

# Learning Not to Learn: Nature versus Nurture in Silico

Robert Tjarko Lange & Henning Sprekeler

Berlin Institute of Technology

Excellence Cluster Science of Intelligence

Marchstr. 23, 10587 Berlin

{robert.t.lange,h.sprekeler}@tu-berlin.de

## Abstract

Animals are equipped with a rich innate repertoire of sensory, behavioral and motor skills, which allows them to interact with the world immediately after birth. At the same time, many behaviors are highly adaptive and can be tailored to specific environments by means of learning. In this work, we use mathematical analysis and the framework of memory-based meta-learning (or ‘learning to learn’) to answer when it is beneficial to learn such an adaptive strategy and when to hard-code a heuristic behavior. We find that the interplay of ecological uncertainty, task complexity and the agents’ lifetime has crucial effects on the meta-learned amortized Bayesian inference performed by an agent. There exist two regimes: One in which meta-learning yields a learning algorithm that implements task-dependent information-integration and a second regime in which meta-learning imprints a heuristic or ‘hard-coded’ behavior. Further analysis reveals that non-adaptive behaviors are not only optimal for aspects of the environment that are stable across individuals, but also in situations where an adaptation to the environment would in fact be highly beneficial, but could not be done quickly enough to be exploited within the remaining lifetime. Hard-coded behaviors should hence not only be those that always work, but also those that are too complex to be learned within a reasonable time frame.

## Introduction

The ‘*nature versus nurture*’ debate (Mutti, Zadnik, and Adams 1996; Tabery 2014) – the question of which aspects of behavior are ‘hard-coded’ by evolution, and which are learned from experience – is one of the oldest and most controversial debates in biology. Evolutionary principles prescribe that hard-coded behavioral routines should be those for which there is no benefit in adaptation. This is believed to be the case for behaviors whose evolutionary advantage varies little among individuals of a species. Mating instincts or flight reflexes are general solutions that rarely present an evolutionary disadvantage. On the other hand, features of the environment that vary substantially for individuals of a species potentially ask for adaptive behavior (Buss 2015).

Copyright © 2022, Association for the Advancement of Artificial Intelligence (www.aaai.org). All rights reserved.

Naturally, the same principles should not only apply to biological but also to artificial agents. But how can a reinforcement learning agent differentiate between these two behavioral regimes?

A promising approach to automatically learn rules of adaptation that facilitate environment-specific specialization is meta-learning (Schmidhuber 1987; Thrun and Pratt 1998). At its core lies the idea of using generic optimization methods to learn inductive biases for a given ensemble of tasks. In this approach, the inductive bias usually has its own set of parameters (Hochreiter, Younger, and Conwell 2001) that are optimized on the whole task ensemble, that is, on a long, ‘evolutionary’ time scale. These parameters in turn control how a different set of parameters (e.g., activities in the network) are updated on a much faster time scale. These rapidly changing parameters then allow the system to adapt to a specific task at hand. Notably, the parameters of the system that are subject to ‘nature’ – i.e., those that shape the inductive bias and are common across tasks – and those that are subject to ‘nurture’ are usually predefined from the start.

In this work, we use the memory-based meta-learning approach for a different goal, namely to acquire a qualitative understanding of which aspects of behavior should be hard-coded and which should be adaptive. Our hypothesis is that meta-learning can not only learn efficient learning algorithms, but can also decide not to be adaptive at all, and to instead apply a generic heuristic to the whole ensemble of tasks. Phrased in the language of biology, meta-learning can decide whether to hard-code a behavior or to render it adaptive, based on the range of environments the individuals of a species could encounter.

We study the dependence of the meta-learned algorithm on three central features of the meta-reinforcement learning problem:

- **Ecological uncertainty:** How diverse is the range of tasks the agent could encounter?
- **Task complexity:** How long does it take to learn the optimal strategy for the task at hand? Note that this could be different from the time it takes to execute the optimal strategy.
- **Expected lifetime:** How much time can the agent spend on exploration and exploitation?

Using analytical and numerical analyses, we show that

non-adaptive behaviors are optimal in two cases – when the optimal policy varies little across the tasks within the task ensemble and when the time it takes to learn the optimal policy is too long to allow a sufficient exploitation of the learned policy.

Our results suggest that not only the design of the meta-task distribution, but also the lifetime of the agent can have strong effects on the meta-learned algorithm of RNN-based agents. In particular, we find highly nonlinear and potentially discontinuous effects of ecological uncertainty, task complexity and lifetime on the optimal algorithm. As a consequence, a meta-learned adaptation strategy that was optimized, e.g., for a given lifetime may not generalize well to other lifetimes. This is essential for research questions that are interested in the conducted adaptation behavior, including curriculum design, safe exploration as well as human-in-the-loop applications. Our work provides a principled way of examining the constraint-dependence of meta-learned inductive biases. Furthermore, we highlight the potential of multiple local optima in the meta loss surface, which correspond to very different behavioral policies. Depending on the parametrization of the meta-training distribution, different random seeds may therefore result in drastically different gradient-based optimization trajectories.

The remainder of this paper is structured as follows: First, we review the background in memory-based meta-reinforcement learning and contrast the related literature. Afterwards, we analyze a Gaussian multi-arm bandit setting, which allows us to analytically disentangle the behavioral impact of ecological uncertainty, task complexity and lifetime. Our derivation of the lifetime-dependent Bayes optimal exploration reveals a highly non-linear interplay of these three factors. We show numerically that memory-based meta-learning reproduces our theoretical results and can learn *not* to learn. Furthermore, we extend our analysis to more complicated exploration problems. Throughout, we analyze the resulting recurrent dynamics of the network and the representations associated with learning and non-adaptive strategies.

