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Fluents valuation in Deep Reinforcement Learning and logic for temporal goals

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Chapter 1

Introduction

In Artificial Intelligence (AI), among the many approaches for building intelligent agents, we can distinguish those mainly focused on knowledge and planning, and those that mainly try out different actions to discover the goodness of their outcomes. With the former, we refer to those developed from *classical planning*, while the latter is the recently-successful field of *reinforcement learning*. While they can be integrated, they use quite different techniques. However, they share a common basic need: the agent must be able to perceive meaningful events happening in the outside world.

In planning, in almost every practical case, there is some form of partial observability or nondeterminism. So, agent’s observations become essential [21]. Observing, however, does not simply refers to reading a raw input from the sensor. Instead, it means “grounding” all symbols that compose the abstraction the agent adopts: essentially, all symbols representing conditions which happen to be true in the environment, should become true for the agent. We refer to these symbols with the term *fluents*. Fluents are atomic propositions can change in time, whose valuation should always reflect the current state of the world.

We could argue that reinforcement learning does not require such valuations. Still, rewards and punishments must be somehow supplied in response to desirable and undesirable events. We could think of providing these feedbacks with programmed ad-hoc conditions, but this can be done just for the simulations we create. As we will see, when the agent needs a component that is based on logic and reasoning, we still need to value the truth of fluents, even in the context of reinforcement learning. In fact, the most successful approaches mix these components somehow.

This thesis addresses the problem of valuating fluents from complex observations of the environment. However, this is a general topic and we’ll only work with specific classes of fluents and observations. Every choice or assumption that restricts the applicability of this method will be pointed out along the text. The first distinction

to do is that we'll only work with games.

1.1 Reinforcement Learning in games

Games in AI are a class static environments with discrete actions. They have always been a classic benchmark for AI, because they provide various levels of complexity, they have few and strict rules and are easy to implement and simulate.

Reinforcement learning (RL) is a field of AI that has shown to be successful for many games. This is the learning method adopted here. In RL, the agent tries out different actions and observes the reward received. Its goal is to learn the optimal policy, the one maximizing the cumulative reward over the whole episode. Most RL algorithms assume that observations and rewards can be modelled with a Markov Decision Process (MDP). This means that: the sequence of states create a Markov chain (the next state only depends on the previous state and action); the rewards only depend on the current state; the observations are an exact representation of the current state. Many learning algorithms exist for this setting [23].

Neural Networks (NN) have brought new possibilities for RL: in Deep Reinforcement Learning, the agent employs a neural network as a very expressive approximation to the quantities it is trying to learn [8]. The Q-value, for example, is a classic quantity in RL that estimates the expected cumulative reward from each pair of observation and action. A Deep Q-Network (DQN) is able to learn this estimate for a complex observation such as the frame of a video game, which is a high-dimensional input [17] that would be hard to manage without neural networks.

All models and experiments in this thesis use games from the Atari 2600 collection. The framework adopted is an interface for the Atari simulator [2] that maps actions to controller inputs and returns images of the game as observations. This is almost the same condition a human player faces when playing the same games. Other successful works also read the current number of lives the player has. Other than that, no internals are employed to simplify the task of the agent.

The reinforcement learning algorithm adopted in this thesis is a deep variant of Double DQN that solves few issues with simple DQN [26]. The motivation of this choice is that this is a relatively simple algorithm, based on DQN, which has also proven to be successful for the specific environments that we'll use in our experiments [16]. In fact, among Q-Network algorithms, the only ones that clearly achieve superior performances in most games adopt a combination of all variants [12].

Not all games inside the Atari 2600 collection are equally hard to solve. Reinforcement learning agents can be trained to achieve higher performances with respect to an average human player, mostly for environments with static map and background, and simple strategies. Many other games, instead, require the agent to remember previous steps and observations, for example, in exploration tasks. One notable example is *Montezuma's Revenge*, in which agents could not improve in any way [16].

Other approaches could succeed in this game with additional information able to guide the agent. For example, with carefully chosen initializations and examples from human experts [15].

One issue with games like Montezuma’s Revenge, is that they require long sequences of correct actions before rewarding the agent. This is called a *sparse reward*. However, there is a more fundamental problem to be considered first: observations and rewards, together, can’t define a Markov Decision Process, because it is essential for the agent to remember some informations collected during the game. For example, the Montezuma’s agent may walk to the right only if it *remembers* that the door in the right room has been previously opened. This additional ability is required because of partial observations: a view of the current room can can’t be considered a complete state of the game, sufficient to predict future rewards.

The setting just described can be modelled with a Non-Markovian Reward Decision Process (NMRDP). Fortunately, it is possible to cast any NMRDP as a MDP, if enough information about the history is included in each observation. In order to render this transformation feasible, we must include as few additional data as possible, still with an exhaustive state with respect to the reward. As humans, we understand which sequences lead to rewards. So, an elegant way to do this, is to declare such sequences with *temporal logics* [1]. As we will see, by tracking the satisfaction of such temporal formula, we can provide enough information to the agent so to employ standard algorithms developed for MDPs [3][6].

This type of construction can be considered as a “logic component” inside the agent, as we’ve previously called it. While an abstraction like this is powerful, it is essential to correctly valuate the symbols it uses, in order to reason about the current situation. This is a complex task for environments with rich observations, as those allowed by Deep Reinforcement Learning.

1.2 Objective of this work

The main purpose of this work is to devise and test a mechanism able to learn functions which valuates the fluents we define. Specifically, learn a function that computes the truth value for a set of boolean conditions, given a frame of an Atari game. Among the many different ways to accomplish this, the most interesting techniques are those which pose the least number of assumptions on the specific environment. In this respect, the following are important achievements of this work to be highlighted:

- Fluents are selected first. Then, the function to evaluate them is trained from a description of each fluent. This is harder to do than just training a features extractor and manually trying to associate a meaning to each feature.
- To describe the fluents we use temporal logic over finite traces such as LTL_f and LDL_f . These are employed as tools to formalize any type of temporal constraints the fluents are always expected to satisfy. The use of such logics for this purpose can be a really generic approach. This thesis is an initial investigation about this possibility. As a description of a fluent, we must consider everything that guides the training process. So, we will certainly consider other types of hints that is useful to include, such as visual hints.
- The training algorithm won't require any manual annotation, nor labelled datasets at all. The main idea is that, inside the agent, two components should coexist: the player and the observer. While the player explores the environment, the observer can be trained from the images received, without further intervention.

The second goal of this thesis is to demonstrate how such trained features can be exploited by a Reinforcement Learning agent to solve hard games. Tests will be conducted on Montezuma's Revenge, a game known to be difficult in this class [16]. In this thesis:

- We provide a flexible implementation of the construction described in [3][6], for temporal goals.
- A deep agent architecture is proposed to merge the technique above for the Deep Reinforcement Learning case.
- This implementation is then used to specify a temporal goal in LDL_f , sufficient to guide the agent through hard environments.

