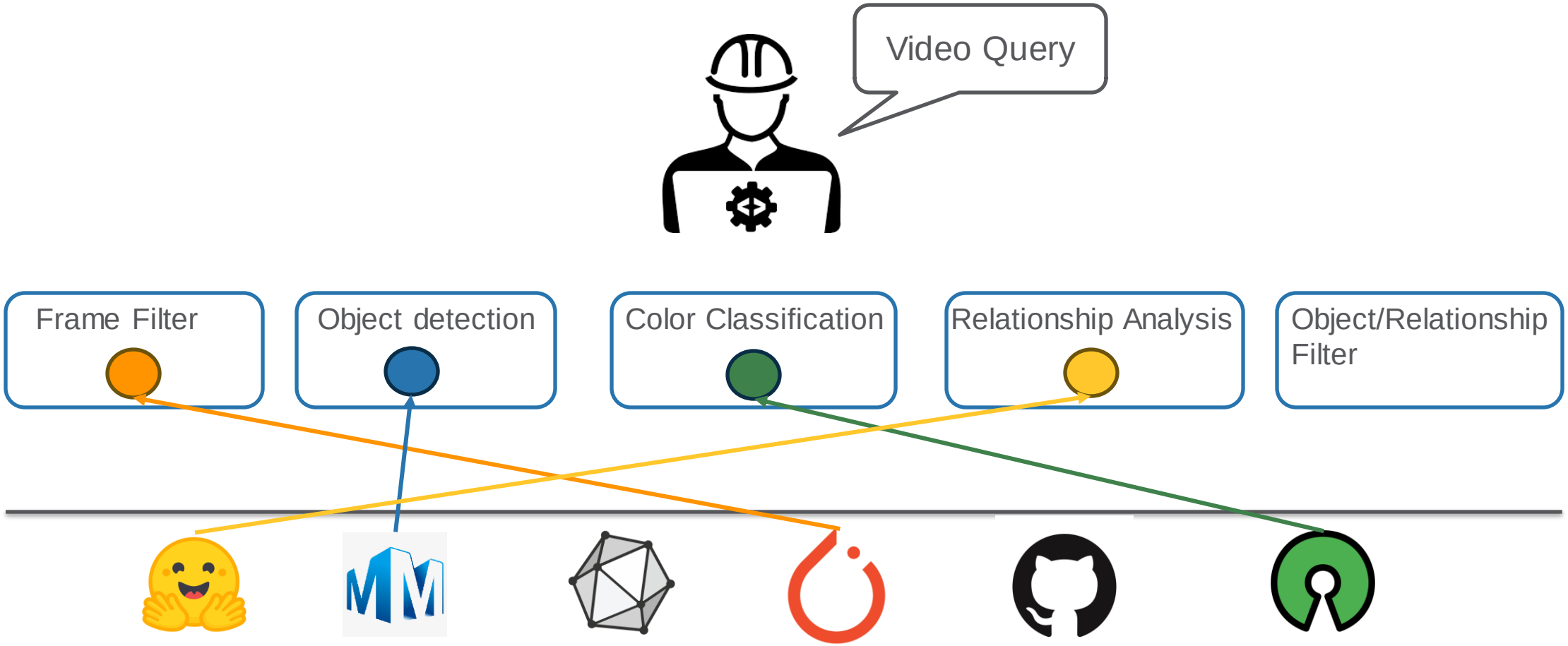
Complexity of Video Queries: Multiple CV Tasks Required



How to efficiently answer specific video queries?

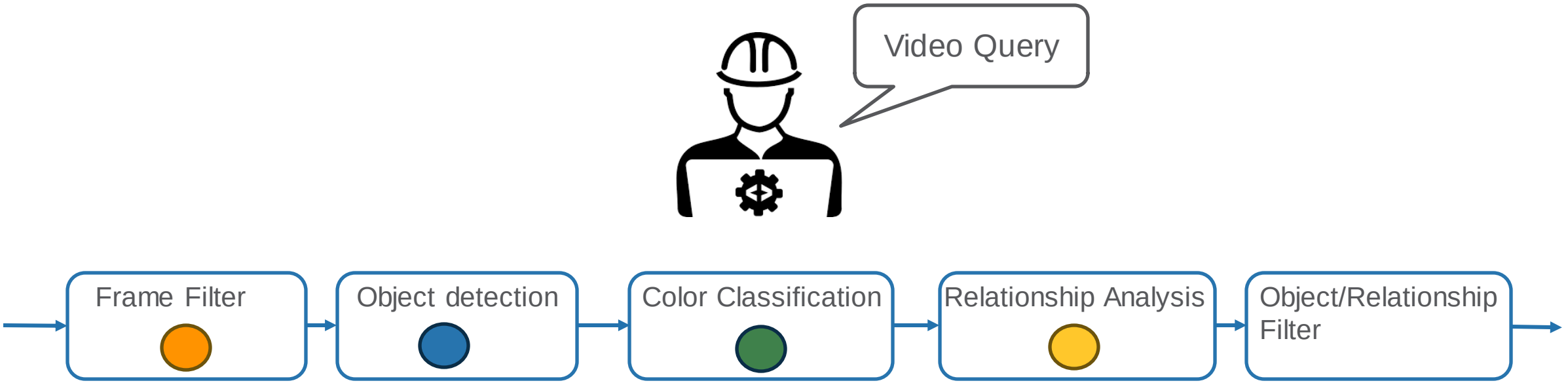
- License Plate Recognition
- Color Classification
- Car Make Classification
- Motion Analysis

Solution 1: Handcrafting Pipelines



Problem 1: Pipelines need to be manually constructed.

