Celebrating Diversity in Shared Multi-Agent Reinforcement Learning

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Abstract

Recently, deep multi-agent reinforcement learning (MARL) has shown the promise to solve complex cooperative tasks. Its success is partly because of parameter sharing among agents. However, such sharing may lead agents to behave similarly and limit their coordination capacity. In this paper, we aim to introduce diversity in both optimization and representation of shared multi-agent reinforcement learning. Specifically, we propose an information-theoretical regularization to maximize the mutual information between agents' identities and their trajectories, encouraging extensive exploration and diverse individualized behaviors. In representation, we incorporate agent-specific modules in the shared neural network architecture, which are regularized by L1-norm to promote learning sharing among agents while keeping necessary diversity. Empirical results show that our method achieves state-of-the-art performance on Google Research Football[2] and super hard StarCraft II micromanagement tasks.

1 Introduction

Cooperative multi-agent reinforcement learning (MARL) has drawn increasing interest in recent years, which provides a promise for solving many real-world challenging problems, such as sensor networks [1], traffic management [2], and coordination of robot swarms [3]. However, learning effective policies for such complex multi-agent systems remains challenging. One central problem is that the joint action-observation space grows exponentially with the number of agents, which imposes high demand on the scalability of learning algorithms.

To address this scalability challenge, *policy decentralization with shared parameters* (PDSP) is widely used, where agents share their neural network weights. Parameter sharing significantly improves learning efficiency because it dramatically reduces the total number of policy parameters, while experiences and gradients of one agent can be used to train others. Enjoying these advantages, many advanced deep MARL approaches adopt the PDSP paradigm, including value-based methods [4–6], policy gradients [7, 8] and communication learning algorithms [9, 10]. These approaches achieve state-of-the-art performance on tasks such as StarCraft II micromanagement [11].

While parameter sharing has been proven to accelerate training [12], its drawbacks are also apparent in complex tasks. These tasks typically require substantial exploration and diversified strategies

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[2]Videos available at https://sites.google.com/view/celebrate-diversity-shared

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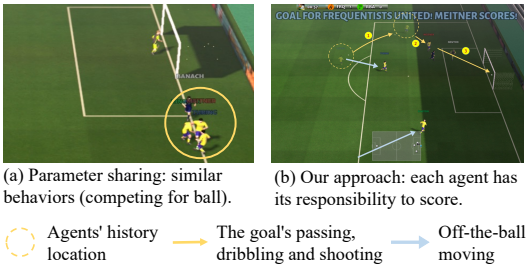
among agents. When parameters are shared, agents tend to acquire homogeneous behaviors because they typically adopt similar actions under similar observations, preventing efficient exploration and the emergence of sophisticated cooperative policies. This tendency becomes particularly problematic for many challenging multi-agent coordination tasks, hindering deep MARL from broader applications. For example, the unsatisfactory performance of state-of-the-art MARL algorithms on Google Research Football (Fig. 1, and [13]) highlights an urgent demand for diverse behaviors.



(a) Parameter sharing: similar behaviors (competing for ball).

(b) Our approach: each agent has its responsibility to score.

Figure 1: Shared parameters induce behaviors (**left**) and can hardly learn successful policies on the challenging Google Research Football task. Our method learns sophisticated cooperative strategies by **trading off diversity and sharing** (**right**).

Notably, sacrificing the merits of parameter sharing for diversity is also unfavorable. Like humans, sharing necessary experience or understanding of tasks can broadly accelerate cooperation learning. Without parameter sharing, agents search in a much larger parameter space, which may be wasteful because they do not need to behave differently all the time. Therefore, the question is how to adaptively trade-off diversity and sharing. In this paper, we solve this dilemma by proposing several structural and learning novelties.

To encourage diversity, we propose a novel information-theoretical objective to maximize the mutual information between agents' identities and trajectories. This objective enables each agent to distinguish themselves from others and thus involves the contribution of all agents. Accordingly, we derive an intrinsic reward for motivating diversity and optimize it with the global environmental reward by learning the total Q-function as a combination of individual Q-functions. Structurally, we further decompose individual Q-functions as the sum of shared and non-shared local Q-functions for sharing experiences while maintaining representation diversity. We hope agents can use and expand shared knowledge whenever possible. Thus we introduce L1 regularization on each non-shared Q-function, encouraging agents to share and be diverse when necessary on several critical actions. Combining these novelties achieves a dynamic balance between diversity and homogeneity, efficiently catalyzing adaptive and sophisticated cooperation.

We benchmark our approach on Google Research Football (GRF) [13], and StarCraft II micromanagement tasks (SMAC) [11]. The extraordinary performance of our approach on challenging benchmarking tasks shows that our approach achieve significantly higher coordination capacity than baselines while using diversity as a catalyst for more robust and talent policies. To our best knowledge, our approach achieves state-of-the-art performance on SMAC super hard maps and challenging GRF multi-agent tasks like `academy_3_vs_1_with_keeper`, `academy_counterattack_hard`, and a full-field scenario `3_vs_1_with_keeper` (`full field`).

2 Background

A fully cooperative multi-agent task can be formulated as a Dec-POMDP [14], which is defined as a tuple $\mathcal{G} = \langle N, S, A, P, R, O, \Omega, n, \gamma \rangle$, where N is a finite set of n agents, $s \in S$ is the true state of the environment, A is the set of actions, and $\gamma \in [0, 1)$ is a discount factor. At each time step, each agent $i \in N$ receives his own observation $o_i \in \Omega$ according to the observation function $O(s, i)$, and selects an action $a_i \in A$, which results in a joint action vector $\boldsymbol{a}$. The environment then transitions to a new state s' based on the transition function $P(s'|s, \boldsymbol{a})$, and inducing a global reward $r = R(s, \boldsymbol{a})$ shared by all the agents. Each agent has its own action-observation history $\tau_i \in \mathcal{T}_i \doteq (\Omega_i \times A)^*$. Due to partial observability, each agent conditions its policy $\pi_i(a_i|\tau_i)$ on τ_i. The joint policy $\boldsymbol{\pi}$ induces the joint action-value function $Q^{\boldsymbol{\pi}}_{tot}(s, \boldsymbol{a}) = \mathbb{E}_{s_{0:\infty}, \boldsymbol{a}_{0:\infty}} \left[\sum_{t=0}^{\infty} \gamma^t r_t \mid s_0 = s, \boldsymbol{a}_0 = \boldsymbol{a}, \boldsymbol{\pi}\right]$.

2.1 Centralized Training with Decentralized Execution

Our method adopts the framework of centralized training with decentralized execution (CTDE) [7, 15, 4, 5, 16, 17, 6]. This framework tackles the exponentially growing joint action space by decentralizing the control policies while adopting centralized training to learn cooperation. Agents learn in a centralized manner with access to global information but execute based on their local

action-observation history. One promising approach to implement the CTDE framework is value function factorization. The IGM (individual-global-max) principle [16] guarantees the consistency between the local and global greedy actions. When IGM is satisfied, agents can obtain the optimal global action by simply choosing the local greedy action that maximizes each agent's individual utility function Q_i. Some algorithms have successfully used the IGM principle [5, 6, 18] to push forward the progress of MARL.

3 Method

In this section, we present a novel diversity-driven MARL framework (Fig. 2) that balances each agent's individuality with group coordination, which is a general approach that can be combined with existing CDTE value factorization methods.

