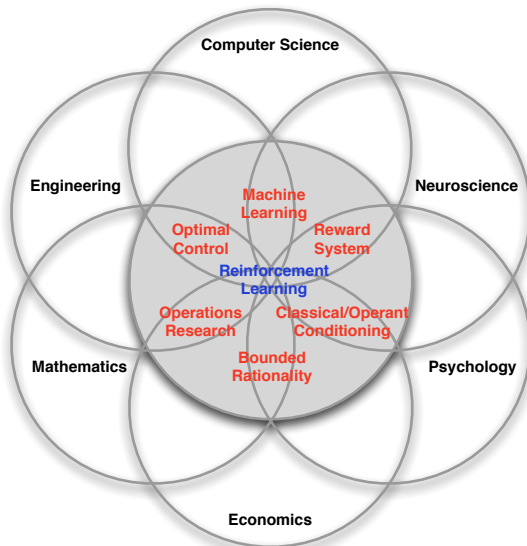
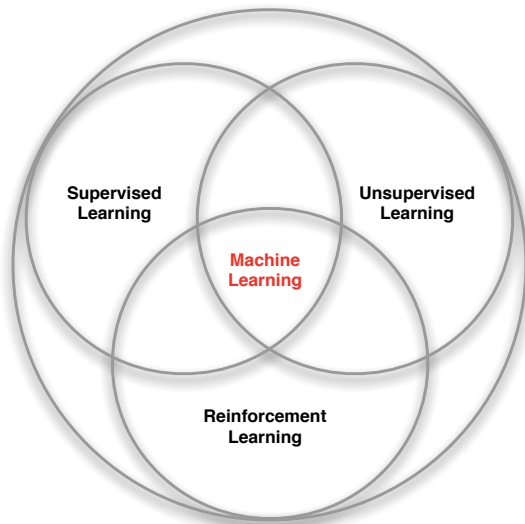


Many Faces of Reinforcement Learning



Branches of Machine Learning



Characteristics of Reinforcement Learning

What makes reinforcement learning different from other machine learning paradigms?

- There is no supervisor, only a *reward* signal
- Feedback is delayed, not instantaneous
- Time really matters (sequential, non i.i.d data)
- Agent's actions affect the subsequent data it receives

Examples of Reinforcement Learning

- Fly stunt manoeuvres in a helicopter
- Defeat the world champion at Backgammon
- Manage an investment portfolio
- Control a power station
- Make a humanoid robot walk
- Play many different Atari games better than humans

Helicopter Manoeuvres

Bipedal Robots

Atari

Rewards

- A **reward** R_t is a scalar feedback signal
- Indicates how well agent is doing at step t
- The agent's job is to maximise cumulative reward

Reinforcement learning is based on the **reward hypothesis**

Definition (Reward Hypothesis)

All goals can be described by the maximisation of expected cumulative reward

Do you agree with this statement?

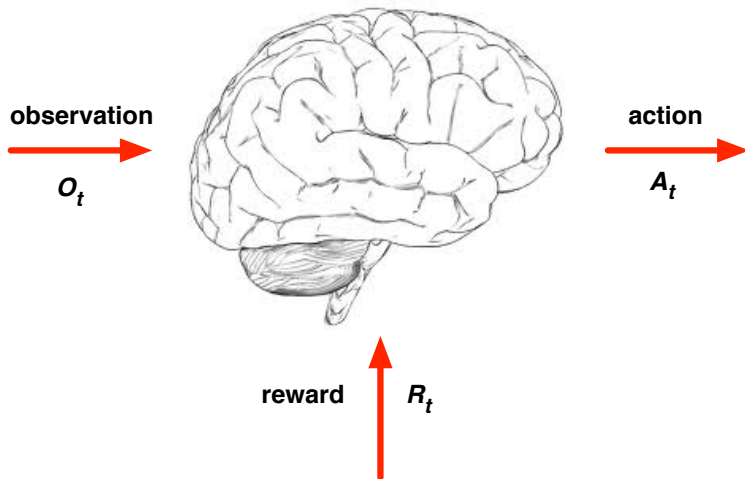
Examples of Rewards

- Fly stunt manoeuvres in a helicopter
 - +ve reward for following desired trajectory
 - -ve reward for crashing
- Defeat the world champion at Backgammon
 - +/ -ve reward for winning/losing a game
- Manage an investment portfolio
 - +ve reward for each \$ in bank
- Control a power station
 - +ve reward for producing power
 - -ve reward for exceeding safety thresholds
- Make a humanoid robot walk
 - +ve reward for forward motion
 - -ve reward for falling over
- Play many different Atari games better than humans
 - +/ -ve reward for increasing/decreasing score

