MAESTRO: OPEN-ENDED ENVIRONMENT DESIGN FOR MULTI-AGENT REINFORCEMENT LEARNING

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ABSTRACT

Open-ended learning methods that automatically generate a curriculum of increasingly challenging tasks serve as a promising avenue toward generally capable reinforcement learning (RL) agents. Existing methods adapt curricula independently over either environment parameters (in single-agent settings) or co-player policies (in multi-agent settings). However, the strengths and weaknesses of co-players can manifest themselves differently depending on environmental features. It is thus crucial to consider the dependency between the environment and co-player when shaping a curriculum in multi-agent domains. In this work, we use this insight and extend Unsupervised Environment Design (UED) to multi-agent environments. We then introduce *Multi-Agent Environment-Space Response Oracles* (MAESTRO), the first multi-agent UED approach for two-player zero-sum settings. MAESTRO efficiently produces adversarial, joint curricula over both environment parameters and co-player policies and attains minimax-regret guarantees at Nash equilibrium. Our experiments show that MAESTRO outperforms a number of strong baselines on competitive two-player environments, spanning discrete and continuous control.[1]

1 INTRODUCTION

The past few years have seen a series of remarkable achievements in producing deep reinforcement learning (RL) agents with expert (Vinyals et al., 2019; Berner et al., 2019; Wurman et al., 2022) and superhuman (Silver et al., 2016; Schrittwieser et al., 2020) performance in challenging competitive games. Central to these successes are adversarial training processes that result in curricula creating new challenges at the frontier of an agent's capabilities (Leibo et al., 2019; Yang et al., 2021). Such automatic curricula, or autocurricula, can improve the sample efficiency and generality of trained policies (Open Ended Learning Team et al., 2021), as well as induce an open-ended learning process (Balduzzi et al., 2019; Stanley et al., 2017) that continues to endlessly robustify an agent.

Autocurricula have been effective in multi-agent RL for adapting to different *co-players* in competitive games (Leibo et al., 2019; Garnelo et al., 2021; Baker et al., 2019; Bansal et al., 2018; Feng et al., 2021), where it is crucial to play against increasingly stronger opponents (Silver et al., 2018) and avoid being exploited by other agents (Vinyals et al., 2019). Here, algorithms such as self-play (Silver et al., 2018; Tesauro, 1995) and fictitious self-play (Brown, 1951; Heinrich et al., 2015) have proven especially effective. Similarly, in single-agent RL, autocurricula methods based on Unsupervised Environment Design (UED, Dennis et al., 2020) have proven effective in producing agents robust to a wide distribution of *environments* (Wang et al., 2019; 2020; Jiang et al., 2021a; Parker-Holder et al., 2022). UED seeks to adapt distributions over environments to maximise some metrics of interest. Minimax-regret UED seeks to maximise the *regret* of the learning agent, viewing this process as a game between a teacher that proposes challenging environments and a student that learns to solve them. At a Nash equilibrium of such games, the student policy provably reaches a minimax-regret policy over the set of possible environments, thereby providing a strong robustness guarantee.

However, prior works in UED focus on single-agent RL and thus ignore the dependency between the environment and the behaviours of other agents within it. In multi-agent domains, the behaviour of other agents plays a critical role in modulating the complexity and diversity of the challenges faced by a learning agent. For example, an empty environment that has no blocks to hide behind might be

[1]Videos of MAESTRO policies are available at `https://sites.google.com/view/marl-ued`.

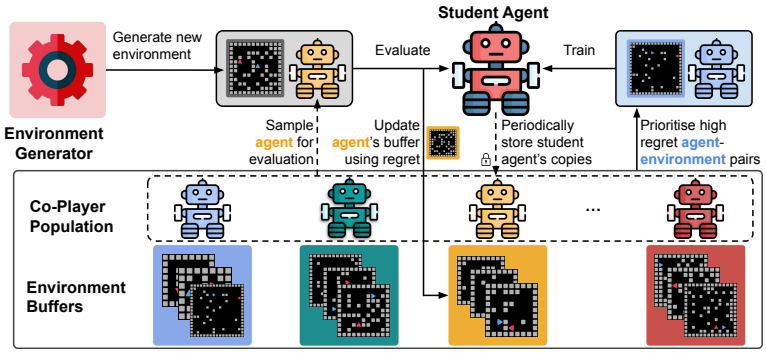


Figure 1: **A diagram of MAESTRO.** MAESTRO maintains a population of co-players, each having an individual buffer of high-regret environments. When new environments are sampled, the student's regret is calculated with respect to the corresponding co-player and added to the co-player's buffer. MAESTRO continually provides high-regret environment/co-player pairs for training the student.

most challenging when playing against opponent policies that attack head-on, whereas environments that are full of winding hallways might be difficult when playing against defensive policies. Robust RL agents should be expected to interact successfully with a wide assortment of other rational agents in their environment (Yang et al., 2021). Therefore, to become widely applicable, UED must be extended to include multi-agent dynamics as part of the environment design process.