3.1 Identity-Aware Diversity

We first introduce how to encourage behavioral diversity by designing intrinsic motivations. Intuitively, to encourage the specialty of individual trajectories, agents need to behave differently to highlight themselves from others, taking different actions and visiting different local observations. To achieve this goal, we use an information-theoretic objective for maximizing the mutual information between individual trajectory and agents' identity:

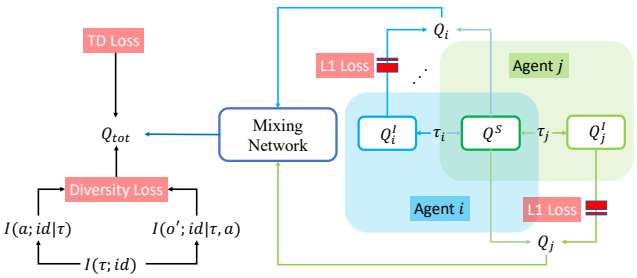


Figure 2: Schematics of our approach.

$$I^{\boldsymbol{\pi}}(\tau_T; id) = H(\tau_T) - H(\tau_T|id) = E_{id,\tau_T\sim\boldsymbol{\pi}}\left[\log\frac{p(\tau_T|id)}{p(\tau_T)}\right], \tag{1}$$

where τ_T and id is the random variable for agent's local trajectory and identity, respectively. $\boldsymbol{\pi}$ is the joint policy. To optimize Eq. 1, we expand $p(\tau_T)$ as $p(o_0)\prod_{t=0}^{T-1} p(a_t|\tau_t)p(o_{t+1}|\tau_t, a_t)$, and $p(\tau_T|id)$ as $p(o_0|id)\prod_{t=0}^{T-1} p(a_t|\tau_t, id)p(o_{t+1}|\tau_t, a_t, id)$. Therefore, the mutual information can be written as:

$$I^{\boldsymbol{\pi}}(\tau_T; id) = E_{id,\tau}\underbrace{\left[\log\frac{p(o_0|id)}{p(o_0)}\right]}_{①} + \underbrace{\sum_{t=0}^{T-1}\log\frac{p(a_t|\tau_t, id)}{p(a_t|\tau_t)}}_{②} + \underbrace{\sum_{t=0}^{T-1}\log\frac{p(o_{t+1}|\tau_t, a_t, id)}{p(o_{t+1}|\tau_t, a_t)}}_{③}. \tag{2}$$

Term ① is determined by the environment, and we can ignore it when optimizing the mutual information. The second term quantifies the information gain about agent's action selection when the identity is given, which measures **action-aware diversity** as $I(a; id|\tau)$. However, $p(a_t|\tau_t, id)$ is typically the distribution induced by ϵ-greedy, which only distinguishes the action with the highest possibility. Therefore, directly optimizing this term conceals most information about the local Q-functions. To solve this problem, we use the Boltzmann softmax distribution of local Q values to replace $p(a_t|\tau_t, id)$, which forms a lower bound of term ②:

$$E_{id,\tau}\left[\log\frac{p(a_t|\tau_t, id)}{p(a_t|\tau_t)}\right] \geq E_{id,\tau}\left[\log\frac{\mathrm{SoftMax}(\frac{1}{\alpha}Q(a_t|\tau_t, id))}{p(a_t|\tau_t)}\right]. \tag{3}$$

The inequity holds because the KL divergence $D_{\mathrm{KL}}(p(\cdot|\tau_t, id)\|\mathrm{SoftMax}(\frac{1}{\alpha}Q(\cdot|\tau_t, id)))$ is non-negative. We maximize this lower bound to optimize Term ②. Direct optimization of Term ③ is intractable because it involves integrals over a continuous observation space. Inspired by variational inference approaches [19], we derive and optimize a tractable lower bound for this term at each timestep by introducing a variational posterior estimator q_ϕ parameterized by ϕ:

$$E_{id,\tau}\left[\log\frac{p(o_{t+1}|\tau_t, a_t, id)}{p(o_{t+1}|\tau_t, a_t)}\right] \geq E_{id,\tau}\left[\log\frac{q_\phi(o_{t+1}|\tau_t, a_t, id)}{p(o_{t+1}|\tau_t, a_t)}\right], \tag{4}$$

Similar to the second term, the inequality holds because for any q_ϕ, the KL divergence $D_{\mathrm{KL}}(p(\cdot|\tau_t, a_t, id)\|q_\phi(\cdot|\tau_t, a_t, id))$ is non-negative. Intuitively, optimizing Eq. 4 encourages agents to have diverse observations that are distinguishable by agents' identification and thus measures **observation-aware diversity** as $I(o'; id|\tau, a)$. To tighten the this lower bound, we minimize the KL divergence with respect to the parameters ϕ. The gradient for updating ϕ is:

$$\begin{aligned}\nabla_\phi \mathcal{L}(\phi) &= \nabla_\phi \mathbb{E}_{\tau,a,id}\left[D_{\mathrm{KL}}\left(p\left(\cdot|\tau,a,id\right)\|q_\phi\left(\cdot|\tau,a,id\right)\right)\right] = \nabla_\phi \mathbb{E}_{\tau,a,id,o'}\left[\log \frac{p\left(o'|\tau,a,id\right)}{q_\phi\left(o'|\tau,a,id\right)}\right] \\ &= -\mathbb{E}_{\tau,a,id,o'}\left[\nabla_\phi \log q_\phi\left(o'|\tau,a,id\right)\right].\end{aligned} \tag{5}$$

Based on the lower bounds shown in Eq. 3 and Eq. 4, we introduce intrinsic rewards to optimise the information-theoretic objective (Eq. 1) for encouraging diverse behaviors:

$$\begin{aligned}r^I = E_{id}\left[\beta_2 D_{\mathrm{KL}}(\mathrm{SoftMax}(\beta_1 Q(\cdot|\tau_t, id))||p(\cdot|\tau_t))\right. \\ \left.+\beta_1 \log q_\phi(o_{t+1}|\tau_t, a_t, id) - \log p(o_{t+1}|\tau_t, a_t)\right].\end{aligned} \tag{6}$$

We introduce two scaling factors $\beta_1, \beta_2 \geq 0$ when calculating intrinsic rewards. When β_1 is 0, we only optimize the entropy term $H(\tau_T)$ in the mutual information objective (Eq. 1). β_2 is used to adjust the importance of policy diversity compared with transition diversity. In Appendix A, we discuss and compare two different approaches for estimating $p\left(a_t|\tau_t\right)$ and $p\left(o_{t+1}|\tau_t, a_t\right)$.

3.2 Action-Value Learning for Balancing Diversity and Sharing

In the previous section, we introduce an information-theoretic objective for encouraging each agent to behave differently from general trajectories. However, the shared local Q-function does not have enough capacity to present different policies for each agent. For solving this problem, we additionally equip each agent i with an individual local Q-function Q_i^I. Defining experiences need to be shared or exclusively learned is inefficient and usually can not generalize. Therefore, we let agents adaptively decide whether to share experiences by decomposing Q_i as:

$$Q_i(a_i|\tau_i) = Q^S(a_i|\tau_i) + Q_i^I(a_i|\tau_i), \tag{7}$$

where Q^S is the shared Q-function among agents. In its current form, agents may learn to decompose its local Q-function arbitrarily. On the contrary, we expect that agents can share as much knowledge as possible so that we apply an L1 regularization on individual local Q-function Q^I as shown in Fig.2. Such a regularization can also prevent agents from being too diverse and ignore cooperating to finish the task. In our experiments, we show that the L1 regularization is critical to achieving a balance between diversity and cooperation.