1.3 Results

1.4 Structure of the thesis

Chapter 2

Deep Reinforcement Learning for non-Markovian goals

2.1 Reinforcement Learning

In this section, we will briefly review the most important aspects of classic *Reinforcement Learning* (RL). These concepts are relevant because they are also found in Deep Reinforcement Learning (Deep RL), which is a central component of the agent we will design. Excellent references for these topics are [23], [22], and [18] for graphical models.

In AI, we commonly isolate two entities, the agent and the environment, which continuously interact. At each instant, the agent receives observations from the environment and it executes actions in response. In RL specifically, the agent observes the current state of the environment and a numerical reward. The environment produces high rewards in response to desirable events. The agent's goal is to maximize the rewards received. The basic setup is illustrated in Figure 2.1.

2.1.1 Markov Decision Processes

Most RL algorithms assume that the environment dynamics can be modelled with a *Markov Decision Process* (MDP). They do so, because under the independence

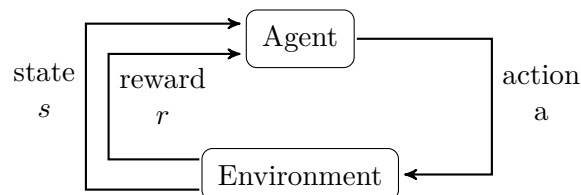


Figure 2.1. How agent and environment interact in RL.

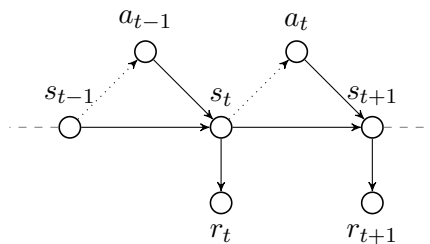


Figure 2.2. The directed graphical model of a MDP.

assumptions taken by MDP, it's possible to efficiently find the optimal agent's policy. A Markov Decision Process is a tuple $\langle S, A, T, R, \gamma \rangle$, where: S is the set of states of the environment; A is the action space; $T : S \times A \times S \rightarrow \mathbb{R}$ is the transition function, which, for $T(s_t, a_t, s_{t+1})$, returns the probability $p(s_{t+1} \mid s_t, a_t)$ of the transition $s_t \xrightarrow{a_t} s_{t+1}$; $R : S \times A \times S \rightarrow \mathbb{R}$ is the reward function; and $\gamma \in [0, 1]$ is called “discount factor”¹.

In a RL problem, the functions T and R are unknown. The agent can only learn them by taking each action and observing the outcomes. Even if they are unknown, by assuming that they can be modelled with functions $S \times A \times S \rightarrow \mathbb{R}$, we introduce some Markov assumptions. In particular, we assume that the next state of the environment is conditionally independent on the whole history, given the previous state and action: $s_{t+1} \perp s_0, \dots, s_{t-1} \mid s_t, a_t$. Similarly, the reward only depends on the last transition of the environment. Although it's not required by the model, it is common that rewards are computed just from desirable configurations of the environment s_t , not from specific transitions (s_{t-1}, a_{t-1}, s_t) . All these assumptions are summarized in the Directed Graphical Model (DGM) of Figure 2.2. In a DGM, directed edges indicate direct conditional probabilities, while missing arcs indicate conditionally independent variables. In Figure 2.2, the lack of any arrow between s_{t-1} and s_{t+1} means that future states, hence the rewards, do not depend on the past history, given the current state s_t . This is the essence of a Markov assumption.

Example 1. Tic-Tac-Toe, Chess and many other board games can be modelled with an MDP. Even games with dice, such as Backgammon. To do so, we define as state space S the set of configurations of the board, and a reward function $R(s)$ that returns 1, if the configuration s is a win, -1 for a loss, and 0 otherwise. Even though most games are deterministic, the presence of an opponent makes the transition function T of the MDP nondeterministic. What these games have in common, is that the player gets to see the complete state of the game, which is the current configuration of the board. Future states of the game and rewards only depend

¹In this chapter, variables with an integer subscript or index refer to the value at the discrete time indicated.

on the current situation, not on the whole play. In Chess, for example, we can determine whether a configuration is a win or loss just by looking for a checkmate; there is no need to ask the players how the game has been carried out.

Proving that Markovian T and R exist is easy for board games, because the rules of the game define them. As we will see in Section 2.4, when T is unknown, as always happens in the real-world, it's much more difficult to prove that we're in fact facing a MDP.

2.1.2 Optimal policies

The *policy* is the criterion the agent uses to select the actions to perform. If the environment dynamics can be modelled with a MDP, the optimal action at time t only depends on s_t . So, there must exist an optimal policy as $\pi^* : S \rightarrow A$. Due to common estimation errors, it is always better to prefer nondeterministic policies, which return a probability distribution over the actions. The action at time t will be sampled according to $a_t \sim \pi(s_t)$. This dependency is represented by the dotted arrows of Figure 2.2.

We will now introduce few basic quantities of RL that serve to define what it means for an action or a policy to be optimal. The *discounted return* G is the combination of all rewards collected:

$$G := r_0 + \gamma r_1 + \gamma^2 r_2 + \cdots = \sum_{t=0}^T \gamma^t r_t \quad (2.1)$$

The discount factor, $0 \leq \gamma \leq 1$, decides the relative importance of immediate and future rewards. Usually, this factor is strictly less than 1 because this stimulates the agent to achieve rewards as soon as possible. It also produces a finite discounted reward, even for an infinite run, where $T \rightarrow \infty$. Since the environments we will experiment with are video games, each play is an episode and the total number of steps in each episode is finite.

It is now clear, that the optimal policy should always maximize the expected discounted return. The *value function* of a policy π computes this quantity from each state s :

$$v_\pi(s) := \mathbb{E}_\pi[G \mid s_0 = s] \quad (2.2)$$

which is the expected value of G , when the agent starts from state s and it follows the policy π . The notation \mathbb{E}_π indicates that the estimation assumes that the actions are sampled according to π . Finally, we can define the *optimal policy* π^* as the one maximizing the value function at all states:

$$\pi^* : \quad v_{\pi^*}(s) \geq v_\pi(s) \quad \forall s \in S, \quad \text{for all } \pi \quad (2.3)$$

The typical Reinforcement Learning problem is to find the optimal policy for an MDP with unknown T and R .

