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Model-Based Reinforcement Learning with State Abstraction: A Survey

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Abstract. Model-based reinforcement learning methods are promising since they can increase sample efficiency while simultaneously improving generalizability. Learning can also be made more efficient through state abstraction, which delivers more compact models. Model-based reinforcement learning methods have been combined with learning abstract models to profit from both effects. We consider a wide range of state abstractions that have been covered in the literature, from straightforward state aggregation to deep learned representations, and sketch challenges that arise when combining model-based reinforcement learning with abstraction. We further show how various methods deal with these challenges and point to open questions and opportunities for further research.

Keywords: Model-based RL · State Abstraction · MDPs

1 Introduction

With roots in sequential analysis [76], Reinforcement Learning (RL) is a general framework for learning how to act near-optimally in sequential decision-making problems. A key challenge for RL is sample-efficiency. Sample efficiency is important because in many problems it can be expensive, in time or monetary costs, to collect samples. The combination of Model-based Reinforcement Learning (MBRL) and abstraction is of interest for improving the sample efficiency of learning methods that aim to find solutions for sequential decision-making problems. We define MBRL as an RL method that explicitly learns a model of the environment. MBRL provides a way to find solutions to difficult problems efficiently [70] and allows for transfer when the tasks shift, or to related tasks [1, 52]. The state representation, the input to a RL method, plays an important role in the learning process. A state representation will often contain irrelevant details, e.g., when the input is an image a large amount can consist of background that has no direct relevance to the task. Abstracting the state representation to remove parts that are irrelevant for optimal decision-making allows RL methods to learn much faster. Learning to decide which parts of the state representation are relevant is a key aspect of abstraction learning.

State abstraction can be carried out in various ways, ranging from state aggregation [2, 44] to deep learned representations [62, 65]. We provide a high-level view of the promising research in the field, covering a wide range of different types of state abstractions known from the literature.

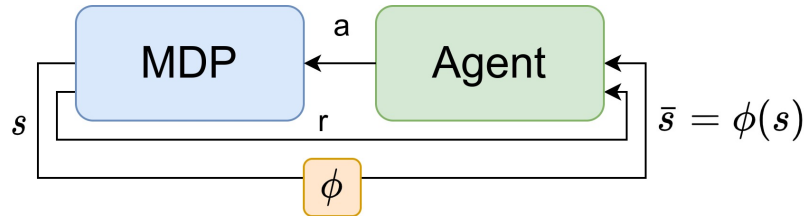


Fig. 1. RL with abstraction, the agent observes $\bar{s} = \phi(s)$ instead of s . Image from [69].

Recently MBRL, abstraction learning, and related topics have received a large amount of attention. There are surveys of decision-making under uncertainty [36], MBRL in general [52], deep MBRL [61], and representation learning in both robotics [42] and MBRL [32]. Our work takes a wider view of abstraction and focuses on the additional challenges that arise when combining MBRL and abstraction [1, 56, 68, 69]. The contributions of this work are the following: We detail challenges that arise for the combination of MBRL with abstraction using the view of abstraction plus RL as a Partially Observable MDP (POMDP). We show how different approaches for MBRL with state abstraction deal with these challenges, in the process providing a unified view of a wide range of approaches. We identify open questions and opportunities for further research.

2 An Overview of State Abstraction for RL

We consider RL in sequential decision-making problems, which can be defined as an Markov decision process (MDP) [63]: $\langle S, A, T, R, \gamma \rangle$, where S is a set of states $s \in S$, A a set of actions $a \in A$, T a transition function $T(s'|s, a) = \Pr(s'|s, a)$, R a reward function $R(s, a)$ which gives the reward received when the agent executes action a in state s , and γ the discount factor ($0 \leq \gamma < 1$). For realistic problems, the state space of the MDP representation is often too large to tackle directly. One way to reduce the size is to use compact representations such as state abstractions. Section 2.1 characterizes different state abstraction methods and briefly describes some of their properties. Section 2.2 describes how abstraction in an MDP can be viewed as a POMDP and the resulting challenge.

