

## Outline

### Lecture 1: Introduction to Reinforcement Learning

David Silver

- 1 Admin
- 2 About Reinforcement Learning
- 3 The Reinforcement Learning Problem
- 4 Inside An RL Agent
- 5 Problems within Reinforcement Learning

## Class Information

## Assessment

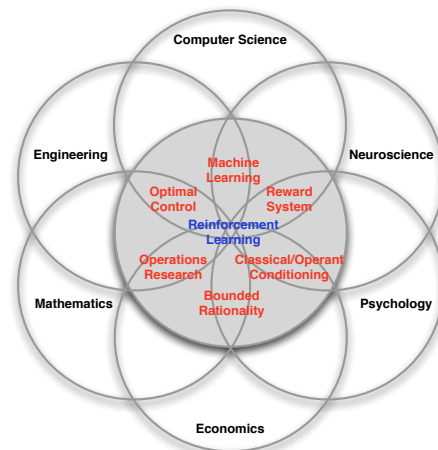
- Thursdays 9:30 to 11:00am
- Website:  
<http://www.cs.ucl.ac.uk/staff/D.Silver/web/Teaching.html>
- Group:  
<http://groups.google.com/group/csml-advanced-topics>
- Contact me: [d.silver@cs.ucl.ac.uk](mailto:d.silver@cs.ucl.ac.uk)

- Assessment will be 50% coursework, 50% exam
- Coursework
  - Assignment A: RL problem
  - Assignment B: Kernels problem
  - Assessment =  $\max(\text{assignment1}, \text{assignment2})$
- Examination
  - A: 3 RL questions
  - B: 3 kernels questions
  - Answer any 3 questions

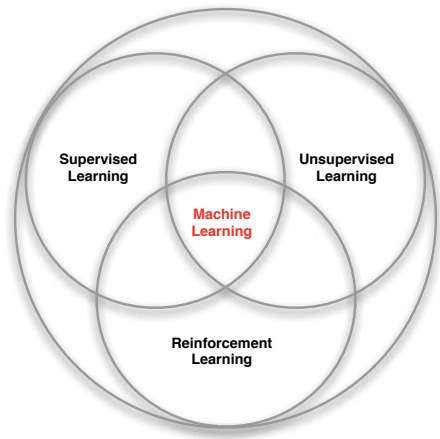
## Textbooks

## Many Faces of Reinforcement Learning

- An Introduction to Reinforcement Learning, Sutton and Barto, 1998
  - MIT Press, 1998
  - ~ 40 pounds
  - Available free online!
  - <http://webdocs.cs.ualberta.ca/~sutton/book/the-book.html>
- Algorithms for Reinforcement Learning, Szepesvari
  - Morgan and Claypool, 2010
  - ~ 20 pounds
  - Available free online!
  - <http://www.ualberta.ca/~szepesva/papers/RLAlgsInMDPs.pdf>



## 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?

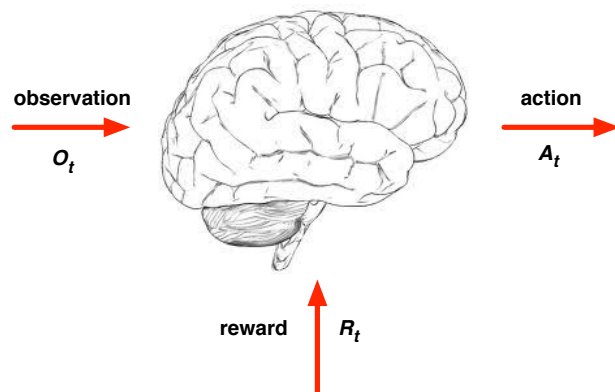
## Examples of Rewards

- 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

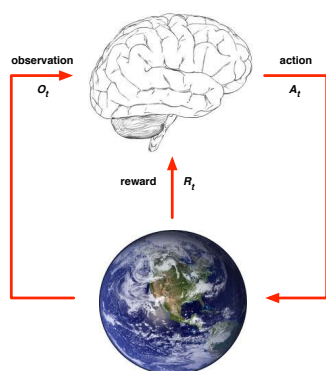
## Sequential Decision Making

- 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

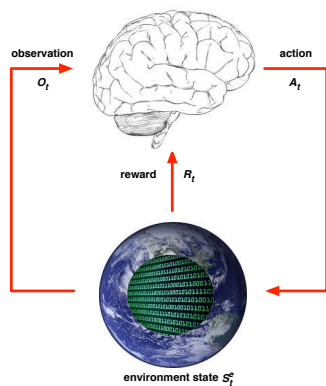
- The **history** is the sequence of observations, actions, rewards