The *action-value function* of a policy π is a similar measure to the value function:

$$q_\pi(s, a) := \mathbb{E}_\pi[G \mid s_0 = s, a_0 = a] \quad (2.4)$$

which also forces the first action to be a . Since the agent can only observe outcomes of single actions, this is usually a much more convenient form for updating the estimate of the expected discounted return. Most important, the optimal policy can be simply expressed as:

$$\pi^*(s) = \arg \max_{a \in A} q_{\pi^*}(s, a) \quad (2.5)$$

So, instead of learning the optimal policy directly, we can learn the optimal state-value function, q_{π^*} (also denoted with q^*). Fortunately, we don't need π^* to value q^* because, assuming optimality, we know it satisfies the Bellman optimality equation:

$$q^*(s, a) = \mathbb{E} [r_{t+1} + \gamma \max_{a'} q^*(s_{t+1}, a') \mid s_t = s, a_t = a] \quad (2.6)$$

$$= \sum_{s', r'} p(s', r' \mid s, a) (r' + \gamma \max_{a'} q^*(s', a')) \quad (2.7)$$

for any t .

Many learning algorithms exist for estimating q^* . Briefly, on-policy algorithms, estimate q_π of the policy π that is being used and improved, $\pi \rightarrow \pi^*$; off-policy algorithms, instead, act according to any exploration policy π_e and directly estimate q^* . Two famous algorithms in these classes are SARSA and Q-learning, respectively. The one used in this thesis is derived from the latter.

2.1.3 Exploration policies

If q^* were known, equation (2.5) would be enough to always select the optimal action. Generalizing for any q , we call that the *greedy policy*, because it always selects the best action according to q :

$$\pi_q(s) := \arg \max_{a \in A} q(s, a) \quad (2.8)$$

Unfortunately, while learning, we only have a rough estimate of the optimal function, $\hat{q} \approx q^*$. Being greedy with respect to sub-optimal values is dangerous, because the agent may deterministically select actions that repeatedly lead to dead-ends. To mitigate this issue, we can choose some actions at random. The ϵ -greedy policy is

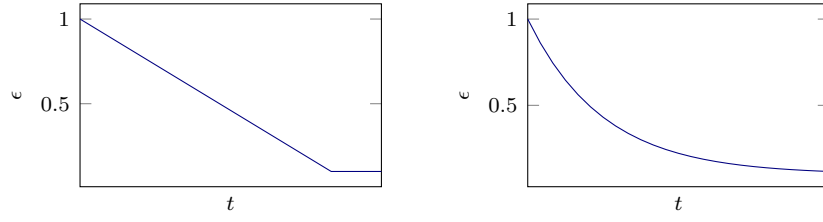


Figure 2.3. Probability of a random action over time: ϵ with linear decay (left), ϵ with exponential decay (right).

defined as:

$$\pi_{q,\epsilon}(s) := \begin{cases} \text{random action } a \in A & \text{with probability } \epsilon \\ \arg \max_{a \in A} q(s, a) & \text{otherwise} \end{cases} \quad (2.9)$$

More precisely, random actions are sampled from a uniform distribution over the set of actions A . By making random moves, the agent might escape from suboptimal environment configurations. If $\epsilon = 1$, definition (2.9) reduces to the random policy:

$$\pi_r(s) := \text{random action } a \in A \quad (2.10)$$

When training begins, the agent has no clue about the optimal q -function. It can just try out all actions by executing the random policy. In this phase, the agent receives low rewards but observes a lot of different outcomes for its actions. This is the purpose of exploration. After a while, the agent can begin to trust in its predictions. So, it may gradually choose the most promising actions in order to achieve higher rewards. This is the exploitation phase. The exploitation–exploration trade-off is a fundamental problem in AI. Unfortunately, there’s no general solution in RL, because the agent has no way to tell when the policy is “good enough”. Usually, we need to try some compromises between the two.

To address this issue, during training, the agent can act according to a policy that is initially stochastic but gradually approaches the greedy policy, over time. There are many ways to do this. One of the most simple options is to select the ϵ -greedy policy of equation (2.9) with ϵ that varies over time according to some schedule. Figure 2.3 shows two common possibilities. On the left-hand figure, the probability of a random action is linearly decreased over time, while on the right, it follows an exponential decay. In both cases ϵ never becomes zero, because that would effectively terminate the learning process. The rate of this decrease is a hyperparameter that can be tuned.

The most important policies are those just described. They can be directly used in a RL algorithm or combined to create more complex policies. The variants adopted in this thesis will be presented in the next chapters. With “exploration

policy” we refer to any policy that has a strong component of nondeterminism and it’s suitable to select the agent’s actions during training.

2.2 Deep Reinforcement Learning

Classic RL algorithms, such as SARSA and Q-learning, are tabular methods. In fact, they store and update the estimate for each pair (s, a) independently. Unfortunately, this requires discrete and small states and actions spaces. To overcome this very limiting assumption, we need parametrized value functions and policies. *Deep Reinforcement Learning* (Deep RL) is a recent field of RL in which Neural Networks (NN) are used as powerful function approximators for policies or value functions.

The main advantage of NNs, and parametric models in general, is that they can be trained in high-dimensional and continuous input spaces. In fact, a good fit does not require a complete exploration of the input space, which may be unfeasible or impossible. Instead, they are trained with some form of Stochastic Gradient Descent (SGD) on the set of parameters from input-output samples. Then, the model can be able to generalize to inputs that have been never observed, in a meaningful way.

Unfortunately, due to approximation and parametrization, Deep RL algorithms allow very little guarantees about convergence and optimality. Even if the input space would be explored completely, updates for recent samples would also affect the regions previously visited. In fact, any effective Deep RL algorithm introduces some techniques in order to generate a stable training.

2.2.1 Environment: Atari 2600 games

The Atari 2600 is a video game platform that was developed in 1977. There are hundreds of classic games available to play: Space Invaders, Ms. Pacman, Breakout and many others. The screen is 160 pixels wide and 210 pixels high, with 8-bits colour depth. The joystick has 9 positions (3 for each axis) and one button, for a total of 18 possible actions. For this reason, we'll only focus on RL methods for discrete action spaces.

The Arcade Learning Environment [2] is a simple interface to the Atari 2600 emulator. It allows agents to play and be trained on these games. At each step, the agent chooses one of the 18 actions available and receives in return a frame of the game and a reward. The reward is the increment in the player's score for the original game. This is really the same interface that a human player would use. Figure 2.4 shows the frames from few games in this collection.

