Visor:

Privacy-Preserving Video Analytics as a Cloud Service

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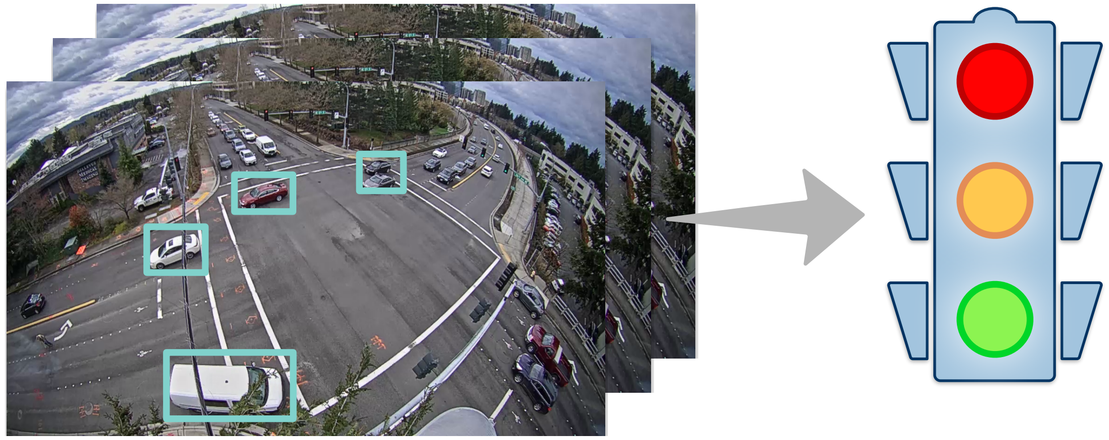
UC Berkeley and **Microsoft Research**

Video analytics as a service

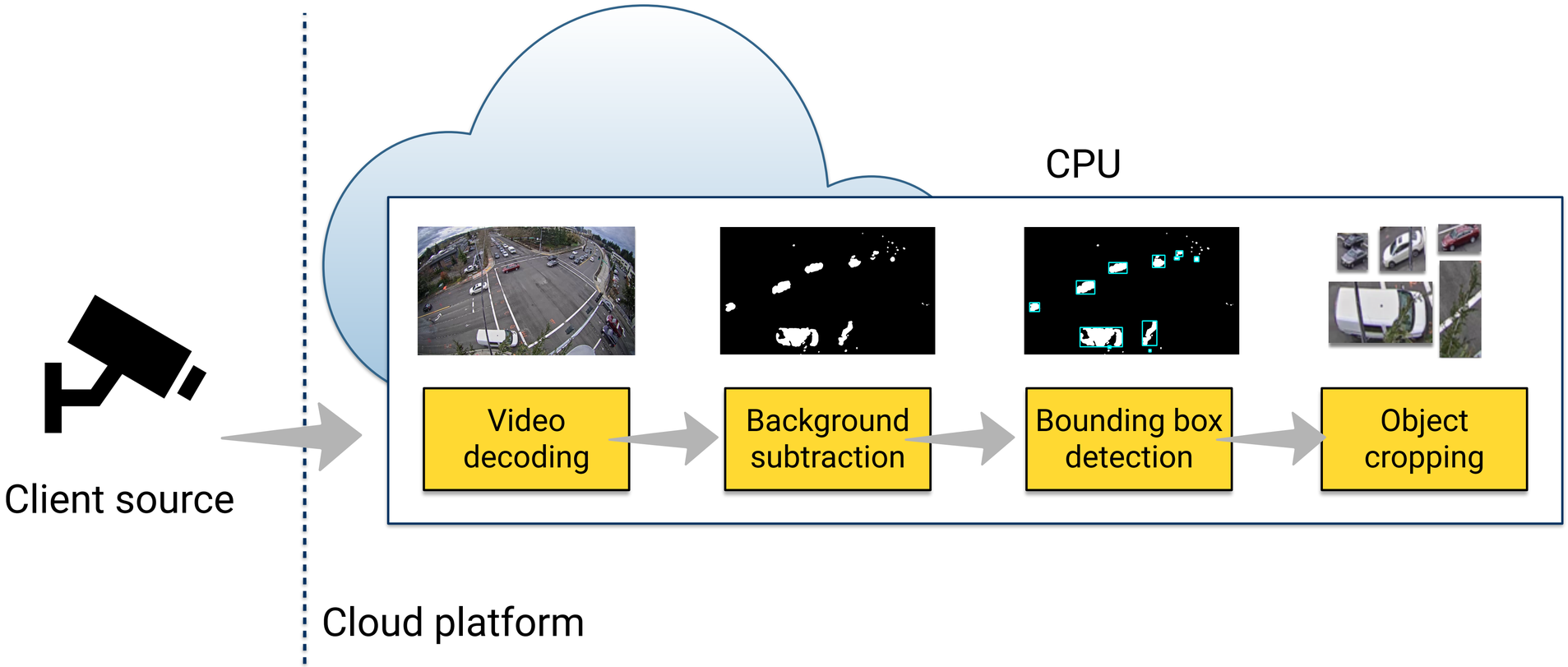
ML applications driven by decisions based on objects in videos

- Raise an alert if a **person** at the main door

- Change the traffic lights if **less than 3 cars** at the intersection



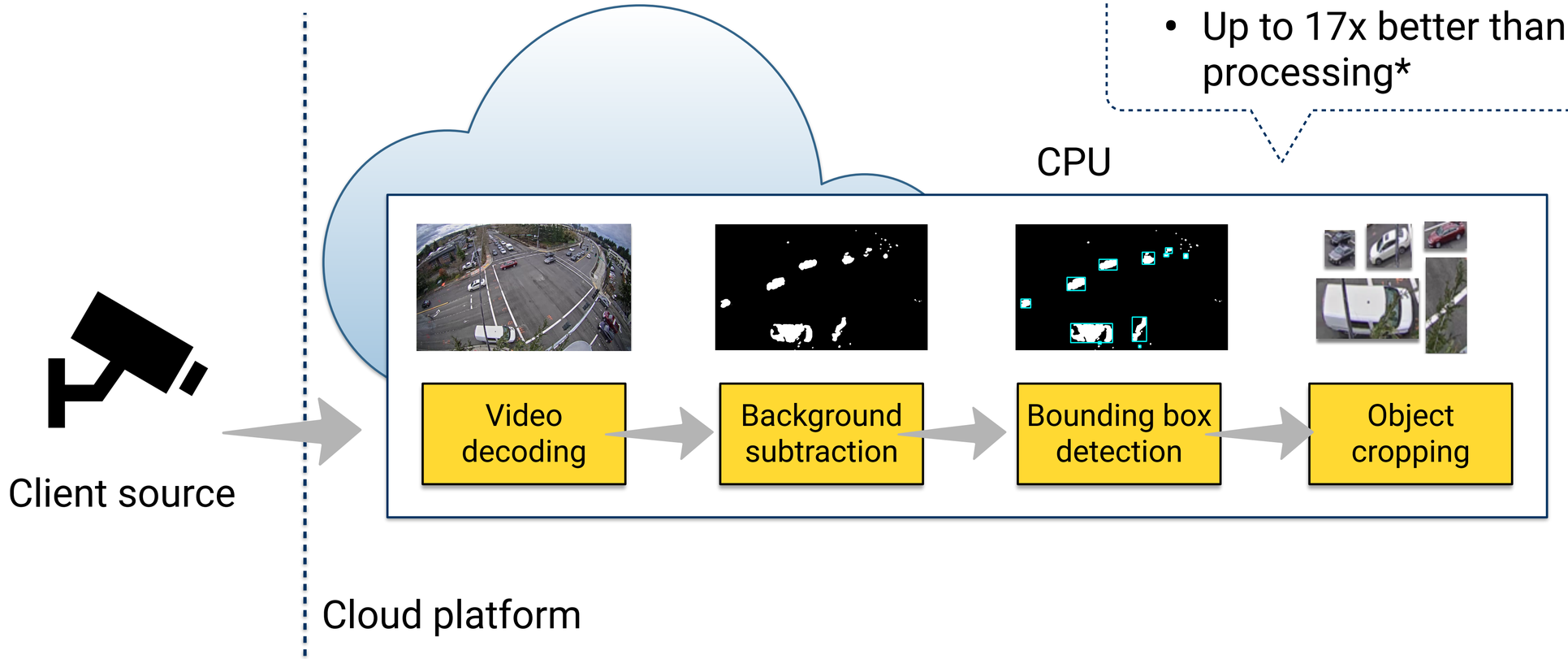
Example video analytics pipeline



Example video analytics pipeline

Cheap filters to discard irrelevant content

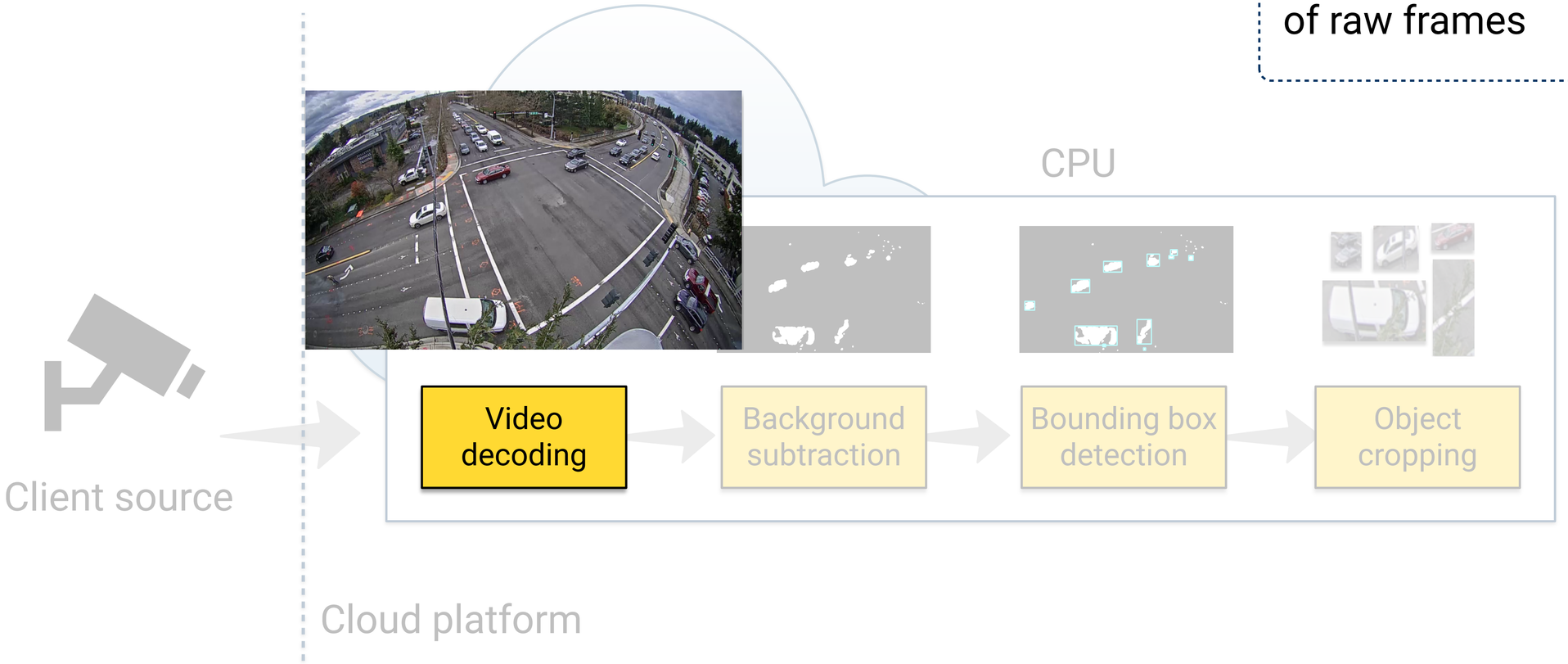
- CPU is under-utilized, unlike GPU
- Up to 17x better than GPU-only processing*



