The Recipe for Imitation Learning in Self-driving

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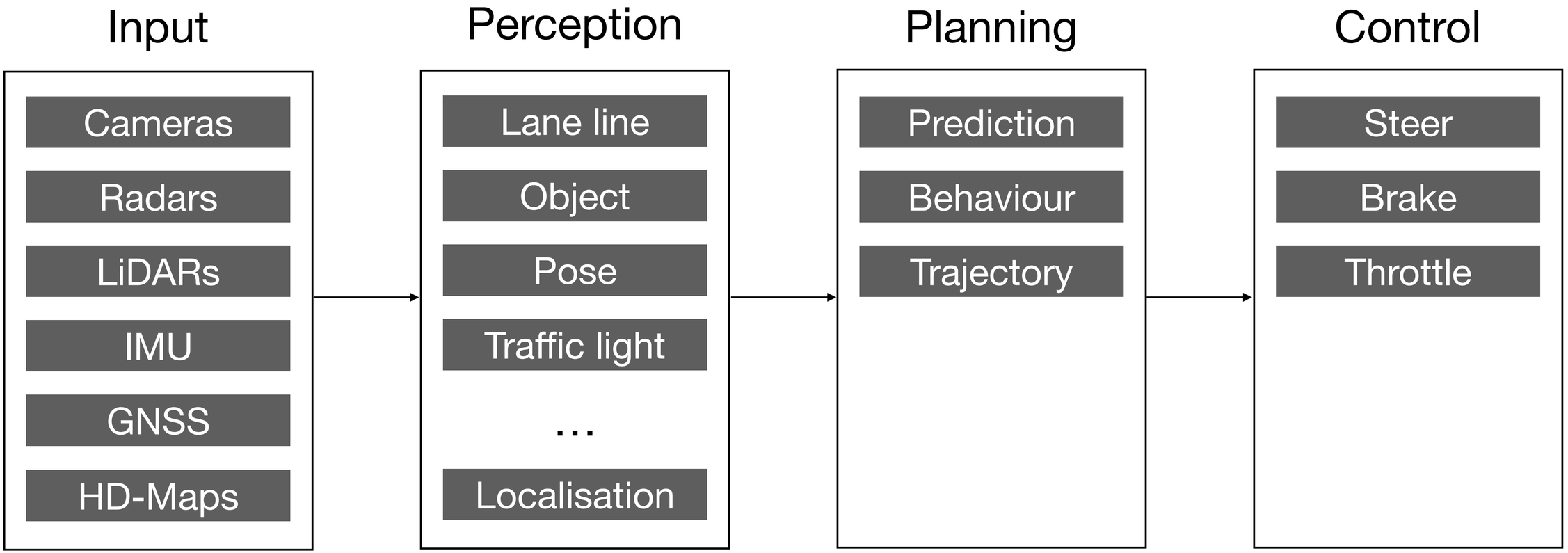
How self-driving has traditionally worked