2.1 Characterization of Abstractions

State abstraction can be used to reduce the problem size, by clustering states into abstract states. This clustering can be defined by using an abstraction function ϕ , which maps (or aggregates) ground states s to abstract states \bar{s} , where the bar notation denotes objects in the abstract space. We write this mapping as $\phi(s) = \bar{s}$, such that the abstract state space can be written as $\bar{S} = \{\phi(s) \mid s \in S\}$. The agent then uses the abstract states \bar{s} and the rewards to learn transitions and rewards over the abstract state space. State abstraction can result in an abstract

state space that is much smaller than the original state space, $|\bar{S}| \ll |S|$, which can make learning easier.

In the planning setting, where we have access to the model of a problem, many different abstraction functions have been considered [2, 44]. Abstractions group together states based on certain criteria of the state or state-action pairs. An example is the (stochastic) bisimulation [21], also known as model-irrelevance abstraction [44]. In this abstraction, states are only grouped together if their reward and transition functions in the abstract space are the same, i.e., $\phi(s_1) = \phi(s_2)$ iff

$$\forall a \in A R(s_1, a) = R(s_2, a), \quad (1)$$

$$\text{and } \forall \bar{s}' \in \bar{S} \sum_{s' \in \bar{s}'} T(s'|s_1, a) = \sum_{s' \in \bar{s}'} T(s'|s_2, a). \quad (2)$$

If we have access to the MDP, we can compute a more compact abstract MDP [13] and find a solution for this smaller problem. One important aspect of these abstractions is whether or not (near) optimal policies for the original policy can be obtained when the policy is learned from the abstract problem. Several results showing that this is possible have been obtained for several forms of abstractions [44, 2]. These results make abstractions interesting for RL as they show that it is possible to significantly reduce the problem size, while still being able to obtain (near) optimal policies for the original problem.

To allow for further reduction in the problem size also approximate versions of abstractions, such as the ϵ -bisimulation, have been considered [2, 44]. In the approximate versions, the grouping criteria are relaxed. E.g., in the ϵ -bisimulation the transition and reward functions for grouped states will be close but not necessarily the same, i.e., $\phi(s_1) = \phi(s_2)$ iff

$$\forall a \in A |R(s_1, a) - R(s_2, a)| \leq \epsilon, \quad (3)$$

$$\text{and } \forall \bar{s}' \in \bar{S} \left| \sum_{s' \in \bar{s}'} T(s'|s_1, a) - \sum_{s' \in \bar{s}'} T(s'|s_2, a) \right| \leq \epsilon. \quad (4)$$

Several other examples of exact and approximate state abstraction functions can be found in the literature [2, 44]. For a given MDP it is possible to build an abstract MDP using ϵ -bisimulation criteria [14]. Recent work has introduced transitive state abstractions, a class of abstractions that can be computed efficiently [1]. If we have a compact model, the goal is to find a good policy. A potential issue is that if a learned model is only an approximation of the true model, small errors can compound when planning for long horizons [72, 80]. Results for planning have shown that for particular approximate state representations, such as ϵ -bisimulation, the policy that is learned can still be approximately optimal [2]. This was also shown when using RL in an abstract MDP [71]. However, these results assume that we have access to the MDP or an abstract MDP, which requires the problem to be known and this is typically not the case in RL.

2.2 Abstraction in an MDP as a POMDP

In the general case of MBRL in an unknown MDP with an abstraction ϕ , the situation will be as depicted in Figure 1. While normally the agent would receive a state s as an observation, this is no longer the case, and the agent receives observations that correspond to abstract states $\phi(s)$. In this case, the agent will no longer know exactly in which state it is, making the environment a POMDP [3, 6, 32, 51, 68, 69]. Abstraction can be seen as a special case of POMDPs because the observation is a result of *perceptual aliasing*, i.e. multiple states are perceived as the same.

To formalize the combination of abstraction and RL in an MDP as a special case of a POMDP, we first give the general definition of an infinite horizon POMDP [34], which can be described by the tuple $\langle S, A, T, R, \Omega, O, \gamma \rangle$, where S, A, T, R , and γ are the same as in the MDP. The Ω is a finite set of observations $o \in \Omega$ that an agent can receive and O is an observation function $O(o|a, s') = \Pr(o|a, s')$ that gives the probability of receiving an observation o after taking an action a and ending in state s' . Now, when an RL agent acts in an MDP but receives observations through ϕ , the uncertainty is only due to perceptual aliasing, which means that the observation is a deterministic function of the state: $O(o|a, s') = \Pr(o = \phi(s')|a, s') = \Pr(o = \phi(s')|s')$. For deterministic functions ϕ , this is 1 iff $o = \phi(s')$. The abstraction function ϕ has taken the role of the observation function O with the observation space being \bar{S} .