* Live Video Analytics with Microsoft Rocket for reducing edge compute costs
https://techcommunity.microsoft.com/t5/internet-of-things/live-video-analytics-with-microsoft-rocket-for-reducing-edge/ba-p/1522305

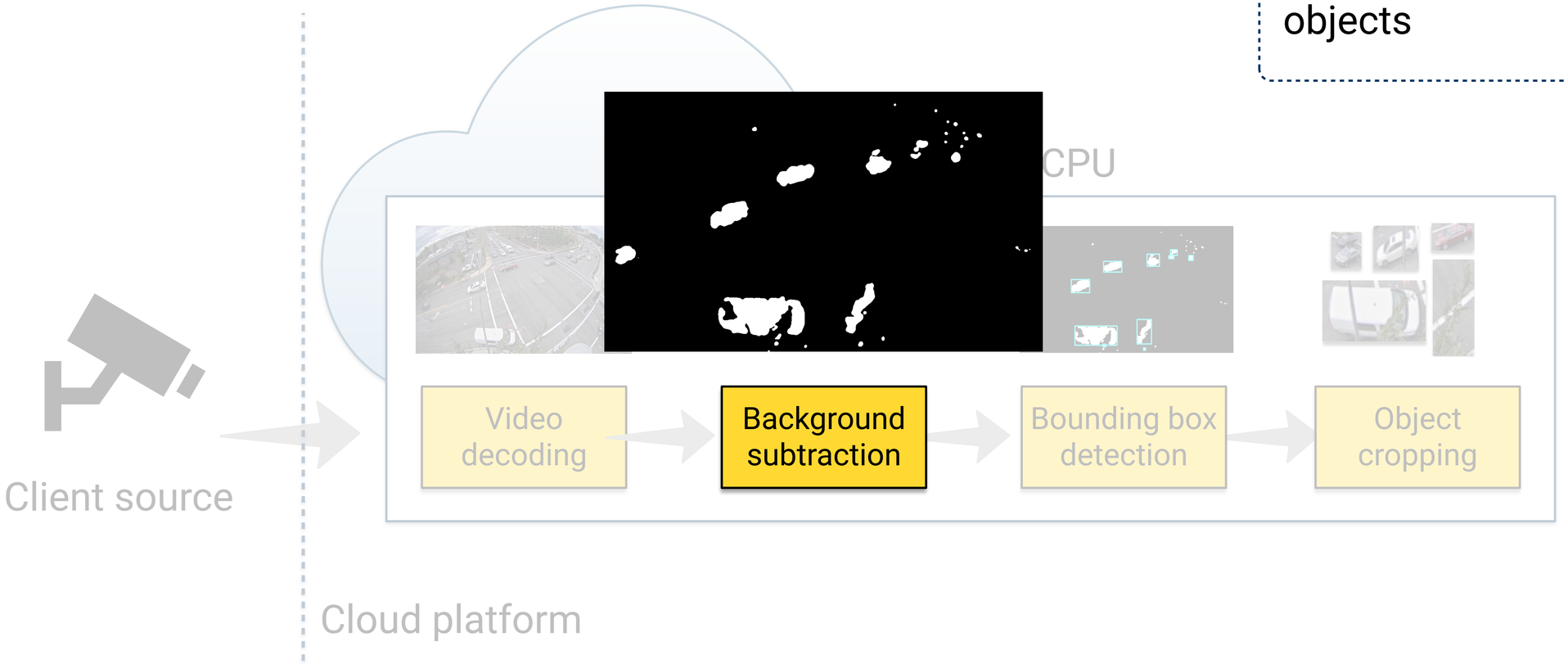
Example video analytics pipeline

Decode video into sequence of raw frames



Example video analytics pipeline

Extract moving “foreground” objects



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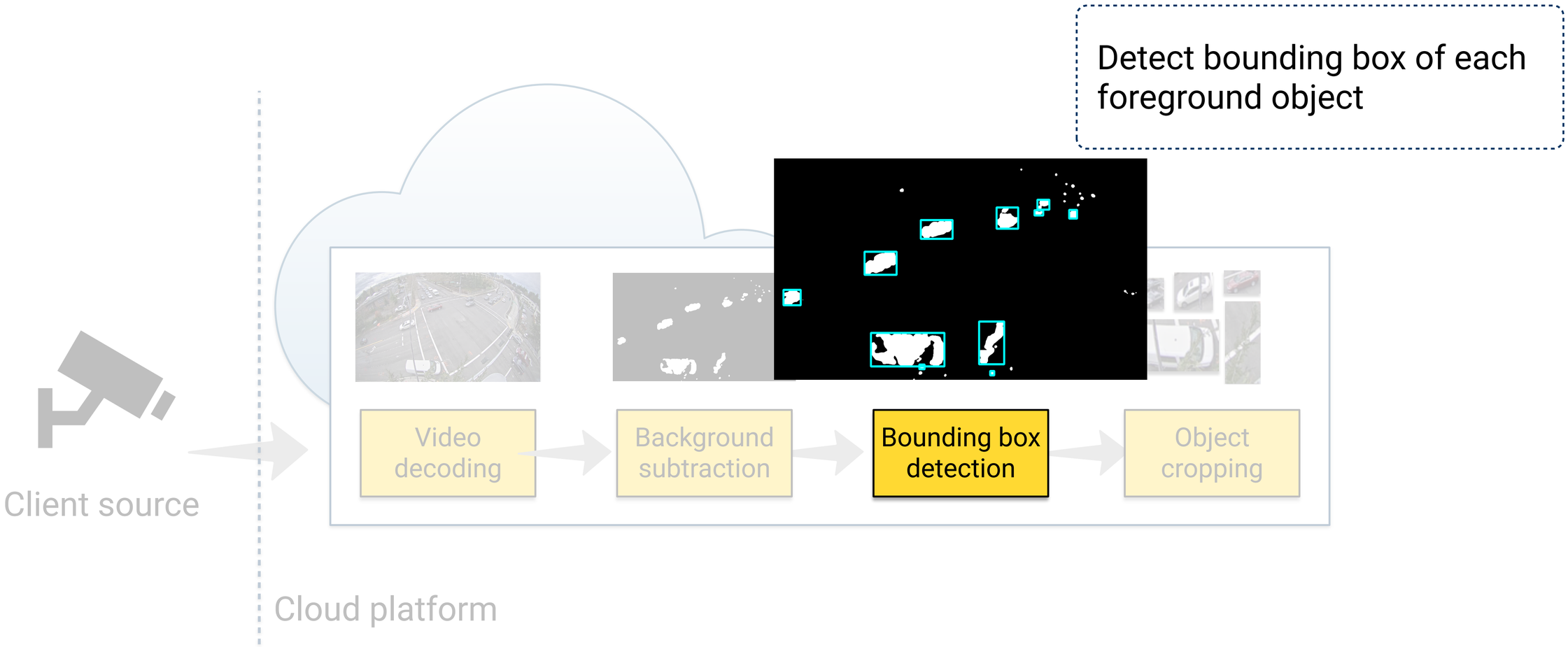

