

# Recurrent Reinforcement Learning: A Hybrid Approach

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## Abstract

Successful applications of reinforcement learning in real-world problems often require dealing with partially observable states. It is in general very challenging to construct and infer hidden states as they often depend on the agent's entire interaction history and may require substantial domain knowledge. In this work, we investigate a deep-learning approach to learning the representation of states in partially observable tasks, with minimal prior knowledge of the domain. In particular, we study reinforcement learning with deep neural networks, including RNN and LSTM, which are equipped with the desired property of being able to capture long-term dependency on history, and thus providing an effective way of learning the representation of hidden states. We further develop a *hybrid* approach that combines the strength of both supervised learning (for representing hidden states) and reinforcement learning (for optimizing control) with joint training. Extensive experiments based on a KDD Cup 1998 direct mailing campaign problem demonstrate the effectiveness and advantages of the proposed approach, which performs the best across the board.

## 1 Introduction

Consider customer relationship management (CRM) of a firm that interacts with users over time. At each decision point, the firm takes an action on its users, such as sending a catalog, a coupon or a greeting card. In response, a user may visit the store, place an order, or simply ignore the action. The goal of the firm is to take optimal actions to maximize total profits from users. In marketing, it is well established that actions taken by the firm can have a long-term effect on user response in the future, implying that myopic optimization of profit is usually sub-optimal. Instead, the lifetime value (LTV) of users is a more desired metric of interest (Dwyer 1997). With LTV as the objective, CRM can be naturally formulated as a reinforcement-learning (RL) problem (Sutton and Barto 1998) where the immediate profit is used as *reward* and LTV as *long-term value function*. A similar motivation was used in a recent application of RL to advertising (Theodorou, Thomas, and Ghavamzadeh 2015).

Like many other real-world problems, e.g., robotics and human-computer interaction applications, CRM is challenging partly because of the partial observability of a user's

(Markovian) state. Roughly speaking, a user's state summarizes her entire interaction history with the firm: conditioned on the state and future actions, future response of the user is independent of the interaction history. In practice, constructing and measuring such a state is difficult in complex problems like CRM. Popular choices such as the Recency-Frequency-Monetary value model (details of which are given in experiments) arguably capture only partial information of a real user state. The problem of state inference therefore becomes critical when applying RL to these non-Markovian problems.

The most common approach to dealing with partially observable states in reinforcement learning is to use a partially observable Markov decision process, or POMDP (Kaelbling, Littman, and Cassandra 1998), which is found successful in a few domains (Pineau, Gordon, and Thrun 2003; Williams and Young 2007). However, defining hidden states in a POMDP requires substantial domain knowledge, while such knowledge is not always available (or hard to obtain) for many complex, real-world tasks.

In this work, inspired by recent success of deep reinforcement learning (Mnih et al. 2015), we investigate the use of deep neural networks to capture and infer hidden states in an automatic way. As opposed to POMDP-based approaches, deep learning holds the promise of automatically finding appropriate representations for a given problem, which can be difficult for a human expert, see Deng and Yu (2014) for an extensive survey of successful applications, thus avoiding the laborious and challenging step of designing hidden states. Our "recipe" for using deep learning to tackle complex tasks like CRM can be summarized as follows:

- First, unlike Mnih et al. (2015), we employ recurrent neural networks (RNN) and long short-term memory (LSTM) (Hochreiter and Schmidhuber 1997) models to learn the representation of states for RL. Since these recurrent models can aggregate partial information in the past, and can capture long-term dependencies in the sequential information, their performance is expected to be superior to the contextual-window-based approach, which was used in the DQN model of Mnih et al. (2015).
- Second, in order to best leverage supervision signals in the training data, we propose a new, hybrid approach that combines the strength of both supervised learning and re-

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