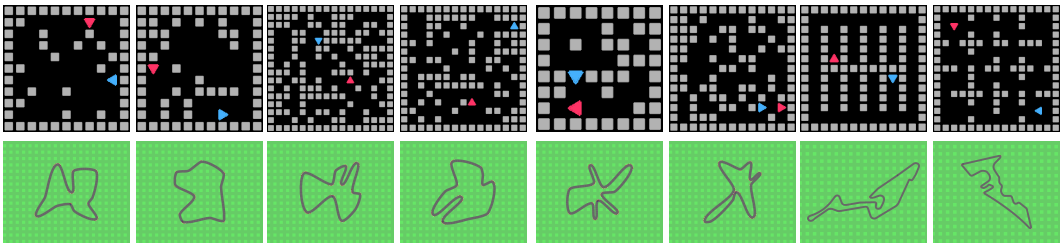
In this work, we formalise this novel problem as an *Underspecified Partially-Observable Stochastic Game* (UPOSG), which generalises UED to multi-agent settings. We then introduce *Multi-Agent Environment-Space Response Oracles* (MAESTRO), the first approach to train generally capable agents in two-player UPOSGs such that they are robust to changes in the environment and co-player policies. MAESTRO is a replay-guided approach that explicitly considers the dependence between agents and environments by jointly sampling over environment/co-player pairs using a regret-based curriculum and population learning (see Figure 1). In partially observable two-player zero-sum games, we show that at equilibrium, the MAESTRO student policy reaches a Bayes-Nash Equilibrium with respect to a regret-maximising distribution over environments. Furthermore, in fully observable settings, it attains a Nash-Equilibrium policy in every environment against every rational agent.

We assess the curricula induced by MAESTRO and a variety of strong baselines in two competitive two-player games, namely a sparse-reward grid-based LaserTag environment with discrete actions (Lanctot et al., 2017) and a dense-reward pixel-based MultiCarRacing environment with continuous actions (Schwarting et al., 2021). In both cases, MAESTRO produces more robust agents than baseline autocurriculum methods on out-of-distribution (OOD) human-designed environment instances against unseen co-players. Furthermore, we show that MAESTRO agents, trained only on randomised environments and having never seen the target task, can significantly outperform *specialist* agents trained directly on the target environment. Moreover, in analysing how the student's regret varies across environments and co-players, we find that a joint curriculum, as produced by MAESTRO, is indeed required for finding the highest regret levels, as necessitated by UED.

In summary, we make the following core contributions: (i) we provide the first formalism for multi-agent learning in underspecified environments, (ii) we introduce MAESTRO, a novel approach to jointly learn autocurricula over environment/co-player pairs, implicitly modelling their dependence, (iii) we prove MAESTRO inherits the theoretical property from the single-agent setting of implementing a minimax-regret policy at equilibrium, which corresponds to a Bayes-Nash or Nash equilibrium in certain settings, and (iv) by rigorously analysing the curriculum induced by MAESTRO and evaluating MAESTRO agents against strong baselines, we empirically demonstrate the importance of the joint curriculum over the environments and co-players.

2 BACKGROUND

In single-agent domains, the problem of *Unsupervised Environment Design* (UED) is cast in the framework of an underspecified POMDP (Dennis et al., 2020), which explicitly augments a standard POMDP with a set of *free parameters* controlling aspects of the environment subject to the design process. We extend this formalism to the multi-agent setting, in the form of a stochastic game.



(a) Start of training (b) Middle of training (c) End of training (d) Zero-shot evaluation

Figure 2: **Emergent complexity of autocurricula induced by MAESTRO**. Example environments provided to the MAESTRO student agent at (a) start, (b) middle, and (c) end of training. Levels become more complex over time. LaserTag levels (top row) increase in wall density and active engagement between the student and opponent. MultiCarRacing tracks (bottom row) become increasingly more challenging with many sharp turns. (d) Example held-out human-designed LaserTag levels and Formula 1 benchmark tracks (Jiang et al., 2021a) used for OOD evaluation. For the full list of evaluation environments see Appendix C.