3.3 Overall Learning Objective

In this section, we discuss how to use the diversity-encouraging reward to train the proposed learning framework. Since the intrinsic rewards r^I inevitably involves the influence from all agents, we add r^I to environment rewards r^e and use the following TD loss:

$$\mathcal{L}_{TD}(\theta) = \left[r^e + \beta r^I + \gamma \max_{\boldsymbol{a}'} Q_{tot}\left(s', \boldsymbol{a}'; \theta^-\right) - Q_{tot}(s, \boldsymbol{a}; \theta)\right]^2, \tag{8}$$

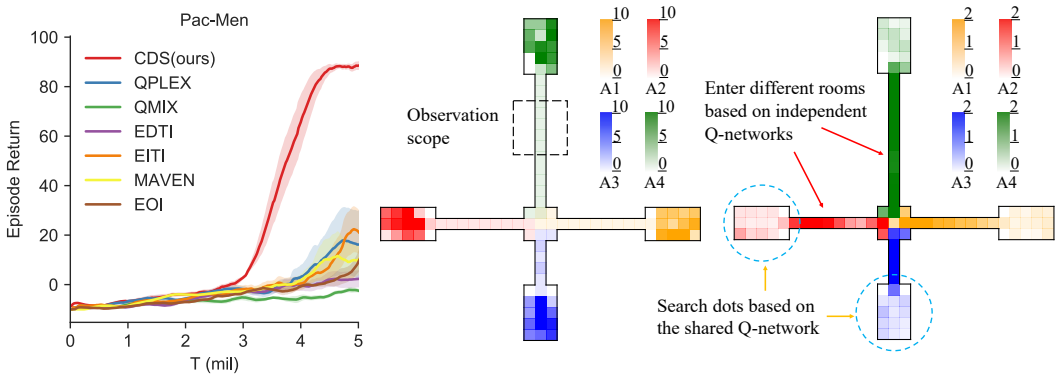
where θ is the parameters in the whole framework, θ^- is periodically frozen parameters copied from θ for a stable update, and β is a hyper-parameter adjusting the weight of intrinsic rewards compared with environment rewards. We use QPLEX to decompose Q_{tot} as a mixing of local Q-functions Q_i and train the framework end-to-end by minimizing the loss:

$$\mathcal{L}(\theta) = \mathcal{L}_{TD}(\theta) + \lambda \sum_i \mathcal{L}_{L_1}(Q_i^I(\theta_i^I)), \tag{9}$$

where θ_i^I is the parameters of Q_i^I, $\mathcal{L}_{L_1}(Q_i^I)$ is the L1 regularization term for independent Q-functions, and λ is a scaling factor.

4 Case study: outperforming by being diverse only when necessary

We design `Pac-Men` shown in Fig. 3 to demonstrate how our approach works. In this task, four agents are initialized at the center room and can only observe a 5×5 grid around them. Three dots are initialized randomly in each edge room. To make this environment more challenging, paths to different rooms have different lengths, which are down : left : up : right = 4 : 8 : 12 : 8. Three out of four rooms are outside agents' observation scope, which brings about the difficulty of exploration. Dots will refresh randomly after all rooms are empty. An ineffective competition between agents occurs when they come together in one room. The total environmental reward is the number of dots eaten in one step or -0.1 if no one eats dots. The time limit of this environment is set to 100 steps.



(a) Comparison against baselines (b) Visitation heatmap (c) Behavior diversity heatmap

Figure 3: Why does our method work? The balance between identity-aware diversity and experience sharing encourages sophisticated strategies.

Fig. 3-middle demonstrates the learned strategies of our approach, with a heatmap showing the visitation number. Driven by the objective of mutual information between individual trajectory and identity, agents achieve diversity and scatter in different rooms to eat dots. We further analyze the role of independent and shared Q-functions during different stages in Fig. 3 right. We visualize the value of $SD(Q_i^I(\cdot))/SD(Q^S(\cdot))$, where SD denotes the standard deviation (SD) of Q values for different actions. A higher SD ratio indicates the independent Q-functions play a leading role, while a lower SD ratio indicates the shared Q function's domination.

We notice that the SD ratio is considerably larger in the central room and four paths than in four edge rooms. This observation means that agents use independent Q networks to reach different rooms while use the shared Q network to search for dots in them. The result shows that our method achieves a good balance between diversity and knowledge sharing. Taking this advantage, our approach significantly outperforms baselines (Fig. 3 left, baselines are introduced in Sec. 6). Other methods, such as influence-based exploration (EITI & EDTI [20]), variational exploration (MAVEN [21]), and individuality emergence (EOI [22]) methods, are slower to learn optimal strategies.

5 Related Work

Deep multi-agent reinforcement learning algorithms have witnessed significant advances in recent years. COMA [15], MADDPG [7], PR2 [23], and DOP [8] study the problem of policy-based multi-agent reinforcement learning. They use a (decomposed) centralized critic to calculate gradients for decentralized actors. Value-based algorithms decompose the joint value function into individual utility functions in order to enable efficient optimization and decentralized execution. VDN [4], QMIX [5], and QTRAN [16] progressively expand the representation capabilities of the mixing network. QPLEX [6] implements the full IGM class [16] by encoding the IGM principle into a duplex dueling network architecture. Weighted QMIX [18] proposes weighted projection to decompose any joint action-value functions. There are other works that investigate into MARL from the perspective of coordination graphs [24–26], communication [27, 28, 10], and role-based learning [12, 29].

Knowledge sharing in MARL From IQL [30] to QPLEX, many works focus on designing mixing network structures and have provided promising empirical and theoretical results. For these works,

experience sharing among agents has been an important component. Learning from others is one essential skill engraved in humans' genes to survive in society. Based on the relationship between teachers and students in human society, a series of research work hopes each agent can learn from others or selectively share its knowledge with others [31–34]. But it is challenging to specify knowledge in practice, let alone deciding what to share or learn. SEAC [35] partially solves this problem by sharing trajectories only for off-policy training. NCC [28] maintains cognition consistency by representation alignment between neighbors. Roy et al. [36] force each agent to predict others' local policies and adds a coach for group experience alignment. In this paper, we do not try to let agents choose whether to learn or share experiences. Our neural network structure shown in Fig. 2 can balance group coordination and diversity by gradient backpropagation.

Diversity In single-agent settings, diversity emerges for exploration or solving sparse reward problems. Existing methods such as curiosity-driven algorithms [37–40] or maximising mutual information [41–43] have shown great promise. When encouraging diversity in MARL settings, agents' coordination must be considered. Several recent works study this problem, such as MAVEN [21], EITI & EDTI [20], and EOI [22]. MAVEN learns a diverse ensemble of monotonic approximations with the help of a latent space to explore. EITI and EDTI consider pairwise mutual influence to encourage the interdependence between agents. EOI [22] combines the gradient from the intrinsic value function (IVF) and the total Q-function to train each agent's local Q-function. In this paper, we encourage agents to explore unique trajectories by optimizing the mutual information between agent's identity and trajectory. Moreover, we propose a novel network structure to enable experience sharing or consensus, which combines all agents' rare ideas, while still maintain independent action-value functions for each agent to behave differently when necessary. The combination of these novelties balances diversity and homogeneity for learning sophisticated cooperation.

6 Experiments

In Sec. 4, we use a toy game to illustrate how our approach adaptively balances experience sharing and identity-aware diversity. In this section, we use challenging tasks from GRF and SMAC benchmark to further demonstrate and illustrate the outperformance of our approach. We compare our approach against multi-agent value-based methods (QMIX [5], QPLEX [6]), influence-based exploration (EITI & EDTI [20]), variational exploration (MAVEN [21]), and individuality emergence (EOI [22]) methods. Different from baselines, we do not include agents' identification in inputs when calculating local Q-functions. We show the average and variance of the performance for our method, baselines, and ablations tested with five random seeds.

