



GPU TECHNOLOGY  
CONFERENCE

AGENDA ▾ ATTEND ▾ PRESENT ▾ EXHIBIT ▾ MORE ▾

SILICON VALLEY ▾

WORKSHOPS MARCH 17, 2019 | CONFERENCE MARCH 18-21, 2019

"A good traveler has no fixed plans and is not intent on arriving." - Lao Tzu

# Demystifying Deep Reinforcement Learning – Part 1 : DQN

All observations are my own & do not represent my employer's or anyone else's

krishna sankar  
@ksankar

I WOULD LIKE TO DIE ON MARS. JUST NOT ON IMPACT  
- ELON MUSK -



Jack Dorsey

@jack

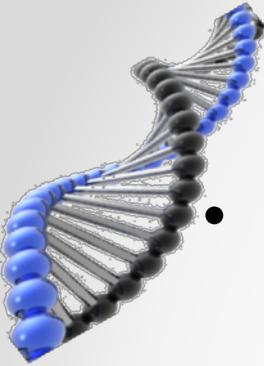
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just setting up my twtr

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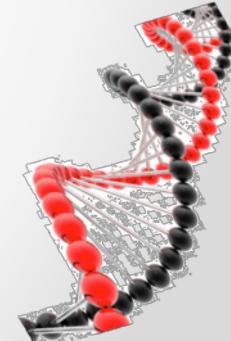
21 Mar 06

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# GTC 2019 SV : Lab Overview

- Deep Reinforcement Learning
  - Principles, Paradigms & Equations in 2 Parts
  - [https://gptechconf2019.smarteventscloud.com/connect/sessionDetail.ww?SESSION\\_ID=279058](https://gptechconf2019.smarteventscloud.com/connect/sessionDetail.ww?SESSION_ID=279058)
  - [https://gptechconf2019.smarteventscloud.com/connect/sessionDetail.ww?SESSION\\_ID=279064](https://gptechconf2019.smarteventscloud.com/connect/sessionDetail.ww?SESSION_ID=279064)
- Part 1 : Start from the Fundamentals
  - Program Value Methods
  - Monte Carlo, TD & Q-learning
  - DQN and it's extensions
- Part 2 : Policy Gradients
  - REINFORCE
  - A<sub>3</sub>C & DDPG
  - Intro to PPO, TRPO & the rest





# DRL Lab Goals

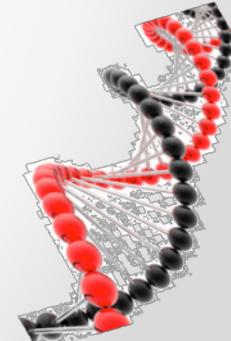
1. Get a reasonably good introduction to DRL (as much as we can do in 4 hrs)
  - o Sometimes the ideas take time to rattle around the brain and sink in; they need reflection; hence we stop Part 1 at DQN and later start Policy Gradients as Part 2
2. Alleviate the Initial Barrier
  - o Discuss intuition and formal notations
  - o Understand the underpinnings
  - o Do hands-on programming and finally,
  - o *Motivate to learn, explore on your own & be proficient in Deep Reinforcement Learning*
3. We will use Autonomous Driving & AlphaGo as background examples
4. Hands on programming
  - o Gridworld = Frozen Lake
  - o Continuous = Cartpole
  - o We will run these 2 examples throughout the lab for all the algorithms
    - With limited time, we don't want to add new examples every time





# Please Do ...

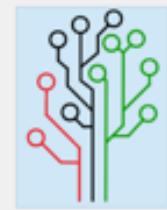
- The Programming Exercises & Quizzes
  - This is a good time to do these - you have a captivated time away from the daily trifles
- Write the formulas, at least 3 times !
  - Why write down formula ? Levine UCB classes ! Kuru Toga icon !
- Read the essential papers
  - Good comprehensive intro:
    - <https://arxiv.org/pdf/1810.06339.pdf>
    - An Introduction to Deep Reinforcement Learning  
<https://arxiv.org/pdf/1811.12560.pdf>
  - Sutton Book <http://incompleteideas.net/book/the-book-2nd.html>
  - AlphaGo nature papers, movies, AlphaZero et al  
<https://deepmind.com/research/alphago/>
  - Rainbow Paper <https://arxiv.org/pdf/1710.02298.pdf>
  - Minh Paper : <https://arxiv.org/abs/1602.01783>
  - DDPG Paper : <https://arxiv.org/pdf/1509.02971.pdf>





## The Rules for the Teacher

1. Remember that you are not your learners...
2. Never hesitate to sacrifice truth for clarity 😊
3. Remember that ...
  - ... no lesson survives first contact with learners...
  - ... that every lesson is too short from the teacher's point of view and too long from the learner's...
  - ... and that nobody will be more excited about the lesson than you are.



[Teaching Tech Together](#)

[EPUB and MOBI versions](#)

[Single page version](#)

[Lessons](#)

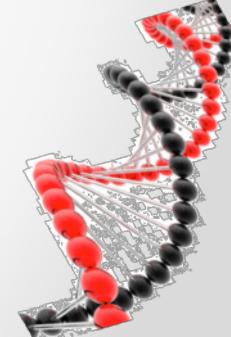
1. [Introduction](#)
2. [Building Mental Models](#)

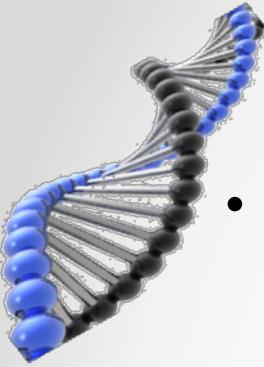
## Teaching Tech Together

Hundreds of grassroots groups have sprung up around the world to traditional classrooms. These groups exist so that people don't have teaching themselves how to teach.

There's a better way. Just as knowing a few basic facts about germs instructional design, inclusivity, and community organization can help use right now, explains why we believe they are true, and points you

- how people learn;
- how to design lessons that work;
- how to deliver those lessons; and
- how to grow a community of practice around teaching.





# You have ...

- Programming experience
  - Know about DeepLearning,
  - Experience using Tensorflow or pytorch,
  - Python programming and familiar with Jupyter/iPython notebook
- No Reinforcement Learning experience is expected or assumed
- Will cover enough of Deep Learning & Pytorch
- Why Pytorch ?
  - Easier & compact, those of you from the world of Tensorflow, this will be a new experience
  - DL is only a small part and are using simpler primitives
- Have installed the prerequisites
- Have downloaded the materials from github
  - [https://github.com/xsankar/GTC\\_2019\\_DRL\\_LAB](https://github.com/xsankar/GTC_2019_DRL_LAB)
- The notebooks in (somewhat) working order





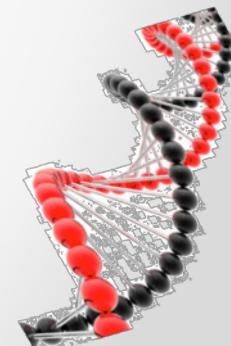
# Lab notebooks & presentation

*good enough*

- Labs have working examples
  - Look at them as starting frameworks - for you to tweak & improve
  - Use as a study tool
  - Share your comments, clarifications, functions and algorithms as pull requests
  - And when you have mastered an algorithm or an environment, add your successes to the OpenAI Gym leaderboard
    - Consider leaderboard as a level of performance

- Lab pragmatics

- In github : [https://github.com/xsankar/GTC\\_2019\\_DRL\\_LAB](https://github.com/xsankar/GTC_2019_DRL_LAB)
  - No esoteric requirements
  - Requirements
    - python 3.6, pytorch, openAI gym, numpy, matplotlib, jupyter notebook
  - Miniconda works fine

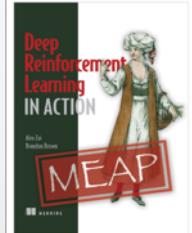
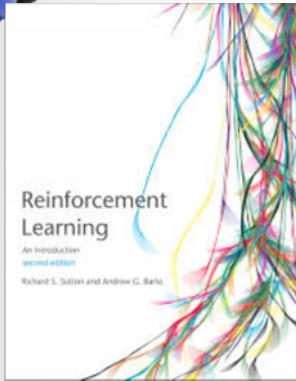




# Pragmas - Deep RL Experimentation

- Be ready for (a lot of) trial-and-error
- There will be many false starts
- Hyper-parameter tuning is important
- Have faith; the network will learn - eventually !!
- Learning is not linear
  - Even after 90% is done, you still might have 90% to go
- Keep a log and try things (somewhat) systematically
- Too many (simultaneous) moving parts will only create chaos





UDACITY

School of Artificial Intelligence  
Deep Reinforcement Learning  
In Collaboration With  
Unity, NVIDIA Deep Learning  
Institute

edX Courses Programs & Degrees Schools & Partners edX for Business Search: Reinforcement Learning Explained

Learn how to frame reinforcement learning problems, tackle classic examples, explore basic algorithms from dynamic programming, temporal difference learning, and progress towards larger state space using function approximation and DQN (Deep Q Network).

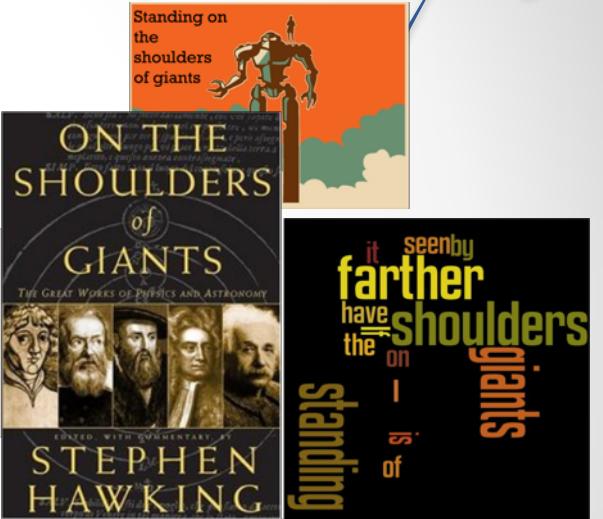


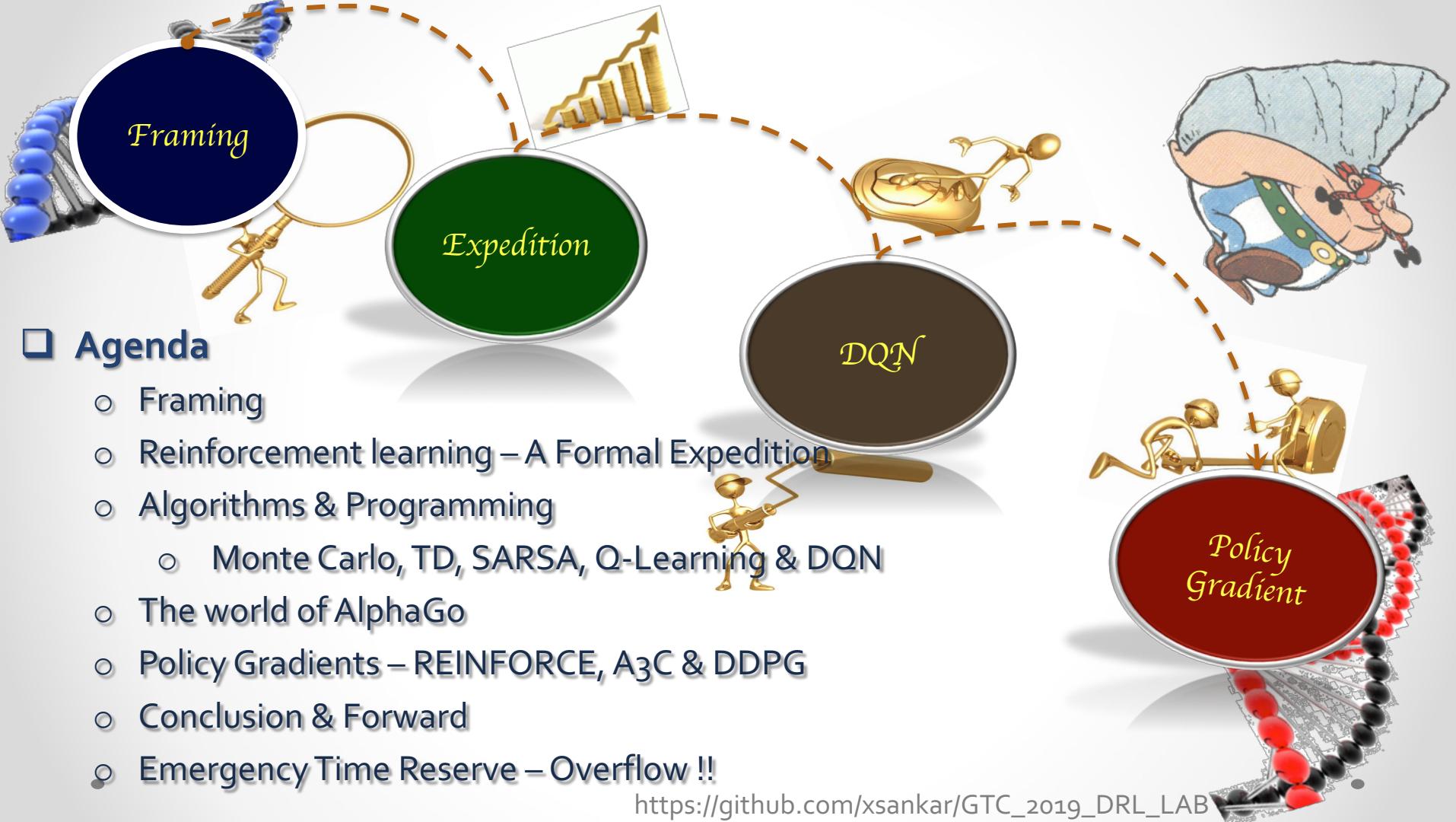
CS 294-112 at UC Berkeley



Deep Reinforcement Learning

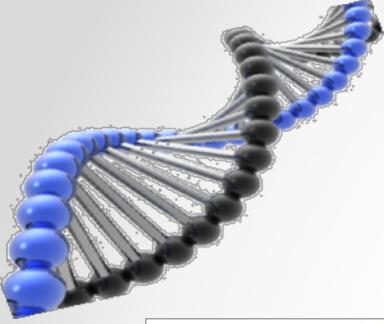
Abbeel & Levine



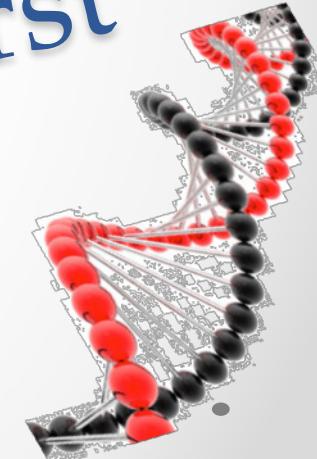


## □ Agenda

- Framing
- Reinforcement learning – A Formal Expedition
- Algorithms & Programming
  - Monte Carlo, TD, SARSA, Q-Learning & DQN
- The world of AlphaGo
- Policy Gradients – REINFORCE, A<sub>3</sub>C & DDPG
- Conclusion & Forward
- Emergency Time Reserve – Overflow !!



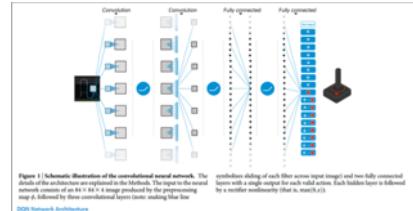
# 1. Framing : Open This First





# What exactly is this Reinforcement Learning ?

RL = Formal framework  
Computationally efficient approach



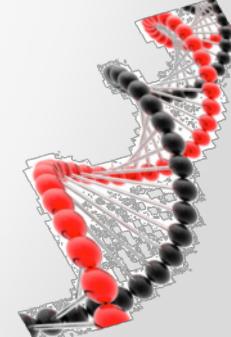
Goal : Maximize rewards

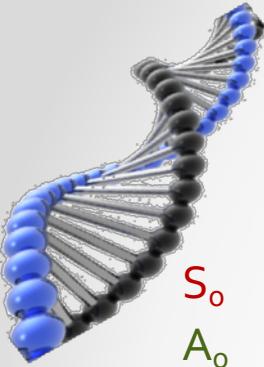


Uncertain; fully observable at best

Acquires new behaviors & skills  
incrementally, using trial-and-error  
experiences  
o a priori batch is OK, in some cases

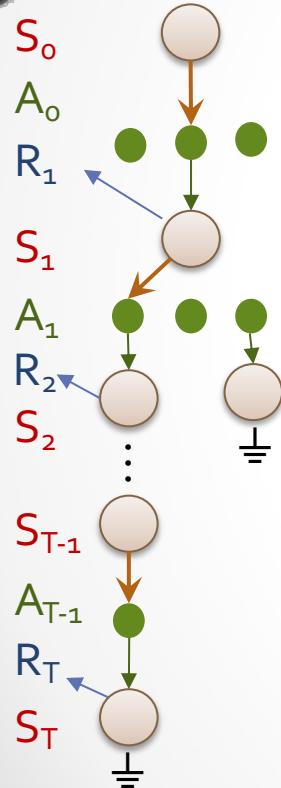
- ✓ Agent - Learn, Decide & Act
- ✓ Nothing less, nothing more !
- ✓ Interacts with the environment
- Collects Information





# RL Sequence

- Agent starts at State  $S_0$ , chooses & takes Action  $A_0$ ,
- The environment transitions to  $S_1$  & emits a reward  $R_1$
- The environment also sends an observation of  $S_1$
- Now the agent is at  $S_1$  and can take action  $A_1$
- The cycle continues, till the end is reached
- *Can be in 1 step, n steps or even continuous (=infinite horizon)*





1. Walking Humanoid figures - UC Berkeley

# DRL in Action (?) – Video Time !!



2. Humanoid avoiding obstacles - UCB

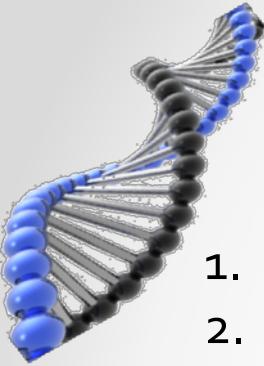


3. Navigating Complex Roundabouts



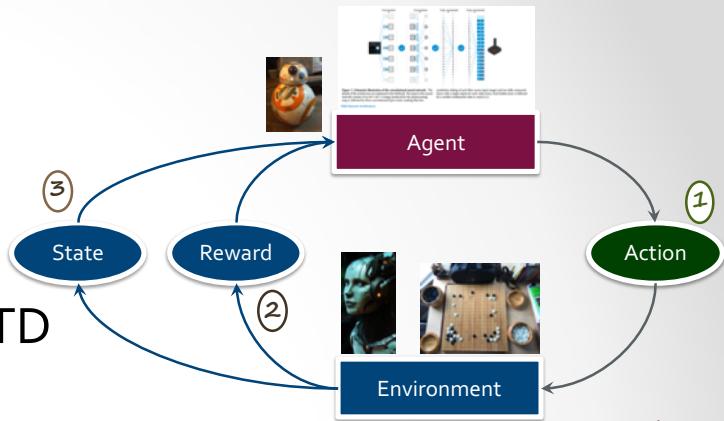
## Goal of the videos : Motivation for DRL

- While, in this lab, we look at relatively smaller problems, the algorithms are very powerful and are solving much larger problems
- As you go through the lab, think of how these problems can be solved using different Reinforcement Learning mechanisms

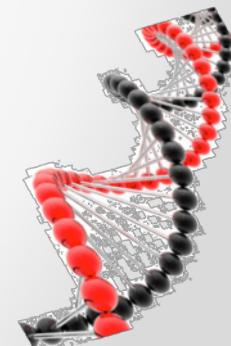


# DRL Challenges

1. Exploration & Convergence – Bandit
2. Reward Shaping & Credit Assignment – TD
3. Representation
  - o DQN, CNN (LSTM,RNN Not yet) Capsule Networks/Transformer Architectures (?)
  - o Lower dimensional than tabular representation
  - o Compact as possible, but can capture the full complexity of the underlying state space
  - o Sample efficiency - replay buffer w/ DQN
  - o Atari representation
4. Generalization - DQN
  - o Atari generalization - same architecture, but trained for each game
5. Context & Content - Knowledge Graph
  - o Encode expert knowledge
  - o Atari - pixels - no knowledge
  - o If it's Tuesday, this must be Belgium - you need Tuesday Belgium 1000 times !
6. Common Sense Reasoning - Logic Representation & Traversal
7. Conversation Chain - Jarvis/Jeeves



If you are planning to do  
PhD (I urge all to earn a  
doctorate degree in AI)  
there are fertile research  
topics here !!!

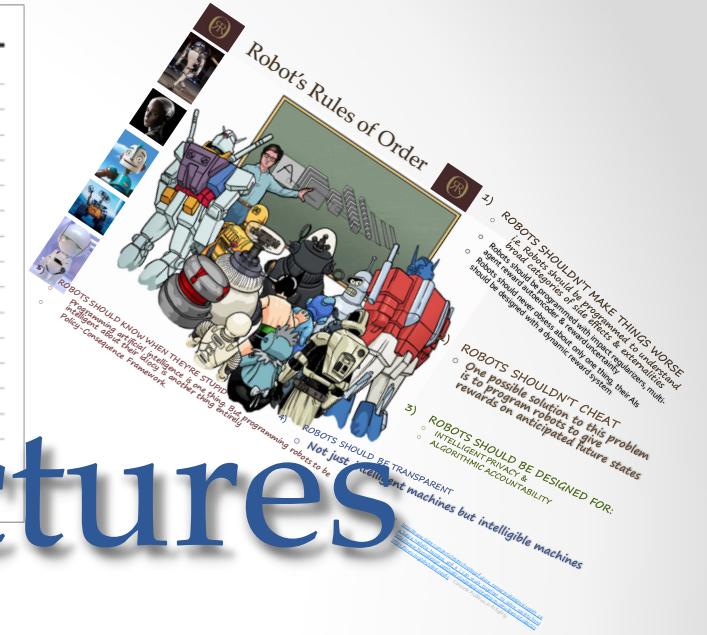
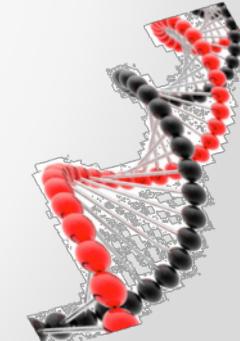
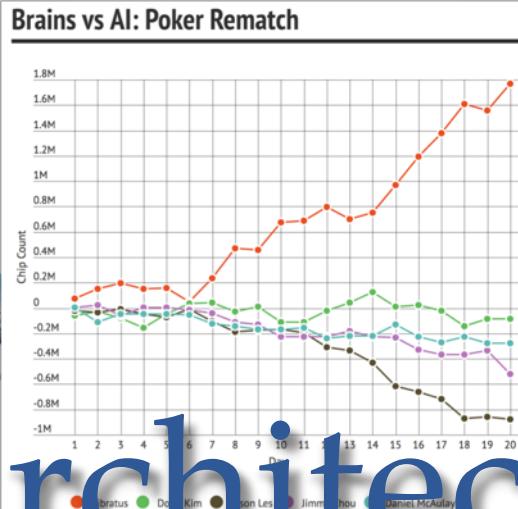




- The image is a collage of several photographs related to artificial intelligence. In the top left, a DNA double helix is shown, symbolizing the biological basis for AI. To its right is a close-up of a blue, articulated robotic head or sensor array. Below these, a large, bold blue 'AI' logo is prominently displayed. In the bottom right corner, there is a whiteboard with handwritten text in black marker. The text on the whiteboard includes: 'AI is:', followed by a bulleted list: 'Contextual & Autonomous i.e. sense the environment, propagate current state across space, knowledge & actions and respond appropriately.', 'Rational i.e. The ability to infer/ actions and respond appropriately.', 'current context/ beliefs, and plan accordingly.', 'Optimal i.e. The capacity to choose one or more actions over the space of actions in the current context/beliefs, and plan accordingly.', 'based upon a set of policies including short & long term optimization of behavior functions & goals (bounded rationality as the system can only see a limited set of behaviors).', 'Remembering i.e. the capability to hold episodic and long term beliefs, which are used in representational formalisms and retrieval mechanisms.', 'Incorporate the lessons in future behavior.', 'Reactive, Adaptive & Self-evolving i.e. the ability to learn from past actions & incorporate the lessons in future behavior.', 'Interactive i.e. the capability to interact with humans with different roles (e.g. passengers, other drivers, pedestrians etc) via multiple interfaces including mobile & HMI.', 'We also add the constraints of reusability, scalability, efficiency & framework, which where the AI system is deployed.'

# Quick Context

# AI Architectures



AI is:

- Contextual & Autonomous i.e. sense the environment, propagate current state across goals, knowledge & actions and respond appropriately.
- Rational i.e. The ability to infer/perceive value/payoff of a set of actions in the current context/ beliefs, and plan accordingly
- Optimal i.e. The capacity to choose one or more actions over the space of behaviors, based upon a set of policies including short & long term optimization of cost functions & goals (bounded rationality as the system can only see a limited set)
- Remembering i.e. the capability to hold episodic and long term beliefs, which adds representational formalisms and retrieval mechanisms
- Reflective, Adaptive & Self-evolving i.e. the ability to learn from past actions & incorporate the lessons in future behavior
- Interactive i.e. the capability to interact with humans with different roles (e.g. passengers, other drivers, pedestrians et al) via multiple interfaces including NLP & NLU
- We also add the constraints of reactivity, redundancy, efficiency & scalability for the infrastructure & the framework stack where the AI system is deployed



**■ Machines need to learn/understand how the world works**

- ▶ Physical world, digital world, people,....
- ▶ They need to acquire some level of common sense

**■ They need to learn a very large amount of background knowledge**

- ▶ Through observation and action

**■ Machines need to perceive the state of the world**

- ▶ So as to make accurate predictions and planning

**■ Machines need to update and remember estimates of the state of the world**

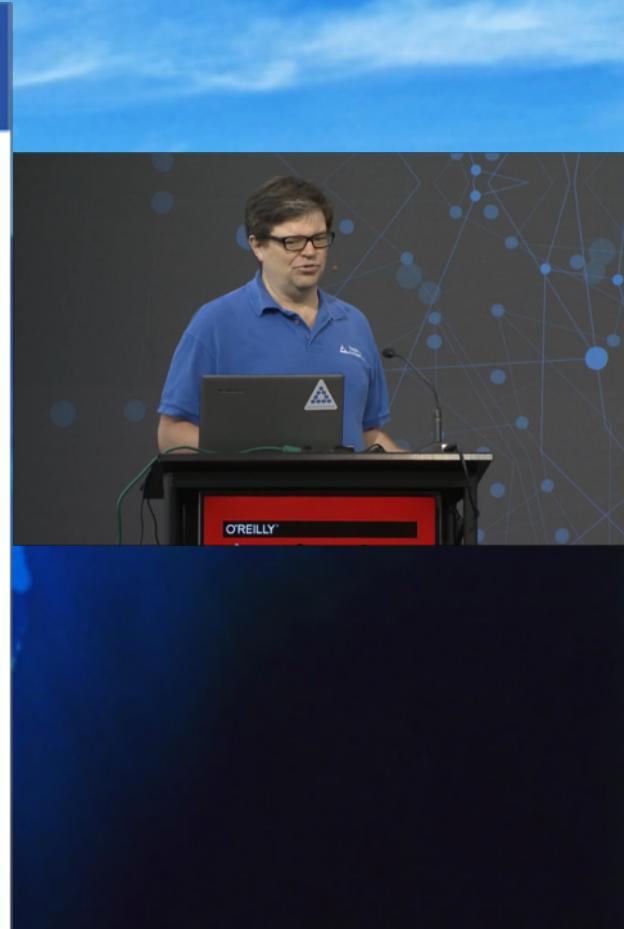
- ▶ Paying attention to important events. Remember relevant events

**■ Machines need to reason and plan**

- ▶ Predict which sequence of actions will lead to a desired state of the world

**■ Intelligence & Common Sense =**

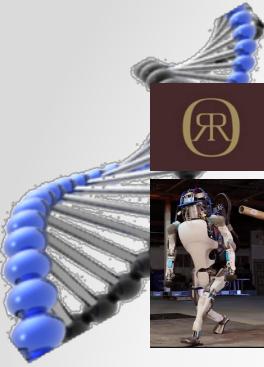
Perception + Predictive Model + Memory + Reasoning & Planning



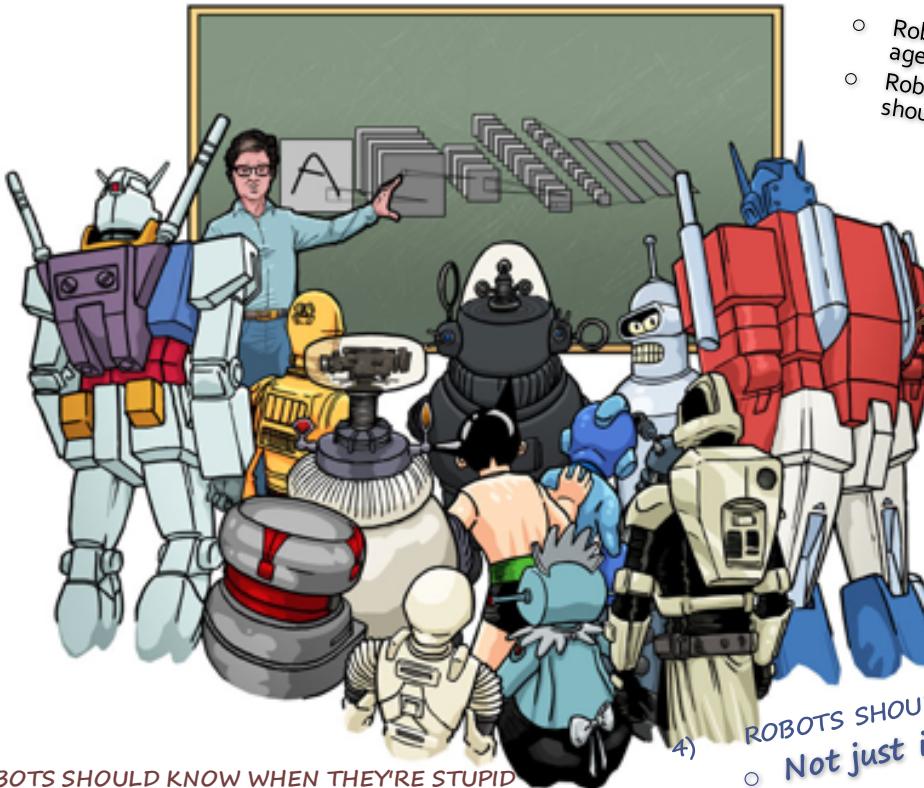
Yann LeCun Retweeted

**Andrew McAfee @amcafee** · 17h

@ylecun Teaching machines common sense is a "Big mountain. And we don't know how many mountains are behind it." #WHFrontiers



# Robot's Rules of Order



## 5) ROBOTS SHOULD KNOW WHEN THEY'RE STUPID

- Programming artificial intelligence is one thing. But programming robots to be intelligent about their idiocy is another thing entirely
- Policy-Consequence Framework.

1) **ROBOTS SHOULDN'T MAKE THINGS WORSE**  
i.e. Robots should be programmed to understand broad categories of side effects & externalities

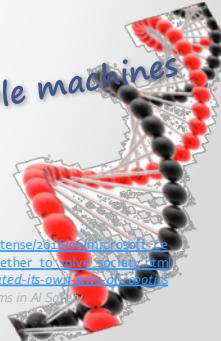
- Robots should be programmed with impact regularizers, multi-agent reward autoencoder & reward uncertainty
- Robots should never obsess about only one thing, their AIs should be designed with a dynamic reward system

2) **ROBOTS SHOULDN'T CHEAT**  
One possible solution to this problem is to program robots to give rewards on anticipated future states

3) **ROBOTS SHOULD BE DESIGNED FOR:**  
○ INTELLIGENT PRIVACY &  
○ ALGORITHMIC ACCOUNTABILITY

4) **ROBOTS SHOULD BE TRANSPARENT**  
○ Not just intelligent machines but intelligible machines

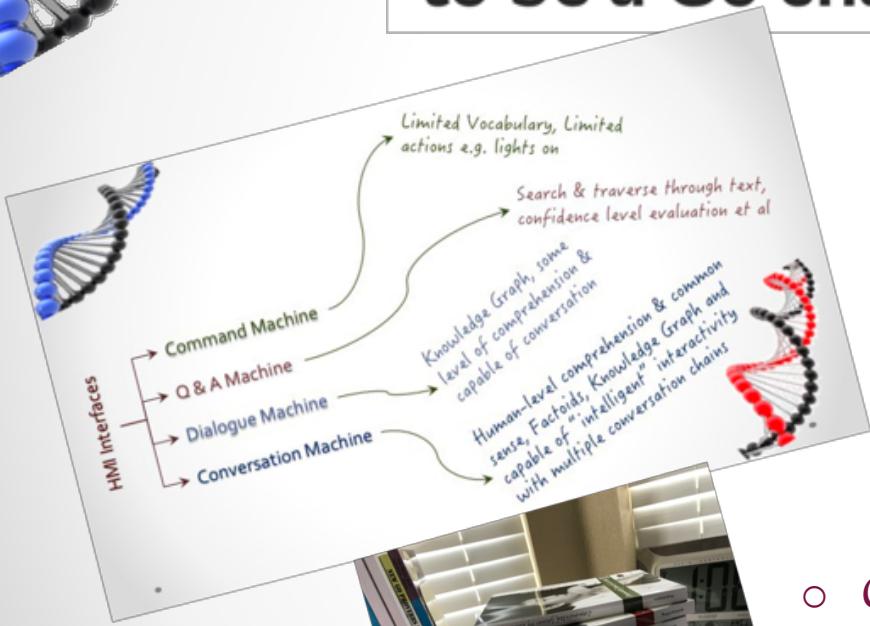
- [http://www.slate.com/articles/technology/future\\_tense/2012/09/microsoft\\_chooses\\_nadella\\_humans\\_and\\_a\\_i\\_can\\_work\\_together\\_to\\_save\\_soc.html](http://www.slate.com/articles/technology/future_tense/2012/09/microsoft_chooses_nadella_humans_and_a_i_can_work_together_to_save_soc.html)
- <http://www.fastcodesign.com/2061230/google-created-its-own-laws-for-robots>
- <https://arxiv.org/abs/1606.06565> - Concrete Problems in AI Safety



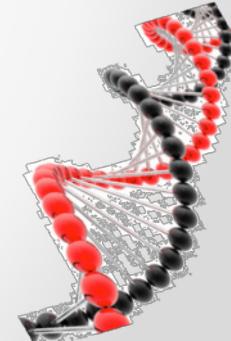


**Ask not if AlphaZero can beat humans in Go—Ask if AlphaZero can teach humans to be a Go champion !!!**

<https://goo.gl/vPzN9B>



- Can a program understand playstyles (e.g. Lee Sedol) & imitate ?
  - Can it adapt to its student's level ?

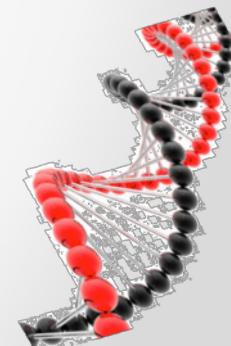




# 2. Reinforcement Learning

## A Formal Expedition

...





## Supervised Learning

## Unsupervised Learning

## Reinforcement Learning

<b>Data</b>	Curated	Curated	Generates data while exploring
<b>Labels</b>	Curated	Machine Generated	Learn via interactions
<b>Signals &amp; Feedback</b>			Curated Reward Signals and Goals
<b>Actions</b>			Actions instead of labels
<b>Defining Characteristics</b>	Classification, Linear Regression	Human Meaning e.g. clusters, survival analysis	Result = Decision making - winning a game, driving cars, manufacturing robots, cleaning robots, conversations, ...

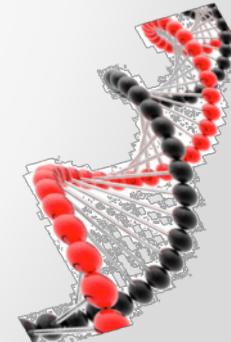




# Frozen Lake !

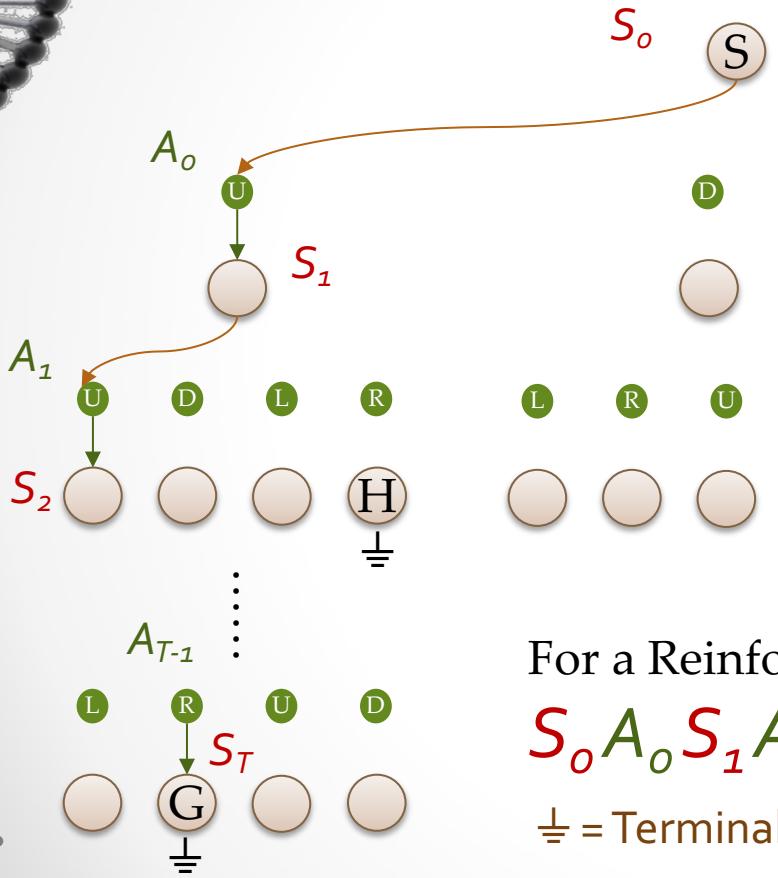


- You are in Siberia and want to visit the foothill under the rock, which is the Goal (G), starting at S
- But the lake is a little treacherous with holes(H)





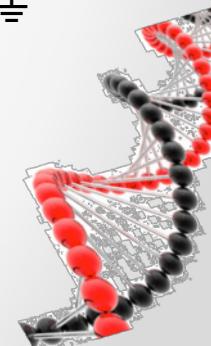
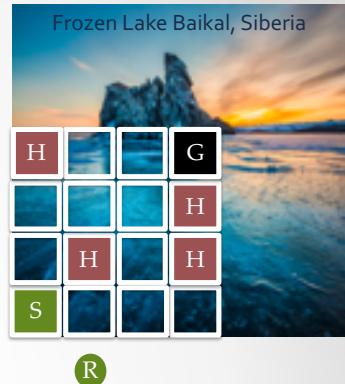
# Notation : State, Action



For a Reinforcement Agent, life is a series of

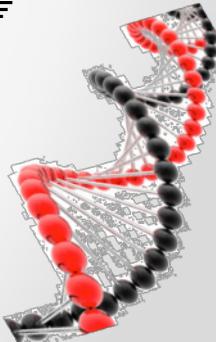
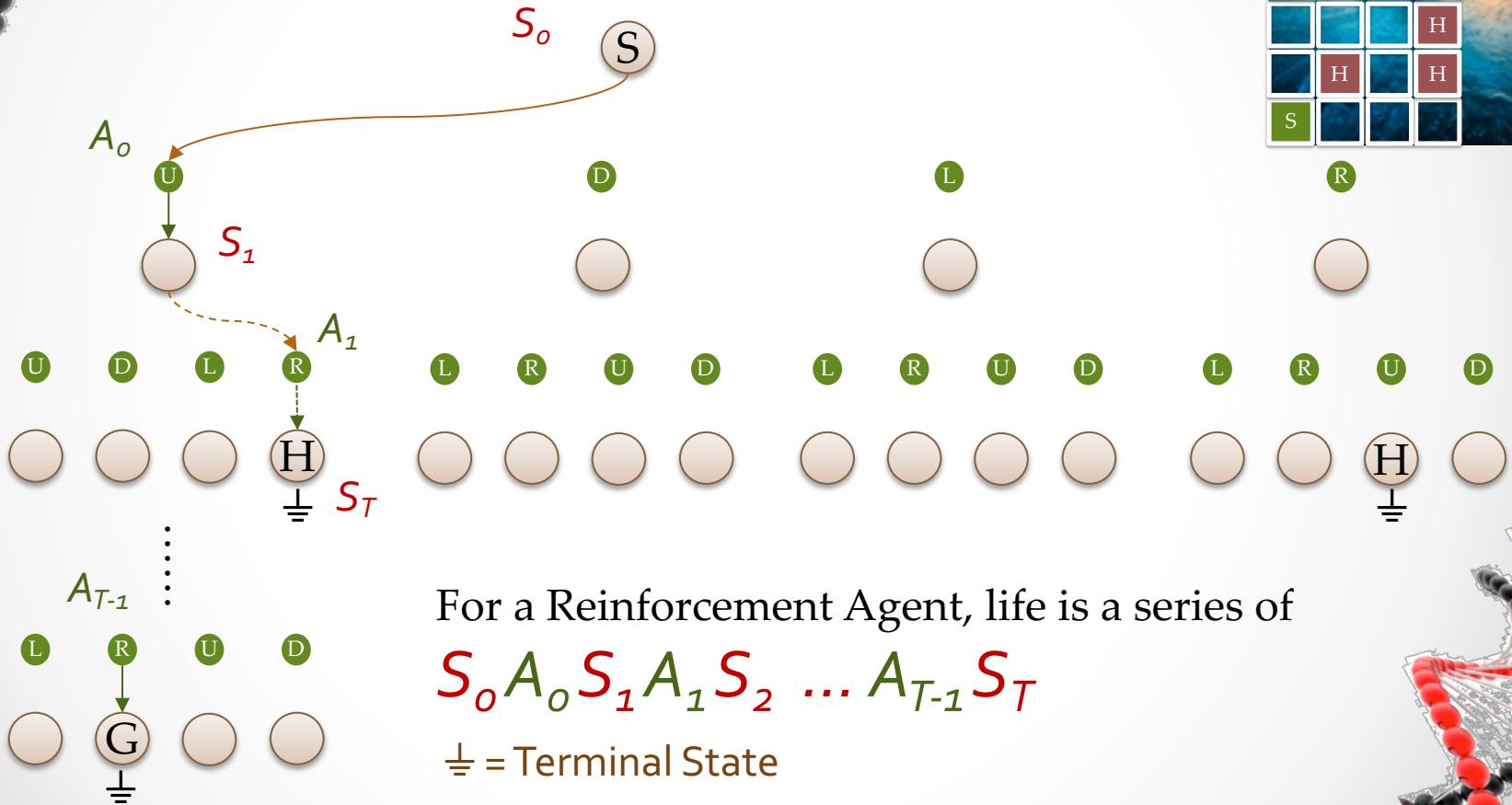
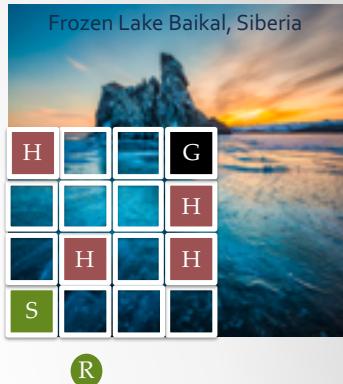
$$S_o A_o S_1 A_1 S_2 \dots A_{T-1} S_T$$

$\perp\!\!\!\perp$  = Terminal State



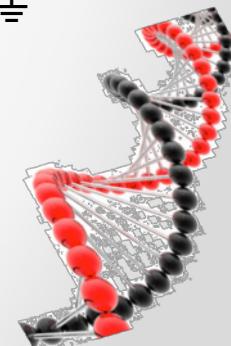
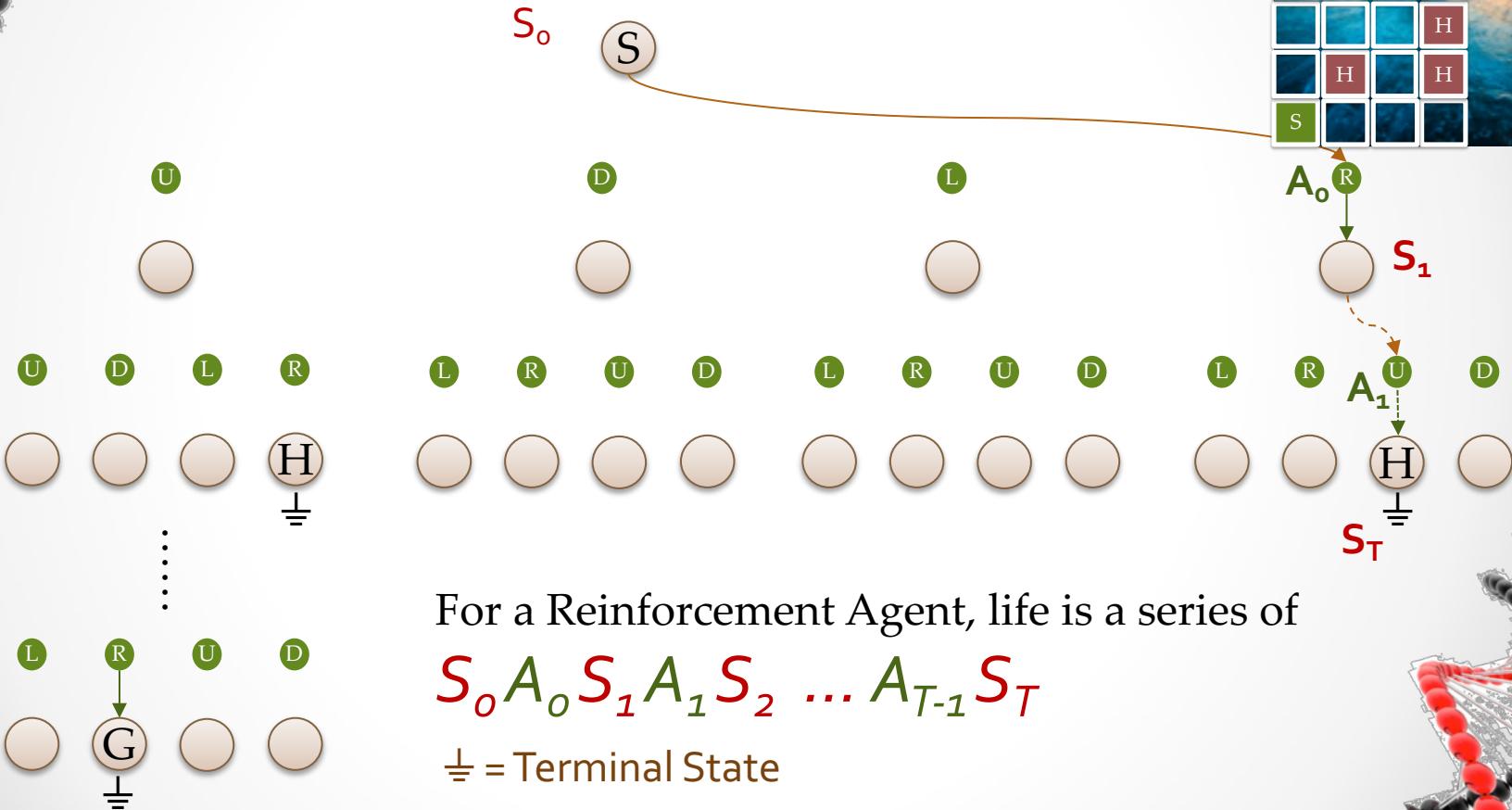