An ***Underspecified Partially Observable Stochastic Game (UPOSG)*** is given by the tuple $\mathcal{M} = \langle n, \mathcal{A}, \mathcal{O}, \Theta, S, \mathcal{T}, \mathcal{I}, \mathcal{R}, \gamma \rangle$. $\mathcal{A}$, $\mathcal{O}$, and S denote the action, observation, and state spaces, respectively. Θ is the set of the environment's free parameters, such as possible positions of walls in a maze or levels of a game. These parameters can be distinct at every time step and are also incorporated into the transition function $\mathcal{T} : S \times \mathbf{A} \times \Theta \to \mathbf{\Delta}(S)$, where $\mathbf{A} \equiv \mathcal{A}^n$ is the joint action of all agents. Each agent draws individual observations according to the observation function $\mathcal{I} : S \times N \to \mathcal{O}$ and obtains reward according to the reward function $\mathcal{R} : S \times \mathbf{A} \times N \to \mathbb{R}$, where $N = \{1, \dots, n\}$. The discount factor is denoted by γ. Each configuration of environment parameters $\theta \in \Theta$ defines a specific instantiation of the environment $\mathcal{M}_\theta$, which is often referred to as a *level* (Jiang et al., 2021a; Parker-Holder et al., 2022). In this work, we will simply refer to a specific instance θ as an *environment* when clear from the context. We use $-i$ to notate all agents *except* i: $\boldsymbol{\pi}_{-i} = (\pi_1, \dots, \pi_{i-1}, \pi_{i+1}, \dots, \pi_N)$. For an agent i with a stochastic policy $\pi_i : \mathcal{O} \times \mathcal{A} \to [0, 1]$, we define the value in $\mathcal{M}_\theta$ with co-players $\boldsymbol{\pi}_{-i}$ as $V^\theta(\pi_i, \boldsymbol{\pi}_{-i}) = \mathbb{E}[\sum_{t=0}^{T} \gamma^t r_t^i]$ where r_t^i are the rewards achieved by agent i when following policy π_i in $\mathcal{M}_\theta$. The goal is to sequentially provide values for Θ and co-players $\boldsymbol{\pi}_{-i}$ during training such that the resulting policy π_i of agent i is robust to any possible environment parameterisation and co-player policies, i.e., $\pi_i = \arg\max_{\pi_i} \min_{\theta, \boldsymbol{\pi}_{-i}} V^\theta(\pi_i, \boldsymbol{\pi}_{-i})$. UPOSGs are general by nature and allow for cooperative, competitive, and mixed scenarios. Furthermore, Θ can represent different reward functions, game layouts, changes in observations, and environment dynamics. When $n = 1$, UPOSGs are identical to UPOMDPs for single-agent tasks. In the remainder of this work, we concentrate on competitive settings with $n = 2$ agents.

2.1 UED APPROACHES IN SINGLE-AGENT RL

A curriculum over the environment parameters θ can arise from a teacher maximising a utility function $U_t(\pi, \theta)$ based on the student's policy π. The most naive form of UED is *domain randomisation* (DR, Jakobi, 1997; Sadeghi & Levine, 2017), whereby environments are sampled uniformly at random, corresponding to a constant utility $U_t^U(\pi, \theta) = C$. Recent UED approaches use *regret* as the objective for maximisation (Dennis et al., 2020; Gur et al., 2021): $U_t^R(\pi, \theta) = \max_{\pi^* \in \Pi}\{\text{REGRET}^\theta(\pi, \pi^*)\} = \max_{\pi^* \in \Pi}\{V_\theta(\pi^*) - V_\theta(\pi)\}$, where π^* is the optimal policy on θ.

Empirically, regret-based objectives produce curricula of increasing complexity that result in more robust policies. Moreover, if the learning process reaches a Nash equilibrium, the student provably follows a minimax-regret policy (Dennis et al., 2020): $\pi \in \arg\min_{\pi_A \in \Pi}\{\max_{\theta, \pi_B \in \Theta, \Pi}\{\text{REGRET}^\theta(\pi_A, \pi_B)\}\}$, where Π and Θ are the strategy sets of the student and the teacher, respectively. While this is an appealing property, the optimal policy π^* is unknown in practice and must be approximated instead.

Prioritized Level Replay (PLR, Jiang et al., 2021a;b) continually curates an *environment buffer* containing the environments generated under domain randomisation with the highest learning potential, e.g., as measured by estimated regret. PLR alternates between evaluating new environments for learning potential and performing prioritised training of the agent on the environments with the highest learning potential so far found. By training the student only on curated high-regret environments, PLR provably results in a minimax-regret student policy at Nash equilibrium. MAESTRO makes use of PLR-style curation of environment buffers to discover high-regret environments during training.

2.2 CO-PLAYER AUTOCURRICULA IN COMPETITIVE MULTI-AGENT RL

The choice of co-players plays a crucial role for training agents in multi-agent domains (Leibo et al., 2019). A simple but effective approach is *self-play* (SP, Silver et al., 2018), whereby the agent always plays with copies of itself. In competitive two-player games, SP produces a curriculum in which opponents match each other in skill level. However, SP may cause cycles in the strategy space when agents forget how to play against previous versions of their policy (Garnelo et al., 2021).

Fictitious Self-Play (FSP, Heinrich et al., 2015) overcomes the emergence of such cycles by training an agent against a uniform mixture of all previous policies. However, FSP can result in wasting a large number of interactions against significantly weaker opponents.

Prioritized Fictitious Self-Play (PFSP, Vinyals et al., 2019) mitigates this potential inefficiency by matching agent A with a frozen opponent B from the set of candidates $\mathcal{C}$ with probability $\frac{f(\mathbb{P}[A \text{ beats } B])}{\sum_{C \in \mathcal{C}} f(\mathbb{P}[A \text{ beats } C])}$, where f defines the exact curriculum over opponents. For example, $f_{hard}(x) = (1-x)^p$, where $p \in \mathbb{R}_+$, forces PFSP to focus on the hardest opponents.