6.1 Performance on Google Research Football (GRF)

We first benchmark our approach on three challenging Google Research Football (GRF) offensive scenarios `academy_3_vs_1_with_keeper`, `academy_counterattack_hard`, and our own designed full-field scenario `3_vs_1_with_keeper` (`full field`). Agents' initial locations for each scenario are shown in Appendix B.3. In GRF tasks, agents need to coordinate timing and positions for organizing offense to seize fleeting opportunities, and only scoring leads to rewards. In our experiments, we control left-side players (in yellow) except the goalkeeper. The right-side players are rule-based bots controlled by the game engine. Agents have a discrete action space of 19, including moving in

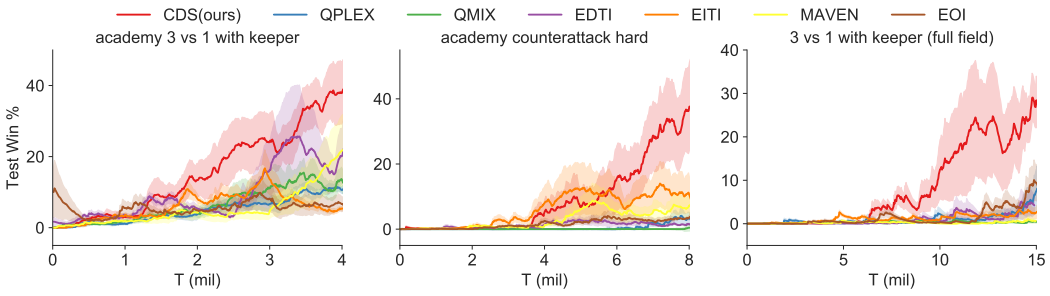


Figure 4: Comparison of our approach against baseline algorithms on Google Research Football.

eight directions, sliding, shooting, and passing. The observation contains the positions and moving directions of the ego-agent, other agents, and the ball. The z-coordinate of the ball is also included. We make a small and reasonable change to the half-court offensive scenarios: our players will lose if they or the ball returns to our half-court. All baselines and ablations are tested with this modification. Environmental reward only occurs at the end of the game. They will get +100 if they win, else get -1.

We show the performance comparison against baselines in Fig. 4. Our approach significantly outperforms on all the scenarios. The win rate of a multi-agent exploration method, MAVEN, needs more time to solve the task, demonstrating that CDS incentives more efficient exploration. Influence-based approaches EITI and EDTI can learn effective strategies. However, these two methods use the sum of all pairwise interaction values between agents, which brings more computational complexity, causing less efficient learning than our approach. EOI lets each agent consider individuality and cooperation by setting local learning objectives but without exclusive Q networks, making cooperation and individuality hard to be persistently coordinated. In comparison, taking advantage of the partially shared network structure, CDS agents learn diverse but coordinated strategies. For example, as shown in Fig. 1, three agents have different behaviors, with the first agent passing the ball, the second scoring, while the third running to threaten. These diverse behaviors closely coordinate with each other, forming a perfect scoring strategy and leading to significant outperformance against EOI.

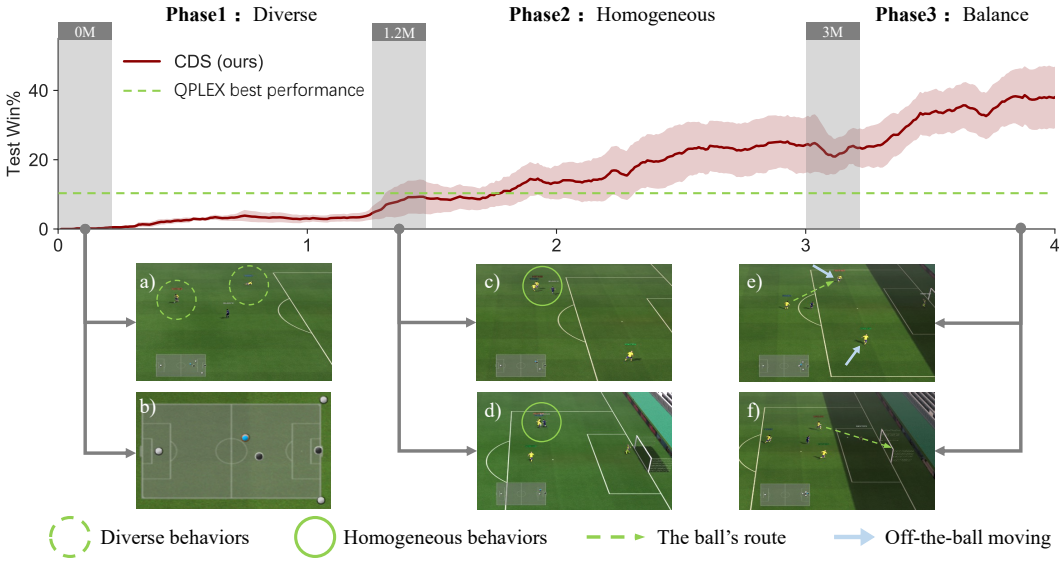


Figure 5: Why does our approach work? The balance between identity-aware diversity and homogeneity encourages sophisticated strategies.

How does CDS work? We further visualize the development of team performance, accompanied by the balancing process between identity-aware diversity and homogeneity, to show why our method works (Fig. 5). We pinpoint three critical points during the training process. In the first training stage ($0 \sim 1.2$M), CDS players attempt to be as diverse as possible due to the sparsity of environmental rewards. Agents behave differently, such as sliding randomly (Fig. 5a) or running aimlessly (Fig. 5b). These behaviors essentially promote distributed exploration. After $T = 1.2$M, agents realize they need to organize an offense to score a goal. They aggregate near the goal and prepare to attack while dribbling. However, in this second training phase, agents focus on the ball rather than cooperation, leading to unnecessary competition. For example, as highlighted by the circle in Fig. 5c and Fig. 5d, our players try to compete for the ball. They lose their individuality after obtaining huge benefits brought by scoring. We believe this is also why some baseline algorithms, such QMIX and QPLEX, encounter a performance bottleneck in GRF scenarios. After $T = 3$M, our approach gradually achieves the balance of diversity and cooperation and again enables players to make diverse decisions when handling the ball for better collaboration. The whole training process shows our approach can coordinate the relationship between agents while keeping a good balance between individuality and group tasks.

6.2 Performance on StarCraft II

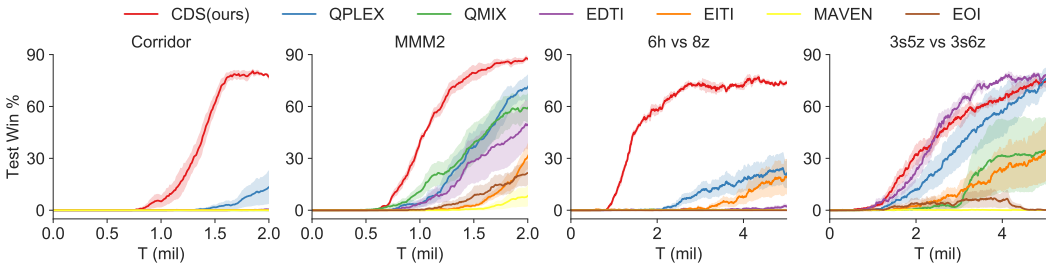


Figure 6: Comparison of our approach against baseline algorithms on four **super hard** SMAC maps: `corridor`, `MMM2`, `6h_vs_8z`, and `3s5z_vs_3s6z`.

In this section, we test our approach on the StarCraft II micromanagement (SMAC) benchmarks [11]. This benchmark consists of various maps classified as easy, hard, and super hard. Here we test our method on four **super hard** maps: `corridor`, `MMM2`, `6h_vs_8z`, and `3s5z_vs_3s6z`. Fig. 6 demonstrates that our approach outperforms all baselines with acceptable variance across random seeds. Comparing our approach with MAVEN shows that our approach is much more efficient in completing complex tasks. The baselines QPLEX and QMIX can achieve satisfactory performance on some challenging benchmarks, such as `3s5z_vs_3s6z`. But on other maps, they need the proposed diversity-celebrating method to get better results. EOI behaves worse than QPLEX, and the cooperation even collapses on `3s5z_vs_3s6z`. This observation shows that, compared to EOI, CDS incentivizes diverse behaviors which are more cooperative in terms of task solving. EITI behaves worse than QPLEX, while EDTI achieves outstanding performance on `3s5z_vs_3s6z`, where our approach achieves similar performance at the end of training. Taking the value of interaction into consideration lets EDTI better facilitate exploration. But the same as EITI, EDTI needs to sum up all the pairwise influence between agents, which is complex to calculate. Our approach simplifies the computational complexity by encouraging agents to highlight themselves from other agents, bypassing calculating pairwise influence. In this way, our approach can be adapted to multi-agent problems of larger scales.