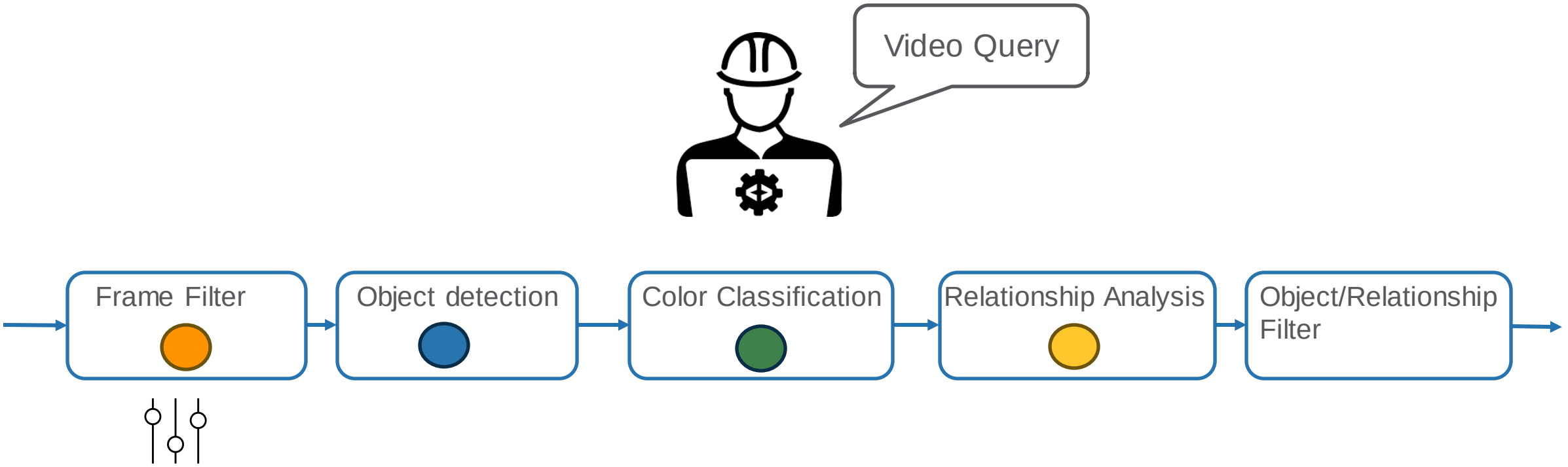
Solution 1: Handcrafting Pipelines



Writing glue code to connect the tasks together

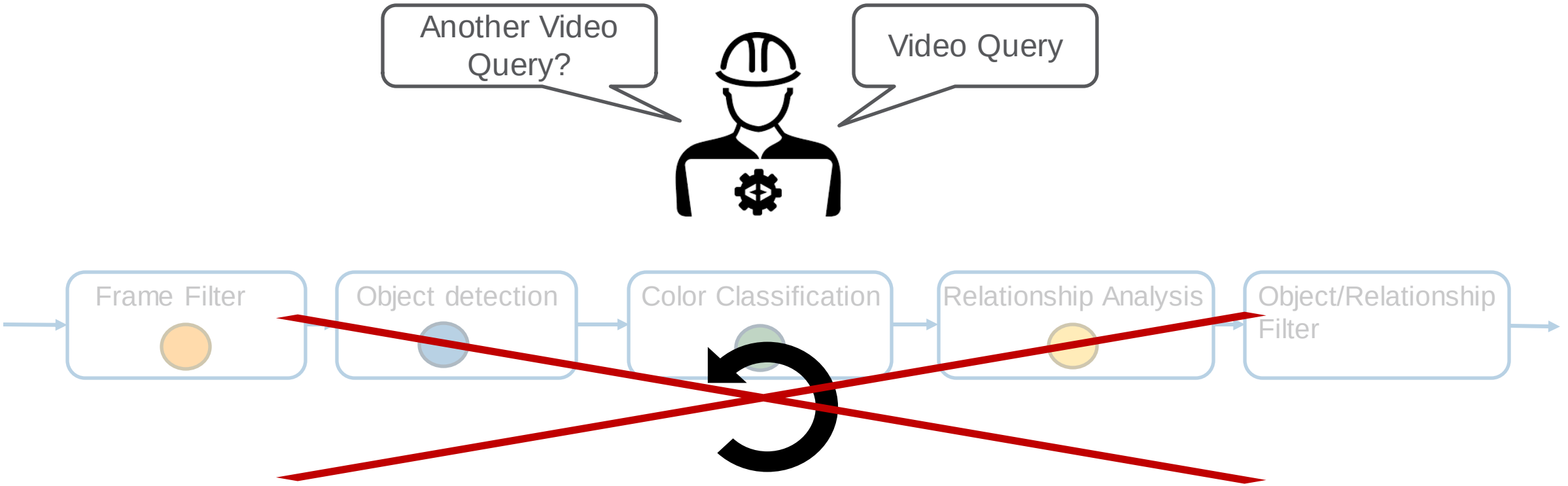
Problem 1: Pipelines need to be manually constructed.

Solution 1: Handcrafting Pipelines



Problem 2: Pipeline need to be manually optimized.

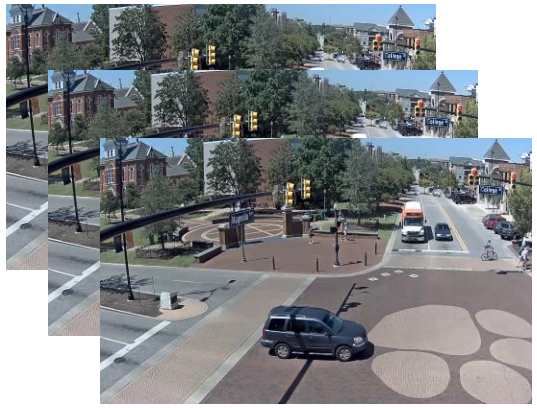
Solution 1: Handcrafting Pipelines



Problem 3: Each pipeline is subject to answer one query.

Solution 2: SQL-based Video Query Frameworks

A SQL-like query expression

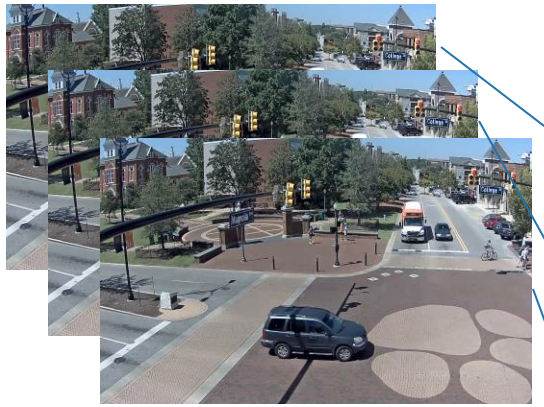


Solution 2: SQL-based Video Query Frameworks

Think like a table

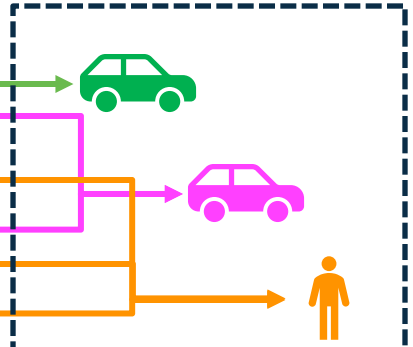
Lack of a video object abstraction

Tabular-based data model



frame_id	bboxes	labels	scores
0	[[1 2, 4, 5], [2, 3, 8, 9], …, [7, 6, 5, 3]]	[car, car, bus, person]	[0.5, 0.9, 0.8, 0.6]
1	[[4, 6, 7,8], [6, 7, 4, 5]]	[car, person]	[0.9. 0.8]
2	[[6, 5, 7, 6], …]	[person, …]	[0.9, …]