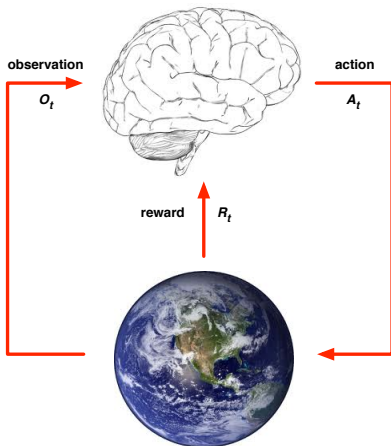
Sequential Decision Making

- Goal: *select actions to maximise total future reward*
- Actions may have long term consequences
- Reward may be delayed
- It may be better to sacrifice immediate reward to gain more long-term reward
- Examples:
 - A financial investment (may take months to mature)
 - Refuelling a helicopter (might prevent a crash in several hours)
 - Blocking opponent moves (might help winning chances many moves from now)

Agent and Environment



Agent and Environment



- At each step t the agent:
 - Executes action A_t
 - Receives observation O_t
 - Receives scalar reward R_t
- The environment:
 - Receives action A_t
 - Emits observation O_{t+1}
 - Emits scalar reward R_{t+1}
- t increments at env. step

History and State

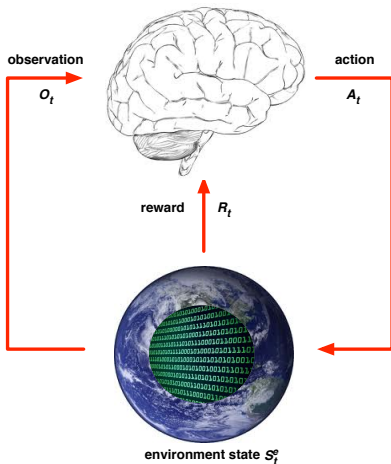
- The **history** is the sequence of observations, actions, rewards

$$H_t = O_1, R_1, A_1, \dots, A_{t-1}, O_t, R_t$$

- i.e. all observable variables up to time t
- i.e. the sensorimotor stream of a robot or embodied agent
- What happens next depends on the history:
 - The agent selects actions
 - The environment selects observations/rewards
- **State** is the information used to determine what happens next
- Formally, state is a function of the history:

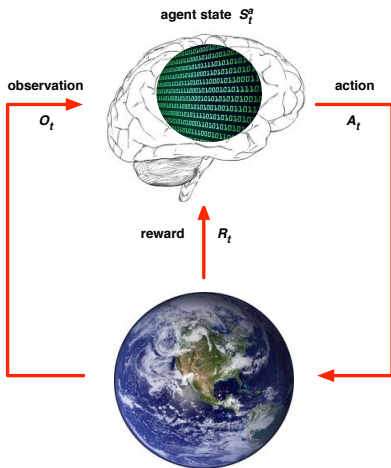
$$S_t = f(H_t)$$

Environment State



- The **environment state** S_t^e is the environment's private representation
- i.e. whatever data the environment uses to pick the next observation/reward
- The environment state is not usually visible to the agent
- Even if S_t^e is visible, it may contain irrelevant information

Agent State



- The **agent state** S_t^a is the agent's internal representation
- i.e. whatever information the agent uses to pick the next action
- i.e. it is the information used by reinforcement learning algorithms
- It can be any function of history:

$$S_t^a = f(H_t)$$

Information State

An **information state** (a.k.a. **Markov state**) contains all useful information from the history.