6.3 Ablations and Visualization

To understand the contribution of each component in the proposed CDS framework, we carry out ablation studies to test the contribution of its three main components: Identity-aware *diversity* (A) encouragement and *partially shared* (B) neural network structure with *L1 regularization* (C) on non-shared Q-functions. To test component A, we ablate our intrinsic rewards to four different levels. (1) CDS-Raw ablates all intrinsic rewards by setting β in Eq. 8 to zero. (2) CDS-No-Identity ablates $H\left(\tau_T|id\right)$ and only optimize $H\left(\tau_T\right)$ in Eq. 1 by setting β_1 in Eq. 6 to zero. (3) CDS-No-Action ablates item ② in Eq. 2 by setting β_2 in Eq. 6 to zero. (4) CDS-No-Obs ablates item ③ in Eq. 2 by ablating $\beta_1 \log q_\phi\left(o_{t+1}|\tau_t, a_t, id\right) - \log p\left(o_{t+1}|\tau_t, a_t\right)$ in Eq. 6. To test component B, we design CDS-All-Shared, which ablates independent action-value functions together with the L1 loss and, like baselines, adds agents' identification to the input. To test component C, we design CDS-No-L1,

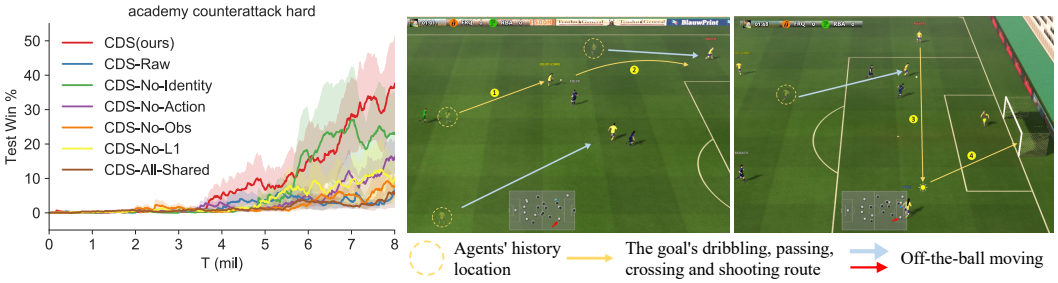


Figure 7: **Left.** Ablation studies on `academy_counterattack_hard`. **Right.** Visualization of trained policies, which achieve complex cooperation with impressive off-the-ball moving strategies.

which ablates L1 regularization terms by setting λ in Eq. 9 to zero.

We first carry out ablation studies on `academy_counterattack_hard` to analyze which part of our novelties lead to the outstanding performance. As shown on the left side of Fig. 7, CDS-No-Identity performs the best among all ablations. However, compared with CDS, CDS-No-Identity is slower to explore winning strategy and performs noticeably worse at the end of training. Thus for the intrinsic reward component in this environment, the superior performance of CDS is primarily due to optimizing group diversity. Still, the specialization of agents' behavior given identification noticeably improves learning. Moreover, the performance of CDS-No-Obs and CDS-Raw perform poorly. CDS-No-Action performs a little better but is similar to QPLEX. Therefore, action- and observation-aware diversity are both crucial. CDS-No-L1 performs similarly to MAVEN, which indicates that unlimited diversity is harmful to cooperation. CDS-All-Shared performs even worse than QPLEX, demonstrating that identity-aware diversity is difficult to emerge without our specially designed network structure.

We further visualize the final trained strategies on the right side of Fig. 7, which shows complex cooperation between agents. Our players first attack down the wing by dribbling and passing the ball. Then one of them draws the attention of the enemy defenders and the goalkeeper, while the ball being passed across the penalty area. Another player catches the ball and completes the shot. The most impressive part of our sophisticated strategies is off-the-ball moving strategies. All agents without the ball try to use their unique and valuable moves to create more scoring opportunities, which shows behavior and position diversity for finishing the goal.

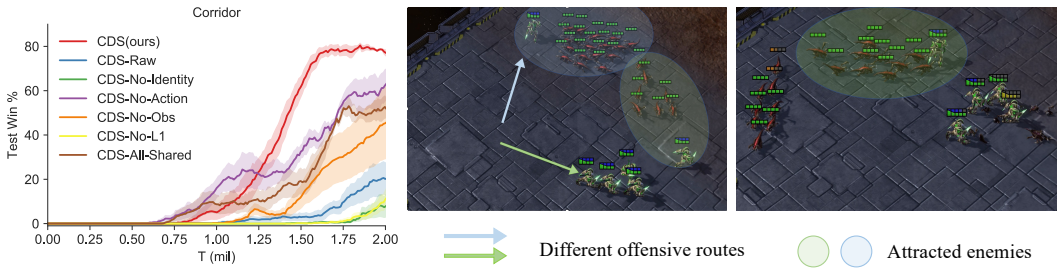


Figure 8: **Left.** Ablation studies in super hard map `corridor`. **Right.** Visualization of the final trained strategies, which achieves a hard-earned victory brought by the sacrifice of a warrior.

We also carry out ablation studies on the super hard map `corridor` as shown in Fig. 8 left. The combination of our novelties still performs the best. We notice considerable differences against the GRF scenario. For instance, CDS-No-Identity performs the worst on `corridor` but the best on `academy_counterattack_hard` among all ablations. This phenomenon indicates the different importance of group diversity and specialization of agents' behavior given identification between GRF and SMAC. For SMAC, the most important intrinsic reward component is optimizing the conditional entropy. Unlimited identity-aware diversity without L1 regularization, CDS-No-L1, has worse performances than QPLEX. Therefore, excessive diversity is harmful to the emerge of complex cooperation, which is the same in both GRF and SMAC.

To better explain why our approach performs well. On `corridor`, we also visualize the final strategies in Fig. 8 right. In this super hard map, six friendly Zealots are facing 24 enemy Zerglings. The disparity in quantity means our agents are doomed to lose if they attack together. One Zealot, whose route is highlighted blue, becomes a warrior leaving the team to attract the attention of most enemies in the blue oval. Although doomed to sacrifice, he brings enough time for the team to eliminate a small part of the enemies in the green oval. After that, another Zealot stands out to attract some enemies and enables teammates to eradicate them. These sophisticated strategies reflect the leverage between diversity and homogeneity by encouraging agents to be diverse only when necessary.

7 Closing Remarks

Observing that behavioral diversity among agents is essential for many challenging and complex multi-agent tasks, in this paper, we introduce a novel mechanism of *being diverse when necessary* into shared multi-agent reinforcement learning. The balance between individual diversity and group

coordination induced by our CDS approach pushes forward state-of-the-art of deep MARL on challenging benchmark tasks while keeping parameter sharing benefits. We hope that our method can shed light on future works to motivate agents to cooperate with diversity to further explore complex multi-agent coordination problems.

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Checklist

1. For all authors...
   (a) Do the main claims made in the abstract and introduction accurately reflect the paper's contributions and scope? [Yes]
   (b) Did you describe the limitations of your work? [Yes] In Appendix. C.3
   (c) Did you discuss any potential negative societal impacts of your work? [N/A] Our approach do not have potential negative societal impacts.
   (d) Have you read the ethics review guidelines and ensured that your paper conforms to them? [Yes]
2. If you are including theoretical results...
   (a) Did you state the full set of assumptions of all theoretical results? [N/A]
   (b) Did you include complete proofs of all theoretical results? [Yes] See Sec. 3.1
3. If you ran experiments...
   (a) Did you include the code, data, and instructions needed to reproduce the main experimental results (either in the supplemental material or as a URL)? [Yes] We include them in the supplemental material.

