[[1]](#footnote-1)

Coordination as Inference in Multi-Agent Reinforcement Learning through

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# I. INTRODUCTION

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协调是多智能体系统的基本问题之一

在多智能体强化学习（RL）中，智能体必须学会在包含多个学习智能体的环境中行动，通常是在部分可观测的情况下

许多现实世界的应用需要多个智能体学习协作解决任务，如自主驾驶[15]、智能电网控制[26]和智能交通控制[25]。然而，由于存在多智能体人的病症，如移动目标问题（非平稳性）、维度诅咒、多代理人信用分配、全局探索和相对过度概括等，多智能体人环境下的学习从根本上说比单智能体人的情况更难。

学习交流的研究工作已经加强，因为许多病症可以通过将交流技能纳入到智能体中来克服，包括非平稳性、代理之间的协调性和部分可观察性。

智能体不仅要决定交流什么，而且要决定何时和与谁交流。所开发的语言必须建立在共同的共识之上，这样所有的智能体人都能理解口语，包括其语义，这是必不可少的。消息将以广播(Learning multiagent communication with backpropagation、Learning multiagent communication with backpropagation、Tarmac: Targeted multi-agent communication、Efficient communication in multi-agent reinforcement learning via variance based control、Multiagent Bidirectionally-Coordinated Nets)方式或通过精简后的通讯图传递给其他智能体。

在多智能体系统中，任何智能体的行动对环境的影响也取决于其他智能体采取的行动，需要协调来不断打破同样好的行动或策略之间的联系（Bu等人，2008）。

特别是在智能体人不能沟通的情况下，这个问题是至关重要的。

在单个智能体部分可观察的设置中，智能体保持对隐藏环境状态的信念显然很有用，因为这是其动作观察历史的充分统计信息。然而，在多智能体环境中，信念是什么并不明显。仅仅维持对环境状态的信念是不够的。因为其他智能体也有无法观察到的内部状态。然而，简单地将单智能体强化学习方法扩展到多智能体环境面临巨大挑战，即智能体之间的协调。

推理其他智能体的意图并能够预测他们的行为在多智能体系统中是很重要的。在多智能体系统中，智能体可能有不同的，有时甚至是相互竞争的目标。这仍然是一个具有挑战性的问题，由于这类领域固有的非稳态性。

当观察他人的行为时，人类会推断出他们为什么会这样做，以及这对世界意味着什么；人类还利用这样一个事实，即他们的行为将以这种方式被解释，从而允许他们以信息的方式行事，从而有效地与他人沟通。

除了管理交通流的官方规则外，人类经常依赖某种形式的非正式规则，这些规则来自于他们之间的非语言交流和对其他交通参与者意图的预测。例如，打算穿过没有停车标志或交通信号的街道的行人经常与司机建立眼神交流，以确保驶来的汽车会为他们停车。其他形式的非语言交流，如手势或身体姿势，也被用来解决典型交通情况下的歧义。

人类经常进行的心理推理理论（Baker等人，2017年）。这种推理旨在理解为什么一个人在几个人中采取了特定的行动，以及这包含了哪些关于私人观察分布的信息

在某些情况下，人类使用他们自己的心理过程来模拟他人的行为通过采用他们的观点（Gordon, 1986; Gallese &

Goldman, 1998）。这使他们能够理解他人的意图或动机，并在社会环境中采取相应的行动。

MARL的一个常见问题是由于每个机器人的独立行动导致的非平稳性。这通常是通过仔细的消息传递来解决的。

虽然智能体之间的通信有助于协调，但训练及时通信不仅需要得到通讯协议，还需要学习到通讯对象，这仍然是一个具有挑战性的问题。 除此之外，显式通信通道需要额外的计算和内存成本，因此难以在分散控制中部署。由于没有显示的通讯渠道，最新的即时通信方法不适用，因此需要一种新的方法。