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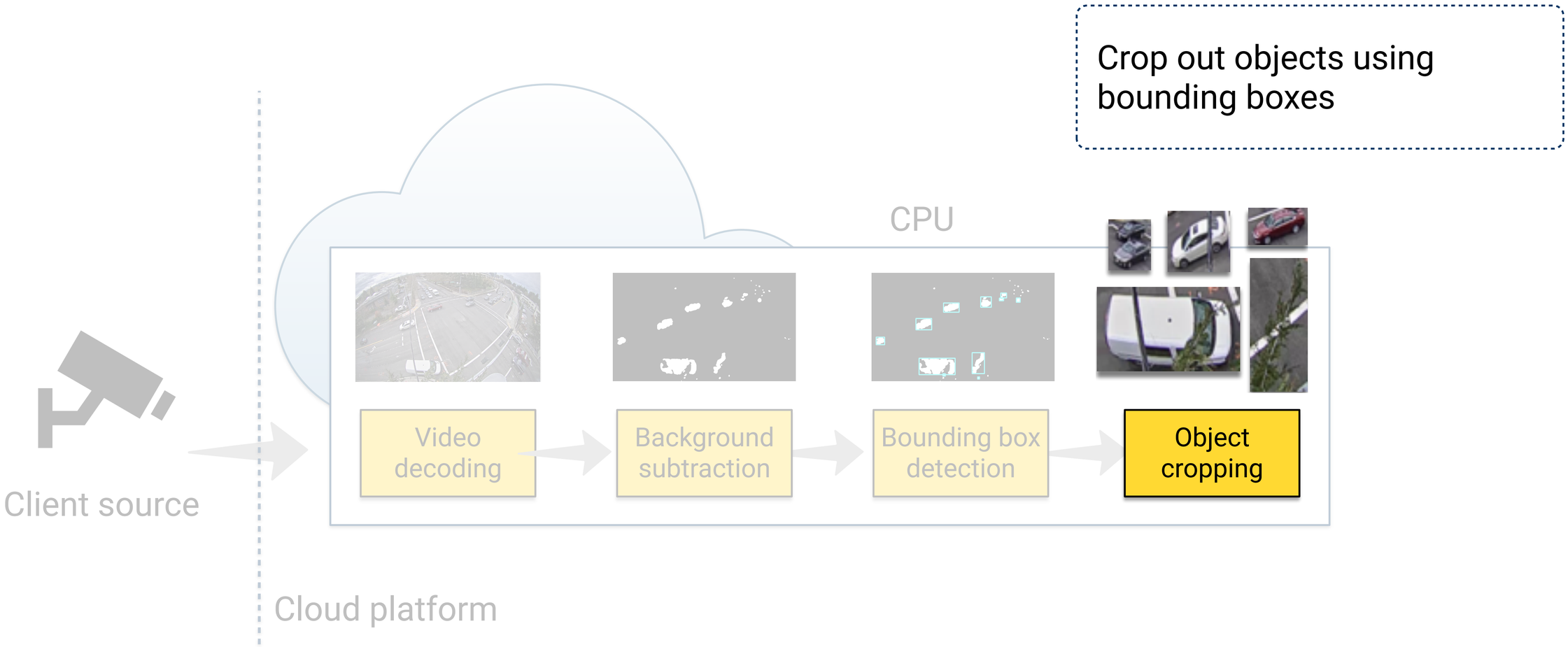

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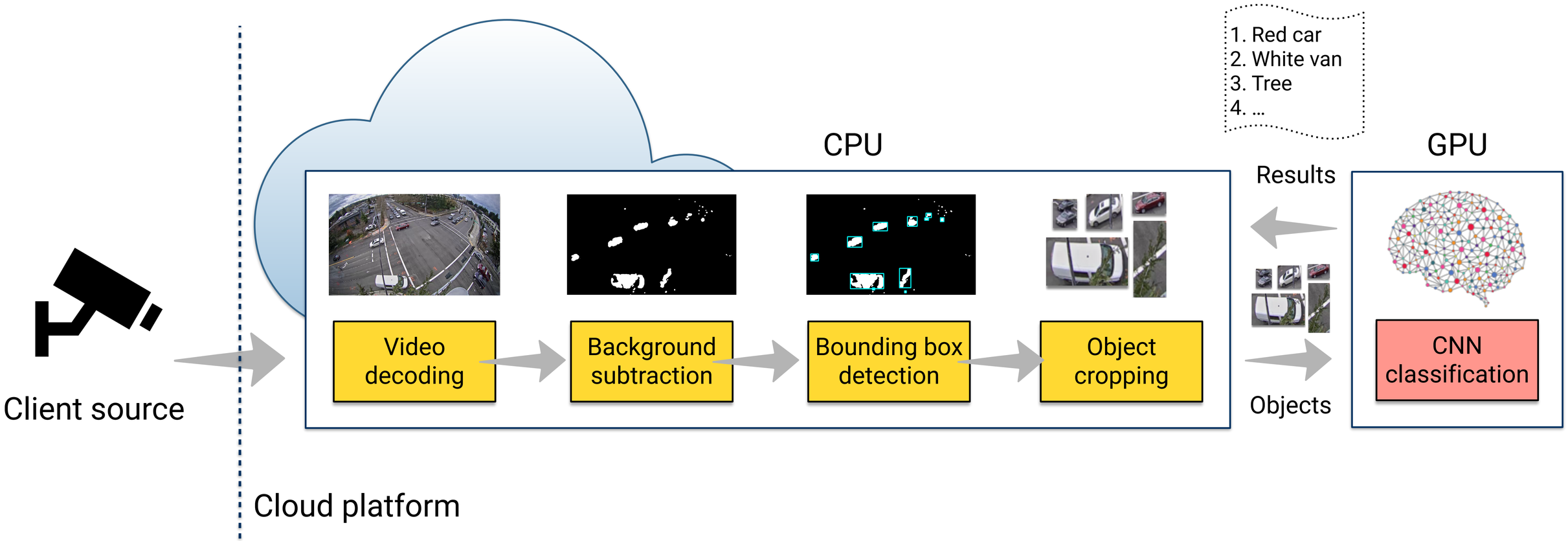
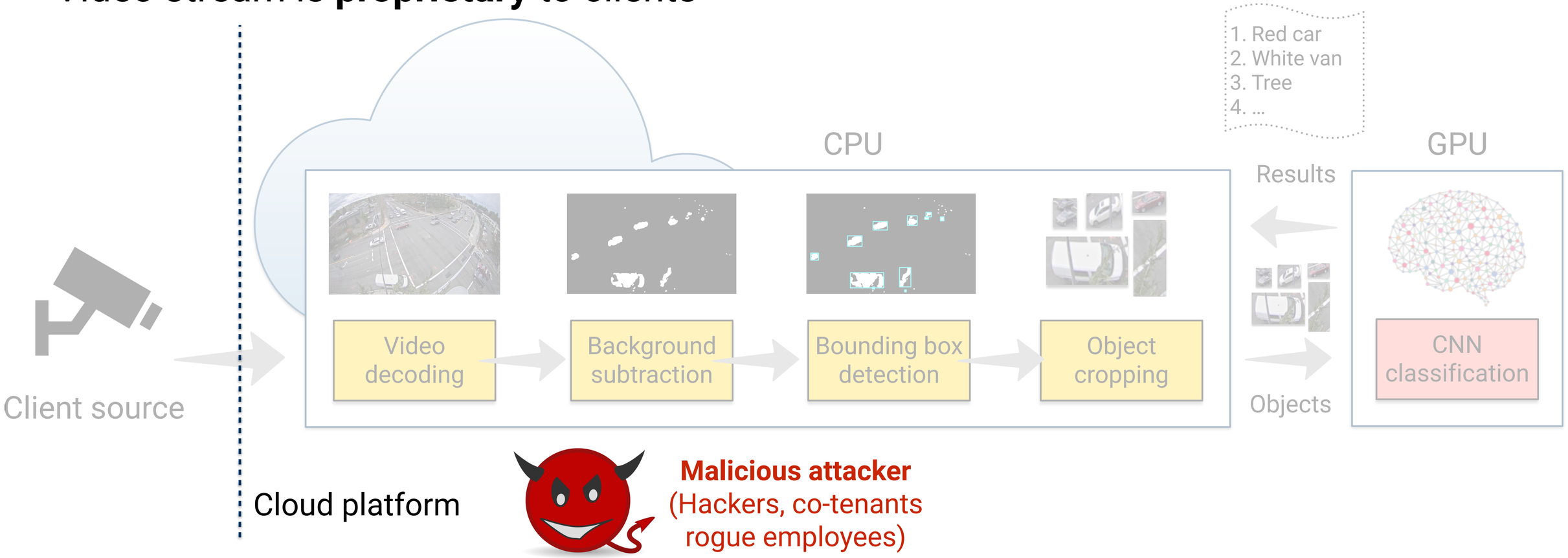


Problem: Privacy

Video stream is **proprietary** to clients



Related work: Privacy-preserving inference

Cryptographic approaches: e.g. SMPC, Homomorphic encryption [MZ17, JVC18]

- High overhead — cannot sustain video frame rate
  (10s to 100s of seconds per frame)

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Trusted hardware-based approaches (enclaves): e.g. Slalom [TB19], Chiron [HSS+18]

- Designed for CPU enclaves — cannot sustain frame rate without GPUs (order of seconds per frame)
- Side-channel leakage — e.g. **memory access patterns**

Visor

Key contributions

1. **Privacy-preserving framework for machine learning services**
   - **Hybrid enclave** architecture (combines CPU and GPU enclaves into a unified trust domain)

2. **Novel data-oblivious algorithms for video analytics**
   - Several orders of magnitude better than alternate solutions for data-obliviousness

Key contributions

1 **Privacy-preserving framework for machine learning services**

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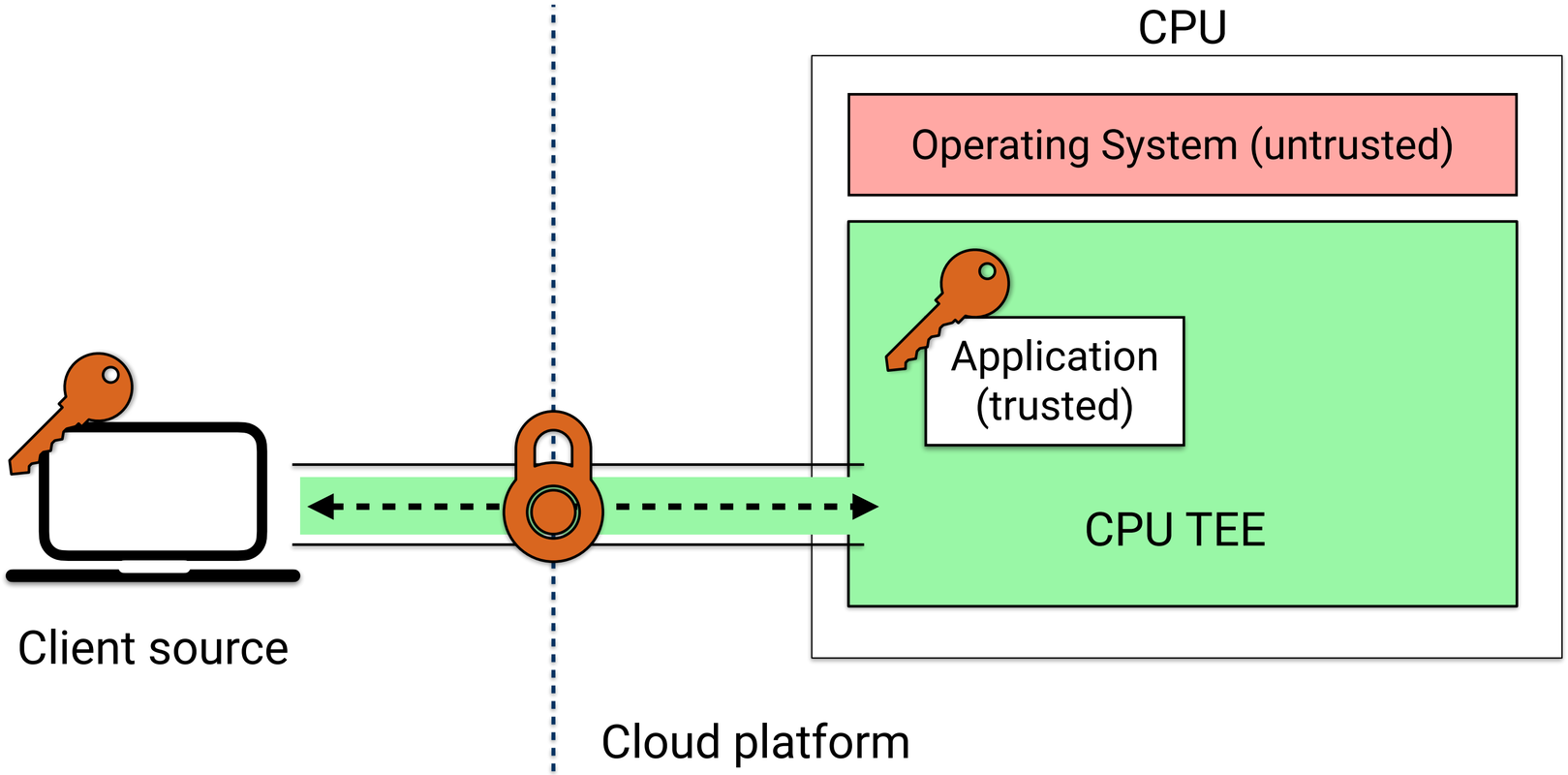
Hybrid trusted execution environment (TEE)

