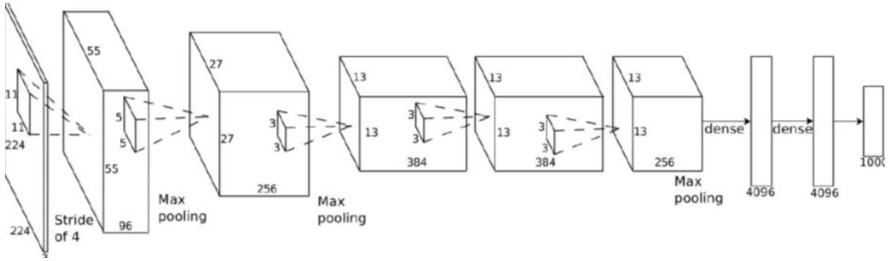
Supervised Learning of Behaviors

CS 285

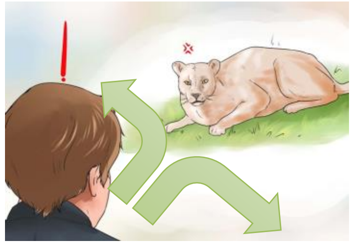
Instructor: Sergey Levine
UC Berkeley

Terminology & notation

$\mathbf{o}_t$



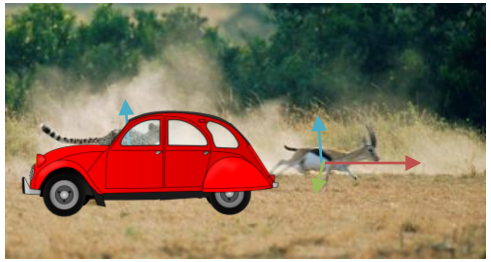
$\pi_\theta(\mathbf{a}_t|\mathbf{o}_t)$



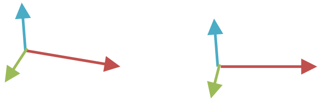
$\mathbf{a}_t$

$\mathbf{s}_t$ – state
$\mathbf{o}_t$ – observation
$\mathbf{a}_t$ – action

$\pi_\theta(\mathbf{a}_t|\mathbf{o}_t)$ – policy
$\pi_\theta(\mathbf{a}_t|\mathbf{s}_t)$ – policy (fully observed)

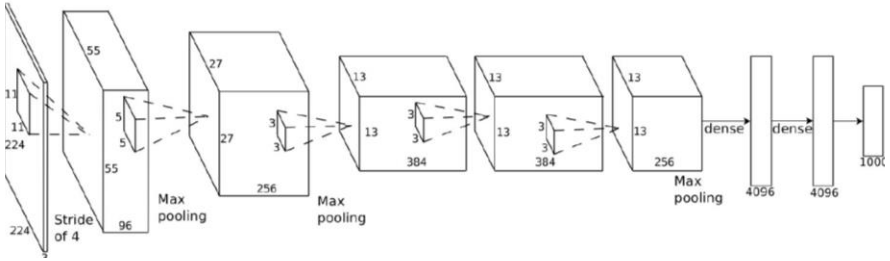


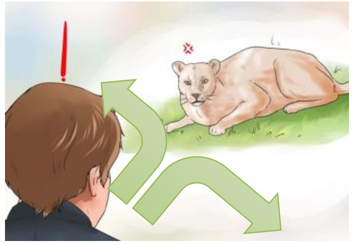
$\mathbf{o}_t$ – observation



$\mathbf{s}_t$ – state

Terminology & notation





$\mathbf{o}_t$ $\pi_\theta(\mathbf{a}_t|\mathbf{o}_t)$ $\mathbf{a}_t$

$\mathbf{s}_t$ – state
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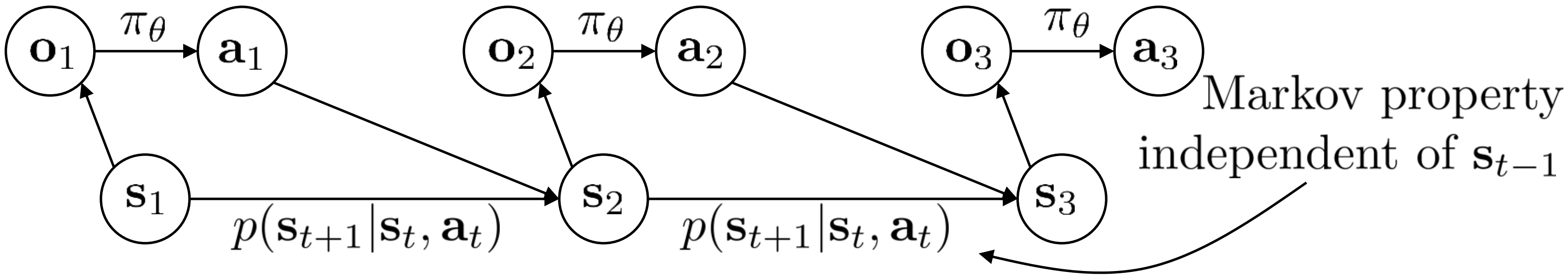
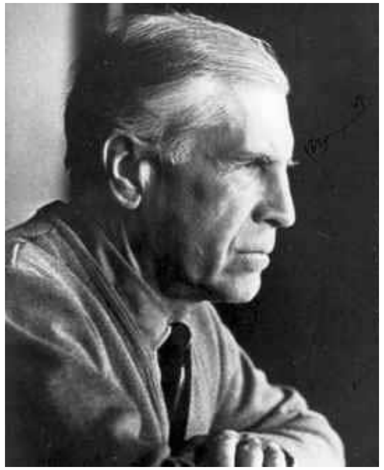


Aside: notation

$\mathbf{s}_t$ – state
$\mathbf{a}_t$ – action

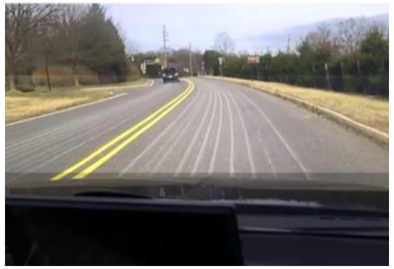
$\mathbf{x}_t$ – state
$\mathbf{u}_t$ – action   управление