通过其他智能体的观察进行学习具有直观的吸引力；然而，智能体之间关于行动能力的明确交流需要相当多的基础设施：交流渠道、充分表达的表示语言以及交流的激励措施。

基于观察的技术，在这种技术中，学习智能体只观察另一个智能体的外在行为，可以减少对明确交流的需要。

动作本身所包含的信息，即一个智能体决定执行某个特定动作而不是另一个动作的事实，而不是由动作引起的状态转换所产生的信息。这对于发现好的策略至关重要

在多智能体环境中，除了先前的信念和个人经验外，还可以利用其他智能体的观察来改善智能体的环境模型。当这些观察为智能体提供关于其尚未访问的状态空间部分的信息时，它们会产生巨大的影响。这些信息可以用来将探索偏向于状态空间中最有希望的区域，从而降低探索成本并大大加快收敛速度。

因果影响是用反事实推理来评估的。导致自己代理人行为发生较大变化的其他代理人的意图被认为是有影响力的，并被反馈给代理人的行动生成器和价值生成器。这相当于增加他们的意图之间的相互信息。不是每个智能体都能提供有用的信息，多余的信息甚至会损害学习过程。

在明确交流受限的情况下，人类合作者通过学习来采取行动。(i) 推断其伙伴行动背后的意义，以及(ii) 通过行动向其伙伴隐含地传达关于状态的私人信息。

分散政策的集中训练。在学习过程中，智能体可以不受限制地分享观察结果、参数、梯度等，但学习的结果是一套分散的策略，这样每个智能体只可以根据自己的观察结果来选择行动。虽然在这个方向已经取得了重大进展，但要求策略必须是完全去中心化的要求严重限制了智能体协调其行为的能力。即使是集中训练和分散执行（CTDE）范式，旨在缓解非平稳性，如MADDPG[10]、COMA[4]、VDN[20]、QMIX[14]、QTRAN[18]和MAAC[5]，智能体在执行过程中仍然很难采取合作行动，因为部分可观察性和随机性可以轻易打破学到的合作策略，导致灾难性的不协调。

通常情况下，智能体被迫忽略他们个人观察中的信息，而这些信息原则上对最大化奖励是有用的。因为这样做会使他们的行为对队友的可预测性降低。

相比之下，基于推断的协调是同时进行的，也就是说，不需要学习通信协议。

然而，在本文中，我们表明，即使无法进行显式通信或共享动作/观察，也可以使用著名的RL算法获得有效的协调。

每个智能体能够利用其学到的先验知识，仅通过局部观察就能找出哪个智能体是相关的和有影响力的。先验知识是通过观察到的其他智能体动作以及因果推理学习的。一个智能体对另一个智能体的影响是由该智能体的意图对另一个智能体的策略的因果效应来体现的。对于任何能够引起对方策略急剧变化的智能体，该智能体被认为是相关的和有影响力的。

在现实世界中的应用，智能体可能需要了解其他智能体的意图，以便执行有用的行动。

它使智能体对与谁协作有一种信念。直观地说，智能体更有可能与那些可能对其策略施加更多影响的人合作，希望获得关于他们倾向于如何行动以及如何作出合作反应的线索。而这可能导致一种即时的现象：动态团队组成

非本地实体之间的结构化和迭代推理将使智能体能够捕捉到复杂问题解决所需的高阶关系。

这个通信框架是以端到端的方式学习的，不需要借助任何监督，这是特定任务奖励的结果。

智能体也应该考虑到它正在被建模，并相应地调整其行为，从而表现出一种心智理论。例如，在协作任务中，一个决策者可以选择采取对其队友有参考价值（互信息）的行动。

我们没有预定义的显式通信协议，也没有学习通过显式通道进行通信。信息交流只能通过行动发生。我们的智能体通过反复的策略和意图更新来学习协作，这样产生的协作机制是相互依赖的。