Intel SGX (CPU TEE)



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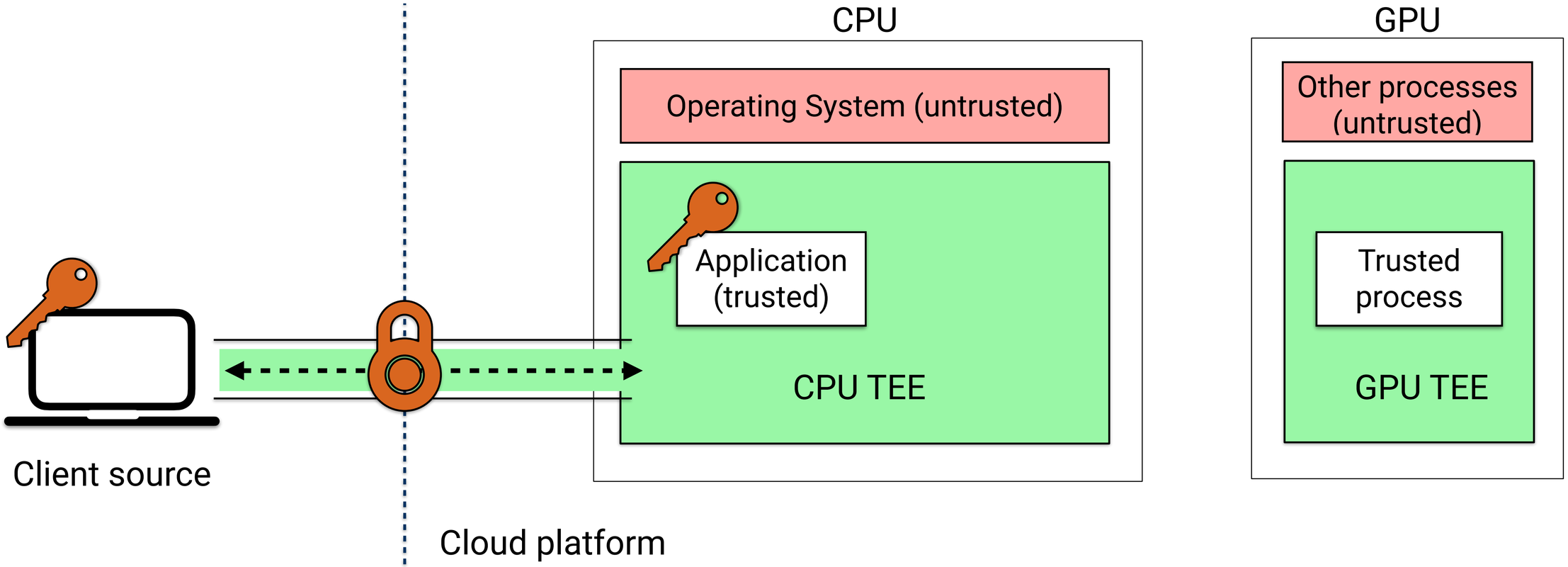
Intel SGX (CPU TEE) + **Graviton** [VVB18] (GPU TEE)

Isolates kernels from other GPU code and privileged software on the host



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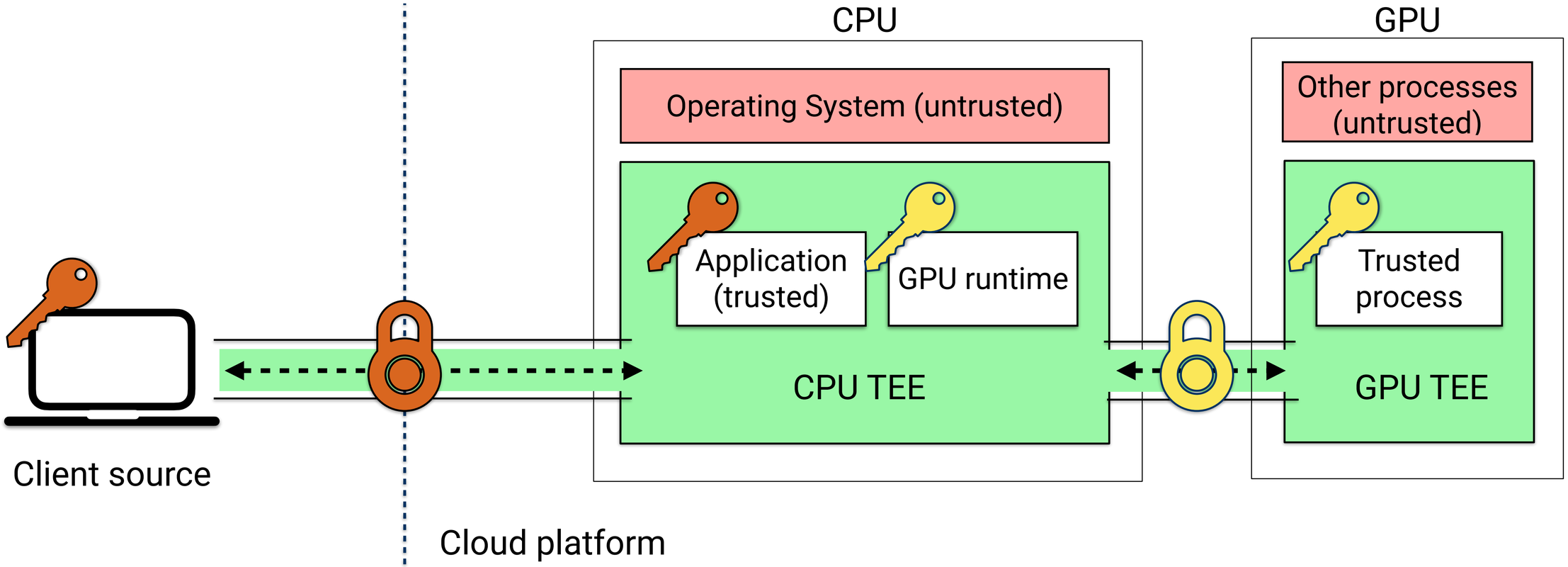
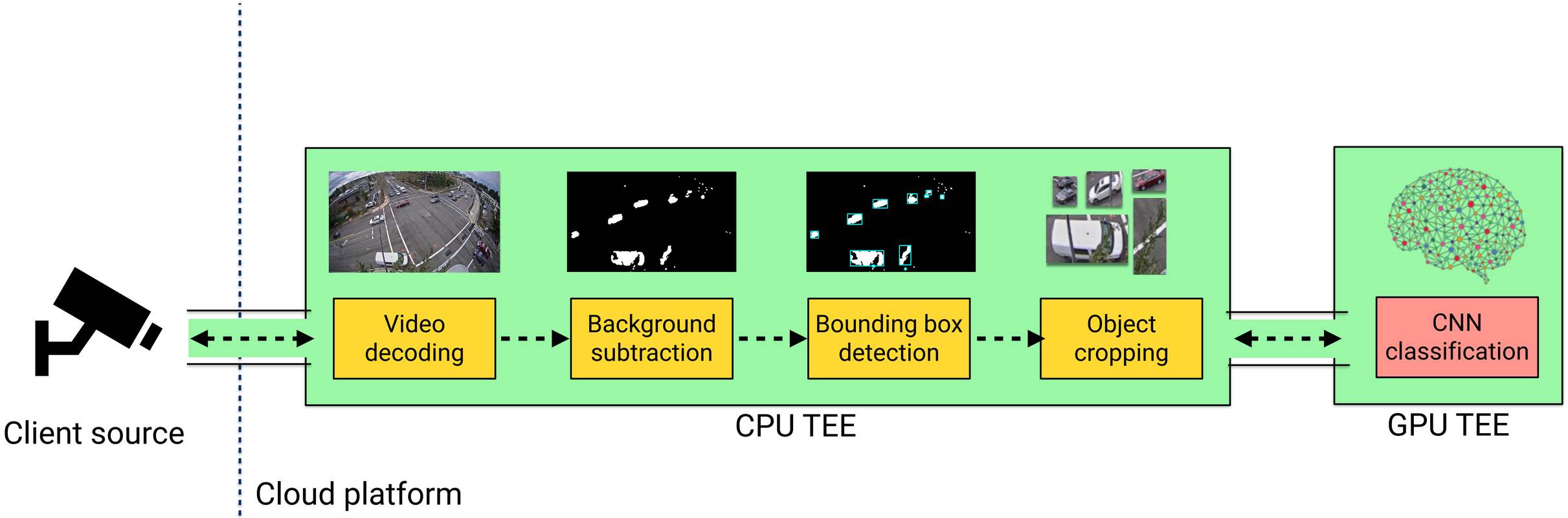