Definition

A state S_t is **Markov** if and only if

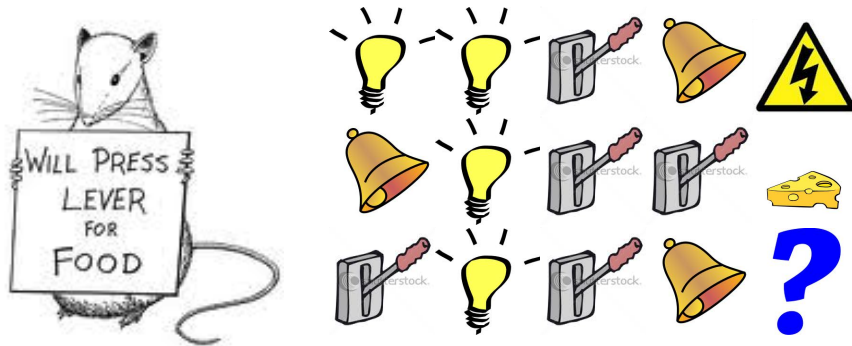
$$\mathbb{P}[S_{t+1} \mid S_t] = \mathbb{P}[S_{t+1} \mid S_1, \dots, S_t]$$

- “The future is independent of the past given the present”

$$H_{1:t} \rightarrow S_t \rightarrow H_{t+1:\infty}$$

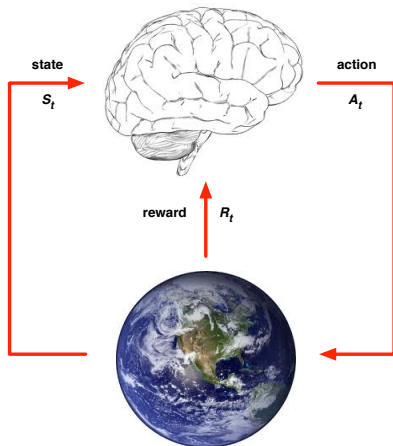
- Once the state is known, the history may be thrown away
- i.e. The state is a sufficient statistic of the future
- The environment state S_t^e is Markov
- The history H_t is Markov

Rat Example



- What if agent state = last 3 items in sequence?
- What if agent state = counts for lights, bells and levers?
- What if agent state = complete sequence?

Fully Observable Environments



Full observability: agent **directly** observes environment state

$$O_t = S_t^a = S_t^e$$

- Agent state = environment state = information state
- Formally, this is a **Markov decision process** (MDP)
- (Next lecture and the majority of this course)

Partially Observable Environments

- **Partial observability**: agent **indirectly** observes environment:
 - A robot with camera vision isn't told its absolute location
 - A trading agent only observes current prices
 - A poker playing agent only observes public cards
- Now agent state \neq environment state
- Formally this is a **partially observable Markov decision process** (POMDP)
- Agent must construct its own state representation S_t^a , e.g.
 - Complete history: $S_t^a = H_t$
 - **Beliefs** of environment state: $S_t^a = (\mathbb{P}[S_t^e = s^1], \dots, \mathbb{P}[S_t^e = s^n])$
 - Recurrent neural network: $S_t^a = \sigma(S_{t-1}^a W_s + O_t W_o)$

Major Components of an RL Agent

- An RL agent may include one or more of these components:
 - Policy: agent's behaviour function
 - Value function: how good is each state and/or action
 - Model: agent's representation of the environment

Policy

- A **policy** is the agent's behaviour
- It is a map from state to action, e.g.
- Deterministic policy: $a = \pi(s)$
- Stochastic policy: $\pi(a|s) = \mathbb{P}[A_t = a | S_t = s]$

Value Function

- Value function is a prediction of future reward
- Used to evaluate the goodness/badness of states
- And therefore to select between actions, e.g.

$$v_{\pi}(s) = \mathbb{E}_{\pi} [R_{t+1} + \gamma R_{t+2} + \gamma^2 R_{t+3} + \dots \mid S_t = s]$$

Example: Value Function in Atari

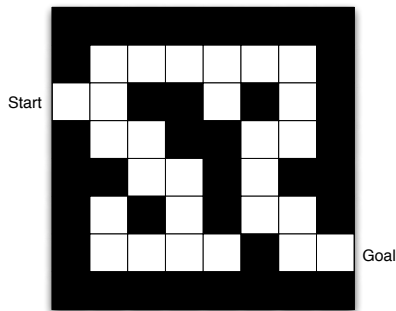
Model

- A **model** predicts what the environment will do next
- \mathcal{P} predicts the next state
- \mathcal{R} predicts the next (immediate) reward, e.g.