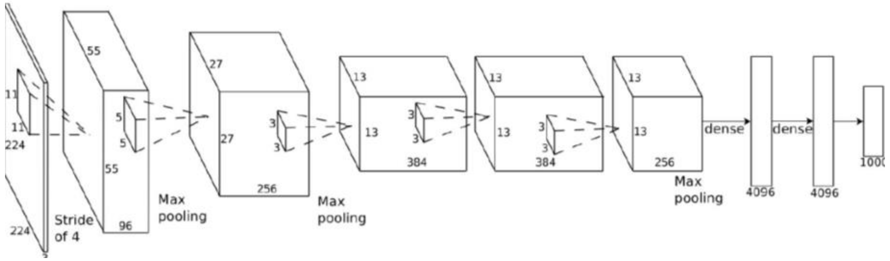
Richard Bellman

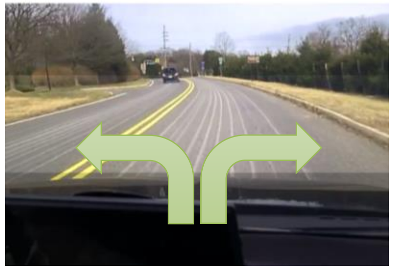


Lev Pontryagin

Imitation Learning



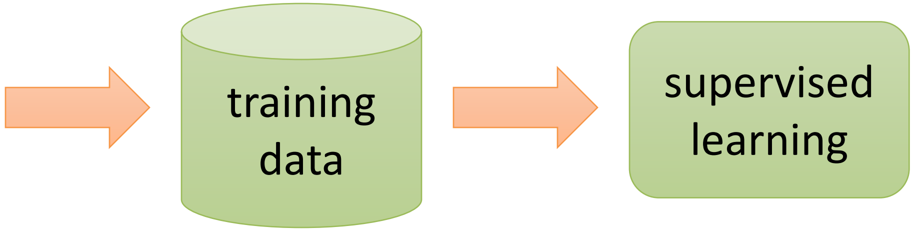




$\mathbf{o}_t$ $\pi_\theta(\mathbf{a}_t|\mathbf{o}_t)$ $\mathbf{a}_t$

$\mathbf{o}_t$

$\mathbf{a}_t$



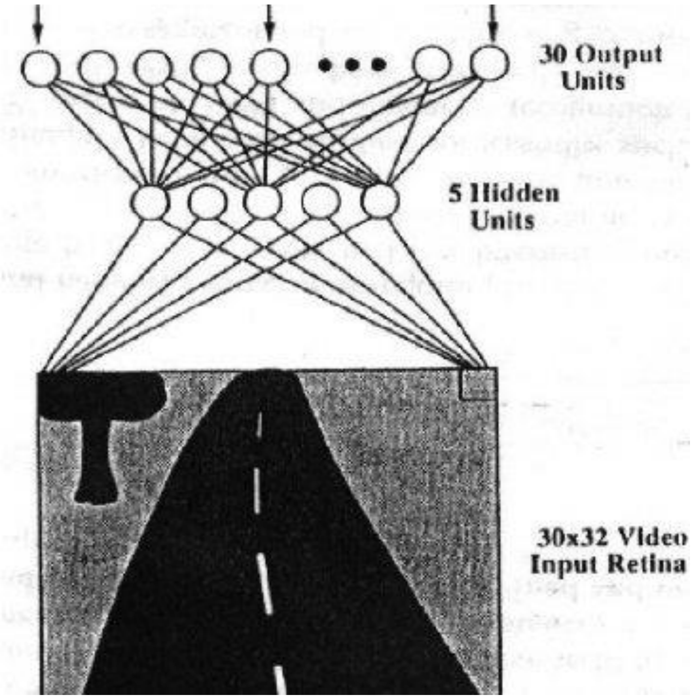
$\pi_\theta(\mathbf{a}_t|\mathbf{o}_t)$

behavioral cloning

Images: Bojarski et al. '16, NVIDIA

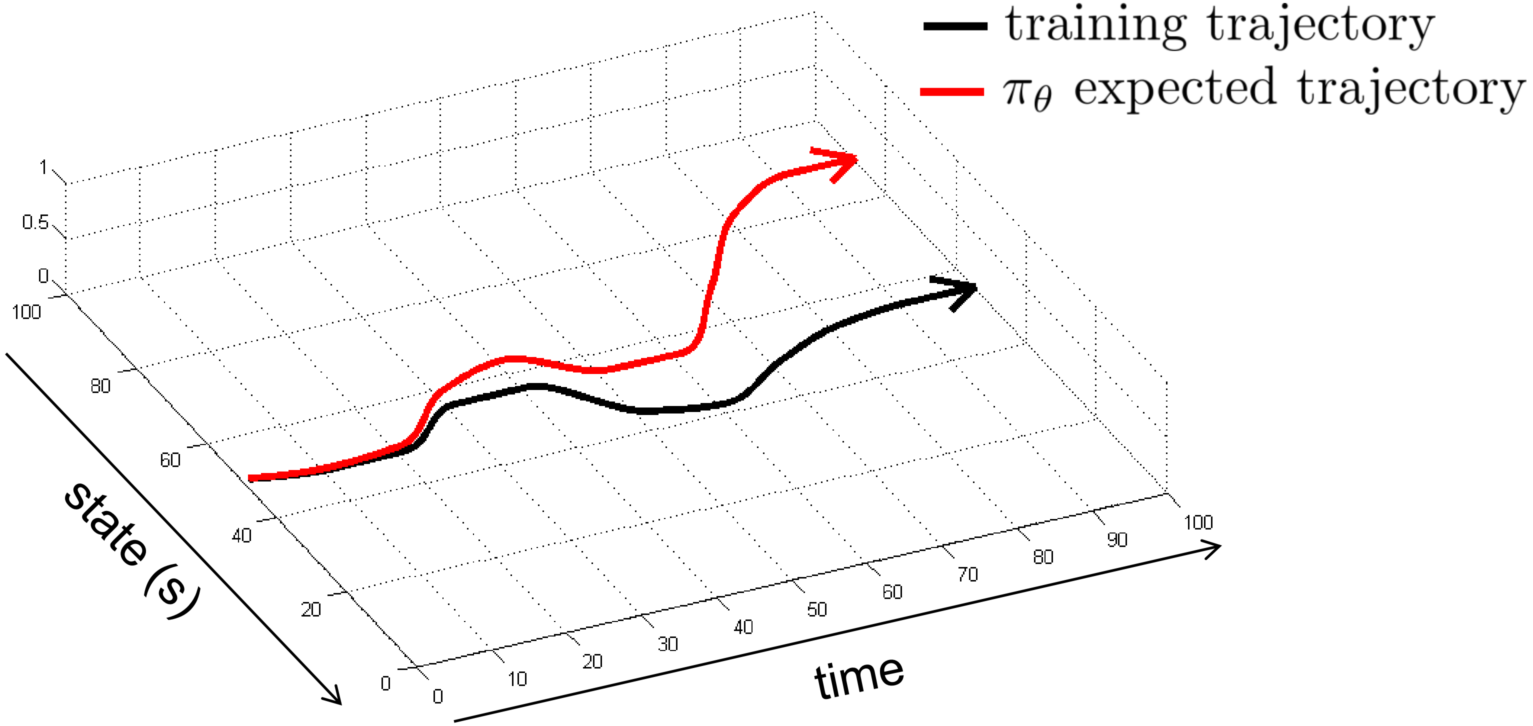
The original deep imitation learning system

ALVINN: **A**utonomous **L**and **V**ehicle **I**n a **N**eural **N**etwork
1989



Does it work?

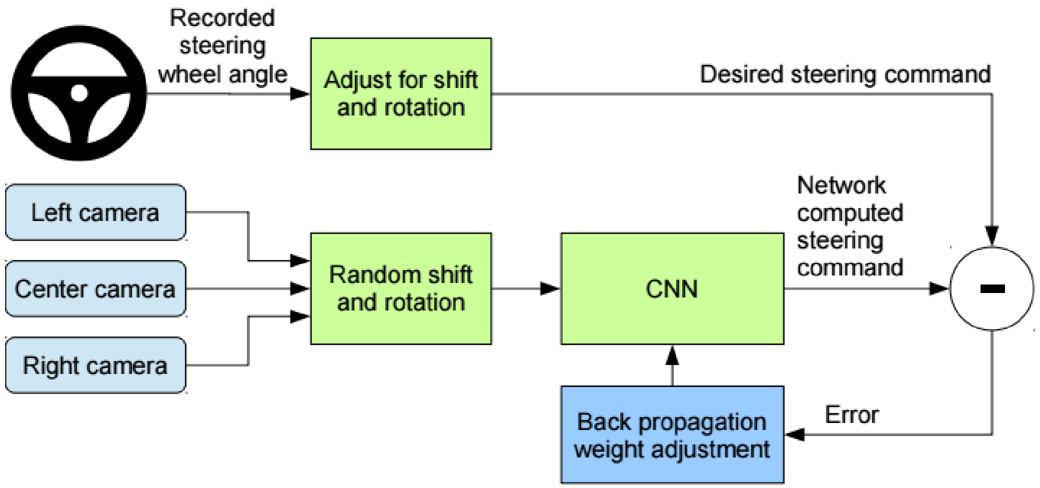
No!

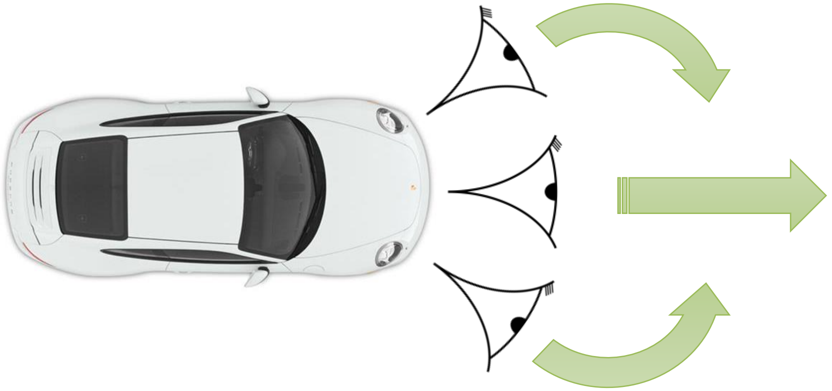


Does it work? Yes!

Video: Bojarski et al. ‘16, NVIDIA

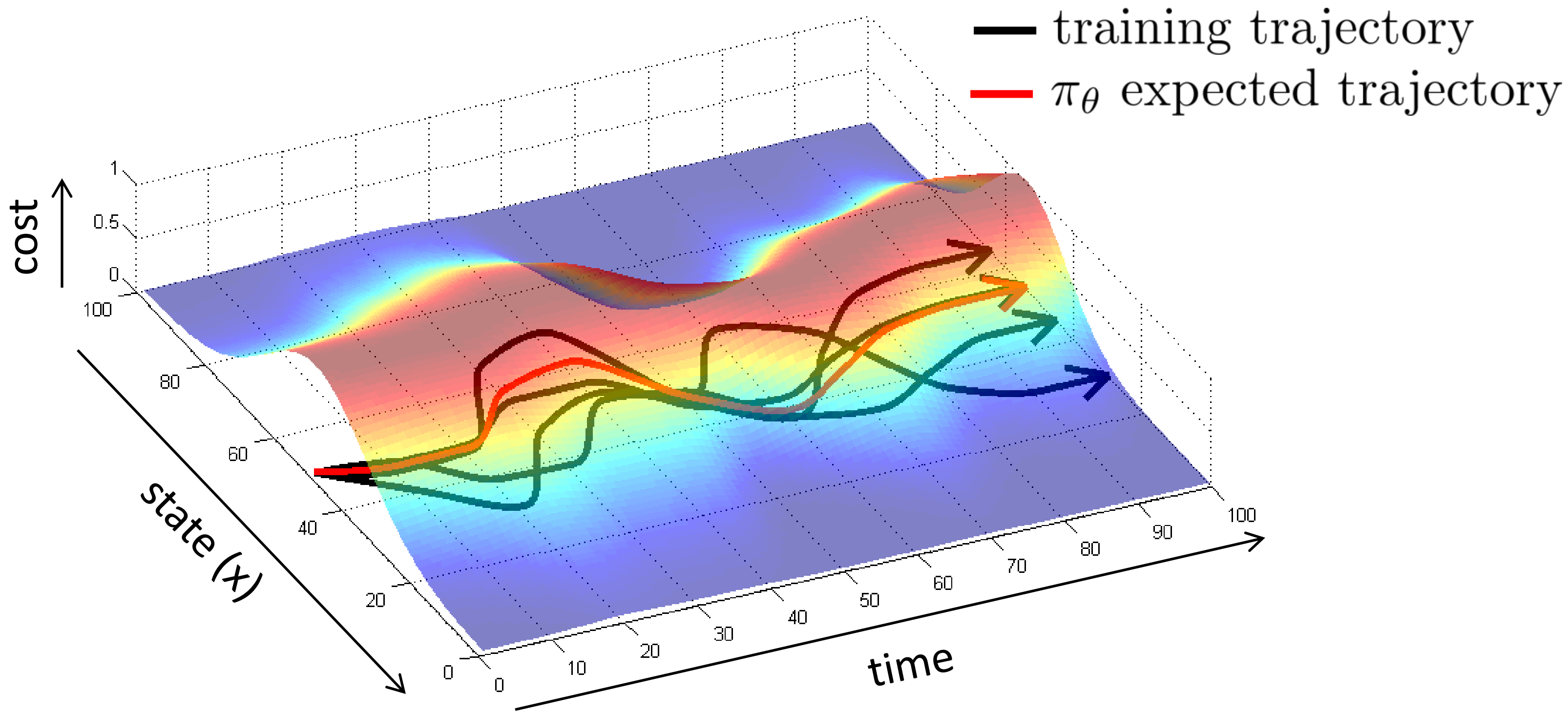
Why did that work?