Since we can view the combination of abstraction and RL in an MDP as a special case of a POMDP, RL methods for POMDPs could be used to find a solution. A common approach to finding solutions in POMDPs is through Bayesian RL, for which the Bayes-Adaptive POMDP (BA-POMDP) provides a framework [64]. Extensions of Bayesian RL for POMDPs are covered in the survey of Ghavamzadeh et al. [20]. In Deep RL using recurrent neural networks is one way in which partial observability has been addressed [30, 77]. Specific focus has been on using variational inference methods [29, 74] and belief tracking [35, 46, 77]. However, these POMDP approaches are often general solutions for any type of POMDP, they are not necessarily optimal for the special case of the POMDP induced by abstraction.

Instead of applying POMDP solution methods, it can be tempting to treat the resulting problem as a Markov problem and try to find a solution in this way. For instance, this could be tempting when the abstraction clusters together states with similar transition and reward functions in the abstract space, such as with a ϵ -bisimulation abstraction. However, it has been observed that treating this problem as a Markov process can lead to policies that are far from optimal and there could be no guarantee of finding an optimal solution [1, 56, 69]. In general, non-stationarity of the collected data, due to changing behavior of the policy, has been shown to lead to worse performance in Deep RL [28], and non-stationarity due to perceptual aliasing can lead to similar problems when not addressed. Therefore, to find good solutions methods that combine RL and abstraction should take into account the perceptual aliasing.

3 Utilizing Given Abstraction Functions

This section presents an overview of the literature that utilizes an abstraction function for MBRL. Table 1 summarizes the findings. First Section 3.1 discusses the relation between abstract MDPs and Robust MDPs (RMDPs), and how solutions methods for RMDP can allow for obtaining better policies when using an abstract learned model. Section 3.2 considers the RL setting where we do not have such a model, but we are given some abstraction function ϕ and see how abstraction can be leveraged to improve performance. Section 3.3 deals with the setting where we are given a set of abstractions and have to learn which one leads to optimal performance. Afterward, Section 4 deals with the setting where the environment is unknown and we do not have an abstraction function ϕ , but have to learn one online.

3.1 Robust Optimization

The RMDP [79], and the related Bounded Parameter MDP (BPMDP) [22], extend the MDP definition by allowing for transition functions and reward functions that are uncertain, as quantified by intervals. This is generally motivated by not having enough data to be sure about the transition functions, but still being able to give some confidence intervals. Another motivation is inherent uncertainty for instance caused by having a ϵ -bisimulation, where the uncertainty intervals are ϵ wide. This makes solution methods for RMDP interesting for RL with abstraction. Since, if we have learned an ϵ -bisimulation model and can estimate ϵ , we could apply solution methods for RMDP.

To solve problems with inherent uncertainty, the RMDP includes an additional set of outcomes B . The transition probabilities and reward function are a function of both $a \in A$ and $b \in B$. From a game-theoretic perspective, B can be seen as the actions of the adversary [60], which can be state-dependent and decide over the distribution of the transition and reward function from within the specified intervals. The solution to a RMDP also includes the policy of the adversary. For general uncertainty sets for B , it has been shown that the problem of finding an optimal robust policy is strongly NP-hard [79]. To find solutions in polynomial time, two main uncertainty sets for B have been considered: s-rectangular and s,a-rectangular sets [60, 79]. In the first case, the adversary can independently choose an outcome for each state s . In the second case, the adversary can choose an outcome for each state s and action a independently. Recent work has also given results when the models of the uncertainty are less strict [23, 50]. Taking into account the uncertainty with robust optimization can lead to better policies for the real environment [45, 79].