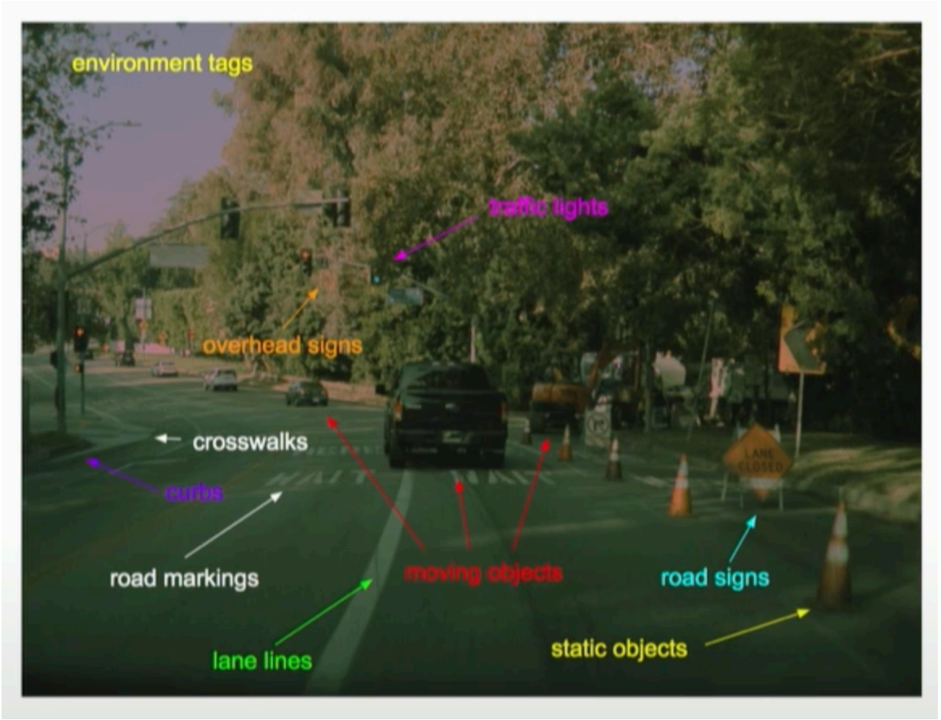
Rules based and modular pipeline



How self-driving has traditionally worked

Rules based and modular pipeline

- Explicit signals: Object bounding boxes, lane lines, traffic lights, etc.



Tesla, 2020: https://www.youtube.com/watch?v=hx7BXih7zx8

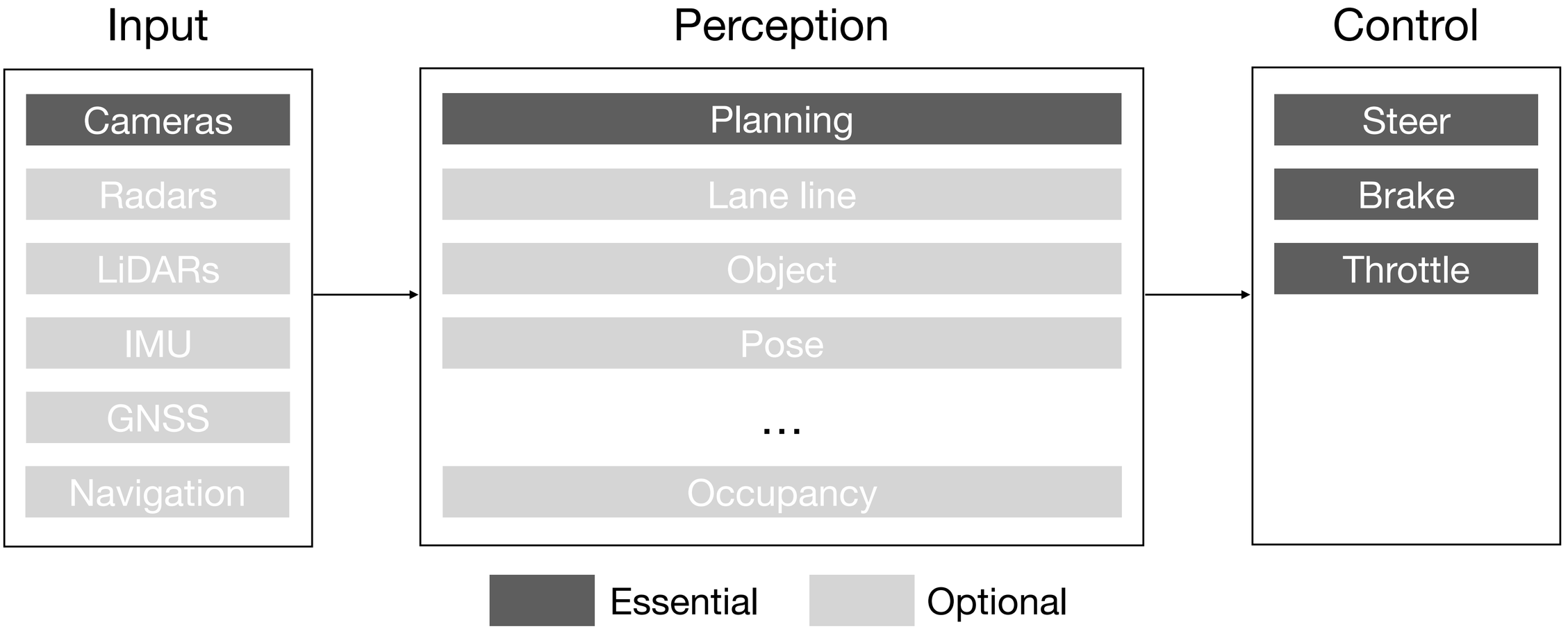
Traditional pipeline vs out-of-distribution