3 METHOD

3.1 AN ILLUSTRATIVE EXAMPLE

To highlight the importance of curricula over the joint space of environments and co-players, we provide an illustrative example of a simple two-player game in Table 1. Here, the goal of the regret-maximising teacher is to select an environment/co-player pair for the student. Ignoring the co-player and selecting the highest regret environment leads to choosing θ_3. Similarly, ignoring environments and selecting the highest regret co-player leads to π_C. This yields a suboptimal pair (θ_3, π_C) with $\text{REGRET}(\theta_3, \pi_C) = 0.4$, whereas a teacher over the joint space yields the optimal pair (θ_1, π_A) with $\text{REGRET}(\theta_1, \pi_A) = 0.6$. Thus, naively treating the environment and co-player as independent can yield a sub-optimal curriculum. Such overspecialisation toward a subset of environmental challenges at the expense of overall robustness commonly emerges in multi-agent settings (Garnelo et al., 2021).

Table 1: **An illustrative two-player game.** Rows correspond to co-player policies and $\Pi = \{\pi_A, \pi_B, \pi_C\}$. Columns indicate different environments and $\Theta = \{\theta_1, \theta_2, \theta_3, \theta_4\}$. The payoff matrix represents the regret of the student on pair (θ, π).

	θ_1	θ_2	θ_3	θ_4	$\mathbb{E}_{\theta \sim \Theta}$
π_A	0.6	0.1	0.4	0.2	0.325
π_B	0.1	0.5	0.4	0.3	0.325
π_C	0.2	0.4	0.4	0.4	0.35
$\mathbb{E}_{\pi \sim \Pi}$	0.3	0.33	0.4	0.3	

3.2 MULTI-AGENT ENVIRONMENT-SPACE RESPONSE ORACLES (MAESTRO)

In this section, we describe a new multi-agent UED approach called *Multi-Agent Environment-Space Response Oracles* (MAESTRO) which induces a regret-based autocurricula jointly over environments and co-players.

MAESTRO is a replay-guided approach (Jiang et al., 2021a) that relies on an environment generator to continuously create new environment instances. Rather than storing a single environment buffer, as done by PLR, MAESTRO maintains a population of policies $\mathfrak{B}$ with each policy assigned its own environment buffer. In each environment θ produced by the generator, MAESTRO evaluates the student's performance against a non-uniform mixture of co-player policies in $\mathfrak{B}$. High-regret environment/co-player pairs are then stored, along with the student agent's regret estimate for that pair, in co-player's corresponding environment buffer.

Algorithm 1: MAESTRO

Input: Environment generator Θ
Initialise: Student policy π, co-player population $\mathfrak{B}$
Initialise: Environment buffers $\forall \pi' \in \mathfrak{B}, \mathbf{\Lambda}(\pi') := \emptyset$.
for $i = \{1, 2, \dots\}$ **do**
  for *many episodes* **do**
    $\pi' \sim \mathfrak{B}$ ▷ Sample a co-player via Equation (1)
    Sample replay decision ▷ see Section 3.2.2
    if *replaying* **then**
      $\theta \sim \mathbf{\Lambda}(\pi')$ ▷ Sample a replay environment
      Collect trajectory τ of π using (θ, π')
      Update π with rewards $\boldsymbol{R}(\tau)$
    else
      $\theta \sim \Theta$ ▷ Sample a random environment
      Collect trajectory τ of π using (θ, π')
    Compute regret score $S = \widetilde{Regret}(\theta, \pi')$
    Update $\mathbf{\Lambda}(\pi')$ with θ using score S
  $\mathfrak{B} \leftarrow \mathfrak{B} \cup \{\pi_i^{\perp}\}, \mathbf{\Lambda}(\pi_i^{\perp}) := \emptyset$ ▷ freezing weights

MAESTRO maintains a dynamic population of co-players of various skill levels throughout training (Czarnecki et al., 2020). Figure 1 presents the overall training paradigm of MAESTRO and Algorithm 1 provides its pseudocode. We note that when applied to a fixed singleton environment, MAESTRO becomes a variation of PFSP (Vinyals et al., 2019), where the mixture of policies from the population is computed based on the agent's regret estimate, rather than the probability of winning.

3.2.1 MAINTAINING A POPULATION OF CO-PLAYERS

A key issue of using replay-guided autocurricula for multi-agent settings is nonstationarity. Specifically, using PLR with SP results in inaccurate regret estimates over environment/co-player pairs, as the co-player policies evolve over training. MAESTRO overcomes this issue by maintaining a population of past policies§ (Lanctot et al., 2017). This approach confers several key benefits. First, re-encountering past agents helps avoid cycles in strategy space (Balduzzi et al., 2019; Garnelo et al., 2021). Second, MAESTRO maintains accurate regret estimates in the face of nonstationarity by employing a separate environment buffer for each policy in the population. Third, MAESTRO always optimises a *single* policy throughout training, rather than a set of distinct policies which can be computationally expensive.