# Notation : State, Action



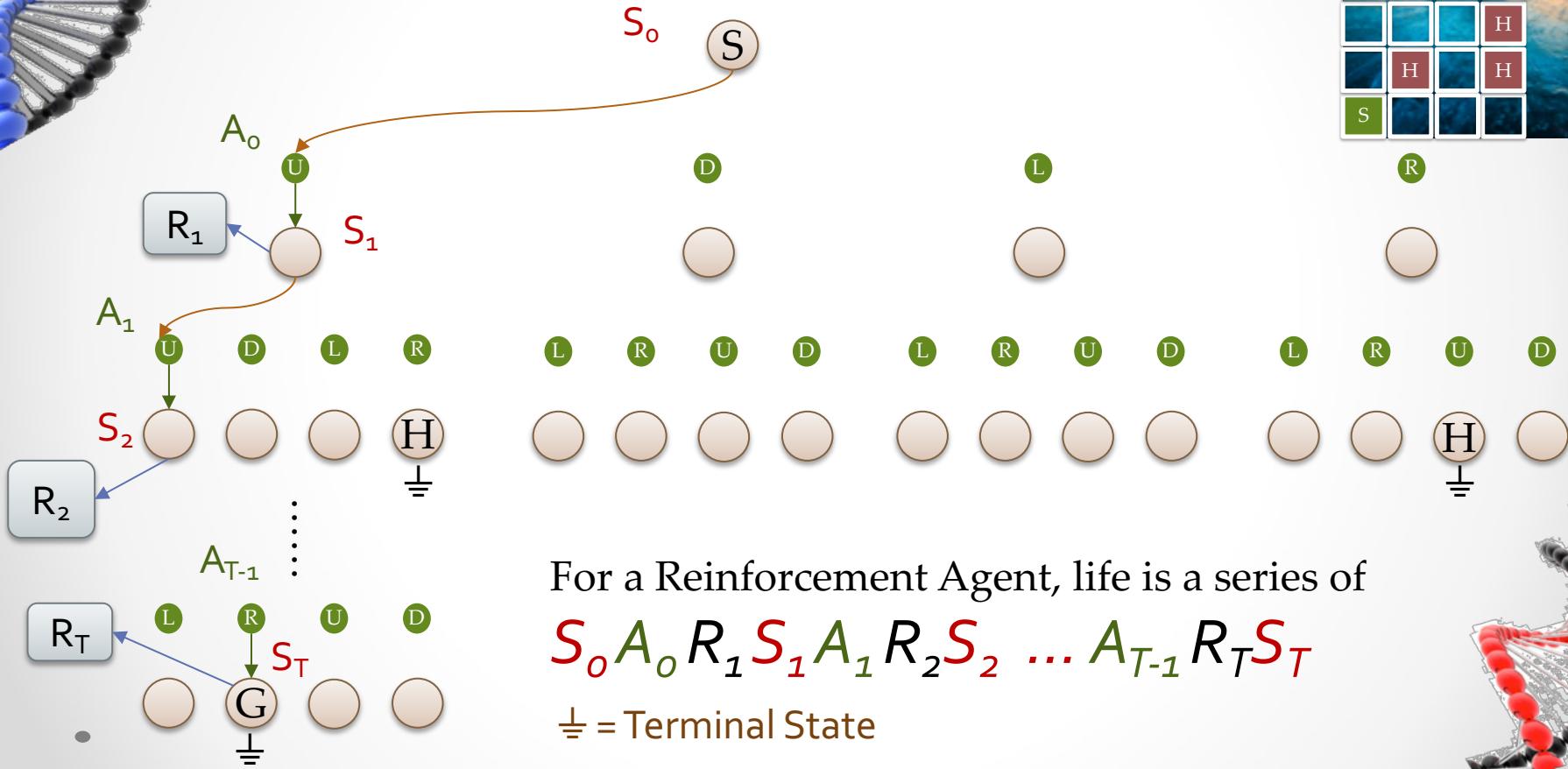
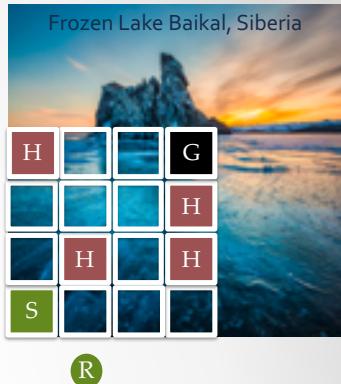


# Notation : State, Action





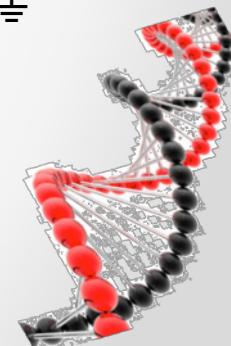
# Notation : State, Action, Reward



For a Reinforcement Agent, life is a series of

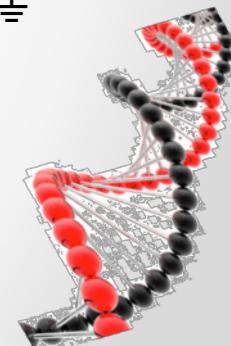
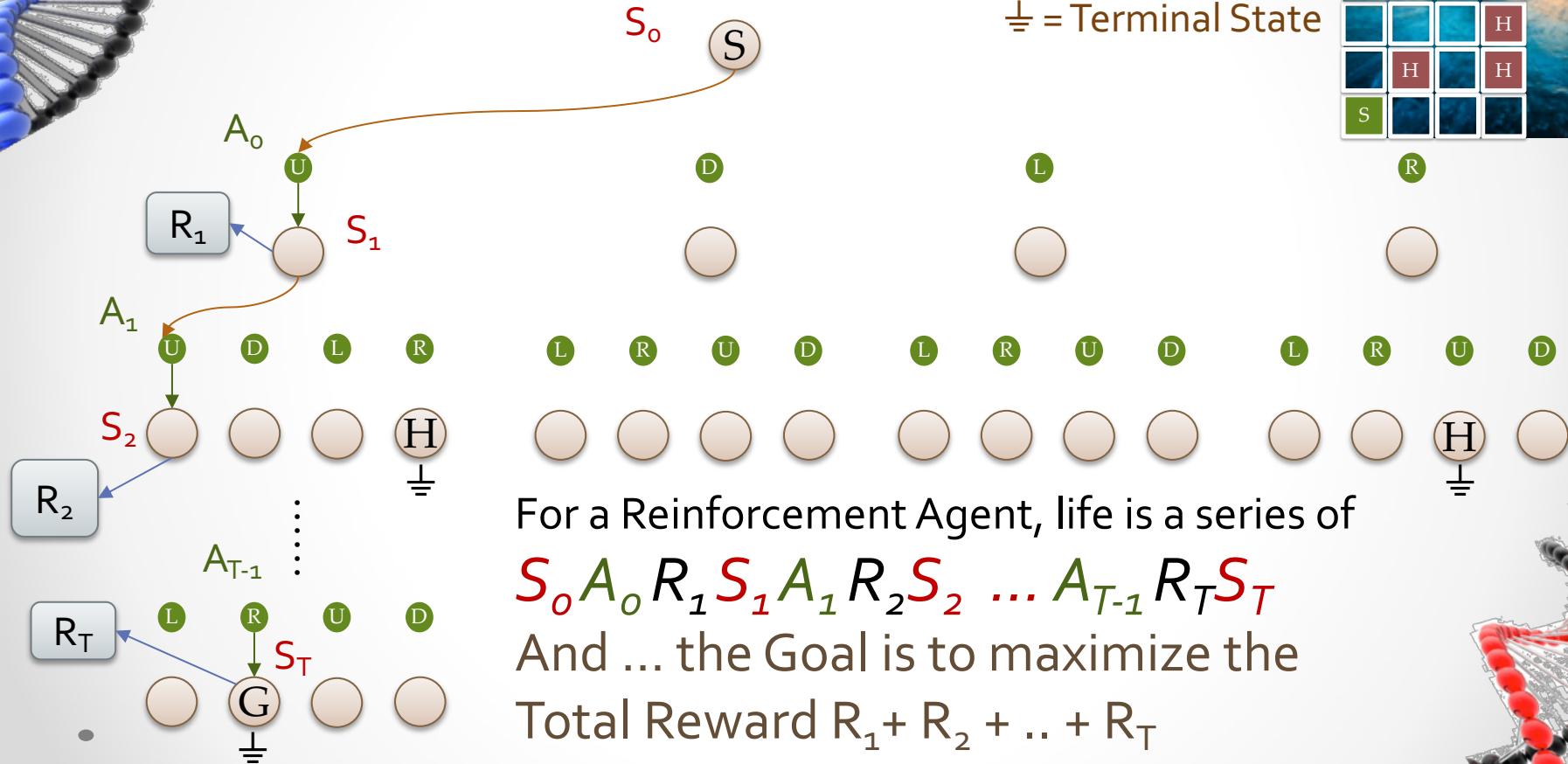
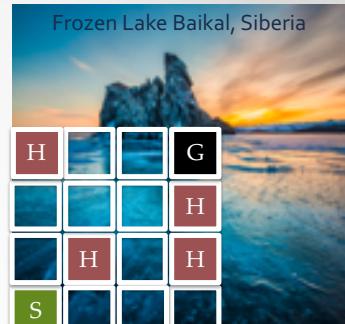
$S_o A_o R_1 S_1 A_1 R_2 S_2 \dots A_{T-1} R_T S_T$

$\perp = \text{Terminal State}$



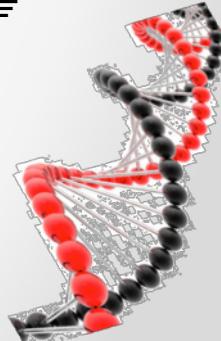
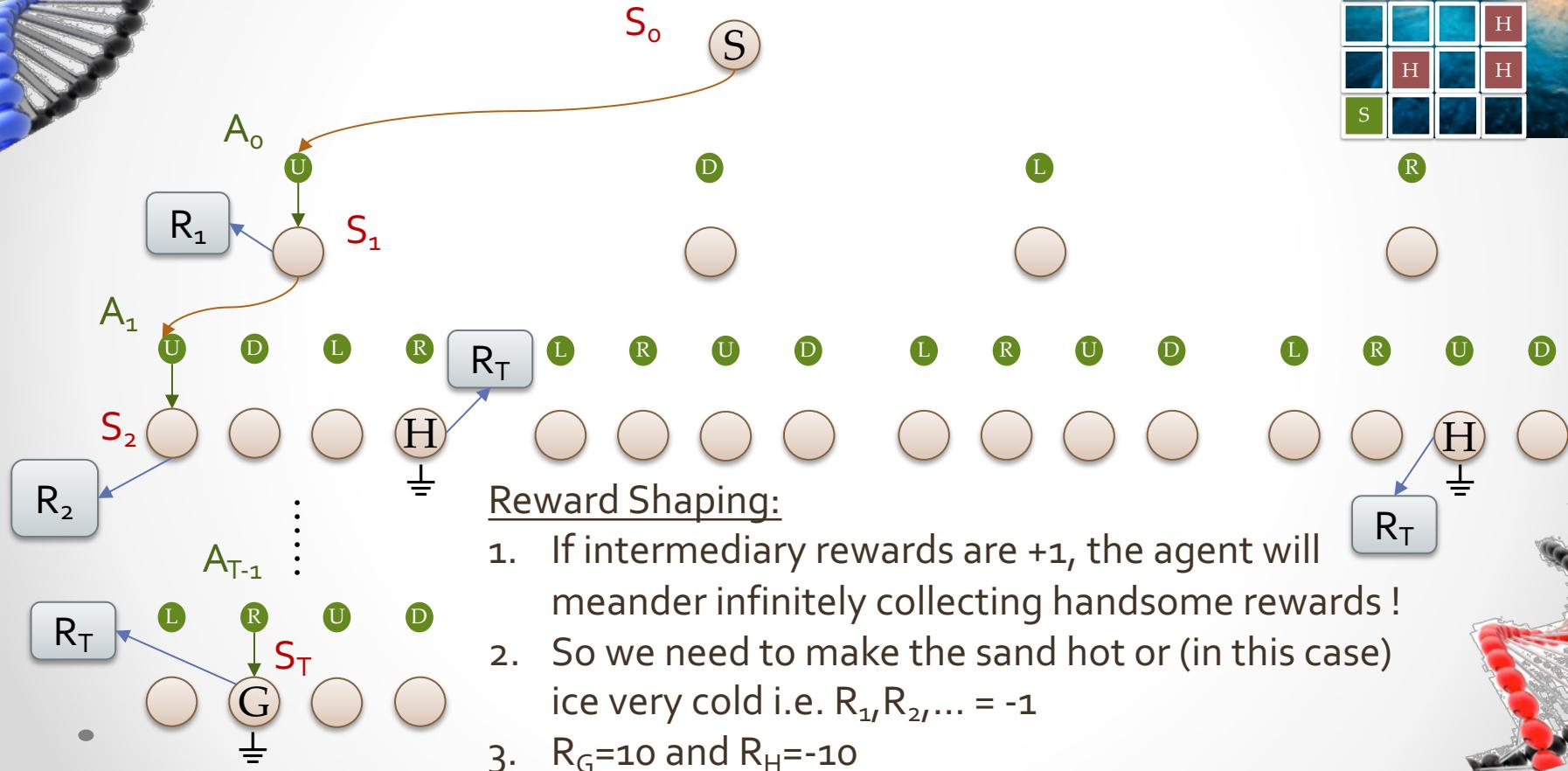
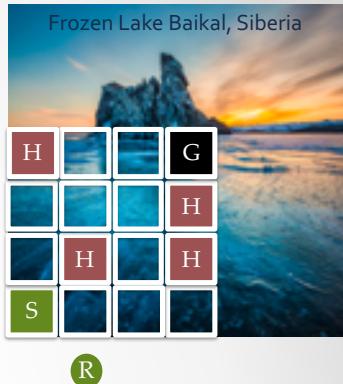


# Notation : State, Action, Reward



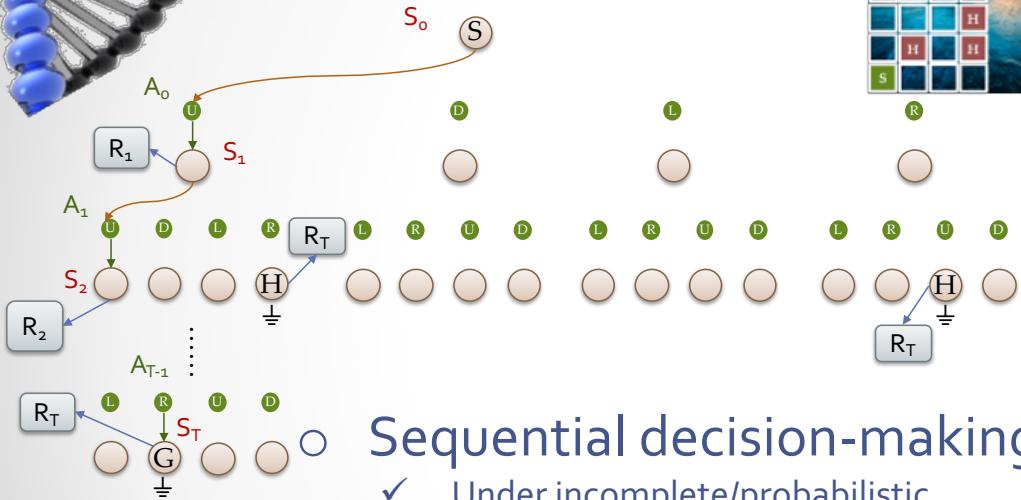


# Notation : State, Action, Reward



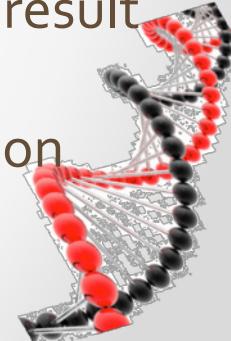


# In short DRL is ...

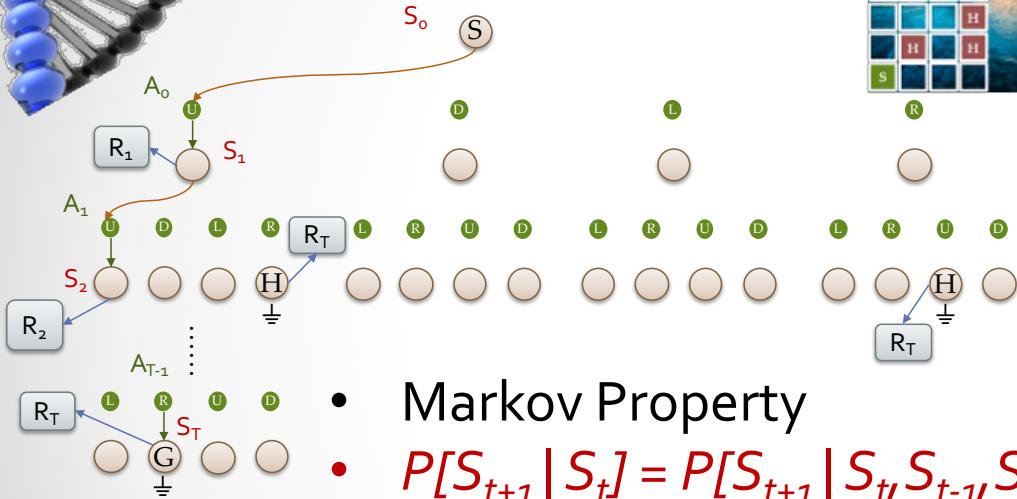


- Sequential decision-making
  - ✓ Under incomplete/probabilistic information, even if we have full observability
  - ✓ Uncertain environment
- Evaluative feedback
- Exhaustive sampling

- There is a State Space
  - State is actually an observation, need not represent the environment
  - *Encoding state requires some thought*
- There is an action space
- There are rewards
  - Goal is to maximize total rewards (= Return)
  - $R_t$  = One step Return
- Same action need not result in same return
- Action to state transition might be stochastic



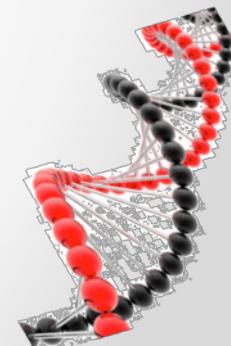
# Markov Process



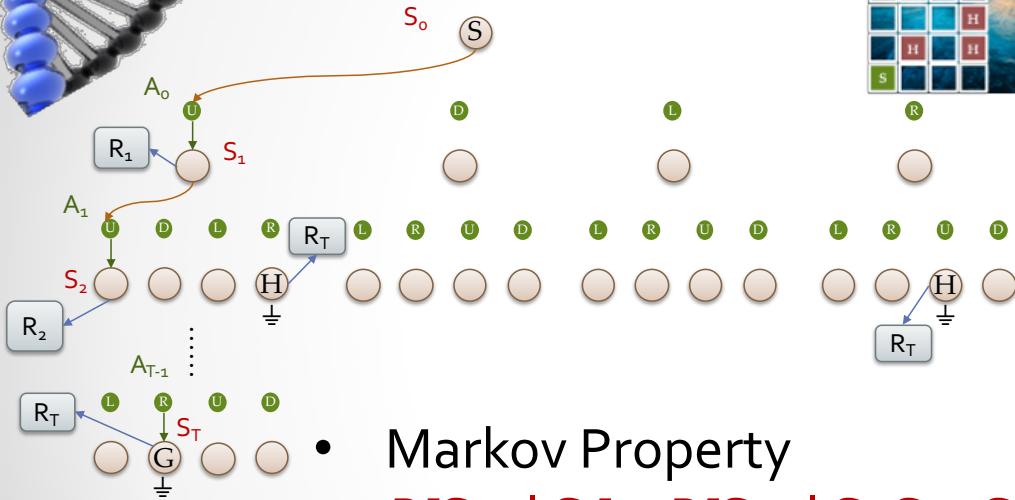
- Markov decision process formally describes an environment for Reinforcement Learning (Silver)
- Powerful Mathematical Framework for RL



- Markov Property
- $P[S_{t+1} | S_t] = P[S_{t+1} | S_t, S_{t-1}, S_{t-2}, \dots]$
- Current state is sufficient to predict the future
- A Markov process is a memoryless sequence of states  $S_1, S_2, S_3, \dots$  with the Markov Property



# Markov Process



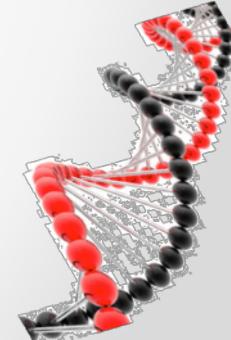
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- Good

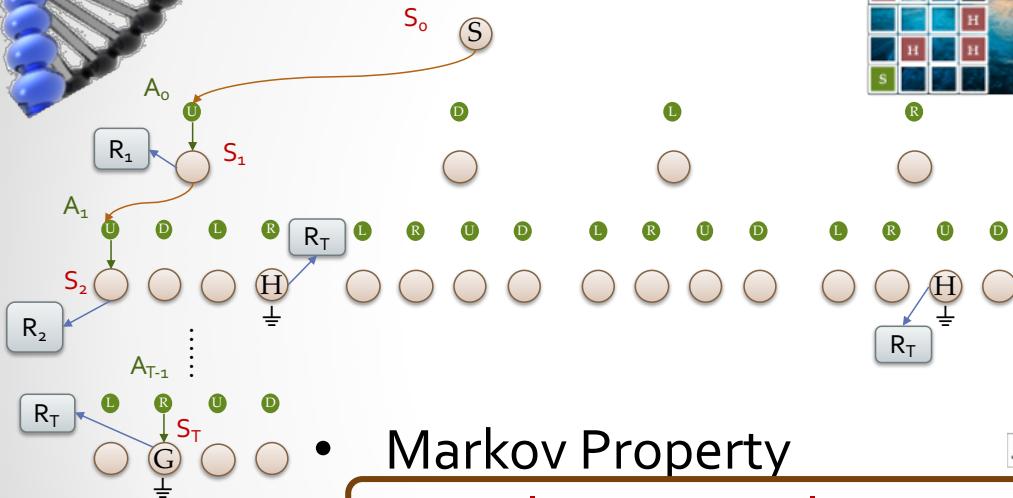
- Don't have to remember all trajectories & paths
- Don't have to consider them for decisions

- Bad

- The state has to be constructed s.t it encodes all the relevant information e.g. 4 frames in Atari RL agent



# Markov Process



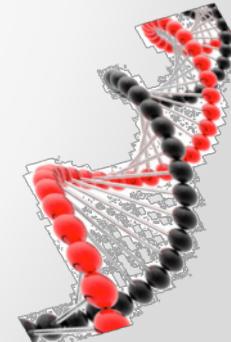
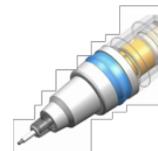
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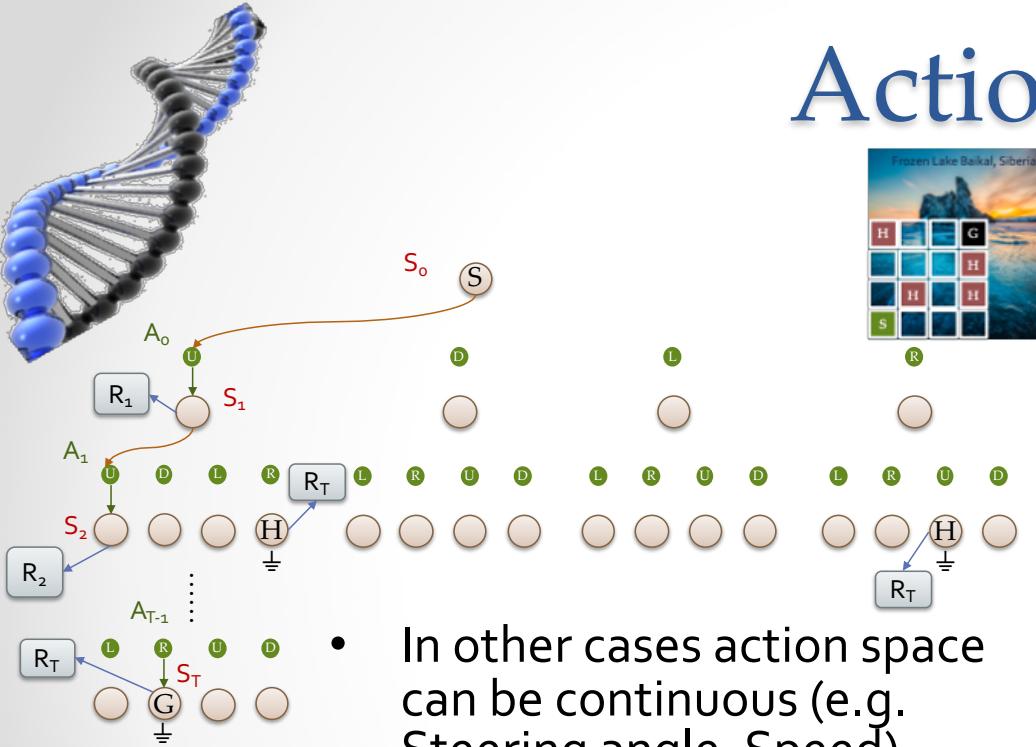
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- Markov Property
- $P[S_{t+1} | S_t] = P[S_{t+1} | S_t, S_{t-1}, S_{t-2}, \dots]$
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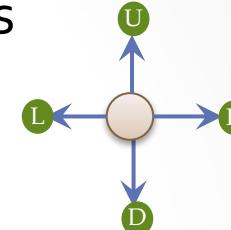


# Action Space



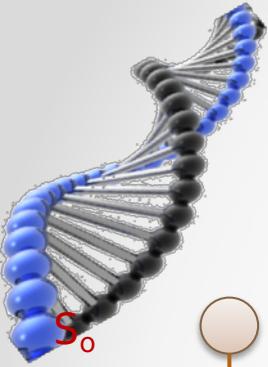
- In other cases action space can be continuous (e.g. Steering angle, Speed)
- Different actions at different states (games, parking vs. merging)
- Large Action space

- 4 actions



- How does an agent choose the actions ?
  - Equi-probable
  - $\epsilon$ -greedy
  - Greedy
  - Softmax distribution
- Best action need not be deterministic
  - E.g. Rock-Paper-Scissor
- We will examine policy later





# Reward Space & Discounting

$R_t$  = Reward at a time step

$G_t$  = Total Return

Goal is to maximize this

$$G_{t(t=0)} = R_1 + R_2 + \dots + R_T$$

$$G_t = R_{t+1} + R_{t+2} + \dots + R_T$$

Add Discount factor  $\gamma$  to account for uncertainties,

$$G_t = \sum_{k=0 \text{ to } \infty} \gamma^k R_{t+k+1} \quad ..(3.8)$$

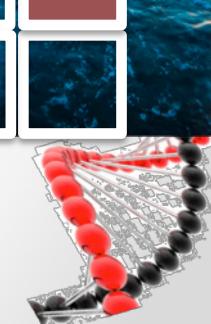
$$\gamma \in (0, 1)$$

close to 0 gives "myopic"

close to 1 gives "far-sighted"

$\gamma = 0.9$  for continuous,

= 1.0 for sequences that terminate





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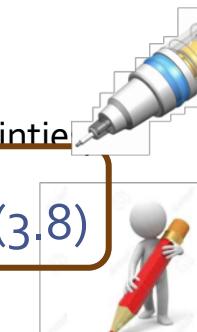
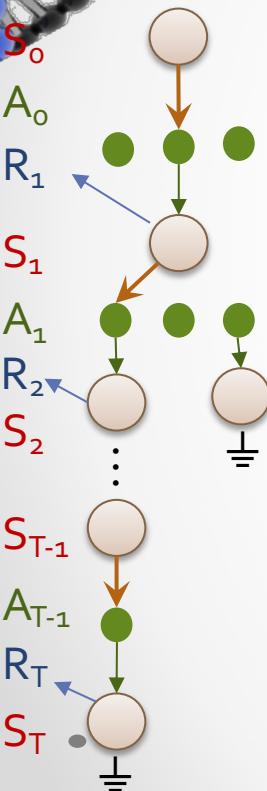
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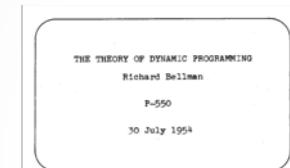
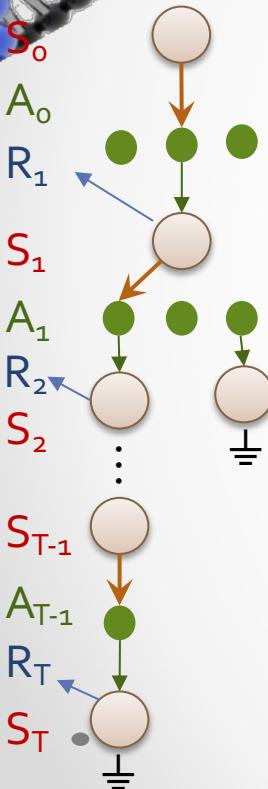
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# Richard Bellman

Richard E. Bellman invented Dynamic Programming  
His formulations form the foundation of  
Reinforcement Learning



Turning to a more precise discussion, let us introduce a small amount of terminology. A sequence of decisions will be called a policy, and a policy which is most advantageous according to some preassigned criterion will be called an optimal policy.

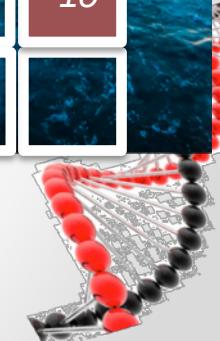
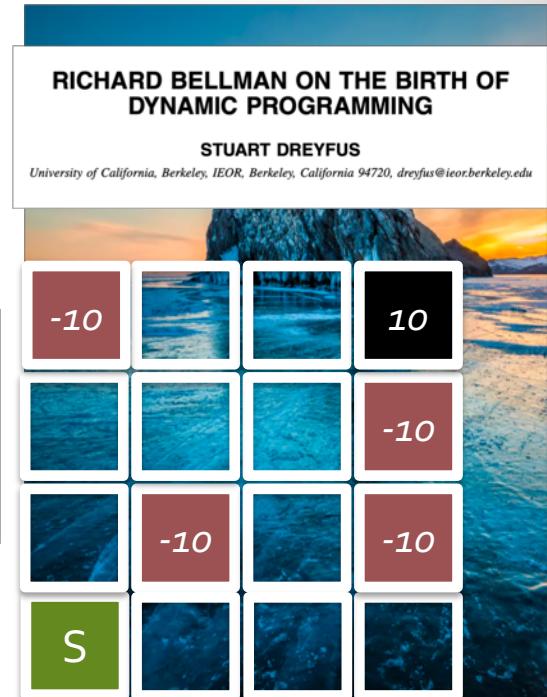
Dynamic Programming – refactor into sub problems

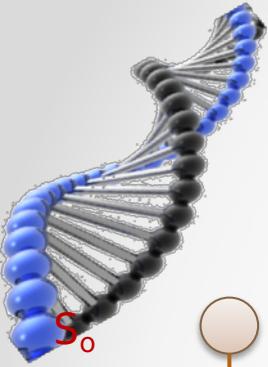
Decomposition & Aggregation

$$\begin{aligned} G_t &= \sum_{k=0 \text{ to } \infty} \gamma^k R_{t+k+1} \\ &= R_{t+1} + \sum_{k=1 \text{ to } \infty} \gamma^k R_{t+k+1} \\ &= R_{t+1} + \gamma G_{t+1} \dots (3.9) \end{aligned}$$



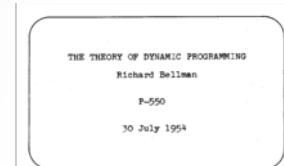
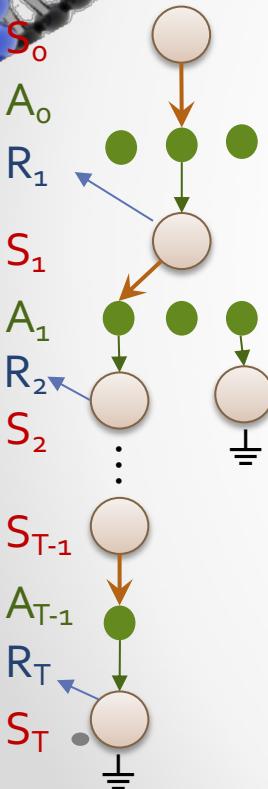
An interesting paper :  
[http://smo.sogang.ac.kr/doc/dy\\_birth.pdf](http://smo.sogang.ac.kr/doc/dy_birth.pdf)





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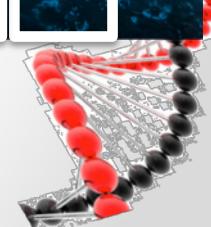


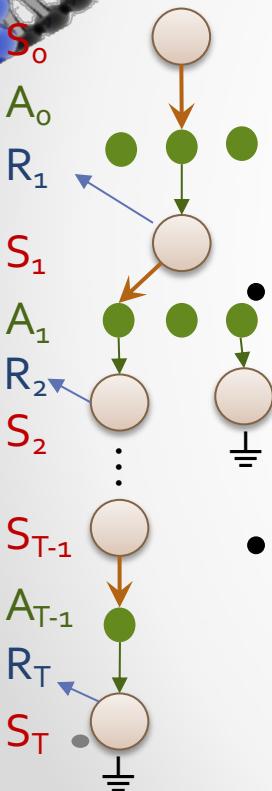
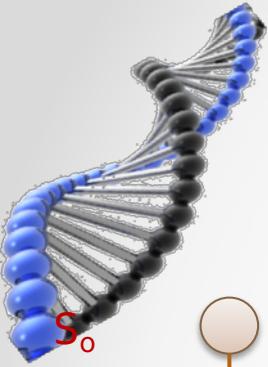
An interesting paper :  
[http://smo.sogang.ac.kr/doc/dy\\_birth.pdf](http://smo.sogang.ac.kr/doc/dy_birth.pdf)

## RICHARD BELLMAN ON THE BIRTH OF DYNAMIC PROGRAMMING

STUART DREYFUS

University of California, Berkeley, IEOR, Berkeley, California 94720, dreyfus@ieor.berkeley.edu





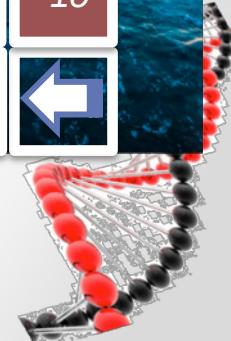
# Policy

- How does an agent choose an action ?

- Equi-probable Random
- $\epsilon$ -Greedy
- Greedy
- Softmax distribution

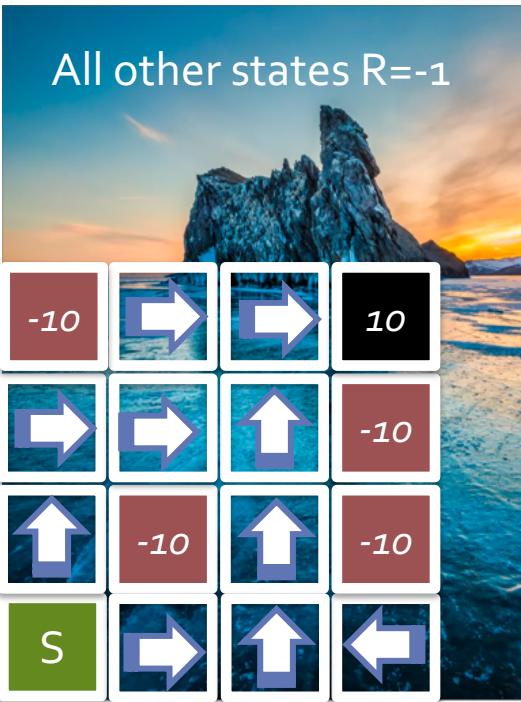
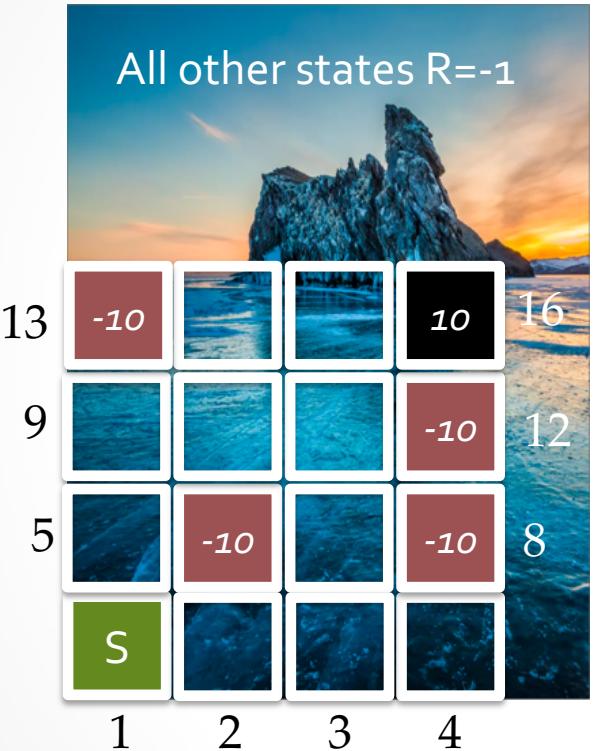
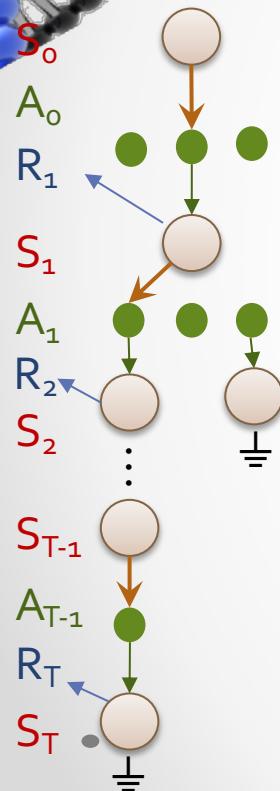
Or A deterministic policy as given here

- Which is possible if we have the full model of the environment
- **Policy *guides* the decisions**
  - For example it could order actions as preferences that reflect the current understanding or belief

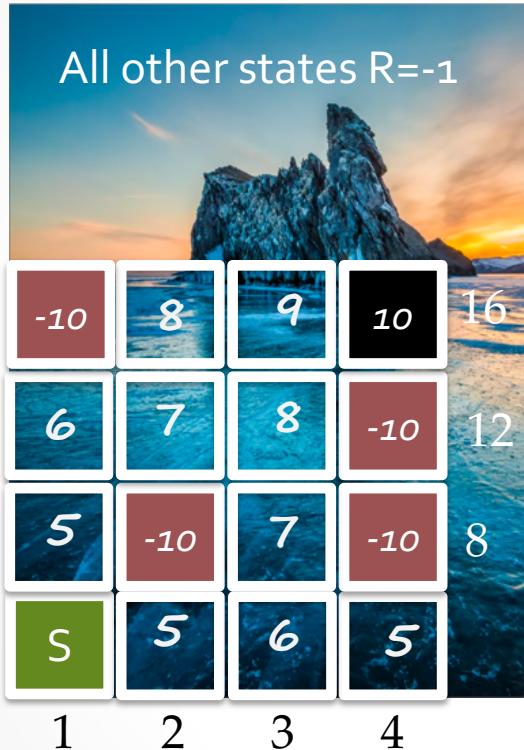
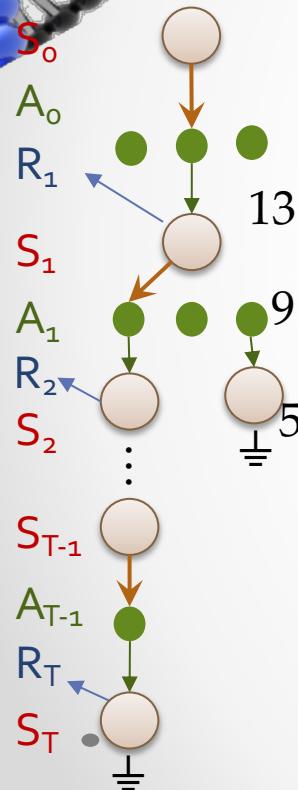




# State Space & Policy



State	Action	Probability
1	U	1.0
2	R	1.0
3	U	1.0
4	L	
5	U	
6		
7	U	
8		
9	R	
10	R	
11	U	
12		
13		
14	R	
15	R	
16		



# State-Value Function

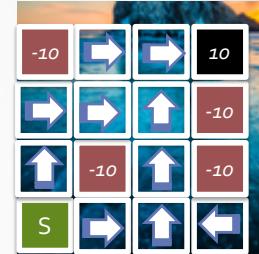
Given a policy, we can compute the value at each state using the Bellman Equation

$$G_t = R_{t+1} + G_{t+1}$$

Or

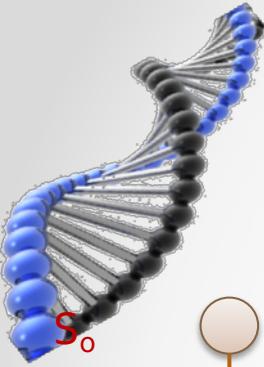
$$V_\pi(s) = R_{t+1} + V_\pi(s_{t+1} | s_t=s)$$

As shown in the diagram

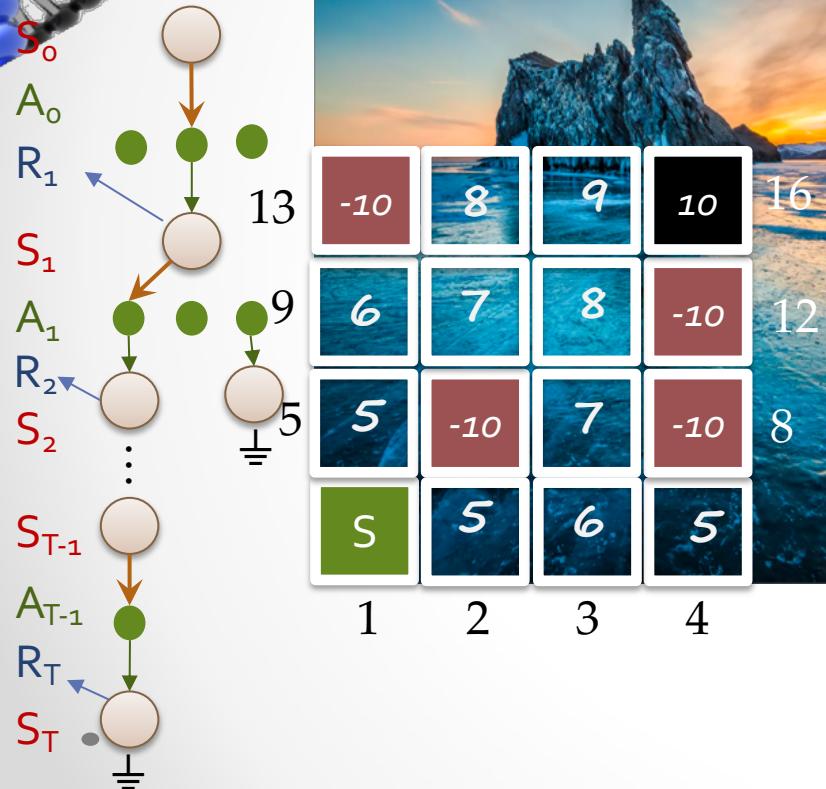


*Of course, we are glossing over a lot of details, which we will explore during the rest of the lab*





# State-Value Function



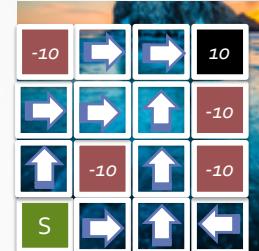
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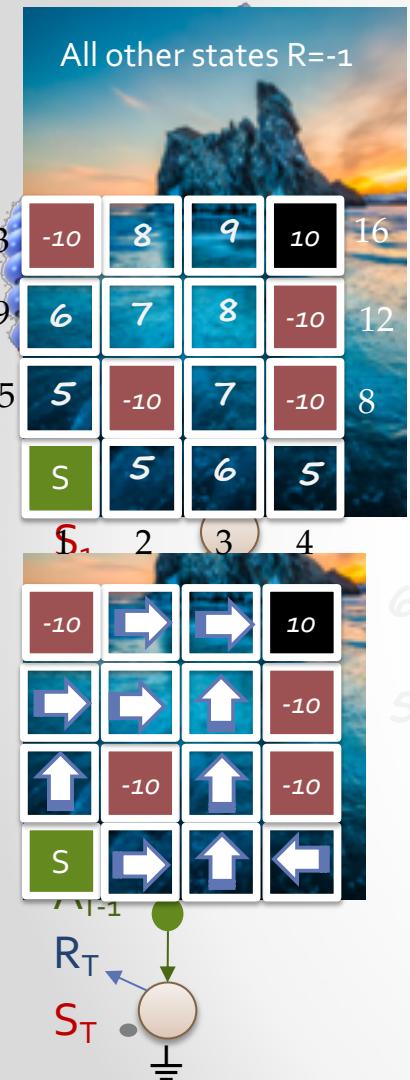
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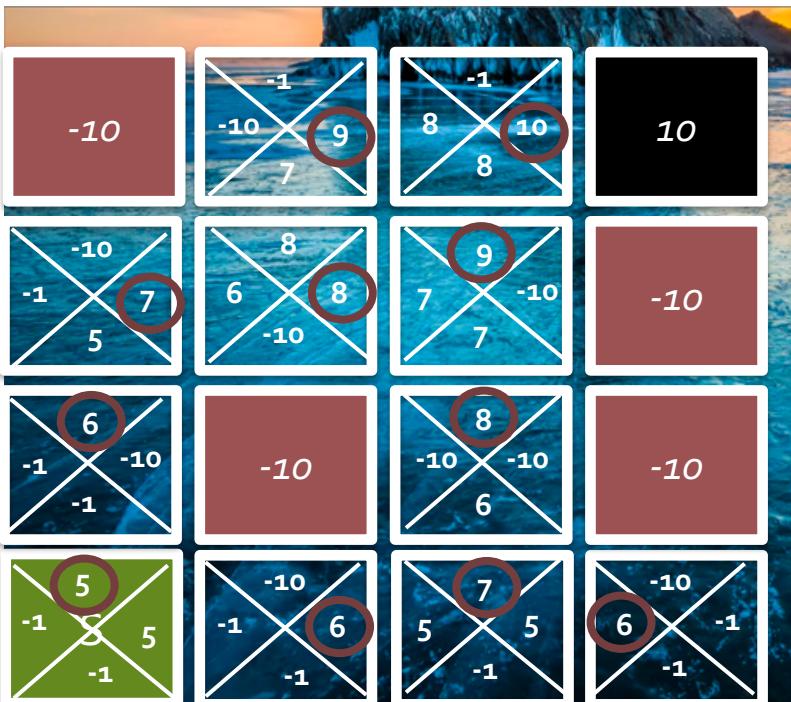