- Neural network trained only on driving scenes would fail to see a toilet bowl!
- It requires handling every object explicitly, not scalable.

Image from https://www.reddit.com/r/toiletswithauras/comments/glx7rc/in_the_middle_of_the_street/

The shift: The end-to-end approach

Data driven and monolithic



The shift: The end-to-end approach

Only a handful of companies are on this path

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WAYVE

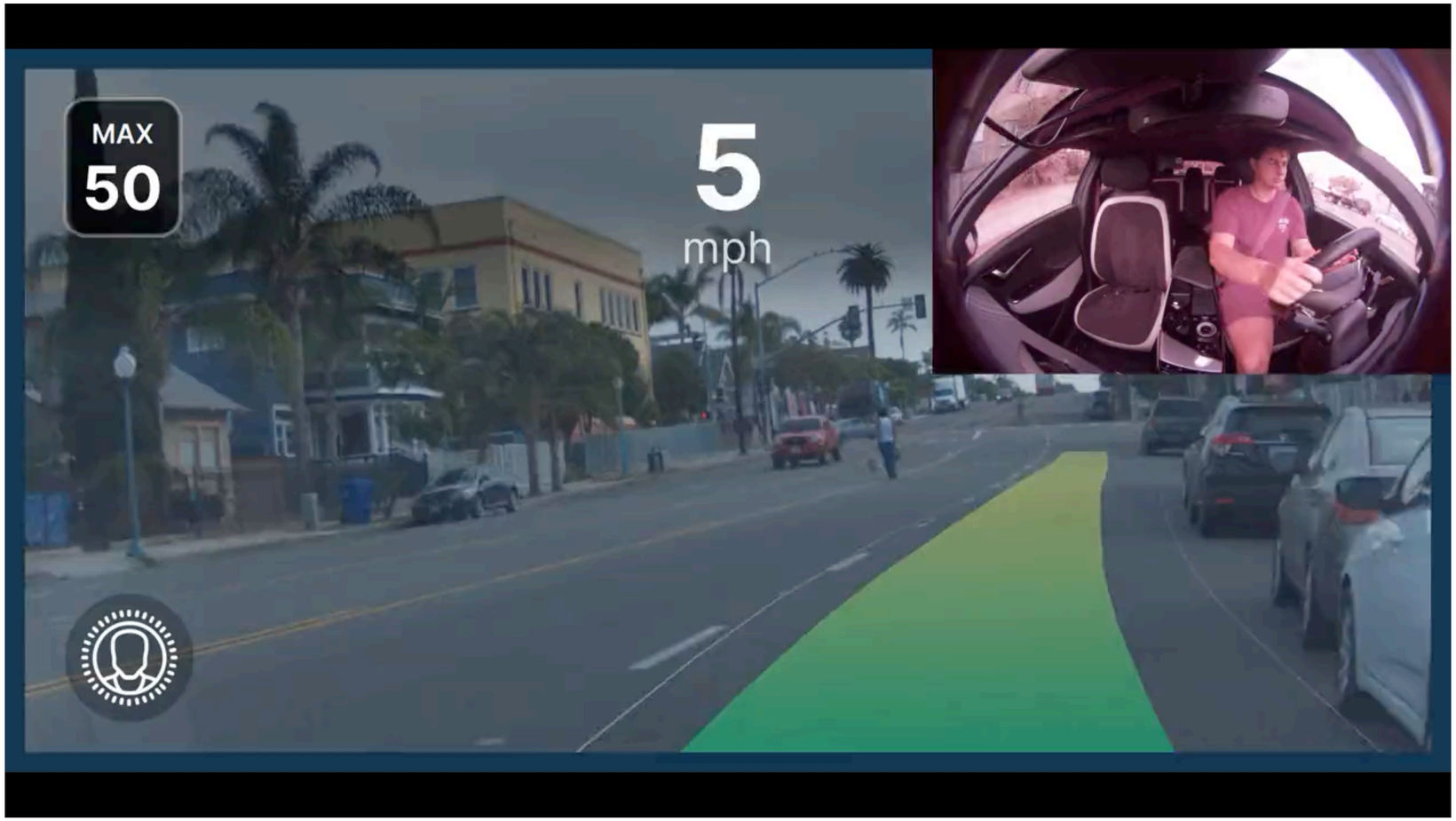
Why is e2e so powerful

Navigate through construction zone without cone detections

Comma, 2025: https://x.com/comma_ai/status/1927506950830371047

Why is e2e so powerful

Stop-and-go without traffic lights detection



Comma, 2022: https://x.com/comma_ai/status/1587584975347515392

Why is e2e so powerful

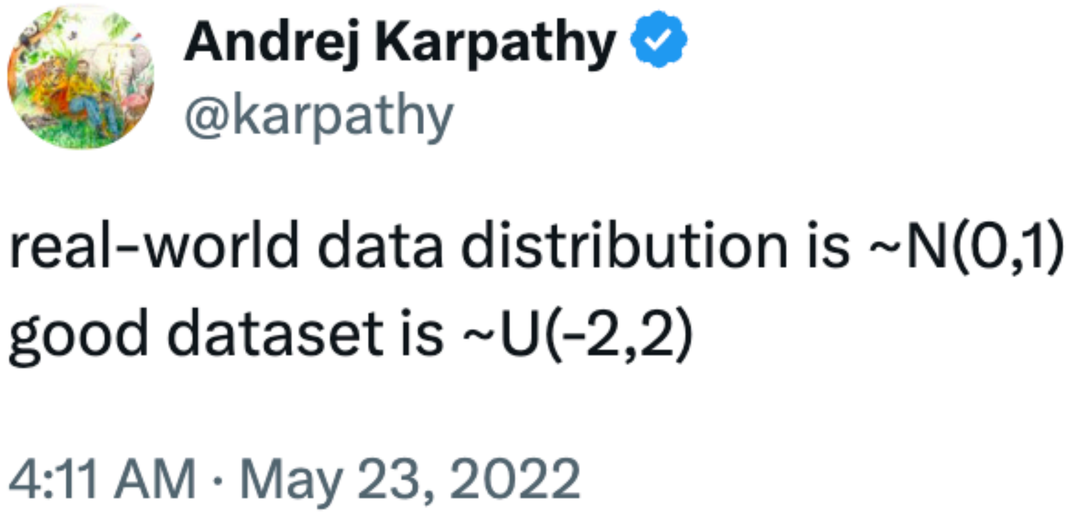
Human-like driving behavior without an explicit pothole detection