3.2.2 CURATING THE ENVIRONMENT/CO-PLAYER PAIRS

To optimise for the global regret over the joint environment/co-player space, a MAESTRO student is trained to best respond to a non-uniform mixture of policies from a population by prioritising training against co-players with high-regret environments in their buffers:

$$\text{CO-PLAYER}^{\text{HR}} \in \arg\max_{\pi' \in \mathfrak{B}} \{ \max_{\theta \in \mathbf{\Lambda}(\pi')} \widetilde{Regret}(\theta, \pi') \}, \tag{1}$$

where $\mathfrak{B}$ is the co-player population, $\mathbf{\Lambda}(\pi')$ is the environment buffer of agent π', and $\widetilde{Regret}$ is the estimated regret of student for the pair (θ, π'). To ensure that the student learns to best respond to high-regret co-players as well as to the entire population $\mathfrak{B}$, we enforce all members of $\mathfrak{B}$ to be assigned a minimum probability $\frac{\lambda}{N}$. For instance, if Equation (1) returns a single highest-regret co-player, then the resulting prioritised distribution assigns a weight of $\frac{N-\lambda(N-1)}{N}$ to the highest-regret co-player and weight of $\frac{\lambda}{N}$ to the remaining co-players. For each co-player $\pi' \in \mathfrak{B}$, MAESTRO maintains a PLR environment buffer $\mathbf{\Lambda}(\pi')$ with the top-K high-regret levels. Once the co-player is sampled, we make a replay decision: with probability p, we use a bandit to sample a training environment from $\mathbf{\Lambda}(\pi')$,[2] and with probability $1-p$, we sample a new environment for evaluation from the environment generator. Similar to Robust PLR (Jiang et al., 2021a), we only update the student policy on environments sampled from the environment buffer. This provides MAESTRO with strong robustness guarantees, which we discuss in Section 3.3.

3.3 ROBUSTNESS GUARANTEES OF MAESTRO

We analyse the expected behaviour of MAESTRO if the system reaches equilibrium: does MAESTRO produce a regret-maximising distribution over environments and co-players, and is the policy optimal with respect to these distributions? We cast this problem in terms of Bayesian Nash Equilibrium (BNE) behaviour on individual environments. BNE is an extension of Nash Equilibrium (NE) where each co-player j has an unknown *type* parameter θ^j, which affects the dynamics of the game and is only known to that player. The distribution over these parameters $\tilde{\Theta}^N$ is assumed to be common knowledge. Equilibria are then defined as the set of policies, conditioned on their unknown type, each being a best response to the policies of the other players. That is, for policy π_j of any player j,

$$\pi_j \in \arg\max_{\hat{\pi}_j \in \Pi_j} \{ \mathop{\mathbb{E}}_{\theta^N \in \tilde{\Theta}^N} [U(\hat{\pi}_j(\theta^j), \boldsymbol{\pi}_{-j}(\theta^{-j}))] \}. \tag{2}$$

In MAESTRO, we can assume each co-player is effectively omniscient, as each is co-evolved for maximal performance against the student on the environments it is paired with in its high-regret environment buffer. In contrast, the student is conferred no special advantages and has access to only the standard observations. We formalise this setting as a $-i$-knowing game. This game corresponds to the POSG with the same set of players, action space, rewards, and states as the original UPOSG, but with θ sampled at the first time step and provided to co-player agents $-i$ as part of their observation.

[2]Sampling is based on environment's regret score, staleness, and other features following (Jiang et al., 2021b).

Definition 1. *The -i-knowing-game of an UPOSG* $M = (N, A = \times_{i \in N} A_i, O = \times_{i \in N} O_i, \Theta, R = \times_{i \in N} R_i, S, I = \times_{i \in N} I_i, T)$ *with parameter distribution* $\tilde{\theta}$ *is defined to be the POSG* $K = (N' = N, A'_i = A_i, O'_i = O_i + \{\Theta \text{ if } i \in -i\}, R'_i = R_i, S' = S, I'_i = I_i + \{\theta \text{ if } \in -i\}, T' = T(\theta))$ *where* θ *is sampled from the distribution* $\tilde{\theta}$ *on the first time step.*

We thus arrive at our main theorem, followed by a convenient and natural corollary for fully observable settings. We include the full proofs in Appendix A.

Theorem 1. *In two-player zero-sum settings, the* MAESTRO *student at equilibrium implements a Bayes-Nash Equilibrium of the* $-i$*-knowing game, over a regret-maximising distribution of levels.*

Corollary 1. *In fully-observable two-player zero-sum settings, the* MAESTRO *student at equilibrium implements a Nash Equilibrium in each environment in the support of the environment distribution.*

Informally, the proof follows from the observation that the $-i$-knowing game in a fully observable setting is equivalent to the original distribution of environments, as there is no longer an information asymmetry between the student and co-players. Moreover, the NE strategy on this distribution of environment instances would be a NE strategy on each instance individually, given that they are fully observable. This argument is formalised in Appendix A.

4 EXPERIMENTAL SETTING

Our experiments aim to understand (1) the interaction between autocurricula over environments and co-players in multi-agent UED, (2) its impact on zero-shot transfer performance of student policies to unseen environments and opponents, and (3) the emergent complexity of the environments provided to the student agent under autocurricula. To this end, we evaluate methods in two distinct domains: discrete control with sparse rewards, and continuous control with dense rewards. We assess student robustness in OOD human-designed environments against previously unseen opponents. Given its strong performance and usage in related works, PPO (Schulman et al., 2017) serves as the base RL algorithm in our experiments. We provide full environment descriptions in Appendix C and detail our model architecture and hyperparameter choices in and Appendix D.