## All other states R=-1



# State-Action-Value Function

# Iterative Policy Evaluation & Improvement



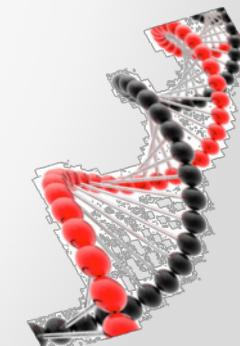
$$q_{\pi}(s,a) = v_{\pi}(s_{t+1}, a_t | s_t=s, a_t=a)$$

$$\pi(a|s) = q_*(s, a) = \text{argmax}_{a'}(q(s, a'))$$

$$v_{\pi}(s) = R_s + q_{\pi}(s, \pi(s))$$

## Q-Table

s,a	Q-Value
z,L	-1
z,D	-1
z,U	-10
z,R	6





# State-Action-Value Function

Iterative Policy Evaluation & Improvement



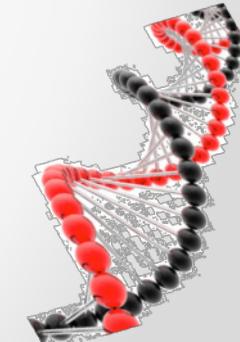
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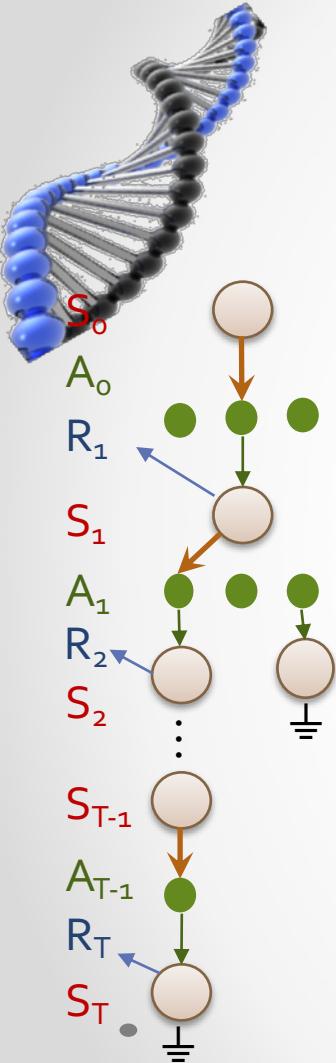
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Q-Table

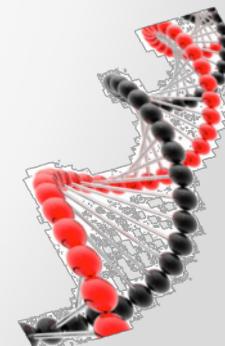
$s, a$	Q-Value
2,L	-1
2,D	-1
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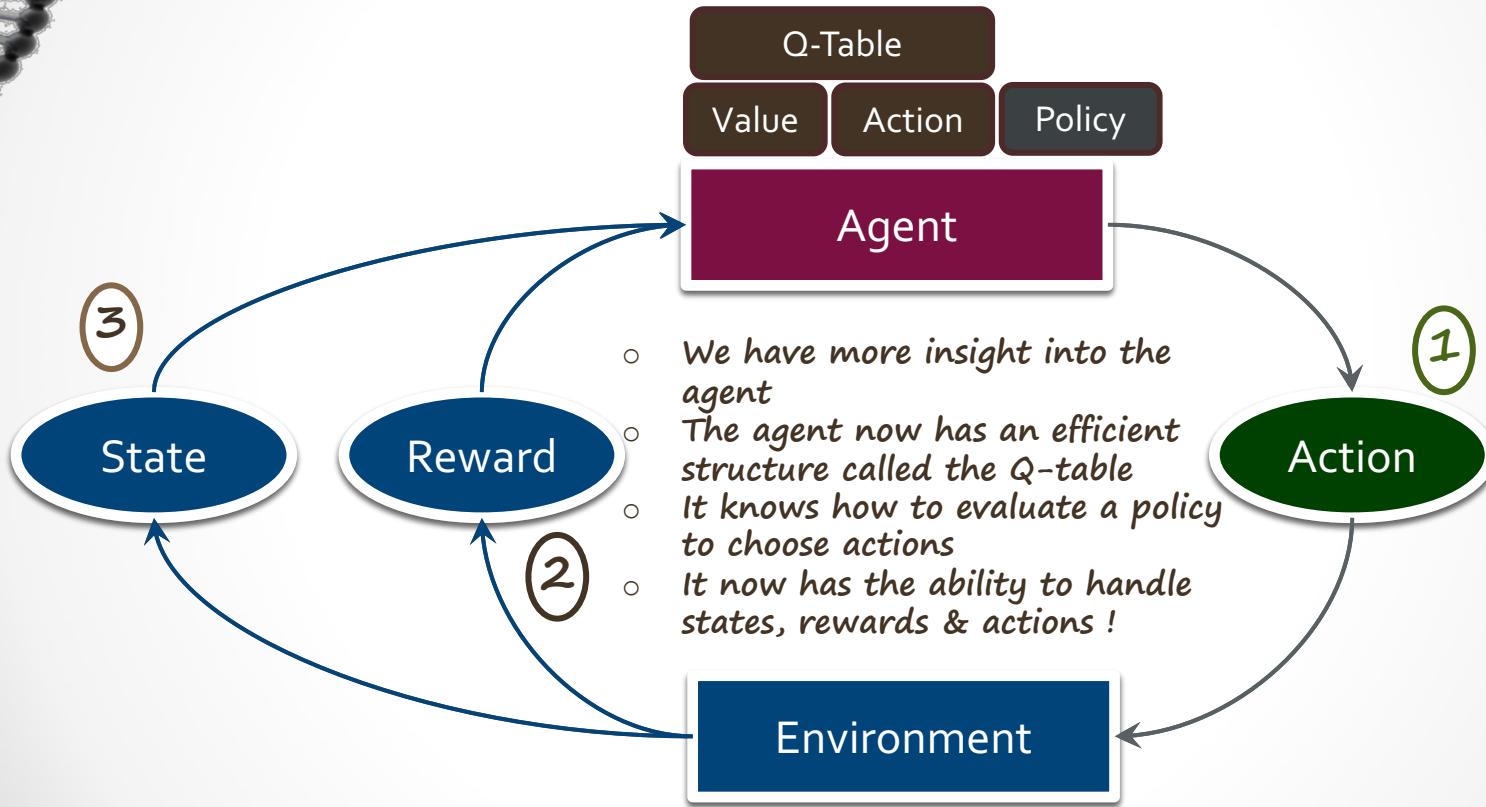
# Recap & Forward



- RL Cycle
- Backup Diagram
- Value Function
- Action-Value Function
  - Value functions define a partial ordering of policies
- Policy – greedy policy ( $\text{argmax}_{a'}$ )
  - state sweep
- Grid World as an example
- Used Dynamic Programming in a model-based fashion
  - Decomposition & Aggregation

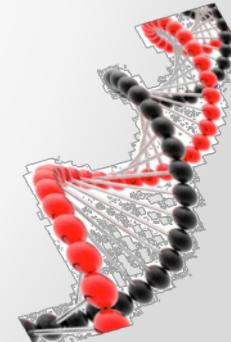
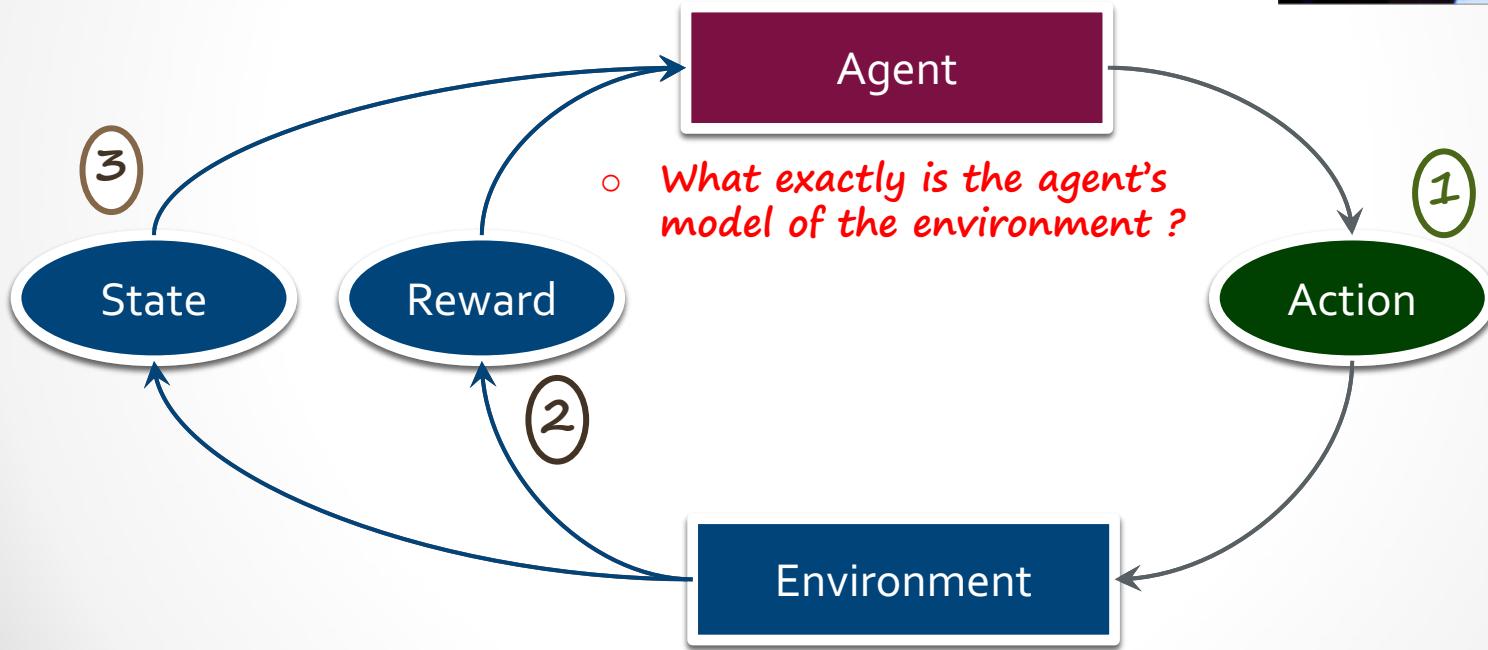


# RL Flow



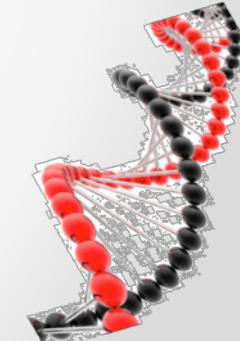
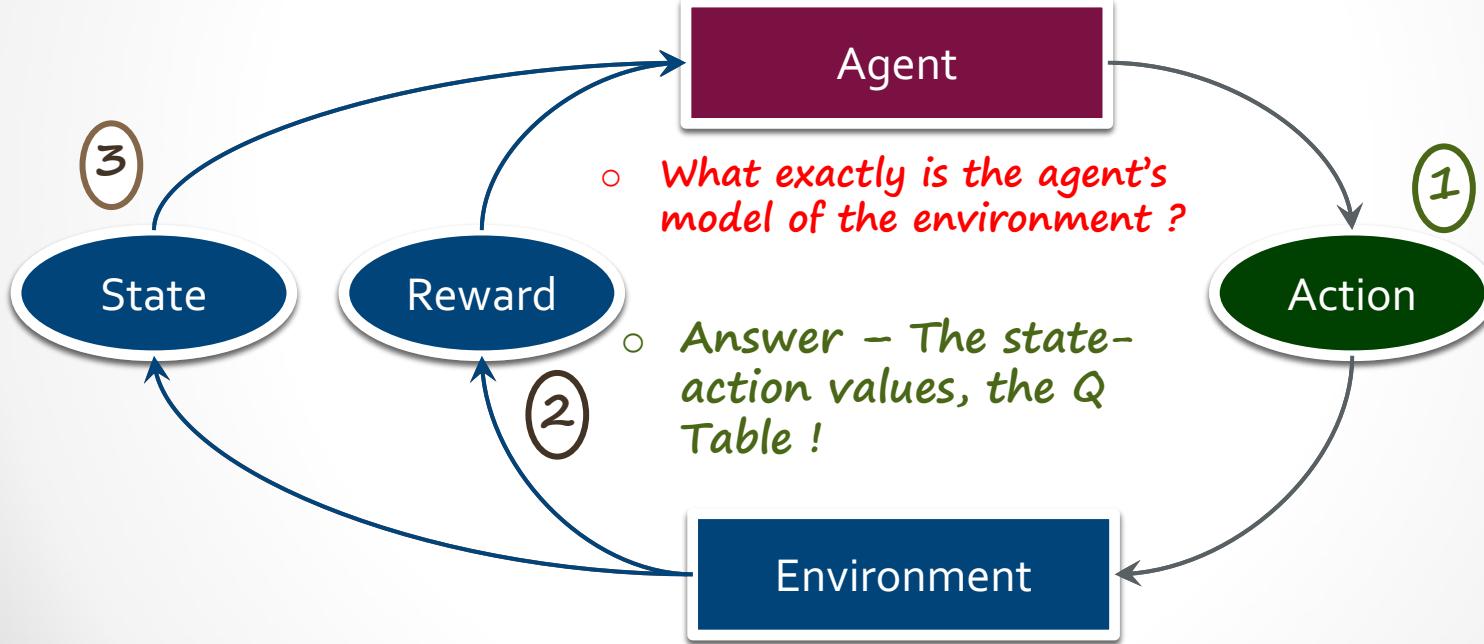


# Quiz



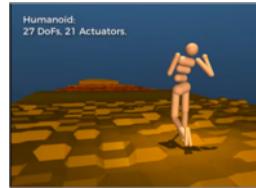


# Quiz





# Examples of representation



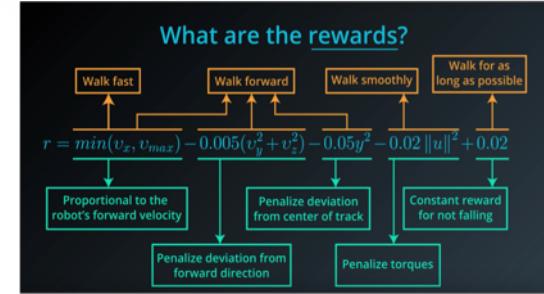
## Atari

- Grey-scale, 84 X 84,
- Stacking 4 frames for context
- CNN as feature extractor

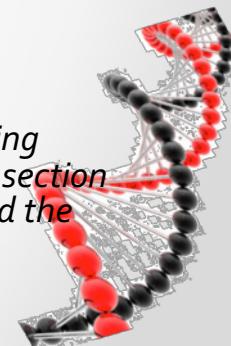
## • Walking Humanoids

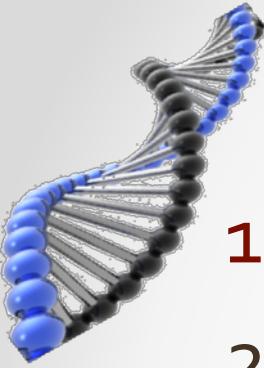
- <https://www.theverge.com/tldr/2017/7/10/15946542/deepmind-parkour-agent-reinforcement-learning>
- Emergence of Locomotion Behaviors in Rich Environments
- <https://arxiv.org/abs/1707.02286>
- Algorithms : PPO, DPPO,A3C
- States – Position & Velocities of the joints, the height of the walker body above the ground, the difference between the agents position and the next sampling grid center
- Actions : Forces and directions on the 21 actuated joints with 28 DoF
- Rewards :

- *The reward consists of a main component proportional to the velocity along the x-axis, encouraging the agent to make forward progress along the track, plus a small term penalizing torques. For the walker the reward also includes the same box constraints on the pose as in section 2. For the quadruped and humanoid we penalize deviations from the center of the track, and the humanoid receives an additional reward per time-step for not falling*



$$r = \min(v_x, v_{\max}) - 0.005(v_y^2 + v_z^2) - 0.05y^2 - 0.02\|u\|^2 + 0.02$$





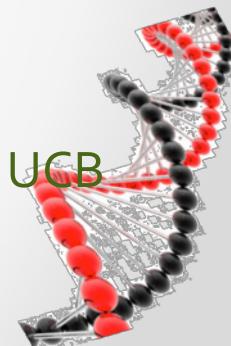
# General Observation on Rewards

1. Specify the goals, not how to do it
2. Do not over specify, even a hint of how

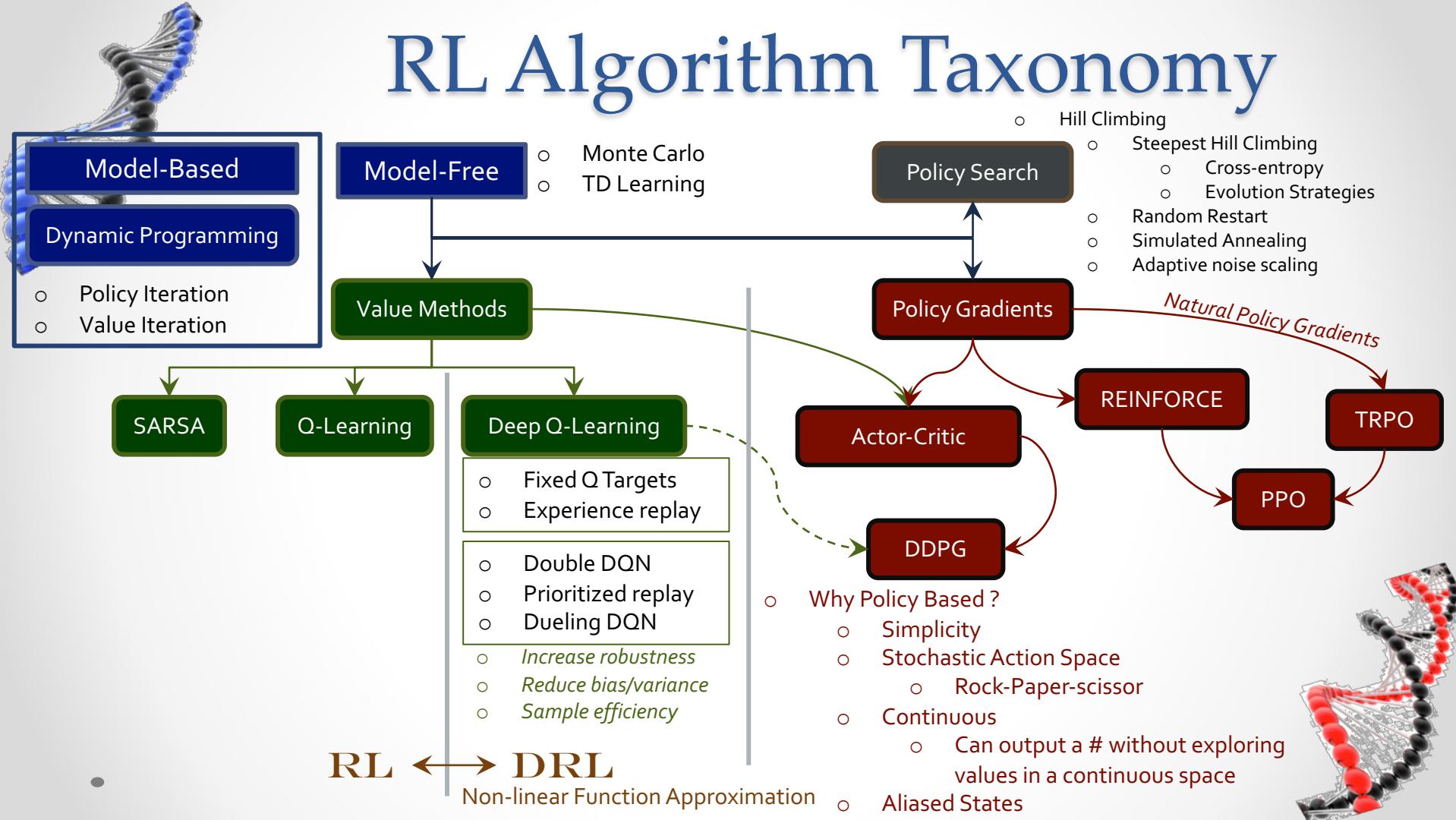
*Enable the agent to pursue novel strategies  
(e.g. Go game) and discover winning  
strategies*

3. Rewards can change over time

- This can break stationary assumptions of mechanisms like UCB action selection and optimistic initialization

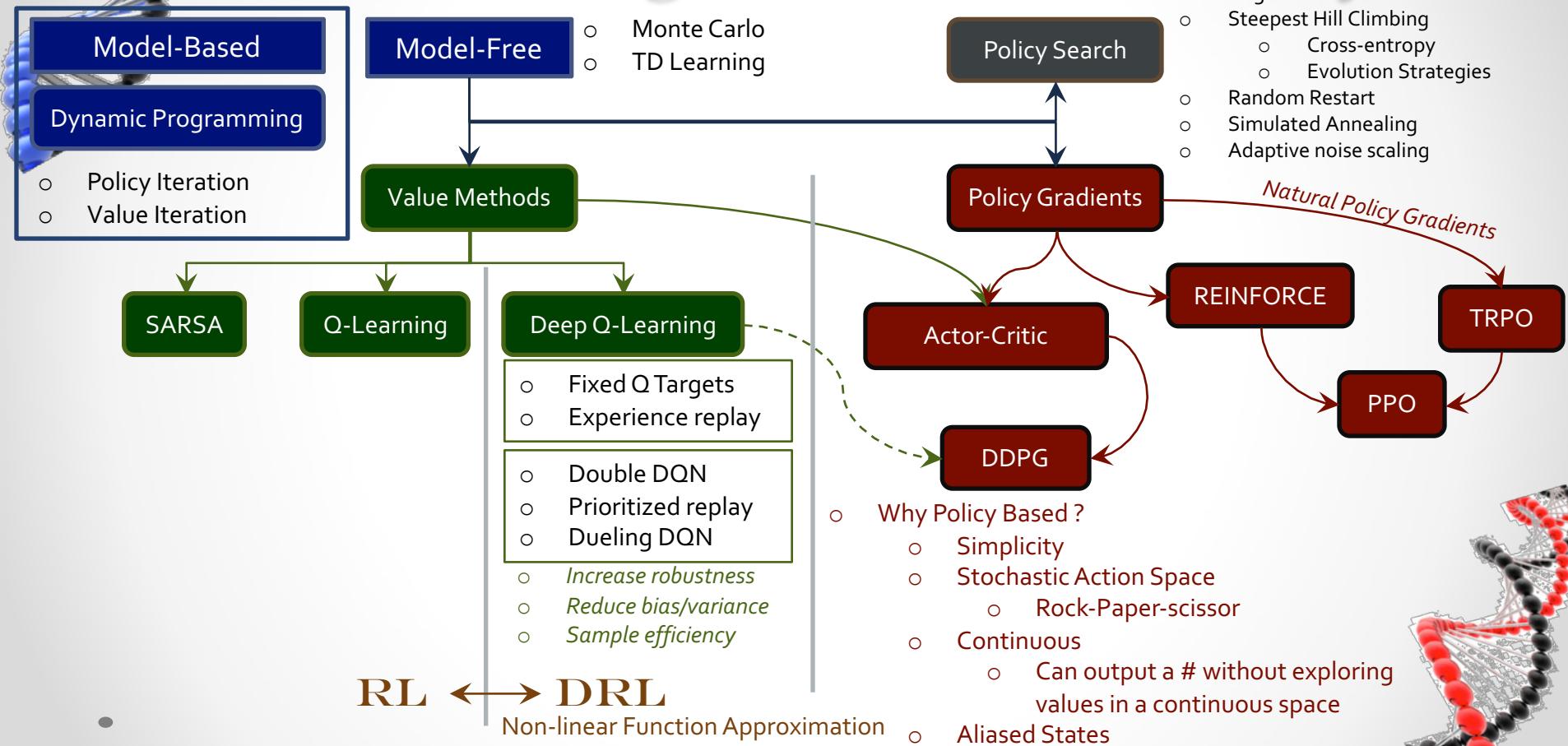


# RL Algorithm Taxonomy





# RL Algorithm Taxonomy





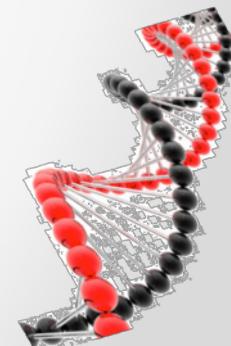
Algorithm Time

PyTorch Time

### 3. Algorithms & Programming : From Monte Carlo to DQN

• • •

Let us implement four algorithms and in the process discuss Monte Carlo, TD(), SARSA and Q-Learning





# Notations & Definitions - Review

- Episode  
Sequence of State-Action-Reward until an episode ends in T steps

- Return

$$G_t = \sum_{k=0 \text{ to } \infty} \gamma^k R_{t+k+1} = R_{t+1} + \sum_{k=1 \text{ to } \infty} \gamma^k R_{t+k+1} = R_{t+1} + \gamma G_{t+1}$$

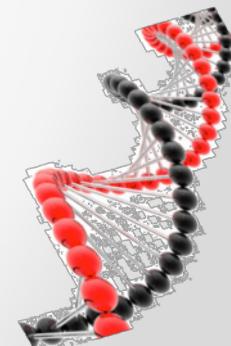
- Policy

Mapping  $\pi : S \times A \mapsto [0,1]$      $\pi(a|s) = P(A_t=a | S_t=s)$

- Value

$$\begin{aligned} v_\pi(s) &= E_\pi[G_t | S_t=s] && \dots \text{state-value Function} \\ &= E_\pi[R_{t+1} + \gamma G_{t+1}(s_{t+1} | s_t=s)] \\ &= E_\pi[R_{t+1} + \gamma v_\pi(s_{t+1} | s_t=s)] \end{aligned}$$

$$q_\pi(s, a) = E_\pi[G_t | S_t=s, A_t=a] \quad \dots \text{action-value function}$$





# Notations & Definitions - Review

- Episode  
Sequence of State-Action-Reward until an episode ends in T steps

- Return

$$G_t = \sum_{k=0 \text{ to } \infty} \gamma^k R_{t+k+1} = R_{t+1} + \sum_{k=1 \text{ to } \infty} \gamma^k R_{t+k+1} = R_{t+1} + \gamma G_{t+1}$$

- Policy

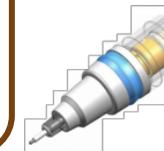
Mapping  $\pi : S \times A \mapsto [0,1]$

$$\pi(a|s) = P(A_t=a, S_t=s)$$

- Value

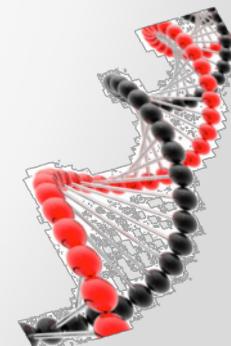
$$\begin{aligned} v_\pi(s) &= E_\pi[G_t | S_t=s] \\ &= E_\pi[R_{t+1} + \gamma G_{t+1}(s_{t+1}) | S_t=s] \\ &= E_\pi[R_{t+1} + \gamma v_\pi(s_{t+1}) | S_t=s] \end{aligned}$$

... state-value Function



$$q_\pi(s, a) = E_\pi[G_t | S_t=s, A_t=a]$$

... action-value function





# Hands On #1 - Skating the Frozen Lake

## Goal:

- Get familiar with programming OpenAI Gym & it's interfaces
- Solve OpenAI Gym : Frozen Lake, given an optimum deterministic policy
- Frozen Lake deterministic : episodes before solve

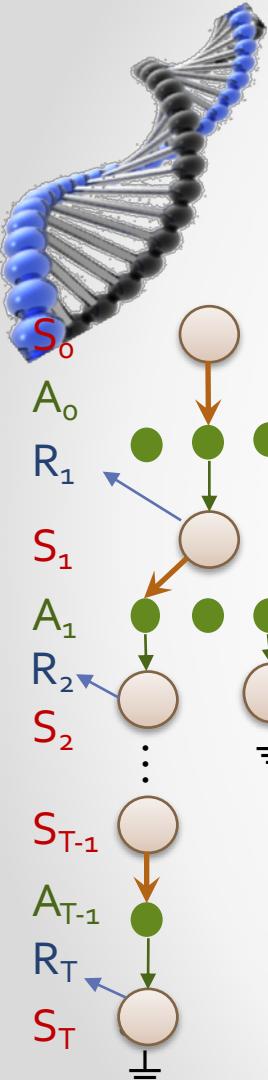
## Steps:

Notebook : frozen\_lake\_01.ipynb

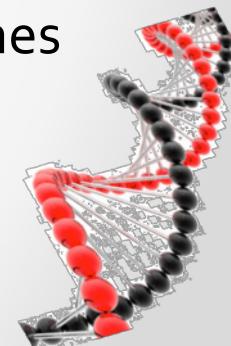
1. Understand OpenAI Setup & interface
2. Examine Random Policy Run
3. Run the cells upto 5. *Hands-on ToDo*
4. Create aPolicy which captures the deterministic policy
5. Use deterministic policy to skate to the goal
6. Metrics that can be programmed:
  - Episodes before solve
  - Solved 0.78 over 100 consecutive runs
  - Max score over 1000 episodes
  - Avg over 1000 episodes



# Monte Carlo



- Model-free method
- Usually we do not have the model or the transition matrix. Then how do we arrive at  $G_t$ ,  $q_\pi(s, a)$  et al ?
- Monte Carlo brings deterministic expectation by repeated random sampling. i.e. even though the underlying problem involves a great degree of randomness, we can infer useful information we can trust, by collecting lots of samples
- Monte Carlo estimates a value by averaging across a large number of episodes
- Remember, a state-action might be visited several times and the q-value can and will be different.
  - Averaging gives the best estimate across a large number of episodes
  - Either average (across episodes) considering only during 1<sup>st</sup> visit in an episode or
    - Consider all visits and average the value





# Monte Carlo Algorithm

1. Initialize variables, set policy  $\pi$
2. Generate episodes using policy  $\pi$  -  $S_o A_o R_1 S_1 A_1 R_2 S_2 \dots A_{T-1} R_T S_T$
3. For each episode
4. For each time step
5. For each state, action pair

6. If 1<sup>st</sup> visit to  $(S_t, A_t)$

7. Calculate the return  $G_t(S_t, A_t)$  -  $G_t = \sum_{k=0 \text{ to } \infty} \gamma^k R_{t+k+1}$

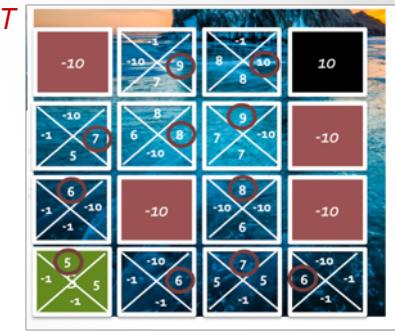
8. Add  $G_t$  to the return column -  $\Sigma q(s, a)$

9. Increment  $N(S_t, A_t)$

10. Average  $G_t(S_t, A_t) = \Sigma q(s, a) / N(S_t, A_t)$  and

11. Return the Q table  $q(s, a)$

$Q(s, a) \mapsto Q_\pi(s, a)$  for a larger number of episodes



Algorithm 9: First-Visit MC Prediction (for action values)

```

Input: policy  $\pi$ , positive integer num_episodes
Output: value function  $Q$  ( $\approx q_\pi$  if num_episodes is large enough)
Initialize  $N(s, a) = 0$  for all  $s \in \mathcal{S}, a \in \mathcal{A}(s)$ 
Initialize returns.sum( $s, a$ ) = 0 for all  $s \in \mathcal{S}, a \in \mathcal{A}(s)$ 
for  $i \leftarrow 1$  to num_episodes do
    Generate an episode  $S_0, A_0, R_1, \dots, S_T$  using  $\pi$ 
    for  $t \leftarrow 0$  to  $T - 1$  do
        if  $(S_t, A_t)$  is a first visit (with return  $G_t$ ) then
             $N(S_t, A_t) \leftarrow N(S_t, A_t) + 1$ 
            returns.sum( $S_t, A_t$ )  $\leftarrow$  returns.sum( $S_t, A_t$ ) +  $G_t$ 
        end
    end
     $Q(s, a) \leftarrow \text{returns.sum}(s, a) / N(s, a)$  for all  $s \in \mathcal{S}, a \in \mathcal{A}(s)$ 
return  $Q$ 

```

---

**Algorithm 9:** First-Visit MC Prediction (*for action values*)

---

**Input:** policy  $\pi$ , positive integer  $num\_episodes$

**Output:** value function  $Q$  ( $\approx q_\pi$  if  $num\_episodes$  is large enough)

Initialize  $N(s, a) = 0$  for all  $s \in \mathcal{S}, a \in \mathcal{A}(s)$

Initialize  $returns\_sum(s, a) = 0$  for all  $s \in \mathcal{S}, a \in \mathcal{A}(s)$

**for**  $i \leftarrow 1$  **to**  $num\_episodes$  **do**

Generate an episode  $S_0, A_0, R_1, \dots, S_T$  using  $\pi$

**for**  $t \leftarrow 0$  **to**  $T - 1$  **do**

**if**  $(S_t, A_t)$  is a first visit (with return  $G_t$ ) **then**

$N(S_t, A_t) \leftarrow N(S_t, A_t) + 1$

$returns\_sum(S_t, A_t) \leftarrow returns\_sum(S_t, A_t) + G_t$

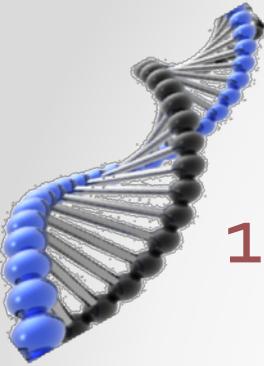
**end**

**end**

$Q(s, a) \leftarrow returns\_sum(s, a) / N(s, a)$  for all  $s \in \mathcal{S}, a \in \mathcal{A}(s)$

**return**  $Q$

---



# Couple of optimizations

## 1. Instead of

- Do this

Increment counter  $N(s) \leftarrow N(s) + 1$

Increment total return  $S(s) \leftarrow S(s) + G_t$

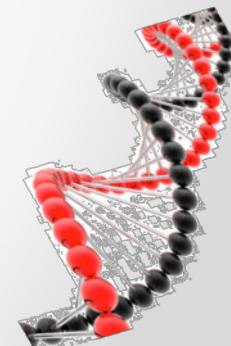
Value is estimated by mean return  $V(s) = S(s)/N(s)$

$$N(S_t) \leftarrow N(S_t) + 1$$

$$V(S_t) \leftarrow V(S_t) + \frac{1}{N(S_t)} (G_t - V(S_t))$$

## 2. Track a running mean

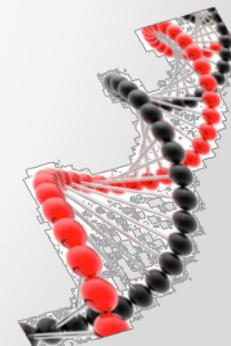
$$V(S_t) \leftarrow V(S_t) + \alpha (G_t - V(S_t))$$

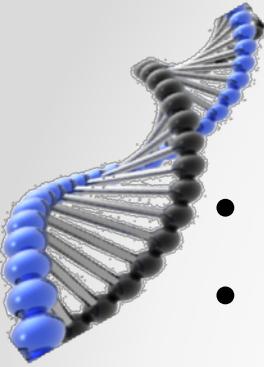




# Incremental Mean

$$\begin{aligned}\mu_k &= \frac{1}{k} \sum_{j=1, k} x_j \\&= \frac{1}{k} [x_k + \sum_{j=1, k-1} x_j] \\&= \frac{1}{k} (x_k + (k-1) \mu_{k-1}) \\&= \frac{1}{k} (x_k + k \mu_{k-1} - \mu_{k-1}) \\&= \mu_{k-1} + \frac{1}{k} (x_k - \mu_{k-1})\end{aligned}$$





# Policy !

- We glossed over 2 points
- Where does the  $\pi$  come from ?
- How do we get to



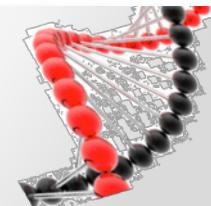
- From a Q table ?

(S,A)	$\Sigma q(s,a)$	N
1,0	-4	4
1,1	5	1
1,2	10	2
1,3	-2	2
2,0	-20	20
2,1	-10	1
2,2	4	24
..		

**Algorithm 9:** First-Visit MC Prediction (for action values)

```
Input: policy  $\pi$ , positive integer num_episodes
Output: value function  $Q$  ( $\approx q_\pi$  if num_episodes is large enough)
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        end
    end
     $Q(s, a) \leftarrow \text{returns\_sum}(s, a) / N(s, a)$  for all  $s \in \mathcal{S}, a \in \mathcal{A}(s)$ 
return  $Q$ 
```

i.e. how does all this help us to make better actions ?





# Policy Evaluation-Improvement Cycle

## Policy Evaluation

The  $q(s,a)$  tells us the utility of a policy

- Collect experience using  $\pi$
- Create Q Table

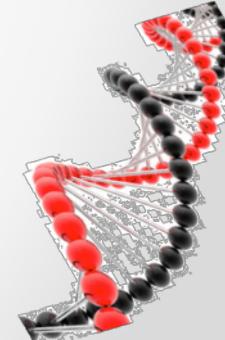
Update agent's behavior based on experience

- Construct better policy  $\pi'$  based on the Q values
- (optionally) Set  $\pi = \pi'$
- Take action using  $\pi'$

$$\pi_0 \mapsto V_{\pi_0} \mapsto \pi_1 \mapsto V_{\pi_1} \mapsto \dots \mapsto \pi_* \mapsto V_*$$

## Policy Improvement

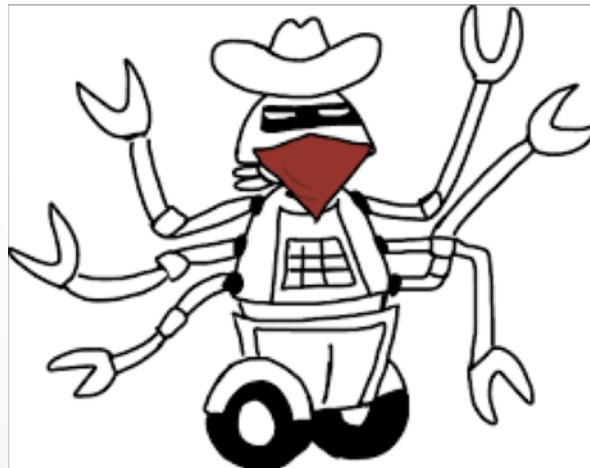
- $\pi$  – Behavior Policy (sample experience)
- $\pi'$  – Target Policy (to optimize behavior)
- Most Common Policies
  - Equiprobable
  - Greedy
  - $\epsilon$ -Greedy (Greedy + Equiprobable)
  - Softmax distribution





# TTD (Things To Do)

- Read & Explore
  - Multi-arm bandits
  - Contextual bandits





# Policy Algorithms

## Equiprobable

- Random Uniform
- All actions equally possible
- *Good starting point, in an unknown environment*

## Greedy

- Follow the action with the max value
- $\pi(a|s) = q_*(s,a) = \text{argmax}_{a'}(q(s,a'))$
- *Pure exploit*

## Softmax

(1) To calculate the probability of selecting an action  $a$

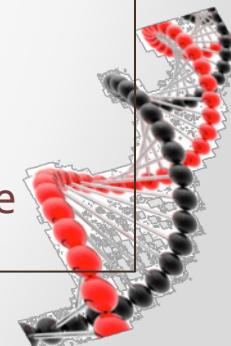
$$\pi(a) = \frac{e^{\frac{Q(a)}{\tau}}}{\sum_{b=1}^k e^{\frac{Q(b)}{\tau}}}$$

(2) Use the action-value function for that action divided by the temperature parameter as the preference

(3) Raise  $e$  to that value

(4) Then calculate the same for all possible action and add them up

(5) Finally, divide the value by the sum to normalize the probabilities



## $\epsilon$ -Greedy

- With  $\epsilon$  follow equiprobable
- With  $1-\epsilon$  follow greedy
- *Gives exploration*
- Decay  $\epsilon$  as the agent learns more



# Policy Algorithms

- A weighted probability across actions, establishing a partial ordering

## Equiprobable

- Random Uniform
- All actions equally possible
- Good starting point, in an unknown environment

## Softmax

(1) To calculate the probability of selecting an action  $a$

$$\pi(a) = \frac{e^{\frac{Q(a)}{\tau}}}{\sum_{b=1}^k e^{\frac{Q(b)}{\tau}}}$$

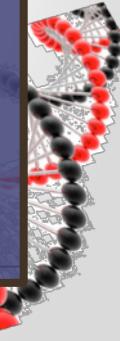
(2) Use the action-value function for that action divided by the temperature parameter as the preference

(3) Raise  $e$  to that value

(4) Then calculate the same for all possible actions

(5) Finally, divide the value by the sum to normalize the probabilities

- Greedy
- Follow the action with the max value
- $\tau = \text{temperature, that scales the probability distribution of actions.}$
- A high temperature will tend the probabilities to be very similar, whereas
- A low temperature will exaggerate differences in probabilities between actions
- Initially, when the values are inaccurate, we are Ok with small difference between the values i.e. uniform random
- Decay  $\tau$  such that as our values get better we want meaningful difference, yet have a small exploration possibility



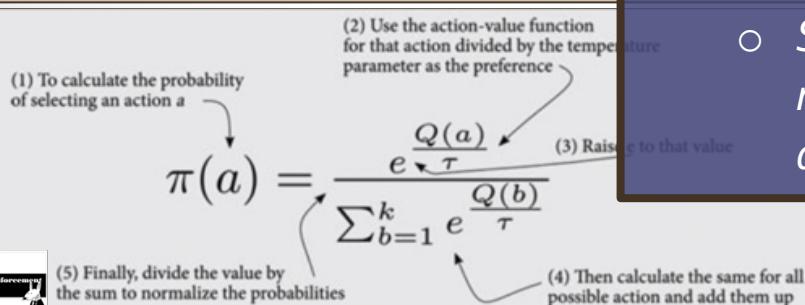


# Policy Algorithms

## Equiprobable

- Random Uniform
- All actions equally possible
- Good starting point, in an unknown environment

## Softmax



- We all would have encountered softmax-based image classifier where there is a single correct classification to an image and there is no temporal association between each prediction.

In our RL case, we want more control over how we make these updates.  $v_t = q_*(s, a) = \text{argmax}_{a'}(q(s, a'))$

- First, we want to make small, smooth updates because we want to maintain some stochasticity in our action sampling to adequately explore the environment.

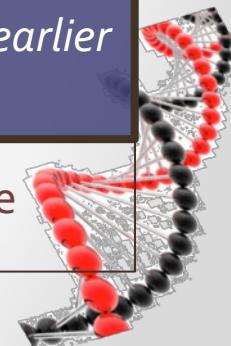
- Secondly, we want to be able to weight how much we assign credit to each action for earlier actions.

With the following equations:

With 1- $\epsilon$  follow greedy

Gives exploration

- Decay  $\epsilon$  as the agent learns more





## Equiprobable

Random Uniform



# Quiz



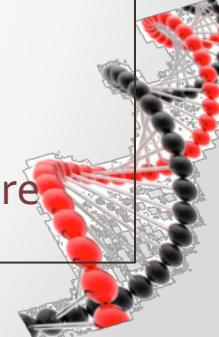
$$\pi(a|s) \leftarrow \begin{cases} 1 - \epsilon + \frac{\epsilon}{|\mathcal{A}(s)|} & \text{if } a = \arg \max_{a' \in \mathcal{A}(s)} Q(s, a') \\ \frac{\epsilon}{|\mathcal{A}(s)|} & \text{otherwise} \end{cases}$$

value

- $\pi(a|s) = q_*(s,a) = \operatorname{argmax}_{a'}(q(s,a'))$
- *Pure exploit*

## $\epsilon$ -Greedy

- With  $\epsilon$  follow equiprobable
- With  $1-\epsilon$  follow greedy
- *Gives exploration*
- Decay  $\epsilon$  as the agent learns more





## Equiprobable

Random Uniform

### Quiz:

1. Which  $\epsilon$  will always be greedy ?  $\epsilon = 0$
2. Always not greedy ? Trick Q. Not possible
3. Is equiprobable a special case of  $\epsilon$ -Greedy ? If so, what is  $\epsilon$  for  $\epsilon$ -Greedy Equiprobable ? Yes.  $\epsilon = 1$
4. Which guarantees non greedy ?  $\epsilon > 0$   
 $\epsilon=0$  ?  $\epsilon=0.25$  ?  $\epsilon=0.75$  ?  $\epsilon=0.99$  ?  $\epsilon=1$  ?
5. What is a good  $\epsilon_{start}$  ?  $\epsilon_{min}$  for decay ?  $\epsilon = 1$ ; decaying over say 10,000 steps to  $\epsilon = 0.1$
6. What is a good policy for Rock-Paper-Scissor ? How will it work ?  $\epsilon = 1$ ; equiprobable
7. When will  $\epsilon$ -Greedy stop learning ?  $\epsilon = 0$ ; Greedy

# Quiz



$$\pi(a|s) \leftarrow \begin{cases} 1 - \epsilon + \frac{\epsilon}{|\mathcal{A}(s)|} & \text{if } a = \arg \max_{a' \in \mathcal{A}(s)} Q(s, a') \\ \frac{\epsilon}{|\mathcal{A}(s)|} & \text{otherwise} \end{cases}$$

value

- $\pi(a|s) = q_*(s,a) = \operatorname{argmax}_{a'}(q(s,a'))$
- Pure exploit

## $\epsilon$ -Greedy

- With  $\epsilon$  follow equiprobable
- With  $1-\epsilon$  follow greedy
- Decay  $\epsilon$  as the agent learns more



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**Algorithm 10:** First-Visit GLIE MC Control
 

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**Input:** positive integer  $\text{num\_episodes}$ , GLIE  $\{\epsilon_i\}$

**Output:** policy  $\pi$  ( $\approx \pi_*$  if  $\text{num\_episodes}$  is large enough)

Initialize  $Q(s, a) = 0$  for all  $s \in \mathcal{S}$  and  $a \in \mathcal{A}(s)$

Initialize  $N(s, a) = 0$  for all  $s \in \mathcal{S}, a \in \mathcal{A}(s)$

**for**  $i \leftarrow 1$  **to**  $\text{num\_episodes}$  **do**

$\epsilon \leftarrow \epsilon_i$

$\pi \leftarrow \epsilon\text{-greedy}(Q)$

Generate an episode  $S_0, A_0, R_1, \dots, S_T$  using  $\pi$

**for**  $t \leftarrow 0$  **to**  $T - 1$  **do**

| **if**  $(S_t, A_t)$  is a first visit (with return  $G_t$ ) **then**

$N(S_t, A_t) \leftarrow N(S_t, A_t) + 1$

$Q(S_t, A_t) \leftarrow Q(S_t, A_t) + \frac{1}{N(S_t, A_t)}(G_t - Q(S_t, A_t))$

**end**    1. Greedy with limited Infinite Exploration

**end**    2. Construct a policy that is  $\epsilon$ -greedy w.r.t the  $Q$  table

**return**  $\pi$     3. Decay  $\epsilon$  as the agent learns more

4. But still maintain a small exploration

*GLIE - Greedy in the Limit with Infinite Exploration (GLIE) means that the behavior policies are required to become greedy (no exploration) in the limit of an online learning setting where the agent has gathered an infinite amount of experience*



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### Algorithm 11: First-Visit Constant- $\alpha$ (GLIE) MC Control

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**Input:** positive integer  $num\_episodes$ , small positive fraction  $\alpha$ , GLIE  $\{\epsilon_i\}$

**Output:** policy  $\pi$  ( $\approx \pi_*$  if  $num\_episodes$  is large enough)

Initialize  $Q$  arbitrarily (e.g.,  $Q(s, a) = 0$  for all  $s \in \mathcal{S}$  and  $a \in \mathcal{A}(s)$ )

**for**  $i \leftarrow 1$  **to**  $num\_episodes$  **do**

$\epsilon \leftarrow \epsilon_i$

$\pi \leftarrow \epsilon\text{-greedy}(Q)$

    Generate an episode  $S_0, A_0, R_1, \dots, S_T$  using  $\pi$

**for**  $t \leftarrow 0$  **to**  $T - 1$  **do**

**if**  $(S_t, A_t)$  is a first visit (with return  $G_t$ ) **then**

$Q(S_t, A_t) \leftarrow Q(S_t, A_t) + \alpha(G_t - Q(S_t, A_t))$

**end**

*$\alpha$  Mean*

**end**

*$\alpha = 0$ , never learns*

**return**  $\pi$

*$\alpha = 1$ , never remembers !*

*$\alpha = \text{small, larger history, learns slowly}$*

*$\alpha = \text{large, focuses more on recent experience, but potentially difficult to converge}$*



# Hands On #2 – Monte Carlo

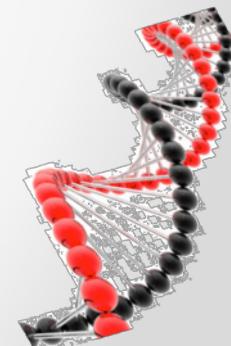
## Goal:

- Implement Monte Carlo
- Explore different policies solving OpenAI Gym : FrozenLake

## Steps:

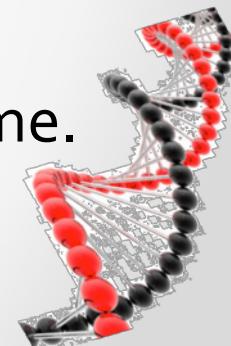
Notebook : Monte\_Carlo\_01.ipynb

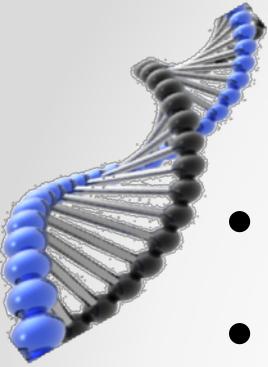
1. Program Monte Carlo – 1<sup>st</sup> Visit or every visit
2. Run the code and understand how it all comes together
3. How is the exploration policy implemented ?
4. How do we finally get the learned policy from the agent ?
5. Does it correspond to our deterministic policy ?