Although these games come from an early stage of video games development, they represent the appropriate challenge for current (Deep) Reinforcement Learning agents. In fact, many papers tested their RL algorithms on these games [17][16][26][12]. In this thesis, we also tested with some of these environments. We will also show how improve on the hardest game in this collection for a RL agent: Montezuma's

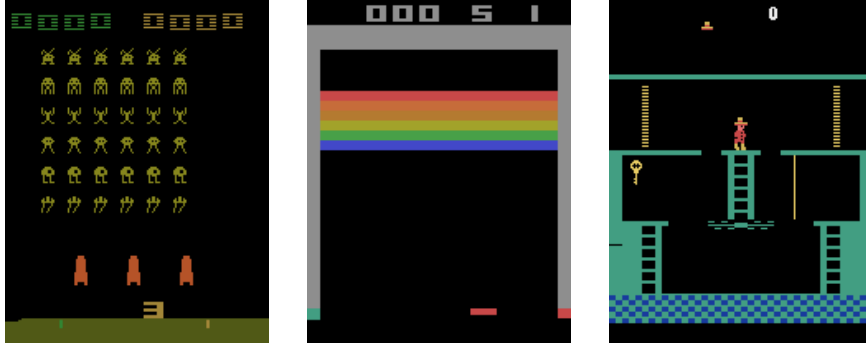


Figure 2.4. Initial frames of some Atari 2600 games (left to right): Space Invaders, Breakout, Montezuma's Revenge.

Revenge.

2.2.2 Deep Q-Network

The *Deep Q-Network* (DQN) [17] was the first algorithm to successfully combine deep learning models and Reinforcement Learning. Although many basic ideas presented here have been already introduced by the Neural Fitted Q iteration algorithm [20], DQN addressed some causes of training instability. They also demonstrated that exactly the same agent can be trained in many Atari games and achieve human-level performances in many of those [16]. These promising results sparked a lively interest in Deep RL, recently.

In DQN, the state-action value is approximated by a deep neural network $Q(s, a; \theta)$, on the parameters θ , that we call Q-Network. The purpose of learning, is to train this network to approximate the optimal q-function: $\hat{\theta} : Q(s, a; \hat{\theta}) \approx q^*(s, a)$. Then, the estimated optimal policy will be:

$$\hat{\pi}(s) = \arg \max_{a \in A} Q(s, a; \hat{\theta}) \quad (2.11)$$

A trained network, for each input (s, a) , should return the expected value of some target $y_{s,a}$. To do so, we select the parameters that minimize the squared difference between the estimates and the targets:

$$\text{loss}(\theta) := (Q(s, a; \theta) - y_{s,a})^2 \quad (2.12)$$

Since this is a Q-Network, the targets are the optimal state-action values $q^*(s, a)$ that the net should estimate. The loss (2.12) contains some random variables. So, we minimize it through any stochastic optimization algorithm. In Stochastic Gradient Descent (SGD), at each step t , we observe an input (s_t, a_t) and the associated target

y_t . Then, we take a small step toward the negative gradient of the loss:

$$\theta_{t+1} = \theta_t - \alpha \nabla_{\theta} \left((Q(s_t, a_t; \theta) - y_t)^2 \right) \Big|_{\theta=\theta_t} \quad (2.13)$$

in which $0 < \alpha < 1$ is a small learning rate. This equation is not the only update rule possible. There are more advanced optimization algorithms, such as: Momentum, RMSprop and Adam. In this thesis, we’ve mostly experimented with Adam.

What has just been described is the usual way of fitting a neural network to a dataset of samples. In RL, however, the targets $q^*(s_t, a_t)$ are unknown, because they depend recursively from the same optimal q-function that we’re trying to learn (see equation (2.7)). In classic RL, this is not a problem: the 1-step approximation of the q-values (derived from equation (2.7)),

$$y_t := r_{t+1} + \gamma \max_{a \in A} \hat{q}(s_{t+1}, a) \quad (2.14)$$

or the n-step approximation, are a valid targets for the function \hat{q} . By updating toward these values on the whole input space, convergence is guaranteed. In other words, targets can be estimates themselves.

With neural networks, instead, any update to the parameters also affects the target, because the weights have a global influence on the function. It’s not possible apply a correction for just one tiny region of the input space (nor it’s desirable, after all). It has been shown [20], that due to this effect, propagating errors slow down convergence or even render the training unstable. To address this issue one must ensure that the targets do not move much.

The DQN [17] algorithm addresses this issue in two ways. First, the targets in equation (2.14) are not generated by the network that is being trained, $Q(s, a; \theta)$, but they are computed from a second net, $Q(s, a; \theta')$. Every C iterations, the target net is updated to match the trained net, with the assignment: $\theta' \leftarrow \theta$. This keeps the targets constant for C steps and helps to stabilize the training.

Second, the network is not trained from the last sample, but from transitions of the recent experience. At each step, the agent acts according to some exploration policy, $a_t \sim \pi_e$. Each transition, of the form $\langle s_t, a_t, r_{t+1}, s_{t+1} \rangle$, is recorded in a buffer of size n_r , called “experience replay”. Then, at each training step, we sample a number of n_b transitions, thus creating a batch, and we perform an update $\theta_{i+1} = \theta_i - \alpha g_i$ on the cumulative gradient g_i of the whole batch.

DQN also includes a number of heuristics that greatly help the training but are specific to the Atari 2600 environments:

- Rewards can be really high, so they are limited in the range $[-1, +1]$; this is called *reward clipping*. It helps to keep the same learning rate for diverse games.

- The agent has a single life available. When a life is lost, the episode ends. This prevents the agent to rely on restarts.
- The frames are slightly down-scaled to further reduce the resolution, they are transformed to gray-scale and mapped to the range $[-1, +1]$. These are common preprocessing steps for NNs.
- Every observation is composed by the last 4 frames stacked together. This allows the agent to observe how the objects in the scene move. See Section 2.4 and Example 7 on page 26.

The algorithm used in this thesis is called *Double DQN* [26]. It is a slight variant of DQN, so all details mentioned so far also apply. The motivation of this algorithm is a known issue of Q-learning: it is likely to make overoptimistic value estimates. To show this, let's rewrite the targets of (2.14) as:

$$y_t := r_{t+1} + \gamma Q(s_{t+1}, \arg \max_{a \in A} Q(s_{t+1}, a; \theta_t); \theta_t) \quad (2.15)$$

where the estimates \hat{q} are computed with the Q-Network. This form makes more evident that the same model is used both to select the next greedy action and to estimate the q-value of state s_t . As result, any action with an overestimated q-value will be selected and its value propagated. To remove this bias, Double DQN decouple the two operations by using different sets of parameters, $\theta^{(1)}$ and $\theta^{(2)}$. The targets y_t are computed as:

$$y_t := r_{t+1} + \gamma Q(s_{t+1}, \arg \max_{a \in A} Q(s_{t+1}, a; \theta_t^{(1)}); \theta_t^{(2)}) \quad (2.16)$$

Then, just the parameters $\theta^{(1)}$ are updated toward this targets; this is called the online network. With random chance, the roles of the two parameters are continuously swapped at each step.

To compute the target, we need to compute the q-values for all actions in state s_{t+1} . To speed up this computation, the network is defined as a function that takes in input a state and computes a vector of state-action values, one for each action. So, just one forward pass is required to select the next action. Common Q-Networks for images are composed of a number of convolutional layers and some fully-connected layers. The specific structure may change, and the network used will be defined in the implementation section.