联合行动需要协调人们在空间和时间上的个人行动。这往往需要在线发生，而且速度非常快--因此，根据对伙伴履行的行动的观察做出反应似乎并不十分充分。相反，有人建议个人预测互动伙伴的行动和相应的后果。因此，人们可以根据这些预测来调整自己的行动，这有利于快速和准确的人际协调。此外，个人在预测他人的行动及其影响时，应该依赖自己的运动系统。

在人际行动协调过程中，人们使用自己的内部模型来模拟其他人的行动，以便进行预测。

使用自己的运动系统来推断他人的行动，有利于快速的人际行动协调，因为互动伙伴可以预测他人将做什么，而不是简单地根据他人已经做了什么做出反应。

为了根据行动伙伴的行动调整自己的行动，个人不仅持有自己的任务表征，而且还持有互动伙伴的任务表征。

让我们想象一对夫妇在舞厅里跳探戈。为了正确有效地表演探戈或任何其他舞蹈，每个舞者不仅要能对对方的动作做出反应，他/她还必须预测他/她的舞伴的动作，否则他/她的动作会太慢。此外，两个舞伴必须有共同的目标和意图，以及对如何跳探戈的共同构想。这些共同的意图、想象和想法也应该被预测，以便有效地完成联合行动。所有这些代表个人、他人和联合前进模型的信息流必须被整合，并在进行动作后反馈给感觉运动系统，以便在必要时纠正或更新所有这些前进模型。

这种缺乏基础的情况造成了各代理人之间的不协调，并带来了一个困难的探索问题

关于为什么在分散的多智能体强化学习环境中，出现协调是困难的。阻碍智能体学习有意义的协调的一个关键问题是缺乏协作的共同基础。首先通过对世界和奖励函数的学习表征使意图有根有据，然后通过学习来解释这些有根有据的意图。

我们的方法简化了完全分散的多Agent环境中的协作学习，并大大改善了多Agent协调任务的性能，这些任务在没有通信的情况下几乎是无法解决的。

其中每个智能体的角色不同，是合作还是竞争。

每个智能体根据其局部观察以及与其他智能体的直接和间接互动采取行动。这种复杂的互动模型往往会在训练过程中引入不稳定性，这可能会严重破坏模型的整体有效性。

近年来，人们提出了许多方法来提高合作式MARL的稳定性。

在这些方法中，集中训练和分散执行的范式[21]由于其优越的性能而获得了广泛的关注。利用这一范式的一个有前途的方法是价值函数分解法

社会互动的要求，如协调自己和他人的行动（Sebanz等人，2006），被描述为联合行动的术语

联合行动需要协调人们在空间和时间上互动的个人行动（Vesper等人，2013）。这往往需要在线发生，而且速度非常快--因此，根据对伙伴履行的行动的观察做出反应似乎并不充分（Knoblich和Jordan，2003；Vesper，2014）。相反，提取行动背后的意图可以达到更高层次的协作。因此，人们可以根据这些意图来调整自己的行动，这有利于快速而准确的人际协调（Vesper，2014；Vesper等人，2017）。此外，个人在预测他人的行动及其影响时，应该依赖自己的运动系统

# II. Related work

“Social Influence as Intrinsic Motivation for Multi-Agent Deep Reinforcement Learning”: Natasha Jaques et.al. achieved coordination and communication through causal inference, however, they assessed the CI in action level which is infeasible in high-dimensional space. And the reward function needs to be modified

“Real-World Human-Robot Collaborative Reinforcement Learning”: 作者将隐式合作运用到一个真实世界中的人在回路中的强化学习装置中，来研究人机合作，并证明了隐式合作在实际应用中的潜力。

“Implicit Communication in a Joint Action”: Knepper等人（2017）提出了一个合作中隐性交流的框架,并表明各种问题都可以映射到这个框架中。

“Online Implicit Agent Modelling”: 隐式方式也同样运用在了智能体建模中，其中智能体的目的是估计预先计算的策略的固定投资组合的效用，相比于显式地建模智能体策略的参数，该方法在复杂环境中是可行的。