Baselines and Ablations We compare MAESTRO against two key baselines methods producing autocurricula over environments: domain randomization (DR; Jakobi, 1997), and (Robust) PLR (Jiang et al., 2021a), a state-of-the-art UED baseline. For co-player curricula, we consider SP, FSP, and PFSP, popular methods that underlie breakthroughs such as AlphaGo (Silver et al., 2016) and AlphaStar (Vinyals et al., 2019). Since these baselines independently produce either curricula over environments or over co-players, our choice of baselines results in a combination of 6 joint curriculum baselines over the environment/co-player space. We present further ablations investigating the importance of MAESTRO's co-player selection mechanism in Appendix B.

4.1 ENVIRONMENTS

LaserTag is a grid-based, two-player zero-sum game proposed by Lanctot et al. (2017) where agents aim to tag each other with laser beams. Success in LaserTag requires agents to master sophisticated behaviours, including chasing opponents, hiding behind walls, keeping clear of long corridors, and maze solving. Each agent observes the 5×5 grid area in front of it and can turn right or left, move forward, and shoot. Upon tagging an opponent, the agent and the opponent receive a reward of 1 and -1, respectively, and the episode terminates. LaserTag training environments are generated by randomly sampling grid size, wall locations, and the initial locations and directions of agents.

MultiCarRacing (MCR, Schwarting et al., 2021) is a high-dimensional, pixel-based continuous control environment with dense rewards. Two agents compete by driving a full lap around the track. Each track consists of n tiles. Agents receive a reward of $1000/n$ or $500/n$ for reaching a tile first or second, respectively. Agents receive a top-down, egocentric $96 \times 96 \times 3$ partial observation and can collide, push, or block each other, allowing for complex emergent behaviour and non-transitive dynamics. The action space is 3-dimensional, controlling changes in acceleration, braking, and steering. All training tracks used for training agents are generated by sampling 12 random control points defining a Bézier curve forming the track.

Figure 2 shows example LaserTag and MCR environments, including human-designed OOD test environments. MCR test environments are the Formula 1 CarRacing tracks from (Jiang et al., 2021a).

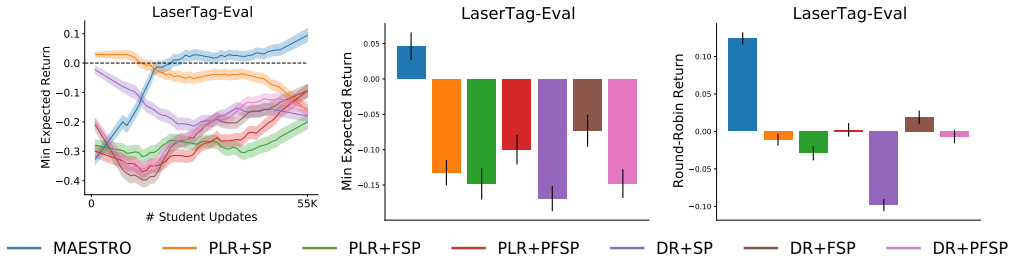


Figure 3: **LaserTag Cross-Play Results**. (Left) MER on LaserTag evaluation environments during training. (Middle) MER and (Right) round-robin returns at the end of training (mean and standard error over 10 seeds).

5 Results and Discussion

5.1 Cross-Play Results

To assess the robustness of the approaches, we evaluate all pairs of methods in cross-play on all OOD human-designed environments (10 episodes on 13 LaserTag evaluation environments and 20 Formula 1 tracks for MCR). Agents are trained for 55000 PPO updates (≈1B steps) on LaserTag and 4500 updates (≈40M steps) on MCR. Full results on individual environments are included in Appendix E.2.

Figure 3 shows the cross-play results on LaserTag throughout training, as well as at the end of training. We use the minimum expected return (MER) against any baseline to estimate the exploitability of each method against all other baselines. Less exploitable agents should attain higher MER across all other agents. We can see that MAESTRO outperforms all baselines in MER, being the only method with positive MER, i.e., it is not exploited by any other baseline. Although SP-based methods achieve an early performance lead due to more frequent policy updates, population-based methods (FSP, PFSP, and MAESTRO) eventually outperform them.

Figure 4 reports the MCR results on challenging F1 tracks, as well as the procedurally generated training tracks. Here, MAESTRO outperforms all baselines individually across all benchmark tracks, while also being the least exploitable policy. PLR-based baselines outperform DR, underscoring the benefits of a curriculum over environments on this task. Nonetheless, MAESTRO produces the most robust agents, highlighting the importance of a joint curriculum over environments and co-players.

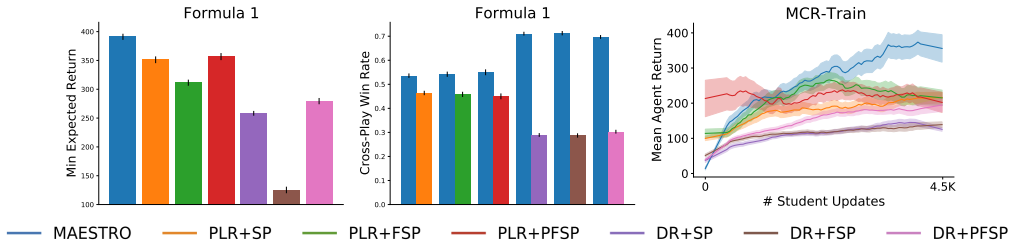


Figure 4: **MultiCarRacing Cross-Play Results**: (Left) MER on Formula 1. (Middle) Cross-play win rate between MAESTRO and baselines on Formula 1. (Right) Mean agent return of methods throughout training. Plots show the mean and standard error across 5 training seeds.