2.3 Temporal logics and Linear Dynamic Logic

2.3.1 Temporal logics on finite traces

Temporal logics are a class of formal languages, more precisely modal logics, that allow to talk about properties and events over time [10]. Among all formalisms, we care about logics that assume a linear time, as opposed to branching, and a discrete sequence of instants, instead of continuous time. In computer science, the most famous logic in this group is the Pnueli's Linear Temporal Logic (LTL) [19].

The assumptions about the nature of time directly reflect to the type of structures these logics are interpreted on: their models are tuples $\mathcal{M} = \langle T, \prec, V \rangle$, where T is a discrete set of time instants, such as \mathbb{N} , \prec is a complete ordering relation on T , like $<$, and V is a valuation function $V : T \times \mathcal{F} \rightarrow \{true, false\}$. For a logic that defines a set \mathcal{F} of proposition symbols, the function V assigns a truth value to each of them, in every instant of time. The symbols in \mathcal{F} represent atomic propositions which may or may not hold in different time instants. They are also called “fluents” (or simply propositional symbols, in this thesis). An equivalent and compact way of defining such structures is with *traces*. A trace π is a sequence $\pi_0 \pi_1 \dots \pi_n$, where each element is a propositional interpretation of the fluents \mathcal{F} . Each symbol π_i in the sequence is the set of true symbols at time i : $\pi_i \in 2^{\mathcal{F}}$. The i -th element is also denoted with $\pi(i)$. $\pi(i, j)$ represents the trace between instants i and j : $\pi_i, \pi_{i+1}, \dots, \pi_{j-1}$.

LTL is a logic that only allows to talk about the future. The semantics of its temporal operators, neXt \bigcirc , Until \mathcal{U} , and of those derived, eventually \Diamond , always \Box , can only access future instants on the sequence. Interpretations for this logic are infinite traces with a first instant, which are equivalent to valuations on the temporal frame $\langle \mathbb{N}, < \rangle$.

As it has been pointed out in [4], most practical uses of LTL interpret the formulae on *finite* traces, not infinite. The pure existence of a last instant of time has strong consequences on the meaning of all formulae, because operators semantics need to handle such instant differently. For example, the “always” operator \Box translates to “until the last instant”, quite naturally. However, the formula $\Box \Diamond \varphi$ no longer requires that φ becomes true an infinite number of times (in LTL, this formula represents the “response” property); instead, it is satisfied exactly by those traces in which φ is true at the last instant. So, it assumes a completely different meaning. Furthermore, both $\Box \Diamond \varphi$ and $\Diamond \Box \varphi$ become equivalent to $\Diamond (Last \wedge \varphi)$: something that doesn't happen in standard LTL². From this example, it should be clear that the expressive power of

²*Last* is an abbreviation for $\neg \bigcirc true$ and it evaluates to true at last instant only. So, $\Diamond (Last \wedge \varphi)$ means: eventually, at the last instant, φ is true.

the language has changed, and LTL interpreted over finite traces should be regarded as a different logic, that we will denote with LTL_f . More precisely, over infinite linearly-ordered interpretations, LTL has the same expressive power of Monadic Second Order Logic (MSO), while LTL_f is equivalent to First-Order Logic (FOL) and star-free regular expressions, which are strictly less expressive than MSO.

In the next section, we will define a temporal logic, called LDL_f , that was purposefully devised to be interpreted over finite traces. This is the formalism that we will use, in Section 2.5, to declare plans and desired behaviours. However, many useful temporal properties can be also expressed with LTL_f . So, one may also use as alternative formalisms LTL_f or any temporal logic over finite traces that can be translated to equivalent finite-state automata; even temporal logics of the past [1].

2.3.2 Linear Dynamic Logic

In this section, we will define the Linear Dynamic Logic of finite traces (LDL_f) [4]. Its syntax combines regular expressions and propositional logic, just like Propositional Dynamic Logic (PDL) does [7][25]. So, we will review regular expressions first.

Regular Temporal Specifications

Regular languages are the class of languages exactly recognized by finite state automata and regular expressions [13]. So, we will use regular expressions as a compact formalism to specify them. Regular expressions are usually said to accept strings. Traces are in fact strings, whose symbols $s \in 2^{\mathcal{F}}$ are propositional interpretations of the fluents \mathcal{F} . Such regular expressions would be:

$$\rho ::= \emptyset \mid s \mid \rho_1 + \rho_2 \mid \rho_1; \rho_2 \mid \rho^* \quad (2.17)$$

where \emptyset denotes the empty language, $s \in 2^{\mathcal{F}}$ is a symbol, $+$ is the disjunction of two constraints, $;$ concatenates two expressions, and ρ^* requires an arbitrary repetition on ρ . Parentheses can be used to group expressions with any precedence. Regular expressions are a basic formalism in computer science and they won't be covered here. The notable difference, though, is that the symbols found in the trace, hence of the regular expression, are propositional interpretations (i.e. sets of true fluents).

Example 2. Briefly, the regular expression $\rho := (\{A\}^* + \{B\}^*); \{\}$ accepts the

following traces:

$$\begin{aligned}\pi_a &:= \langle \{A\}, \{A\}, \{A\}, \{\} \rangle \\ \pi_b &:= \langle \{B\}, \{\} \rangle \\ \pi_c &:= \langle \{\} \rangle\end{aligned}$$

but not $\pi_d := \langle \{A, B\} \rangle$.

We call the regular expressions of equation (2.17) Regular Temporal Specifications RE_f , because they are interpreted on finite linear temporal structures. Unfortunately, writing specifications in terms of single interpretations can be very cumbersome, as we lack a construct for negation and all sets need to match exactly. Instead, we can substitute the symbols $s \in 2^{\mathcal{F}}$ with formulae of Propositional Logic. In fact, a propositional formula ϕ concisely represents all interpretations that satisfy it: $\text{Sat}(\phi) := \{s \in 2^{\mathcal{F}} \mid s \models \phi\}$.

The new definition for the syntax of Regular Temporal Specifications RE_f is:

$$\rho ::= \phi \mid \rho_1 + \rho_2 \mid \rho_1; \rho_2 \mid \rho^* \quad (2.18)$$

where ϕ is a propositional formula on the set of atomic symbols \mathcal{F} . The language generated by a RE_f ρ , denoted $\mathcal{L}(\rho)$, is the set of traces that match the temporal specification. The only difference with regular expressions standard semantics is that a symbol $s \in 2^{\mathcal{F}}$ matches a propositional formula ϕ if and only if $s \in \text{Sat}(\phi)$. A trace that match the regular expression $\pi \in \mathcal{L}(\rho)$ is said to be generated or accepted by the specification ρ .