There has also been some work that combines abstraction with RMDP [45, 60]. The RAAM algorithm [60] receives as input an abstraction function and an MDP, then it first constructs an RMDP and uses this to compute an approximately optimal policy for the original MDP. It is shown that this can be beneficial in the limit, bounds on the performance are given that are similar to the bounds for ϵ -bisimulation abstractions in planning [2]. The RAAM approach

was later extended by Lim and Autef [45] who use a kernel-based approach, of which state abstraction can be seen as a special case.

The work in this section shows that uncertainty about the transition and reward functions can be dealt with in a principled way, given some uncertainty intervals. While some work exists that connects this work to abstraction it only focuses on results in the limit.

3.2 Leveraging an Abstraction Function

Often in RL, the environment will be unknown, but sometimes we have access to an abstraction function ϕ . This ϕ could for instance come from a domain expert, or it could be the result of the discretization of a continuous problem. With ϕ one could try to learn an abstract model, which is typically done by collecting data and then constructing a maximum likelihood model for the transition and reward functions in the abstract space. If we learn a correct abstract model and find the optimal policy for this problem then this solution can be near-optimal in the true MDP, depending on the abstraction used [2]. Learning in this way could be more sample-efficient than learning a model of the full MDP because the abstract space is smaller.

One difficulty in this setting is learning a correct abstract model in the first place. In RL, samples usually can be considered independent, and this is used to show that an accurate model can be learned. In the combination of RL and abstraction, samples can no longer be considered independent, due to perceptual aliasing [27, 68, 69]. To be able to give sample efficiency results RL plus abstraction, some work uses the assumption that the collected samples are independent [17, 59]. The work by Paduraru et al. [59] assumes that they receive a data set with independent and identically distributed (i.i.d.) samples and show there is a trade-off between the quality of the abstraction and the quality of the transition model. The quality of the abstraction is measured in terms of the ϵ of ϵ -bisimulation, where a larger ϵ means a coarser abstraction and a larger error. The second error relates to the number of samples we can get for a state-action pair, where a coarser abstraction gives more samples per state-action pair and a lower error. Like the work by Paduraru et al. [59], other work has also shown that the error of the agent can be decomposed into multiple components, which are based on the asymptotic bias of the representation and overfitting due to limited data (variance) [17, 66]. This bias-variance trade-off indicates that using abstractions can be especially beneficial when the available data is limited while being less beneficial when a lot of data is available, which has been illustrated in experiments [17].

The assumption that the generated data consists of independent samples does not hold in general. Another way to show that we can learn an accurate abstract model is by looking at convergence in the limit. The convergence to an accurate estimation of the abstract model is possible under several conditions, e.g., when the policy is fixed or when the abstraction is a bisimulation [27, 68]. Having to use a fixed policy can be seen as a downside because a changing policy that explores helps to learn efficiently [70]. Another downside is that in the limit

using the full model will be better than using an abstract model, since only the error introduced by the bias remains, which is zero for the full model.

Recently, the work by Starre et al. [69] has shown that an accurate abstract model can still be learned by applying martingale theory [11]. They give the first finite-sample performance analysis for model-based RL plus abstraction, by extending the results of an existing algorithm (R-MAX [9]) with the use of an ϵ -bisimulation abstraction.

This section shows that abstractions can lead to better performance with fewer data, trading it off with less accuracy when a lot of data is available. For these methods to work it is required to already have a good abstraction function, which can be challenging.

3.3 Abstraction Selection

While the work in the previous section focused mostly on the case where we have one particular abstraction function, there is also a considerable amount that has focused on state representation selection, where the agent is provided with a set of state representations (or abstraction functions). It is usually assumed that these representations are provided by a domain expert and the goal is to select the best representation, often in terms of regret.

Most of this work focuses on finding representations that make the problem Markov, rather than on finding good approximate abstractions. To deal with perceptual aliasing most work makes the assumption that the provided set contains a Markov model of the environment [25, 47, 48, 53, 58]. To find a correct representation in the online setting these algorithms eliminate non-Markov models by comparing the obtained rewards during execution with a threshold based on a Markov model. The work by Lattimore et al. [41] considers a similar setting, where the dynamics of the true environment depend arbitrarily on the history of actions, rewards, and observations. Instead of getting a set of representation functions, they assume access to a given set of models, one of which is a correct model of the true environment. In this way, they can compare the calculated expected reward for the given model with the rewards obtained during the process and eliminate the unlikely models.