AI DRIVR, 2025: https://x.com/aidrivr/status/1909681810969420079

How to train an e2e model

The ingredients

- Dataset with diverse (long-tail edge cases) human expert demonstrations

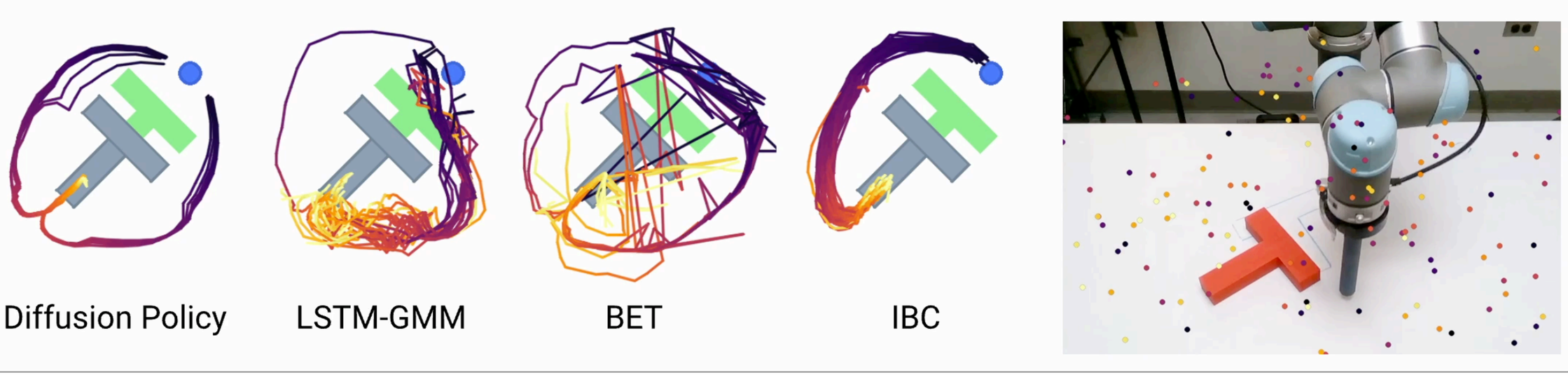


Karpathy, 2022: https://x.com/karpathy/status/1528453604515778560

How to train an e2e model

The ingredients

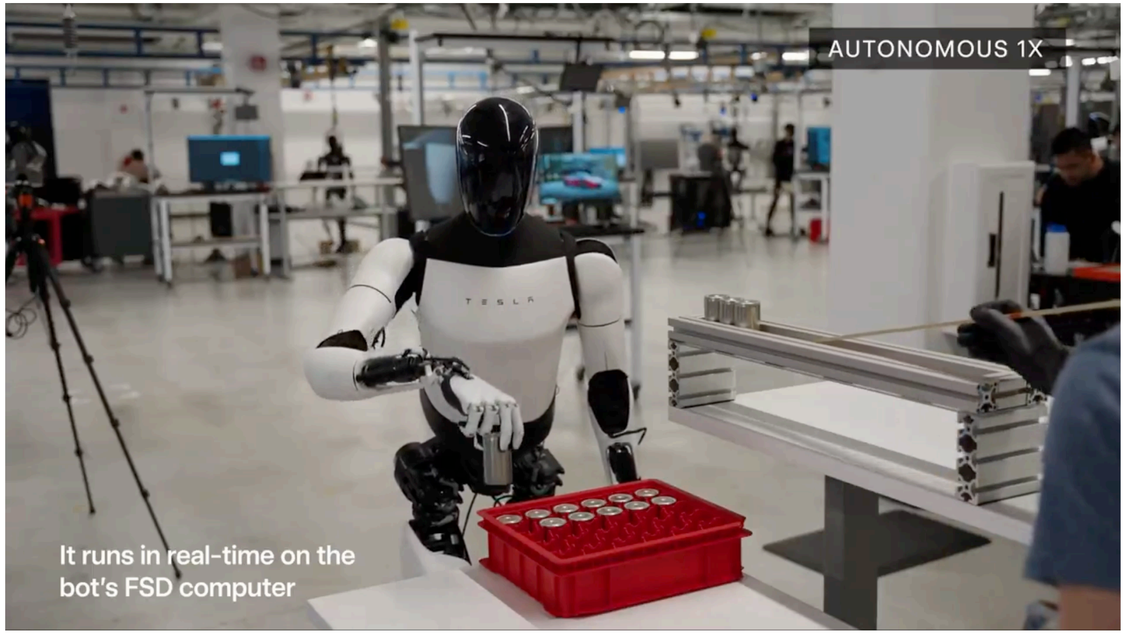
- Dataset with diverse (long-tail edge cases) human expert demonstrations
- Multimodal policy learning