Example 3. As an example, let's define a RE_f expression $\rho := \text{true}; (\neg B)^*; (A \wedge B)$ and the following traces:

$$\begin{aligned}\pi_a &:= \langle \{\}, \{A\}, \{A\}, \{A, B\} \rangle \\ \pi_b &:= \langle \{B\}, \{A, B\} \rangle \\ \pi_c &:= \langle \{A, B\}, \{B\}, \{B\} \rangle\end{aligned}$$

The first two traces are accepted by the expression, $\pi_a, \pi_b \in \mathcal{L}(\rho)$, but the third is not, $\pi_c \notin \mathcal{L}(\rho)$. Of course, the symbols A and B may represent any meaningful property of the environment that we may want to ensure at some time instants.

Linear Dynamic Logic

We can now move on to the *Linear Dynamic Logic of finite traces* (LDL_f). This logic was first defined in [4]. The definition we see here, also adopted in this thesis, is a small variant that can also be interpreted over the empty trace, $\pi_\epsilon = \langle \rangle$, unlike most logics, which assume a non-empty temporal domain T . This definition appears in [3].

Definition 1. A LDL_f formula φ is built as follows:

$$\begin{aligned}\varphi &::= tt \mid \neg\varphi \mid \varphi_1 \wedge \varphi_2 \mid \langle \rho \rangle \varphi \\ \rho &::= \phi \mid \varphi? \mid \rho_1 + \rho_2 \mid \rho_1; \rho_2 \mid \rho^*\end{aligned}\tag{2.19}$$

where tt is a constant that stands for logical true and ϕ is a propositional formula over a set of symbols \mathcal{F} . We also define the following abbreviations:

$$ff := \neg tt \quad [\rho]\varphi := \neg \langle \rho \rangle \neg \varphi \quad \phi := \langle \phi \rangle tt$$

together with all those of propositional logic, which are all to be considered part of the language.

The syntax just defined is really similar to PDL [7], a well known and successful formalism in Computer Science for describing states and events of programs. However, LDL_f formulae are interpreted over finite traces instead of Labelled Transition Systems.

Example 4. All the following formulae are all well-formed:

$$\begin{aligned}A \vee \neg B \\ \langle A; B^* \rangle (A \wedge B) \\ [\text{true}^*] \neg C \\ [A^*] \langle \neg B \rangle tt \wedge [\text{true}^*; C] ff \\ [A?; B] B\end{aligned}$$

Instead, these are not:

$$\langle tt \rangle A \quad \langle A \rangle \quad [A]B [A]B \quad B?$$

Before moving to the semantics, we can intuitively understand the meaning of these constructs. A LDL_f formula φ is a combination of temporal expressions, $\langle \rho \rangle$, $[\rho]$, and propositional formulae. The former are modal expressions that allow to make statements that refer to future instants. $\langle \rho \rangle \varphi$ states that, from the current step i , there exists a future instant j , such that the path $\pi(i, j)$ is accepted by the

RE_f ρ , and φ is satisfied at step j . Essentially, as in PDL, regular expressions are used to select some future states in which the formulae that follow should hold. Similarly, $[\rho]\varphi$ states that, from the current step, all executions satisfying ρ are such that their last instant satisfy φ . There is a clear similarity between $\langle \rangle, []$ operators and \exists, \forall from first-order logic, because we defined them to obey a similar relation to the De Morgan rule. In fact, if we consider the set S_ρ of future instants that are selected by a regular expression ρ , $\langle \rho \rangle$ can be read as “*there exists* one instant in S_ρ such that ...”, and $[\rho]$ is read as “*for all* instants in S_ρ ...”.

The LDL_f semantics is defined in terms of finite traces. We denote with $|\pi|$ the length of the trace π , i.e. the total number of time instants. Also, for non-empty traces, *last* refers to the index of the last instant in the sequence: $\text{last} := |\pi| - 1$.

Definition 2. Given a finite trace π , we inductively define when a LDL_f formula φ is true in π at time i , in symbols $\pi, i \models \varphi$, as follows:

$$\begin{aligned}
& \pi, i \models tt \\
& \pi, i \models \neg\varphi \quad \text{iff} \quad \pi, i \not\models \varphi \\
& \pi, i \models \varphi_1 \wedge \varphi_2 \quad \text{iff} \quad \pi, i \models \varphi_1 \quad \text{and} \quad \pi, i \models \varphi_2 \\
& \pi, i \models \langle \phi \rangle \varphi \quad \text{iff} \quad i < |\pi| \quad \text{and} \quad \pi(i) \models \phi \quad \text{and} \quad \pi, i+1 \models \varphi \\
& \quad \text{(for a propositional formula } \phi) \\
& \pi, i \models \langle \rho_1 + \rho_2 \rangle \varphi \quad \text{iff} \quad \pi, i \models \langle \rho_1 \rangle \varphi \vee \langle \rho_2 \rangle \varphi \\
& \pi, i \models \langle \rho_1; \rho_2 \rangle \varphi \quad \text{iff} \quad \pi, i \models \langle \rho_1 \rangle \langle \rho_2 \rangle \varphi \\
& \pi, i \models \langle \psi? \rangle \varphi \quad \text{iff} \quad \pi, i \models \psi \quad \text{and} \quad \pi, i \models \varphi \\
& \pi, i \models \langle \rho^* \rangle \varphi \quad \text{iff} \quad \pi, i \models \varphi \quad \text{or} \\
& \quad i < |\pi| \quad \text{and} \quad \pi, i \models \langle \rho \rangle \langle \rho^* \rangle \varphi \quad \text{and} \quad \rho \text{ is not test-only}
\end{aligned}$$

We say that ρ is test-only if it is a RE_f whose atoms are only tests $\psi?$.

NOTE: The only doubly-inductive semantics for the empty-trace version of LDL_f that I could find was in Marco Favorito’s thesis at page 15. With respect to that, I’ve just corrected $i < \text{last}$ with $i < |\pi| = \text{length}(\pi)$.

Definition 3. A formula φ is true in (or, is satisfied by) a trace π , written $\pi \models \varphi$, iff $\pi, 0 \models \varphi$. A formula φ is *satisfiable* iff there exists a trace that satisfy it; it is *valid* iff it is true in every trace.