Other work does not assume that a Markov representation is available [31, 57], these both use an ϵ -bisimulation type abstraction. The work of Ortner et al. [57] builds on the work by Maillard et al. [47], by removing the necessity of having a Markov representation in the set of available representations. However, the analysis is invalid since it has been shown that there is an issue in the proof on which they build [18]. They also do not take into perceptual aliasing, since they use a concentration inequality that requires i.i.d. samples. The work by Jiang et al. [31] deals with perceptual aliasing by explicitly assuming in their analysis that a data set consisting of samples that are i.i.d. is available. They give a performance bound for policies based on a learned abstract model and split the error into two components, similar to some of the work mentioned in Section 3.2 [17, 59]. These two components are used to create an algorithm that decides which representation should be used based on the available data.

The methods in this section show that we can learn to select a correct (Markov) representation, given an initial set of representations. Most of these methods are not very scalable, as they are tabular, and it can be difficult to find a good (Markov) representation/abstraction in larger problems.

4 Online Abstraction Learning

The previously discussed works have mostly assumed that an abstract representation (or a set thereof) is readily available. However, this is not always possible. Thus, there is work that considers the situation where such an abstraction is not yet available, and instead has to be learned first, while at the same time learning about the environment. Two early studies on this topic provided promising experimental results [40, 51]. In Section 4.1, we cover tabular approaches which have mostly been more theoretical, and in Section 4.2, we cover deep learned representations focused on scaling up.

4.1 Tabular Approaches

The combination of MBRL and abstraction has also been approached theoretically. The work by Bernstein and Shimkin [7] gives results for online abstraction when the transition functions are deterministic, while the work by Ortner [56] explores the more general case of stochastic transition functions when trying to learn a ϵ -bisimulation. To learn a ϵ -bisimulation they maintain an interval on the estimation of the transition and reward functions for each state-action pair, which is used to create a BPMDP [22]. Subsequently, the BPMDP is abstracted, by clustering the states that have an overlap in the transition and reward function for all actions, but only if they have a similar amount of samples. They give an example to show that it is necessary for clustered states to have a similar amount of samples for all the actions to obtain good performance. This is an interesting observation since it points out a problem that should be taken into account when learning an abstraction in combination with MBRL. A downside of the method is that it is focused on the computational benefit abstraction can bring, from the perspective of sample efficiency, a method that utilizes abstraction to learn more efficiently is desirable.

In the Bayesian RL setting, the work by Mandel et al. [49] proposes an algorithm that does online clustering and exploration. The clustering is done over state-action pairs, rather than only over states. State-action abstractions allow for a wider class of abstractions since state abstractions can be considered a subset of state-action abstractions, while potentially still being optimality preserving. This gives additional power in doing the abstraction since in some domains there could be no similar states while similar state-action pairs exist. State-action pairs are grouped together when the relative outcomes are likely to be the same. Relative outcomes are similar to observations and given a relative outcome the agent knows both the transition and reward, but it needs to learn the distribution over relative outcomes for each state.

Work in block MDPs, or MDPs with rich observations, is a related approach where the assumption is that each state can generate multiple different observations [5, 15, 24, 39, 81]. Instead of having multiple states that generate the same observation (due to the abstraction function), each type of observation is only generated by 1 state, but each state can generate multiple observations. This is quite similar to representation learning, specifically learning a bisimulation [5, 15, 81]. A common approach in this setting is to use spectral methods [5, 24, 39]. For these to work it is necessary to be able to uniquely identify states from the observation function. While this is possible for model-irrelevance abstractions, generally in the abstraction setting this will not be possible.

The focus of tabular approaches has been on block MDPs which can lead to a large reduction in the state space in suitable problems. This does however require the problem to have a lot of states with the exact same behavior in an abstract space, i.e., there needs to be a bisimulation abstraction. This restricts the number of problems these methods can be applied to.