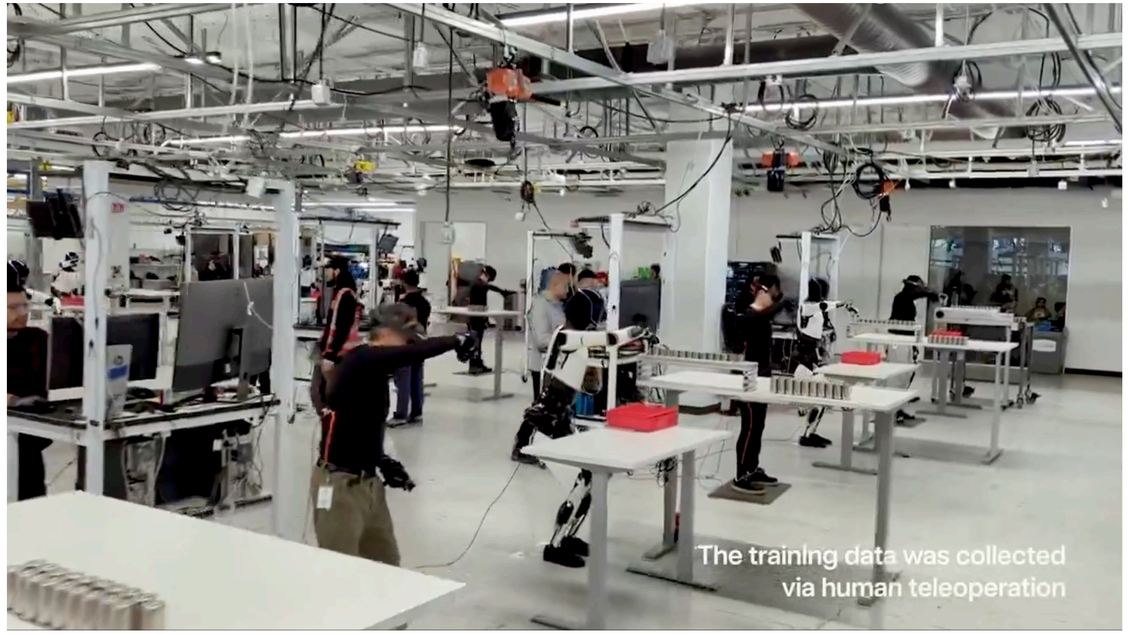


Learning from human expert

Imitation learning for manipulation task

- Diverse and high quality expert demonstrations





Tesla Optimus, 2024: https://x.com/Tesla_Optimus/status/1787027808436330505

Learning from human expert

Imitation learning challenge for driving task

- **Diverse environment**
  - Different lighting and weather conditions
- **Interaction with other agents**
- **Human driving demonstrations contain only optimal / near-optimal behavior**
  - No demonstrations like drifting out of lane and recovery
  - Or, near collision with other obstacles and recovery

Learning from human expert

Imitation learning challenge for driving task

Can be solved by collecting more data

- **Diverse environment**
  - Different lighting and weather conditions
- **Interaction with other agents**
- **Human driving demonstrations contain only optimal / near-optimal behavior**
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Cannot be solved by collecting more data

Learning from human expert

What happened if it’s trained with pure imitation learning?

- It quickly drifts out of lane due to error accumulation over time.
- Failed to recover as the model never encountered the scene before.