## Related Work & Background

Meta-learning or ‘learning to learn’ (Schmidhuber 1987; Thrun and Pratt 1998; Hochreiter, Younger, and Conwell 2001; Duan et al. 2016; Wang et al. 2016; Finn, Abbeel, and Levine 2017) has been proposed as a computational framework for acquiring task distribution-specific learning rules. During a costly outer loop optimization, an agent crafts a niche-specific adaptation strategy, which is applicable to an engineered task distribution. At inference time, the acquired inner loop learning algorithm is executed for a fixed amount of timesteps (lifetime) on a test task. This framework has successfully been applied to a range of applications such as the meta-learning of optimization updates (Andrychowicz et al. 2016; Flennerhag et al. 2018; Flennerhag et al. 2019), agent (Rabinowitz et al. 2018) and world models (Nagabandi et al. 2018) and explicit models of memory (Santoro et al. 2016; Bartunov et al. 2019). Already, early work by (Schmidhuber 1987) suggested an evolutionary perspective on recursively learning the rules of learning.

This perspective holds the promise of explaining the emergence of mechanisms underlying both natural and artificial behaviors. Furthermore, a similarity between the hidden activations of LSTM-based meta-learners and the recurrent activity of neurons in the prefrontal cortex (Wang et al. 2018) has recently been suggested.

Previous work has shown that LSTM-based meta-learning is capable of distilling a sequential integration algorithm akin to amortized Bayesian inference (Ortega et al. 2019; Rabinowitz 2019; Mikulik et al. 2020). Here we investigate when the integration of information might not be the optimal strategy to meta-learn. We analytically characterize a task regime in which not adapting to sensory information is optimal. Furthermore, we study whether LSTM-based meta-learning is capable of inferring when to learn and when to execute a non-adaptive program. (Rabinowitz 2019) previously studied the outer loop learning dynamics and found differences across several tasks, the origin of which is however not fully understood. Our work may provide an explanation for these different meta-learning dynamics and the dependence on the task distribution as well as the time horizon of adaptation.

Our work is closely related to (Pardo et al. 2017), (Zintgraf et al. 2019) and (Yin et al. 2019). (Pardo et al. 2017) study the impact of fixed time limits and time-awareness on deep reinforcement learning agents. They propose using a timestamp as part of the state representation in order to avoid state-aliasing and the non-Markovianity resulting from a finite horizon treatment of an infinite horizon problem. Our setting differs in several aspects. First, we study the case of meta-reinforcement learning where the agent has to learn within a single lifetime. Second, we focus on a finite horizon perspective with limited adaptation. (Zintgraf et al. 2019), on the other hand, investigate meta reinforcement-learning for Bayes-adaptive Markov Decision Processes and introduce a novel architecture that disentangles task-specific belief representations from policy representations. Similarly to our work, (Zintgraf et al. 2019) are interested in using the meta-learning framework to distill Bayes optimal exploration behavior. While their adaptation setup extends over multiple episodes, we focus on single lifetime adaption and analytically analyze when it is beneficial to learn in the first place. (Yin et al. 2019) studies when gradient-based meta-learning does not yield an initialization optimized for adaptation but learns a single zero-shot model. Our study focuses on memory-based meta-learning and does consider input-independence as a bug, but in fact derive analytically that it is optimal for a wide range of meta-training task distributions. We show that the settings in which memorization is optimal, that there can be a sharp transition in task distribution space between memorization and adaptation.

Finally, our work extends upon the efforts of computational ethology (Stephens 1991) and experimental evolution (Dunlap and Stephens 2009; Dunlap and Stephens 2016; Marcus et al. 2018), which aims to characterize the conditions under which behavioral plasticity may evolve. Their work shows that both environmental change and the predictability of the environment shape the selection pressure, which evolves adaptive traits. Our work is based on

memory-based meta-learning with function approximation and aims to extend these original findings to task distributions for which no analytical solution may be available.

## Learning not to Learn

To disentangle the influence of ecological uncertainty, task complexity, and lifetime on the nature of the meta-learned strategy, we first focus on a minimal two-arm Gaussian bandit task, which allows for an analytical solution. The agent experiences episodes consisting of  $T$  arm pulls, representing the lifetime of the agent. The statistics of the bandit are constant during each episode, but vary between episodes. To keep it simple, one of the two arms is deterministic and always returns a reward of 0. The task distribution is represented by the variable expected reward of the other arm, which is sampled at the beginning of an episode, from a Gaussian distribution with mean  $-1$  and standard deviation  $\sigma_p$ , i.e.  $\mu \sim \mathcal{N}(-1, \sigma_p^2)$ . The standard deviation  $\sigma_p$  controls the uncertainty of the ecological niche. For  $\sigma_p \ll 1$ , the deterministic arm is almost always the better option. For  $\sigma_p \gg 1$ , the chances of either arm being the best in the given episode are largely even. While the mean  $\mu$  remains constant for the lifetime  $T$  of the agent, the reward obtained in a given trial is stochastic and is sampled from a second Gaussian,  $r \sim \mathcal{N}(\mu, \sigma_l)$ . This trial-to-trial variability controls how many pulls the agent needs to estimate the mean reward of the stochastic arm. The standard deviation  $\sigma_l$  hence controls how quickly the agent can learn the optimal policy. We therefore use it as a proxy for task complexity.