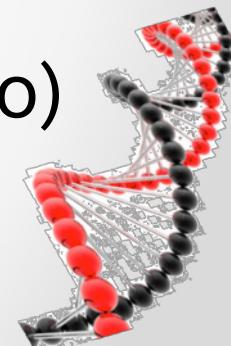


# Points to Ponder

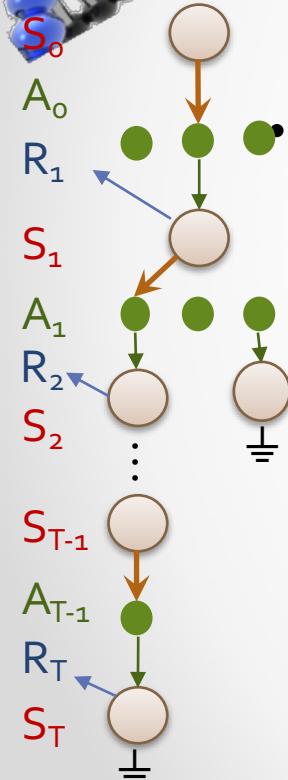
1. There are different ways of decaying  $\epsilon$ 
    - o Or we could just keep  $\epsilon = 1$ , making it uniformly random; but this won't work.  
We will see some interesting results
  2. GLIE – decay  $\epsilon$  as decreasing function of episodes
  3. Exponentially decay  $\epsilon$ 
    - o The  $\epsilon$  decay is to incorporate the learning & make the action more deterministic
  4. We could use softmax & keep the policy constant i.e. weighted random.
    - o As it learns, its belief of the grid world changes and that shows up in the preferences
  5. After 1,000,000 episodes, it usually wins all the time.
    - o I had the  $\epsilon_{\min} = 0.1$ . Probably it should be reduced
- 



# TD

- Temporal Difference Algorithm
  - Motivation
    - Monte Carlo requires full episodes
    - MC has high Variance (but low Bias)
    - MC : Slow to converge
    - MC : Easy to understand
  - So instead of waiting for a full episode, update the values after every step – TD( $\alpha$ ) or every  $n$  steps – TD( $\lambda$ )
- 

# TD vs. MC



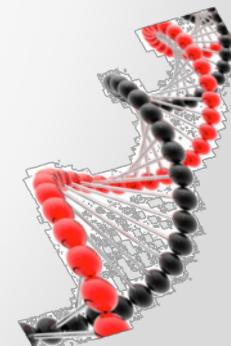
- MC :  $Q(S_t, A_t) = Q(S_t, A_t) + \alpha(G_t - Q(S_t, A_t))$

We observe from a full episode & update all

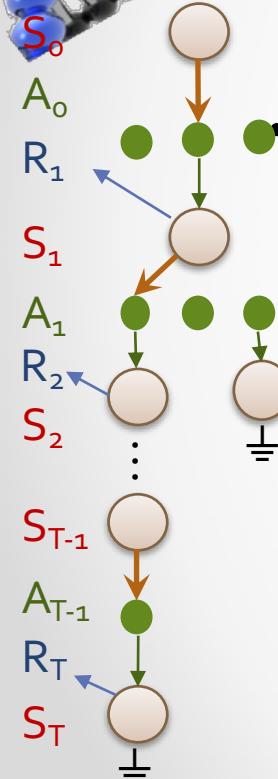
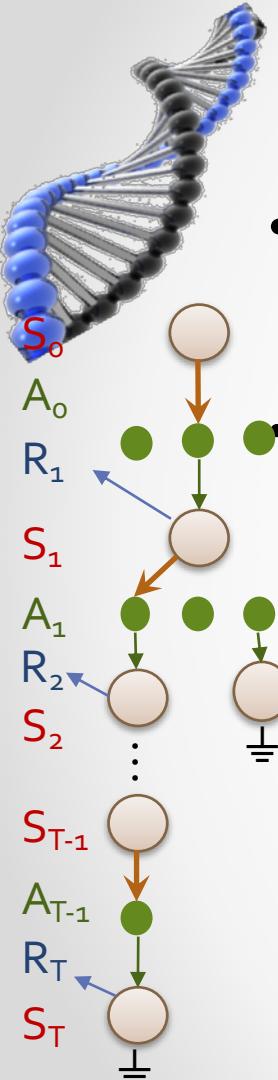
- TD :  $Q(S_t, A_t) = Q(S_t, A_t) + \alpha(R_{t+1} + \gamma Q(S_{t+1}, A_{t+1}) - Q(S_t, A_t))$

$R_{t+1} + \gamma Q(S_{t+1}, A_{t+1})$  TD Target = Alternate Estimate  
 $- Q(S_t, A_t)$  Current Estimate  
TD Error

- TD Target
- TD Error
- At every timestep, so we have  $R_{t+1}$  not  $G_t$
- We bootstrap  $Q(S_{t+1}, A_{t+1})$ , but as we take more steps and more episodes it all converges
- TD learns from incomplete episodes by bootstrapping
- TD lends itself to function approximation
  - And scale to large state space
- Remember, we have to select  $S_{t+1}$  &  $A_{t+1}$ 
  - That is policy & more later



# TD vs. MC



- 

$$\text{MC} : Q(S_t, A_t) = Q(S_t, A_t) + \alpha(G_t - Q(S_t, A_t))$$



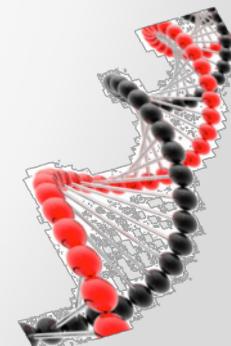
We observe from a full episode & update all

- 

$$\text{TD} : Q(S_t, A_t) = Q(S_t, A_t) + \alpha(R_{t+1} + \gamma Q(S_{t+1}, A_{t+1}) - Q(S_t, A_t))$$

- TD Target
- TD Error

- At every timestep, so we have  $R_{t+1}$  not  $G_t$
- We bootstrap  $Q(S_{t+1}, A_{t+1})$ , but as we take more steps and more episodes it all converges
- TD learns from incomplete episodes by bootstrapping
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- Remember, we have to select  $S_{t+1}$  &  $A_{t+1}$ 
  - That is policy & more later

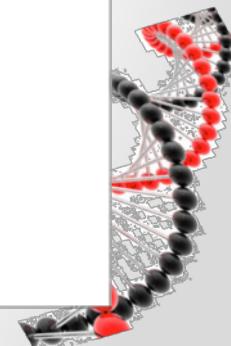




# TD Intuition from Sutton Book/D.SLiver

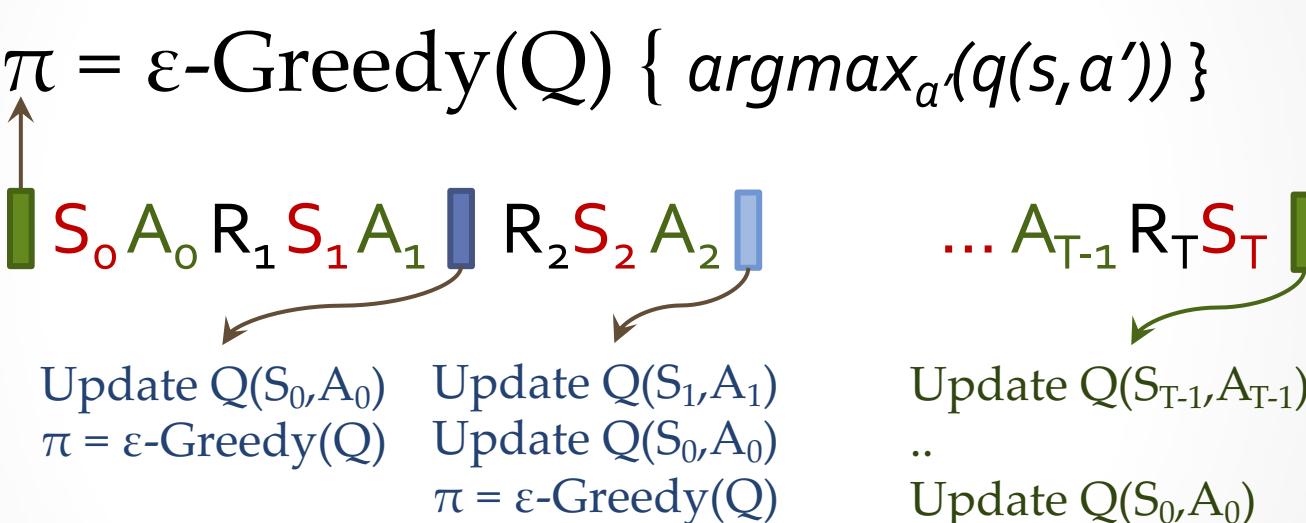
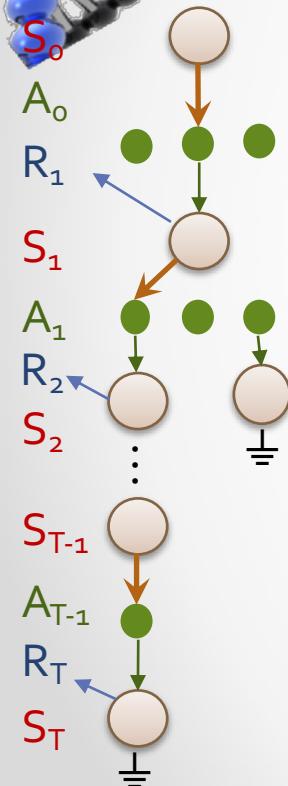
## Driving Home Example

State	Elapsed Time (minutes)	Predicted Time to Go	Predicted Total Time
leaving office	0	30	30
reach car, raining	5	35	40
exit highway	20	15	35
behind truck	30	10	40
home street	40	3	43
arrive home	43	0	43



# SARSA(0)

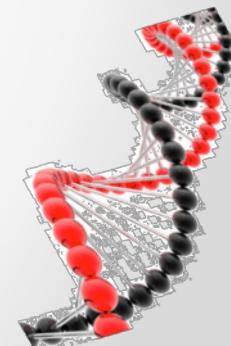
- Initialize  $Q(s,a) \forall s \in \mathbb{S}, a \in \mathbb{A}$
- $\pi = \varepsilon\text{-Greedy}(Q) \{ \operatorname{argmax}_a(q(s,a')) \}$



*Update Rule:*

$$Q(S_t, A_t) = Q(S_t, A_t) + \alpha(R_{t+1} + \gamma Q(S_{t+1}, A_{t+1}) - Q(S_t, A_t))$$

*$A_{t+1}$  selected using  $\varepsilon\text{-Greedy}(Q)$*



---

**Algorithm 13:** Sarsa

---

**Input:** policy  $\pi$ , positive integer  $num\_episodes$ , small positive fraction  $\alpha$ , GLIE  $\{\epsilon_i\}$

**Output:** value function  $Q$  ( $\approx q_\pi$  if  $num\_episodes$  is large enough)

Initialize  $Q$  arbitrarily (e.g.,  $Q(s, a) = 0$  for all  $s \in \mathcal{S}$  and  $a \in \mathcal{A}(s)$ , and  $Q(terminal-state, \cdot) = 0$ )

**for**  $i \leftarrow 1$  **to**  $num\_episodes$  **do**

$\epsilon \leftarrow \epsilon_i$

    Observe  $S_0$

    Choose action  $A_0$  using policy derived from  $Q$  (e.g.,  $\epsilon$ -greedy)

$t \leftarrow 0$

**repeat**

        Take action  $A_t$  and observe  $R_{t+1}, S_{t+1}$

        Choose action  $A_{t+1}$  using policy derived from  $Q$  (e.g.,  $\epsilon$ -greedy)

$Q(S_t, A_t) \leftarrow Q(S_t, A_t) + \alpha(R_{t+1} + \gamma Q(S_{t+1}, A_{t+1}) - Q(S_t, A_t))$

$t \leftarrow t + 1$

**until**  $S_t$  is terminal;

**end**

**return**  $Q$

---



# Hands On #3 – SARSA

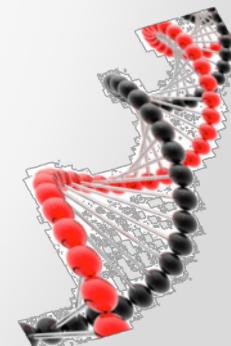
## Goal:

- Implement SARSA for Frozen lake

## Steps:

1. Program SARSA
2. Plot Value

Skipping - we will work  
on  $SARSA_{\max}$  next





# Q-Learning

SARSA Update Rule:

$$Q(S_t, A_t) = Q(S_t, A_t) + \alpha( R_{t+1} + \gamma Q(S_{t+1}, A_{t+1}) - Q(S_t, A_t) )$$

$Q(S_{t+1}, A_{t+1})$  : Selected using  $\epsilon$ -Greedy( $Q$ ) for update

$A_{t+1}$  : Selected using  $\epsilon$ -Greedy( $Q$ ) for evaluation

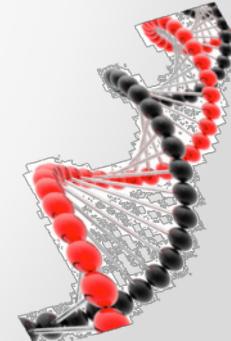
Q Learning Update Rule:

$$Q(S_t, A_t) = Q(S_t, A_t) + \alpha( R_{t+1} + \gamma \max_{a \in \mathbb{A}} Q(S_{t+1}, a) - Q(S_t, A_t) )$$

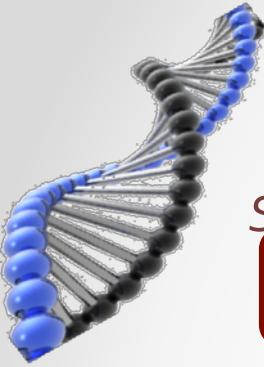
$\max_{a \in \mathbb{A}} Q(S_{t+1}, a)$  : Selected using Greedy( $Q$ ) for update

$A_{t+1}$  : Selected using  $\epsilon$ -Greedy( $Q$ ) for evaluation

- SARSA : Behavior = Target  $\mapsto$  On-Policy
- Q-Learning : Behavior  $\neq$  Target  $\mapsto$  Off-Policy
- *Learn Optimal policy while following exploratory policy*
- *Reuse data collected/Experience Replay/Prioritized Replay*



# Q-Learning



SARSA Update Rule:

$$Q(S_t, A_t) = Q(S_t, A_t) + \alpha( R_{t+1} + \gamma Q(S_{t+1}, A_{t+1}) - Q(S_t, A_t) )$$

$Q(S_{t+1}, A_{t+1})$  : Selected using  $\epsilon$ -Greedy( $Q$ ) for update

$A_{t+1}$  : Selected using  $\epsilon$ -Greedy( $Q$ ) for evaluation

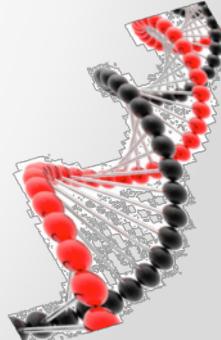
Q Learning Update Rule:

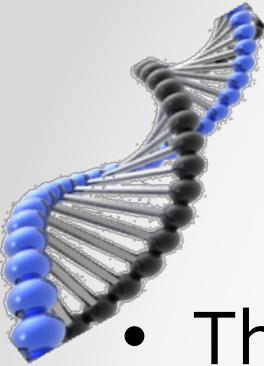
$$Q(S_t, A_t) = Q(S_t, A_t) + \alpha( R_{t+1} + \gamma \max_{a \in \mathbb{A}} Q(S_{t+1}, a) - Q(S_t, A_t) )$$

$\max_{a \in \mathbb{A}} Q(S_{t+1}, a)$  : Selected using Greedy( $Q$ ) for update

$A_{t+1}$  : Selected using  $\epsilon$ -Greedy( $Q$ ) for evaluation

- SARSA : Behavior = Target  $\mapsto$  On-Policy
- Q-Learning : Behavior  $\neq$  Target  $\mapsto$  Off-Policy
- *Learn Optimal policy while following exploratory policy*
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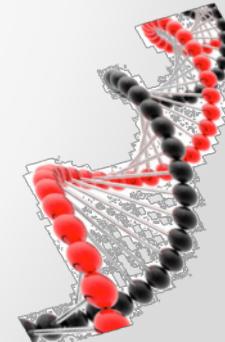




# Quiz



- This Algorithm implements TD(0)
  - What is ?
- Q-Learning in terms of SARSA
  - What is ?
- This algorithm learns the best exploratory policy
  - What is ?
- This algorithm learns the optimum policy
  - What is ?

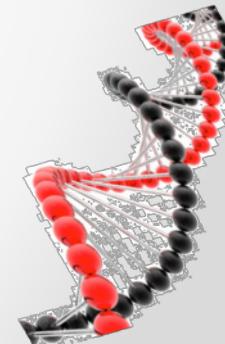




# Quiz



- This Algorithm implements TD(0)
  - What is SARSA ?
- Q-Learning in terms of SARSA
  - What is  $SARSA_{max}$  ?
- This algorithm learns the best exploratory policy
  - What is SARSA ?
- This algorithm learns the optimum policy
  - What is Q-Learning ?



---

**Algorithm 14:** Sarsamax (Q-Learning)

**Input:** policy  $\pi$ , positive integer  $\text{num\_episodes}$ , small positive fraction  $\alpha$ , GLIE  $\{\epsilon_i\}$

**Output:** value function  $Q$  ( $\approx q_\pi$  if  $\text{num\_episodes}$  is large enough)

Initialize  $Q$  arbitrarily (e.g.,  $Q(s, a) = 0$  for all  $s \in \mathcal{S}$  and  $a \in \mathcal{A}(s)$ , and  $Q(\text{terminal-state}, \cdot) = 0$ )

**for**  $i \leftarrow 1$  **to**  $\text{num\_episodes}$  **do**

$\epsilon \leftarrow \epsilon_i$

  Observe  $S_0$

$t \leftarrow 0$

**repeat**

    Choose action  $A_t$  using policy derived from  $Q$  (e.g.,  $\epsilon$ -greedy)

    Take action  $A_t$  and observe  $R_{t+1}, S_{t+1}$

$Q(S_t, A_t) \leftarrow Q(S_t, A_t) + \alpha(R_{t+1} + \gamma \max_a Q(S_{t+1}, a) - Q(S_t, A_t))$

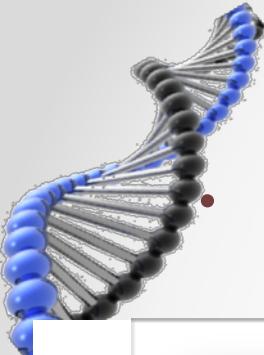
$t \leftarrow t + 1$

**until**  $S_t$  is terminal;

**end**

**return**  $Q$

---



# Introducing the CartPole

- Balance an Inverted Pendulum by applying force on the cart

1

2

3

4

Num	Observation	Min	Max
0	Cart Position	-2.4	2.4
1	Cart Velocity	-Inf	Inf
2	Pole Angle	~ -41.8°	~ 41.8°
3	Pole Velocity At Tip	-Inf	Inf

Num	Action
0	Push cart to the left
1	Push cart to the right

Solved after 211 episodes. Best 100-episode average reward was 195.27 ± 1.53. (CartPole-v0 is considered "solved" when the agent obtains an average reward of at least 195.0 over 100 consecutive episodes.)

Episodes to solve: 211   Total episodes: 500   Solved: ✓   Time to solve: 83s

Download   Tweet

State:  $\{x, \dot{x}, \theta, \dot{\theta}\}$

2 Discrete Actions: Apply force to cart left/right

Rewards: +1 for each step

<https://gym.openai.com/envs/CartPole-v0/>

<https://github.com/openai/gym/wiki/CartPole-v0>





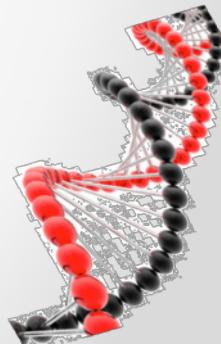
# Hands On #4 – Q Learning

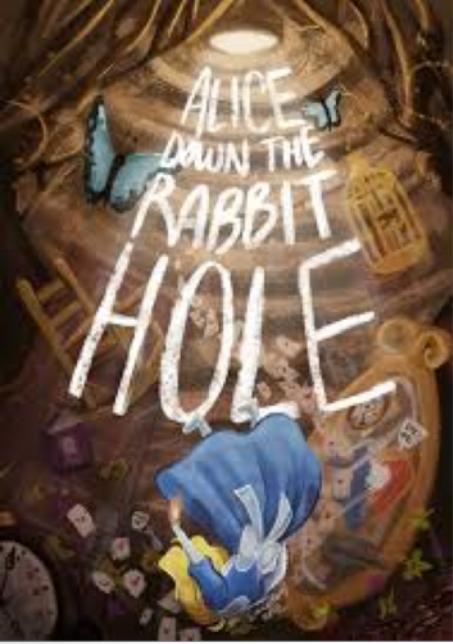
## Goal:

- Introduce the CartPole Environment
  - *More complex, Continuous*
- Implement Q-Learning for digitized CartPole
  - *Later we will use function approximation & remove the requirement for digitization*

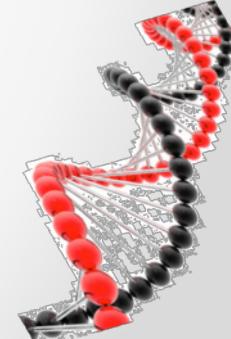
## Steps:

1. Notebook : Q\_Learning\_01.ipynb
2. Get familiar with Cartpole environment
  - np.linspace() and np.digitize() for state space aggregation
3. Program Q Learning – 4 To Dos
4. Track & Plot Metrics to solve Cart Pole

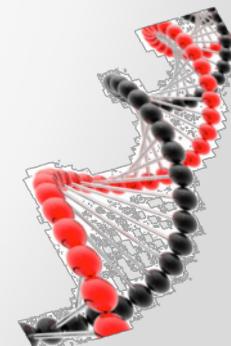
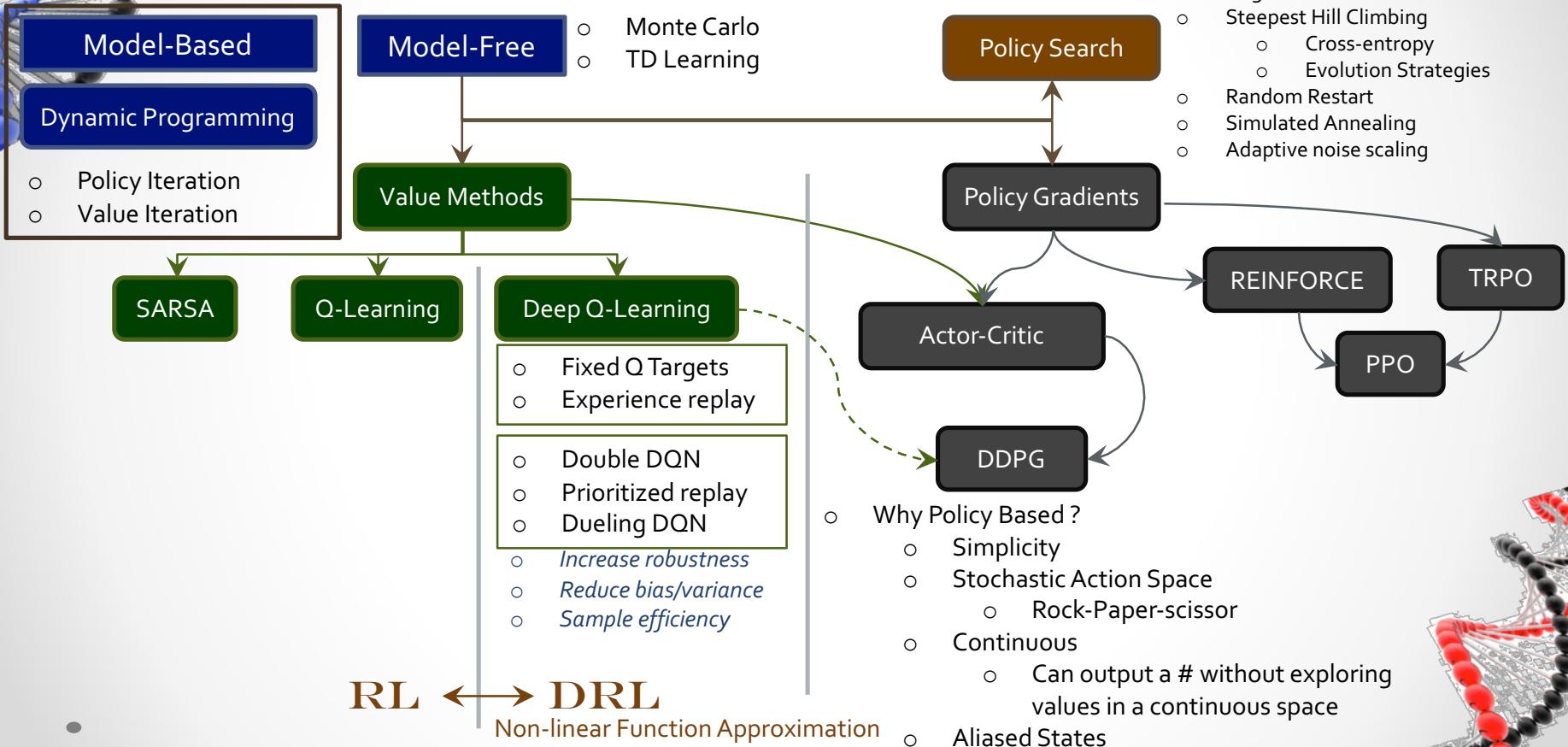
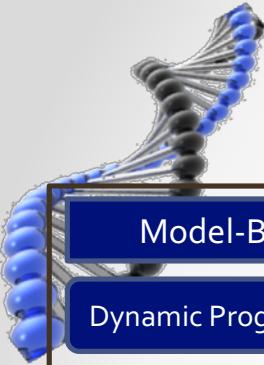




# Down the DRL-Land



# RL Algorithm Taxonomy



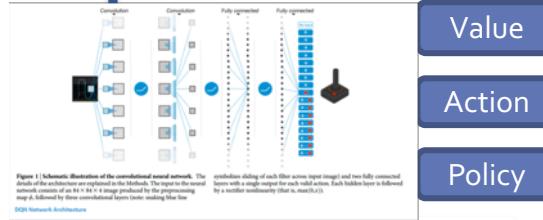


# Deep reinforcement Learning

- We have interesting algorithms, but they won't scale easily for large state spaces or for continuous state spaces
  - For example, GO has possibly  $10^{170}$  states, more than the number of atoms in the observable universe ( $10^{80}$ )
  - We want something that can sample and generalize; *that gets better with more data*
- Fortunately, Reinforcement Learning research has progressed so far that machines are able to win over Go world champions - 10 years ahead of the predicted timeframe !
  - Methodological breakthroughs in Deep Learning !!
- The latest DOTA 5 uses 120,000 CPUs & 256 GPUs to win over human players in a complex strategic game !



# DeepRL Schematic



State

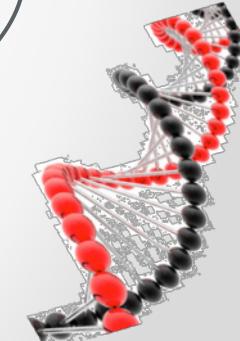
Reward

Agent

Actions

Environment

- We will first look at the simple mechanism
  - Replace our Q-Table with a function approximation ie a Neural Network, to make it work on the top of DL structures
  - Then we can get values, actions or even policies
  - Then we will look at extensions
  - And finally, we will see how these ideas scale to games with video frames, games like Go with huge state spaces and complex semantics



# DQN Intuition

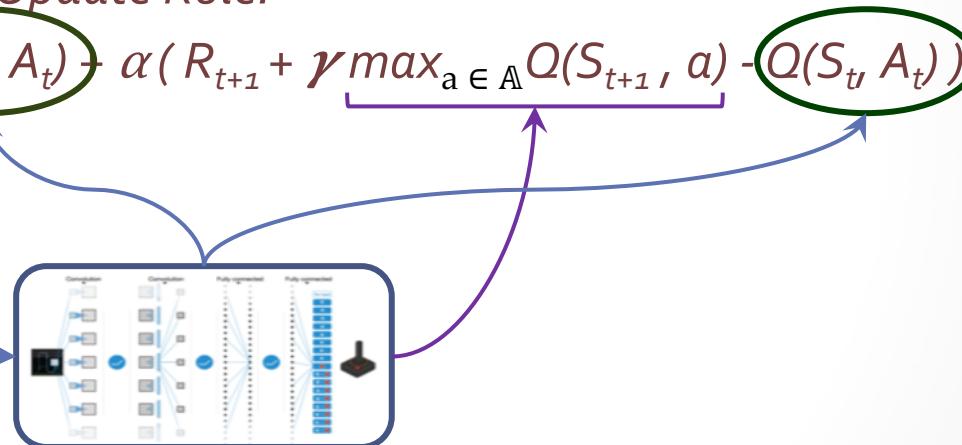
*Q Learning Update Rule:*

$$Q(S_t, A_t) = Q(S_t, A_t) + \alpha(R_{t+1} + \gamma \max_{a \in \mathcal{A}} Q(S_{t+1}, a) - Q(S_t, A_t))$$

*Deep Q Learning Update Rule:*

$$Q(S_t, A_t) = Q(S_t, A_t) + \alpha(R_{t+1} + \gamma \max_{a \in \mathcal{A}} Q(S_{t+1}, a) - Q(S_t, A_t))$$

Please note the direction  
of the arrows

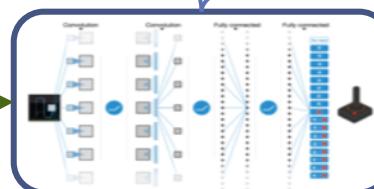


# DQN Intuition

Deep Q Learning Update Rule:

$$Q(S_t, A_t)$$

$$= Q(S_t, A_t) + \alpha (R_{t+1} + \gamma \max_{a \in \mathbb{A}} Q(S_{t+1}, a) - Q(S_t, A_t))$$



$$Y_t = R_{t+1} + \gamma \max_{a \in \mathbb{A}} Q(S_{t+1}, a; \theta_t)$$

Action to get Max next state value = Target

Gradient Descent

$$\theta_{t+1} = \theta_t + \alpha \frac{Y_t - Q(S_t, A_t; \theta_t)}{\text{TD Error}} \frac{\nabla_{\theta} Q(S_t, A_t; \theta_t)}{\text{Gradient}}$$

DQN Parameter changed

TD Error

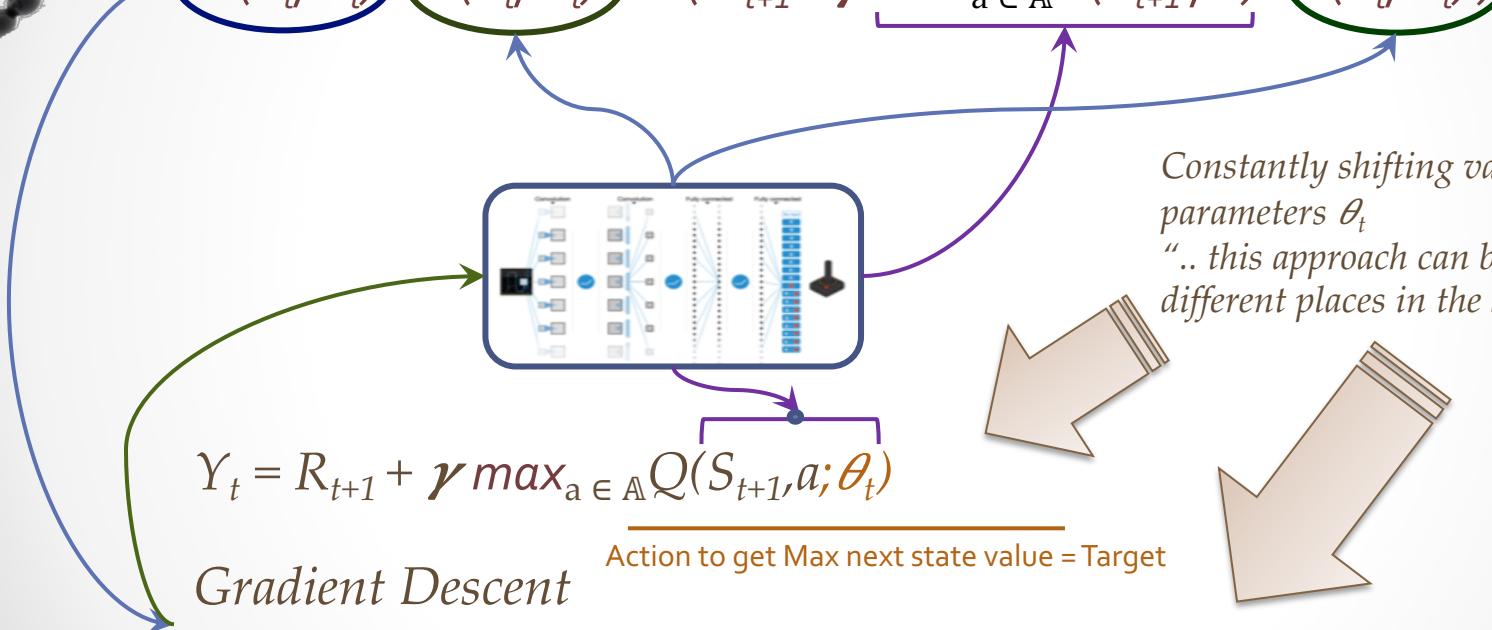
Gradient

# DQN Intuition



## Deep Q Learning Update Rule:

$$Q(S_t, A_t) = Q(S_t, A_t) + \alpha(R_{t+1} + \gamma \max_{a \in \mathcal{A}} Q(S_{t+1}, a) - Q(S_t, A_t))$$

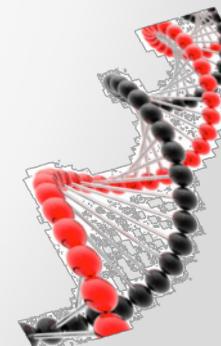


Constantly shifting values with the same parameters  $\theta_t$   
 “.. this approach can build large errors at different places in the state-action space ..”

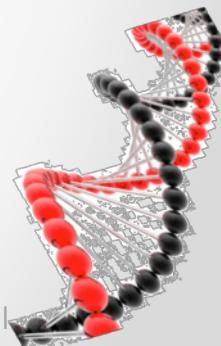
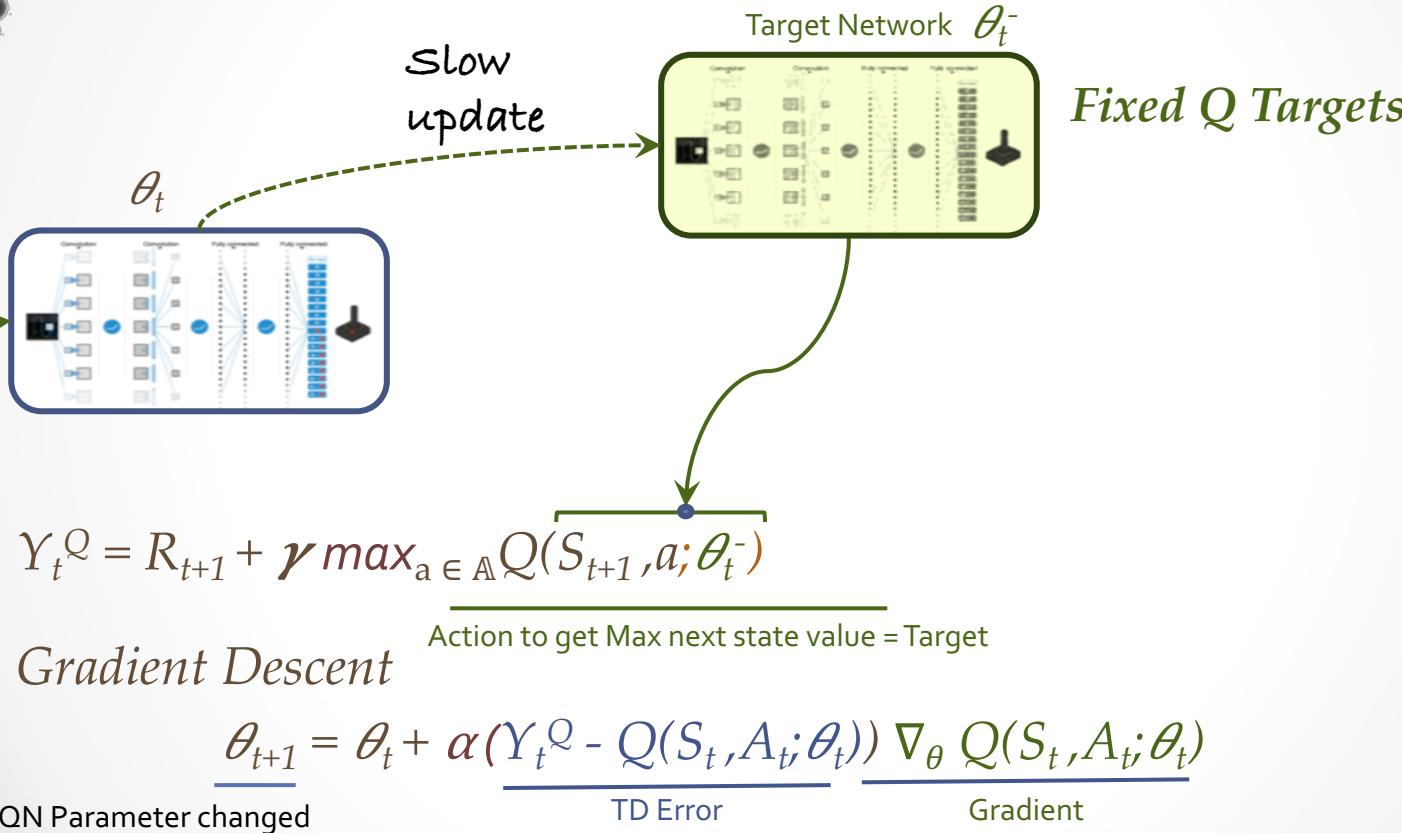
$$Y_t = R_{t+1} + \gamma \max_{a \in \mathbb{A}} Q(S_{t+1}, a; \theta_t)$$

## *Gradient Descent*

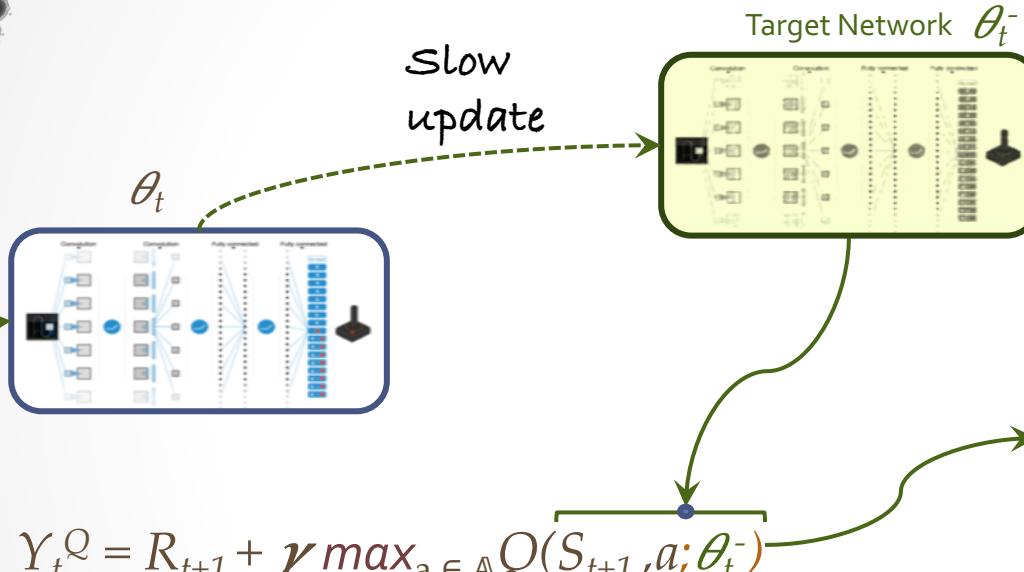
$$\theta_{t+1} = \theta_t + \alpha \frac{(Y_t - Q(S_t, A_t; \theta_t))}{\text{TD Error}} \frac{\nabla_{\theta} Q(S_t, A_t; \theta_t)}{\text{Gradient}}$$



# DQN Intuition



# DQN Intuition



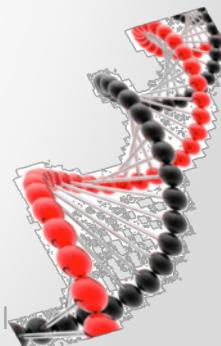
*Gradient Descent*

$$\underline{\theta_{t+1}} = \theta_t + \alpha \underline{(Y_t^Q - Q(S_t, A_t; \theta_t))} \underline{\nabla_{\theta} Q(S_t, A_t; \theta_t)}$$

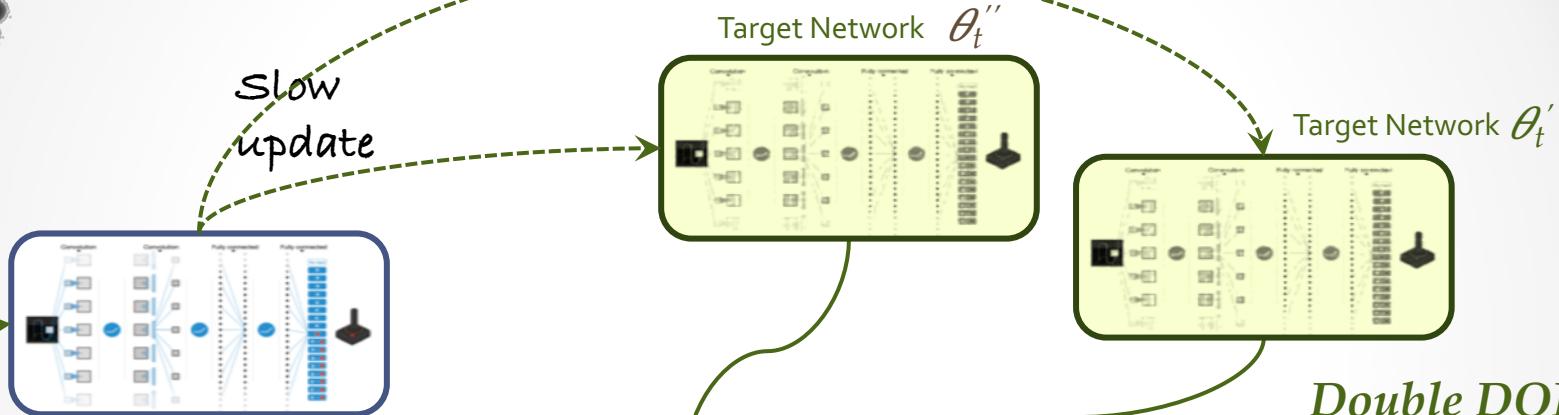
DQN Parameter changed      TD Error      Gradient

*Fixed Q Targets*

<https://arxiv.org/abs/1509.06461>  
Over estimation (upward) Bias:  
 Over optimism w.r.t estimation errors - Selection & Evaluation with the same network  $\theta_t^-$   
 Solution : Double DQN



# DQN Intuition



$$Y_t^Q = R_{t+1} + \gamma Q(S_{t+1}, \text{argmax}_{a \in \mathcal{A}} Q(S_{t+1}, a; \theta_t'); \theta_t'')$$