Video objects



A SQL-like query expression

```
LOAD VIDEO 'video.mp4'
INTO MyVideo;

CREATE FUNCTION Add1
IMPL './add1.py';

CREATE FUNCTION Velocity
IMPL './velocity.py';

CREATE FUNCTION Color
IMPL './color.py';

CREATE TABLE
    TrackResult
AS
SELECT
        id, Color(Crop(data, bbox)), T.iid,
            T.bbox, T.score, T.label
FROM MyVideo
    JOIN LATERAL
        UNNEST(EXTRACT_OBJECT(
                data, Yolo, NorFairTracker))
        T(iid, label, bbox, score);

CREATE TABLE
    TrackResultAdd1
AS
SELECT
        Add1(id, iid, bbox)
    FROM
TrackResult

CREATE TABLE
    TrackResultJoin
AS
SELECT
        trackresult.id, trackresult.iid,
        trackresult.color, trackresult.bbox,
        trackresult.label, trackresult.score,
        trackresultadd1.last_bbox
    FROM
        TrackResult JOIN TrackResultAdd1
    ON
        trackresult.id = trackresultadd1.added_id
    AND
        trackresult.iid = trackresultadd1.cur_iid;

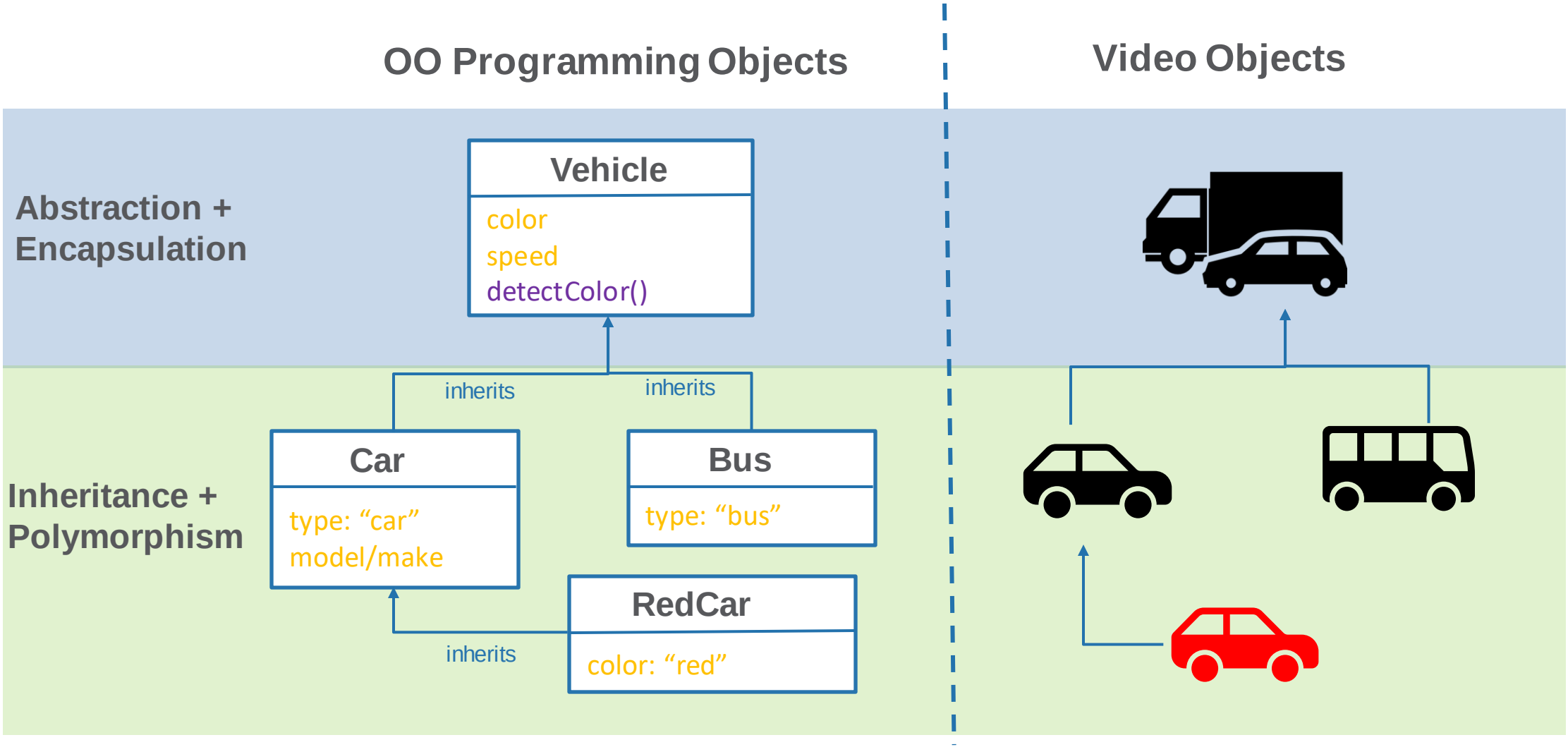
SELECT
    id, iid, bbox
FROM
    TrackResultJoin
WHERE
    Velocity(bbox, last_bbox) > 1
AND
    color = 'red' AND label = 'car';

DROP TABLE IF EXISTS MyVideo;
DROP TABLE IF EXISTS TrackResult;
DROP TABLE IF EXISTS TrackResultAdd1;
```

A red speeding car query

Can we have a video object abstraction for video queries?