Hybrid trusted execution environment (TEE)

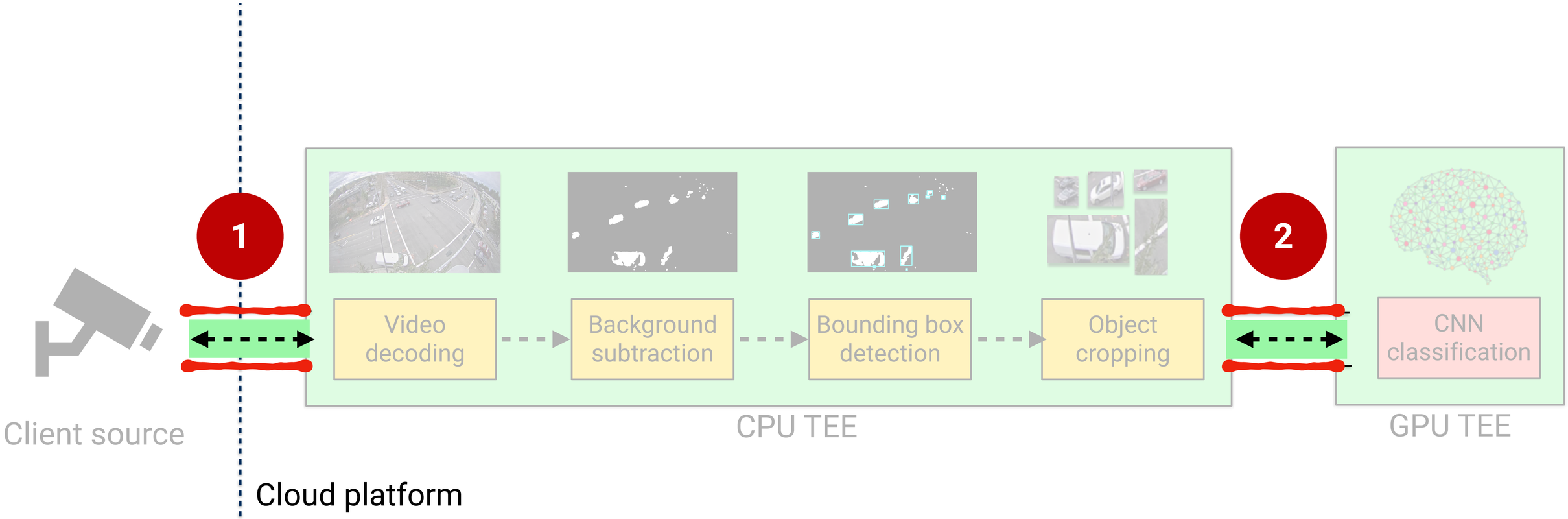
Video analytics pipeline within the hybrid TEE



Mitigating leakage

Encrypted traffic pattern leakage

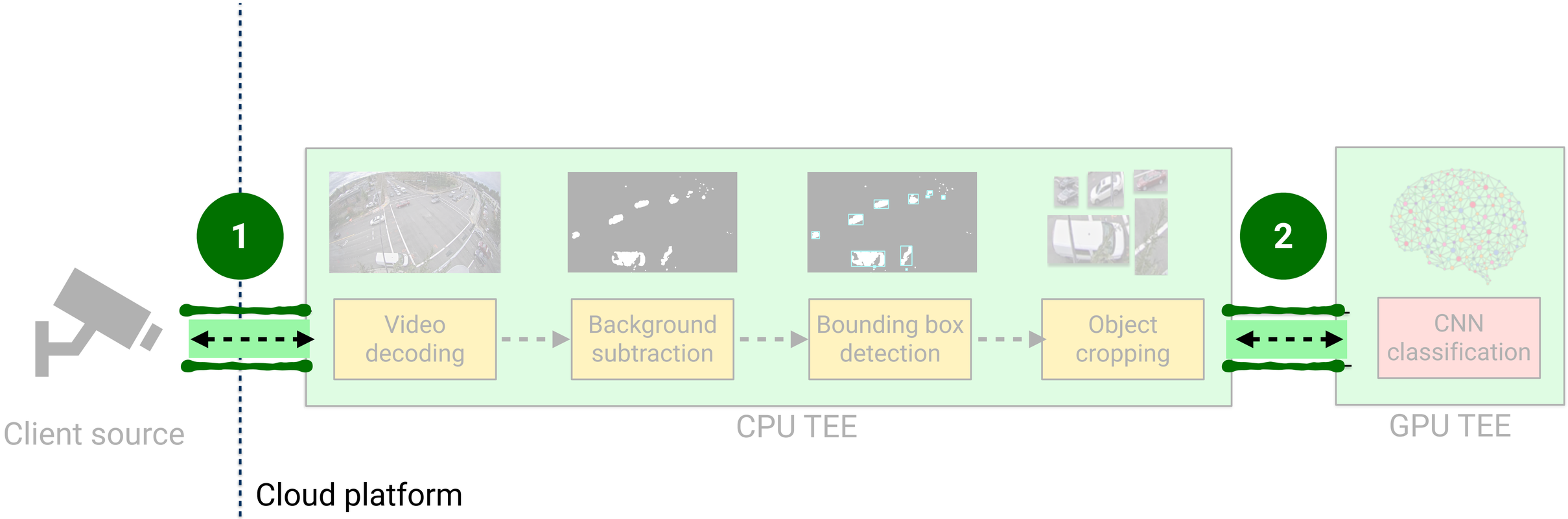
- E.g. **times of activity** in video stream [SST17]
- E.g. **number / size** of objects per frame



Mitigating leakage

Data-oblivious communication protocols optimized for pipeline performance

- Padded video streams
- Data-oblivious CPU-GPU queues



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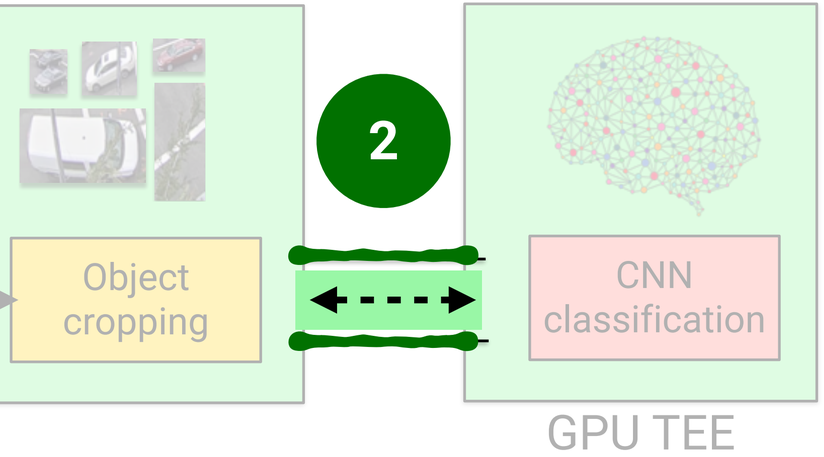

Data-oblivious CPU-GPU queue that minimizes GPU consumption

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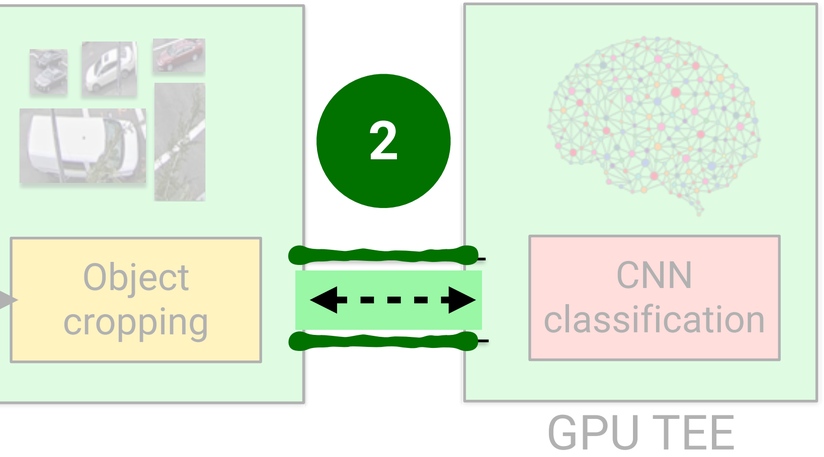

Data-oblivious CPU-GPU queue that minimizes GPU consumption

- CPU pushes N_1 objects into queue per frame, comprised of **real** and **dummy** objects

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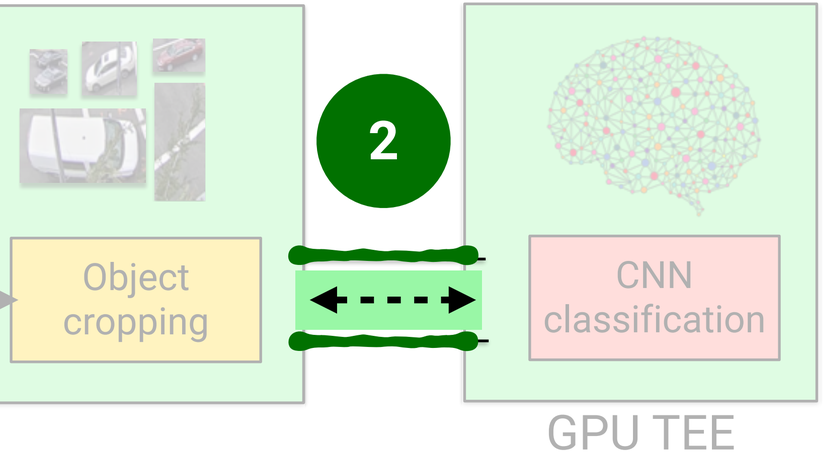