Example 5. We’ll now list few examples that may help to better understand the semantics just defined. Given the following trace,

$$\pi_a := \langle \{A\}, \{A\}, \{A, B\} \rangle$$

we have³:

$$\begin{array}{ll}
\pi_a, 2 \models A \wedge B & \pi_a, 1 \not\models B \\
\pi_a \models \langle A^* \rangle (A \wedge B) & \pi_a \not\models [A^*]B \\
\pi_a \models [(\neg B)^*]A & \pi_a \not\models \langle A; B \rangle tt
\end{array}$$

Now that the fundamental mechanics are clear, we can highlight some peculiarities of the language:

- The test operator “?” is typical of PDL. In the middle of a RE_f computation, I can check whether a condition is verified before moving on. As we can see from Definition 1, the condition is a full LDL_f formula; so it acts as a powerful look-ahead operation.
- The two expressions *true* and *tt* may mistakenly look equivalent at first sight. Instead, *tt* is an atomic formula that is *always* satisfied (it evaluates to logical true); while *true* is a propositional formula and, as such, it is an abbreviation for $\langle \text{true} \rangle tt$. The latter is satisfied if and only if there exists at least one next instant in the trace.
- According to the semantics of $\langle \phi \rangle \varphi$, if we evaluate this formula on the last instant of a trace, φ needs to be verified at step *last* + 1. This is fine, indeed. As the truth of $\pi, i \models \varphi$, with $i \geq |\pi|$, is perfectly defined in LDL_f (and it’s equivalent to $\langle \rangle \models \varphi$).

The last observation has some profound consequences that we should consider when writing the formulae. Let’s suppose we want to encode that *A* must always hold, just like the LTL_f “always *A*”, $\Box A$. The LDL_f formula $[true^*]A$ doesn’t represent this concept: it is, instead, unsatisfiable. What we’re actually saying is that at each point of the trace, even at the end, *A* must follow; which is impossible. What we meant is $[true^*](A \vee \text{End})$, or $[true^*; (\neg \text{End})?]A$.

³We shouldn’t get confused about the different uses of the angle brackets: in $\langle \{A\}, \{A, B\} \rangle$, they delimit a sequence of sets (that is a trace); in the formula $\langle A^*; true \rangle B$, instead, they represent the temporal operator containing a regular temporal specification.

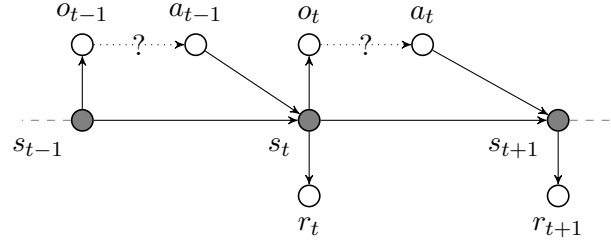


Figure 2.5. The Directed Graphical Model of a POMDP. Gray nodes are unobservable. For simplicity, the rewards in this graph depend just on the current state s_t , not on transitions (s_t, a_t, s_{t+1}) .

2.4 Non-Markovian goals

The goal of a RL agent is to maximize the rewards received. A goal, or a task, is said *non-Markovian* if the rewards do not satisfy the Markov assumption on rewards, i.e:

$$r_{t+1} \not\perp s_t, a_t, r_t \quad 0 \leq i < t \quad \text{for some } t \quad (2.20)$$

Of course, this can happen only if the environment cannot be modelled with an MDP. Excellent algorithms exist for MDPs; instead, non-Markovian goals are much more difficult to learn. There are two main causes for non-Markovian rewards: partial observations and temporally-extended tasks. We'll thoroughly analyze both scenarios.

2.4.1 Partial observations

Up to this point, we didn't need to distinguish between observations and states. In fact, we assumed that the agent can directly observe the environment states and act accordingly (we defined the policy as a function of the state). Unfortunately, this is often not the case: we only get to see something that depends on the current state, but it's not. These systems can be modelled with a *Partially Observable Markov Decision Process* (POMDP). POMDPs are a generalization of MDPs for partial observations. From now on, we will denote with S the environment state space and with Ω the observation space. Formally, a discrete-time POMDP is a 7-tuple $\langle S, A, T, R, \Omega, O, \gamma \rangle$, where S, A, T, R are defined as usual, Ω is the observation space, and O is the observation function $O : S \rightarrow \Omega$.

The graphical model of a POMDP is shown in Figure 2.5. The sequence of states $\langle s_0, s_1, \dots \rangle$, which is the environment dynamics, still satisfies the Markov assumption (it forms a Markov chain). In a POMDP, this dynamics exists but is unobservable. What we can see, instead, is a sequence of observations $\langle o_0, o_1, \dots \rangle$. Each of them is generated from the corresponding state, through the (possibly nondeterministic)

observation function. Actions and policies can only act in response to observations, not states.

The dotted arrows in Figure 2.5 have a question mark on them, because that dependency is our choice. As designers, we're free to select the informations that the agent should take into account when selecting an action. Is the last observation enough to decide? Or, more precisely, among all possible policies, do non-Markovian goals always admit an optimal policy of the form $\pi^* : \Omega \rightarrow A$? Unfortunately, the answer is no. As we will see, other informations are needed.

If the transition and observation functions are known, a common solution is to estimate the states and decide the action from this belief. With deterministic functions, the agent can iteratively restrict the set of possible states by eliminating those inconsistent with the observations received. More commonly, these functions are nondeterministic. In this case, a probabilistic methods can be effective estimation algorithms. The iterative probabilistic filter applied to the sequence of observations would produce the belief distribution on the current state. We can represent the general procedure, at any instant t , with the following computation:

$$\begin{array}{ccc} \langle o_0, o_1, \dots, o_t \rangle & \searrow & \\ & b(s_t) & \longrightarrow a_t \\ \langle a_0, a_1, \dots, a_{t-1} \rangle & \nearrow & \end{array}$$

where $b(s)$ denotes the belief of s , being either a set of states or a probability distribution. Since each state estimate depends on the whole sequence of observations, also the next action is implicitly based on the whole history.

Standard RL algorithms cannot be applied to POMDPs, because the state space is not observable. Also, since we commonly assume the transition and observation functions to be unknown, no estimation could be carried out anyway. There is a clear difference between MDPs and POMDPs. Still, RL algorithms are frequently applied to POMDPs. Not surprisingly, they perform very poorly on these environments. See, for example, the games with worst performances in [16]. This is a subtle mistake, because determining whether we're observing the state space is the same as answering the following question: does the observation space capture the whole dynamics of the system being observed? Or, more precisely, does an equivalent MDP $\langle \Omega, A, T_\Omega, R_\Omega, \gamma' \rangle$ that produces the same rewards exist? If both $T_\Omega : \Omega \times A \times \Omega \rightarrow \mathbb{R}$ and $R_\Omega : \Omega \times A \times \Omega \rightarrow \mathbb{R}$ exist and produce the same rewards, the environment can be successfully modelled and solved with an MDP. Figure 2.6 represents this situation.