(b) Did you specify all the training details (e.g., data splits, hyperparameters, how they were chosen)? [Yes] Please refer to Appendix. B.2

(c) Did you report error bars (e.g., with respect to the random seed after running experiments multiple times)? [Yes] We include them in all our figures (Fig. 3, 4, 5, 6, 7, and 8).

(d) Did you include the total amount of compute and the type of resources used (e.g., type of GPUs, internal cluster, or cloud provider)? [Yes] In Appendix B.4

4. If you are using existing assets (e.g., code, data, models) or curating/releasing new assets...

(a) If your work uses existing assets, did you cite the creators? [Yes] Our code is based on the open-sourced repository PyMARL, and we cite the paper [11] in our paper.

(b) Did you mention the license of the assets? [Yes] We mention that the open-sourced repository PyMARL is licensed under Apache License v2.0 in the supplemental material.

(c) Did you include any new assets either in the supplemental material or as a URL? [Yes] We include our codebase for the CDS framework in the supplemental material.

(d) Did you discuss whether and how consent was obtained from people whose data you're using/curating? [Yes] Please refer to Appendix B.1

(e) Did you discuss whether the data you are using/curating contains personally identifiable information or offensive content? [N/A] Our data does not include such content.

5. If you used crowdsourcing or conducted research with human subjects...

(a) Did you include the full text of instructions given to participants and screenshots, if applicable? [N/A]

(b) Did you describe any potential participant risks, with links to Institutional Review Board (IRB) approvals, if applicable? [N/A]

(c) Did you include the estimated hourly wage paid to participants and the total amount spent on participant compensation? [N/A]

A Estimating Intrinsic Reward Functions

In our approach, the intrinsic reward can be separated into two parts. One is related to action-aware diversity, while the other is related to observation-aware diversity. We revisit the formulation of our information-theoretic objective (Eq. 2) and discuss how to better estimate it.

A.1 Intrinsic Rewards for Action-Aware Diversity

First we analyze term ②, which is related to action-aware diversity. This part can be written as:

$$② = \sum_{t=0}^{T-1} E_{id,\tau}\left[\log \frac{p(a_t|\tau_t, id)}{p(a_t|\tau_t)}\right] \tag{10}$$

The computational problem here is how to estimate $p\left(a_t|\tau_t\right)$, which can be expanded as:

$$p\left(a_t|\tau_t\right) = \sum_{id} p\left(id|\tau_t\right)\pi\left(a_t|\tau_t, id\right), \tag{11}$$

where $p\left(id|\tau_t\right)$ needs estimation. Any approximation will result in an upper bound of the objective:

$$② = \sum_{t=0}^{T-1}\left(E_{id,\tau}\left[\log \frac{p(a_t|\tau_t, id)}{q(a_t|\tau_t)}\right] - D_{\mathrm{KL}}\left(p\left(a_t|\tau_t\right)\|q\left(a_t|\tau_t\right)\right)\right) \leq \sum_{t=0}^{T-1} E_{id,\tau}\left[\log \frac{p(a_t|\tau_t, id)}{q(a_t|\tau_t)}\right]. \tag{12}$$

However, to optimize term ②, we need a lower bound (Eq. 3). Additional approximation of $p\left(id|\tau_t\right)$ may render the optimization intractable. Fortunately, as we will show in this section, a good but not accurate approximation of $p\left(id|\tau_t\right)$ can still lead to satisfactory learning performance. We now discuss two ways to estimate $p\left(id|\tau_t\right)$.

First, we can follow previous work [42] and make the assumption that $p\left(id|\tau_t\right) \approx p\left(id\right)$, which conforms to a uniform distribution. Then, we can calculate $p\left(a_t|\tau_t\right)$ as below:

$$p\left(a_t|\tau_t\right) \approx \frac{1}{n}\sum_{id} \pi\left(a_t|\tau_t, id\right), \tag{13}$$

where n is the number of agents.

However, in this paper, we encourage each agent to behave differently from others when necessary. As a result, it is likely that $p\left(id\right)$ might occasionally be different from $p\left(id|\tau_t\right)$, which means the above assumption might not be valid all the time.

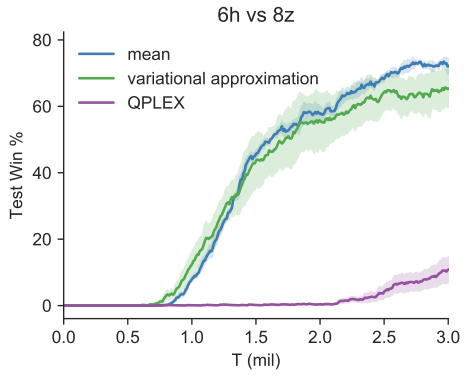

Figure 9: Comparison of assuming $p\left(id|\tau_t\right) \approx p\left(id\right)$ and estimating $p\left(id|\tau_t\right)$ with variational inference on a SMAC super hard map `6h_vs_8z`.

As an alternative, we can leave out the assumption by using the Monte Carlo method (MC) for estimating the distribution $p\left(id|\tau_t\right)$. In tabular cases, we count from samples to calculate the frequency $p\left(id|\tau_t\right) = \frac{N(id,\tau_t)}{N(\tau_t)}$, where $N(\cdot)$ is the time of visitation. However, MC becomes impractical in complex environments such as GRF and SMAC with long horizons and continuous spaces. For these complex cases, inspired by Wang et al. [20], we adopt variational inference to learn a distribution $q_\xi\left(id|\tau_t\right)$, parameterized by a neural network with parameters ξ, to estimate $p\left(id|\tau_t\right)$ by optimizing the evidence lower bound (ELBO).

We empirically test these two estimation methods on a SMAC super hard map `6h_vs_8z` (Fig. 9) (the observation-aware diversity is estimated with Eq. 15). The experimental results demonstrate that the two methods have similar performance but assuming $p\left(id|\tau_t\right) \approx p\left(id\right)$ outperforms estimating

$p\left(id|\tau_t\right)$ with variational approximation in both average performance and variance between random seeds. We hypothesize that the estimation error renders the variational inference approach unstable. Therefore, we decide to use Eq. 13 to estimate $p\left(a_t|\tau_t\right)$ in this paper.

A.2 Intrinsic Rewards for Observation-Aware Diversity

We then analyze term ③, which is related to observation-aware diversity. This part can be written as:

$$③ = \sum_{t=0}^{T-1} E_{id,\tau}\left[\log \frac{p(o_{t+1}|\tau_t, a_t, id)}{p(o_{t+1}|\tau_t, a_t)}\right]. \tag{14}$$

The computational problem here is how to estimate $p\left(o_{t+1}|\tau_t, a_t\right)$. We can directly adopt variational inference and learn the variational distribution $q_{\phi_2}\left(o_{t+1}|\tau_t, a_t\right)$, parameterized by a neural network with parameters ϕ_2, by optimizing the evidence lower bound. With $q_{\phi_2}\left(o_{t+1}|\tau_t, a_t\right)$, r^I can be written as:

$$\begin{aligned} r^I = & E_{id}\left[\beta_2 D_{\mathrm{KL}}(\mathrm{SoftMax}(\beta_1 Q(\cdot|\tau_t, id))||p(\cdot|\tau_t))\right. \\ & \left.+\beta_1 \log q_\phi\left(o_{t+1}|\tau_t, a_t, id\right) - \log q_{\phi_2}\left(o_{t+1}|\tau_t, a_t\right)\right]. \end{aligned} \tag{15}$$

This method use a **forward** prediction model of agents' next observation.