Data-oblivious CPU-GPU queue that minimizes GPU consumption

- Obliviously sort the queue, pushing **real** objects to the tail

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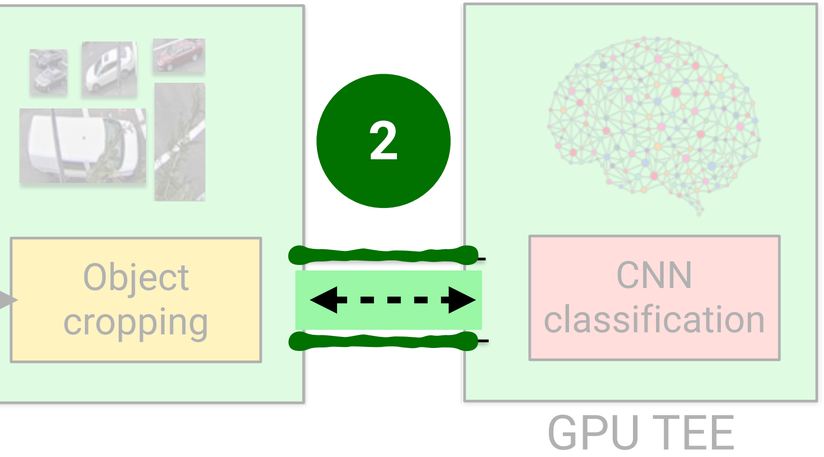

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- GPU consumes N_2 objects from the tail ($N_2 < N_1$)

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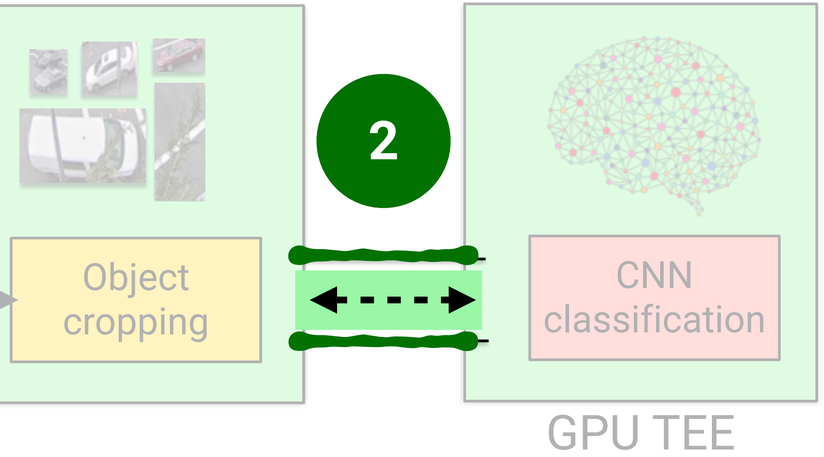
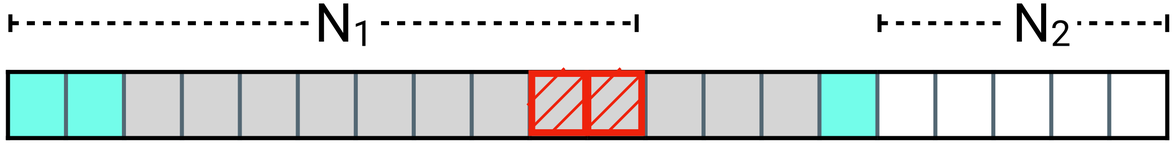


Data-oblivious CPU-GPU queue that minimizes GPU consumption

- Cycle repeats: push, sort, consume



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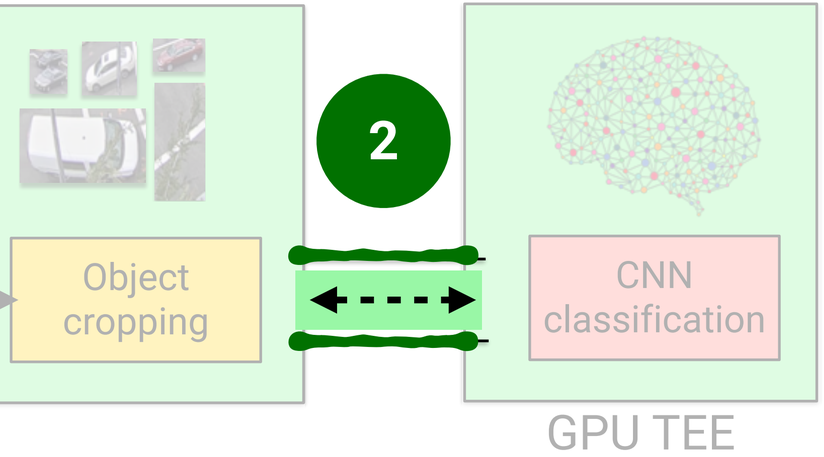

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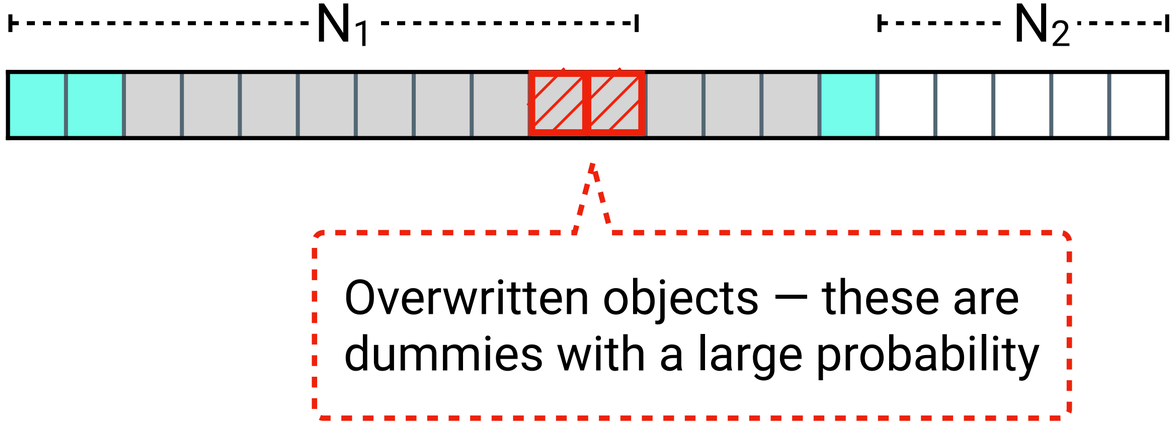

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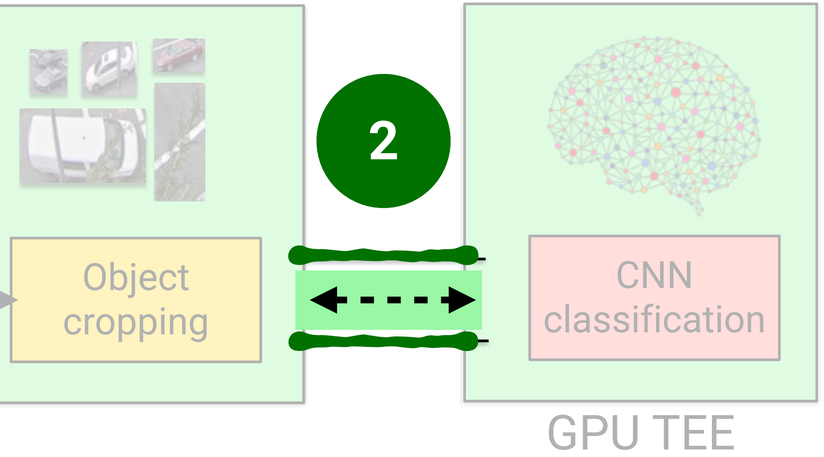

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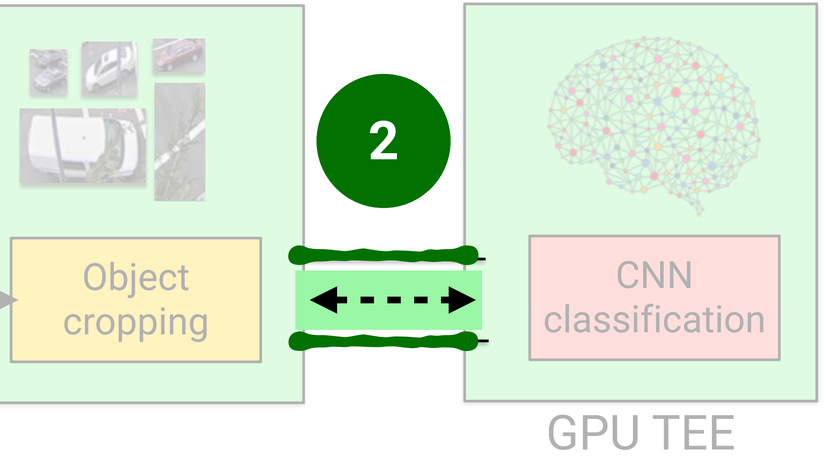

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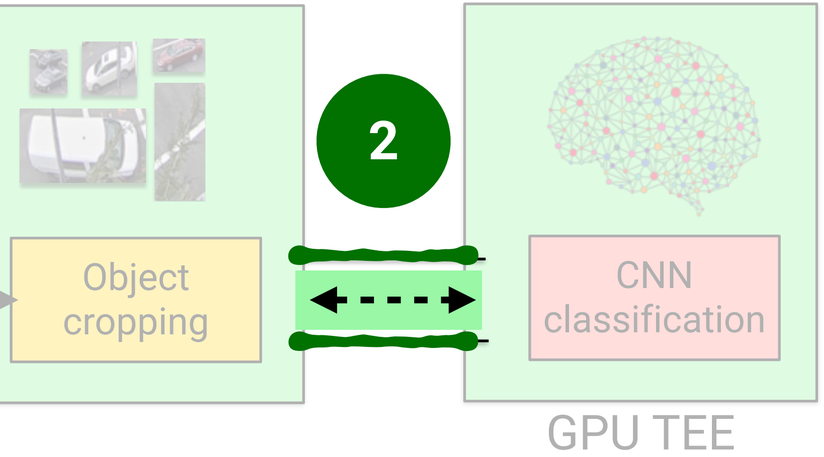