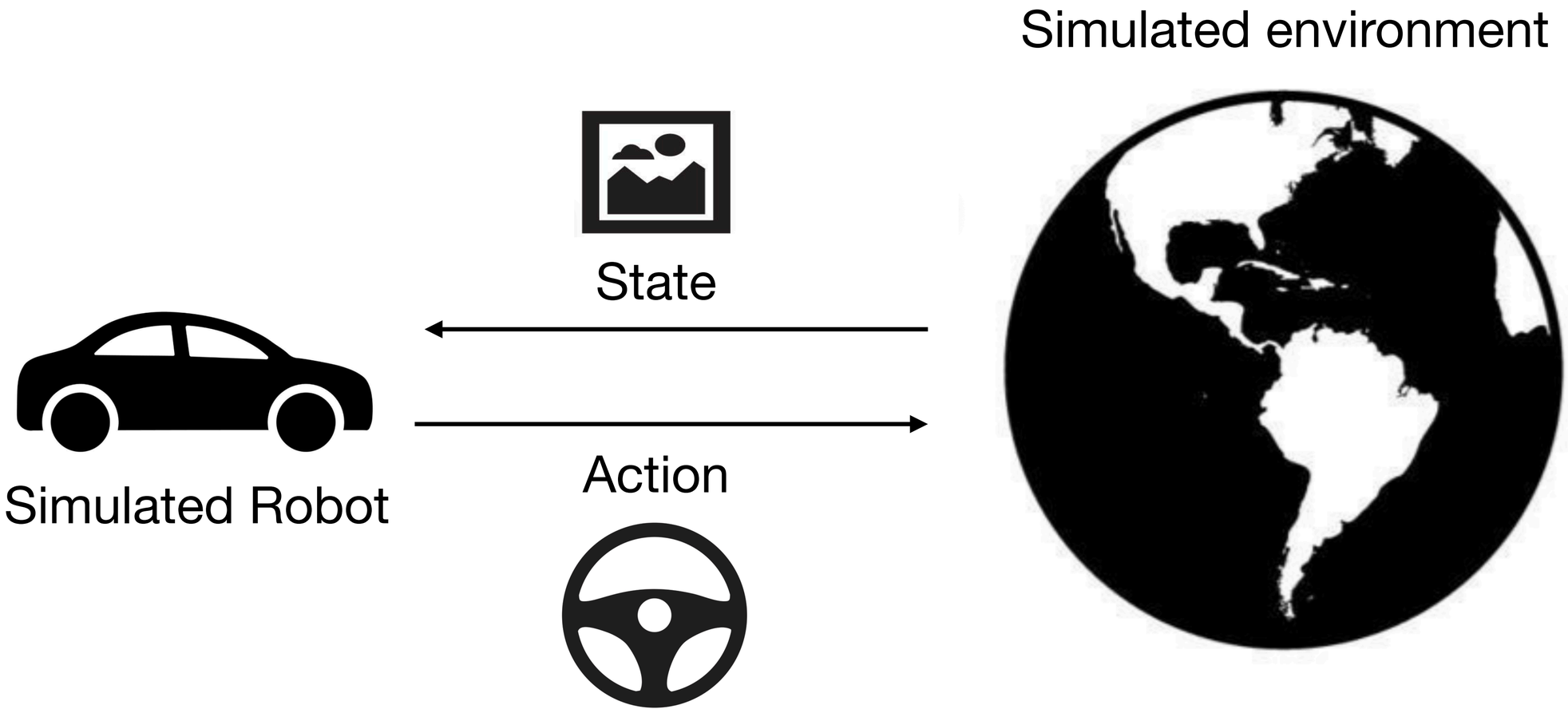
Comma, 2021: https://blog.comma.ai/end-to-end-lateral-planning/

What can we do?

- **Human collection**
  - Ask drivers to intentionally deviate and perform recovery actions
  - **Dangerous and not scalable**
- **Build a simulator**
  - Inject perturbations (position, heading, speed)
  - **Safe and scalable**

The recipe

Training in a photorealistic simulator + perturbations injection



The recipe

Training in a photorealistic simulator + perturbations injection

- On policy training in a simulator with perturbations injection
- A photorealistic simulator that’s build from actual driving data
  - Not a synthetic 3D graphics simulator