Insight: Video Objects Are Similar to Objects in OO Programming



VQPy – An Object-Oriented Approach to Video Analytics

Frontend: A Python library for video-object-oriented programming

Express a Red Speeding Car Query

With a SQL-like language

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DROP TABLE IF EXISTS TrackResultAdd1;
```

With VQPy

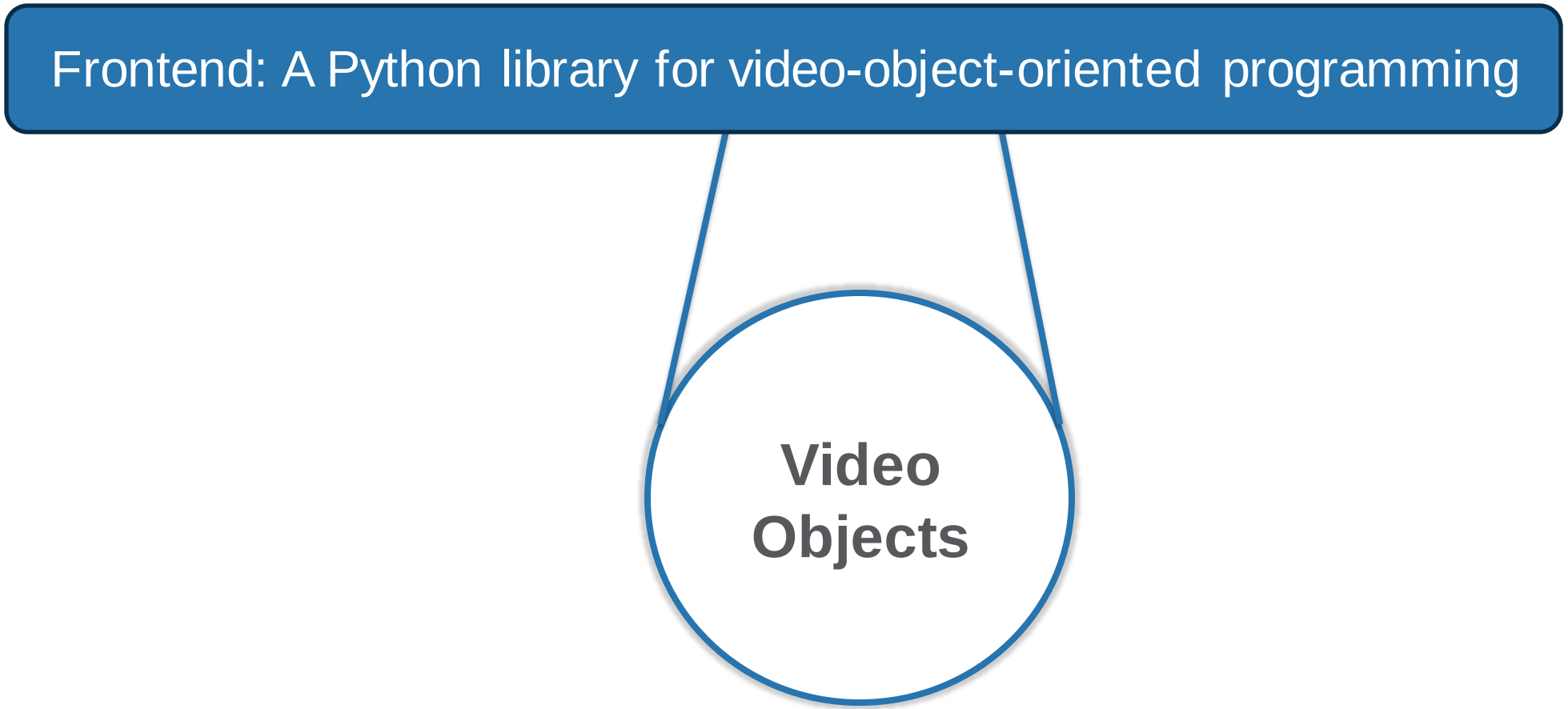
```
vobj Car(vqpy.Vehicle):
    def __init__(self):
        self.model = "yolov8m"
    # inherit color and velocity properties from Vehicle

query RedSpeedCar(vqpy.Query):
    def __init__(self):
        self.car = Car()

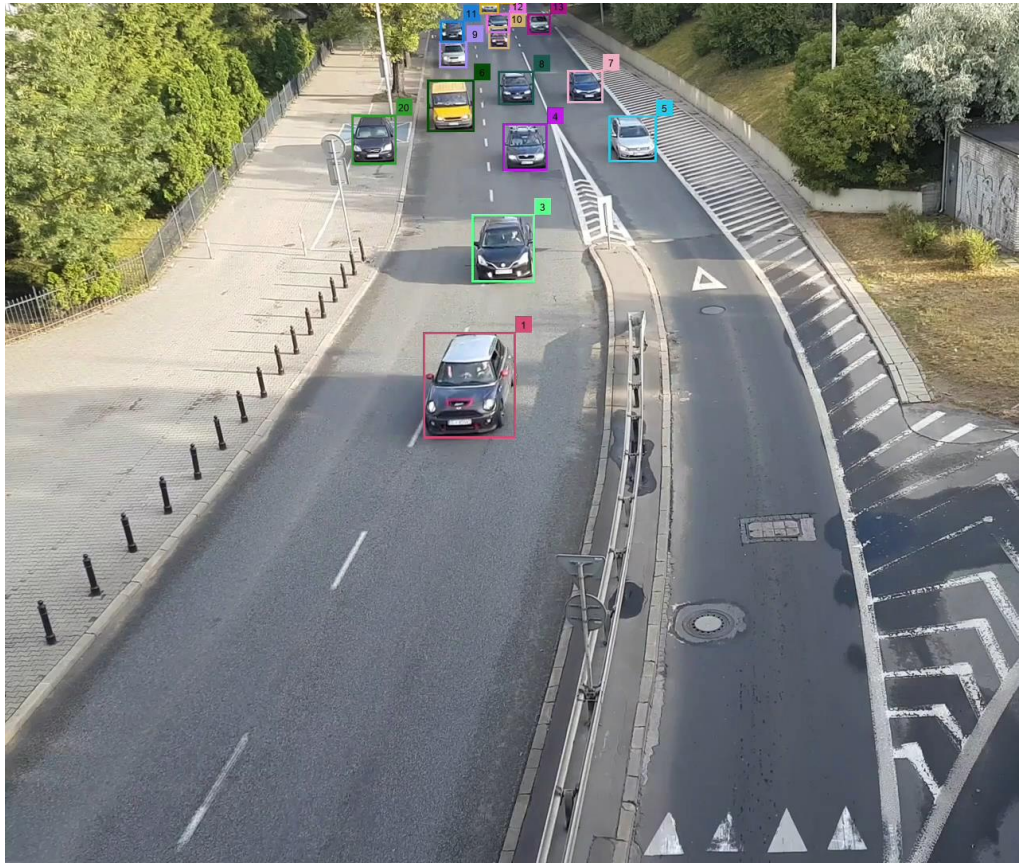
    def frame_constraint(self):
        return self.car.color == "red" and self.car.velocity > 100