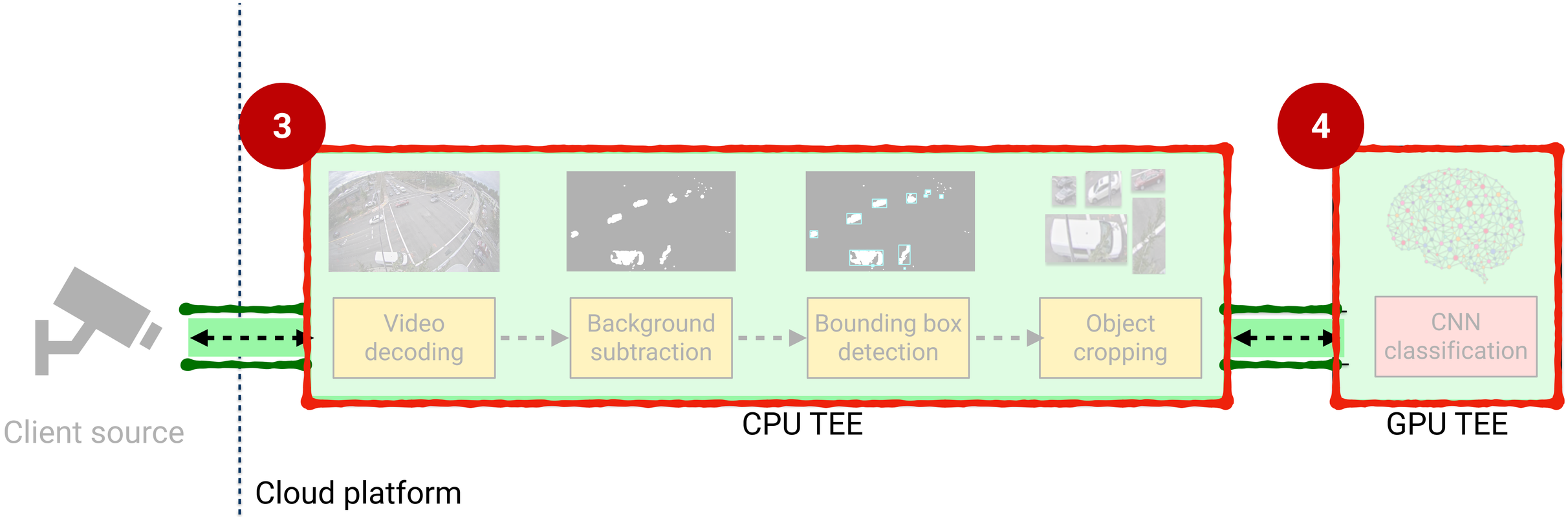
Data-oblivious CPU-GPU queue that minimizes GPU consumption

- Implemented using a circular buffer, with priorities associated with each object

Mitigating leakage

Memory **access pattern leakage** in TEEs

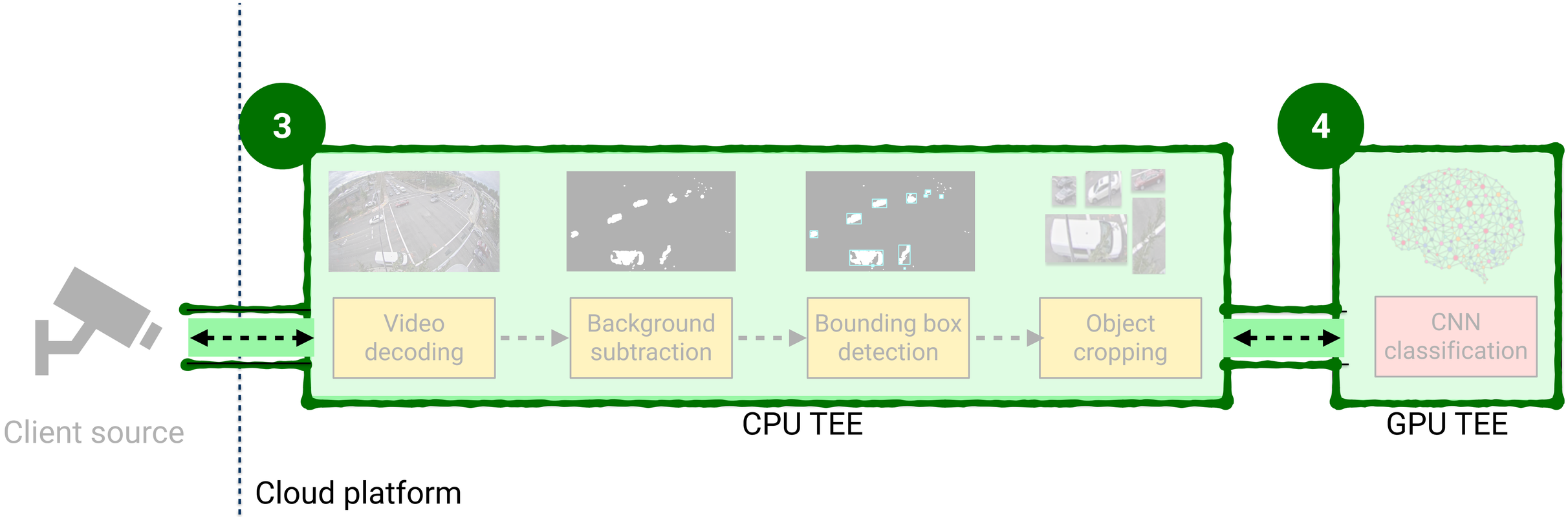
- Large subset of known side-channel attacks on CPU TEEs (Intel SGX)



Mitigating leakage

Data-oblivious modules

- Suite of primitives for developing data-oblivious CPU modules
- Data-oblivious CNN on the GPU



Key contributions

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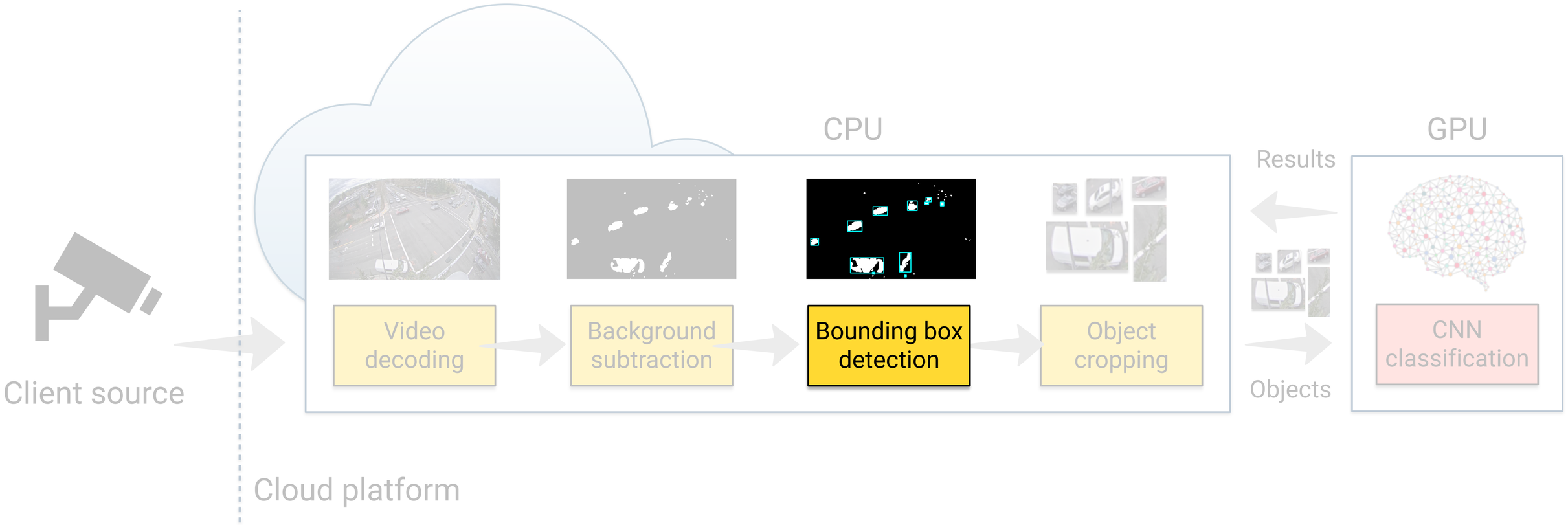
- **Hybrid enclave** architecture (combines CPU and GPU enclaves into a unified trust domain)

2 **Novel data-oblivious algorithms for video analytics**

- Several orders of magnitude better than alternate solutions for data-obliviousness

Memory access pattern leakage

Example: Bounding box detection module

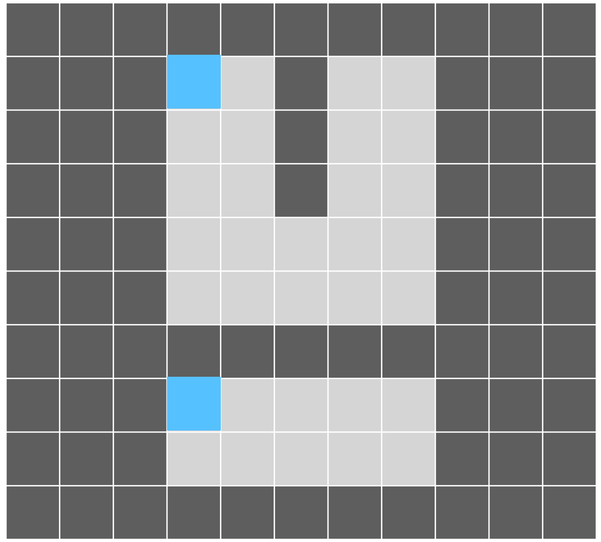


Memory access pattern leakage

Original bounding box detection algorithm:

- Detect white pixel, then follow border (leaks object shape and location)

Binary image



Memory access pattern leakage

Original image
(processed within SGX enclave)

Location of
accessed pixels

Recovered image: Leaks **shapes and positions** of all objects

Design approach

Goal: Transform algorithm into a pattern that processes each pixel identically

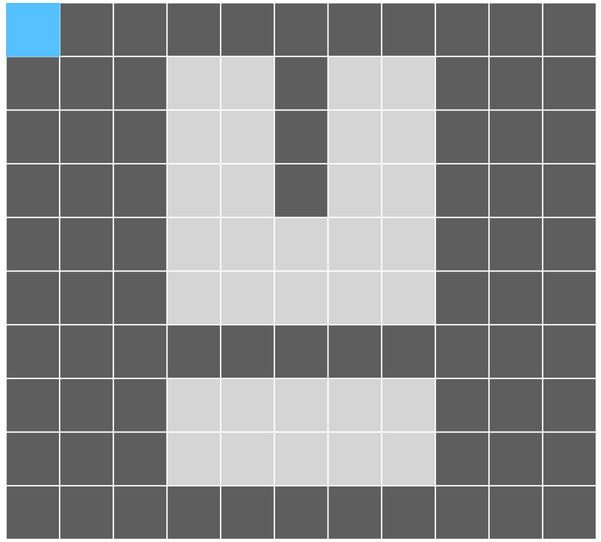
How to apply this design pattern efficiently?