Action to get Max next state value = Target

Gradient Descent

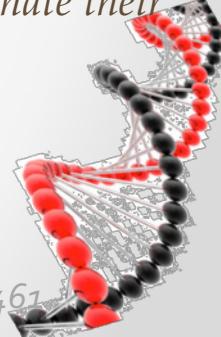
$$\theta_{t+1} = \theta_t + \alpha \frac{(Y_t^Q - Q(S_t, A_t; \theta_t))}{\text{TD Error}} \nabla_{\theta} Q(S_t, A_t; \theta_t)$$

DQN Parameter changed

**Double DQN**

Selection & Evaluation in two separate target networks,  $\theta_t'$  and  $\theta_t''$  which alternate their roles

Double DQN paper <https://arxiv.org/abs/1509.06461>



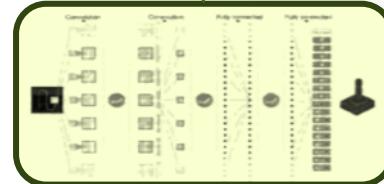
# DQN Intuition



Slow update

Target Network  $\theta_t''$

Target Network  $\theta_t'$



**Double DQN**

Selection & Evaluation in two separate target networks,  $\theta_t'$  and  $\theta_t''$  which alternate their roles

$$Y_t^Q = R_{t+1} + \gamma Q(S_{t+1}, \text{argmax}_{a \in \mathcal{A}} Q(S_{t+1}, a; \theta_t'); \theta_t'')$$

Action to get Max next state value = Target

Gradient Descent

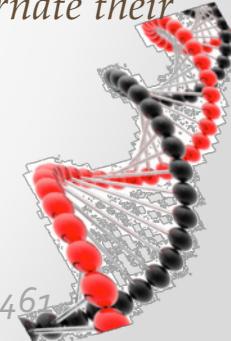
$$\theta_{t+1} = \theta_t + \alpha (Y_t^Q - Q(S_t, A_t; \theta_t)) \nabla_{\theta} Q(S_t, A_t; \theta_t)$$

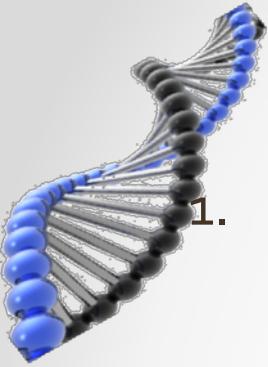
DQN Parameter changed

TD Error

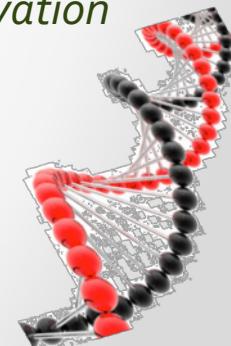
Gradient

Double DQN paper <https://arxiv.org/abs/1509.06461>





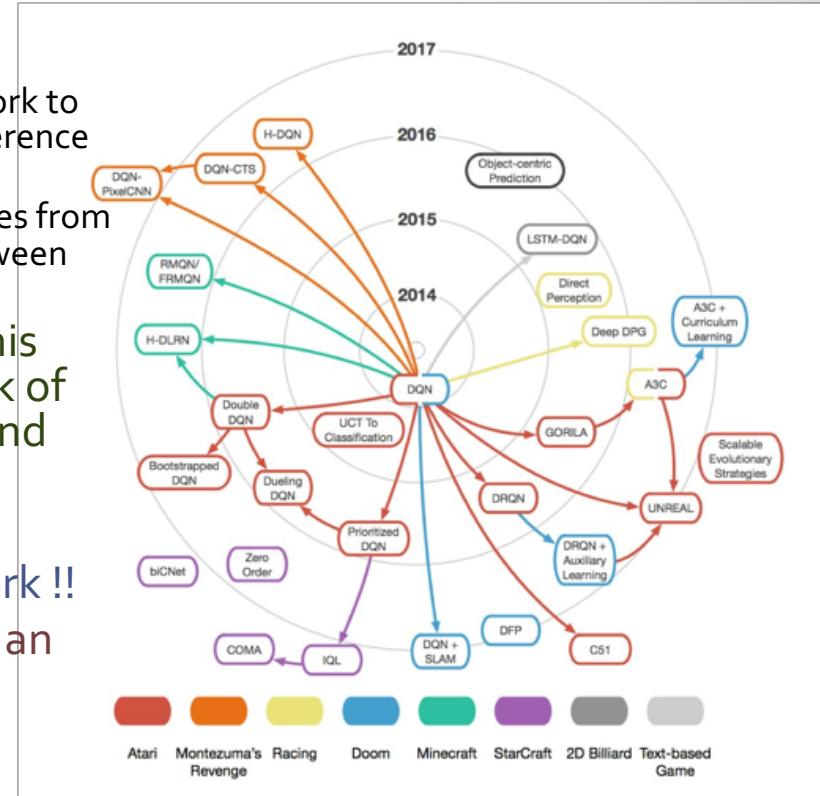
# Experience Replay

1. Most optimization algorithms assume that the samples are independently and identically distributed(i.i.d).
    - Obviously, when the samples are generated from exploring sequentially in an environment this assumption no longer holds
  2. To make efficient use of hardware optimizations, it is essential to learn in minibatches, rather than online
- Solution : Experience Replay
    - Buffer the  $(s_t, a_t, r_t, s_{t+1})$  tuple in a "*finite-sized circular cache*"
    - Sample a mini batch of appropriate size & train !
    - *"randomizes over the data, thereby removing correlations in the observation sequence and smoothing over changes in the data distribution"*
    - Decorrelate & Data efficiency
    - Prevent Catastrophic Forgetting
- 



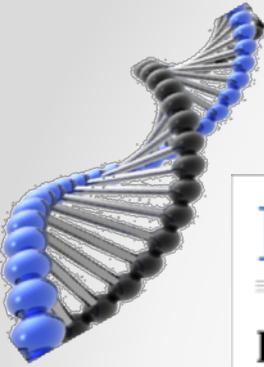
# A word on the evolution

- DQN has two main innovations:
  1. The network is trained with a target Q network to give consistent targets during temporal difference backups
  2. The network is trained off-policy with samples from a replay buffer to minimize correlations between samples
- It looks a lot easier when we look from this side, but this is the result of a good chunk of research by David Silver, Volod, Dennis and team ...
- Am sure they spent tons of hours on mechanisms and schemes that didn't work !!
- And, I think, this work paved the way for an explosion of research and pragmatic applications based on Reinforcement Learning



<https://arxiv.org/abs/1708.07902>

<http://fzruniverse.life/2018/03/24/Modular-Architecture-for-Implementing-RL-Agent/>



# Deep Q Networks

## LETTER

doi:10.1038/nature14236

### Human-level control through deep reinforcement learning

Volodymyr Mnih<sup>1\*</sup>, Koray Kavukcuoglu<sup>1\*</sup>, David Silver<sup>1\*</sup>, Andrei A. Rusu<sup>1</sup>, Joel Veness<sup>1</sup>, Marc G. Bellemare<sup>1</sup>, Alex Graves<sup>1</sup>, Martin Riedmiller<sup>1</sup>, Andreas K. Fidjeland<sup>1</sup>, Georg Ostrovski<sup>1</sup>, Stig Petersen<sup>1</sup>, Charles Beattie<sup>1</sup>, Amir Sadik<sup>1</sup>, Ioannis Antonoglou<sup>1</sup>, Helen King<sup>1</sup>, Dharshan Kumaran<sup>1</sup>, Daan Wierstra<sup>1</sup>, Shane Legg<sup>1</sup> & Demis Hassabis<sup>1</sup>

- We tested this agent on the challenging domain of classic Atari 2600 games
- We demonstrate that the deep Q-network agent, receiving only the pixels and the game score as inputs, was able to achieve a professional human level across a set of 49 games
- *Same algorithm, network architecture and hyperparameters*



<https://storage.googleapis.com/deepmind-media/dqn/DQNNaturePaper.pdf>

[https://eecs.wsu.edu/~taylorm/17\\_580/Yunshu\\_DQNpresentation\\_10102016.pdf](https://eecs.wsu.edu/~taylorm/17_580/Yunshu_DQNpresentation_10102016.pdf)

**Input:** the pixels and the game score  
**Output:** Q action value function (from which we obtain a policy and select actions)

initialize replay memory  $D$

initialize action-value function  $Q$  with random weight  $\theta$

initialize target action-value function  $\hat{Q}$  with weights  $\theta^- = \theta$

**for** episode = 1 to  $M$  **do**

    initialize sequence  $s_1 = \{x_1\}$  and preprocessed sequence  $\phi_1 = \phi(s_1)$

**for**  $t = 1$  to  $T$  **do**

        following  $\epsilon$ -greedy policy, select  $a_t = \begin{cases} \text{a random action} & \text{with probability } \epsilon \\ \arg \max_a Q(\phi(s_t), a; \theta) & \text{otherwise} \end{cases}$

        execute action  $a_t$  in emulator and observe reward  $r_t$  and image  $x_{t+1}$

        set  $s_{t+1} = s_t, a_t, x_{t+1}$  and preprocess  $\phi_{t+1} = \phi(s_{t+1})$

        store transition  $(\phi_t, a_t, r_t, \phi_{t+1})$  in  $D$

        // experience replay

        sample random minibatch of transitions  $(\phi_j, a_j, r_j, \phi_{j+1})$  from  $D$

        set  $y_j = \begin{cases} r_j & \text{if episode terminates at step } j + 1 \\ r_j + \gamma \max_{a'} \hat{Q}(\phi_{j+1}, a'; \theta^-) & \text{otherwise} \end{cases}$

        perform a gradient descent step on  $(y_j - Q(\phi_j, a_j; \theta))^2$  w.r.t. the network parameter  $\theta$

        // periodic update of target network

        in every  $C$  steps, reset  $\hat{Q} = Q$ , i.e., set  $\theta^- = \theta$

**end**

**end**

Sample

Learn

<https://arxiv.org/pdf/1810.06339.pdf>

Minh Paper : <https://arxiv.org/abs/1602.01783>

**Algorithm 8:** Deep Q-Network (DQN), adapted from Mnih et al. (2015)



UDACITY Explore ▾ Cata

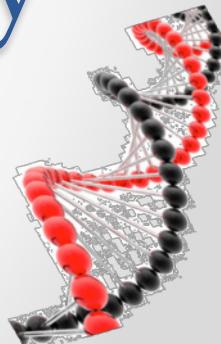
[Home](#) > [Catalog](#) > [Intro to Deep Learning with PyTorch](#)

FREE COURSE

Intro to Deep Learning  
with PyTorch  
by [facebook Artificial Intelligence](#)

Use PyTorch to implement your first deep neural network

A detour – to DL machinery  
with *pytorch*



# Introducing PYTORCH

Adam Paszke, Sam Gross, Soumith Chintala, Francisco Massa, Adam Lerer, James Bradbury, Gregory Chanan, Trevor Killeen, Zeming Lin, Natalia Gimelshein, Christian Sarofeen, Alban Desmaison, Andreas Kopf, Edward Yang, Zach Devito, Martin Raison, Alykhan Tejani, Sasank Chilamkurthy

• Origin <https://classroom.udacity.com/courses/ud188/>

- Started early, but matured at FAIR –
- Initially Soumith, Adam Paszke & Sam Gross
- slowly opened for “power users”
- Adopted by the “fun, long tail” (research) people, not the enterprise crowd ... so the core design is (more) research-friendly ... pythonic debugging capabilities
- But also is production-ready .. Function annotation ... IR export to C++ run-time or any other VM and so forth
- Hybrid frontend – parts of the model compiled – like the core RESNET, but leave the other parts not compiled
- JIT compiler – long term goal is to make the model faster leveraging hardware, optimizing fusing operations and so forth



- We exist!
- Launched Jan 2017
- An imperative programming model
- Eager evaluation (unlike Dynet which is lazy)
- Simplicity as a philosophy

- “Large part of pytorch live in C++
- Whatever user facing is in python ...”
- Giving it flexibility (“hackable”) and performance ...

# PYTORCH

<http://pytorch.org>

Released Jan 2017

500,000+ downloads

2700+ community repos

17,200+ user posts

351 contributors

facebook



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INSTITUT DES SCIENCES ET TECHNOLOGIES  
GRADUATE INSTITUTE OF TECHNOLOGY

Carnegie Mellon University

UNIVERSITE PARIS-Saclay, CURIE

Digital Reasoning

Stanford University

UNIVERSITY OF OXFORD

NYU

Inria

ENS  
ÉCOLE NORMALE SUPÉRIEURE

EPFL  
ÉCOLE POLYTECHNIQUE  
FÉDÉRALE DE LAUSANNE

Berkeley  
UNIVERSITY OF CALIFORNIA

UBER



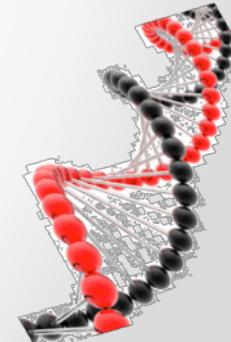
# Code Review – pytorch DL Machinery

## Goal:

- Get familiar with a basic pytorch neural network

## Steps:

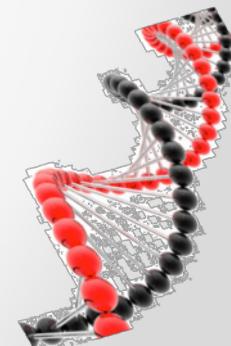
1. Define Network, loss & optimizer
2. Get Dataset - MNIST
3. Construct minibatch dataloader
4. Forward pass
5. Calculate error/loss
6. Do backprop
7. Update weights using Gradient Descent
8. Train & Test





# pytorch DL Machinery

- Much simpler and easy to create a network
- Intuitive pythonic interface
- Things to keep in mind
  - Use with `torch.no_grad()` for inferencing
    - Disables autograd which is needed only for backpropagation
  - Use `model.eval()` for testing
    - Disables dropout
    - Can enable dropout by `model.train()`
  - Do `optimizer.zero_grad()` to clear the gradient
    - To reset the accumulation of gradient – **very important !!**
  - Enabling GPU is easy and idiomatic
    - `device = torch.device("cuda" if torch.cuda.is_available() else "cpu")`
    - ..
    - `model.to(device)` **<- Move model to GPU**
    - ..
    - `inputs, labels = inputs.to(device), labels.to(device)` **<- Move data to GPU**
    - ..





# Hands On #5 – Deep Q Learning

## Goal:

- Implement Deep Q-Learning for CartPole
  - No digitization
  - Handle continuous state

## Steps:

1. Notebook : DQN\_o1.ipynb
2. Understand the Deep Q Learning Code
3. Understand DNN implementation in pytorch
4. Metrics to solve Cart Pole
5. Plot Values
6. Answer the quiz in next page



“Confidence is recursive ! You have to come thru a few times to be certain and confident that you can beat it !”



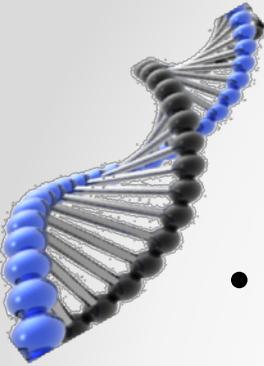


# Quiz



- What is the DQN DNN topology ?
  -
- What is the input size ? Output size ?
  -
- How does the output translate to an action ?
  -
- How is the target network updated ?
  -
- Did it solve the environment ?
  -
- Can it be tuned to solve with lesser number of steps ?
  -

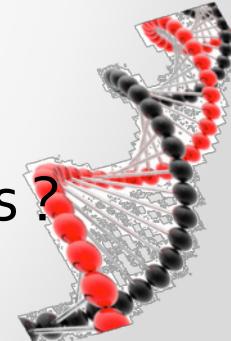


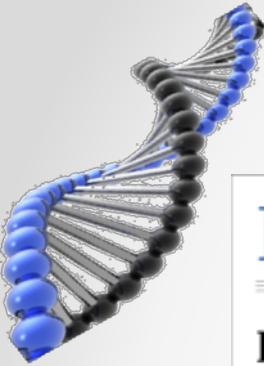


# Quiz



- What is the DQN DNN topology ?
  - FC16-FC2
- What is the input size ? Output size ?
  - Input = 4 (state), output = 2 (actions) – *notice that we get all actions in one shot!*
- How does the output translate to an action ?
  - np.argmax(action\_values,...)
- How is the target network updated ?
  - Soft\_update with  $\tau=0.001$
- Did it solve the environment ?
  - Yep, in ~ 3300 steps, with a particular set of hyperparameters
- Can it be tuned to solve with lesser number of steps ?
  - May be, probably, approximately definitely !





# Deep Q Networks

## LETTER

doi:10.1038/nature14236

### Human-level control through deep reinforcement learning

Volodymyr Mnih<sup>1\*</sup>, Koray Kavukcuoglu<sup>1\*</sup>, David Silver<sup>1\*</sup>, Andrei A. Rusu<sup>1</sup>, Joel Veness<sup>1</sup>, Marc G. Bellemare<sup>1</sup>, Alex Graves<sup>1</sup>, Martin Riedmiller<sup>1</sup>, Andreas K. Fidjeland<sup>1</sup>, Georg Ostrovski<sup>1</sup>, Stig Petersen<sup>1</sup>, Charles Beattie<sup>1</sup>, Amir Sadik<sup>1</sup>, Ioannis Antonoglou<sup>1</sup>, Helen King<sup>1</sup>, Dharshan Kumaran<sup>1</sup>, Daan Wierstra<sup>1</sup>, Shane Legg<sup>1</sup> & Demis Hassabis<sup>1</sup>

- Hyperparameters
  - Minibatch size = 32
  - Replay buffer = 1 Million
  - Agent history = 4 frames
  - Target Network update frequency = 10,000
  - $\epsilon$  = 1 to 0.1 ; linearly annealed in 1 million steps



<https://storage.googleapis.com/deepmind-media/dqn/DQNNaturePaper.pdf>  
[https://eecs.wsu.edu/~taylorm/17\\_580/Yunshu\\_DQNpresentation\\_10102016.pdf](https://eecs.wsu.edu/~taylorm/17_580/Yunshu_DQNpresentation_10102016.pdf)



# Deep Q Learning - Extensions

## Fixed Q Targets – improve stability with Target Networks

- “an iterative update that adjusts the action-values ( $Q$ ) towards target values that are only periodically updated, thereby reducing correlations with the target”

- TD Error clipping to  $[-1,1]$

- Experience replay

- “randomizes over the data, thereby removing correlations in the observation sequence and smoothing over changes in the data distribution”
- Decorrelate & Data efficiency
- Prevent Catastrophic Forgetting

- Prioritized replay

- Pay more attention to interesting experience
- Replying more often transitions from which there is more to learn

- Double DQN

- Dueling DQN

- Noisy nets - add parametric noises to network weights (we will see this later)

- Without  $\epsilon$ -greedy - “Adding noise to a deep network is often equivalent or better than adding noise to an action like that in the  $\epsilon$ -greedy method”

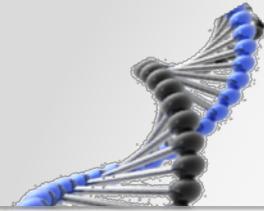
- Rainbow

- To address challenges robustness & stability
- Increase robustness, reduce bias/variance, sample efficiency
- The Integrated Agent – Rainbow !! <https://arxiv.org/abs/1710.02298>

- Another interesting paper : <https://medium.freecodecamp.org/improvements-in-deep-q-learning-dueling-double-dqn-prioritized-experience-replay-and-fixed-58b130cc5682>

- Homework : Can Rainbow solve Pong ? Breakout ?



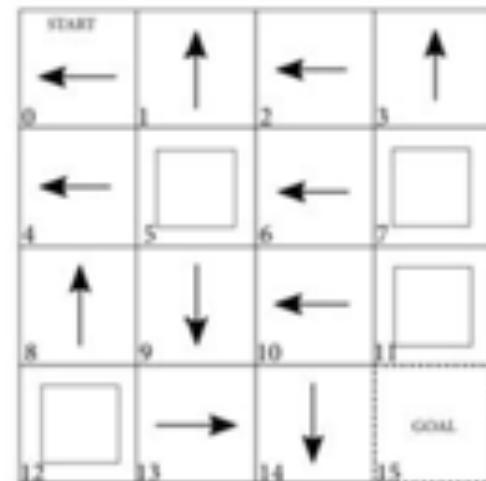


## Hands On #6 – Skating slippery Frozen Lake with DQN

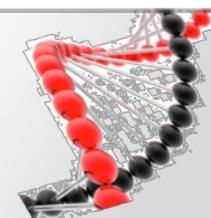
Yes, this is Frozen Lake's optimal policy!

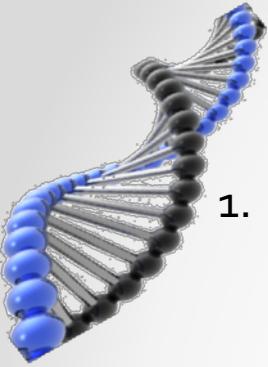
And I wish you at least question the validity of it. How is it possible that in state 14 the optimal action is to go DOWN? Shouldn't it be RIGHT?

Since the Frozen Lake environment stochasticity is so large, it makes it a great example to illustrate the difficulty of sequential decision making under uncertainty of action effects. The fact is, the RIGHT action would send us to state 10, 14 or 15 with equal probability. While DOWN would send us to state 13, 14 or 15. If you think about it, state 13 is preferred to 10 because we can only get to state 15 safely going LEFT in 10, DOWN in 9, RIGHT in 13 and DOWN in 14. On the other hand, going DOWN in state 14 keeps us only a few steps away from 15 regardless of where the environment sends us.

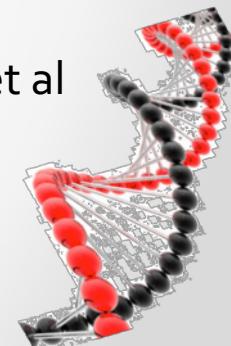


*Homework : See if DQN-Rainbow finds this policy  
Compare with DDPG*



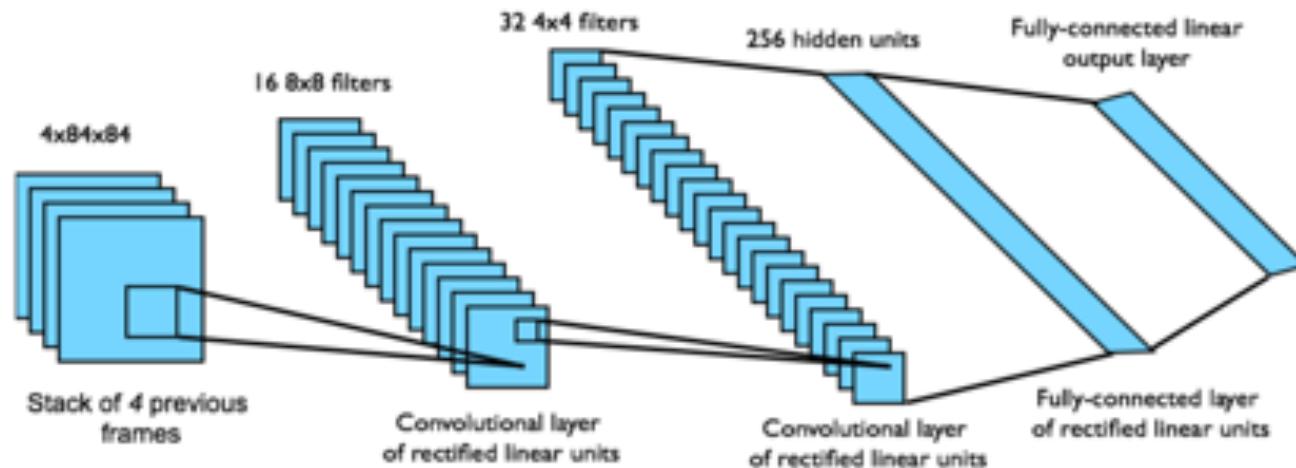


# References

1. Human Level Control Through Deep Reinforcement Learning, Volodymyr Mnih et al <https://deepmind.com/research/publications/human-level-control-through-deep-reinforcement-learning/>
    - o *We demonstrate that the deep Q-network agent, receiving only the pixels and the game score as inputs, was able to surpass the performance of all previous algorithms and achieve a level comparable to that of a professional human games tester across a set of 49 games, using the same algorithm, network architecture and hyperparameters*
  2. Neural Fitted Q Iteration by Martin Riedmiller et al
    - o <https://qiita.com/Rowing0914/items/3d1b9a6ad4fe0a53cf5b>
  3. Deep Reinforcement Learning with Double Q-learning by Hado van Hasselt, Arthur Guez, David Silver
    - o <https://arxiv.org/abs/1509.06461>
  4. Prioritized Experience Replay by Tom Schaul, John Quan, Ioannis Antonoglou, David Silver
    - o <https://arxiv.org/abs/1511.05952>
  5. A Brief Survey of Deep Reinforcement Learning by Kai Arulkumaran et al
    - o <https://arxiv.org/abs/1708.05866>
- 

# DQN in Atari

- End-to-end learning of values  $Q(s, a)$  from pixels  $s$
- Input state  $s$  is stack of raw pixels from last 4 frames
- Output is  $Q(s, a)$  for 18 joystick/button positions
- Reward is change in score for that step



Network architecture and hyperparameters fixed across all games



# Pause & Reflect

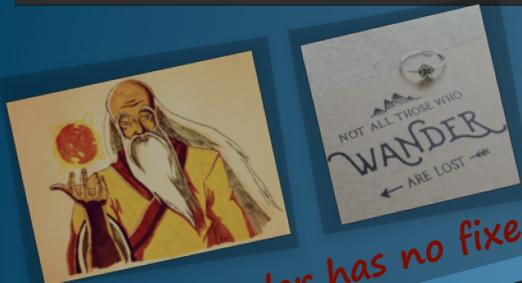


## GPU TECHNOLOGY CONFERENCE

AGENDA ▾ ATTEND ▾ PRESENT ▾ EXHIBIT ▾ MORE ▾

SILICON VALLEY ▾

WORKSHOPS MARCH 17, 2019 | CONFERENCE MARCH 18-21, 2019



"A good traveler has no fixed plans and is not intent on arriving." - Lao Tzu

# Demystifying Deep Reinforcement Learning – Part 2 : Policy Gradients

All observations are my own & do not represent my employer's or anyone else's

krishna sankar  
@ksankar

“ I WOULD LIKE  
TO DIE  
ON MARS.  
JUST NOT ON IMPACT ”

- ELON MUSK -

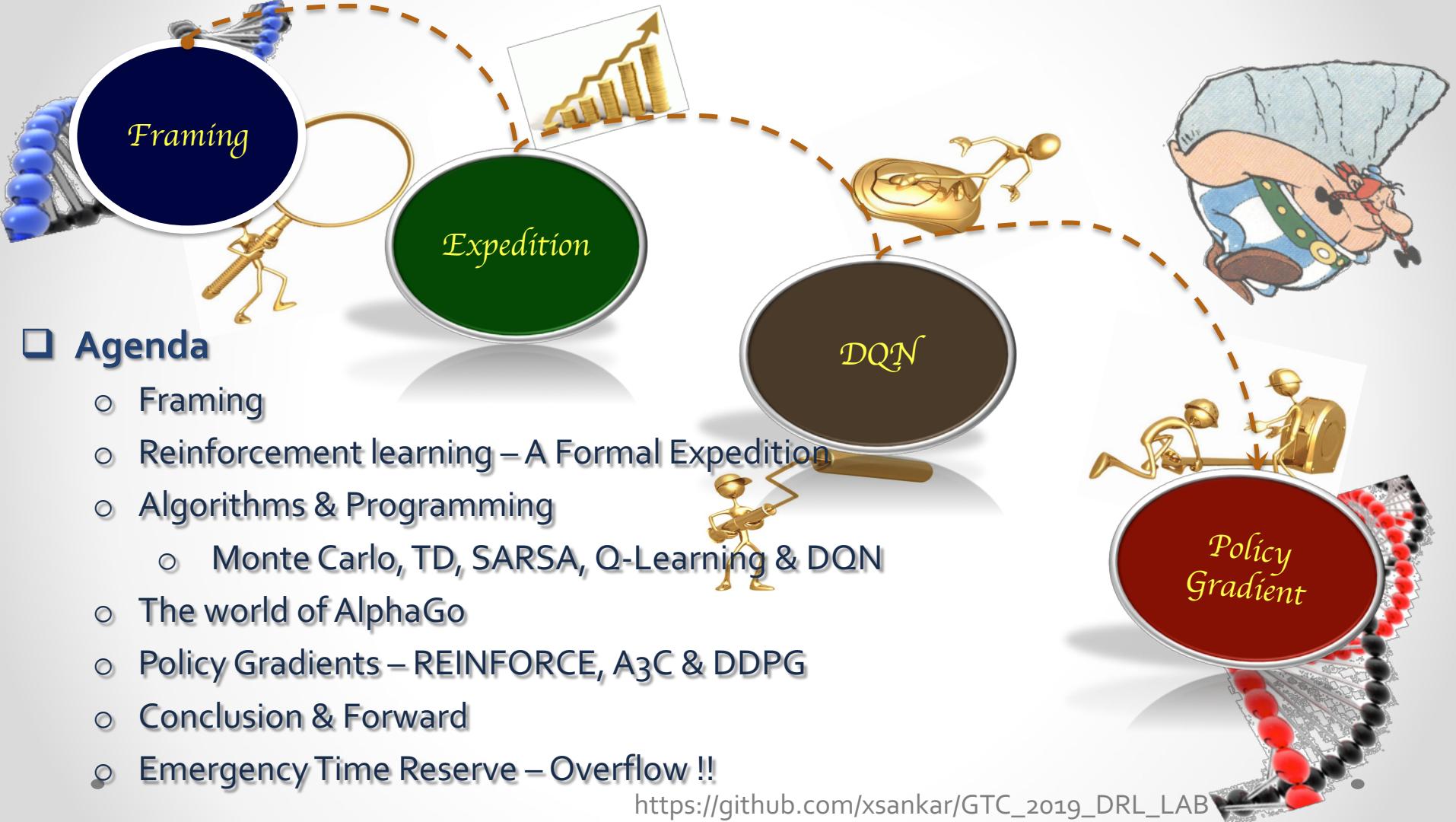


just setting up my twtr

Retweeted by @First30Tweets

21 Mar 06

Reply Retweet Favorite



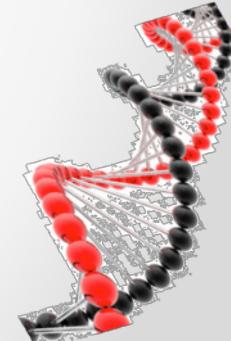
## □ Agenda

- Framing
- Reinforcement learning – A Formal Expedition
- Algorithms & Programming
  - Monte Carlo, TD, SARSA, Q-Learning & DQN
- The world of AlphaGo
- Policy Gradients – REINFORCE, A<sub>3</sub>C & DDPG
- Conclusion & Forward
- Emergency Time Reserve – Overflow !!



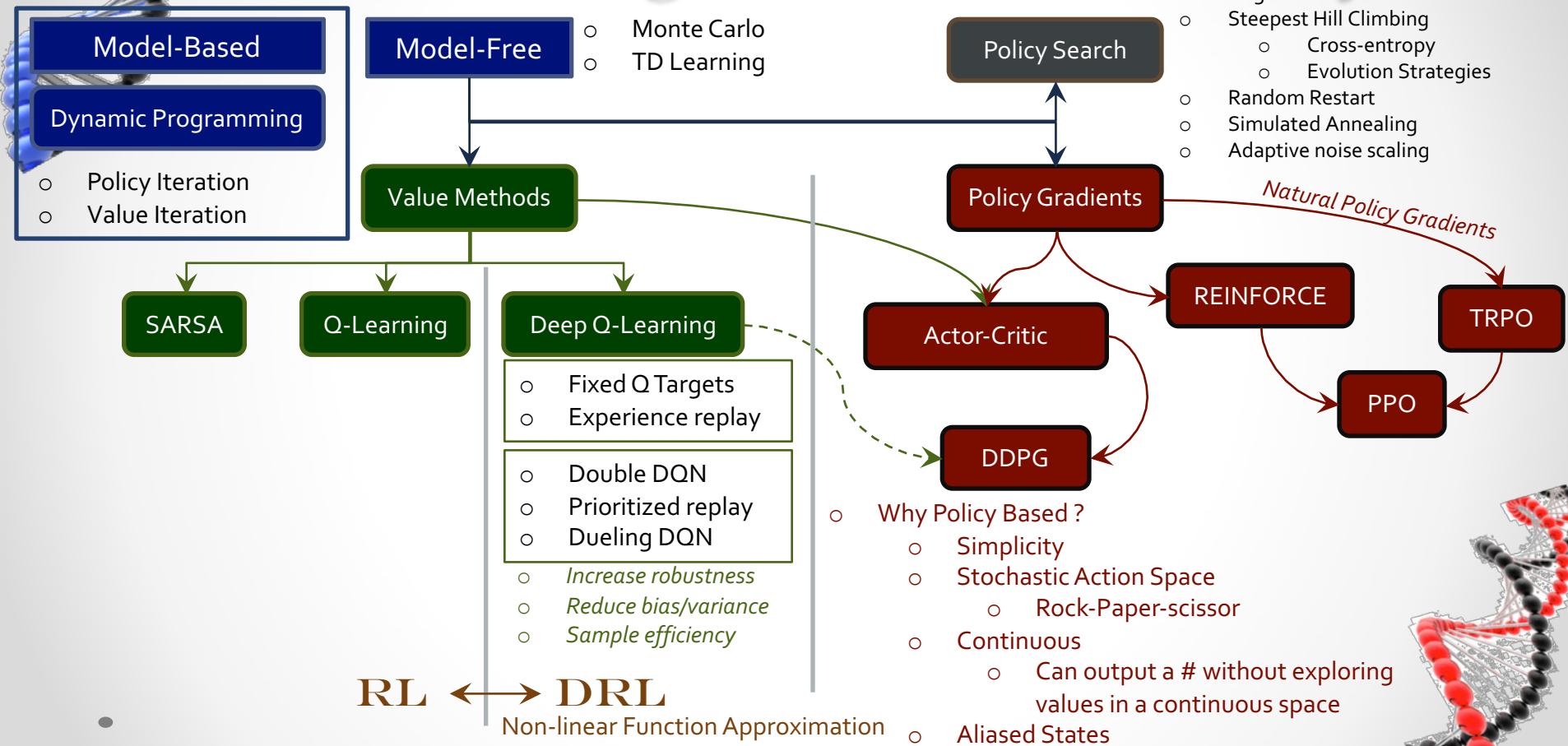
# 5. Policy Gradients

...

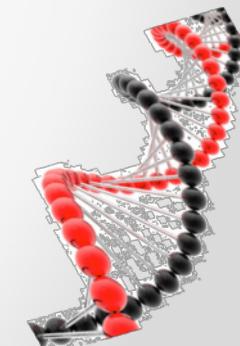
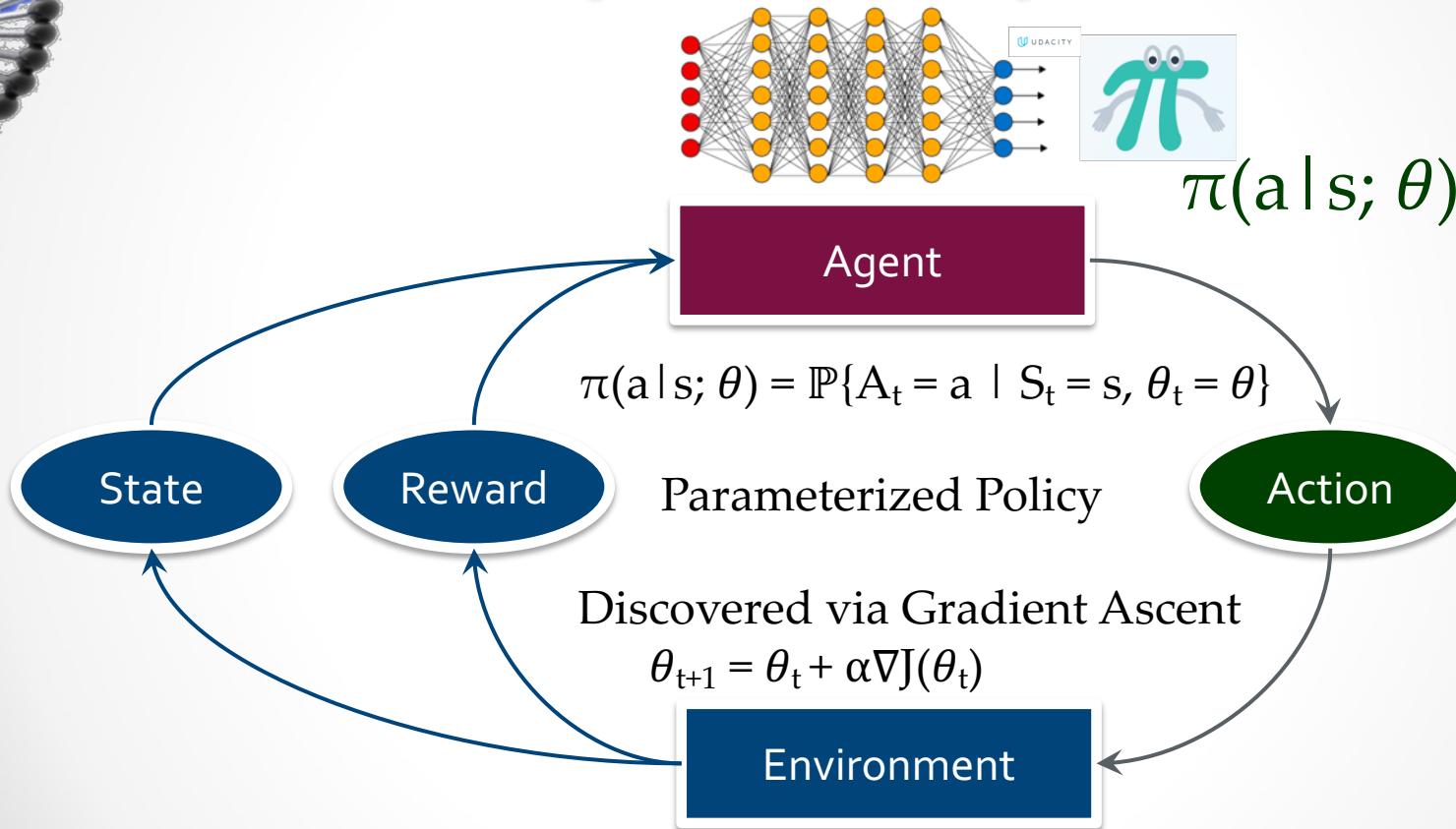




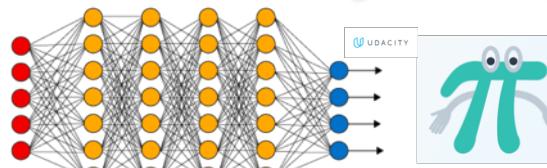
# RL Algorithm Taxonomy



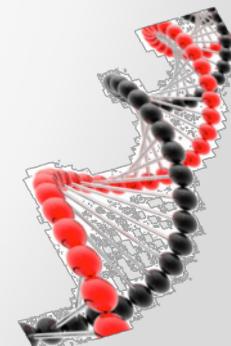
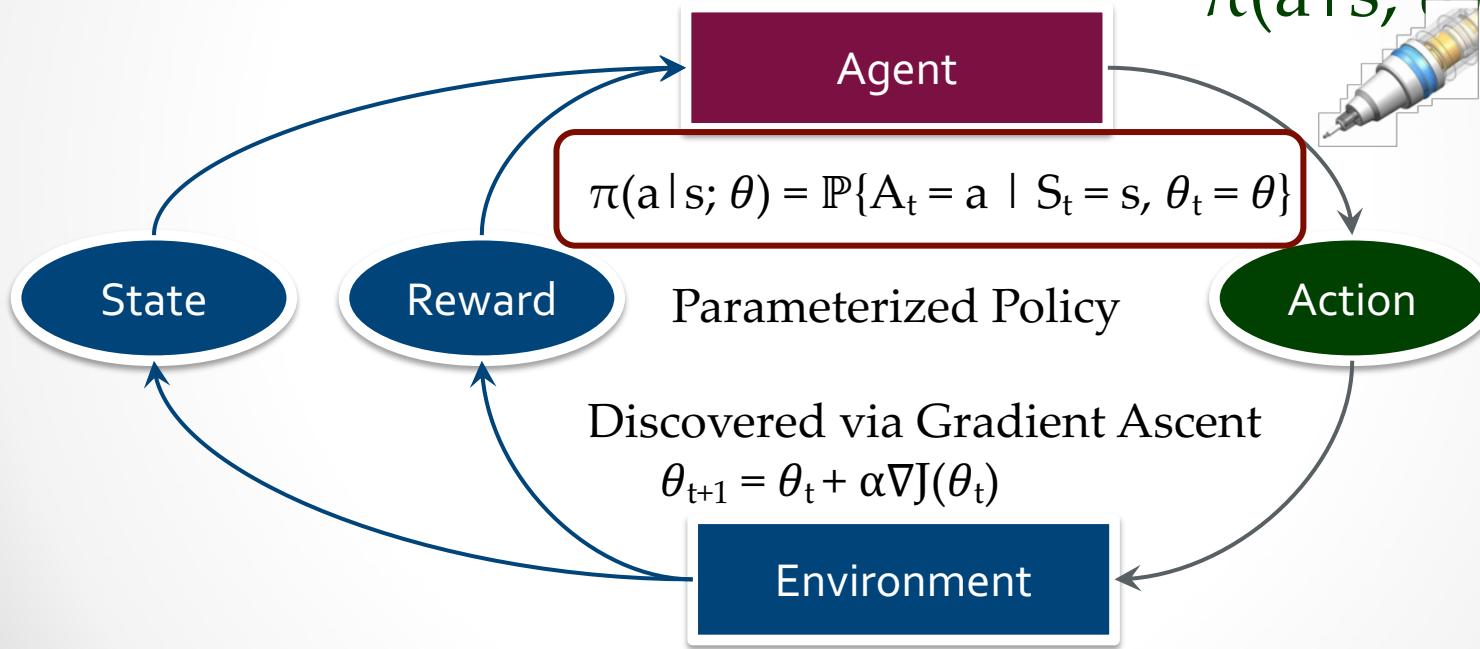
# Policy in Policy Gradient



# Policy in Policy Gradient



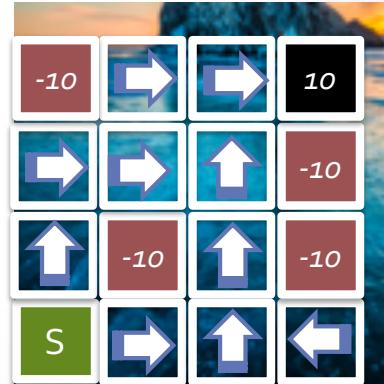
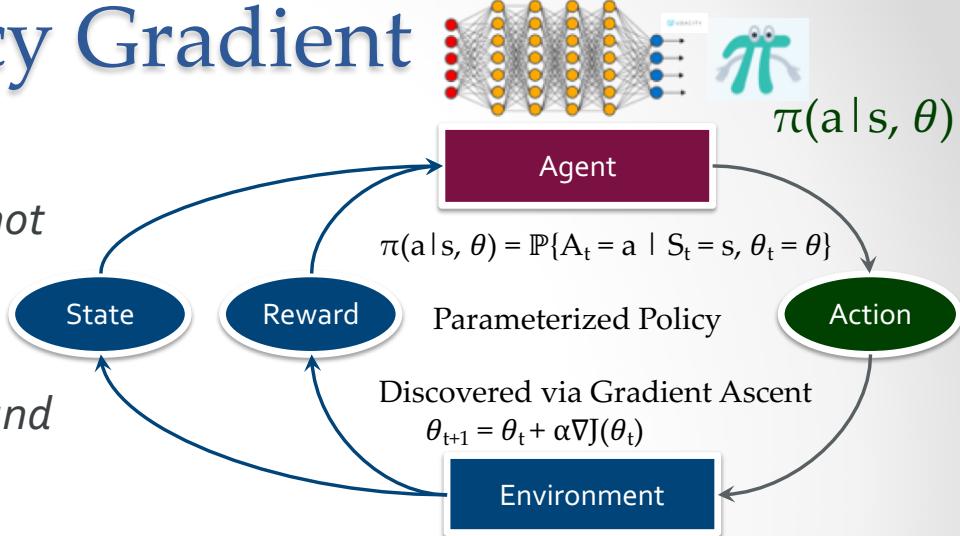
$$\pi(a|s; \theta)$$

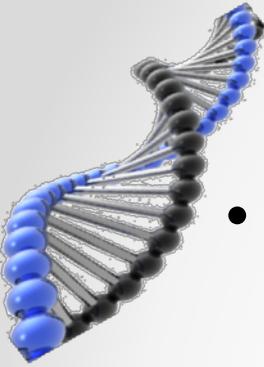




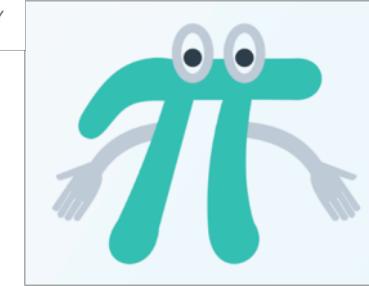
# Policy in Policy Gradient

- All methods that follow this general schema we call policy gradient methods, whether or not they also learn an approximate value function.
- Methods that learn approximations to both policy and value functions are often called actor-critic methods
- Stochastic Policy  $\pi(a|s; \theta) = \mathbb{P}\{a|s; \theta\}$ 
  - e.g. Softmax
  - Probability - A degree of belief (i.e. Credence), a subjective assessment of how much I can predict an event given the knowledge I currently possess. Bayesian prior-ish !
- Deterministic Policy  $\pi : s \mapsto a$ 
  - Our 1<sup>st</sup> exercise was a symbolic deterministic policy injecting domain knowledge

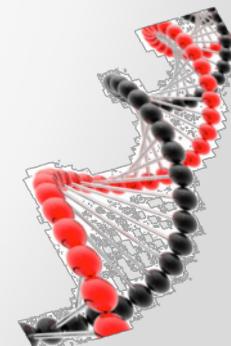


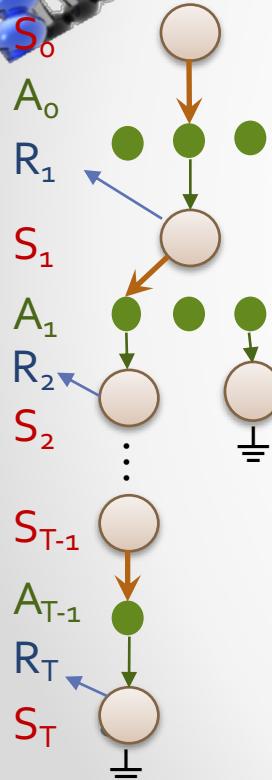


# Policy Gradients

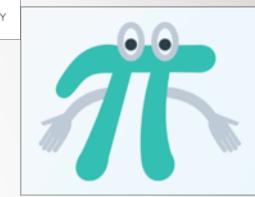


- Why Policy Gradients
  - Compact Representation
  - Better Convergence properties
  - Can handle Continuous space
  - Better for High Dimensional space
  - Stochastic Policies (rock-paper-scissor !)
  - Aliased States (Using uniform Stochastic Policy)
  - Simple
    - Enables the agent to devise robust strategies for navigating the environment directly (e.g. Left or Right)
- Challenges
  - Susceptible to converging to local minima
  - High Variance