4.2 Deep Learned Representations

There have also been a number of Deep RL approaches that focus on learning compact state representations, which can be viewed as an instance of state abstraction, for instance, the approaches by Sermanet et al. [67], Thomas et al. [73], Biza and Platt [8], François-Lavet et al. [16], Van der Pol et al. [62], Schrittwieser et al. [65], Allen et al. [3], and Ye et al. [80]. One important notion for abstraction in deep RL is a collapse of the latent representation [3, 12, 16, 62]. When considering only the transition function, it would be optimal to cluster all states into just one abstract state. It has been shown that losses that require both the transition and reward function of grouped states to be exactly the same can avoid this collapse [19], making it important to group states based on both transitions and rewards.

Recently, multiple contrastive methods have been used to learn compact representations for predicting the next state [4, 37, 55]. Their representation learning tries to maximize the mutual information between the present and future samples. To train the network they use positive and negative next state samples, where the positive samples are transitions that actually occurred, while the negative samples are transitions that did not occur. These negative samples should help to prevent the potential collapse of the state representation. Their methods do not use the model to plan the policy but instead use actor-critic and policy optimization methods on top of the representation. The proposed representation learning method was able to help improve the performance of these methods.

Other work has focused on learning deep representations for robotics [12, 33, 43]. This has investigated adding several types of robotic priors in order to bias the representation learning, which are added to the network as an auxiliary loss [30]. These priors encode knowledge about physics, e.g., that changes in the state are often gradual rather than abrupt. The state-representation objectives were especially useful in generalizing, as they significantly improved the results in the test domain. This shows that learning a compact model of the environment

| Section | Method | Environment | Model | Abstraction ϕ | Abstraction Type | Theory | Scalability | Perceptual Aliasing |
|------------------|-------------------------------|-----------------------------------|------------------|--------------------|----------------------|--------|-------------|---|
| 2.1 | Planning | MDP | Given | Constructed | Many | V | ~ | Not an issue |
| | Tabular RL | Abstract MDP | Given | Build-in | Bisimulation related | V | X | Not an issue |
| 3.1 | Robust Optimization | MDP | Given (interval) | Build-in | Bisimulation | V | ~ | Assumption on uncertainty |
| | Robust Optimization | MDP + ϕ | Given | Given | Bisimulation related | ~ | X | Not an issue |
| 3.2 | Tabular RL | MDP + ϕ | Unknown | Given | Bisimulation related | V | X | Assumptions on data gathering |
| 3.3 | Abstraction Selection | MDP + [ϕ_1, \dots, ϕ_n] | Unknown | Given | Several | V | X | Markov representation, assumption on data gathering |
| 4.1 | Tabular RL | MDP + ϕ | Unknown | Learned | Bisimulation related | V | X | Markov representation, specific check |
| | Bayesian RL | MDP + ϕ | Unknown | Learned | (s,a)-abstraction | V | X | Markov representation |
| Spectral Methods | | Block-MDP | Unknown | Learned | Bisimulation related | V | ~ | Markov representation |
| | Deep RL | MDP + ϕ | Unknown | Learned | Bisimulation related | ~ | V | Markov representation, potential problem |
| 4.2 | Contrastive Loss | MDP + ϕ | Unknown | Learned | Bisimulation related | X | V | Markov representation, potential problem |
| | Linear Latent Representations | MDP + ϕ | Unknown | Learned | Linear Function | X | V | Markov representation, potential problem |

Table 1. Characterization of MBRL methods in combination with a type of state abstraction.

can be beneficial even if the model itself is not directly used for planning. Other methods for robotics focus on finding compact linear representations of a problem and finding a policy for this smaller model [75, 78, 82]. For robotics, where many of the important state features could be approximately linear, this has shown good results.

Most of the work in this section focused on learning exact abstractions. That is, they try to reduce the problem in such a way that the resulting latent representation still makes the problem an MDP. This can be difficult to ensure, especially in Deep RL, so it is likely that the resulting representation is actually an approximate abstraction. Since most work does not acknowledge this, they do not consider the resulting perceptual aliasing, and algorithms can experience the problem illustrated by [56]: when states are grouped together that have a different number of visitations this can lead to suboptimal policies. When this is not taken into account, this can lead an agent to be stuck in a suboptimal loop.