$$\mathcal{P}_{ss'}^a = \mathbb{P}[S_{t+1} = s' \mid S_t = s, A_t = a]$$

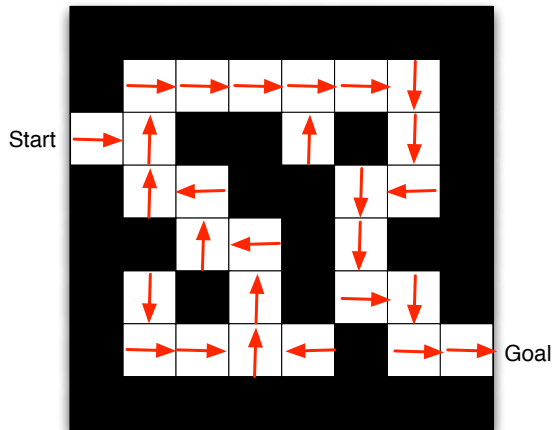
$$\mathcal{R}_s^a = \mathbb{E}[R_{t+1} \mid S_t = s, A_t = a]$$

Maze Example



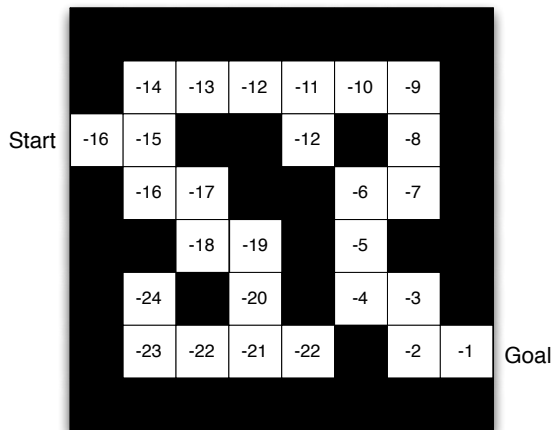
- Rewards: -1 per time-step
- Actions: N, E, S, W
- States: Agent's location

Maze Example: Policy



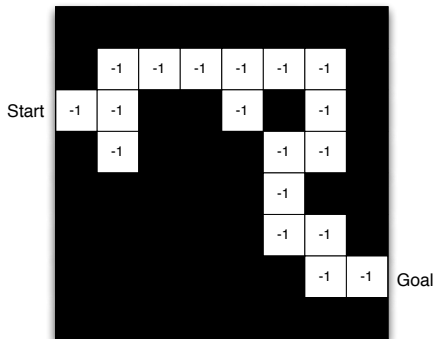
- Arrows represent policy $\pi(s)$ for each state s

Maze Example: Value Function



- Numbers represent value $v_{\pi}(s)$ of each state s

Maze Example: Model



- Agent may have an internal model of the environment
- Dynamics: how actions change the state
- Rewards: how much reward from each state
- The model may be imperfect

- Grid layout represents transition model $\mathcal{P}_{ss'}^a$
- Numbers represent immediate reward \mathcal{R}_s^a from each state s (same for all a)

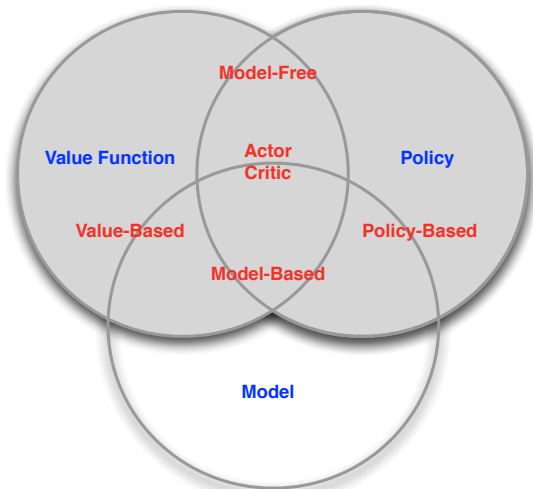
Categorizing RL agents (1)

- Value Based
 - No Policy (Implicit)
 - Value Function
- Policy Based
 - Policy
 - No Value Function
- Actor Critic
 - Policy
 - Value Function

Categorizing RL agents (2)