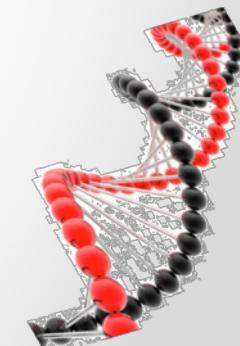


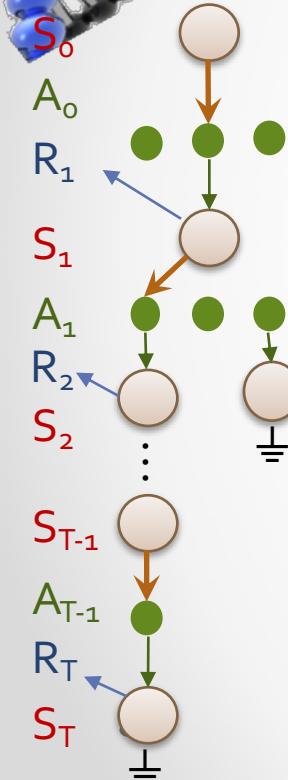


# Policy Gradients - Nomenclature

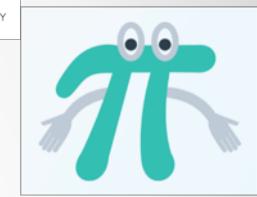


- Trajectory  $\tau$  over a horizon  $H$ 
  - $S_0 A_0 R_1 S_1 A_1 R_2 S_2 \dots A_{H-1} R_H S_H$
- Reward  $R(\tau)$ 
  - $R(\tau) = \sum_{t=0 \text{ to } H} R(s_t, a_t)$
- Trajectory can be an episode ( $H=T$ ), but doesn't dictate it





# Policy Gradients - Nomenclature



- Trajectory  $\tau$  over a horizon H

○  $S_0 A_0 R_1 S_1 A_1 R_2 S_2 \dots A_{H-1} R_H S_H$

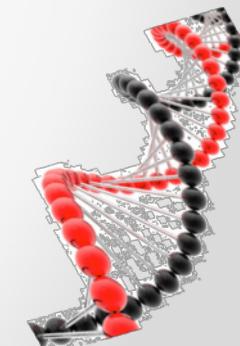


- Reward  $R(\tau)$

○ 
$$R(\tau) = \sum_{t=0 \text{ to } H} R(s_t, a_t)$$

This is the  $G_t$  we are used to.  
Some literature calls it  $R_\tau$

- Trajectory can be an episode (H=T), but doesn't dictate it





# Unrolling the Math

- Expected Return

$$U_{\theta} = \mathbb{E}[\sum_{t=0 \text{ to } \tau} R(s_t, a_t); \pi(\theta)] = \sum_{\tau} \mathbb{P}(\tau; \theta) R(\tau) \dots \text{some literature calls it } J_{\theta}$$

- Goal : Maximize  $J_{\theta}$

$$\max_{\theta}(U_{\theta}) = \max_{\theta} \{ \mathbb{E}[\sum_{t=0 \text{ to } \tau} R(s_t, a_t); \pi(\theta)] \} = \max_{\theta} \{ \sum_{\tau} \mathbb{P}(\tau; \theta) R(\tau) \}$$

- Likelyhood Ratio Method

- Forms the foundation for Policy Gradients, e.g. REINFORCE
- In essence, it means our policy makes some trajectories more likely to happen than others
  - With weighting those returns from those trajectories by the probability that they actually take place





# Unrolling the Math



- Expected Return

$$U_{\theta} = \mathbb{E}[\sum_{t=0 \text{ to } \tau} R(s_t, a_t); \pi(\theta)] = \sum_{\tau} \mathbb{P}(\tau; \theta) R(\tau)$$

... some literature calls it  $J_{\theta}$

- Goal : Maximize  $J_{\theta}$

$$\max_{\theta}(U_{\theta}) = \max_{\theta} \{ \mathbb{E}[\sum_{t=0 \text{ to } \tau} R(s_t, a_t); \pi(\theta)] \} = \max_{\theta} \{ \sum_{\tau} \mathbb{P}(\tau; \theta) R(\tau) \}$$

- Likelyhood Ratio Method

- Forms the foundation for Policy Gradients, e.g. REINFORCE
- In essence, it means our policy makes some trajectories more likely to happen than others
  - With weighting those returns from those trajectories by the probability that they actually take place





# Likelyhood Policy Gradient

$$\max_{\theta} U(\theta) = \max_{\theta} \{ \mathbb{E} [ \sum_{t=0 \text{ to } T} R(s_t, a_t); \pi(\theta) ] \} = \max_{\theta} \{ \sum_{\tau} \mathbb{P}(\tau; \theta) R(\tau) \}$$

Discovered via Gradient Ascent :  $\theta_{t+1} = \theta_t + \alpha \nabla U(\theta_t)$

$$\nabla_{\theta} U(\theta) = \nabla_{\theta} \sum_{\tau} \mathbb{P}(\tau; \theta) R(\tau)$$

$$= \sum_{\tau} \nabla_{\theta} \mathbb{P}(\tau; \theta) R(\tau)$$

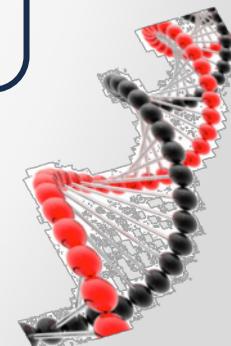
$$= \sum_{\tau} \frac{\mathbb{P}(\tau; \theta)}{\mathbb{P}(\tau; \theta)} \nabla_{\theta} \mathbb{P}(\tau; \theta) R(\tau)$$

$$= \sum_{\tau} \mathbb{P}(\tau; \theta) \frac{\nabla_{\theta} \mathbb{P}(\tau; \theta)}{\mathbb{P}(\tau; \theta)} R(\tau)$$

Def:

$$\nabla_x \log f(x) = \frac{\nabla_{\theta} f(x)}{f(x)}$$

$$\nabla_{\theta} U(\theta) = \sum_{\tau} \mathbb{P}(\tau; \theta) \nabla_{\theta} \log \mathbb{P}(\tau; \theta) R(\tau)$$





# Likelyhood Policy Gradient

$$\max_{\theta} U(\theta) = \max_{\theta} \{ \mathbb{E} [ \sum_{t=0 \text{ to } T} R(s_t, a_t); \pi(\theta) ] \} = \max_{\theta} \{ \sum_{\tau} \mathbb{P}(\tau; \theta) R(\tau) \}$$

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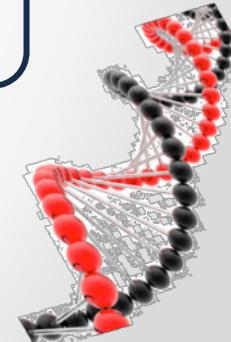
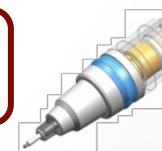
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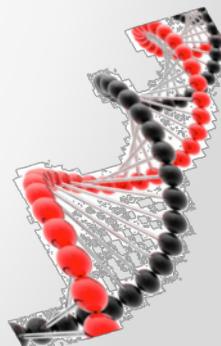
# Likelyhood Policy Gradient

$$\nabla_{\theta} U(\theta) = \sum_{\tau} \mathbb{P}(\tau; \theta) \nabla_{\theta} \log \mathbb{P}(\tau; \theta) R(\tau)$$

Now we can perturb our parameter space  $\theta$  and it will ascend or descend depending on  $R(\tau)$

But we have 2 problems:

1. We don't have probabilities in terms of trajectories;  
we have states and actions !
2. We assume infinite trajectories; not feasible for mere mortals
  - *Even though OpenAI 5 is using 120,000 CPUs and 256 GPUs,  
learning the equivalent of 180 years of play per day !*



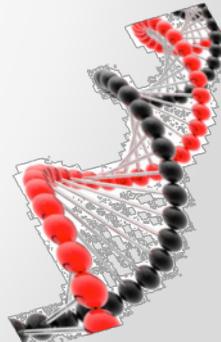


# Unrolling the Math

$$\nabla_{\theta} U(\theta) = \sum_{\tau} \mathbb{P}(\tau; \theta) \nabla_{\theta} \log \mathbb{P}(\tau; \theta) R(\tau)$$

- Considering all possible trajectories is an impossible task. While in the math world, we can image as elegant as possible.
- Down in the real world, we estimate empirically by sampling  $m$  trajectories(paths) under  $\pi_{\theta}$  and average

$$\nabla_{\theta} U(\theta) \approx \frac{1}{m} \sum_{i=1 \text{ to } m} \nabla_{\theta} \log \mathbb{P}(\tau^i; \theta) R(\tau^i)$$



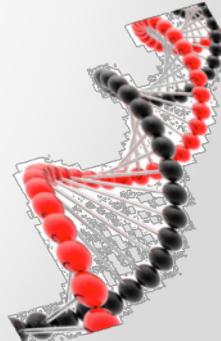
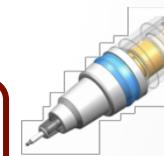


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# Decomposing trajectories to states & actions

$$\nabla_{\theta} U(\theta) = \frac{1}{m} \sum_{i=1 \text{ to } m} \nabla_{\theta} \log \mathbb{P}(\tau^i ; \theta) R(\tau^i)$$

- Let us reason about states and actions than probabilities of trajectories

$$\begin{aligned}\nabla_{\theta} \log \mathbb{P}(\tau ; \theta) &= \nabla_{\theta} \log [\prod_{t=0 \text{ to } T} \mathbb{P}(s_{t+1} | s_t, a_t) \pi(a_t | s_t, \theta)] \\ &= \nabla_{\theta} [\sum_{t=0 \text{ to } T} \log \mathbb{P}(s_{t+1} | s_t, a_t) + \sum_{t=0 \text{ to } T} \log \pi(a_t | s_t, \theta)] \\ &= \nabla_{\theta} \sum_{t=0 \text{ to } T} \log \mathbb{P}(s_{t+1} | s_t, a_t) + \nabla_{\theta} \sum_{t=0 \text{ to } T} \log \pi(a_t | s_t, \theta) \\ &= \nabla_{\theta} \sum_{t=0 \text{ to } T} \log \pi(a_t | s_t, \theta) \dots \text{since } \nabla_{\theta} \sum_{t=0 \text{ to } T} \log \mathbb{P}(s_{t+1} | s_t, a_t) = 0\end{aligned}$$

$$\nabla_{\theta} U(\theta) = \frac{1}{m} \sum_{i=1 \text{ to } m} \sum_{t=0 \text{ to } T} \nabla_{\theta} \log \pi(a_t | s_t, \theta) R(\tau^i)$$

*... and this is the REINFORCE algorithm !*

(<http://www-anw.cs.umass.edu/~barto/courses/cs687/williams92simple.pdf>)

Simple Statistical Gradient-Following Algorithms for  
Connectionist Reinforcement Learning

Ronald J. Williams  
College of Computer Science  
Northeastern University  
Boston, MA 02115

Appears in *Machine Learning*, 8, pp. 229-256, 1992.

## Abstract

This article presents a general class of associative reinforcement learning algorithms for connectionist networks containing stochastic units. These algorithms, called REINFORCE algorithms, are shown to make weight adjustments in a direction that lies along the gradient of expected reinforcement in both immediate-reinforcement tasks and certain limited forms of





# Decomposing trajectories to states & actions

$$\nabla_{\theta} U(\theta) = \frac{1}{m} \sum_{i=1 \text{ to } m} \nabla_{\theta} \log \mathbb{P}(\tau^i ; \theta) R(\tau^i)$$

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$$\boxed{\nabla_{\theta} U(\theta) = \frac{1}{m} \sum_{i=1 \text{ to } m} \sum_{t=0 \text{ to } T} \nabla_{\theta} \log \pi(a_t | s_t, \theta) R(\tau^i)}$$

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Simple Statistical Gradient-Following Algorithms for Connectionist Reinforcement Learning

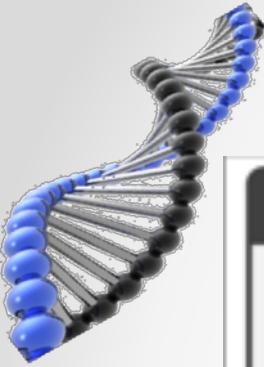
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# REINFORCE = Monte Carlo PG

REINFORCE: Monte-Carlo Policy-Gradient Control (episodic) for  $\pi_*$ .

Input: a differentiable policy parameterization  $\pi(a|s, \theta)$

Algorithm parameter: step size  $\alpha > 0$

Initialize policy parameter  $\theta \in \mathbb{R}^{d'}$  (e.g., to  $\mathbf{0}$ )

Loop forever (for each episode):

Generate an episode  $S_0, A_0, R_1, \dots, S_{T-1}, A_{T-1}, R_T$ , following  $\pi(\cdot| \cdot, \theta)$

Loop for each step of the episode  $t = 0, 1, \dots, T - 1$ :

$$G \leftarrow \sum_{k=t+1}^T \gamma^{k-t-1} R_k \quad (G_t)$$
$$\theta \leftarrow \theta + \alpha \gamma^t G \nabla \ln \pi(A_t | S_t, \theta) \quad \alpha = 0.1 \text{ or } 0.2$$

*Discounted  
return for  
variance  
reduction*

- Reinforce = MonteCarlo PG
  - i.e. full episode as Trajectory
  - *Just nudges the policy depending on the reward from a trajectory (could be a partial trajectory)*
- Low bias, but high variance
- REINFORCE Paper : <http://www-anw.cs.umass.edu/~barto/courses/cs687/williams92simple.pdf>





# REINFORCE

1. Create initial policy  $\pi_\theta$
2. Act in the environment  $a_t \sim \pi(s_t)$  for an episode storing states, actions, rewards:  $s_0, a_0, r_0, \dots, s_T, a_T, r_T$
3. Compute return  $R = \sum_{t=0}^T r_t$
4. Compute policy gradient  $\nabla_\theta J(\theta) = \sum_{t=0}^T \nabla_\theta \log \pi_\theta(a_t|s_t) R$
5. Take a step in the direction of the gradient:  $\theta = \theta + \alpha \nabla_\theta J(\theta)$
6. Repeat until convergence  
 $\alpha = 0.1$  or  $0.2$

**Input:** policy  $\pi(a|s, \theta)$ ,  $\hat{v}(s, w)$

**Parameters:** step sizes,  $\alpha > 0$ ,  $\beta > 0$

**Output:** policy  $\pi(a|s, \theta)$

initialize policy parameter  $\theta$  and state-value weights  $w$   
for *true* do

generate an episode  $s_0, a_0, r_1, \dots, s_{T-1}, a_{T-1}, r_T$ , following  $\pi(\cdot| \cdot, \theta)$

for each step  $t$  of episode  $0, \dots, T-1$  do

$G_t \leftarrow$  return from step  $t$

$\delta \leftarrow G_t - \hat{v}(s_t, w)$

$w \leftarrow w + \beta \delta \nabla_w \hat{v}(s_t, w)$

$\theta \leftarrow \theta + \alpha \gamma^t \delta \nabla_\theta \log \pi(a_t|s_t, \theta)$

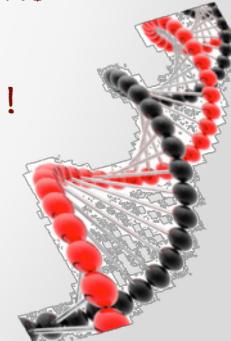
end

end

The algorithm from the  
edx course is a lot  
easier to understand !

**Algorithm 6:** REINFORCE with baseline (episodic), adapted from Sutton and Barto (2018)

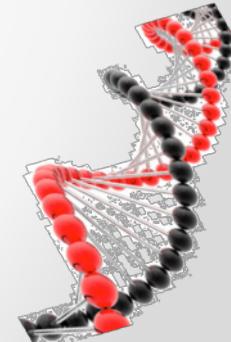
<https://arxiv.org/pdf/1810.06339.pdf>





# Hands-On #10 : Balancing the Cart Pole w/ Policy Gradient (REINFORCE)

- Goal:
  - Implement Policy Gradient Network for CartPole
    - It is a lot simpler !!
- Steps:
  - Notebook : REINFORCE\_o1.ipynb
  - Understand the REINFORCE code
  - Plot Values

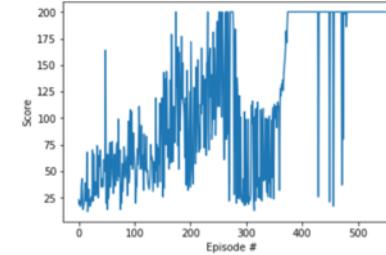




# Implementation Lessons

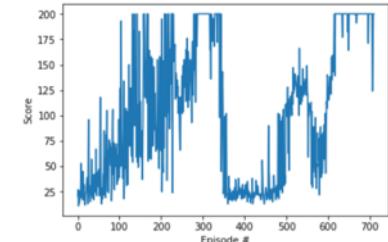
1. Very Simple
2. No digitization – neural network takes care of generalization
3. Solves the environment in less number of steps
4. It does oscillate a bit, but converges reasonably well

```
Episode 100    Average Score: 47.22
Episode 200    Average Score: 80.94
Episode 300    Average Score: 116.19
Episode 400    Average Score: 112.00
Episode 500    Average Score: 191.65
Environment solved in 450 episodes!      Average Score: 195.18
Elapsed : 0:00:23.645272
2019-01-12 11:47:30.619834
```

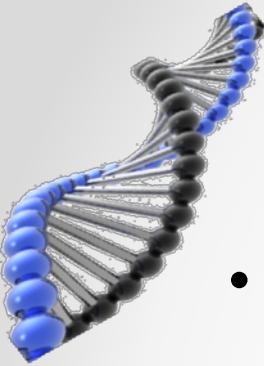


```
Max Score 200.000000 at 174
Percentile [25,50,75] : [ 51. 111. 200. ]
Variance : 4779.687
```

```
Episode 100    Average Score: 41.11
Episode 200    Average Score: 102.92
Episode 300    Average Score: 142.24
Episode 400    Average Score: 102.35
Episode 500    Average Score: 31.79
Episode 600    Average Score: 98.43
Episode 700    Average Score: 189.09
Environment solved in 610 episodes!      Average Score: 195.07
Elapsed : 0:00:22.520751
2019-02-08 13:10:04.801406
```



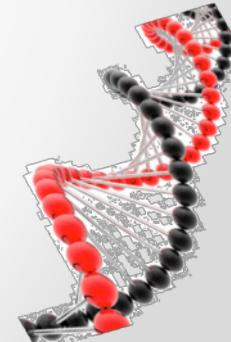
```
Max Score 200.000000 at 171
```

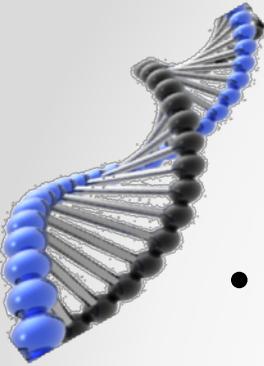


# Quiz



- What is the DQN DNN topology ?
  -
- What is the input size ? Output size ?
  -
- What is the output of the network ?
  -
- How does the output translate to an action ?
  -
- Is the policy deterministic or stochastic ?
  -
- How do you characterize this w.r.t others ?
  -

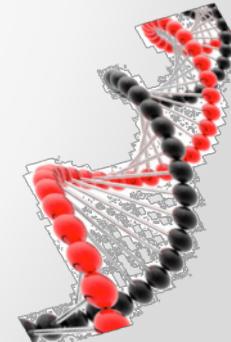




# Quiz

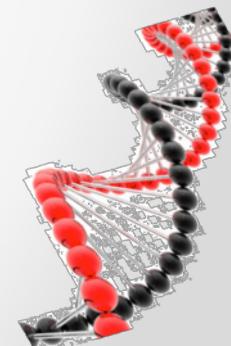
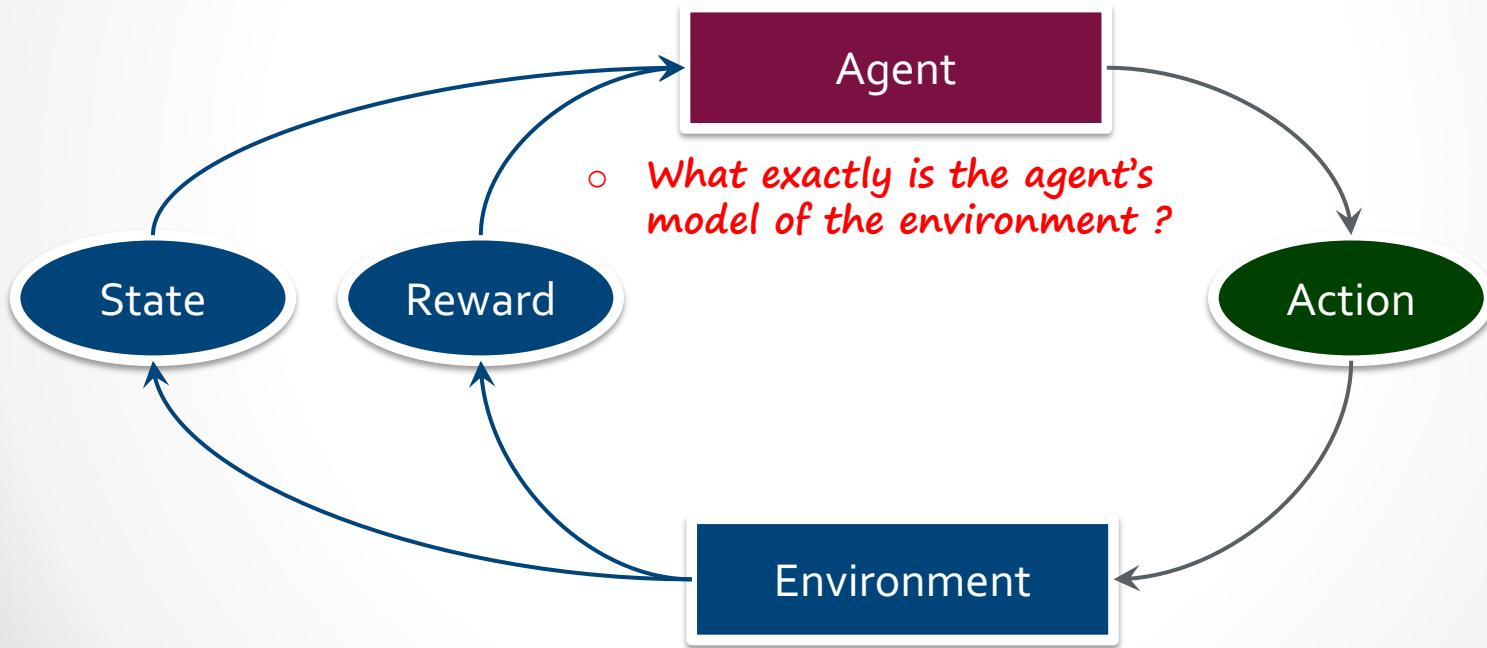
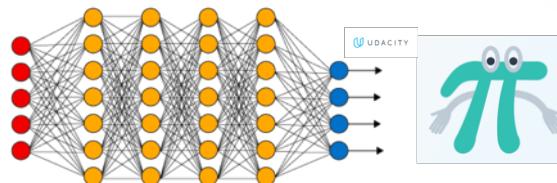


- What is the DQN DNN topology ?
  - FC16-FC2
- What is the input size ? Output size ?
  - Input = 4 (state), output = 2 (actions)
- What is the output of the network ?
  - softmax
- How does the output translate to an action ?
  - sample
- Is the policy deterministic or stochastic ?
  - Stochastic ! We get it as a part of the architecture !
- How do you characterize this w.r.t others ?
  - A better solution ! Probably the right solution for Cartpole.



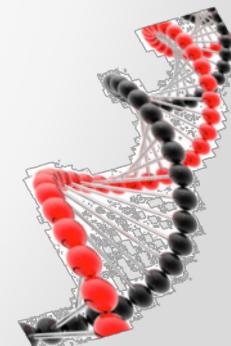
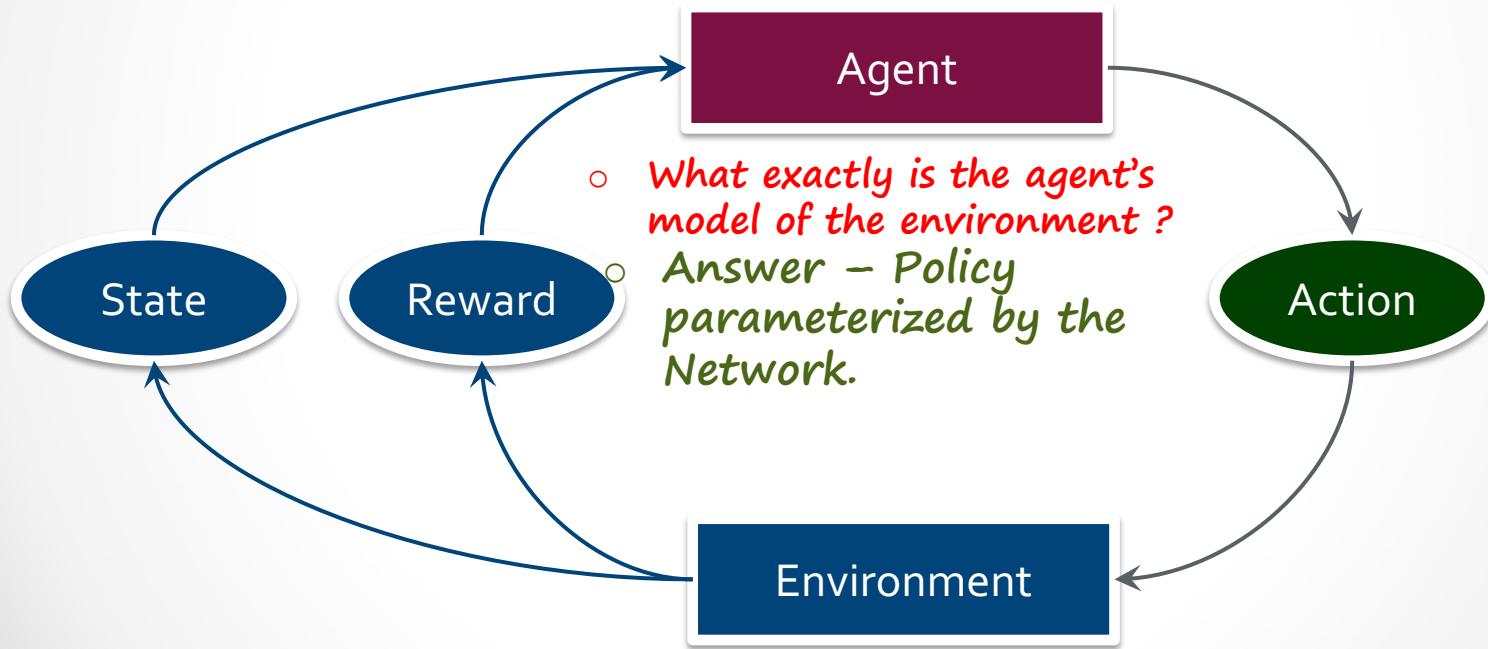
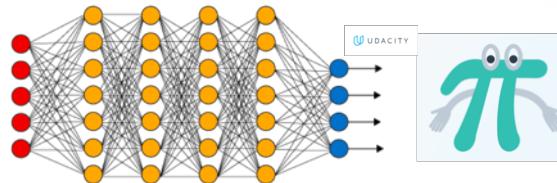


# Quiz



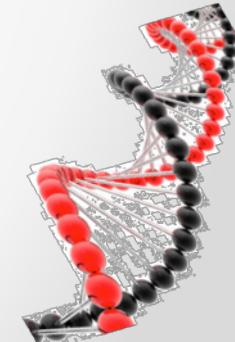
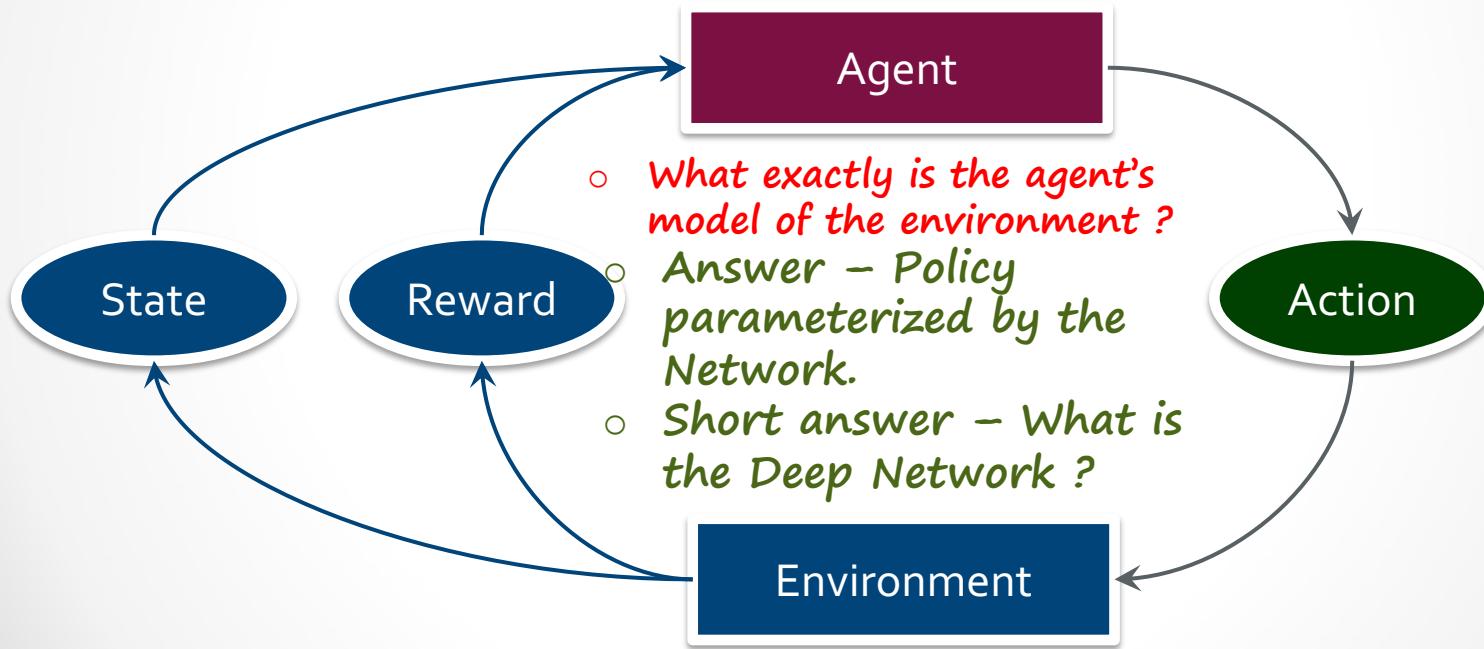
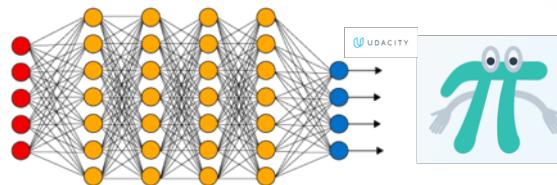


# Quiz



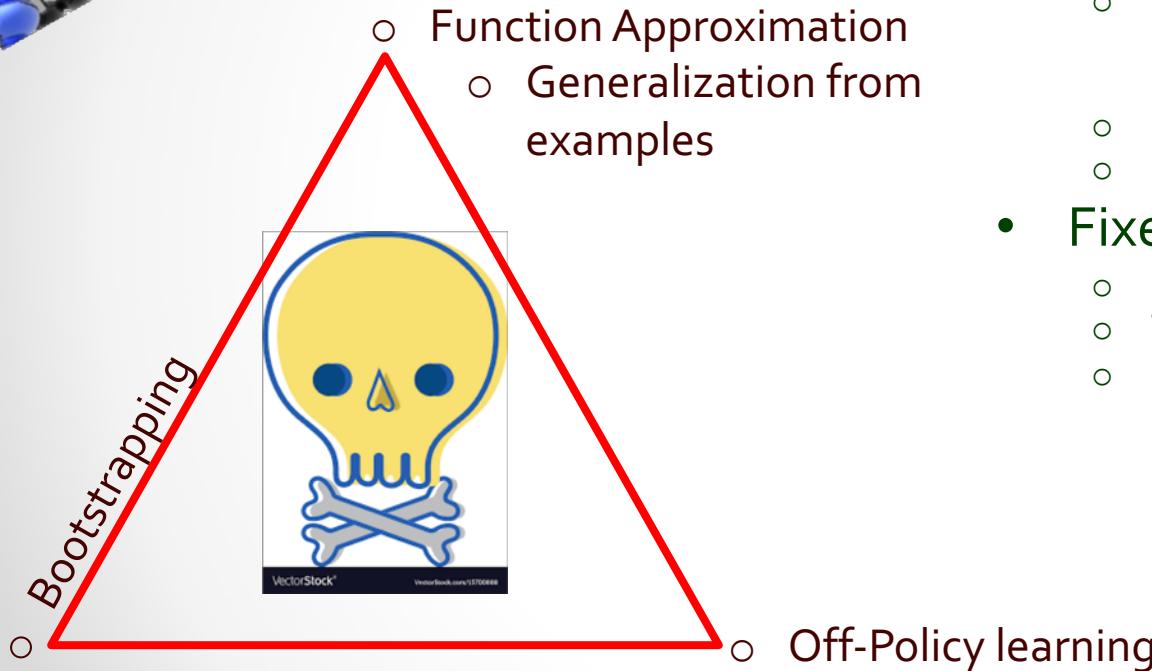


# Quiz





# The Deadly Triad--Sutton

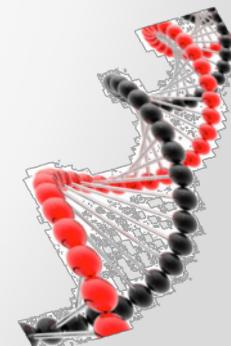


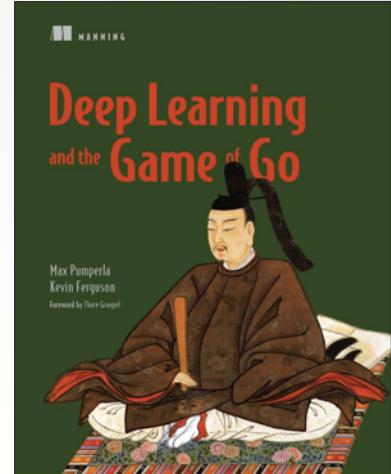
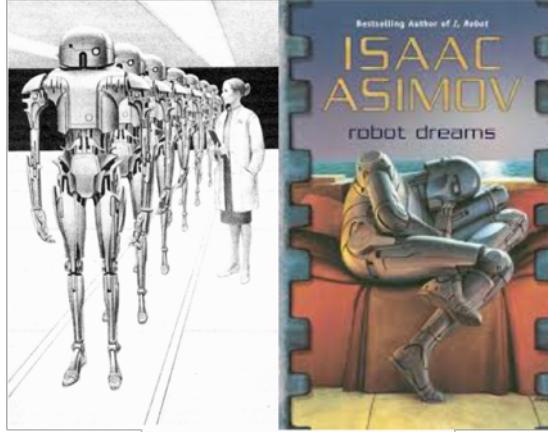
- REINFORCE

- Unbiased, very noisy
  - We are sampling one out of millions of trajectories, for each iteration
- Sample in-efficient
- Credit Assignment

- Fixes

- Baseline
- Temporal Structure
- KL-Divergence trust Region





# Deep Learning: Sky's the Limit?

The generally accepted idea is that deep learning neural networks are as good as the data you feed them. In this blog, we review recent achievements of deep learning and address whether such systems are able to surpass and transcend the original learning material through self-learning, and ultimately can become – even better – than the data you feed them.

**Machine**

Wednesday, April 8, 2015

**Part 2: AlphaGo under a Magnifying Glass (The historic match of deep learning AlphaGo vs. Lee Sedol) REVISED**

**[Read, Verse]**

## AlphaGo under a Magnifying Glass

Deep Learning program AlphaGo was developed by the Google DeepMind team specifically to play Go, the Chinese Go board game, developed in London in 2010 by Demis Hassabis, Shane Legg and Mustafa Sutskever. The name of DeepMind is to solve intelligence and use it to make the world a better place (as in a real achievement slogan). DeepMind was at the time supported by the most prominent tech entrepreneurs and investors who had a clear vision of the future, prior to being acquired by Google 2014, their biggest European acquisition ever at \$400 million.

**Deep Learning AlphaGo under a Magnifying Glass**

Part 2: AlphaGo under a Magnifying Glass (The historic match of deep learning AlphaGo vs. Lee Sedol) REVISED





Read von den Hawk  
Published: 10 days ago  
Comments: 0



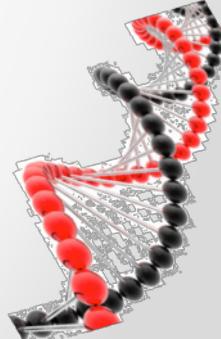
# The world of $\alpha_{\text{Go}}$



- AlphaGo AI program from Google's DeepMind defeated Go Champion
  - Lee Sedol (9-dan professional with 18 world titles)
- AlphaGo has the ability to look “globally” across a board—and find solutions that humans either have been trained not to play or would not consider.
  - This has huge potential for using AlphaGo-like technology to find solutions that humans don't necessarily see in other areas
- Search & Optimization
  - Policy Network with Values & search
  - “This ability of neural networks to bottle intuition / pattern recognition from one environment & apply to other contexts ”

## GENERATIONAL GAP !

- Unlike IBM's Deep Blue, which defeated chess champion Garry Kasparov in 1997, AlphaGo was not programmed with decision trees, or equations on how to evaluate board positions, or with if-then rules. “
- AlphaGo learned how to play go essentially from self-play and from observing big professional games
  - During training, AlphaGo played a million go games against itself.

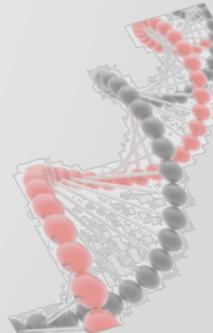




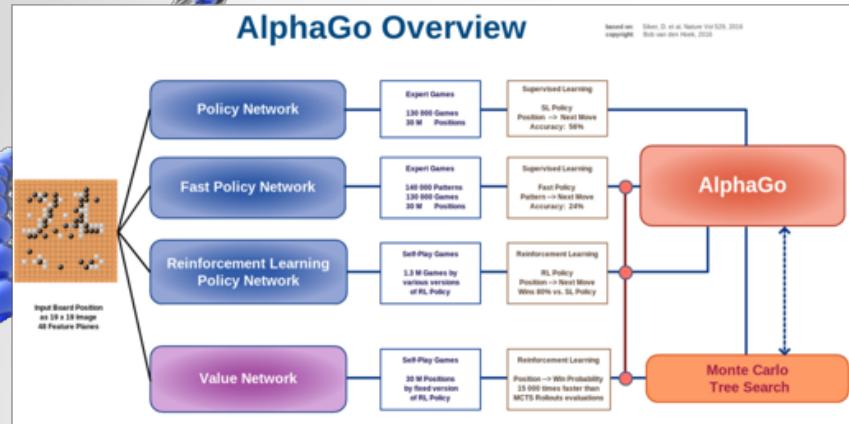
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## AlphaGo Overview



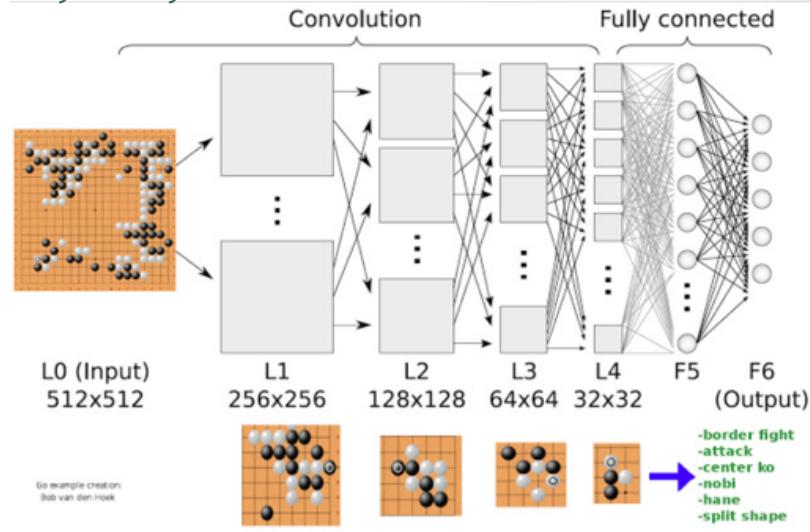
- It uses 4 networks :
- **Fast Rollout Policy Network (P-Network)** :It rolls out a quick plan for the game.
- **Supervised Learning Policy Network (SL-Network)** :The P-Network and the SL-Network are trained to predict human expert moves in a data set of positions.
- **Reinforcement Learning Policy Network (RL-Network)** :The RL Network is initialized as the SL policy network, and is then improved by policy gradient learning to maximize the outcome (that is, winning more games) against previous versions of the policy network. A new data set is generated by playing games of self-play with the RL policy network.
- **Value network** : a Value Network  $V$  is trained by regression to predict the expected outcome (that is, whether the current player wins) in positions from the self-play data set.

<https://medium.com/@arnabghosh93/deep-reinforcement-learning-driving-alpha-go-9881f1a90be4#.f462gnebl>

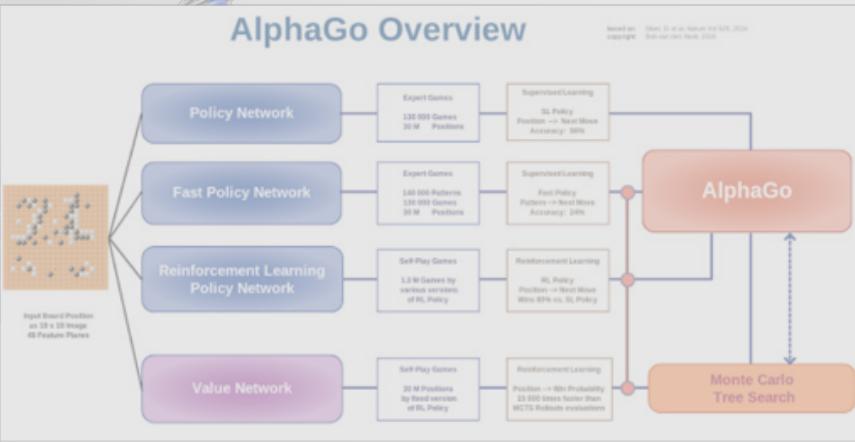
- AlphaGo is not a revolutionary breakthrough in itself, but rather a leading edge of an extremely important development

- **#AlphaGo** appeared to have a weakness in responding to unorthodox moves; Toward the end of the game, **#AlphaGo** played desperate moves similar to those of humans facing defeat ...