5 Discussion and Conclusion

We summarize our overview in Table 1, which compares the approaches on the type of environment, whether or not a model is given, how an abstraction ϕ is obtained, what kind of abstraction is used, available theoretical support, scalability, and how they deal with perceptual aliasing.

The methods in Sections 2 and 3 generally have strong theoretical support (V) in the form of bounded loss (e.g., [2, 79]), finite-sample guarantees (e.g., [59, 69]), or regret bounds (e.g., [48]). Most of these methods are not (X) scalable due to being tabular or only somewhat scalable (\sim) due to needing to be given a model, which in many cases is not possible. In most these works, the problem of perceptual aliasing does not arise, either because of assumptions on data gathering, or because an MDP, or MDP representation, is provided. Starre et al. [69] show that finite-sample bounds for MBRL in an MDP with an approximate abstraction, without making the assumption that samples are independent, can be obtained, at least when an ϵ -bisimulation abstract is used. *Extending these results to other types of abstractions is still an open question.*

In Section 3.2, we saw that with abstractions there is a bias-variance trade-off [17, 31, 59, 66]. Because of this trade-off, *an interesting direction would be to combine learning multiple representations with abstraction selection, to decide which representation to use at which time.*

Results for optimization under uncertainty as discussed in Section 3.1 could make it interesting to maintain confidence intervals for the learned models and use robust optimization to find policies. Since during learning the model will generally not be completely accurate, robust optimization could improve performance [45]. Tabular work discussed in Sections 3.1 and 4.1 investigated this idea [56, 60], *scaling such approaches to larger problems is an interesting future direction.*

Most of the focus has been on abstractions related to bisimulation. As touched upon in Section 4.1, abstractions that aggregate state-action pairs can be more

powerful than state abstractions [49]. An open question is *what are the best types of abstraction to use?* Non-deterministic abstraction [68], temporal abstraction, or combinations of abstractions could be powerful but have not been as well studied [38].

In the work by Schrittwieser et al. [65], there is some indication that in online planning using a coarser learned model rather than the true model can be beneficial. With limited planning time, planning with a compact learned model outperformed planning with the true model of the environment. *There could be a trade-off for learning between the coarseness of the model and the allotted planning time, a coarser model could perform better with a shorter planning time but worse with a longer planning time.*

The methods in Section 4.2 focus on learning abstractions that result in a Markov representation, e.g., bisimulation abstractions. However, *during learning, when the abstraction is likely not a Markov representation, perceptual aliasing occurs. How can the resulting non-stationarity be addressed?* In Section 4.1, we saw that the tabular work by Ortner [56] deals with perceptual aliasing, but to do so it maintains visitation counts for all state-action pairs. Methods that are able to maintain counts in an approximate way, such as pseudo-counts [71], could enable a scalable version of the approach by Ortner [56]. Another approach to deal with perceptual aliasing in a more sample-efficient way could be using an algorithm such as ITER [28], which tackles the general non-stationarity of the data distribution caused by the RL algorithm. The idea of the algorithm is to frequently transfer the knowledge of the trained network to a new network, and then use the new network for training. The knowledge is transferred through samples that are obtained from the collected data set as if they had been generated with the final policy of the trained network.

In multi-agent RL the challenge is to behave optimally in the presence of other agents whose behavior may be non-stationary [26]. *Approaches for the multi-agent RL problem that address non-stationarity could be insightful for the combination of RL and abstraction.* One approach that could be relevant is trying to capture the non-stationarity that is the result of perceptual aliasing, which could for instance be done by using influence-based abstraction [54]. Influence-based abstraction aims to abstract a problem into a smaller local problem with a predictor that quantifies the influence of variables outside the local problem on the local problem. Given an accurate predictor, this results in a Markov problem. Such a predictor could capture the non-stationarity due to perceptual aliasing and improve performance. Influence-based abstraction has been applied together with Deep model-free RL, using a recurrent neural network to capture the influence, which has shown promising results [10].

Other approaches in multi-agent RL do not deal with the non-stationarity but simply ignore it, by abstracting away the internal states of the other agents. Since this can be seen as a special case of the non-stationarity in the combination of RL and abstraction, insights from this combination on how to deal with non-stationarity as a result of perceptual aliasing could provide interesting directions for these multi-agent RL approaches.

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