Bojarski et al. '16, NVIDIA

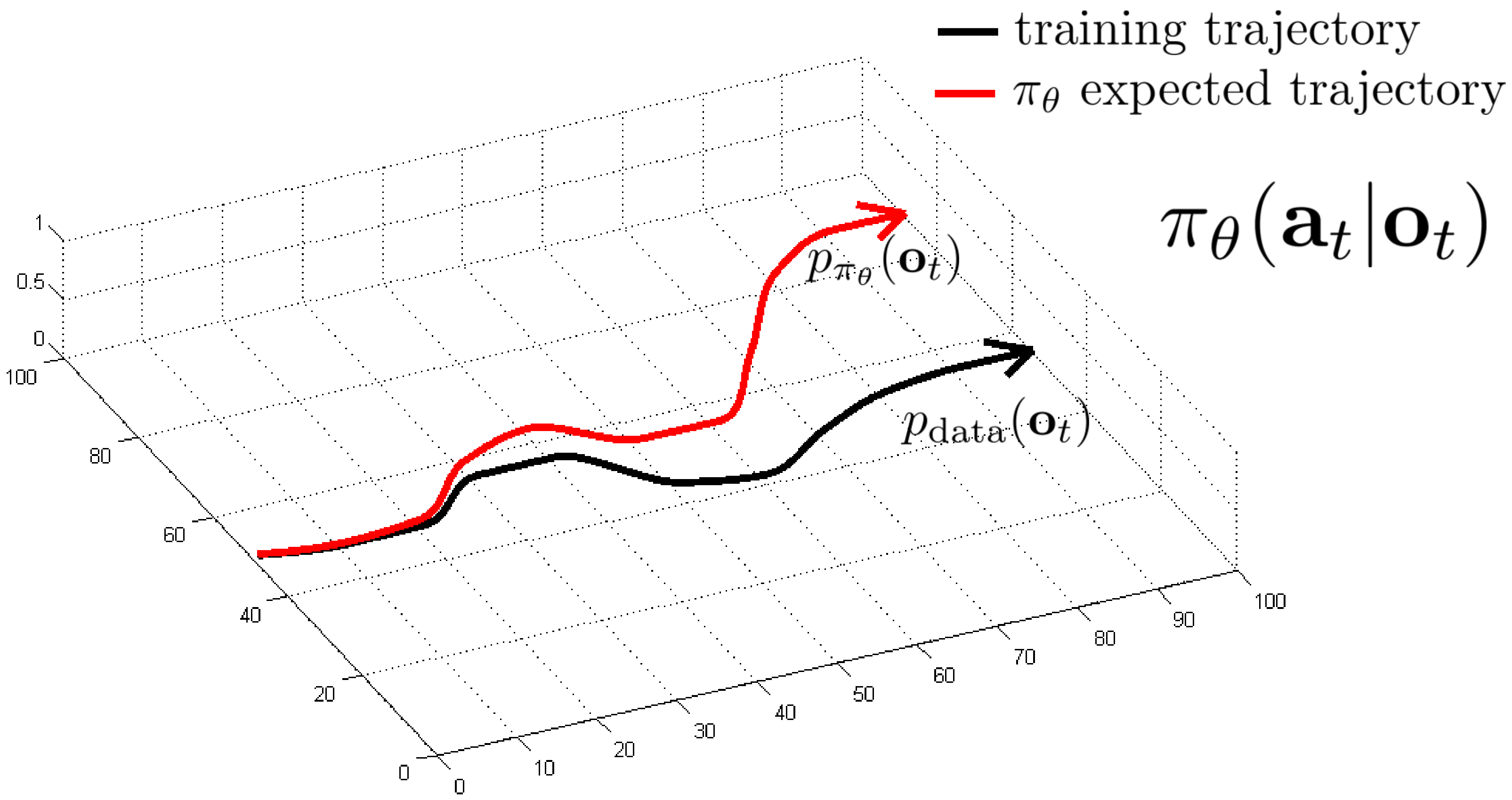
Can we make it work more often?



stability

(more on this later)

Can we make it work more often?



$$\pi_\theta(\mathbf{a}_t|\mathbf{o}_t)$$

can we make $p_{\text{data}}(\mathbf{o}_t) = p_{\pi_\theta}(\mathbf{o}_t)$?

Can we make it work more often?

can we make $p_{\text{data}}(\mathbf{o}_t) = p_{\pi_\theta}(\mathbf{o}_t)$?

idea: instead of being clever about $p_{\pi_\theta}(\mathbf{o}_t)$, be clever about $p_{\text{data}}(\mathbf{o}_t)$!

DAgger: **D**ataset **Agg**regation

goal: collect training data from $p_{\pi_\theta}(\mathbf{o}_t)$ instead of $p_{\text{data}}(\mathbf{o}_t)$

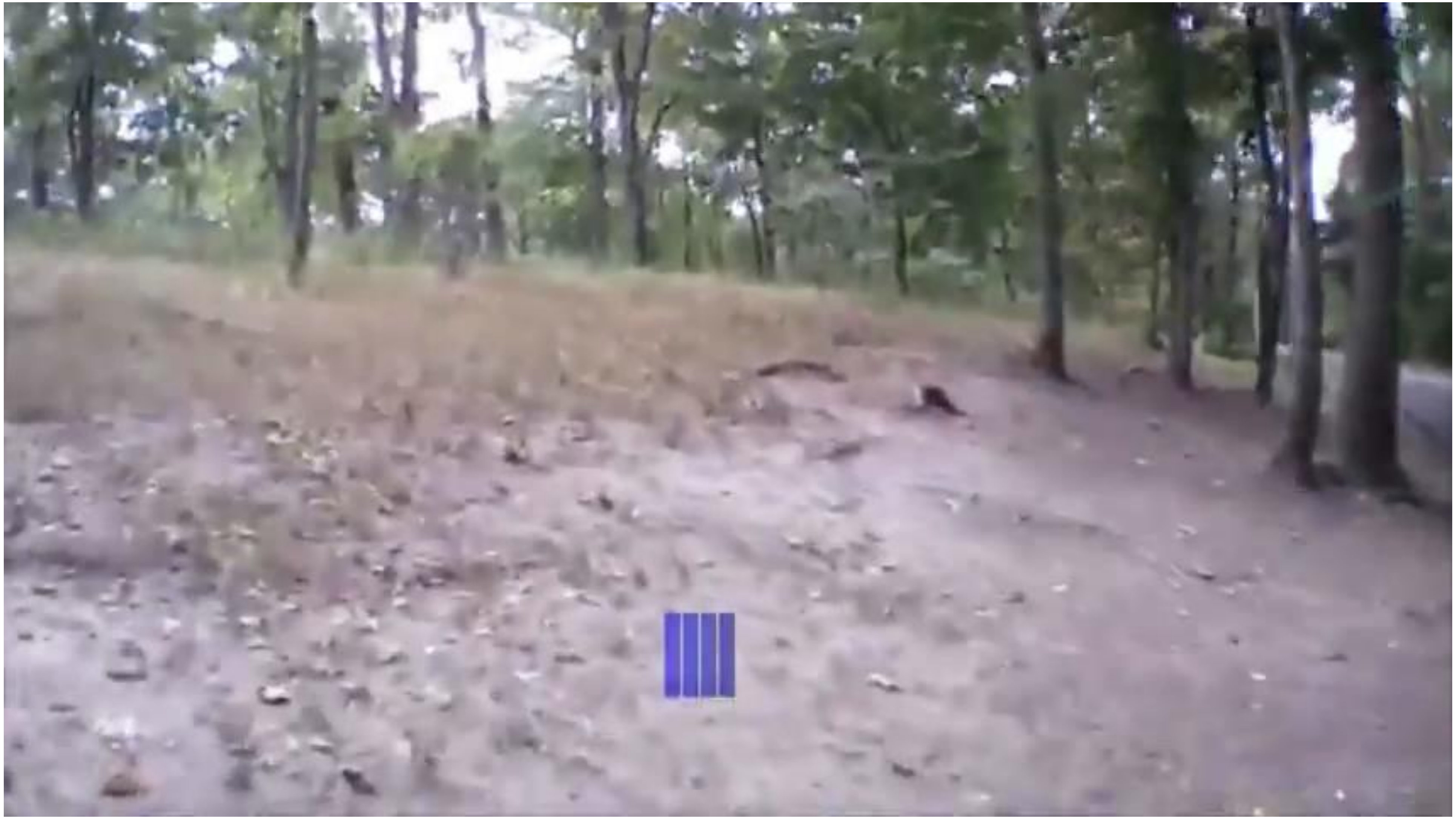
how? just run $\pi_\theta(\mathbf{a}_t|\mathbf{o}_t)$

but need labels $\mathbf{a}_t$!

1. train $\pi_\theta(\mathbf{a}_t|\mathbf{o}_t)$ from human data $\mathcal{D} = \{\mathbf{o}_1, \mathbf{a}_1, \ldots, \mathbf{o}_N, \mathbf{a}_N\}$
2. run $\pi_\theta(\mathbf{a}_t|\mathbf{o}_t)$ to get dataset $\mathcal{D}_\pi = \{\mathbf{o}_1, \ldots, \mathbf{o}_M\}$
3. Ask human to label $\mathcal{D}_\pi$ with actions $\mathbf{a}_t$
4. Aggregate: $\mathcal{D} \leftarrow \mathcal{D} \cup \mathcal{D}_\pi$

Ross et al. '11

DAgger Example



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What's the problem?

1. train $\pi_\theta(\mathbf{a}_t|\mathbf{o}_t)$ from human data $\mathcal{D} = \{\mathbf{o}_1, \mathbf{a}_1, \ldots, \mathbf{o}_N, \mathbf{a}_N\}$
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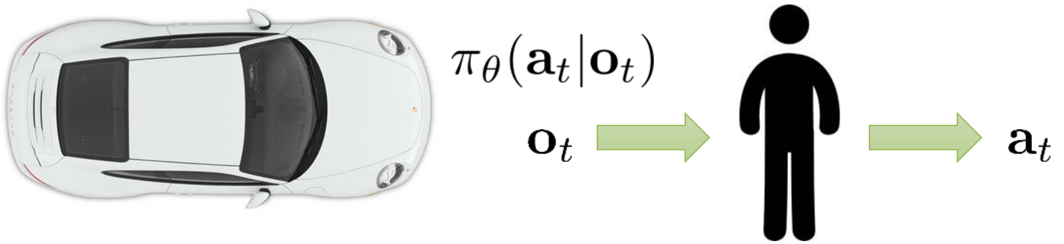
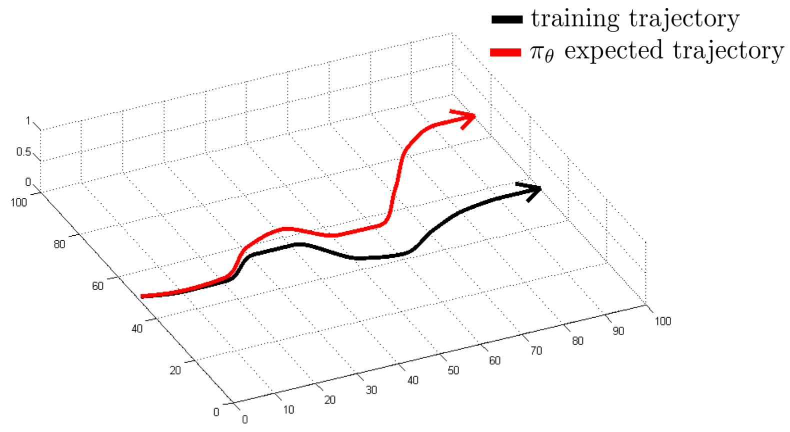


Ross et al. '11

Deep imitation learning in practice

Can we make it work without more data?

- DAgger addresses the problem of distributional "drift"
- What if our model is so good that it doesn't drift?
- Need to mimic expert behavior very accurately
- But don't overfit!



Why might we fail to fit the expert?