- Ultimately, the scary thing about the rise of intelligent machines is not that they could someday have a mind of their own, but they could someday have a mind that we humans – with all our flaws and complexity – design and build for them



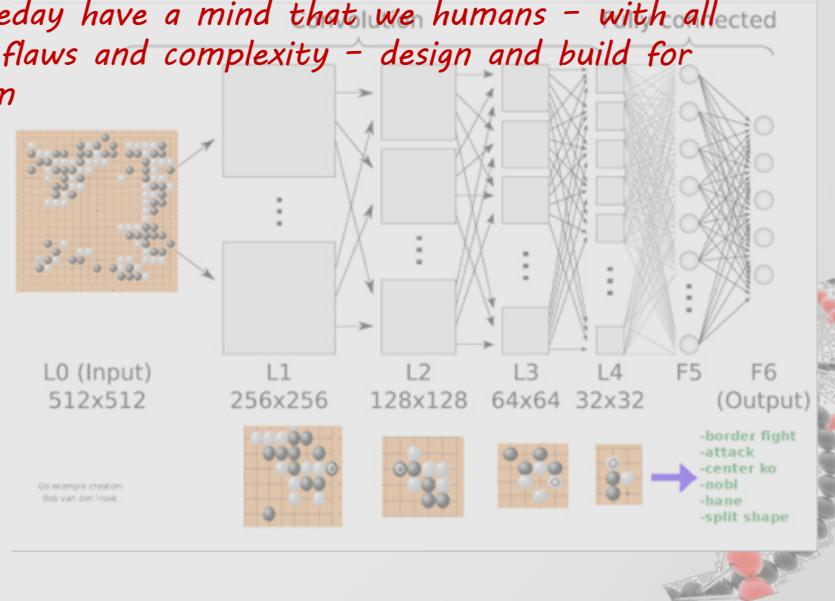
## AlphaGo Overview



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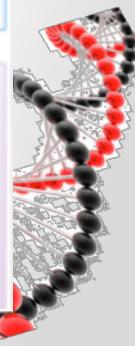
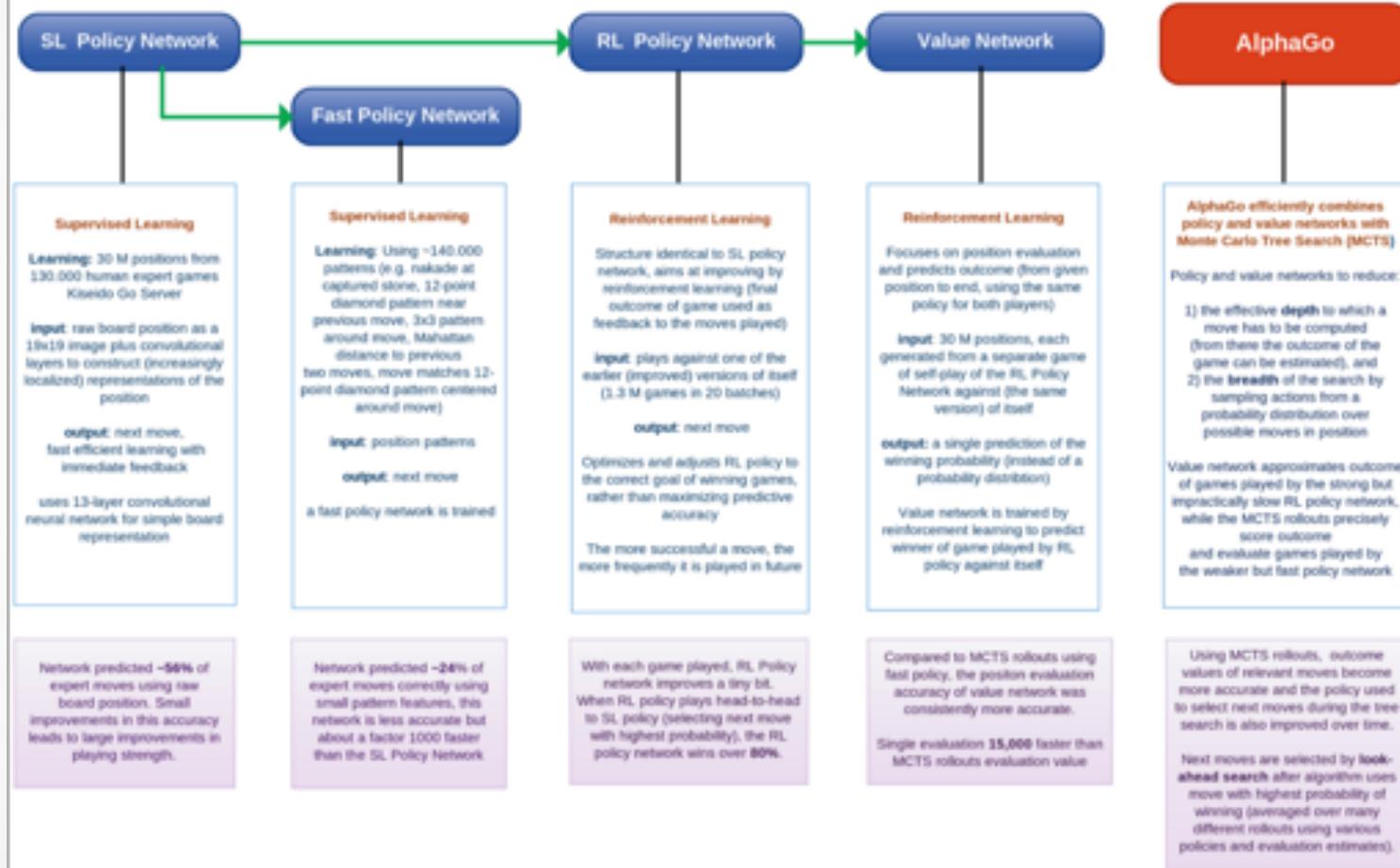
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# AlphaGo in a Nutshell

based on: Silver, D. et al. Nature Vol. 529, 2016  
copyright: Bob van den Hoek, 2016





# ARTICLE

doi:10.1038/nature16961

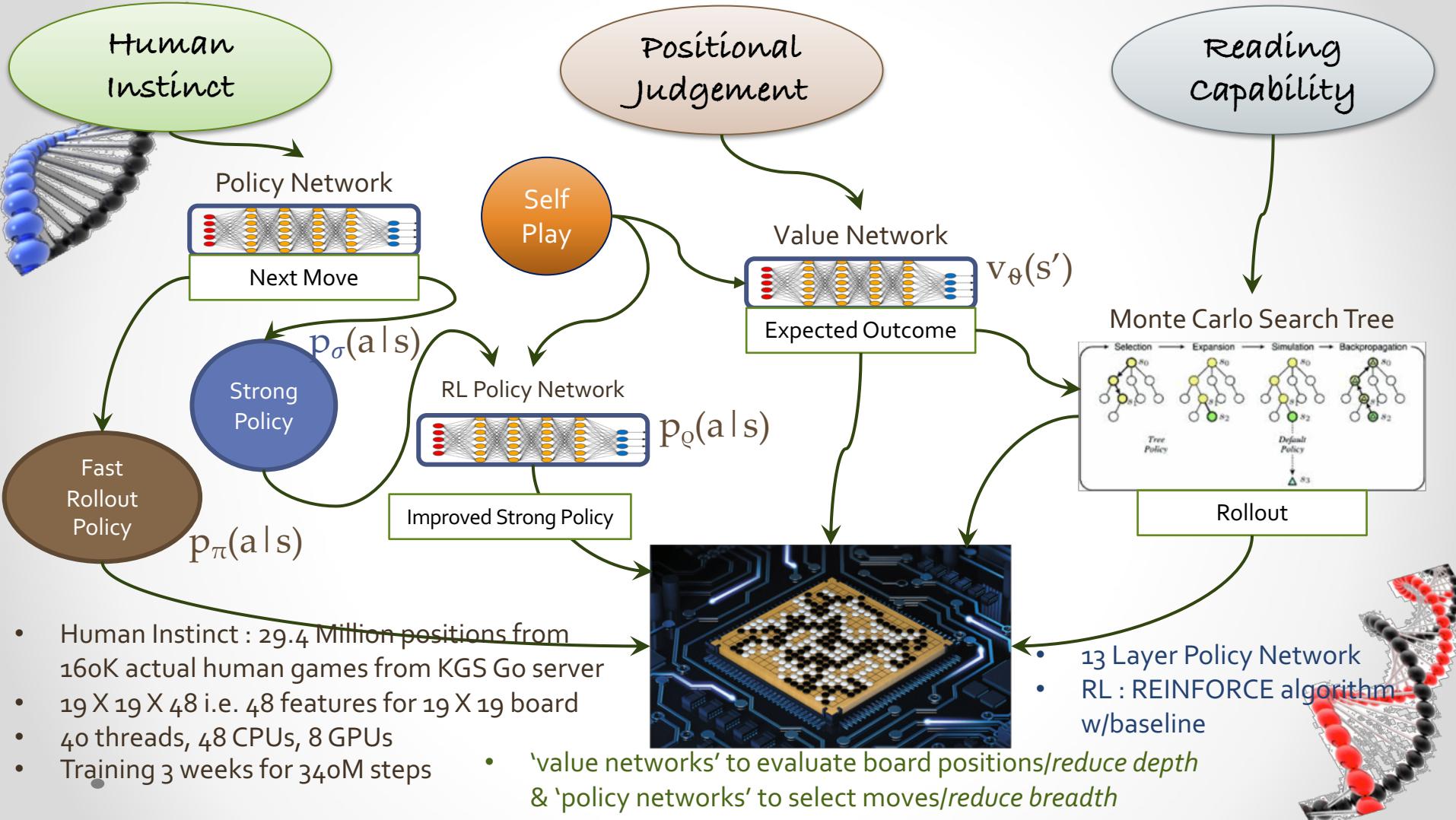
## Mastering the game of Go with deep neural networks and tree search

David Silver<sup>1\*</sup>, Aja Huang<sup>1\*</sup>, Chris J. Maddison<sup>1</sup>, Arthur Guez<sup>1</sup>, Laurent Sifre<sup>1</sup>, George van den Driessche<sup>1</sup>, Julian Schrittwieser<sup>1</sup>, Ioannis Antonoglou<sup>1</sup>, Veda Panneershelvam<sup>1</sup>, Marc Lanctot<sup>1</sup>, Sander Dieleman<sup>1</sup>, Dominik Grewe<sup>1</sup>, John Nham<sup>2</sup>, Nal Kalchbrenner<sup>1</sup>, Ilya Sutskever<sup>2</sup>, Timothy Lillicrap<sup>1</sup>, Madeleine Leach<sup>1</sup>, Koray Kavukcuoglu<sup>1</sup>, Thore Graepel<sup>1</sup> & Demis Hassabis<sup>1</sup>

- Combination of model-free and model-based approach
- Look ahead search using MCTS

<https://storage.googleapis.com/deepmind-media/alphago/AlphaGoNaturePaper.pdf>  
<https://pdfs.semanticscholar.org/2088/c55ec3e52a8beg9cd933907020c70b281383.pdf>







- DQN can even book tickets !
- Given an instruction "Book a flight from WTK to LON on 21-Oct-2016", the DQN agent navigates through the web form and selects the cheapest flight

# curriculum-DQN to book tickets !

LEARNING TO NAVIGATE THE WEB

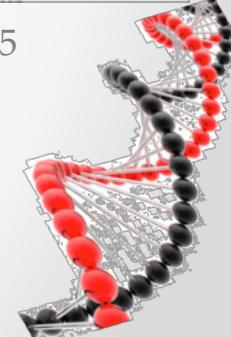
Izzeddin Gur, Ulrich Rueckert, Aleksandra Faust, Dilek Hakkani-Tur  
Google AI  
izzeddin@cs.ucsb.edu, {rueckert, faust}@google.com, dilek@ieee.org

ABSTRACT

Learning in environments with large state and action spaces, and sparse rewards, can hinder a Reinforcement Learning (RL) agent's learning through trial-and-error. For instance, following natural language instructions on the Web (such as booking a flight ticket) leads to RL settings where input vocabulary and number of actionable elements on a page can grow very large. Even though recent approaches improve the success rate on relatively simple environments with the help of human demonstrations to guide the exploration, they still fail in environments where the set of possible instructions can reach millions. We approach the aforementioned problems from a different perspective and propose guided RL approaches that can generate unbounded amount of experience for an agent to learn from. Instead of learning from a complicated instruction with a large vocabulary, we decompose it into multiple sub-instructions and schedule a curriculum in which an agent is tasked with a gradually increasing subset of these relatively easier sub-instructions. In addition, when the expert demonstrations are not available, we propose a novel meta-learning framework that generates new instruc-

ss.LG] 21 Dec 2018

<https://arxiv.org/abs/1812.09195>





# Will leave this section with 2 thoughts ...

Should we fear the machine's strengths and (try to) control them ?

[Update 3/6/16] An interesting post from [Tom Devenport](#) about Cognitive Computing.

- Good insights into what Cognitive Computing is, as a combination of [Intelligence\(Algorithms\)](#), [Inference\(Knowledge\)](#) and [Interface \(Visualization, Recommendation, Prediction,...\)](#)
- IMHO, Cognitive Computing is more than Analytics over unstructured data, it also has touches of AI in there.
- Reason being, Cognitive Computing understands humans – whether it is about buying patterns or the way different bodies reacts to drugs or the various forms of diseases or even the way humans work and interact
- And that knowledge is the difference between Analytics and Cognitive Computing !

“

I like Cognitive Computing as an important part of AI, probably that is where most of the applications are ... again understanding humans rather than being humans !

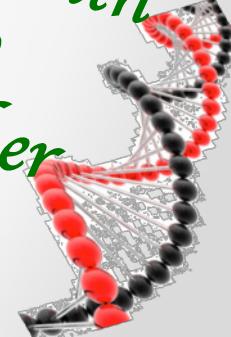
Is #AlphaGo's 3rd win a prelude of things to come ? "it played so well that it was almost scary"; "We're now convinced that AlphaGo is simply stronger than any known human Go player"; "Perhaps it's time for broader discussion about how human society will adapt to this emerging technology !!!" <https://goo.gl/htmOzR> show less



AlphaGo shows its true strength in 3rd victory against Lee Sedol

[gogameguru.com](http://gogameguru.com) • AlphaGo made history once again on Saturday, as the first computer program to defeat a top profes...

*Or should we work with the machines - who understand us, rather than being us ?*





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- Cognitive Computing is a combination of Intelligence(Algorithms), Inference(Knowledge) and Integration, Optimization, Recommendation,...)
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Self-awareness between  
self & Task –  
interesting paper from  
Columbia  
[https://www.eurekalert.org/pub\\_releases/2019-01/cuso-asco12819.php](https://www.eurekalert.org/pub_releases/2019-01/cuso-asco12819.php)

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- Researchers are now exploring whether robots can model not just their own bodies, but also their own minds, whether robots can think about thinking"
- And the knowledge gap between Analytics and Cognitive Computing !

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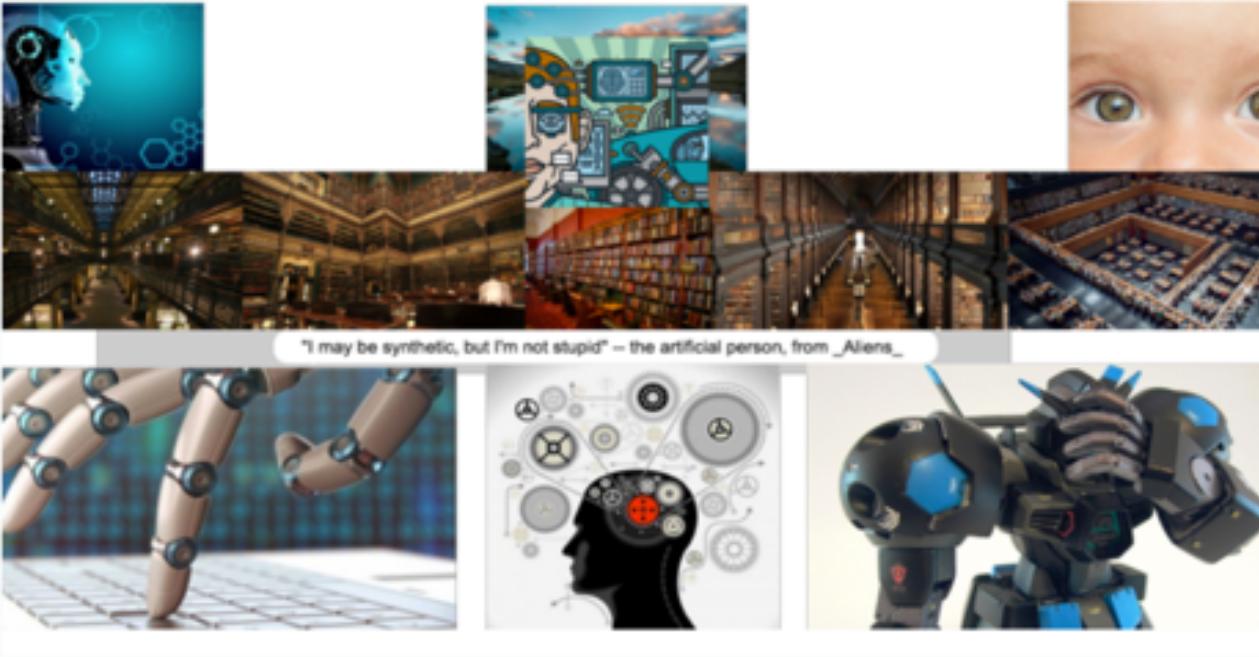


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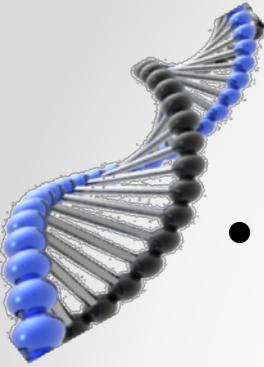




**WHAT WOULD YOU WANT AI TO DO, IF IT COULD DO WHATEVER YOU  
WANTED IT TO DO ?**

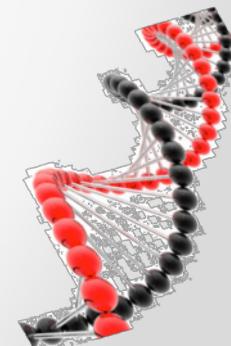
<https://goo.gl/6pKvgY>





# Back to the main feature ...

- REINFORCE
  - High variance
  - Difficult to converge
  - The dependence on  $R(\tau^i)$ 
    - Pushes probabilities for all actions in that trajectory
    - Which is not fully meaningful
  - What if we have a better yardstick ?
    - i.e. better or worse than what you expect ?
    - i.e. compare with a baseline





# Policy Gradients with a Baseline

- Bias and variance

- MonteCarlo has *low bias* – because it accumulates an estimate of reward from actual episodes
  - But because a state can participate in many different trajectories, there is the *high variance* of the cumulated rewards
- TD has low variance, because it works with a few steps, single step in many cases, instead of full rollout
  - But it has a high bias because it depends on estimates of estimates !

- Adding a TD baseline to REINFORCE reduces the variance

- Thus improves the convergence properties - results in better and consistent convergence
- And because of TD, speeds up learning as well !





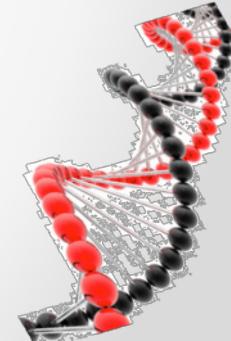
# Reinforce with Baseline

$$\begin{aligned}\nabla_{\theta} U(\theta) &= \frac{1}{m} \sum_{i=1 \text{ to } m} \sum_{t=0 \text{ to } T} \nabla_{\theta} \log \pi(a_t | s_t, \theta) R(\tau^i) \\ &= \frac{1}{m} \sum_{i=1 \text{ to } m} \sum_{t=0 \text{ to } T} \nabla_{\theta} \log \pi(a_t | s_t, \theta) (R(\tau^i) - b)\end{aligned}$$

Many interesting choice for a baseline:

1. Average of all rewards so far i.e.  $\mu\{R(\tau)\}$  – constant moving average
2. Optimal Baseline
3. Time dependent baseline
4. State dependent expected baseline i.e.  $V_{\pi}(s)$

$$\nabla_{\theta} U(\theta) = \frac{1}{m} \sum_{i=1 \text{ to } m} \sum_{t=0 \text{ to } T} \nabla_{\theta} \log \pi(a_t | s_t, \theta) (R(\tau^i) - V_{\phi}(s))$$





# Reinforce with Baseline

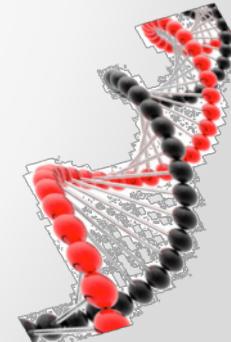
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$$= \frac{1}{m} \sum_{i=1 \text{ to } m} \sum_{t=0 \text{ to } T} \nabla_{\theta} \log \pi(a_t | s_t, \theta) (R(\tau^i) - b)$$

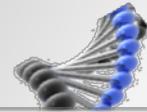
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$$\boxed{\nabla_{\theta} U(\theta) = \frac{1}{m} \sum_{i=1 \text{ to } m} \sum_{t=0 \text{ to } T} \nabla_{\theta} \log \pi(a_t | s_t, \theta) (R(\tau^i) - V_{\phi}(s))}$$





## REINFORCE with Baseline (episodic), for estimating $\pi_\theta \approx \pi_*$ .

Input: a differentiable policy parameterization  $\pi(a|s, \theta)$

Input: a differentiable state-value function parameterization  $\hat{v}(s, w)$

Algorithm parameters: step sizes  $\alpha^\theta > 0$ ,  $\alpha^w > 0$

Initialize policy parameter  $\theta \in \mathbb{R}^{d'}$  and state-value weights  $w \in \mathbb{R}^d$  (e.g., to  $\mathbf{0}$ )

Loop forever (for each episode):

Generate an episode  $S_0, A_0, R_1, \dots, S_{T-1}, A_{T-1}, R_T$ , following  $\pi(\cdot | \cdot, \theta)$

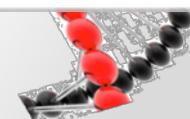
Loop for each step of the episode  $t = 0, 1, \dots, T - 1$ :

$$G \leftarrow \sum_{k=t+1}^T \gamma^{k-t-1} R_k \tag{G_t}$$

$$\delta \leftarrow G - \hat{v}(S_t, w)$$

$$w \leftarrow w + \alpha^w \delta \nabla \hat{v}(S_t, w)$$

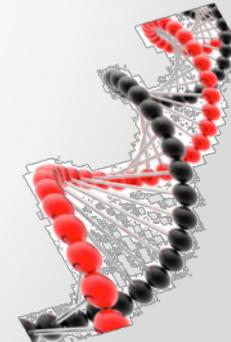
$$\theta \leftarrow \theta + \alpha^\theta \gamma^t \delta \nabla \ln \pi(A_t | S_t, \theta)$$





# A Simpler Algorithm from edX

- 
1. Initialize policy  $\pi_\theta$  and value function  $V_\phi$
  2. For episode 1,2,...,n do:
    1. Collect trajectory  $\tau$  by running current policy
    2. For each step in  $\tau$  compute the discounted return  $R_t = \sum_{t'=t}^T \gamma^{t'-t} r_{t'}$
    3. Re-fit the baseline minimizing  $\|V_\phi(s_t) - R_t\|^2$  over all steps
    4. Update  $\pi_\theta$  using gradient  $\sum_{t=0}^T \nabla_\theta \log \pi_\theta(a_t | s_t) (R_t - V_\phi(s_t))$
- 





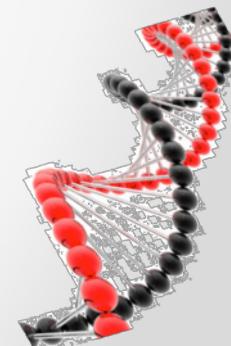
# Morphing to A3C

- Would a better baseline reduce the variance for REINFORCE ? And generalize ?
  - Can we use a Neural Network to establish this baseline ?
  - Of course, Yes to both
    - A<sub>3</sub>C & it's synchronous twin A<sub>2</sub>C
  - And, ... if we use a TD-Critic, instead of a MonteCarlo baseline
    - Faster Learning than MC alone
    - Consistent Convergence than value based methods
    - And, we gain generalization
  - And that in essence leads us to A<sub>3</sub>C & then to DDPG !
- 



# Advantage

- Interestingly,  $R_t$  is nothing but  $Q_\pi(s_t, a_t)$
  - So  $R_t - V_\phi(s_t)$  becomes  $Q_\pi(s_t, a_t) - V_\phi(s_t)$ 
    - Which says how much better the new state-action value is over the current value i.e. Advantage
  - $A(s_t, a_t) = Q_\pi(s_t, a_t) - V_\phi(s_t)$



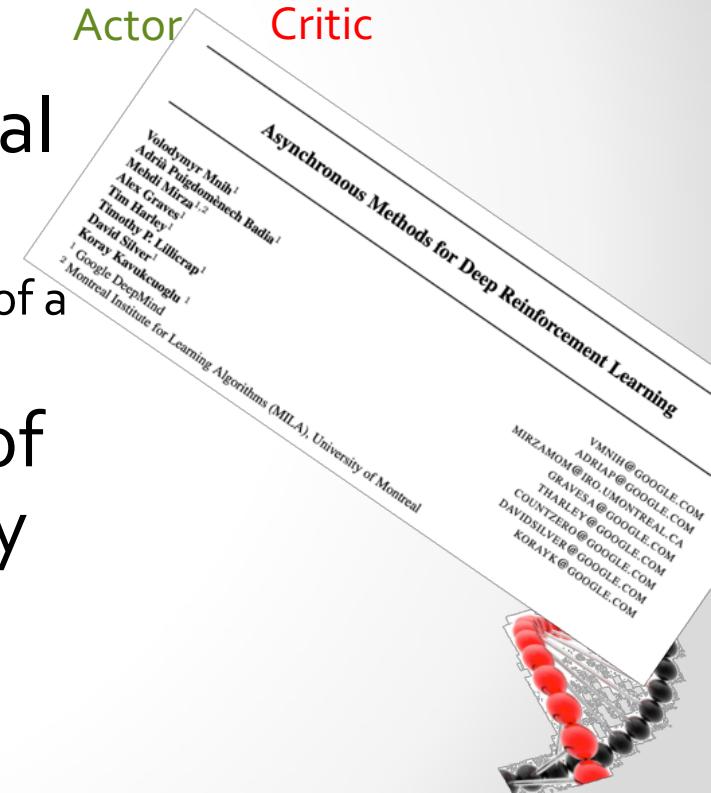


# A Basic Actor-Critic Agent

$$\nabla_{\theta} U(\theta) = \sum_{i=1 \text{ to } m} \sum_{t=0 \text{ to } T} \nabla_{\theta} \log \pi(a_t | s_t, \theta) A_t$$

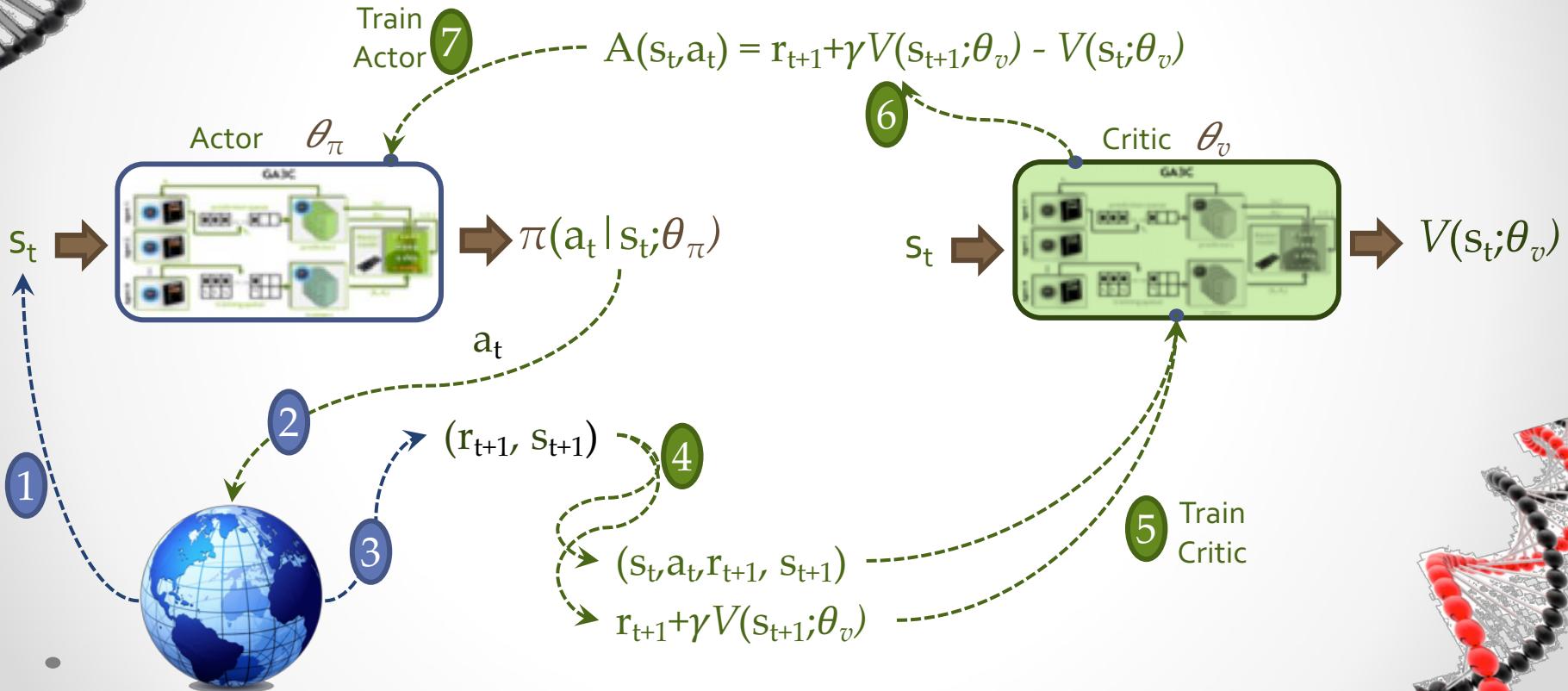
Actor      Critic

- Function Approximation ie neural network for Actor and Critic
  - i.e. the Policy and the Predictor of Advantage of a policy using TD estimate
- Once you know the advantage of a policy, we can tweak the policy up or down
  - <https://arxiv.org/abs/1602.01783>



# A3C Intuition

$$\pi_{\theta} = \pi_{\theta} + \alpha \sum \nabla \log \pi(a_t | s_t, \theta_{\pi}) (R(\tau) - V(s_t; \theta_v))$$



## One-step Actor-Critic (episodic), for estimating $\pi_\theta \approx \pi_*$

Input: a differentiable policy parameterization  $\pi(a|s, \theta)$

Input: a differentiable state-value function parameterization  $\hat{v}(s, w)$

Parameters: step sizes  $\alpha^\theta > 0$ ,  $\alpha^w > 0$

Initialize policy parameter  $\theta \in \mathbb{R}^{d'}$  and state-value weights  $w \in \mathbb{R}^d$  (e.g., to  $\mathbf{0}$ )

Loop forever (for each episode):

    Initialize  $S$  (first state of episode)

$I \leftarrow 1$

    Loop while  $S$  is not terminal (for each time step):

$A \sim \pi(\cdot|S, \theta)$

        Take action  $A$ , observe  $S', R$

$\delta \leftarrow R + \gamma \hat{v}(S', w) - \hat{v}(S, w)$                  (if  $S'$  is terminal, then  $\hat{v}(S', w) \doteq 0$ )

$w \leftarrow w + \alpha^w \delta \nabla \hat{v}(S, w)$

$\theta \leftarrow \theta + \alpha^\theta I \delta \nabla \ln \pi(A|S, \theta)$

$I \leftarrow \gamma I$

$S \leftarrow S'$

---

**Input:** policy  $\pi(a|s, \theta)$ ,  $\hat{v}(s, w)$   
**Parameters:** step sizes,  $\alpha > 0$ ,  $\beta > 0$   
**Output:** policy  $\pi(a|s, \theta)$

---

initialize policy parameter  $\theta$  and state-value weights  $w$

**for** *true* **do**

    initialize  $s$ , the first state of the episode

$I \leftarrow 1$

**for**  $s$  is not terminal **do**

$a \sim \pi(\cdot|s, \theta)$

        take action  $a$ , observe  $s', r$

$\delta \leftarrow r + \gamma \hat{v}(s', w) - \hat{v}(s, w)$  (if  $s'$  is terminal,  $\hat{v}(s', w) \doteq 0$ )

$w \leftarrow w + \beta \delta \nabla_w \hat{v}(s_t, w)$

$\theta \leftarrow \theta + \alpha I \delta \nabla_\theta \log \pi(a_t|s_t, \theta)$

$I \leftarrow \gamma I$

$s \leftarrow s'$

**end**

**end**

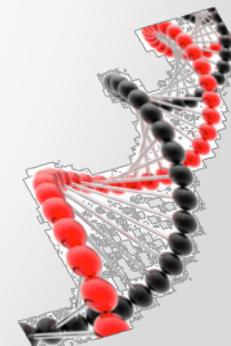
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**Algorithm 7:** Actor-Critic (episodic), adapted from Sutton and Barto (2018)

---



# A3C

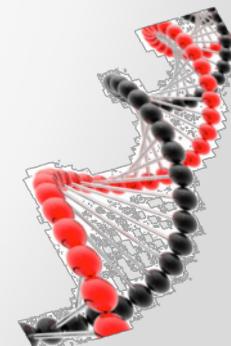
- A3C can share networks between the Actor and Critic.
    - But harder to train – so start with 2 networks, do hyperparameter and architecture tuning and then combine for performance
  - N-step bootstrapping TD(lambda) with lambda = n
    - More n, less bias while keeping variance under control
    - Usually 4-5 step bootstrapping are the best
      - Update last n steps
  - A3C doesn't use experience replay but gets diversity from parallel training ie running multiple agents to a common buffer
  - On or off policy ? On ! Stable and consistent convergence property !
    - Off policy often unstable and can diverge with nn
    - But there is work to make off-policy critic better
      - Q-Prop: Sample-Efficient Policy Gradient with An Off-Policy Critic <https://arxiv.org/abs/1611.02247>
  - A2C – Synchronous A3C !
    - Synchronous point, update network and update gradients of all agents
    - A3C CPU is Ok. A2C – better on a GPU
  - UC Berkeley Soft Actor Critic ! New development as of Jan'19
    - <https://bair.berkeley.edu/blog/2018/12/14/sac/>
- 

global shared parameter vectors  $\theta$  and  $\theta_v$ , thread-specific parameter vectors  $\theta'$  and  $\theta'_v$   
 global shared counter  $T = 0, T_{max}$   
 initialize step counter  $t \leftarrow 1$   
**for**  $T \leq T_{max}$  **do**  
     reset gradients,  $d\theta \leftarrow 0$  and  $d\theta_v \leftarrow 0$   
     synchronize thread-specific parameters  $\theta' = \theta$  and  $\theta'_v = \theta_v$   
     set  $t_{start} = t$ , get state  $s_t$   
     **for**  $s_t$  not terminal and  $t - t_{start} \leq t_{max}$  **do**  
         take  $a_t$  according to policy  $\pi(a_t|s_t; \theta')$   
         receive reward  $r_t$  and new state  $s_{t+1}$   
          $t \leftarrow t + 1, T \leftarrow T + 1$   
     **end**  
      $R = \begin{cases} 0 & \text{for terminal } s_t \\ V(s_t, \theta'_v) & \text{otherwise} \end{cases}$   
     **for**  $i \in \{t - 1, \dots, t_{start}\}$  **do**  
          $R \leftarrow r_i + \gamma R$   
         accumulate gradients wrt  $\theta'$ :  $d\theta \leftarrow d\theta + \nabla_{\theta'} \log \pi(a_i|s_i; \theta')(R - V(s_i; \theta'_v))$   
         accumulate gradients wrt  $\theta'_v$ :  $d\theta_v \leftarrow d\theta_v + \nabla_{\theta'_v}(R - V(s_i; \theta'_v))^2$   
     **end**  
     update asynchronously  $\theta$  using  $d\theta$ , and  $\theta_v$  using  $d\theta_v$   
**end**

---

**Algorithm 10:** A3C, each actor-learner thread, based on Mnih et al. (2016)

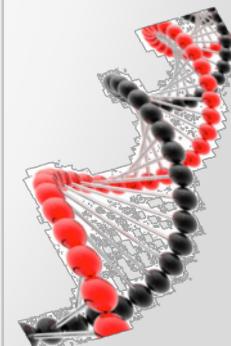
<https://arxiv.org/pdf/1810.06339.pdf>





## Algorithm S2 Asynchronous n-step Q-learning - pseudocode for each actor-learner thread.

```
// Assume global shared parameter vector  $\theta$ .  
// Assume global shared target parameter vector  $\theta^-$ .  
// Assume global shared counter  $T = 0$ .  
Initialize thread step counter  $t \leftarrow 1$   
Initialize target network parameters  $\theta^- \leftarrow \theta$   
Initialize thread-specific parameters  $\theta' = \theta$   
Initialize network gradients  $d\theta \leftarrow 0$   
repeat  
    Clear gradients  $d\theta \leftarrow 0$   
    Synchronize thread-specific parameters  $\theta' = \theta$   
     $t_{start} = t$   
    Get state  $s_t$   
    repeat  
        Take action  $a_t$  according to the  $\epsilon$ -greedy policy based on  $Q(s_t, a; \theta')$   
        Receive reward  $r_t$  and new state  $s_{t+1}$   
         $t \leftarrow t + 1$   
         $T \leftarrow T + 1$   
    until terminal  $s_t$  or  $t - t_{start} == t_{max}$   
     $R = \begin{cases} 0 & \text{for terminal } s_t \\ \max_a Q(s_t, a; \theta^-) & \text{for non-terminal } s_t \end{cases}$   
    for  $i \in \{t - 1, \dots, t_{start}\}$  do  
         $R \leftarrow r_i + \gamma R$   
    Accumulate gradients wrt  $\theta'$ :  $d\theta \leftarrow d\theta + \frac{\partial(R - Q(s_i, a_i; \theta'))^2}{\partial \theta'}$   
    end for  
    Perform asynchronous update of  $\theta$  using  $d\theta$ .  
    if  $T \bmod I_{target} == 0$  then  
         $\theta^- \leftarrow \theta$   
    end if  
until  $T > T_{max}$ 
```



---

**Algorithm S3** Asynchronous advantage actor-critic - pseudocode for each actor-learner thread.

---

// Assume global shared parameter vectors  $\theta$  and  $\theta_v$ , and global shared counter  $T = 0$

// Assume thread-specific parameter vectors  $\theta'$  and  $\theta'_v$

Initialize thread step counter  $t \leftarrow 1$

**repeat**

    Reset gradients:  $d\theta \leftarrow 0$  and  $d\theta_v \leftarrow 0$ .

    Synchronize thread-specific parameters  $\theta' = \theta$  and  $\theta'_v = \theta_v$

$t_{start} = t$

    Get state  $s_t$

**repeat**

        Perform  $a_t$  according to policy  $\pi(a_t | s_t; \theta')$

        Receive reward  $r_t$  and new state  $s_{t+1}$

$t \leftarrow t + 1$

$T \leftarrow T + 1$

**until** terminal  $s_t$  **or**  $t - t_{start} == t_{max}$

$R = \begin{cases} 0 & \text{for terminal } s_t \\ V(s_t, \theta'_v) & \text{for non-terminal } s_t // \text{Bootstrap from last state} \end{cases}$

**for**  $i \in \{t - 1, \dots, t_{start}\}$  **do**

$R \leftarrow r_i + \gamma R$

        Accumulate gradients wrt  $\theta'$ :  $d\theta \leftarrow d\theta + \nabla_{\theta'} \log \pi(a_i | s_i; \theta') (R - V(s_i; \theta'_v))$

        Accumulate gradients wrt  $\theta'_v$ :  $d\theta_v \leftarrow d\theta_v + \partial (R - V(s_i; \theta'_v))^2 / \partial \theta'_v$

**end for**

    Perform asynchronous update of  $\theta$  using  $d\theta$  and of  $\theta_v$  using  $d\theta_v$ .

**until**  $T > T_{max}$

---



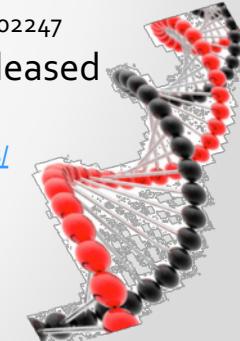
# Evolution of Policy Gradients

## DDPG

- Silver et al. released the DPG algorithm in 2014
  - <http://proceedings.mlr.press/v32/silver14.pdf>
- Lillicrap et al. iterated DPG with DDPG in 2015
  - <https://arxiv.org/abs/1509.02971>
- Ornstein–Uhlenbeck process
  - [https://en.wikipedia.org/wiki/Ornstein–Uhlenbeck\\_process](https://en.wikipedia.org/wiki/Ornstein–Uhlenbeck_process)
- A3c vs DDPG
  - <https://yodahuang.github.io/articles/DDPG-vs-A2C/>

## PPO

- In 2016, Schulman et al. released TRPO() and GAE algorithms(GAE on TRPO)
  - TRPO : <https://arxiv.org/abs/1502.05477>
  - GAE : <https://arxiv.org/abs/1506.02438>
- PPO (Proximal Policy Optimization Algorithms)
  - <https://arxiv.org/abs/1707.06347>
- Q-Prop: Sample-Efficient Policy Gradient with An Off-Policy Critic
  - Gu, Lillicrap, Levine : <https://arxiv.org/abs/1611.02247>
- Sergey Levine, Chelsea Finn, et al. released the GPS algorithm
  - Guided Policy Search <http://rll.berkeley.edu/gps/>





# A3C vs DDPG

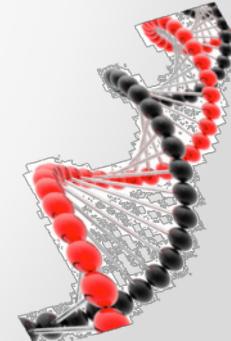
## A3C

- Episode (~MC paradigm)
- On-line, on-policy
- Loss = loglikelihood
- Continuous action can be modelled as a Gaussian vector

## DDPG

- TD() & TD( $\lambda$ )
- Off-Policy
- Experience Replay
- Target network mix-in & blending via soft update
- Better for continuous state & action space

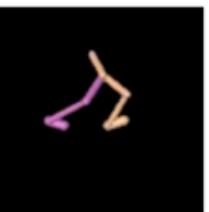
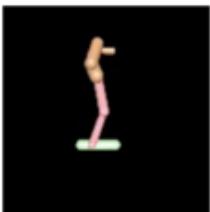
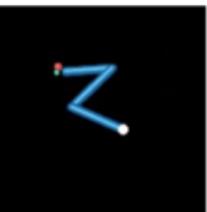
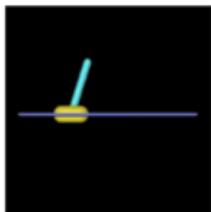
They both use the Actor-Critic design – approximately ! - finer semantics might differ





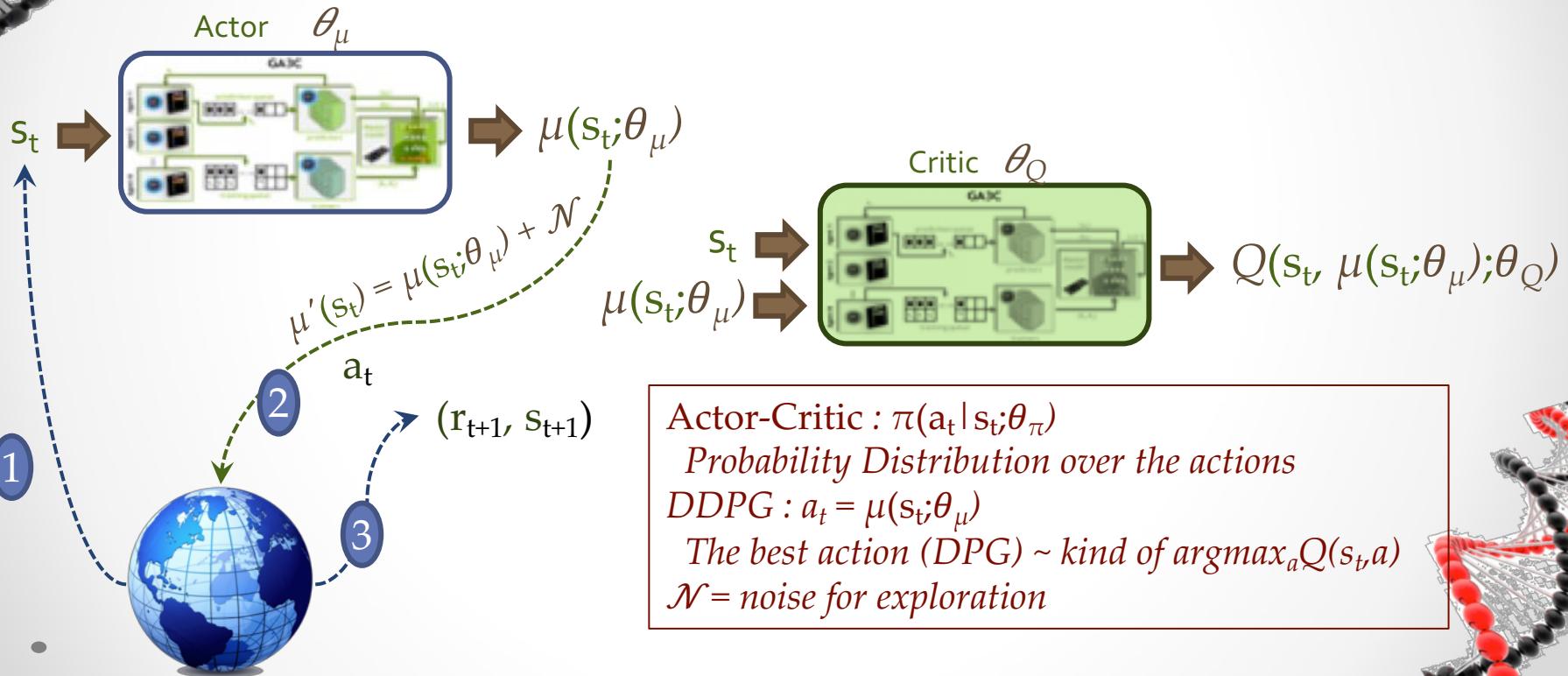
# DDPG

- Paper <https://arxiv.org/abs/1509.02971>
- Deterministic Policy :  $a_t = \mu(s_t | \theta^\mu)$
- Paper says it is actor-critic
  - Morales – it is more of an approx. DQN for continuous *action* space similar to NAF(<https://arxiv.org/abs/1603.00748>)
  - The critic is a maximizer not a baseline
- A key feature of the approach is its simplicity
  - *It requires only a straightforward actor-critic architecture and learning algorithm with very few “moving parts”, making it easy to implement and scale to more difficult problems and larger networks*



# DDPG Intuition


$$\mu_{\theta(t+1)} = \mu_\theta + \alpha \sum \nabla_a Q(s_t, a; \theta_Q) | (a = \mu(s_t)) \nabla_{\theta_\mu} \mu(s_t; \theta_\mu)$$





---

**Algorithm 1** DDPG algorithm

---

Randomly initialize critic network  $Q(s, a | \theta^Q)$  and actor  $\mu(s | \theta^\mu)$  with weights  $\theta^Q$  and  $\theta^\mu$ .

Initialize target network  $Q'$  and  $\mu'$  with weights  $\theta^{Q'} \leftarrow \theta^Q, \theta^{\mu'} \leftarrow \theta^\mu$

Initialize replay buffer  $R$

**for** episode = 1, M **do**

    Initialize a random process  $\mathcal{N}$  for action exploration

    Receive initial observation state  $s_1$

**for** t = 1, T **do**

        Select action  $a_t = \mu(s_t | \theta^\mu) + \mathcal{N}_t$  according to the current policy and exploration noise

        Execute action  $a_t$  and observe reward  $r_t$  and observe new state  $s_{t+1}$

        Store transition  $(s_t, a_t, r_t, s_{t+1})$  in  $R$

        Sample a random minibatch of  $N$  transitions  $(s_i, a_i, r_i, s_{i+1})$  from  $R$

        Set  $y_i = r_i + \gamma Q'(s_{i+1}, \mu'(s_{i+1} | \theta^{\mu'}) | \theta^{Q'})$

        Update critic by minimizing the loss:  $L = \frac{1}{N} \sum_i (y_i - Q(s_i, a_i | \theta^Q))^2$

        Update the actor policy using the sampled policy gradient:

$$\nabla_{\theta^\mu} J \approx \frac{1}{N} \sum_i \nabla_a Q(s, a | \theta^Q) |_{s=s_i, a=\mu(s_i)} \nabla_{\theta^\mu} \mu(s | \theta^\mu) |_{s_i}$$

    Update the target networks:

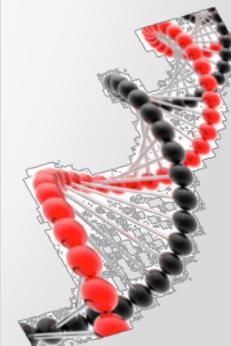
$$\theta^{Q'} \leftarrow \tau \theta^Q + (1 - \tau) \theta^{Q'}$$

$$\theta^{\mu'} \leftarrow \tau \theta^\mu + (1 - \tau) \theta^{\mu'}$$

**end for**

**end for**

---





---

**Algorithm 1** Deep Deterministic Policy Gradient

---

1: Input: initial policy parameters  $\theta$ , Q-function parameters  $\phi$ , empty replay buffer  $\mathcal{D}$   
2: Set target parameters equal to main parameters  $\theta_{\text{targ}} \leftarrow \theta$ ,  $\phi_{\text{targ}} \leftarrow \phi$   
3: **repeat**  
4:   Observe state  $s$  and select action  $a = \text{clip}(\mu_\theta(s) + \epsilon, a_{\text{Low}}, a_{\text{High}})$ , where  $\epsilon \sim \mathcal{N}$   
5:   Execute  $a$  in the environment  
6:   Observe next state  $s'$ , reward  $r$ , and done signal  $d$  to indicate whether  $s'$  is terminal  
7:   Store  $(s, a, r, s', d)$  in replay buffer  $\mathcal{D}$   
8:   If  $s'$  is terminal, reset environment state.  
9:   **if** it's time to update **then**  
10:     **for** however many updates **do**  
11:       Randomly sample a batch of transitions,  $B = \{(s, a, r, s', d)\}$  from  $\mathcal{D}$   
12:       Compute targets

$$y(r, s', d) = r + \gamma(1 - d)Q_{\phi_{\text{targ}}}(s', \mu_{\theta_{\text{targ}}}(s'))$$

13:     Update Q-function by one step of gradient descent using

$$\nabla_\phi \frac{1}{|B|} \sum_{(s, a, r, s', d) \in B} (Q_\phi(s, a) - y(r, s', d))^2$$

14:     Update policy by one step of gradient ascent using

$$\nabla_\theta \frac{1}{|B|} \sum_{s \in B} Q_\phi(s, \mu_\theta(s))$$

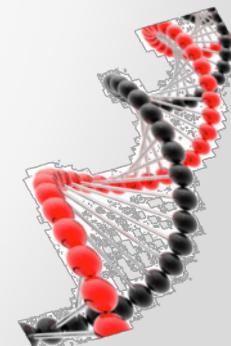
15:     Update target networks with

$$\begin{aligned}\phi_{\text{targ}} &\leftarrow \rho\phi_{\text{targ}} + (1 - \rho)\phi \\ \theta_{\text{targ}} &\leftarrow \rho\theta_{\text{targ}} + (1 - \rho)\theta\end{aligned}$$

16:     **end for**

17:     **end if**

18: **until** convergence





# Hands-On #11 : Balancing the Cart Pole w/ DDPG

- **Goal:**
  - Implement DDPG on the CartPole Environment
  - It is an overkill, but we will get a good understanding and also can compare against other algorithms
- **Steps:**
  - Program DDPG Algorithm
  - Run and Optimize
  - Plot Values, like we did in other exercises
- **DDPG for discrete actions**
  - DDPG for Discrete Action Domains  
[https://www.reddit.com/r/reinforcementlearning/comments/8k8bye/ddpg\\_for\\_discrete\\_action\\_domains/](https://www.reddit.com/r/reinforcementlearning/comments/8k8bye/ddpg_for_discrete_action_domains/)

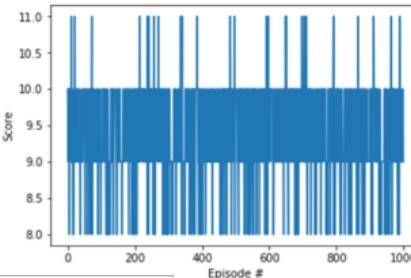




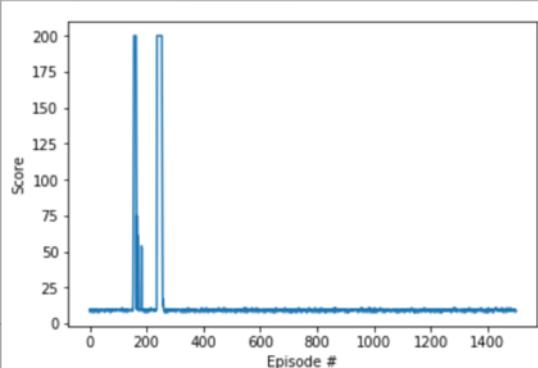
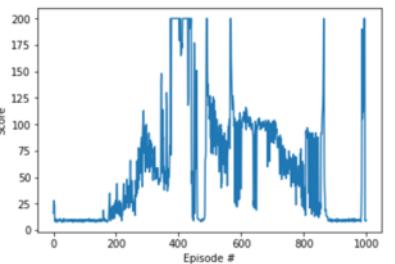
# Bad Runs ..