In this simple setting, the optimal meta-learned strategy can be calculated analytically. The optimal exploration strategy is to initially explore the stochastic arm for a given trial number  $n$ . Afterwards, it chooses the best arm based on its maximum a posteriori-estimate of the remaining episode return. The optimal amount of exploration trials  $n^*$  can then be derived analytically:<sup>1</sup>

$$\begin{aligned} n^* &= \arg \max_n \mathbb{E} \left[ \sum_{t=1}^T r_t | n, T, \sigma_l, \sigma_p \right] \\ &= \arg \max_n [-n + \mathbb{E}_{\mu, r} [(T - n) \times \mu \times p(\hat{\mu} > 0)]] , \end{aligned}$$

where  $\hat{\mu}$  is the estimate of the mean reward of the stochastic arm after the  $n$  exploration trials. We find two distinct types of behavior (left-hand side of figure 1): A regime in which learning via exploration is effective and a second regime in which not learning is the optimal behavior. It may be optimal not to learn for two reasons: First, the ecological uncertainty may be so small that it is very unlikely that the stochastic arm is better. Second, if the trial-to-trial variability is too large relative to the range of potential ecological niches, it may simply not be possible to integrate sufficient information given a limited lifespan. We make two observations:

<sup>1</sup>Please refer to the supplementary material for a detailed derivation of this analytical result as well as the hyperparameters of the numerical experiments.

1. There exists a hard nonlinear threshold between learning and not learning behaviors described by the ratio of  $\sigma_l$  and  $\sigma_p$ . If  $\sigma_l$  is too large, the value of exploration (or the reduction in uncertainty) is too small to be profitable within the remaining lifetime of the agent. Instead, it is advantageous to hard-code a heuristic choice.
2. The two regimes consistently exist across different lifetimes. As the lifetime grows, the learning regime becomes more and more prevalent. Given a sufficient amount of time, learning by exploring the uncertain arm is the best strategy.

Is the common meta-learning framework capable of reproducing these different qualitative behaviors and performing Bayes optimal amortized inference across the entire spectrum of meta-task distributions? Or differently put: Can memory-based meta-learning yield agents that do not only learn to learn but that also learn *not* to learn? To answer this question, we train LSTM-based RL<sup>2</sup> (Wang et al. 2016) agents with the standard synchronous actor-critic (Mnih et al. 2016) setup on the same grid of ecological uncertainties  $\sigma_p$  and "task complexities"  $\sigma_l$ . The input  $x_t$  to the network at time  $t$  consists of the action of the previous timestep, a monotonically increasing timestamp within the current episode and crucially the reward of the previous timestep,  $x_t = \{a_{t-1}, \phi(t), r_{t-1}\}$ . The recurrent weight dynamics of the inner loop can then implement an internal learning algorithm that integrates previous experiences. After collecting a set of trajectories, we optimize the weights and initial condition of the hidden state with an outer loop gradient descent update to minimize the common actor-critic objective.

We obtain the amount of meta-learned exploration by testing the RL<sup>2</sup> agents on hold-out bandits for which we set  $\sigma_p = 0$  and only vary  $\sigma_l$ . Thereby, it is ensured that the deterministic arm is the better arm. We can then define the number of exploration trials as the pulls from the suboptimal stochastic arm. We observe that meta-learning is capable of yielding agents that behave according to our derived theory of a Bayes optimal agent, which explicitly knows the given lifetime as well as uncertainties  $\sigma_l, \sigma_p$  (figure 1). Importantly, the meta-learned behavior also falls into two regimes: A regime in which the meta-learned strategy resembles a learning algorithm and a regime in which the recurrent dynamics encode a hard-coded choice of the deterministic arm. Furthermore, the edge between the two meta-learned regimes shifts with the agent's lifetime as predicted by the Bayesian theory. As the lifetime increases, wider ecological niches at higher levels of task complexity become solvable and the strategy of learning profitable.

In the Bayesian model, the edge between the two regimes is located at parameter values where the learning strategy and the non-learning strategy perform equally well. Because these two strategies are very distinct, we wondered whether the reward landscape for the memory-based meta-learner has two local maxima corresponding to the two strategies (figure 2). To test this, we trained  $N = 1000$  networks with different initial conditions, for task parameters close to the edge, but in the regime where the theoretically optimal strategy would be to learn. We then evaluated for each network