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

- 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:

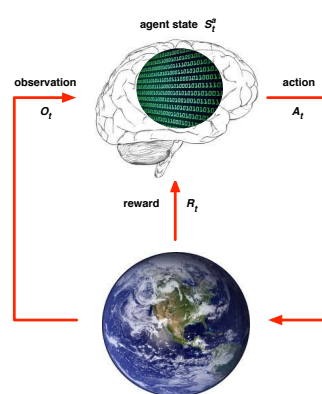
$$S_t = f(H_t)$$

## 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

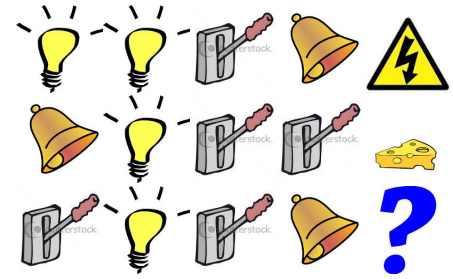
$$\mathbb{P}[S_{t+1} \mid S_t] = \mathbb{P}[S_{t+1} \mid S_1, \dots, S_t]$$

- "The future is independent of the past given the present"

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

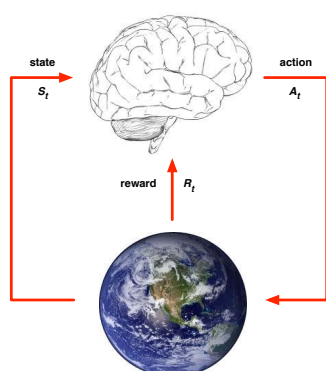
- Once the state is known, the history may be thrown away
- i.e. The state is a sufficient statistic of the future
- The environment state  $S_t^e$  is Markov
- The history  $H_t$  is Markov

## 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

## Policy

- 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

- 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

## Example: Value Function in Atari

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

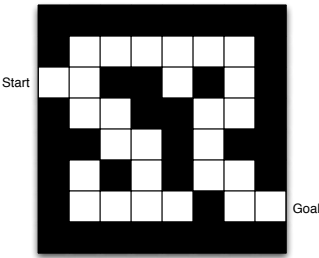
$$v_{\pi}(s) = \mathbb{E}_{\pi} [R_{t+1} + \gamma R_{t+2} + \gamma^2 R_{t+3} + \dots | S_t = s]$$

## Model

## Maze Example

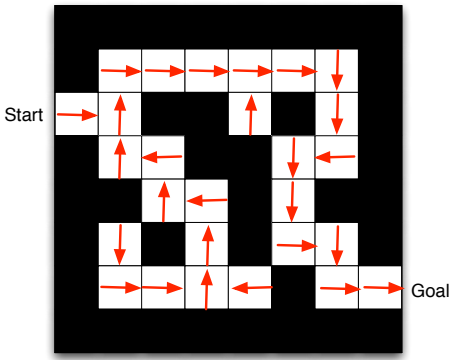
- A **model** predicts what the environment will do next
- $\mathcal{P}$  predicts the next state
- $\mathcal{R}$  predicts the next (immediate) reward, e.g.

$$\mathcal{P}_{ss'}^a = \mathbb{P}[S_{t+1} = s' | S_t = s, A_t = a]$$
$$\mathcal{R}_s^a = \mathbb{E}[R_{t+1} | S_t = s, A_t = a]$$



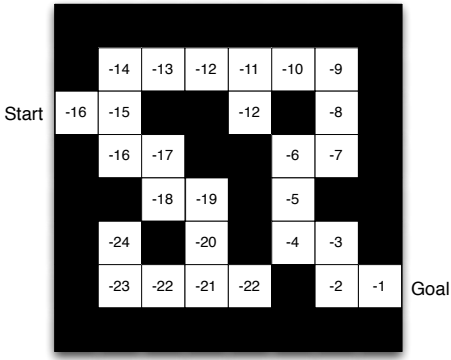
- Rewards: -1 per time-step
- Actions: N, E, S, W
- States: Agent's location