1. Non-Markovian behavior
2. Multimodal behavior

$$\pi_\theta(\mathbf{a}_t|\mathbf{o}_t)$$

behavior depends only on current observation

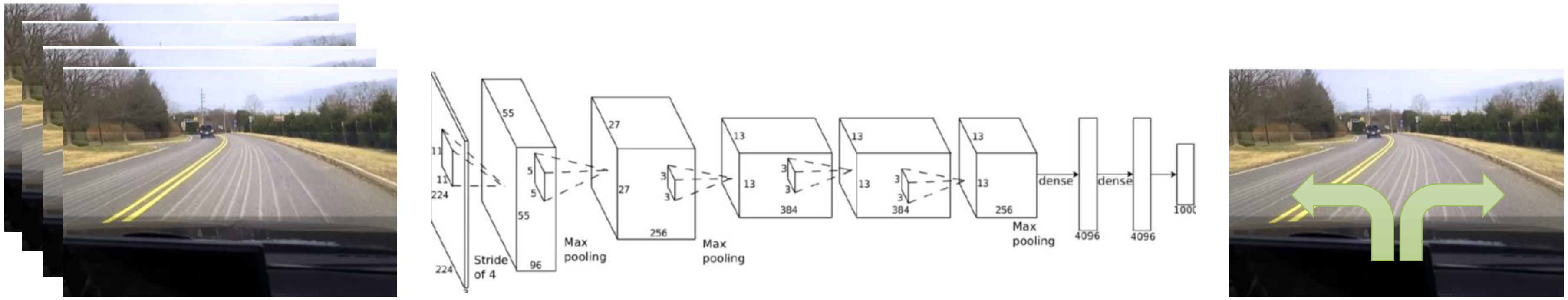
$$\pi_\theta(\mathbf{a}_t|\mathbf{o}_1, ..., \mathbf{o}_t)$$

behavior depends on all past observations

If we see the same thing twice, we do the same thing twice, regardless of what happened before

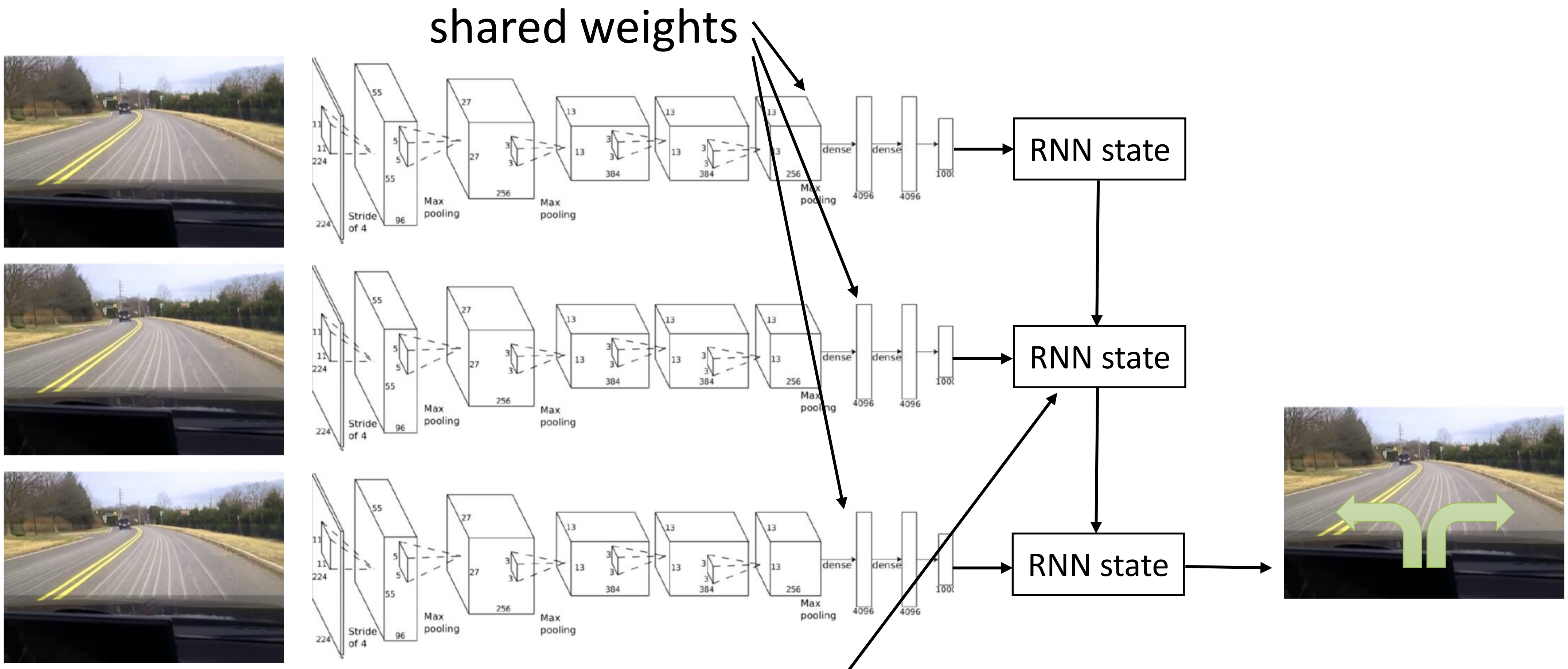
Often very unnatural for human demonstrators

How can we use the whole history?



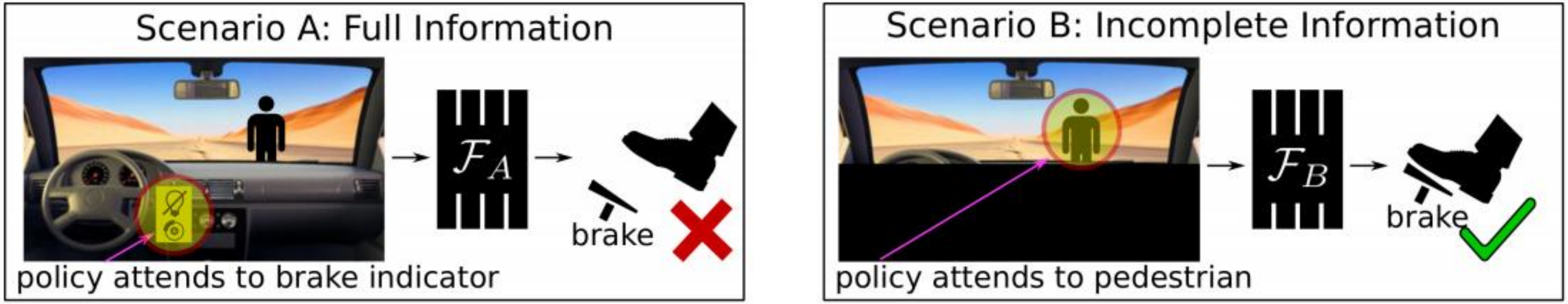
variable number of frames,
too many weights

How can we use the whole history?



Typically, LSTM cells work better here

Aside: why might this work **poorly**?



"causal confusion"

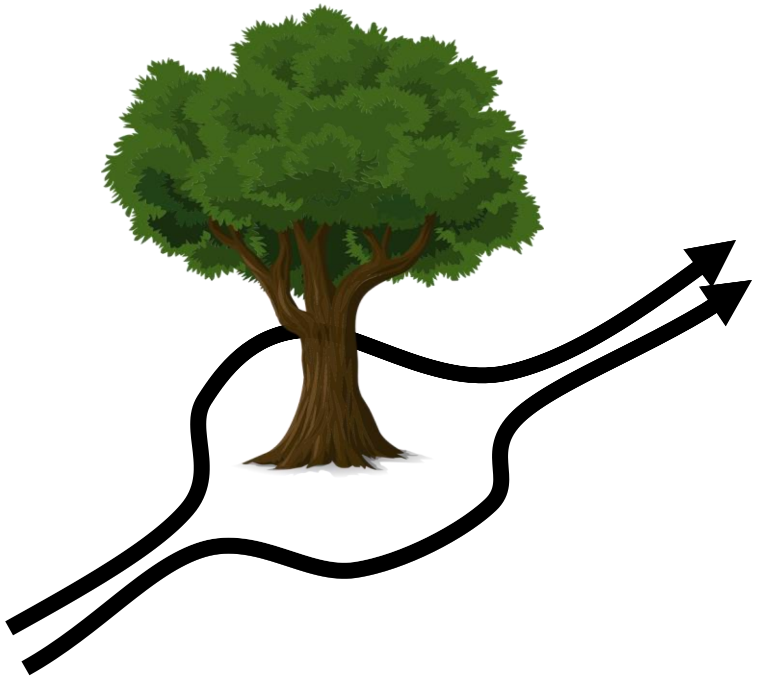
see: de Haan et al., "Causal Confusion in Imitation Learning"

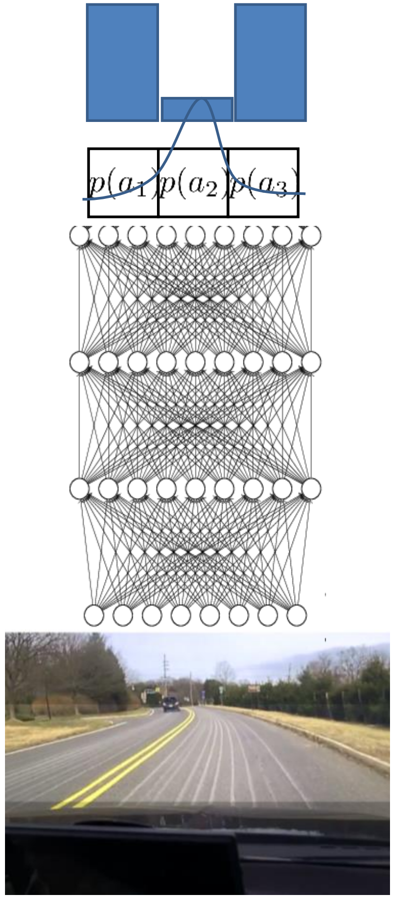
Question 1: Does including history mitigate causal confusion?

Question 2: Can DAgger mitigate causal confusion?

Why might we fail to fit the expert?

1. Non-Markovian behavior
2. Multimodal behavior



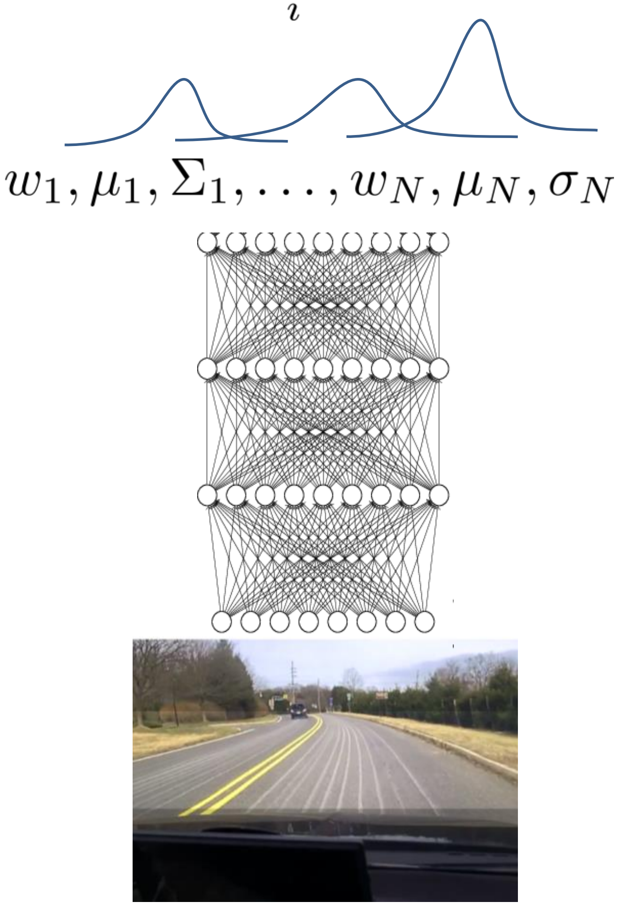


1. Output mixture of Gaussians
2. Latent variable models
3. Autoregressive discretization

Why might we fail to fit the expert?