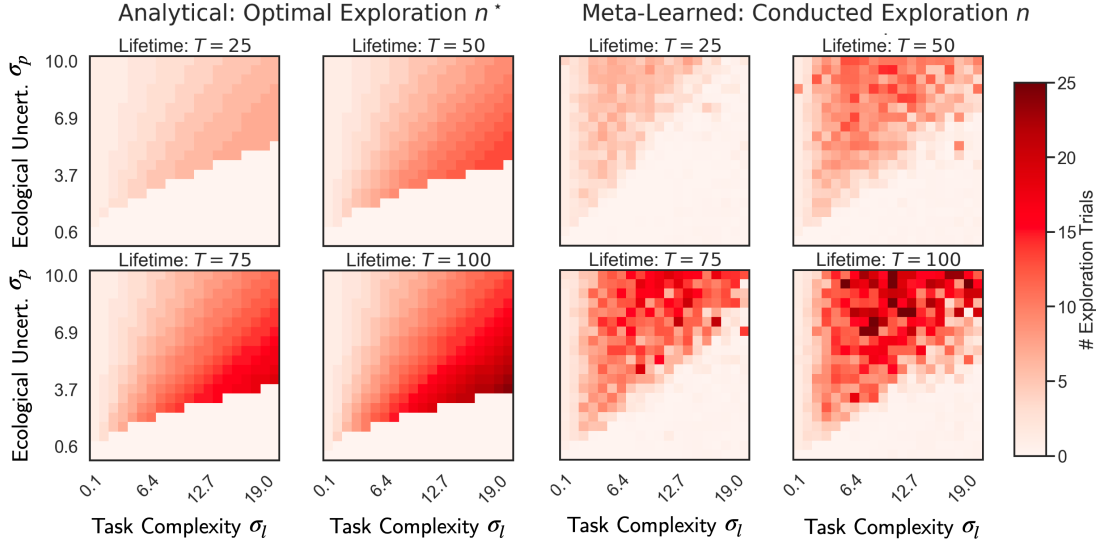


Figure 1: Theory and meta-learned exploration in a two-arm Gaussian bandit. **Left:** Bayes optimal exploration behavior for different lifetimes and across uncertainty conditions  $\sigma_l, \sigma_p$ . **Right:** Meta-learned exploration behavior using the RL<sup>2</sup> (Wang et al. 2016) framework. There exist two behavioral regimes (learning by exploration and a heuristic non-explorative strategy) for both the theoretical result and the numerical meta-learned behaviors. The amount of meta-learned exploration is averaged both over 5 independent training runs and 100 episodes for each of the 400 trained networks.

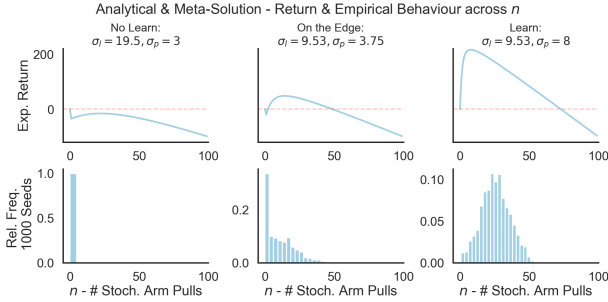


Figure 2: Bimodality of the reward landscape. **Upper row.** The Bayesian model predicts a bimodal dependence of the expected return on the policy. Parameters for lifetime  $T = 100$  in the non-learning (left) and learning regime (right) and close the transition edge (middle). **Bottom row.** Distribution of the mean number of explorative pulls in 1000 separately trained networks with different random seeds. Close to the edge, the networks fall into two classes: networks either abandon all exploration (peak at  $n = 0$ ) or explore and learn. Away from the transition, all 1000 networks adopt a similar strategy.

the number of explorative pulls of the stochastic arm, averaged across 100 episodes. The distribution of the number of explorative pulls across the 1000 networks shows *i*) a peak at zero exploration and *ii*) a broad tail of mean explorative pulls (figure 2), suggesting that there are indeed two classes of networks. One class never pulls the stochastic arm, i.e., those networks adopt a non-learning strategy. The other class has learned to learn. For task parameters further

away from the edge, this bimodality disappears.

The two behavioral regimes are characterized by distinct recurrent dynamics of the trained LSTM agents. The two left-most columns of figure 3 display the policy entropy and hidden state statistics for a network trained on a  $\sigma_l, \sigma_p$ -combination associated with the regime in which learning is the optimal behavior. We differentiate between the case in which the deterministic arm is the better one ( $\mu < 0$ ) and the case in which the second arm should be preferred ( $\mu > 0$ ). In both cases the agent first explores in order to identify the better arm. Moreover, the hidden dynamics appear to display two different attractors, which correspond to either of the arms being the better choice. The better arm can clearly be identified from the PCA-dimensionality reduced hidden state dynamics (bottom row of figure 3). The two right-most columns of figure 3, on the other hand, depict the same statistics for a network that was meta-trained on the regime in which the optimal strategy is not to learn. Indeed, the agent always chooses the deterministic arm, regardless of whether it is the better choice. Accordingly, the network dynamics seem to fall into a single attractor.

We examined how these strategies evolve over the course of meta-training and find that there are two phases: After an initial period of universal random behavior across all conditions, the distinct behavioral regimes emerge (supplementary figure). We note that this observation may be partially caused by the linear annealing of the entropy regularization coefficient in the actor-critic objective which we found to be important in training the networks.

In summary, we observe that the meta-learned strategy shows a highly nonlinear, partially discontinuous dependence on task parameters. In transition regions between



Figure 3: Recurrent dynamics of two meta-trained bandits for task conditions that favour learning (blue) and not learning (red), for a lifetime  $T = 100$ . Each bandit is tested both for the case where the deterministic arm is the better option and for the case where the stochastic arm is the better option. **First two columns.** Bandit for which an adaptive strategy is predicted by the theory. The inner loop dynamics integrate information which is reflected by the convergence of the hidden state to two different fixed points depending on which arm is optimal. **Last two columns.** Bandit for which the heuristic choice of the deterministic arm is the Bayes optimal behavior. Not learning manifests itself in non-explorative, rigid behavior and activations. The final row visualizes the PCA-dimensionality reduced hidden state dynamics ( $\tilde{h}_t$ ) averaged over 100 episodes. A darker color indicates a more frequent occupancy in the discretized PCA space of the transformed hidden states.

strategies, we find local maxima in the reward landscape that correspond to different learning strategies. In the simple bandit setting, these local maxima correspond to a learning and a non-learning strategy, respectively, hence providing a minimal model for a sharp nature-nurture trade-off. Next, we investigate whether these insights generalize to more complex domains by studying spatial reasoning.