One concern is that the forward method involves inference on the continuous observation space, which may be too large to estimate accurately on complex tasks. We can omit it by deriving a lower bound.

We have that

$$E[\log p(o'|\tau, a, id) - \log p(o'|\tau, a)] = I(o'; id|\tau, a). \tag{16}$$

Therefore, optimising term ③ is equivalent to optimising $I(o'; id|\tau, a)$. Notice that

$$I(o'; id|\tau, a) = H(o'|\tau, a) - H(o'|\tau, a, id), \tag{17}$$

we have

$$\begin{aligned} I(o'; id|\tau, a) &= -H\left(o'|\tau, a, id\right) + H\left(o'|\tau, a\right) \\ &= -H\left(o'|\tau, a, id\right) + \sum_{o', \tau, a} p(o', \tau, a) \log \frac{p(\tau, a)}{p(o', \tau, a)} \\ &= -H\left(o'|\tau, a, id\right) + \sum_{o', \tau, a} p(o', \tau, a) \log \sum_{id} q\left(id|o', \tau, a\right) \frac{p(\tau, a)}{p(o', \tau, a)} \\ &= -H\left(o'|\tau, a, id\right) + \sum_{o', \tau, a} p(o', \tau, a) \log \sum_{id} q\left(id|o', \tau, a\right) \frac{p(id|o', \tau, a)p(\tau, a)}{p(o', id, \tau, a)} \\ &\geq -H\left(o'|\tau, a, id\right) + \sum_{o', \tau, a} p(o', \tau, a) \sum_{id} p\left(id|o', \tau, a\right) \log \frac{q(id|o', \tau, a)p(\tau, a)}{p(o', id, \tau, a)} \\ &= -H\left(o'|\tau, a, id\right) + \sum_{o', id, \tau, a} p(o', id, \tau, a) \log \frac{q(id|o', \tau, a)}{p(o', id|\tau, a)} \\ &= -H\left(o'|\tau, a, id\right) + E\left[\log q\left(id|o', \tau, a\right)\right] + H\left(o', id|\tau, a\right), \end{aligned} \tag{18}$$

where $q(id|o', \tau, a)$ can be an arbitrary distribution. We use variational inference and a neural network parameterized by η_1 to estimate it. Moreover, $H\left(o', id|\tau, a\right)$ can be decomposed as:

$$H\left(o', id|\tau, a\right) = H(id|\tau, a) + H\left(o'|\tau, a, id\right). \tag{19}$$

With Eq. 19, Eq 18 can be further written as:

$$\begin{aligned} I(o'; id|\tau, a) &\geq -H\left(o'|\tau, a, id\right) + E\left[\log q_{\eta_1}\left(id|o', \tau, a\right)\right] + H\left(o', id|\tau, a\right) \\ &= -H\left(o'|\tau, a, id\right) + E\left[\log q_{\eta_1}\left(id|o', \tau, a\right)\right] + H(id|\tau, a) + H\left(o'|\tau, a, id\right) \\ &= E\left[\log q_{\eta_1}\left(id|o', \tau, a\right)\right] + H(id|\tau, a) \\ &= E\left[\log q_{\eta_1}\left(id|o', \tau, a\right) - \log p(id|\tau, a)\right]. \end{aligned} \tag{20}$$

With the above mathematical derivation, we bypass the estimation of $p\left(o_{t+1}|\tau_t, a_t\right)$. Although $p(id|\tau_t, a_t)$ is introduced, we now infer in a much smaller and discrete space rather than the continuous observation space. We can estimate $p(id|\tau_t, a_t)$ using similar methods introduced in the previous section. We adopt variational inference to learn the distribution $q_{\eta_2}\left(id|\tau_t, a_t\right)$, parameterized by a neural network with parameters η_2, by optimizing the evidence lower bound. With this **backward** prediction model of agents' identity, r^I can be written as:

$$\begin{aligned} r^I = E_{id}\left[\beta_2 D_{\mathrm{KL}}(\mathrm{SoftMax}(\beta_1 Q(\cdot|\tau_t, id))||p(\cdot|\tau_t))\right. \\ \left.+\beta_1 \log q_{\eta_1}\left(id|o_{t+1}, \tau_t, a_t\right) - \log q_{\eta_2}\left(id|\tau_t, a_t\right)\right]. \end{aligned} \tag{21}$$

We empirically compare these two methods on a SMAC super hard map `6h_vs_8z` as shown in Fig. 10 ($p(\cdot|\tau_t)$ is estimated with Eq. 13). The experimental results demonstrate that estimating r^I with a forward prediction model noticeably outperforms estimating with a backward prediction model, although the forward model might be more difficult to estimate as discussed before. We hypothesize that simultaneously and independently estimating $q_\phi\left(o_{t+1}|\tau_t, a_t, id\right)$ and $q_{\phi_2}\left(o_{t+1}|\tau_t, a_t\right)$ might bring advantages similar to those of curiosity-driven methods, leading to outstanding performance on tasks requiring extensive exploration, so we use Eq. 15 to encourage diversity in this paper.

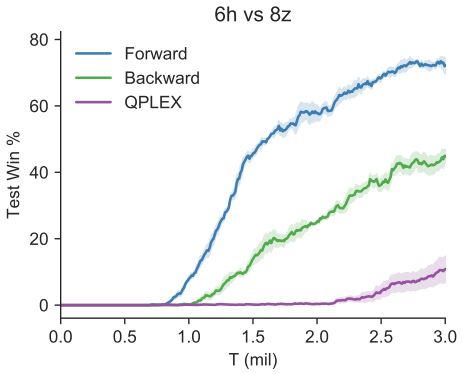

Figure 10: Comparison of forward and backward estimation for observation-aware diversity on a SMAC super hard map `6h_vs_8z`.

B Experiment Details

B.1 Baselines

We compare our approach with multi-agent value-based methods (QMIX [5] & QPLEX [6]), influence-based exploration methods (EITI & EDTI [20]), a variational exploration method (MAVEN [21]), and an individuality emergence (EOI [22]) method. For QMIX, QPLEX, MAVEN, and EOI, we use the codes provided by the authors where the hyper-parameters have been fine-tuned. For EITI and EDTI, we improve the original methods by combining the proposed intrinsic rewards with QPLEX.

B.2 Architecture and Hyperparameters

In this paper, we use a QPLEX style mixing network with its default hyperparameters suggested by the original paper. Specifically, in complex environments (GRF and SMAC), the transformation part has four 32-bits attentional heads, each with one middle layer of 64 units. Weights in the joint advantage function of the dueling mixing part are produced by a four-head attention module without hidden layers. In toy environment `Pac-Men`, we do not use the transformation part but still generate weights in the joint advantage function of the dueling mixing part by the four-head module without hidden layers. For individual Q-functions, agents share a trajectory encoding network consisting of two layers, a fully connected layer followed by a GRU layer with a 64-dimensional hidden state. After the trajectory encoding network, all agents share a one-layer Q network, while each agent has its independent Q network with the same structure as the shared Q network.

For all experiments, the optimization is conducted using RMSprop with a learning rate of 5×10^{-4}, α of 0.99, and with no momentum or weight decay. For exploration, we use ϵ-greedy, with ϵ annealed linearly from 1.0 to 0.05 over $500K$ time steps and kept constant for the rest of the training, for both CDS and all the baselines and ablations. Our method introduces four important hyperparameters: β, β_1, β_2, that are related to the intrinsic rewards, and λ, which is the scaling weight of the L1 regularization term. For the environment in the case study (`Pac-Men`), λ is set to 0.01. For GRF and SMAC, we set λ to 0.1 to strengthen *being diverse only when necessary*. In the case study environment `Pac-Men`, $\{\beta, \beta_1, \beta_2\} = \{0.15, 2.0, 1.0\}$. For GRF scenarios, we search the best hyperparameters for intrinsic rewards on `academy_3_vs_1_with_keeper`, and use $\{\beta, \beta_1, \beta_2\} = \{0.05, 0.5, 2.0\}$ for all GRF tasks. On SMAC, we first search the best hyperparameters of intrinsic rewards on

MMM2, with $\{\beta, \beta_1, \beta_2\} = \{0.07, 2.0, 1.0\}$. These hyperparameters are fine-tuned on other SMAC tasks. We set $\beta = 0.1$ for 6h_vs_8z and $\beta = 0.03$ for 3s5z_vs_3s6z. For corridor, we set $\{\beta, \beta_1, \beta_2\} = \{0.1, 0.5, 0.5\}$. Moreover, for GRF scenarios, we use a prioritized replay buffer of the TD error for both CDS and all the baselines and ablations.