1. Output mixture of Gaussians
2. Latent variable models
3. Autoregressive discretization

$$\pi(\mathbf{a}|\mathbf{o}) = \sum_i w_i \mathcal{N}(\mu_i, \Sigma_i)$$



Why might we fail to fit the expert?

1. Output mixture of Gaussians
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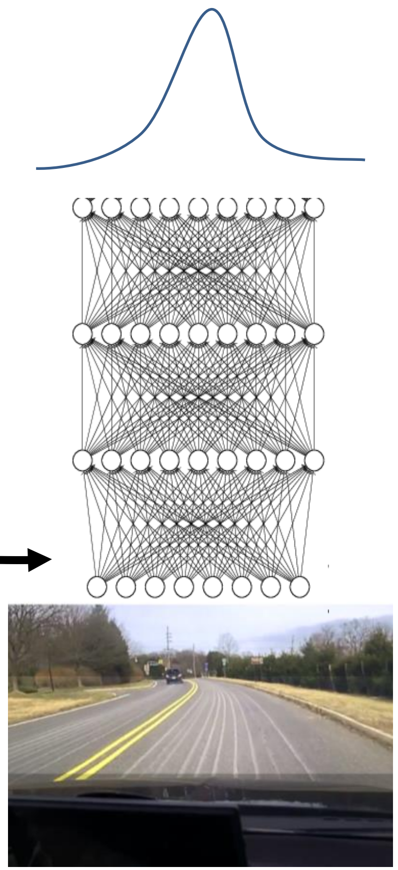
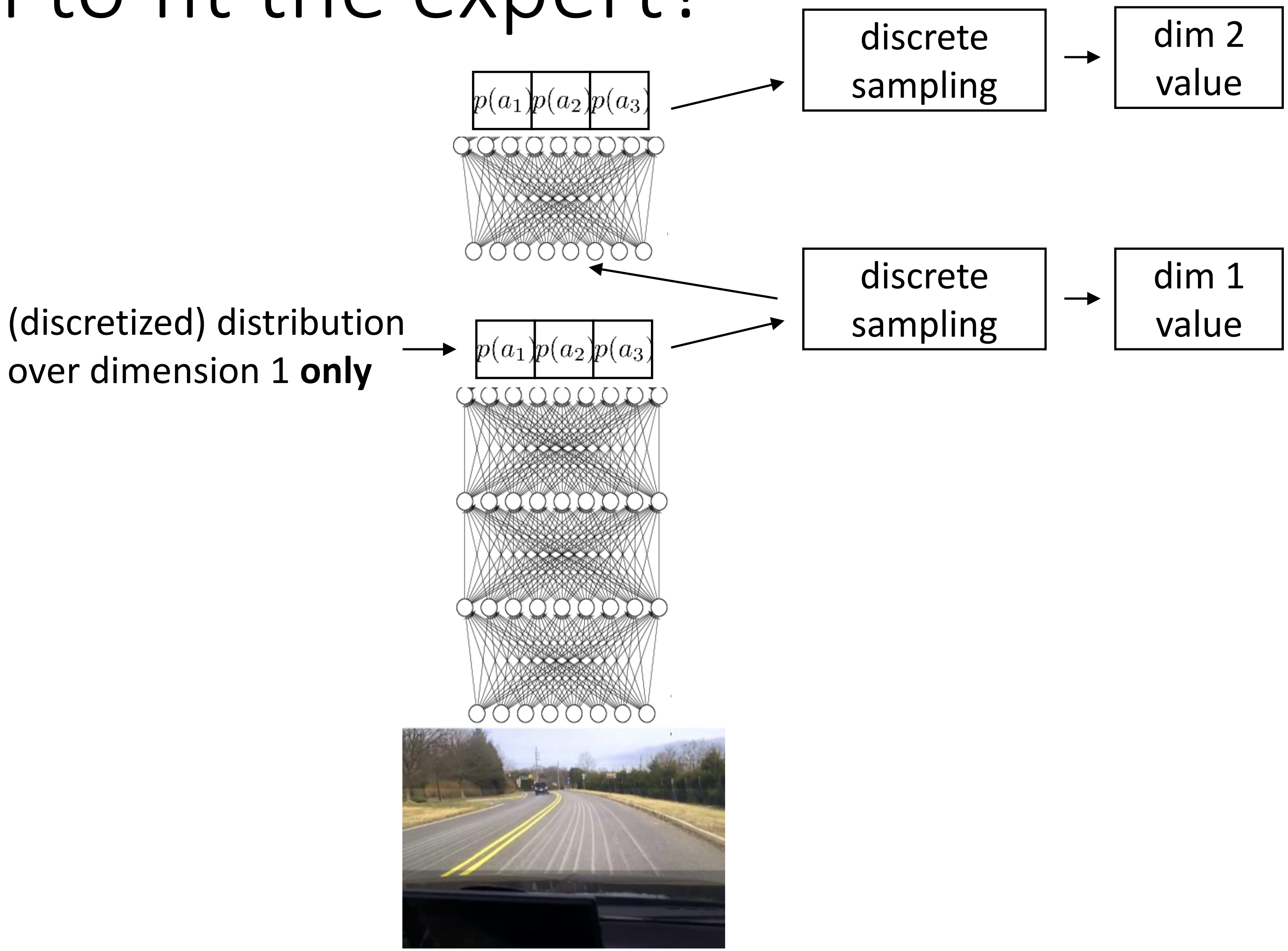


$\xi \sim \mathcal{N}(0, \mathbf{I})$

Look up some of these:
- Conditional variational autoencoder
- Normalizing flow/realNVP
- Stein variational gradient descent

Why might we fail to fit the expert?

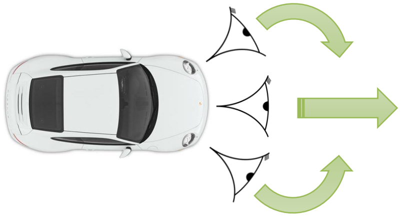
1. Output mixture of Gaussians
2. Latent variable models
3. Autoregressive discretization



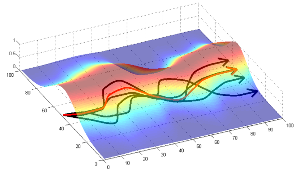
Imitation learning: recap

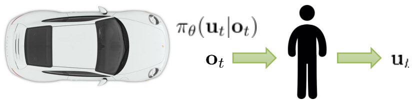
$\mathbf{o}_t$
$\mathbf{a}_t$ → training data → supervised learning → $\pi_\theta(\mathbf{a}_t|\mathbf{o}_t)$

- Often (but not always) insufficient by itself
  - Distribution mismatch problem



- Sometimes works well
  - Hacks (e.g. left/right images)
  - Samples from a stable trajectory distribution
  - Add more **on-policy** data, e.g. using Dagger
  - Better models that fit more accurately



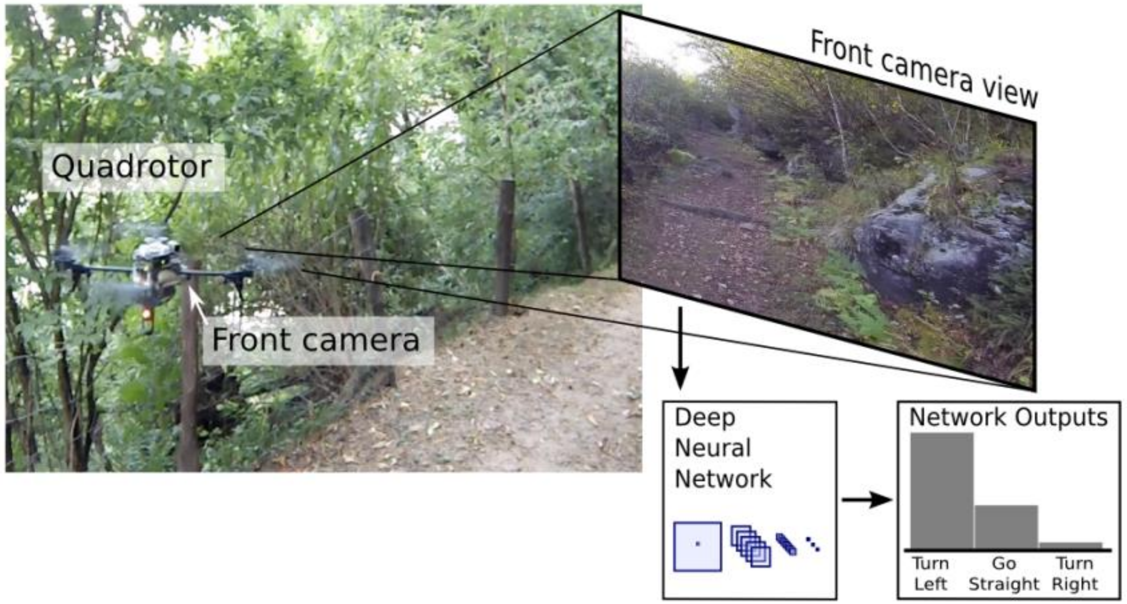


A case study: trail following from human demonstration data

Case study 1: trail following as classification

A Machine Learning Approach to Visual Perception of Forest Trails for Mobile Robots

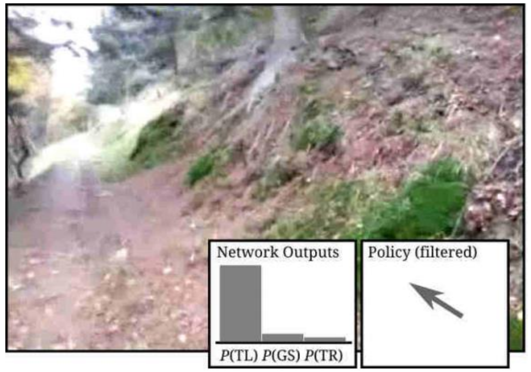
Alessandro Giusti[1], Jérôme Guzzi[1], Dan C. Cireşan[1], Fang-Lin He[1], Juan P. Rodríguez[1]
Flavio Fontana[2], Matthias Faessler[2], Christian Forster[2]
Jürgen Schmidhuber[1], Gianni Di Caro[1], Davide Scaramuzza[2], Luca M. Gambardella[1]

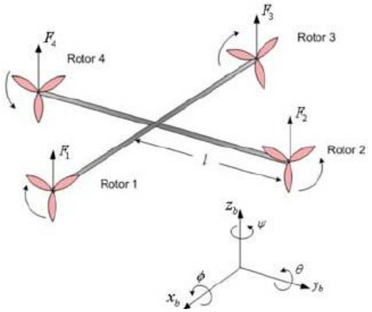


Cost functions, reward functions, and a bit of theory

Imitation learning: what's the problem?