### Time Horizons, Meta-Learned Strategies & Entropy Reduction

While the simple bandit task provides an analytical perspective on the trade-off of learning versus hard-coded behavior, it is not obvious that the obtained insights generalize to more complex situations, i.e., to distributions of finite-horizon MDPs. To investigate this, we studied exploration behavior in an ensemble of grid worlds task. We hypothesize that meta-learning yields qualitatively different spatial exploration strategies depending on the lifetime of the agent. For short a lifetime, the agent should opt for small rewards that are easy to find. For longer lifetimes, the agent can spend time to explore the environment and identify higher rewards that are harder to find.

To test this hypothesis, we train a RL<sup>2</sup>-based meta learner to explore a maze with three different types of goal lo-

cations (top row of figure 4):  $g_h$  (green object),  $g_m$  (yellow object) and  $g_s$  (pink object) with transition rewards  $R(g_h) > R(g_m) > R(g_s)$ .

During an episode/lifetime the goal locations are fixed. At the beginning of the episode  $g_m$  and  $g_h$  are randomly sampled. The location of  $g_s$ , on the other hand, remains fixed across all training episodes. We sample the possible locations for  $g_h$  from the outermost column and row (11 locations) while  $g_m$  varies along the third row and column (excluding the borders, 5 locations). Thereby, the three goals encode destinations with varying degrees of spatial uncertainty and payoff. The agent can move up, down, left and right. After it (red circle) transitions into a goal location, it receives the associated reward and is teleported back to the initial location in the bottom left corner. Within one episode, the agent can hence first perform one or several exploration runs, in which it identifies the object location, and then do a series of exploitation runs, in which it takes the shortest path to that location. Importantly, the agent does not observe the goal locations but instead has to infer the locations based on the observed transition rewards.

Depending on the lifetime of the agent during the inner loop adaptation, we find that meta-learning can imprint 3

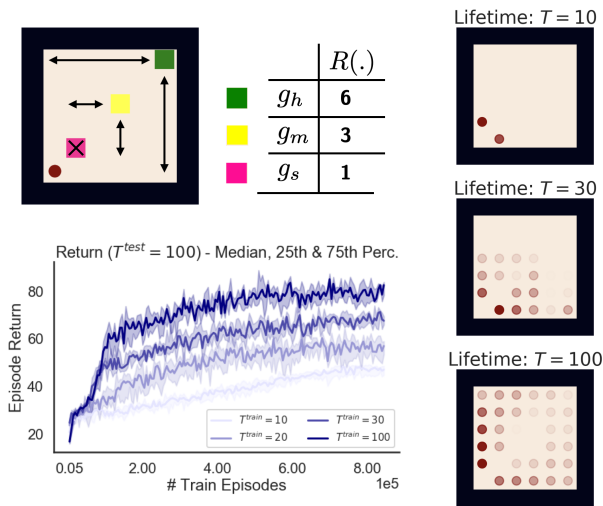


Figure 4: Grid navigation task with 3 different rewards, which differ in the amount of reward and the uncertainty in location. **Top-Left:** Task formulation. **Bottom-Left:** Learning curves ( $T^{test} = 100$ ) for different training lifetime. We plot the median, 25th and 75th percentile of the return distribution aggregated over 10 independent training runs and 10 evaluation episodes. Agents trained on a shorter lifetime gradually generalize worse to the larger test lifetime. **Right:** Relative state occupancy of meta-learned exploration strategies for different training lifetimes during meta-learning (averaged over 100 episodes of length 100). With increasing lifetime the agent explores larger parts of the state space and actively avoids suboptimal object location transition.

qualitatively different strategies (figure 4 right column; figure 5): For small lifetimes the agent executes a hard-coded policy that repeatedly walks to the safe, low-reward pink object. As the lifetime and consequently inner loop adaptation is increased, we find that the agent’s meta-learned policy starts to explore a broader range of locations in the maze, first exploring possible locations of the medium-reward object and – for long lifetimes – the distant and uncertain high-reward object (figure 4 right column). Consistently, the agent exploits increasingly uncertain rewards with increasing lifetime (figure 5).

Furthermore, we investigated how meta-learned strategies generalize across different timescales of adaptation. More specifically, we trained an agent to learn (or not) with a given lifetime and tested how the learned behavior performed in a setting where there is more or less time available. As predicted, we find that the test time-normalized return of the agents decreased with the discrepancy between training and test lifetime (figure 6). This can be problematic in settings where the agent does not have access to its exact lifetime and highlights the lack of time-robustness of meta-adaptation.