    query frame_output(self):
        return self.car.id
```

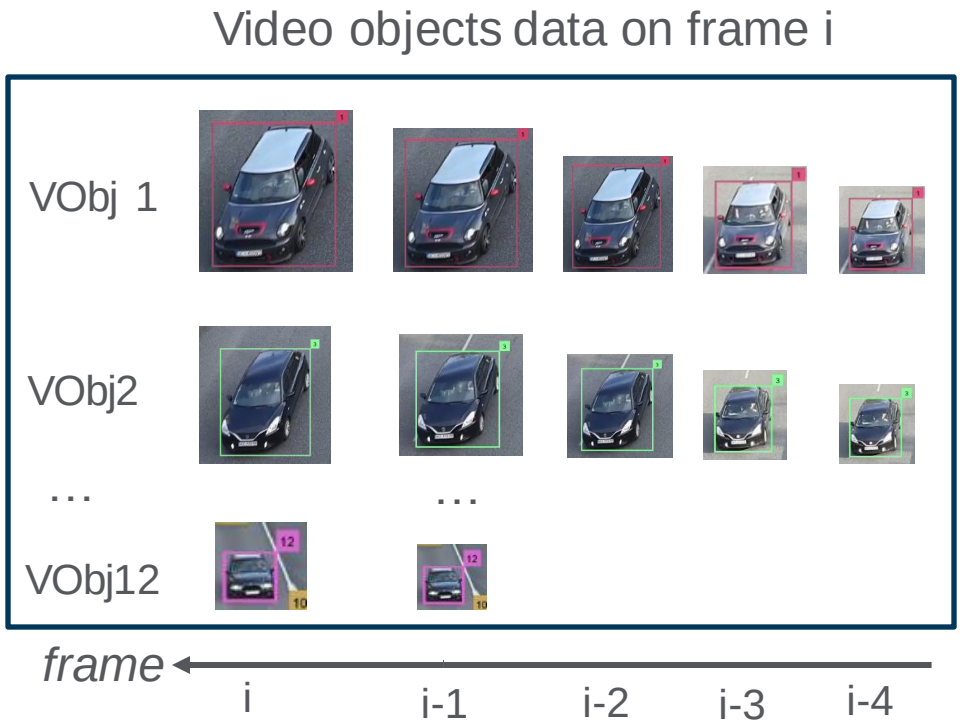
VQPy – An Object-Oriented Approach to Video Analytics



Video Object Abstraction in VQPy



A video object represents a unique entity that may appear across multiple frames.



https://www.kaggle.com/datasets/trainingdatapro/cars-video-object-tracking

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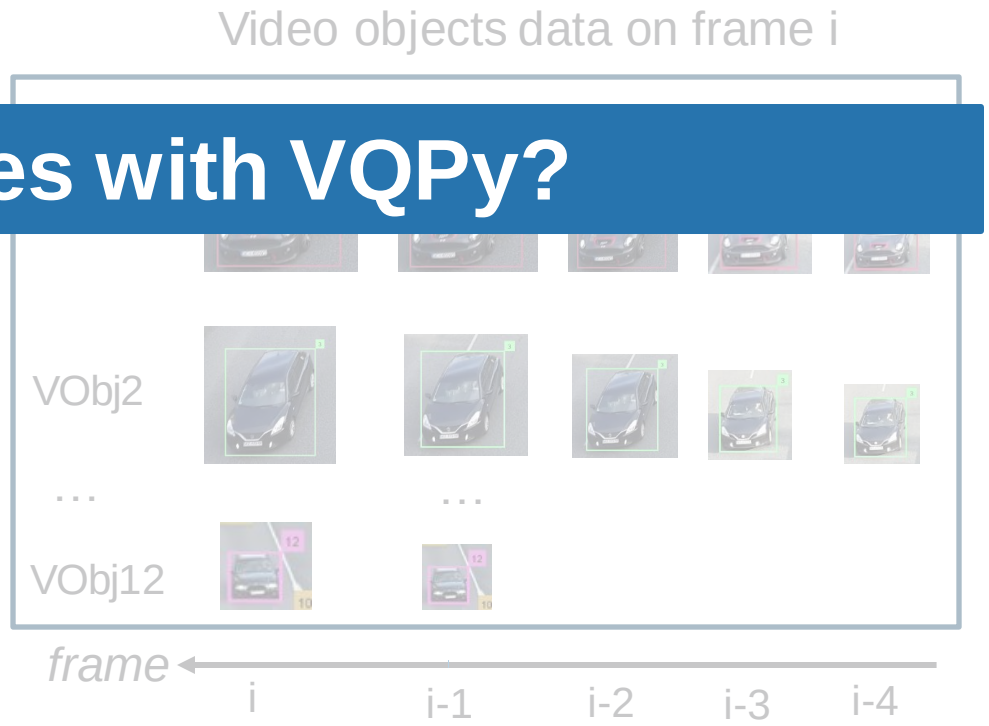

How to program video queries with VQPy?

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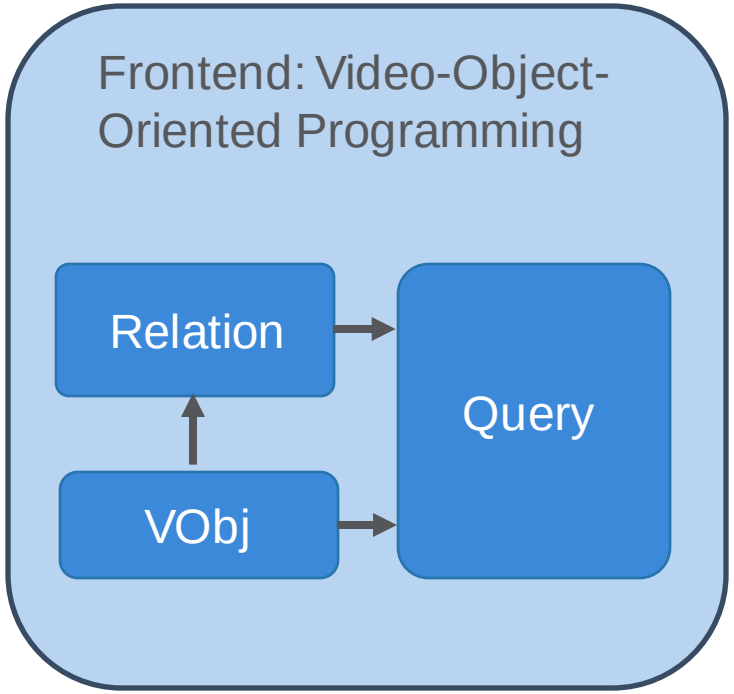
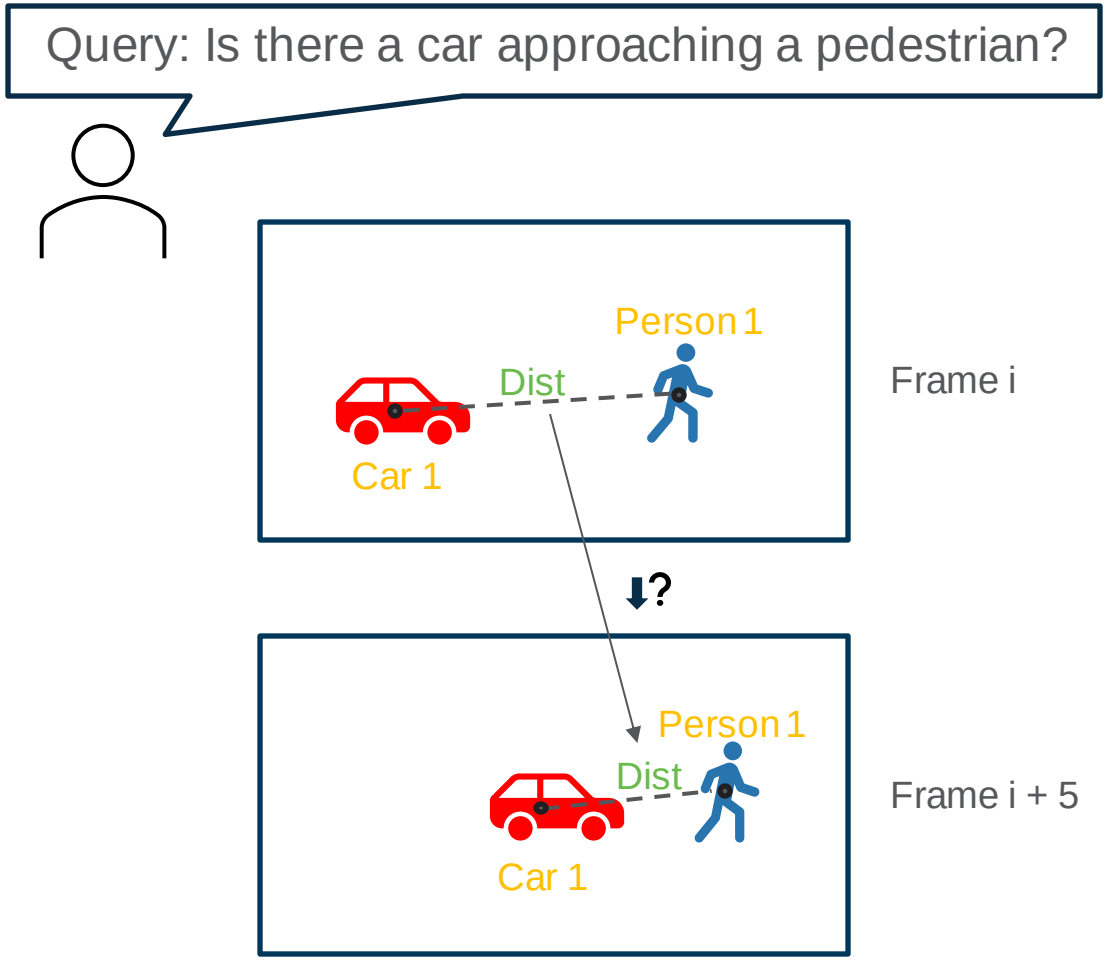
Frontend Overview





Query on Video Objects

Retrieve the license plates of vehicles traveling at speeds exceeding 80 mph.

Frame 1

{'Vehicle': [{'license_plate': 'FX66 UUW'}]}

Frame 2

{'Vehicle': [{'license_plate': 'FX66 UUW'},
{'license_plate': 'HX14 UHH'}]}

Frame 3

{'Vehicle': [{'license_plate': 'FX66 UUW'},
{'license_plate': 'HX14 UHH'}]}