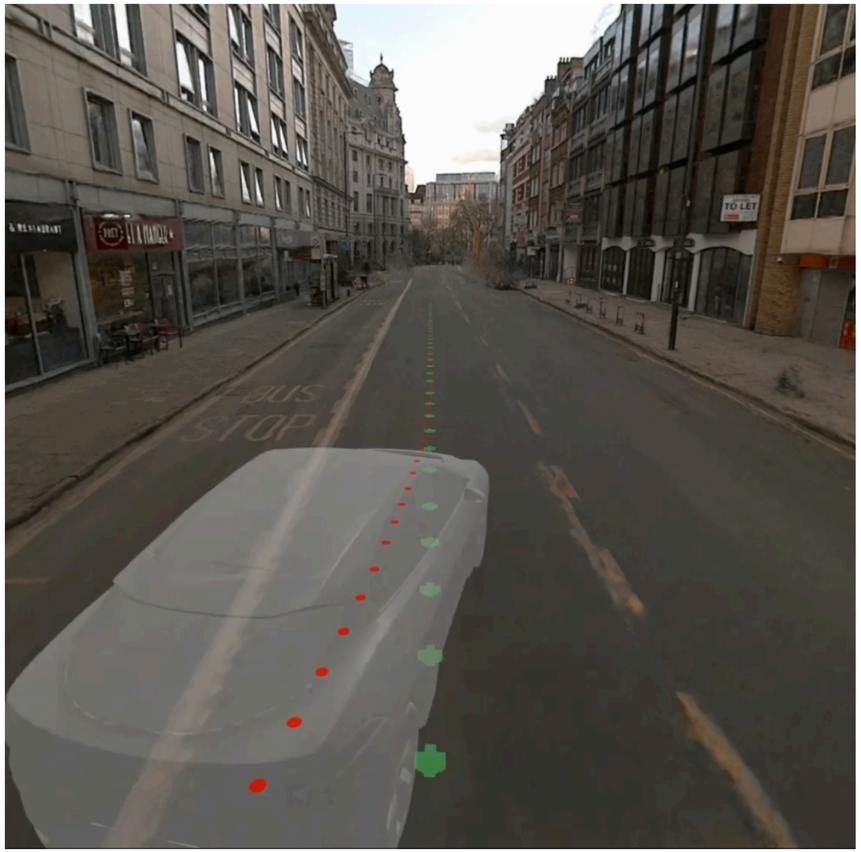
Simulator: 3D reconstruction

Modern techniques: Nerf, 3DGS, VGGT

Tesla, 2023: https://www.youtube.com/watch?v=6x-Xb_uT7ts

Simulator: 3D reconstruction

Perturbations injection and view point rendering



Wayve, 2023: https://www.youtube.com/watch?v=8fivoXbT1Ao

Simulator: 3D reconstruction

Limitations

- Does not work well with dynamic objects, extreme illuminations, adverse weather conditions.
- Can we do better?

Simulator: Data driven generative model

A world model trained on very diverse scenes

Tesla, 2023: https://www.youtube.com/watch?v=6x-Xb_uT7ts

Simulator: Data driven generative model

Prompt and rollout

Tesla, 2023: https://www.youtube.com/watch?v=6x-Xb_uT7ts

Simulator: Data driven generative model

Challenges

- Video frames rollout can diverge over time
- Requires precise 6-DOF controllability to navigate in the world model
- No human action ground truth

Simulator: Data driven generative model

Challenges

- Video frames rollout can diverge over time
  - Can be solved by conditioning on desired future states
- Requires precise 6-DOF controllability to navigate in the world model
  - Can be solved by conditioning on a 6-DOF input during the training
- No human action ground truth
  - Can be solved by learning to generate the action not just the image

Comma AI, 2025: https://arxiv.org/pdf/2504.19077

The e2e imitation learning caveats

There is no free lunch

- **Pros**
  - The deployment pipeline is very simple: Eliminate hand coded rules
  - Improves with data scale: Performance improve by adding more diverse data
- **Cons**
  - Complex training pipeline: Requires more engineering efforts
  - Limited interpretability: Harder to understand / debug
  - Lacks formal safety guarantees: No clear intermediate signals

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