5.2 Importance of the curriculum over the environment/co-player space

Figure 5 shows the co-player×environment regret landscape of a MAESTRO student agent on randomly-sampled environments against each co-player from MAESTRO's population at the end of training (as done in the motivating example in Section 3.1). We observe that high regret estimates depend on both the choice of the environment and the co-player. Most importantly, maximising mean regrets over environments and co-players independently does not lead to maximum regret over the joint space, highlighting the importance of the curricula over the joint environment/co-player space.

5.3 Evaluation Against Specialist Agents

While we show that MAESTRO outperforms baselines trained on a large number of environments, we are also interested in evaluating MAESTRO against *specialist* agents trained only on single, *fixed* environments. Figure 6 shows that, despite having never seen the target environments, the MAESTRO

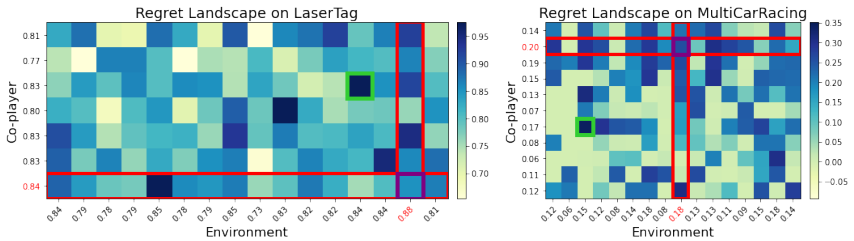


Figure 5: **Regret landscapes on LaserTag and MultiCarRacing.** Shown are regret estimates of the student on 16 random environment (columns) against each policy from MAESTRO's co-player population (rows). Highlighted in red are the regret estimates of the co-player and environment with the highest mean values when considered in isolation, whereas in green we highlight the overall highest regret environment/co-player pair.

agent beats specialist agents trained exclusively on them for the same number of updates. This is possible because the MAESTRO agent was trained with an autocurriculum that promotes the robustness of the trained policy, allowing it to transfer better to unseen opponents on OOD environments. These results demonstrate the potential of multi-agent UED in addressing key problems in multi-agent RL, such as exploration (Leonardos et al., 2021) and co-player overfitting (Lanctot et al., 2017).

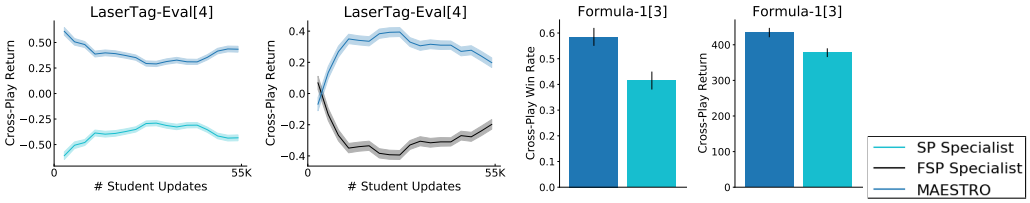


Figure 6: **Cross-Play Results vs Specialists**. Cross-play evaluation between MAESTRO vs specialist agents trained directly on the target task. We use different specialist agents for each fixed environment. Shown are averaged metrics across 4 target LaserTag levels and 3 Formula 1 tracks. Full results on individual environments are included in Appendix E.1.

5.4 EMERGENT CURRICULUM ANALYSIS

To better understand MAESTRO's superior performance, we analyse the curriculum over environments induced by MAESTRO and compare it with the curricula generated by the baselines. Figure 7 demonstrates that, as training progresses, MAESTRO provides agents with LaserTag environments with an increasing density of walls, which contributes to a gradual increase in environment complexity. Initially, the size of the grid also increases as the teacher challenges the student to navigate the mazes. However, after more adept opponent agents enter the population, larger mazes yield lower regret. Instead, MAESTRO starts prioritising smaller grid sizes compared to other baselines. Smaller environments with high wall density challenge the student to navigate maze structures while succeeding in more frequent multi-agent interactions against increasingly more capable opponents throughout an episode. Figure 2c illustrates such challenging environments, which, due to the smaller grid, require the student to engage with the opponent earlier in the episode. PLR-based methods also prioritise high wall density but do not shrink the grid size to prioritise competitive interactions to the same extent as MAESTRO.