```
vobj Vehicle:

  def __init__(self):
    self.model = “yolox”

  @stateful(input="center", history_len=2)
  def speed(self, hist_centers):
    ...

  @stateless(input=”image")
  def license_plate(self, vehicle_image):
    ...
```

Construct a Vehicle VObj

```
query SpeedTicketing:

  def __init__(self):
    self.vehicle = Vehicle()

  def frame_constraint(self):
    return self.vehicle.speed > 80

  def frame_output(self):
    return self.vehicle.license_plate
```

Construct a SpeedTicketing Query

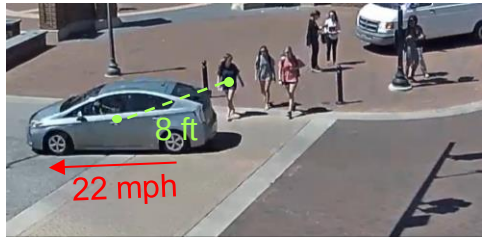
Query on VObjs and Relations

Retrieve the event that a car speeds past a person.

{'frame_id': [5,6]}

Frame 5

Frame 6



Frame 7

```
relation SpatialRelation(vqpy.Relation):

  def __init__(self, vobj1, vobj2):
    self.vobj1 = vobj1
    self.vobj2 = vobj2

  @stateless(input1="center", input2="center")
  def distance(self, centers):
    return math.dist(centers[0], centers[1])
```

VQPy Spatial Relation

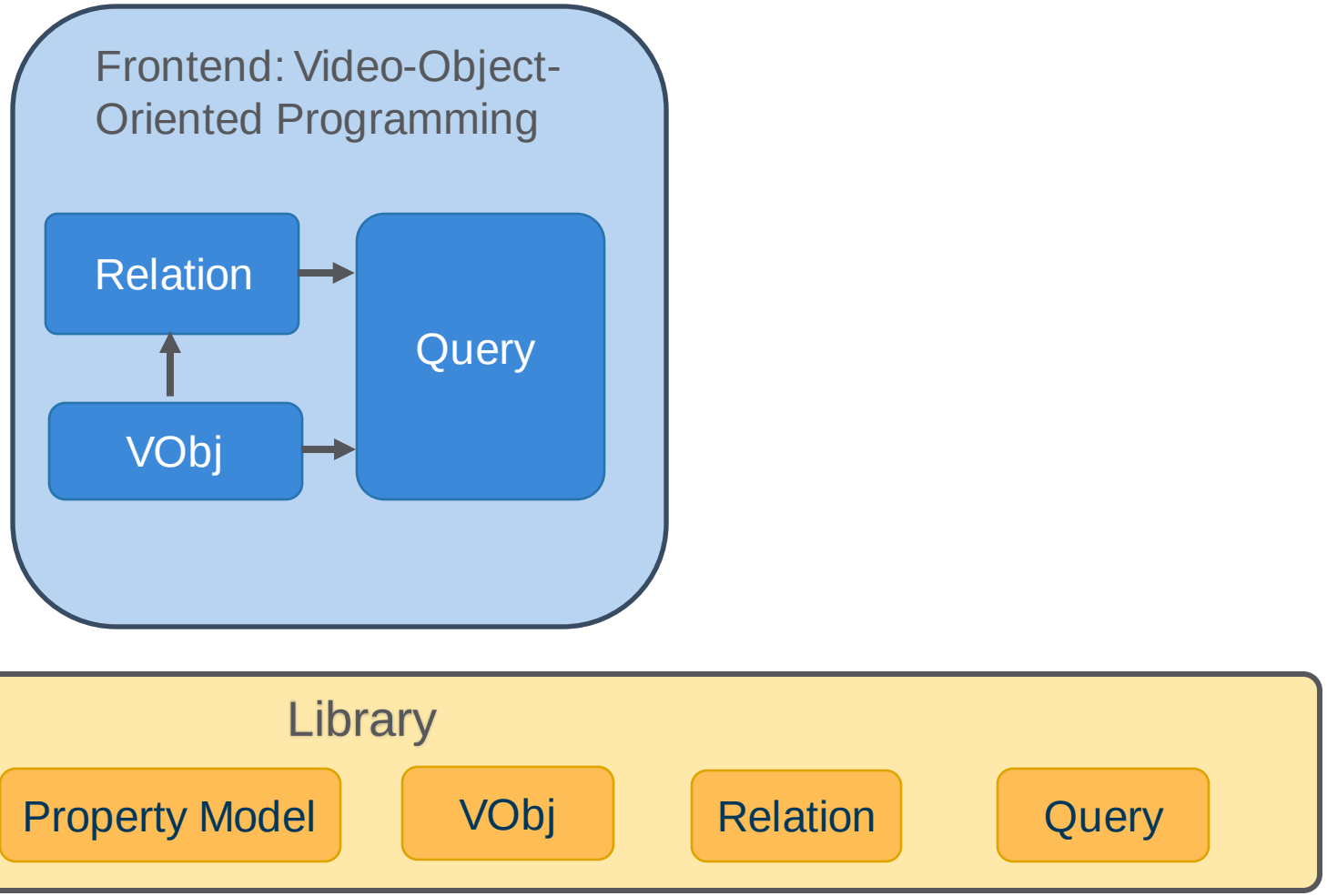
```
query TrafficHazards(vqpy.Query):