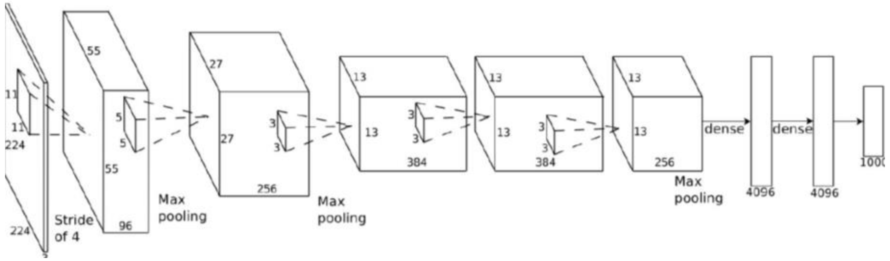
- Humans need to provide data, which is typically finite
  - Deep learning works best when data is plentiful
- Humans are not good at providing some kinds of actions





- Humans can learn autonomously; can our machines do the same?
  - Unlimited data from own experience
  - Continuous self-improvement

Terminology & notation



$\mathbf{o}_t$ $\qquad$ $\pi_\theta(\mathbf{a}_t|\mathbf{o}_t)$ $\qquad$ $\mathbf{a}_t$

$\mathbf{s}_t$ – state
$\mathbf{o}_t$ – observation
$\mathbf{a}_t$ – action

$c(\mathbf{s}_t, \mathbf{a}_t)$ – cost function
$r(\mathbf{s}_t, \mathbf{a}_t)$ – reward function

$$\min_{\boldsymbol{\theta}} E_{\mathbf{a}\sim\pi_\theta(\mathbf{a}|\mathbf{s}),\mathbf{s}'\sim p(\mathbf{s}'|\mathbf{s},\mathbf{a})}[\delta(\mathbf{s}' = \text{eaten by tiger})]$$

$$\min_{\boldsymbol{\theta}} E_{\mathbf{s}_{1:T},\mathbf{a}_{1:T}}\left[\left[\sum_t \delta(\mathbf{s}_t = \text{eaten by tiger})\right]\right]$$

$$\sum_t c(\mathbf{s}_t, \mathbf{a}_t)$$

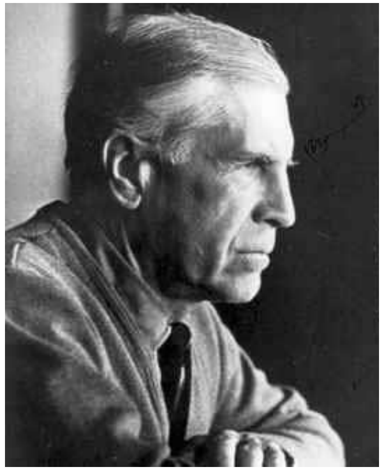
Aside: notation

$\mathbf{s}_t$ – state
$\mathbf{a}_t$ – action
$r(\mathbf{s}, \mathbf{a})$ – reward function

$\mathbf{x}_t$ – state
$\mathbf{u}_t$ – action
$c(\mathbf{x}, \mathbf{u})$ – cost function

$$r(\mathbf{s}, \mathbf{a}) = -c(\mathbf{x}, \mathbf{u})$$

Richard Bellman



Lev Pontryagin

Cost functions, reward functions, and a bit of theory

A cost function for imitation?

$\mathbf{o}_t$

$\mathbf{a}_t$

training data

supervised learning

$\pi_\theta(\mathbf{a}_t|\mathbf{o}_t)$

$$r(\mathbf{s},\mathbf{a}) = \log p(\mathbf{a} = \pi^\star(\mathbf{s})|\mathbf{s})$$

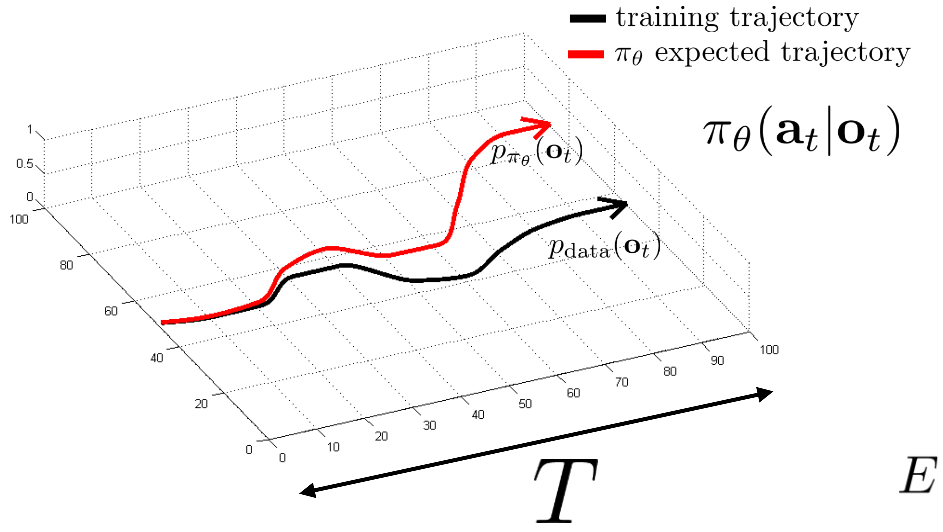
$$c(\mathbf{s},\mathbf{a}) = \begin{cases} 0 \text{ if } \mathbf{a} = \pi^\star(\mathbf{s}) \\ 1 \text{ otherwise} \end{cases}$$

1. train $\pi_\theta(\mathbf{a}_t|\mathbf{o}_t)$ from human data $\mathcal{D} = \{\mathbf{o}_1, \mathbf{a}_1, \dots, \mathbf{o}_N, \mathbf{a}_N\}$
2. run $\pi_\theta(\mathbf{a}_t|\mathbf{o}_t)$ to get dataset $\mathcal{D}_\pi = \{\mathbf{o}_1, \dots, \mathbf{o}_M\}$
3. Ask human to label $\mathcal{D}_\pi$ with actions $\mathbf{a}_t$
4. Aggregate: $\mathcal{D} \leftarrow \mathcal{D} \cup \mathcal{D}_\pi$

Ross et al. '11

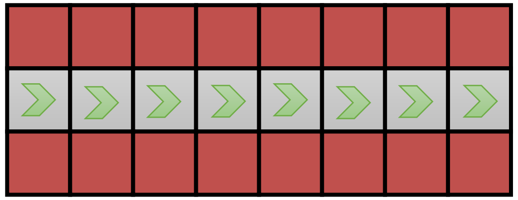
Some analysis

$$c(\mathbf{s}, \mathbf{a}) = \begin{cases} 0 \text{ if } \mathbf{a} = \pi^\star(\mathbf{s}) \\ 1 \text{ otherwise} \end{cases}$$



assume: $\pi_\theta(\mathbf{a} \neq \pi^\star(\mathbf{s})|\mathbf{s}) \leq \epsilon$

for all $\mathbf{s} \in \mathcal{D}_{\text{train}}$



$$\underbrace{E\left[\sum_t c(\mathbf{s}_t, \mathbf{a}_t)\right]}_{O(\epsilon T^2)} \leq \epsilon T + \underbrace{\qquad\qquad\qquad\qquad\qquad\qquad}_{T \text{ terms, each } O(\epsilon T)}$$

More general analysis

assume: $\pi_\theta(\mathbf{a} \neq \pi^\star(\mathbf{s})|\mathbf{s}) \leq \epsilon$

~~for all $\mathbf{s} \in \mathcal{D}_{\text{train}}$~~ for $\mathbf{s} \sim p_{\text{train}}(\mathbf{s})$

actually enough for $E_{p_{\text{train}}(\mathbf{s})}[\pi_\theta(\mathbf{a} \neq \pi^\star(\mathbf{s})|\mathbf{s})] \leq \epsilon$

if $p_{\text{train}}(\mathbf{s}) \neq p_\theta(\mathbf{s})$:

$$p_\theta(\mathbf{s}_t) = \underbrace{(1-\epsilon)^t}_{\text{probability we made no mistakes}} p_{\text{train}}(\mathbf{s}_t) + (1 - (1-\epsilon)^t)) \underbrace{p_{\text{mistake}}(\mathbf{s}_t)}_{\text{some } \textit{other} \text{ distribution}}$$

$$c(\mathbf{s}, \mathbf{a}) = \begin{cases} 0 \text{ if } \mathbf{a} = \pi^\star(\mathbf{s}) \\ 1 \text{ otherwise} \end{cases}$$

with DAgger, $p_{\text{train}}(\mathbf{s}) \rightarrow p_\theta(\mathbf{s})$

$$E\left[\sum_t c(\mathbf{s}_t, \mathbf{a}_t)\right] \leq \epsilon T$$

For more analysis, see Ross et al. "A Reduction of Imitation Learning and Structured Prediction to No-Regret Online Learning"

More general analysis

assume: $\pi_\theta(\mathbf{a} \neq \pi^\star(\mathbf{s})|\mathbf{s}) \leq \epsilon$

for all $\mathbf{s} \in \mathcal{D}_{\text{train}}$ for $\mathbf{s} \sim p_{\text{train}}(\mathbf{s})$

$$p_\theta(\mathbf{s}_t) = \underbrace{(1-\epsilon)^t}_{\text{probability we made no mistakes}} p_{\text{train}}(\mathbf{s}_t) + (1-(1-\epsilon)^t)) \underbrace{p_{\text{mistake}}(\mathbf{s}_t)}_{\text{some } \textit{other} \text{ distribution}}$$

$$|p_\theta(\mathbf{s}_t) - p_{\text{train}}(\mathbf{s}_t)| = (1-(1-\epsilon)^t)|p_{\text{mistake}}(\mathbf{s}_t) - p_{\text{train}}(\mathbf{s}_t)| \leq 2(1-(1-\epsilon)^t)$$

useful identity: $(1-\epsilon)^t \geq 1 - \epsilon t$ for $\epsilon \in [0,1]$ $\quad \leq 2\epsilon t$

$$\sum_t E_{p_\theta(\mathbf{s}_t)}[c_t] = \sum_t \sum_{\mathbf{s}_t} p_\theta(\mathbf{s}_t) c_t(\mathbf{s}_t) \leq \sum_t \sum_{\mathbf{s}_t} p_{\text{train}}(\mathbf{s}_t) c_t(\mathbf{s}_t) + |p_\theta(\mathbf{s}_t) - p_{\text{train}}(\mathbf{s}_t)| c_{\max}$$