The agents displayed clear hallmarks of model-based behavior and behavioral changes over their lifetime (figure 7). When the agent has encountered the high reward once, it resorts to a deterministic exploitation strategy that follows

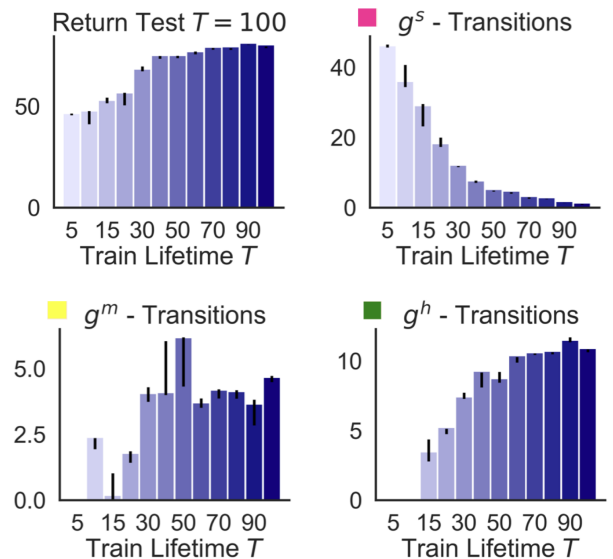


Figure 5: Lifetime dependence of the performance and the visitation counts of the goal locations for an  $RL^2$  agent trained on random  $6 \times 6$  grid worlds and evaluated on  $T^{test} = 100$ . For small lifetimes the meta-learned strategy only exploits the small safe object. For larger lifetimes the agent first explores the more uncertain medium (and later high) reward object locations. The displayed statistics (median, 25th/75th percentile) are aggregated over 5 independent training runs and 500 evaluation episodes.

a shorter trajectory through the environment than the one initially used during exploration. Furthermore, the adaptive policies identify when there is not enough time left in the episode to reach the previously exploited goal location. In that case the policies switch towards the easier to reach small goal location. The policy entropy (column three of figure 7) is state-specific and indicates that the meta-learned strategies have correctly learned a transition model of the relevant parts of the environment. If an action does not affect the overall length of the trajectory to a goal, this is reflected in the entropy of the policy. Finally, we analyzed the distinct recurrent dynamics for the three different strategies (final column of figure 7). We find that the dimensionality of the dynamics increases with the adaptivity of the behavior. As the training lifetime increases, the participation ratio (Gao et al. 2017) of the hidden state dynamics increases and the explained variance of the first three principal components drops.

## Discussion & Future Work

This work has investigated the interplay of three considerations when designing meta-task distributions: The diversity of the task distribution, task complexity and training lifetime. Depending on these, traditional meta-learning algorithms are capable of flexibly interpolating between distilling a learning algorithm and hard-coding a heuristic behavior. The different regimes emerge in the outer loop of meta-learning and are characterized by distinct recurrent dy-



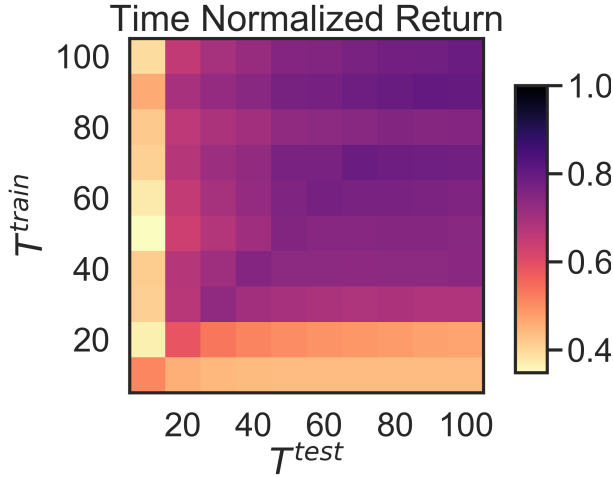


Figure 6: Episode return for agents trained on  $T^{train}$  and tested on  $T^{test}$ . The returns are normalized by the test lifetime. Agents which were meta-trained on a fixed lifetime do not generalize well to smaller or larger test lifetimes. The statistics are averaged over 5 independent training runs and 500 test episodes.

namics shaping the hidden activity. Meta-learned strategies showed limited generalization to timescales they were not trained on, emphasizing the importance of the training lifetime in meta-learning.

A key take-home from our results is the highly nonlinear and potentially discontinuous dependence of the meta-learned strategy on the parameters of the task ensemble. For certain parameter ranges, the reward landscape of the meta-learning problem features several local maxima that correspond to different learning strategies. The relative propensity of these strategies to emerge over the course of meta-learning depends on the task parameters and on the initialization of the agent. Generally, this supports the notion that there is not a single inductive bias for a given task distribution. Rather, there could be a whole spectrum of inductive biases that are appropriate for different amounts of training data. Even for the same task setting, different training runs can result in qualitatively different solutions, providing a note of caution for interpretations drawn by pooling over ensembles of trained networks.