- Model Free
 - Policy and/or Value Function
 - No Model
- Model Based
 - Policy and/or Value Function
 - Model

RL Agent Taxonomy



Learning and Planning

Two fundamental problems in sequential decision making

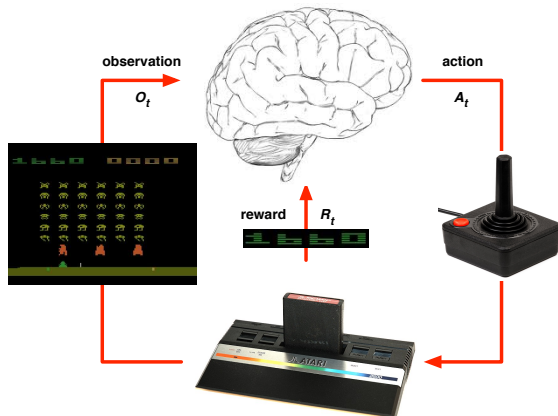
- Reinforcement Learning:

- The environment is initially unknown
- The agent interacts with the environment
- The agent improves its policy

- Planning:

- A model of the environment is known
- The agent performs computations with its model (without any external interaction)
- The agent improves its policy
- a.k.a. deliberation, reasoning, introspection, pondering, thought, search

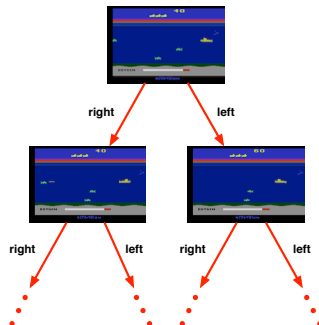
Atari Example: Reinforcement Learning



- Rules of the game are unknown
- Learn directly from interactive game-play
- Pick actions on joystick, see pixels and scores

Atari Example: Planning

- Rules of the game are known
- Can query emulator
 - perfect model inside agent's brain
- If I take action a from state s :
 - what would the next state be?
 - what would the score be?
- Plan ahead to find optimal policy
 - e.g. tree search



Exploration and Exploitation (1)

- Reinforcement learning is like trial-and-error learning
- The agent should discover a good policy
- From its experiences of the environment
- Without losing too much reward along the way

Exploration and Exploitation (2)

- *Exploration* finds more information about the environment
- *Exploitation* exploits known information to maximise reward
- It is usually important to explore as well as exploit

Examples

■ Restaurant Selection

Exploitation Go to your favourite restaurant

Exploration Try a new restaurant

■ Online Banner Advertisements

Exploitation Show the most successful advert

Exploration Show a different advert

■ Oil Drilling

Exploitation Drill at the best known location

Exploration Drill at a new location

■ Game Playing

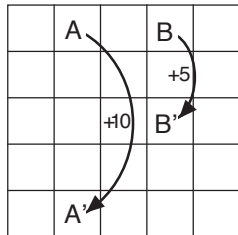
Exploitation Play the move you believe is best

Exploration Play an experimental move

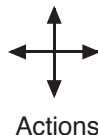
Prediction and Control

- Prediction: evaluate the future
 - Given a policy
- Control: optimise the future
 - Find the best policy

Gridworld Example: Prediction



(a)

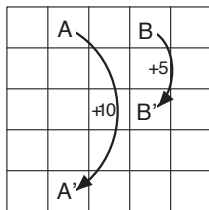


3.3	8.8	4.4	5.3	1.5
1.5	3.0	2.3	1.9	0.5
0.1	0.7	0.7	0.4	-0.4
-1.0	-0.4	-0.4	-0.6	-1.2
-1.9	-1.3	-1.2	-1.4	-2.0

(b)

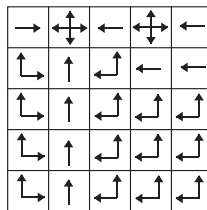
What is the value function for the uniform random policy?

Gridworld Example: Control



a) gridworld

22.0	24.4	22.0	19.4	17.5
19.8	22.0	19.8	17.8	16.0
17.8	19.8	17.8	16.0	14.4
16.0	17.8	16.0	14.4	13.0
14.4	16.0	14.4	13.0	11.7

b) v_* c) π_*

What is the optimal value function over all possible policies?

What is the optimal policy?