Maze Example: Policy



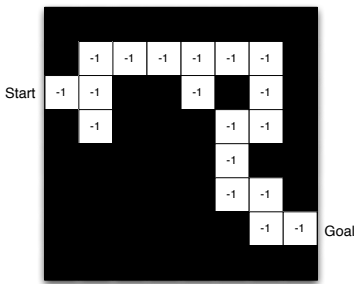
- Arrows represent policy  $\pi(s)$  for each state  $s$

Maze Example: Value Function



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

Maze Example: Model



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

- 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

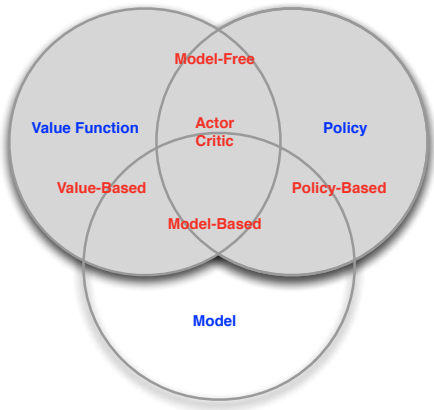
Categorizing RL agents (1)

- 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

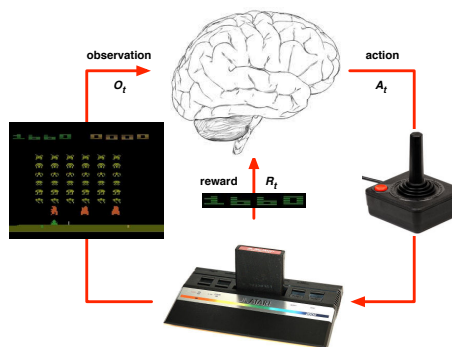


## Learning and Planning

## Atari Example: Reinforcement Learning

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

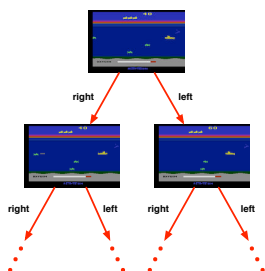


- Rules of the game are unknown
- Learn directly from interactive game-play
- Pick actions on joystick, see pixels and scores

## Atari Example: Planning

## Exploration and Exploitation (1)

- 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



- 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)

## Examples

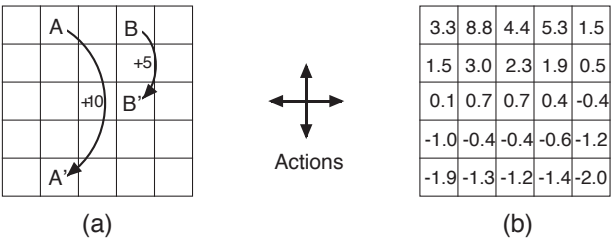
- *Exploration* finds more information about the environment
- *Exploitation* exploits known information to maximise reward
- It is usually important to explore as well as exploit

- 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

Gridworld Example: Prediction

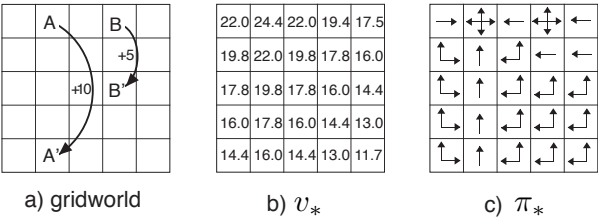
- Prediction: evaluate the future
  - Given a policy
- Control: optimise the future
  - Find the best policy



What is the value function for the uniform random policy?

Gridworld Example: Control

Course Outline



What is the optimal value function over all possible policies?  
What is the optimal policy?

- Part I: Elementary Reinforcement Learning
  - 1 Introduction to RL
  - 2 Markov Decision Processes
  - 3 Planning by Dynamic Programming
  - 4 Model-Free Prediction
  - 5 Model-Free Control
- Part II: Reinforcement Learning in Practice
  - 1 Value Function Approximation
  - 2 Policy Gradient Methods
  - 3 Integrating Learning and Planning
  - 4 Exploration and Exploitation
  - 5 Case study - RL in games