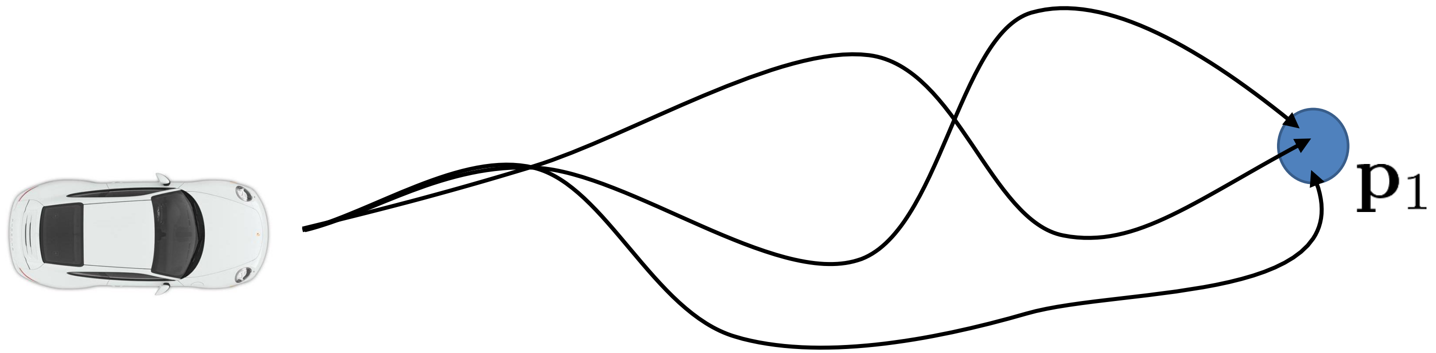
$$\leq \sum_t \epsilon + 2\epsilon t$$

$$O(\epsilon T^2)$$

For more analysis, see Ross et al. “A Reduction of Imitation Learning and Structured Prediction to No-Regret Online Learning”

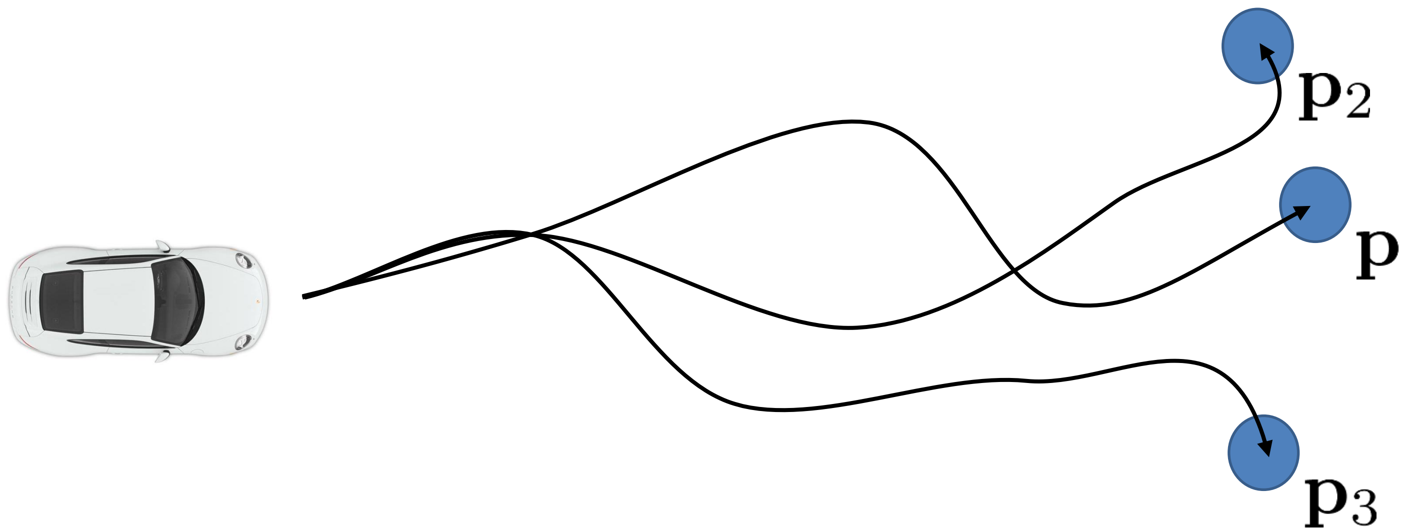
Another way to imitate

Another imitation idea



$$\pi_\theta(\mathbf{a}|\mathbf{s})$$

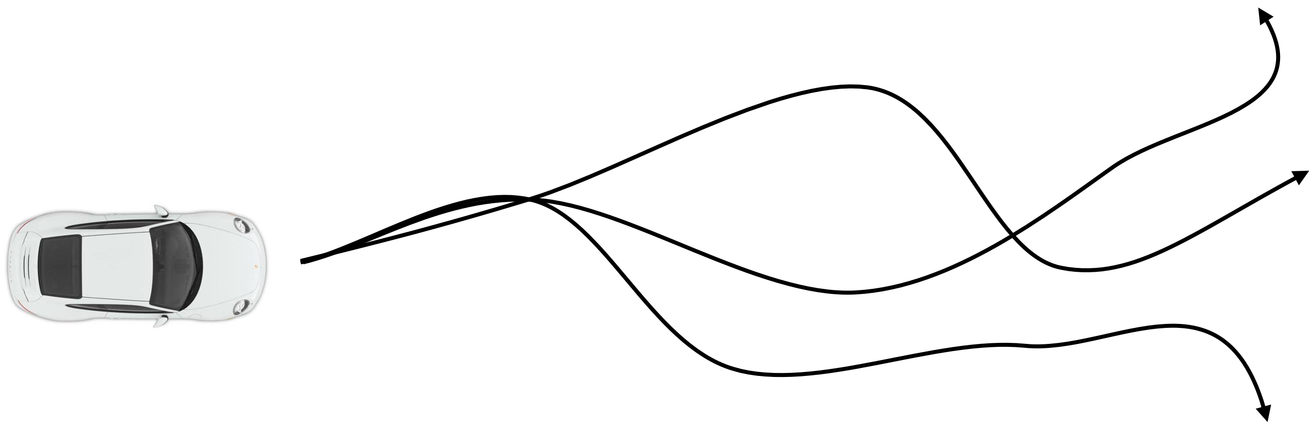
policy for reaching $\mathbf{p}_1$



$$\pi_\theta(\mathbf{a}|\mathbf{s}, \mathbf{p})$$

policy for reaching *any* $\mathbf{p}$

Goal-conditioned behavioral cloning



training time:

demo 1: $\{\mathbf{s}_1, \mathbf{a}_t, \ldots, \mathbf{s}_{T-1}, \mathbf{a}_{T-1}, \mathbf{s}_T\}$ ⟵ successful demo for reaching $\mathbf{s}_T$

demo 2: $\{\mathbf{s}_1, \mathbf{a}_t, \ldots, \mathbf{s}_{T-1}, \mathbf{a}_{T-1}, \mathbf{s}_T\}$

demo 3: $\{\mathbf{s}_1, \mathbf{a}_t, \ldots, \mathbf{s}_{T-1}, \mathbf{a}_{T-1}, \mathbf{s}_T\}$

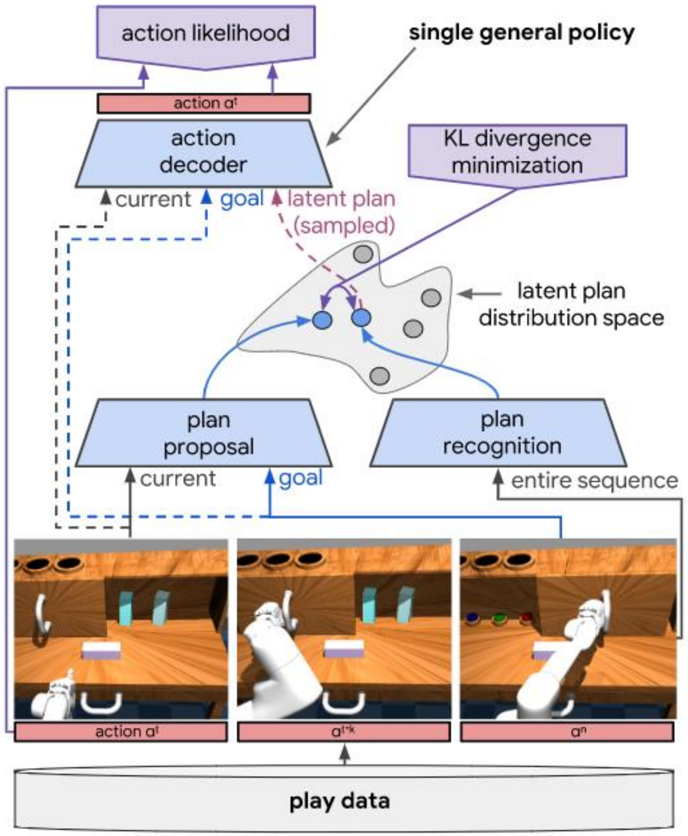
learn $\pi_\theta(\mathbf{a}|\mathbf{s}, \mathbf{g})$ ⟵ goal state

for each demo $\{\mathbf{s}_1^i, \mathbf{a}_1^i, \ldots, \mathbf{s}_{T-1}^i, \mathbf{a}_{T-1}^i, \mathbf{s}_T^i\}$

maximize $\log \pi_\theta(\mathbf{a}_t^i|\mathbf{s}_t^i, \mathbf{g} = \mathbf{s}_T^i)$