The observed nonlinear dependence of the obtained solution may be relevant, e.g., for robotic applications, in which a rapid adaption of controllers trained in simulation to real-world robotic devices is desirable (Nagabandi et al. 2018; Belkhale et al. 2020; Julian et al. 2020). It is beneficial to ensure rapid adaptation on the real robot, e.g., to avoid physical damage. To achieve this, the meta-learner should be optimized for a short horizon. This, however, introduces a bias towards not learning, or in more complex settings, for heuristic solutions that explore less than is required to discover the optimal policy. For such problems, the curation of the meta-learning task ensemble may have to additionally take into account potential nonlinear and long-lasting

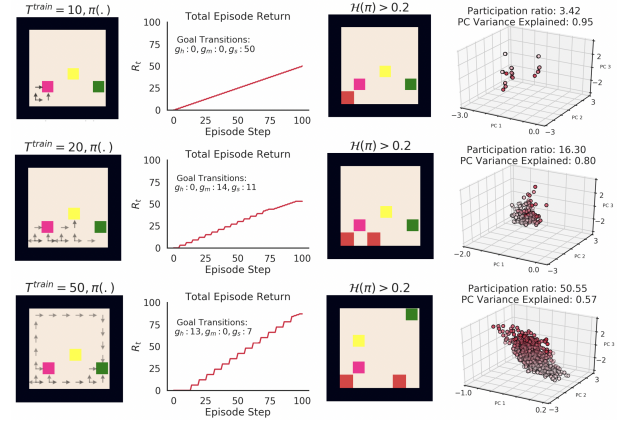


Figure 7: Characteristic trajectories for three different types of meta-learned strategies. **Top to bottom:** Episode rollouts ( $T^{test} = 100$ ) for inner loop training lifetimes  $T^{train} = \{10, 20, 50\}$ . **First three columns:** The agents’ trajectories, episode return, states with high average policy entropy (red squares) and the policy entropy for the same sampled environment. **Final column.** PCA-dimensionality reduced hidden state dynamics for different 100 rollout episodes and the agents’ respective training lifetimes. A lighter color indicates later episode trials. With increasing lifetime the meta-learned strategies become more adaptive and the recurrent dynamics higher dimensional.

trade-offs between final performance and speed of adaptation. The observed sharp transition between exploratory learning behavior(s) and hard-coded, non-learning strategies can be seen as a proof-of-concept example for a “nature-nurture” trade-off that adds new aspects to earlier work in theoretical ecology (Stephens 1991). From this perspective of animal behavior, meta-learning with a finite time horizon could provide an inroad into understanding the benefits and interactions of instinctive and adaptive behaviors. Potential applications could be the meta-learning of motor skills in biologically inspired agents (Merel et al. 2019) or instinctive avoidance reactions to colours or movements. The degree of biological realism that can be reached will be limited by computational resources, but qualitative insights could be gained, e.g., for simple instinctive behaviors. A different extension of our analysis is that to non-stationary environments, although we suspect a qualitative analogy of lifetime in our approach and auto-correlation times in non-stationary environments.

**Acknowledgments** We thank Nir Moneta for many discussions, Ben Beyret, Peter Dayan, Florin Gorgianu, Loreen Hertäg, Joram Keijser & Owen Mackwood for feedback on the manuscript. This work is funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany’s Excellence Strategy - EXC 2002/1 “Science of Intelligence” - project number 390523135.