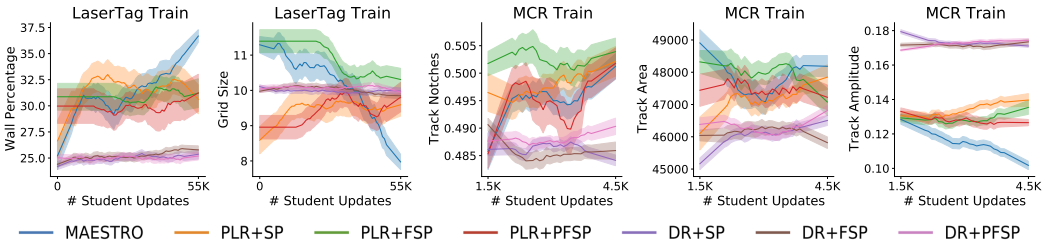


Figure 7: **Characteristics of emergent autocurricula in LaserTag and MultiCarRacing.**

We observe similar emergent complexity in the MCR domain. Here the PLR-based baselines and MAESTRO all prioritise tracks that have a high number of notches (i.e. the non-convex parts of the track) and enclosed area. Here, as in the LaserTag domain, MAESTRO gradually shrinks the track

amplitude, which corresponds to a lower intensity of the winding portions of the track. Such tracks may contain more segments where competitive interactions can play out without sacrificing overall episodic return, thus inducing policies more adept at the competitive aspects of this domain. Figure 2 illustrates randomly sampled environments curated by MAESTRO at different stages of training.

6 RELATED WORK

Unsupervised Environment Design (UED, Dennis et al., 2020) is a family of methods that provide an agent with a sequence of environments for training robust policies. The simplest UED approach is *Domain Randomisation* (DR, Jakobi, 1997; Sadeghi & Levine, 2017) which has demonstrated strong empirical gains in domains such as robotics (Tobin et al., 2017; James et al., 2017) and magnetic control of tokamak plasmas (Degrave et al., 2022). PAIRED (Dennis et al., 2020; Gur et al., 2021) trains an environment generator that maximises the student's regret, approximated as the difference in return between the student and an antagonist agent. *Prioritized Level Replay* (PLR, Jiang et al., 2021a;b) curates environment instances (i.e., levels) for training, by performing a random search of domain randomised levels for those with high learning potential, e.g. as measured by estimated regret. *ACCEL* (Parker-Holder et al., 2022) is a replay-guided UED approach that extends PLR by making edits to previously high-regret environments. Several methods generate curricula by adapting the environment parameters in response to the agent's performance (Portelas et al., 2019; Matiisen et al., 2020; Klink et al., 2019; Eimer et al., 2021). This adaptation is largely heuristic-driven, without the robustness guarantees shared by minimax-regret UED methods. Notably, all these methods focus on single-agent RL, while MAESTRO is designed for the two-player multi-agent setting.

Many prior works study curricula over opponents in two-player zero-sum settings. The most naive approach, self-play (SP), consists of pitting the agent against a copy of itself. Combined with search, SP has led to superhuman performances in board games such as Backgammon (Tesauro, 1995), Chess and Go (Silver et al., 2016). *Fictitious self-play* (FSP) learns a best-response to the uniform mixture of all previous versions of the agent (Brown, 1951; Leslie & Collins, 2006; Heinrich et al., 2015). *Prioritised fictitious self-play* (PFSP, Vinyals et al., 2019) trains agents against a non-uniform mixture of policies based on the probability of winning against each policy. PFSP is a practical variant of *Policy-Space Response Oracles* (PSRO, Lanctot et al., 2017), a general population learning framework, whereby new policies are trained as best responses to a mixture of previous policies following a meta-strategy solver. MAESTRO is related to PSRO but adapted for UPOSGs. In MAESTRO, the population meta-strategy is based on the student's regret when playing against policies on environments observed during training. Unlike our work, these prior autocurricula methods for competitive multi-agent environments do not directly consider variations of the environment itself.

Several prior works have applied DR in multi-agent domains. Randomly modifying the environment has proven critical for the emergence of complex behaviours in Hide&Seek (Baker et al., 2019) and Capture the Flag (Jaderberg et al., 2019). In XLand (Open Ended Learning Team et al., 2021), a curriculum is provided over both environments and tasks to create general learners. This work differs from ours in multiple aspects. Open Ended Learning Team et al. (2021) uses handcrafted heuristics and rejection sampling for selecting environments for training and evaluating agents, while MAESTRO automatically selects environments based on regret rather than hand-coded heuristics. Further, unlike the autocurricula used in XLand, MAESTRO does not rely on population-based training, a computationally expensive algorithm for tuning the autocurriculum hyperparameters.

7 CONCLUSION

In this paper, we provided the first formalism for multi-agent learning in underspecified environments, and we introduced MAESTRO, an approach for producing a joint autocurriculum over both environments and co-players. Moreover, we proved that MAESTRO attains minimax-regret robustness guarantees at Nash equilibrium. Empirically in two challenging domains, we found MAESTRO produces agents that are more robust to the environment and co-player variations than a number of strong baselines. MAESTRO agents even outperform specialist agents in these domains. Our work opens up many interesting directions for future work. MAESTRO could be extended to n-player competitive games, as well as cooperative or mixed settings. Furthermore, MAESTRO could be combined with search-based methods in order to further improve sample efficiency and generalisation. Finally, co-evolutionary dynamics in the MAESTRO autocurricula hints that the intersection of underspecified multi-agent problems and evolutionary computing could be a generally fruitful research direction.

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