Learning Latent Plans from Play

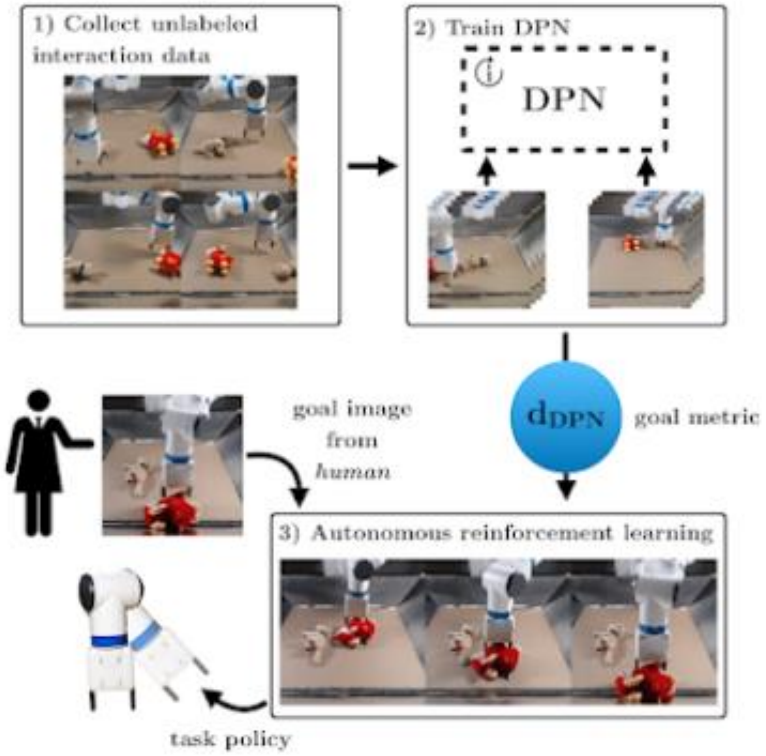
COREY LYNCH Google Brain
MOHI KHANSARI Google X
TED XIAO Google Brain
VIKASH KUMAR Google Brain
JONATHAN TOMPSON Google Brain
SERGEY LEVINE Google Brain
PIERRE SERMANET Google Brain



Unsupervised Visuomotor Control through Distributional Planning Networks

Tianhe Yu, Gleb Shevchuk, Dorsa Sadigh, Chelsea Finn

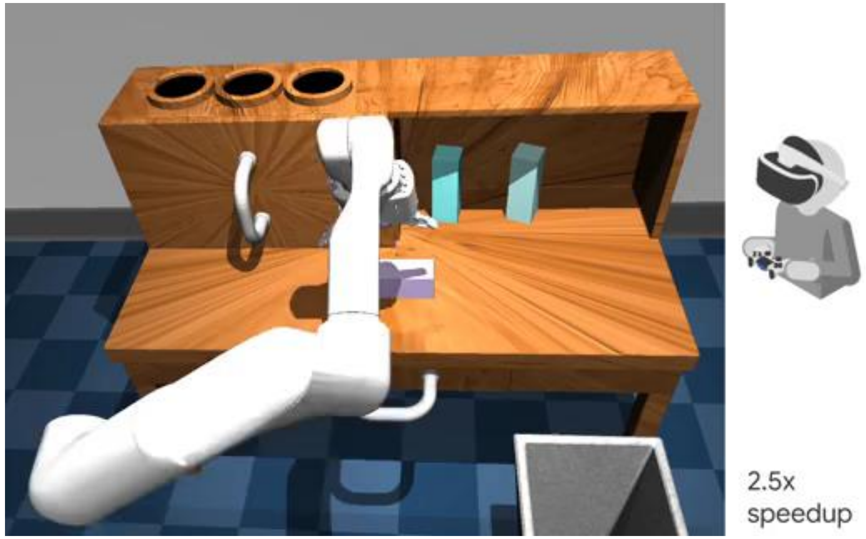
Stanford University



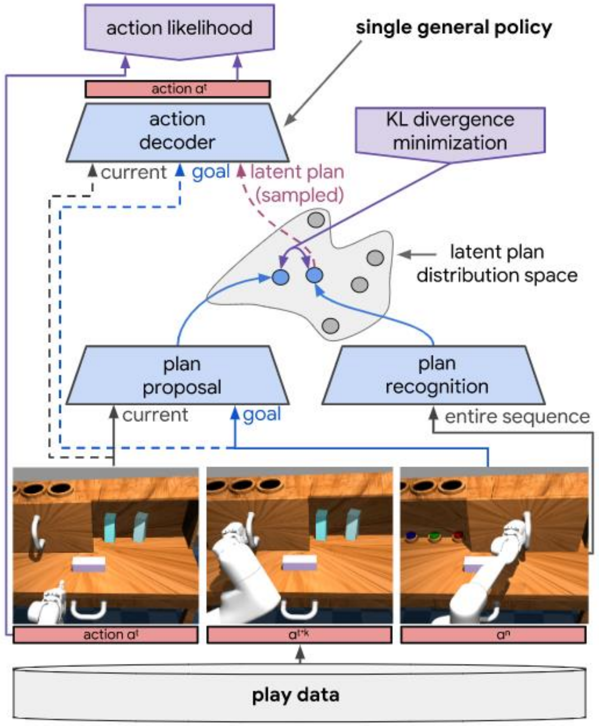
Learning Latent Plans from Play

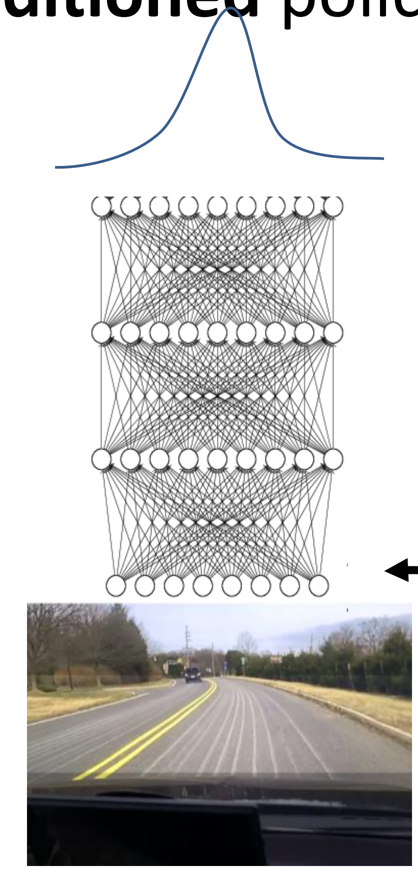
COREY LYNCH Google Brain | MOHI KHANSARI Google X | TED XIAO Google Brain | VIKASH KUMAR Google Brain | JONATHAN TOMPSON Google Brain | SERGEY LEVINE Google Brain | PIERRE SERMANET Google Brain

1. Collect **data**



2. Train **goal conditioned** policy





$$\xi \sim \mathcal{N}(0, \mathbf{I})$$

Learning Latent Plans from Play

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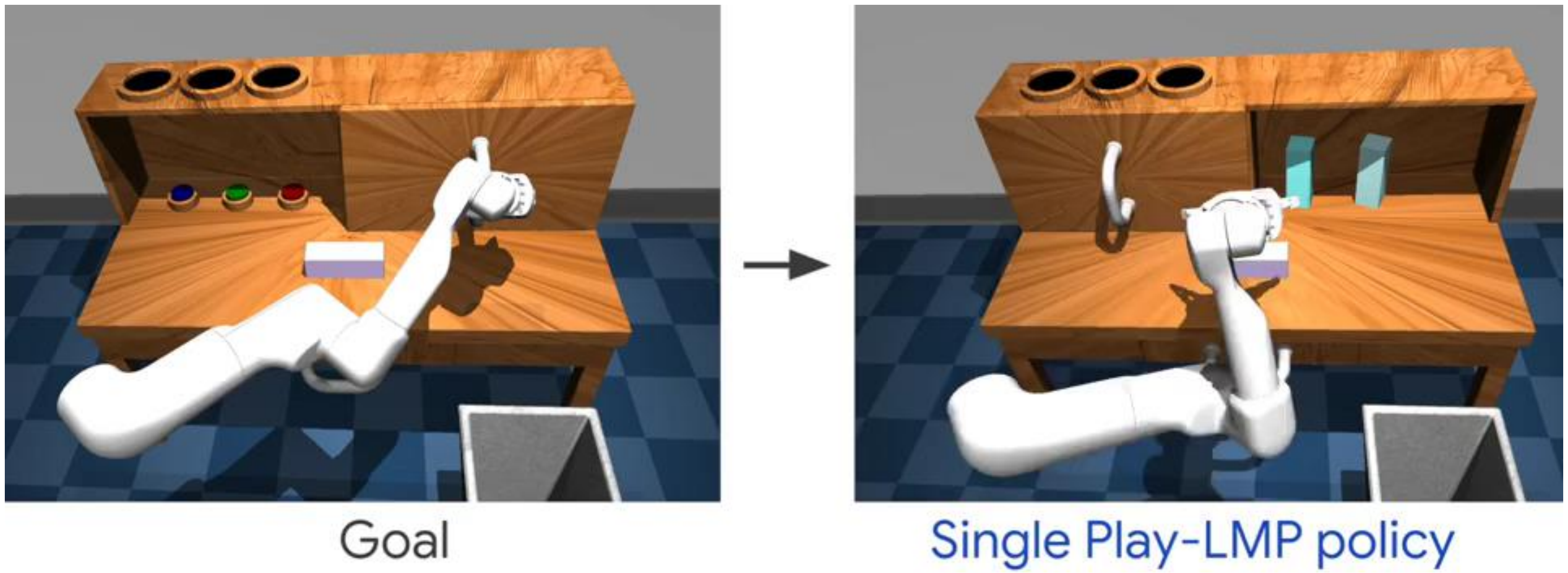
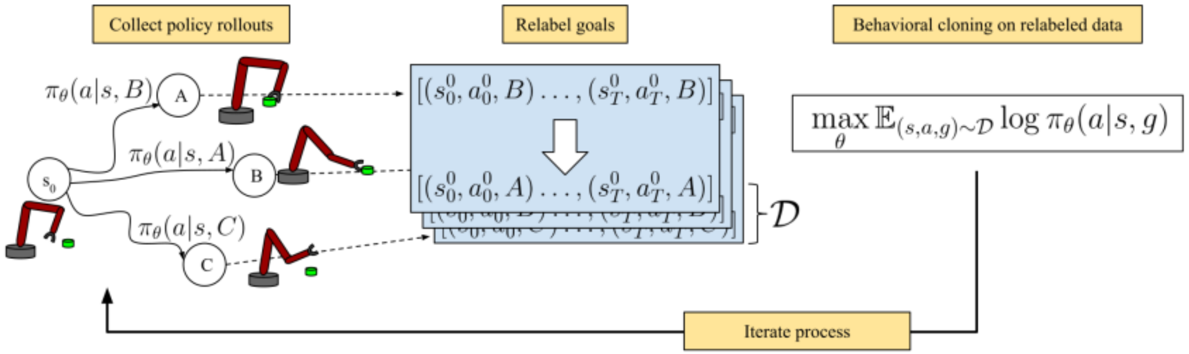
3. Reach goals



Going **beyond** just imitation?

Learning to Reach Goals via Iterated Supervised Learning

Dibya Ghosh* UC Berkeley
Abhishek Gupta* UC Berkeley
Ashwin Reddy UC Berkeley
Justin Fu UC Berkeley
Coline Devin UC Berkeley
Benjamin Eysenbach Carnegie Mellon University
Sergey Levine UC Berkeley



- Start with a **random** policy
- Collect data with **random** goals
- Treat this data as “demonstrations” for the goals that were reached
- Use this to improve the policy
- Repeat