  def __init__(self):
    self.car = Car()
    self.person = Person()
    self.relation = \
      SpatialRelation(self.car, self.person)

  def frame_constraint():
    return (self.relation.distance < 6)
                & (self.car.speed > 15)
```

A car speeds past a person Query

Frontend Summary



VQPy's Backend

Backend: An Object-Based Optimization Framework

- How to choose the right data model?
- How to automatically construct a pipeline for frontend queries?
- How to optimize the pipeline based on video objects?
- How to build the backend to be easily extensible with custom optimizations?

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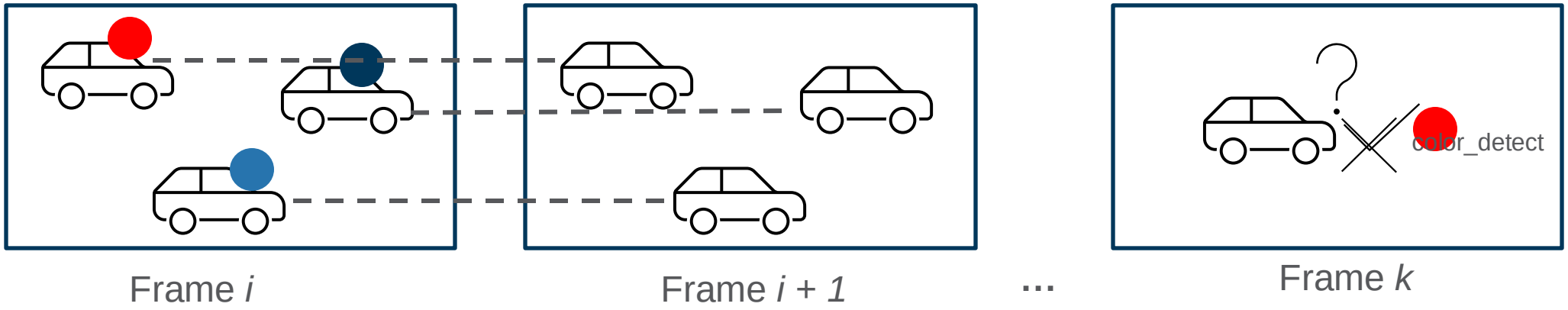
Object-level Computation Reuse

```
vobj Vehicle(vqpy.VObj):