Example 6. As we've seen from Example 1 on page 8, the game of Chess can be modelled with an MDP if we consider as states the vectors of positions of all pieces

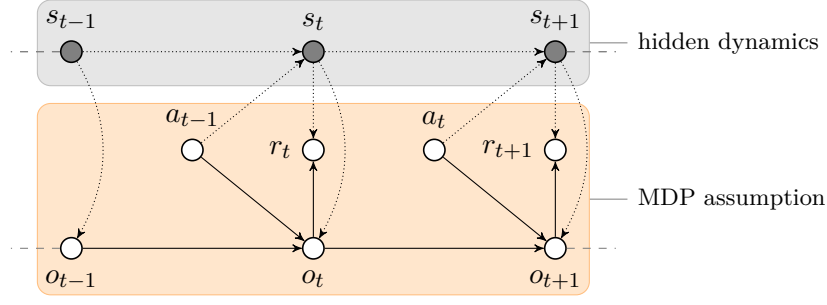


Figure 2.6. The dotted arrows $\cdots \rightarrow$ represent the dependencies in a POMDP model. Solid arrows \rightarrow show the MDP model over the same quantities.

on the board. Let's suppose, instead, the observations available are images of the board after each move (if the pieces can be distinguished, these could even come from a real play). Each image completely captures the state of the game because, for each move of the agent and the opponent, we're able to accurately predict image that will follow. This is a transition T_Ω over images. Similarly, a reward function R_Ω can simply return $+1$ or -1 for images with checkmates and 0 otherwise. These functions can be unknown and don't need to be defined.

Suppose, instead, that the agent can only observe the left-hand side of the board (columns a-d, for example). In this case, each image provides an incomplete view over the state of the game. In fact, in order to determine the best action we must consider whether there are some attacking pieces on the hidden region. In this case, classic RL algorithms would perform poorly, because an image it's not sufficient to predict the next image and reward.

Example 7. Let's consider a classic control problem: the swing-up of an inverted pendulum. A pendulum can freely rotate by 360° around a hinge. The agent, at each discrete time step, can apply torques to this active joint. The goal is to stabilize the pendulum in the upward position, which is the configuration of unstable equilibrium. In order to solve this problem with Reinforcement Learning, we need to define the spaces S and A of the MDP. In this domain, actions are continuous torques. So, assuming a normalized range, $A := [-1, +1] \subseteq \mathbb{R}$. The angle of the pendulum θ with respect to some fixed reference completely determines the position of the masses. Is the reward Markovian with respect to $S = \{\theta \in [-\pi, +\pi]\}$? No, because the agent is rewarded when the pendulum stops in the upward position. So, the appropriate state space consists of both θ and $\dot{\theta}$ (or, rather its discrete-time approximation).

Including the momentum in the state space is very common for mechanical systems. However, this can be also necessary for games. In fact, just looking at a single frame, the agent has no clue about how all the elements in the picture are moving. For example, an optimal policy would need to take into account the

direction of an approaching ball in order to hit it.

2.4.2 Temporally-extended goals

The previous section has shown how partial observations may falsify the Markov assumption on rewards. A second possibility is to have a complete observation of the state ($\Omega = S$) but a task that is intrinsically non-Markovian. In this case, each reward is computed from the whole history of events

$$r_t = R(\langle s_0, s_1, \dots, s_t \rangle) \quad \forall t \in \mathbb{Z} \quad (2.21)$$

with $R : S^* \rightarrow \mathbb{R}$. The sequence of states $\pi := \langle s_0, s_1, \dots, s_t \rangle$ will be also called execution *trace*. In general, with the term “trace” we indicate any sequence that is produced during a run. $\pi(i, j)$, with $i \leq j$, denotes a slice of the trace π between instants i and j ; $\pi(i)$ is the value at time i ; $|\pi|$ denotes the number of instants of the sequence; and $\langle \rangle$ is the empty trace.

Why should we define a reward function that is explicitly non-Markovian? Because, for example, instead of just reaching a desirable state, we might want our agent to drive the environment through a sequence of states.

Example 8. Let’s suppose the agent can control a light bulb through a switch, and we want the light to be set on, then off again. This environment is extremely simple: its state is completely described by a Boolean variable, “lightOn”, which reflects the status of the light. Still, to valuate whether the task has been accomplished at time t , it’s not sufficient to determine whether the light is off in state s_t . Instead, we also need to see whether at some previous instant $s_{t'} \prec s_t$ the light was set on.

We now define a model that by generalizing MDPs can describe this class of problems. A *Non-Markovian Reward Decision Process* (NMRDP) [1] is a tuple $\langle S, A, T, R, \gamma \rangle$, where S, A, T, γ are defined as for MDPs, and $R : S^* \rightarrow \mathbb{R}$ is a non-Markovian reward function, which computes the reward at time t as $r_t = R(\langle s_0, s_1, \dots, s_t \rangle)$.

2.5 Reinforcement Learning with restraining specifications

Restraining Bolt method [5][9].

Chapter 3

Learning to value fluents in games

The importance of correctly value the fluents.

3.1 Temporal constraints

How we can use temporal logic to express legal traces of interpretations; e.g. expected behaviours.

3.2 Assumptions

A temporal constraints aren't definitions; they are just minimal constraints. We need additional clues: visual description of fluents. Now follow my assumptions:

- Local properties (with regions I don't have to find elements in a frame).
- The property is visually apparent, inside the region.

Limitations and other ideas for a stronger grounding.

3.3 General structure of the model

Illustration and general description of the model.

3.4 Encoding

Encoder: the model, how it works, what does it learn, size of the encoding.

References: Training Restricted Boltzmann Machines and Deep Belief Networks [24][18].

3.4.1 Model: Deep Belief Network

3.4.2 What does it learn

3.5 Boolean functions

The fluents are true in a set of those configurations.

3.5.1 Learning with genetic algorithms

Ideas from concept learning; genetic algorithm.

References: Genetic Algorithms for Concept learning[14], Genetic Algorithms review[11].

3.5.2 Boolean rules

Representation of boolean functions and training details.

Chapter 4

AtariEyes package

Intro to the software. What we can do:

- Train a Reinforcement Learning agent.
- Train the features extraction.
- Run a Restraining Bolt while training and playing an agent.

4.1 How to use the software

4.1.1 Tools and setup

4.1.2 Commands

Small user reference.

4.2 Implementation

4.2.1 agent Module

training Module

playing Module

4.2.2 streaming Module

4.2.3 features Module

models Module

genetic Module

temporal Module

Chapter 5

Experiments

5.1 Breakout

5.1.1 Definitions

5.1.2 Training

5.1.3 Comments

5.2 Montezuma's Revenge

5.2.1 Definitions

5.2.2 Training

5.2.3 Comments

5.3 New example

I'll try to train one additional environment just to show a case in which the role of the temporal constraints is more evident, like in Breakout (something like a simple game with many rules).

Chapter 6

Conclusions and future work

What I have done (concretely); what I haven't done; how I'd improve the results and how to possibly relax some assumptions.

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