B.3 GRF Scenarios

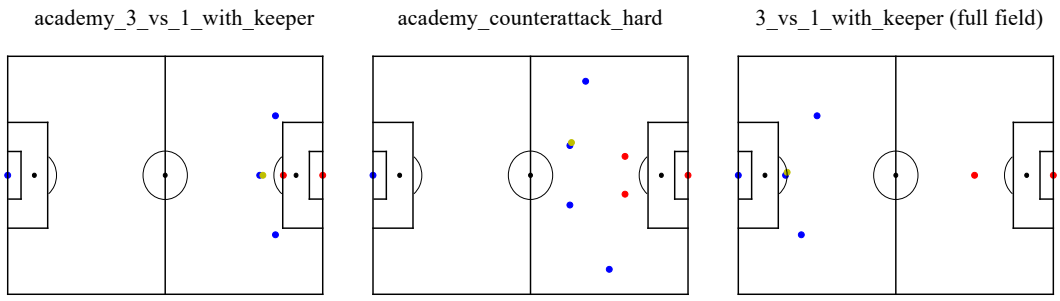

Figure 11: Visualization of the initial position of each agent in three GRF environments considered in our paper, where blue points represent our agents, red points represent opponents, and the yellow point represents the ball.

In this paper, we achieve state-of-the-art performance on all the tested GRF tasks, including two official scenarios academy_3_vs_1_with_keeper and academy_counterattack_hard. Furthermore, we design one full-field scenario 3_vs_1_with_keeper (full field) to compare the performance of our approach and baselines on a task with a more complex problem space. The visualization of the initial position of each agent for the three GRF scenarios are shown in Fig. 11.

B.4 Infrastructure

Experiments are carried out on NVIDIA GTX 2080 Ti GPU. And the training of our approach on all environments can be finished in less than two days.

C Additional Experimental Results

C.1 More Experiments on Pac-Men

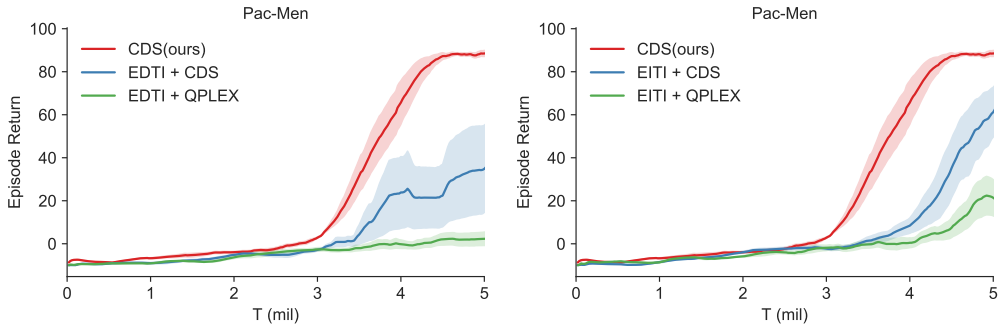

Figure 12: Comparison against EDTI and EITI with partial network sharing on Pac-Men.

In Sec. 4, we show that our approach outperforms baselines in a toy game Pac-Men, where EDTI or EITI is combined with a current state-of-the-art multi-agent factored Q-learning algorithm QPLEX. In this section, we further test EDTI and EITI augmented by the CDS novelties (agents share a local Q-function, and each has an individual Q-function regularized by the L1 loss). As shown in Fig. 12, with more diversity capacity provided by CDS, EDTI and EITI achieve better performance, but still underperform our method. These results indicate that (1) our structural contribution that enables

agents to have exclusive knowledge is readily to be combined with other MARL methods and is likely to improve their performance; (2) our learning objective is more efficient on tasks that require diversity among agents.

C.2 More Experiments on Google Research Football

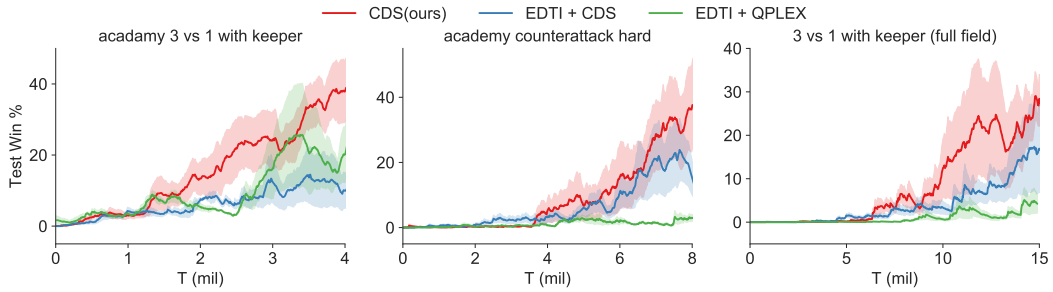

Figure 13: Comparison against EDTI with partial network sharing on GRF.

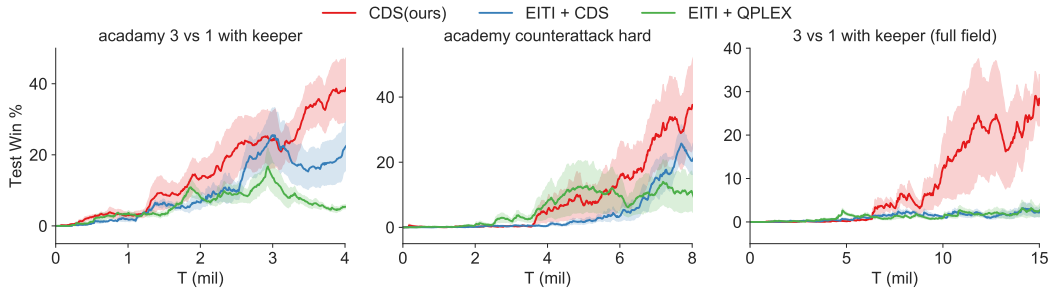

Figure 14: Comparison against EITI with partial network sharing on GRF.

In this section, we further test EDTI and EITI augmented by CDS innovations on Google Research Football. As shown in Fig. 13 and 14, augmented EDIT and EITI perform noticeably better in complex Football scenarios, demonstrating the power of our neural network structures shown in Fig. 2. Moreover, our diversity learning objective still outperforms EDTI and EITI, showing its efficiency in challenging multi-agent tasks.

C.3 Advantages and Limitations of Our Approach

In this paper, we achieve *being diverse when necessary* with the combination of structural and motivational novelties. Our approach pushes forward the state of the art on challenging GRF scenarios and significantly outperforms baselines on three super hard maps from the SMAC benchmark. Our approach encourages each agent to highlight itself from the group and balance this diversity with sharing to learn sophisticated strategies. But when facing larger problem spaces, this balancing process will require more training. Further, we only maintain one shared neural network among agents. The representational capacity might not be enough when dealing with more complex tasks that require multiple types of shared behaviors, such as learning offense and defense at the same time. We plan to explore how to improve our approach's scalability and representational ability for the GRF full game in future works.