## References

- [Andrychowicz et al. 2016] Andrychowicz, M.; Denil, M.; Gomez, S.; Hoffman, M. W.; Pfau, D.; Schaul, T.; Shillingford, B.; and De Freitas, N. 2016. Learning to learn by gradient descent by gradient descent. In *Advances in neural information processing systems*, 3981–3989.
- [Bartunov et al. 2019] Bartunov, S.; Rae, J. W.; Osindero, S.; and Lillicrap, T. P. 2019. Meta-learning deep energy-based memory models. *arXiv preprint arXiv:1910.02720*.
- [Belkhale et al. 2020] Belkhale, S.; Li, R.; Kahn, G.; McAllister, R.; Calandra, R.; and Levine, S. 2020. Model-based meta-reinforcement learning for flight with suspended payloads. *arXiv preprint arXiv:2004.11345*.
- [Buss 2015] Buss, D. 2015. *Evolutionary psychology: The new science of the mind*. Psychology Press.
- [Duan et al. 2016] Duan, Y.; Schulman, J.; Chen, X.; Bartlett, P. L.; Sutskever, I.; and Abbeel, P. 2016.  $RI^2$ : Fast reinforcement learning via slow reinforcement learning. *arXiv preprint arXiv:1611.02779*.
- [Dunlap and Stephens 2009] Dunlap, A. S., and Stephens, D. W. 2009. Components of change in the evolution of learning and unlearned preference. *Proceedings of the Royal Society B: Biological Sciences* 276(1670):3201–3208.
- [Dunlap and Stephens 2016] Dunlap, A. S., and Stephens, D. W. 2016. Reliability, uncertainty, and costs in the evolution of animal learning. *Current opinion in behavioral sciences* 12:73–79.
- [Finn, Abbeel, and Levine 2017] Finn, C.; Abbeel, P.; and Levine, S. 2017. Model-agnostic meta-learning for fast adaptation of deep networks. In *Proceedings of the 34th International Conference on Machine Learning-Volume 70*, 1126–1135. JMLR. org.
- [Flennerhag et al. 2018] Flennerhag, S.; Moreno, P. G.; Lawrence, N. D.; and Damianou, A. 2018. Transferring knowledge across learning processes. *arXiv preprint arXiv:1812.01054*.
- [Flennerhag et al. 2019] Flennerhag, S.; Rusu, A. A.; Pascanu, R.; Visin, F.; Yin, H.; and Hadsell, R. 2019. Meta-learning with warped gradient descent. *arXiv preprint arXiv:1909.00025*.
- [Gao et al. 2017] Gao, P.; Trautmann, E.; Yu, B.; Santhanam, G.; Ryu, S.; Shenoy, K.; and Ganguli, S. 2017. A theory of multineuronal dimensionality, dynamics and measurement. *BioRxiv* 214262.
- [Hochreiter, Younger, and Conwell 2001] Hochreiter, S.; Younger, A. S.; and Conwell, P. R. 2001. Learning to learn using gradient descent. In *International Conference on Artificial Neural Networks*, 87–94. Springer.
- [Julian et al. 2020] Julian, R.; Swanson, B.; Sukhatme, G. S.; Levine, S.; Finn, C.; and Hausman, K. 2020. Efficient adaptation for end-to-end vision-based robotic manipulation. *arXiv preprint arXiv:2004.10190*.
- [Marcus et al. 2018] Marcus, M.; Burnham, T. C.; Stephens, D. W.; and Dunlap, A. S. 2018. Experimental evolution of color preference for oviposition in *drosophila melanogaster*. *Journal of Bioeconomics* 20(1):125–140.
- [Merel et al. 2019] Merel, J.; Aldarondo, D.; Marshall, J.; Tassa, Y.; Wayne, G.; and Ölveczky, B. 2019. Deep neuroethology of a virtual rodent. *arXiv preprint arXiv:1911.09451*.
- [Mikulik et al. 2020] Mikulik, V.; Delétang, G.; McGrath, T.; Genewein, T.; Martic, M.; Legg, S.; and Ortega, P. 2020. Meta-trained agents implement bayes-optimal agents. *Advances in Neural Information Processing Systems* 33.
- [Mnih et al. 2016] Mnih, V.; Badia, A. P.; Mirza, M.; Graves, A.; Lillicrap, T.; Harley, T.; Silver, D.; and Kavukcuoglu, K. 2016. Asynchronous methods for deep reinforcement learning. In *International conference on machine learning*, 1928–1937.
- [Mutti, Zadnik, and Adams 1996] Mutti, D. O.; Zadnik, K.; and Adams, A. J. 1996. Myopia. the nature versus nurture debate goes on. *Investigative ophthalmology & visual science* 37(6):952–957.
- [Nagabandi et al. 2018] Nagabandi, A.; Clavera, I.; Liu, S.; Fearing, R. S.; Abbeel, P.; Levine, S.; and Finn, C. 2018. Learning to adapt in dynamic, real-world environments through meta-reinforcement learning. *arXiv preprint arXiv:1803.11347*.
- [Ortega et al. 2019] Ortega, P. A.; Wang, J. X.; Rowland, M.; Genewein, T.; Kurth-Nelson, Z.; Pascanu, R.; Heess, N.; Veness, J.; Pritzel, A.; Sprechmann, P.; et al. 2019. Meta-learning of sequential strategies. *arXiv preprint arXiv:1905.03030*.
- [Pardo et al. 2017] Pardo, F.; Tavakoli, A.; Levdiv, V.; and Kormushev, P. 2017. Time limits in reinforcement learning. *arXiv preprint arXiv:1712.00378*.
- [Rabinowitz et al. 2018] Rabinowitz, N. C.; Perbet, F.; Song, H. F.; Zhang, C.; Eslami, S.; and Botvinick, M. 2018. Machine theory of mind. *arXiv preprint arXiv:1802.07740*.
- [Rabinowitz 2019] Rabinowitz, N. C. 2019. Meta-learners’ learning dynamics are unlike learners’. *arXiv preprint arXiv:1905.01320*.
- [Santoro et al. 2016] Santoro, A.; Bartunov, S.; Botvinick, M.; Wierstra, D.; and Lillicrap, T. 2016. Meta-learning with memory-augmented neural networks. In *International conference on machine learning*, 1842–1850.
- [Schmidhuber 1987] Schmidhuber, J. 1987. *Evolutionary principles in self-referential learning, or on learning how to learn: the meta-meta-... hook*. Ph.D. Dissertation, Technische Universität München.
- [Stephens 1991] Stephens, D. 1991. Change, regularity, and value in the evolution of animal learning. *Behavioral Ecology* 2(1):77–89.
- [Tabery 2014] Tabery, J. 2014. *Beyond versus: The struggle to understand the interaction of nature and nurture*. MIT Press.
- [Thrun and Pratt 1998] Thrun, S., and Pratt, L. 1998. Learning to learn: Introduction and overview. In *Learning to learn*. Springer. 3–17.
- [Wang et al. 2016] Wang, J. X.; Kurth-Nelson, Z.; Tirumala, D.; Soyer, H.; Leibo, J. Z.; Munos, R.; Blundell, C.; Ku-



maran, D.; and Botvinick, M. 2016. Learning to reinforcement learn. *arXiv preprint arXiv:1611.05763*.

[Wang et al. 2018] Wang, J. X.; Kurth-Nelson, Z.; Kumaran, D.; Tirumala, D.; Soyer, H.; Leibo, J. Z.; Hassabis, D.; and Botvinick, M. 2018. Prefrontal cortex as a meta-reinforcement learning system. *Nature neuroscience* 21(6):860–868.

[Yin et al. 2019] Yin, M.; Tucker, G.; Zhou, M.; Levine, S.; and Finn, C. 2019. Meta-learning without memorization. *arXiv preprint arXiv:1912.03820*.

[Zintgraf et al. 2019] Zintgraf, L.; Shiarlis, K.; Igl, M.; Schulze, S.; Gal, Y.; Hofmann, K.; and Whiteson, S. 2019. Varibad: A very good method for bayes-adaptive deep rl via meta-learning. *arXiv preprint arXiv:1910.08348*.