- Just meanders around
- Doesn't go beyond a score of 11
- Or learns well
- Then unlearns

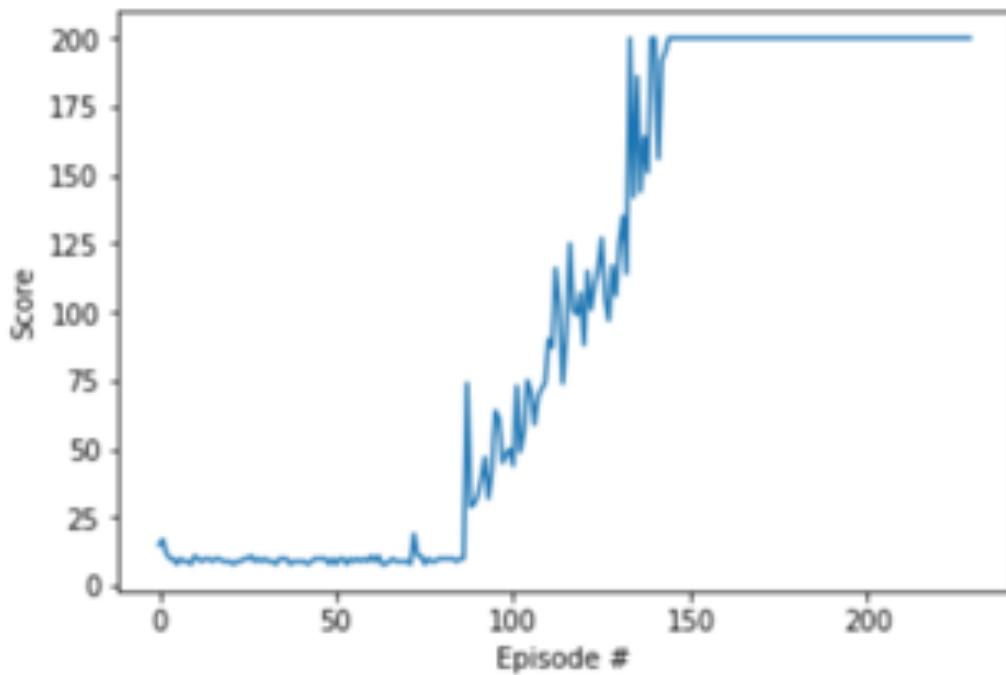
```
Episode 100    Average Score: 9.3131   Score:  9.00   Max_steps : 8
Episode 200    Average Score: 9.2929   Score: 10.00   Max_steps : 9
Episode 300    Average Score: 9.4242   Score:  8.00   Max_steps : 7
Episode 400    Average Score: 9.3232   Score: 10.00   Max_steps : 9
Episode 500    Average Score: 9.3333   Score: 10.00   Max_steps : 9
Episode 600    Average Score: 9.3333   Score:  9.00   Max_steps : 8
Episode 700    Average Score: 9.4343   Score: 10.00   Max_steps : 9
Episode 800    Average Score: 9.3838   Score: 10.00   Max_steps : 9
Episode 900    Average Score: 9.2929   Score: 10.00   Max_steps : 9
Episode 1000   Average Score: 9.2828   Score:  9.00   Max_steps : 8
Elapsed : 0:00:37.123424
2019-02-02 09:10:54.042185
```



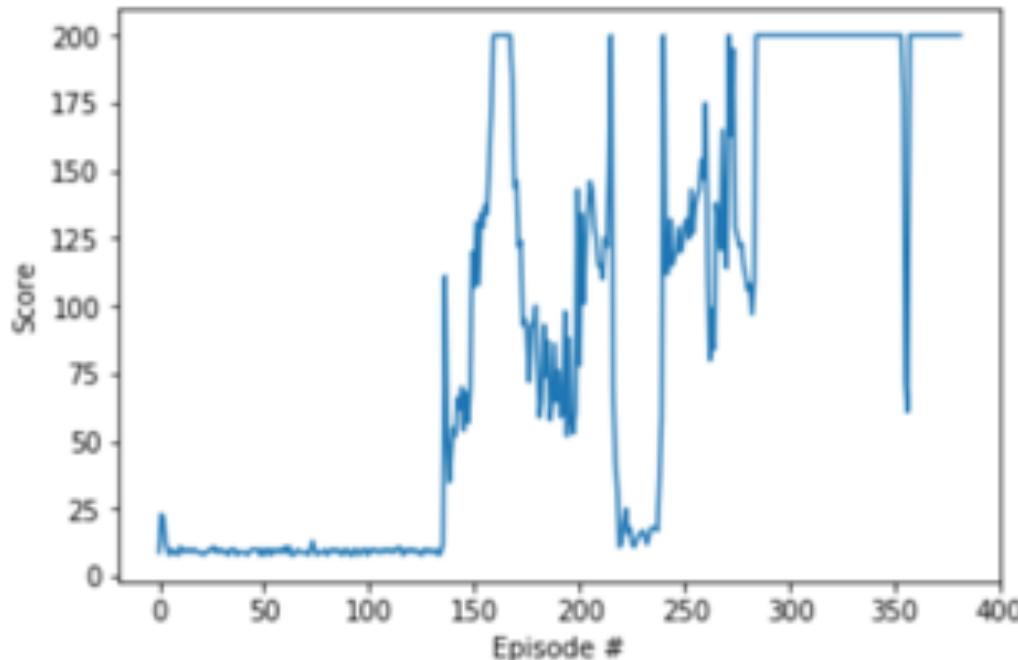
```
Episode 100    Average Score: 9.8080   Score:  8.00   Max_steps : 7
Episode 200    Average Score: 11.433   Score: 18.00   Max_steps : 17
Episode 300    Average Score: 42.622   Score: 59.00   Max_steps : 58
Episode 400    Average Score: 98.055   Score: 200.00  Max_steps : 199
Episode 500    Average Score: 113.16   Score: 110.00  Max_steps : 109
Episode 600    Average Score: 89.211   Score: 100.00  Max_steps : 99
Episode 700    Average Score: 94.122   Score: 85.00   Max_steps : 84
Episode 800    Average Score: 65.322   Score: 30.00   Max_steps : 29
Episode 900    Average Score: 44.555   Score: 10.00   Max_steps : 9
Episode 1000   Average Score: 24.555   Score:  9.00   Max_steps : 8
Elapsed : 0:03:46.871175
2019-02-02 09:18:48.363542
```



Episode 100      Average Score: 14.377      Score: 50.00      Max\_steps : 49  
Episode 200      Average Score: 162.22      Score: 200.00      Max\_steps : 199  
Episode 230      Average Score: 195.04      Score: 200.00      Max\_steps : 199  
Environment solved in 130 episodes!      Average Score: 195.04  
Elapsed : 0:01:16.801558  
2019-02-08 12:59:29.923779



Episode 100      Average Score: 9.61      Score: 8.00      Max\_steps : 79  
Episode 200      Average Score: 71.03      Score: 143.00      Max\_steps : 142  
Episode 300      Average Score: 114.96      Score: 200.00      Max\_steps : 199  
Episode 382      Average Score: 195.17      Score: 200.00      Max\_steps : 199  
Environment solved in 282 episodes!      Average Score: 195.17  
Elapsed : 0:02:29.415469  
2019-01-13 18:14:48.885969

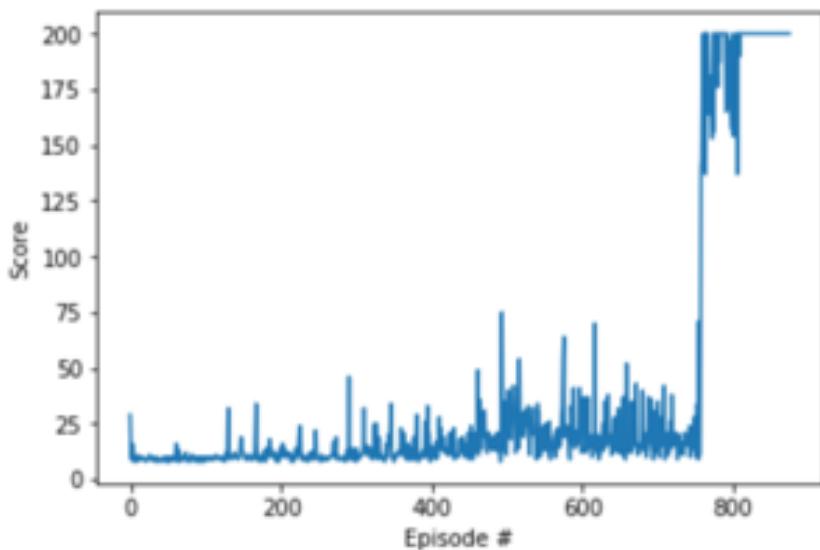


*Perfect Test Score!*

Episode : 1 Score : 200.00 Steps : 199  
Episode : 2 Score : 200.00 Steps : 199  
Episode : 3 Score : 200.00 Steps : 199  
Episode : 4 Score : 200.00 Steps : 199  
Episode : 5 Score : 200.00 Steps : 199  
Episode : 6 Score : 200.00 Steps : 199  
Episode : 7 Score : 200.00 Steps : 199  
Episode : 8 Score : 200.00 Steps : 199  
Episode : 9 Score : 200.00 Steps : 199  
Episode : 10 Score : 200.00 Steps : 199  
Mean of 10 episodes = 200.0  
Elapsed : 0:00:00.517737  
2019-01-13 18:18:07.700678



Episode 100	Average Score: 9.8282	Score: 8.00	Max_steps : 7
Episode 200	Average Score: 11.033	Score: 14.00	Max_steps : 13
Episode 300	Average Score: 11.300	Score: 8.00	Max_steps : 7
Episode 400	Average Score: 13.588	Score: 11.00	Max_steps : 10
Episode 500	Average Score: 16.977	Score: 11.00	Max_steps : 10
Episode 600	Average Score: 22.666	Score: 26.00	Max_steps : 25
Episode 700	Average Score: 20.444	Score: 12.00	Max_steps : 11
Episode 800	Average Score: 89.944	Score: 200.00	Max_steps : 199
Episode 875	Average Score: 195.33	Score: 200.00	Max_steps : 199
Environment solved in 775 episodes!	Average Score: 195.33		
Elapsed : 0:02:12.733915			
2019-01-18 09:19:16.580979			

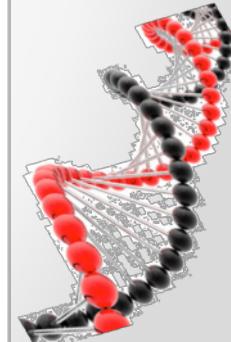
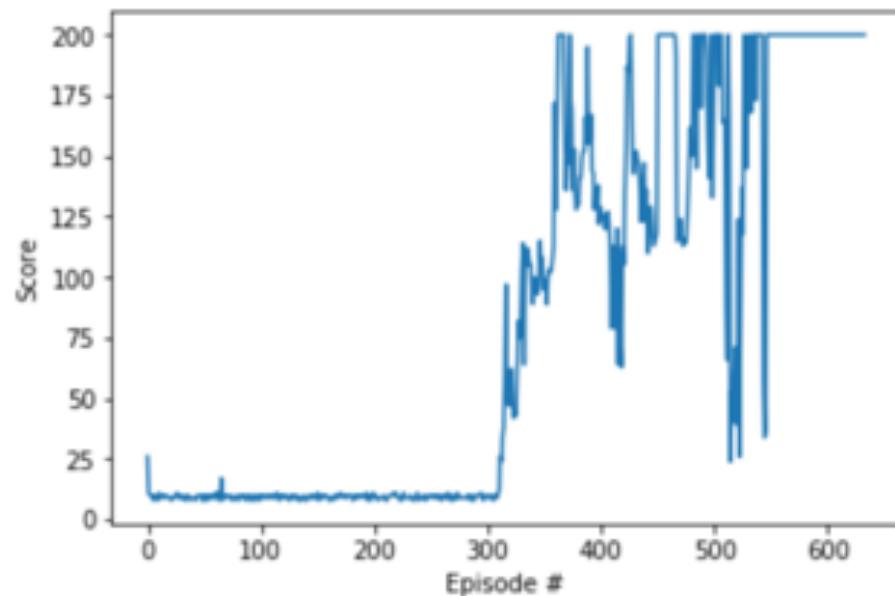


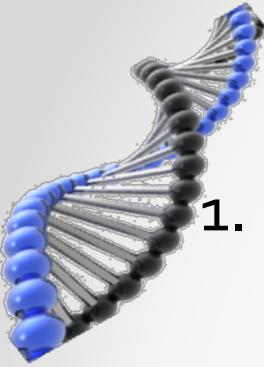


Episode 100	Average Score: 9.5858	Score: 8.00	Max_steps : 7
Episode 200	Average Score: 9.4444	Score: 11.00	Max_steps : 10
Episode 300	Average Score: 9.3535	Score: 10.00	Max_steps : 9
Episode 400	Average Score: 104.71	Score: 129.00	Max_steps : 128
Episode 500	Average Score: 149.30	Score: 170.00	Max_steps : 169
Episode 600	Average Score: 173.89	Score: 200.00	Max_steps : 199
Episode 633	Average Score: 195.01	Score: 200.00	Max_steps : 199
Environment solved in 533 episodes!		Average Score: 195.01	

Elapsed : 0:03:13.291465

2019-02-02 09:44:52.322328

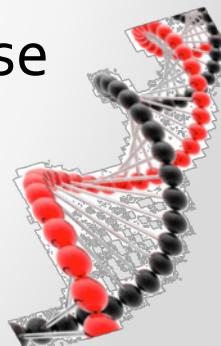


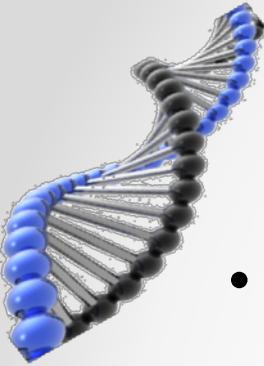


# Lessons from Implementation

1. Ornstein-Uhlenbeck process for exploration noise !
  - o “.. Deterministic policy gradient might not explore the full state and action space”
  - o Need a noise process to encourage exploration :  $a_t = \mu(s_t|\theta^\mu) + \mathcal{N}_t$
  - o “Generates temporally correlated exploration”
  - o “Exploration efficiency with inertia”
2. Unlearn & diverge / slow
  - o We can see what Lillicrap, Silver\* et al refers to as “*instability in learning wherein progress on a problem is either destroyed by subsequent learning updates, or else learning is too slow to be practical*”
3. A good solution for the cartpole
4. Very sensitive to hyperparameters – may be because DDPG is an overkill for the cartpole
5. Remember to restart the Kernel between tries

\*<https://arxiv.org/pdf/1509.02971.pdf>

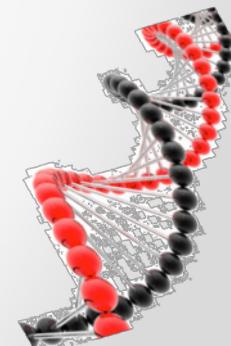




# Quiz



- What is the DQN DNN topology ?
  -
- What is the input size ? Output size ?
  -
- What is the output of the actor network ?
  -
- How does the output translate to an action ?
  -
- Is the policy deterministic or stochastic ?
  -
- How do you characterize this w.r.t others ?
  -



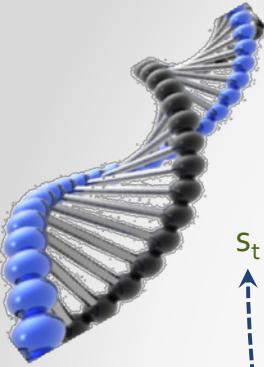


# Quiz

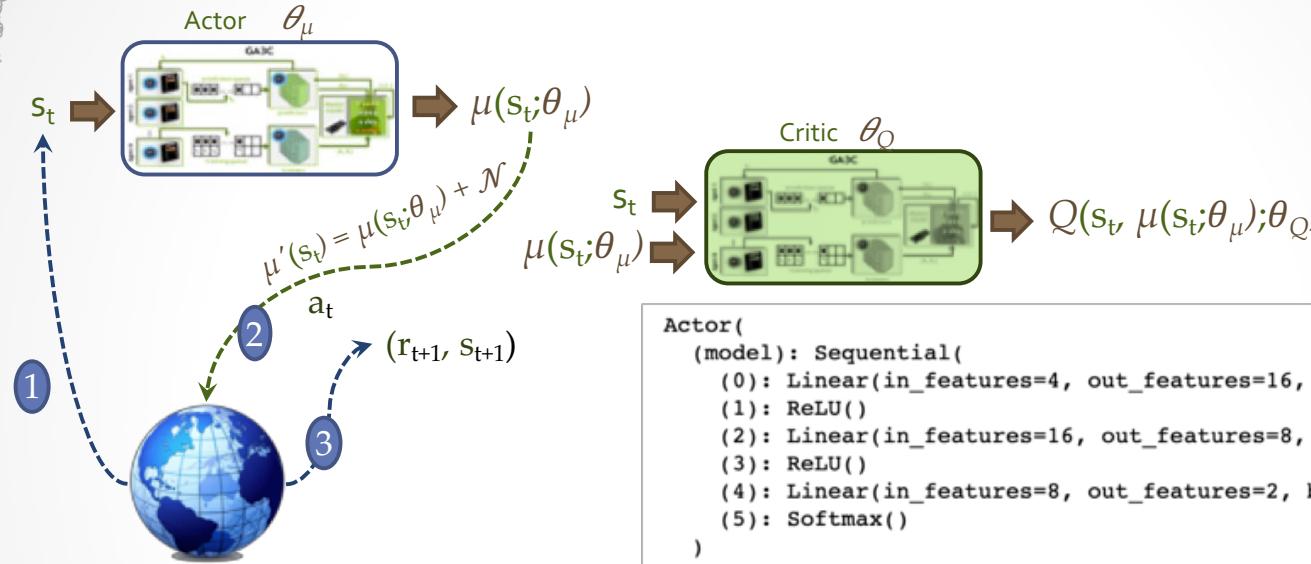


- What is the DQN DNN topology ?
  - FC16-FC8-FC2
- What is the input size ? Output size ?
  - Input = 4 (state), output = 2 (actions)
- What is the output of the actor network ?
  - softmax
- How does the output translate to an action ?
  - sample
- Is the policy deterministic or stochastic ?
  - Stochastic ! We get it as a part of the architecture !
- How do you characterize this w.r.t others ?
  - A good solution ! But sensitive to hyperparameters – [probably an overkill]



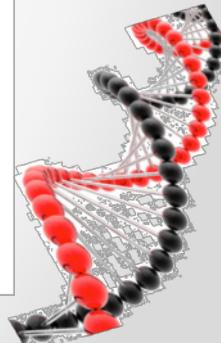


# Notice the Critic Network



The actions are fed into the network after the FC16 layer

```
Actor(  
    (model): Sequential(  
        (0): Linear(in_features=4, out_features=16, bias=True)  
        (1): ReLU()  
        (2): Linear(in_features=16, out_features=8, bias=True)  
        (3): ReLU()  
        (4): Linear(in_features=8, out_features=2, bias=True)  
        (5): Softmax()  
    )  
)  
Critic(  
    (hc_1): Sequential(  
        (0): Linear(in_features=4, out_features=16, bias=True)  
        (1): ReLU()  
    )  
    (hc_2): Sequential(  
        (0): Linear(in_features=18, out_features=8, bias=True)  
        (1): ReLU()  
        (2): Linear(in_features=8, out_features=1, bias=True)  
    )  
)
```





# Natural Policy Gradients & Trust Region variants

- Policy Gradients tend to get stuck in local plateaus
- Natural Policy Gradients operate in a different space than the parameter space, the Fisher metric
  - Instead of following the usual steepest direction in the parameter space, NPG algorithms follow the steepest direction with respect to the Fisher metric
  - The caveat with natural gradients is that, in the case of neural networks and their large number of parameters, it is usually impractical to compute, invert, and store the Fisher information matrix
- Trust Region algorithms leverage the natural gradients
  - As a modification to the natural gradient method, policy optimization methods based on a trust region aim at improving the policy while changing it in a controlled way.



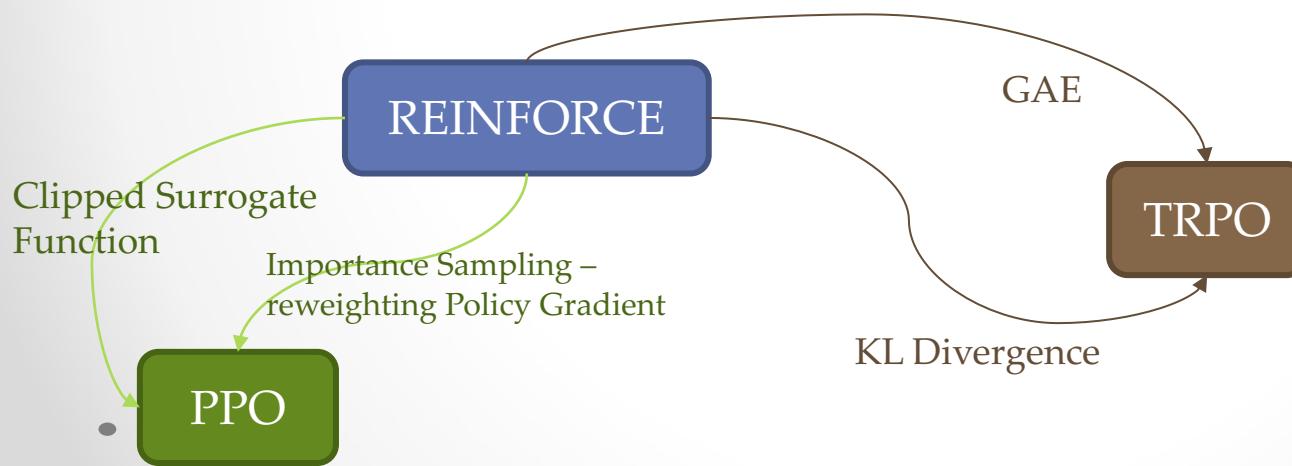


# PPO & TRPO

- Another interesting set of ideas that have become mainstream
- *“PPO has become the default reinforcement learning algorithm at OpenAI because of its ease of use and good performance”*
  - <https://blog.openai.com/openai-baselines-ppo/>
  - PPO paper <https://arxiv.org/abs/1707.06347>
- TRPO
  - <https://spinningup.openai.com/en/latest/algorithms/trpo.html>

The image shows the OpenAI Spinning Up logo, which consists of a green hexagon with a white atom-like symbol inside, followed by the text "OpenAI Spinning Up". Below the logo is a dark sidebar with the following menu items:

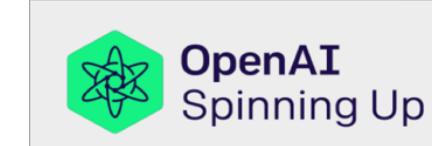
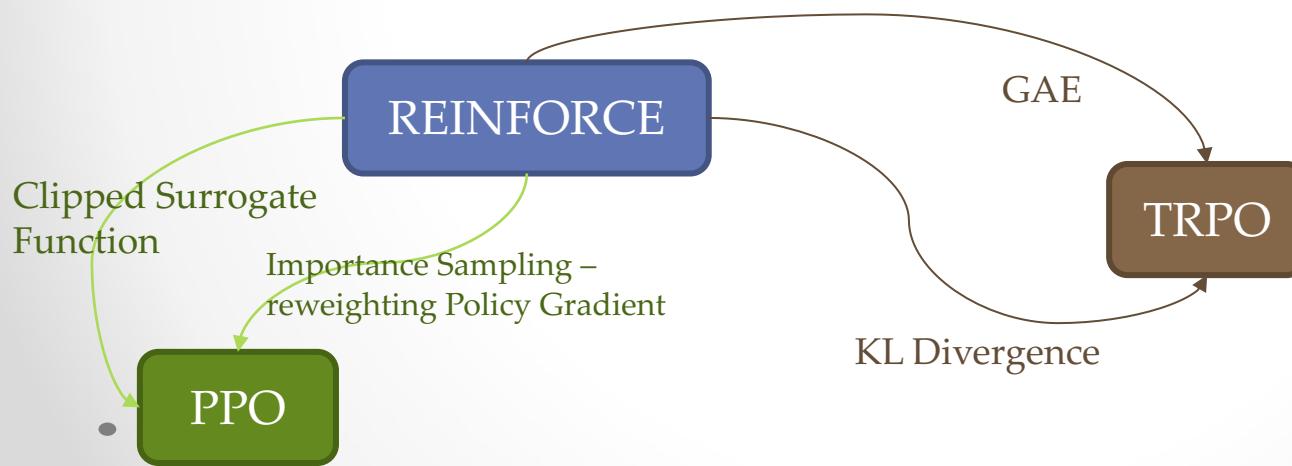
- ALGORITHMS DOCS
- Vanilla Policy Gradient
- Trust Region Policy Optimization
- Proximal Policy Optimization
- Deep Deterministic Policy Gradient
- Twin Delayed DDPG
- Soft Actor-Critic





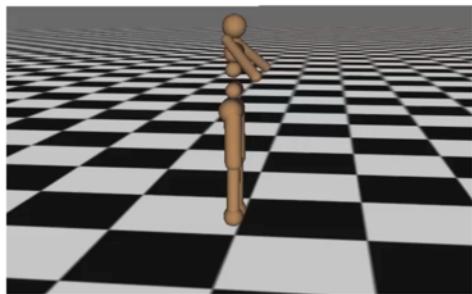
# PPO & TRPO

- These constraint-based policy optimization methods focus on restricting the changes in a policy using mechanisms like the KL divergence between the action distributions
- TRPO uses constrained updates and advantage function estimation to perform the update, resulting in the reformulated optimization
- Proximal Policy Optimization (PPO) is a variant of the TRPO algorithm, which formulates the constraint as a penalty or a clipping objective, instead of using the KL constraint

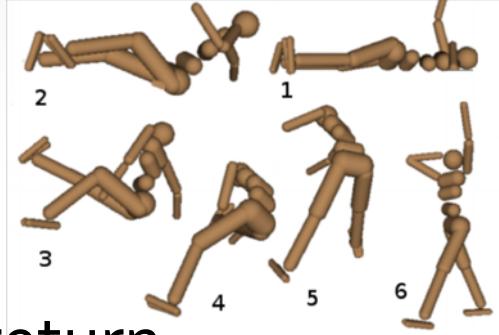


ALGORITHMS DOCS

- Vanilla Policy Gradient
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- Deep Deterministic Policy Gradient
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- Soft Actor-Critic



# GAE



- GAE (is a mechanism) – mixture of lambda return.  
Difficult to say which n is better
  - Combination of all n step weighted by exponentially decaying lambda
- High-Dimensional Continuous Control Using Generalized Advantage Estimation <https://arxiv.org/abs/1506.02438>
- Learning LocomoQon (TRPO + GAE)
  - Schulman, Moritz, Levine, Jordan, Abbeel, 2016

An interesting paper experiments with the agent's physical structure as a parameter  
Reinforcement Learning for Improving Agent Design  
• <https://arxiv.org/pdf/1810.03779.pdf>



# Actor-Critic with A3C or GAE

- Policy Gradient + Generalized Advantage Estimation:

- Init  $\pi_{\theta_0}$   $V_{\phi_0}^{\pi}$

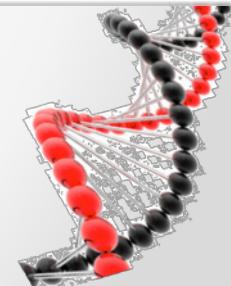
- Collect roll-outs  $\{s, u, s', r\}$  and  $\hat{Q}_i(s, u)$

- Update:  $\phi_{i+1} \leftarrow \min_{\phi} \sum_{(s, u, s', r)} \|\hat{Q}_i(s, u) - V_{\phi}^{\pi}(s)\|_2^2 + \kappa \|\phi - \phi_i\|_2^2$

$$\theta_{i+1} \leftarrow \theta_i + \alpha \frac{1}{m} \sum_{k=1}^m \sum_{t=0}^{H-1} \nabla_{\theta} \log \pi_{\theta_i}(u_t^{(k)} | s_t^{(k)}) \left( \hat{Q}_i(s_t^{(k)}, u_t^{(k)}) - V_{\phi_i}^{\pi}(s_t^{(k)}) \right)$$

**Async Advantage Actor Critic (A3C) [Mnih et al, 2016]**

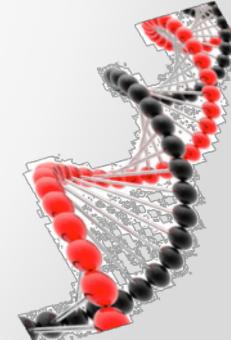
one of the above choices (e.g. k=5 step lookahead)





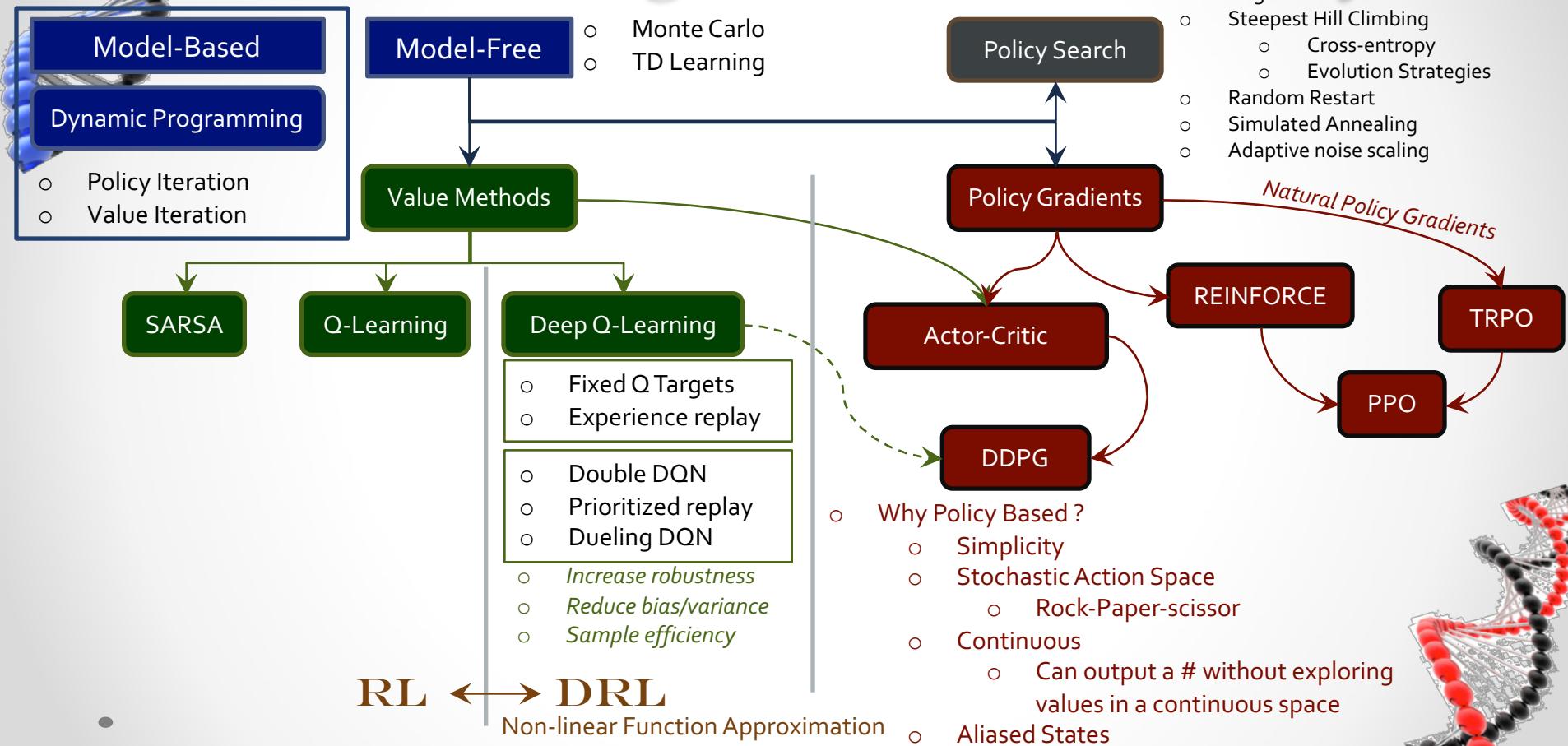
# 6. Conclusion

...





# RL Algorithm Taxonomy

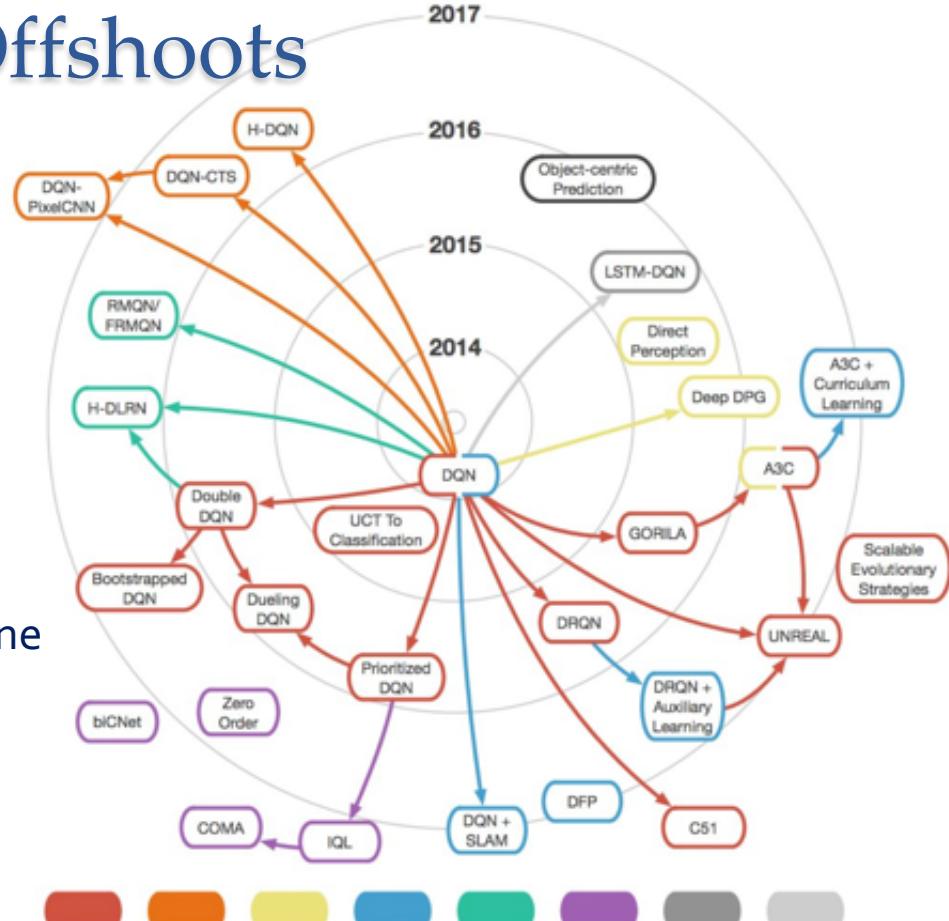




# Influences & Offshoots



- My view is throw it all away and start again,...
- Max Planck said, 'Science progresses one funeral at a time'
- *The future depends on some graduate student who is deeply suspicious of everything I have said.*



<https://wwwaxios.com/artificial-intelligence-pioneer-says-we-need-to-start-over-1513305524-f619efbd-9dbo-4947-a9b2-7a4c310a28fe.html>

<https://arxiv.org/abs/1708.07902>



# AlphaStar: Mastering the Real-Time Strategy Game StarCraft II

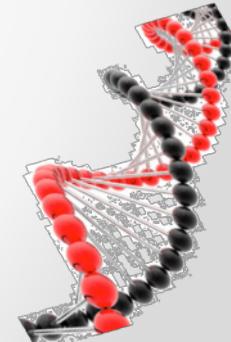
StarCraft, considered to be one of the most challenging Real-Time Strategy games and one of the longest-played esports of all time, has emerged by consensus as a "grand challenge" for AI research. Here, we introduce our StarCraft II program AlphaStar, the first Artificial Intelligence to defeat a top professional player.



The AlphaStar team  
10 hours ago



## Summary, technologies and networks



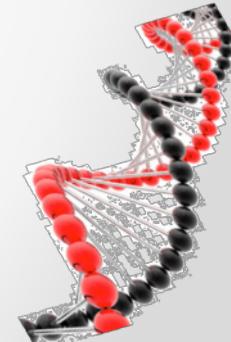
<https://deepmind.com/blog/alphastar-mastering-real-time-strategy-game-starcraft-ii/>

<https://www.theverge.com/2019/1/24/18196135/google-deepmind-ai-starcraft-2-victory>

We use our visual system not only to survive & navigate, but also to socialize, entertain, understand & learn the world @drfeifei



Can a machine understand the nuances and humor in this picture ?



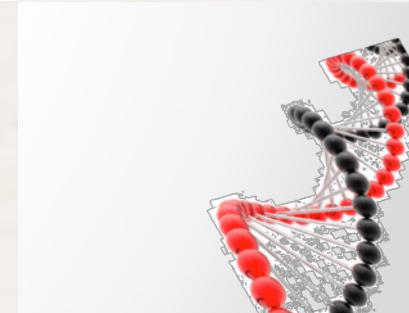
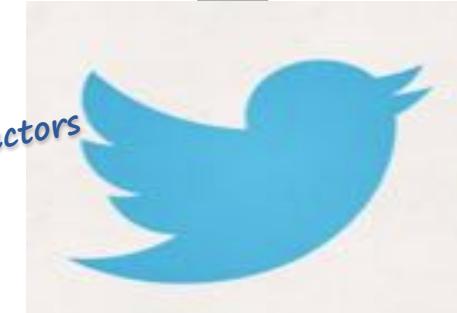


Thanks



Gracias

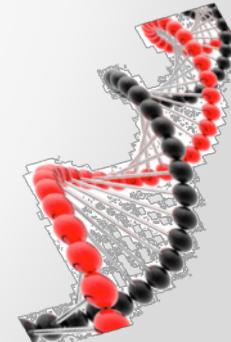
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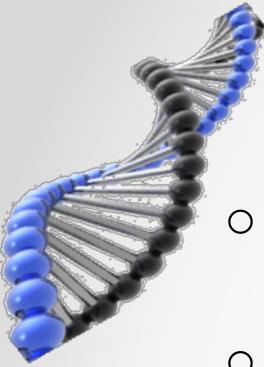




WIP, Notes & backup

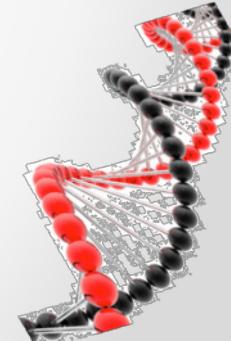
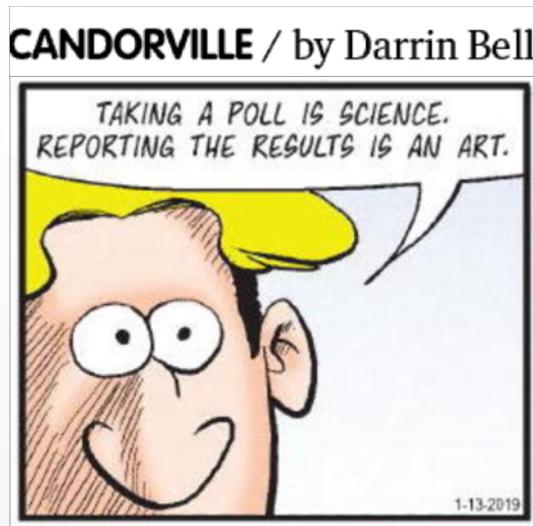
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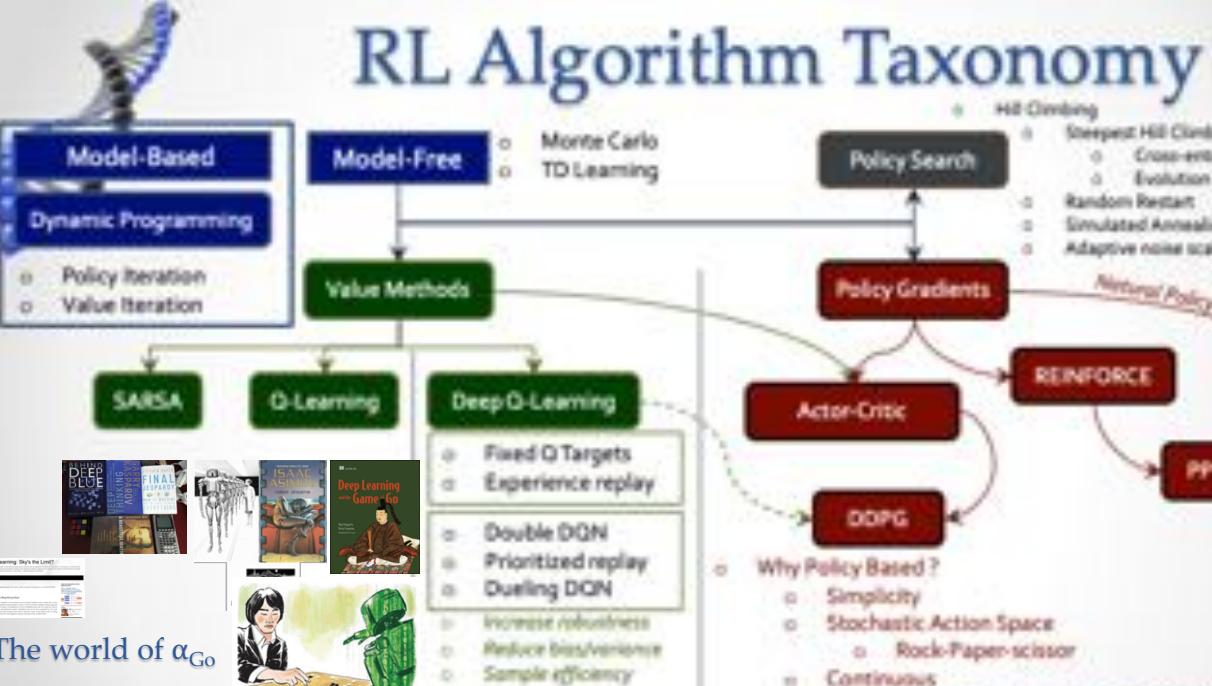
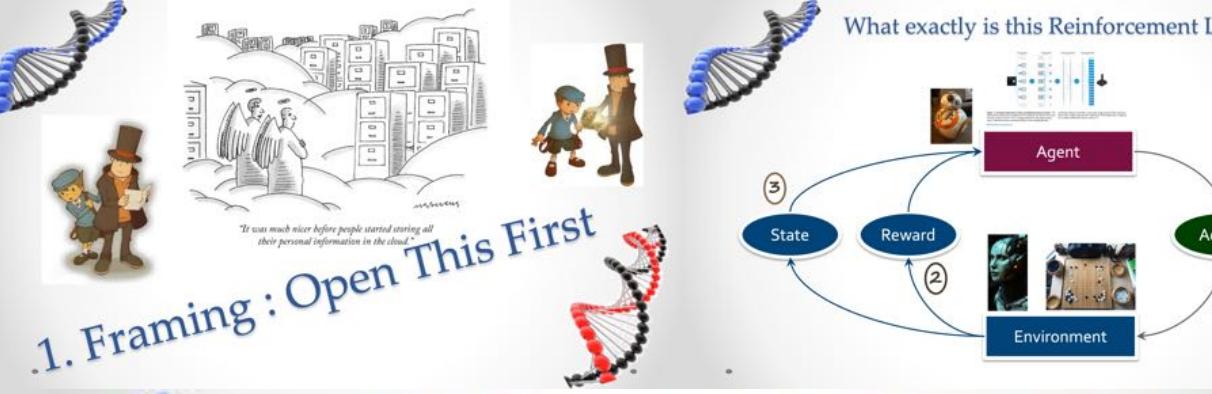




# Proposal Links

- <http://proposals.gptechconf.com/gtc-2019-training-sessions/edit.php?s=JYs1rgU3CUsh3ADzPpgs>
- <http://proposals.gptechconf.com/gtc-2019-training-sessions/edit.php?s=vYOO796coqXyMGclfbK7>





The world of  $\alpha_{Go}$