- **General strategy** based the properties of vision modules
- Exploits the structure of the algorithms for efficiency

Illustration: Bounding box detection

Oblivious algorithm strategy:

1. Cast algorithm into a form that scans the image
   - Assign a **label** to each pixel based on its neighbors



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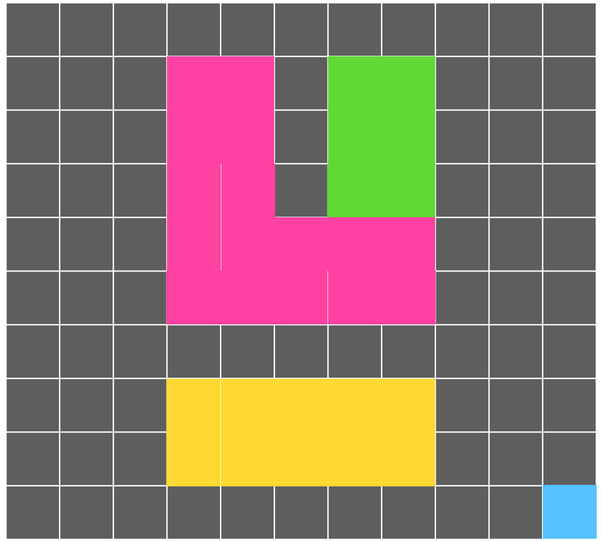

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Oblivious algorithm strategy:

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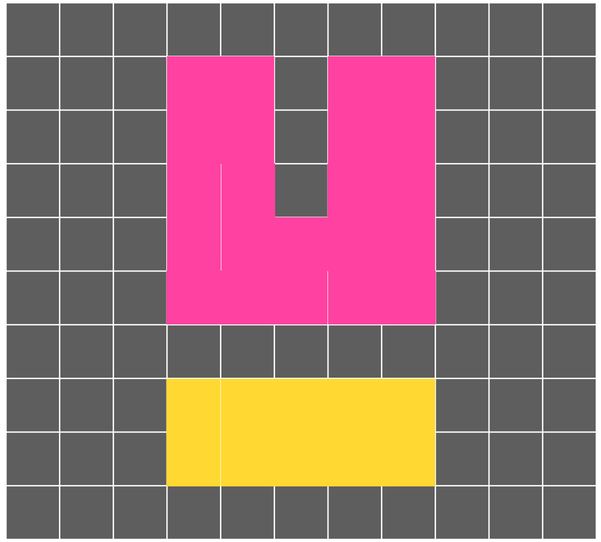
   - Perform another pass to resolve connected labels



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Oblivious algorithm strategy:

2. Divide-and-conquer to improve performance
   - Detect bounding boxes in separate strips of the image

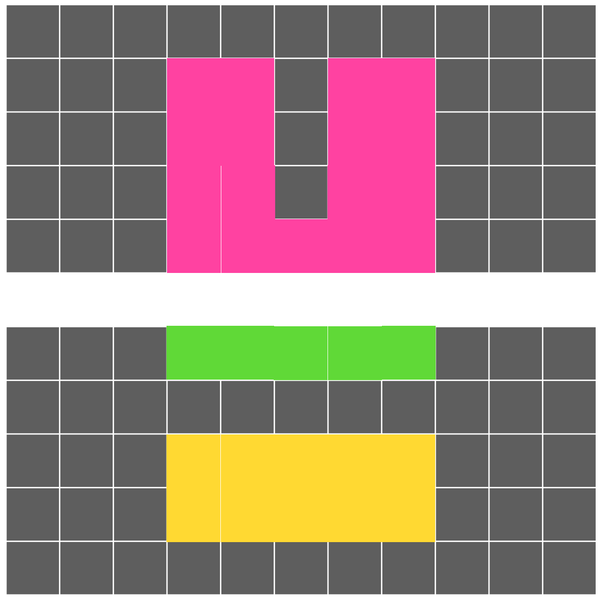


Illustration: Bounding box detection

Oblivious algorithm strategy:

2. Divide-and-conquer to improve performance
   - Detect bounding boxes in separate strips of the image
   - Resolve boundaries

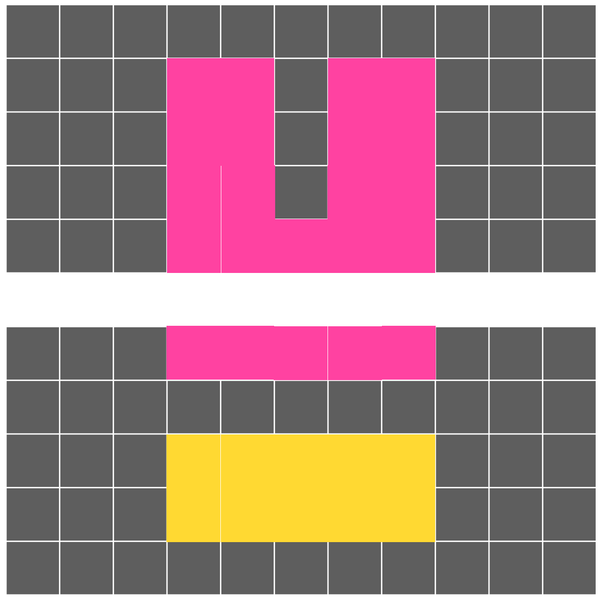
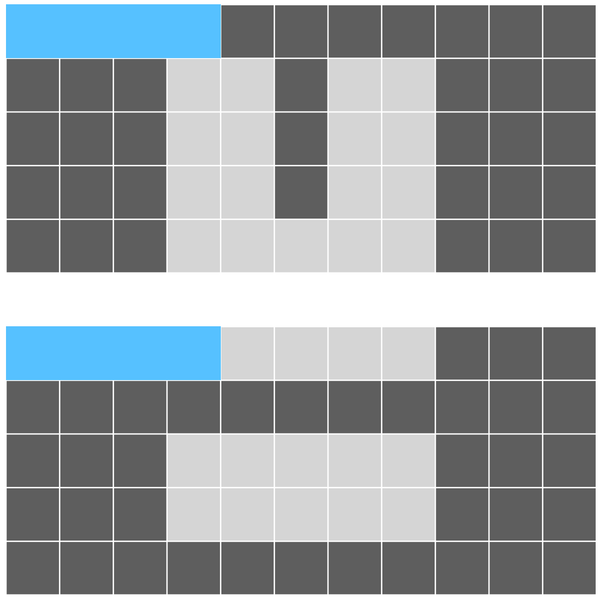


Illustration: Bounding box detection

Oblivious algorithm strategy:

3. Amortize processing cost across groups of pixels
   - E.g. use SIMD instructions to vectorize pixel operations



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2 **Novel data-oblivious algorithms for video analytics**

- Several orders of magnitude better than alternate solutions for data-obliviousness

Formal **proofs of security** for the algorithms present in the extended version of the paper

Evaluation highlights

Evaluation setup

Testbed

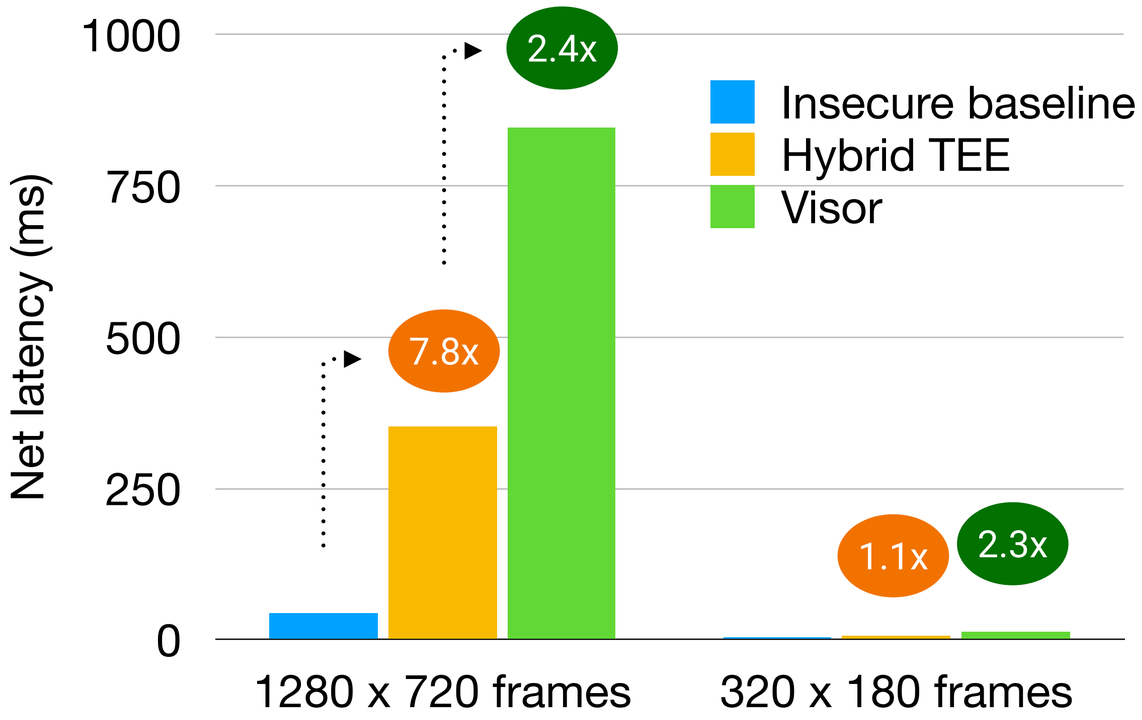
- Intel i7-8700K with 6 cores at 3.7 GHz
- NVIDIA GTX 780 GPU with 2304 CUDA cores operating at 863 MHz

Workload

- 4 real HD video streams (traffic / security cameras)
- 2 video analytics pipelines (object detection and tracking)

End-to-end overhead

- Overhead of hybrid enclave up to 8x with limited enclave memory (improves with sufficient enclave memory)
- Overhead of data-obliviousness 2.4x
- Over 6 orders of magnitude better than general-purpose alternatives[AJX+19], [RLT15]



Summary

Visor

- Privacy-preserving framework for CNN-based services spanning both CPU and GPU resources based on a hybrid enclave design
- Novel data-oblivious algorithms for video analytics pipelines
- End-to-end overhead 2.5x — 20x

Thanks!

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