 @stateless(model="color_detect", intrinsic=True)
 def color(self, images):
  # built-in color_detect model
  ...
```



Evaluation

Evaluated with 14 video queries on 5 datasets from real-world surveillance video streams.

- Handcrafted pipelines
  - Complex vehicle retrieval queries
  - Baseline: CVIP[1]
- SQL-based frameworks
  - Video-object-based queries
  - Baseline: EVA [2]
- Multi-modal LLMs
  - Diverse types of video queries
  - Baseline: VideoChat [3]

[1] Le, H. D.-A., Nguyen, Q. Q.-V., Luu, D. T., Chau, T. T.-T., Chung, N. M., and Ha, S. V.-U. Tracked-vehicle retrieval by natural language descriptions with multi-contextual adaptive knowledge. In Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR) Workshops, pp. 5510–5518, June 2023.
[2] Xu, Z., Kakkar, G. T., Arulraj, J., and Ramachandran, U. Eva: A symbolic approach to accelerating exploratory video analytics with materialized views. In Proceedings of the 2022 International Conference on Management of Data, SIGMOD '22 URL https://doi.org/ 10.1145/3514221.3526142.
[3] Li, K., He, Y., Wang, Y., Li, Y., Wang, W., Luo, P., Wang, Y., Wang, L., and Qiao, Y. Videochat: Chat- centric video understanding. arXiv preprint arXiv:2305.06355, 2023.

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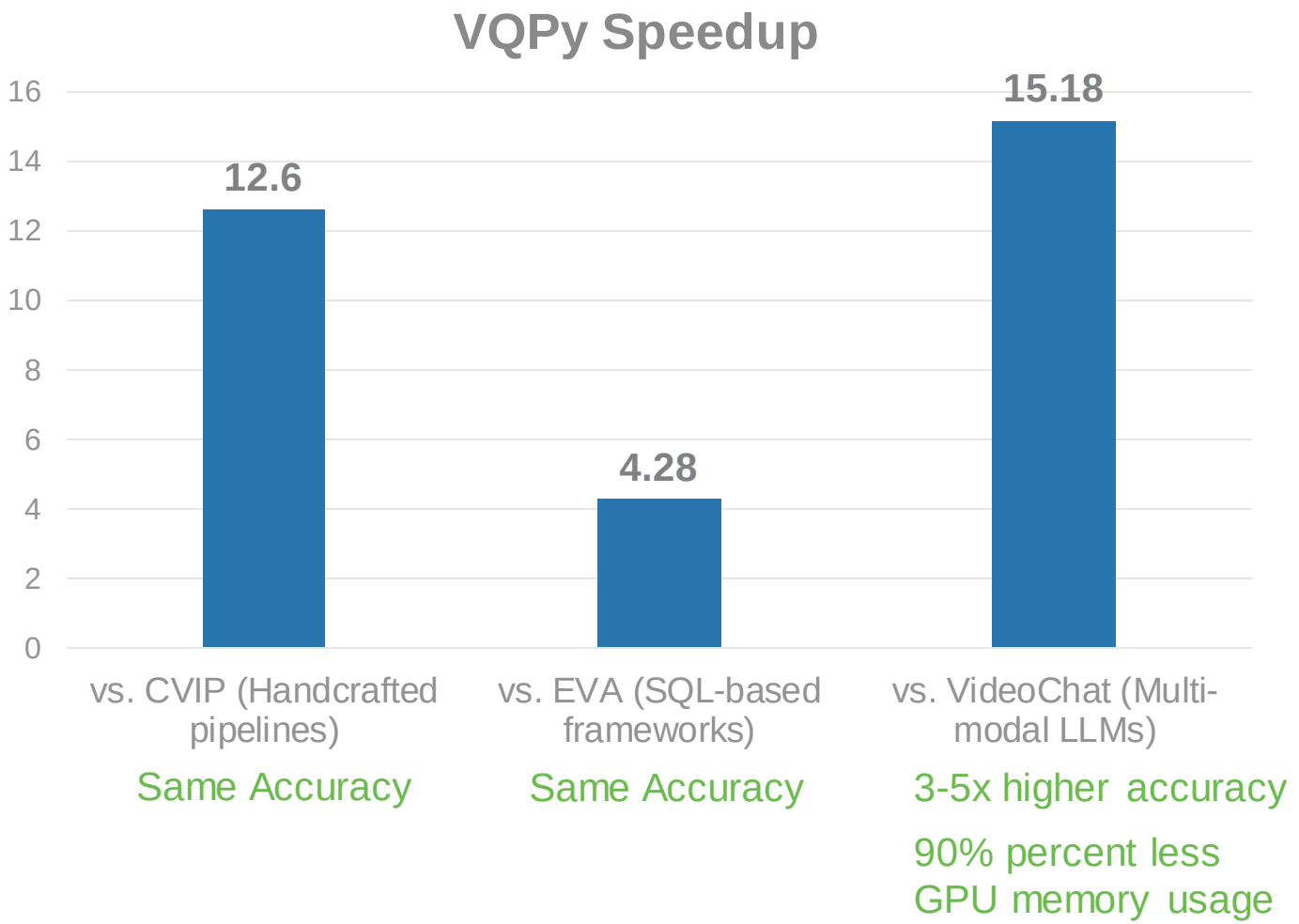
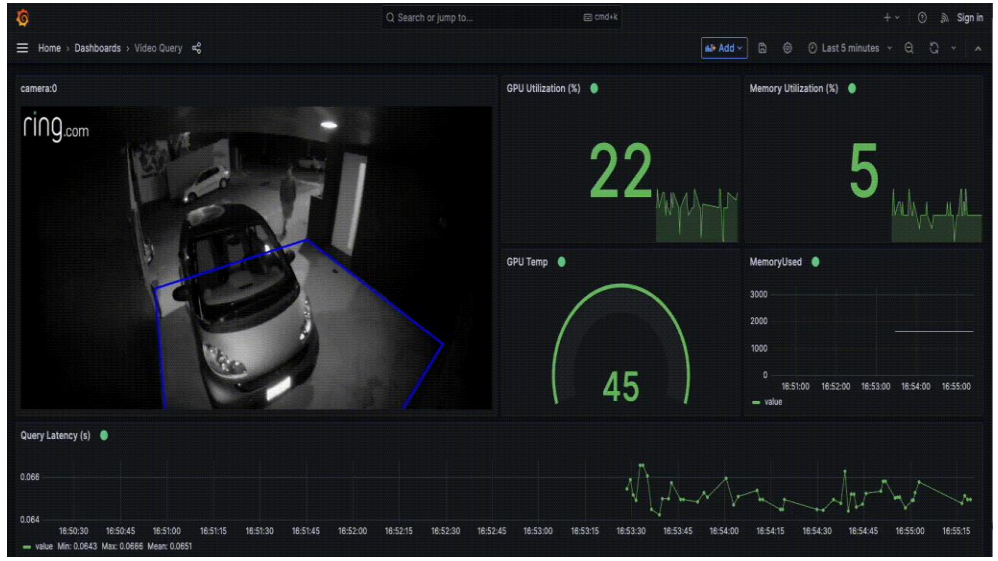


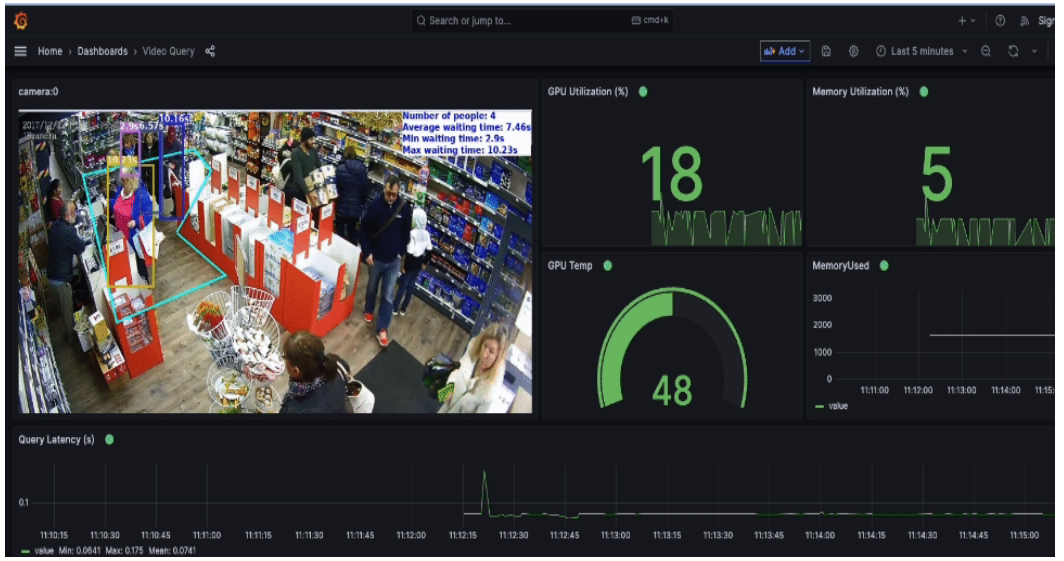
Industrial Adoption

VQPy has been integrated into Cisco as a query development/execution layer in its DeepVision framework.

Loitering Alert



Queue Analysis



Conclusion

VQPy: a video-object-oriented approach towards video analytics

- Expressiveness: Easily express video queries on video objects and their interactions, with an object-oriented programming frontend.
- Efficiency: Streamlines the efficient execution of video-object-oriented queries, with an object-based optimization backend.

https://github.com/vqpy/vqpy

Thank you