“Multi-Agent Common Knowledge Reinforcement Learning”: 本文使用一个层次化的策略树，利用适当级别的智能体群体之间的共同知识，端到端地学习复杂的协调策略。尽管其最终可以学到一个协调分散的策略，但仍需要集中式的训练方式，且仅根据共同知识无法学习到非对称信息。

“Modeling Others using Oneself in Multi-Agent Reinforcement Learning”: 从其他玩家的行为中发现他们的隐藏目标，并使用这些估计来选择行动。尽管这项工作与本文都是对其他智能体的意图进行推理，但这项工作将意图直接建模为最终的目标，这样可能导致损失某些有用的信息，而我们则是更抽象的层次。并且这项工作尚未在有两个以上玩家的更复杂环境中评估。

“Bayesian Action Decoder for Deep Multi-Agent Reinforcement Learning”: defines a new Markov process, the public belief Markov decision process (PuB-MDP) and proposed BAD which uses an approximate Bayesian update to obtain a public belief. 然而，由于BAD依赖于一个被视为第三方的公共智能体，因此难以在分散控制中部署。

“Agreeing To Cross: How Drivers and Pedestrians Communicate”: 我们提出了一些关于行人在不同的过马路情况下采取的行动过程和使用的非语言提示的发现。我们表明，横穿马路的行为会受到各种环境因素的影响，如十字路口的结构、司机的行为、与临近车辆的距离等等。

“A Study of Reinforcement Learning Algorithms for Aggregates of Minimalistic Robots”: 研究最低限度的机器人集合体的控制，这些可以感知目标位置和附近的障碍物，但缺乏通过信息传递等方式进行明确的交流。将通讯设置为隐性的，即通过每个机器人对物体施加的聚合推拉来进行调解。

“A Bayesian Approach to Imitation in Reinforcement Learning”: 提出贝叶斯模仿，允许学习者顺利地汇集先前的知识，通过与环境的互动获得的数据，以及从专家智能体行为的观察中推断出的信息，而不需要与这些其他智能体进行明确的沟通或合作。

In interactive POMDPs (I-POMDPs; Gmytrasiewicz & Doshi 2005), agents model each other’s beliefs, beliefs over these beliefs, and so on, but this is often computationally intractable.

“A mathematical theory of cooperative communication”: 我们将合作通信解释为一个最佳运输的问题

“Bi-Level Actor-Critic for Multi-Agent Coordination”: 从博弈论角度将协作问题定义为具有SE均衡的博弈，并定义了寻找Stackelberg均衡的双层强化学习问题。并提出了一种新颖的双级行为体批评学习方法。然而他们假设智能体间的决策具有优先级顺序。

“Coordination Between Individual Agents in Multi-Agent Reinforcement Learning”: introduces three correlation coefficients to analyze the agent’s roles and the correlation between individual agents and proposes correlation-based communication information and reward function. Although we both consider coordination among individual agents, however, this method relies on a specific correlation coefficient and requires modification of the reward function, whereas our approach is end-to-end and does not require any other modifications.

“Learning Efficient Multi-agent Communication: An Information Bottleneck Approach”: proves that when communication capacity is restricted, the limited bandwidth constraint requires low-entropy messages and develops an Informative Multi-Agent Communication (IMAC) method to learn efficient communication protocols as well as scheduling.

“Learning Individually Inferred Communication for Multi-Agent Cooperation”: To reduce information redundancy, proposes Individually Inferred Communication (I2C) to enable agents to learn a prior for agent-agent communication via causal inference.

“Learning Multi-Agent Communication through Structured Attentive Reasoning”: Rangwala and Williams proposes a new communication architecture, the Structured Attentive Reasoning Network (SARNet), where agents extract the relevance of other agents’ information and reason over received communications and past memories before performing an action.(broadcasting)

“Learning to Communicate Implicitly by Actions”: proposes Policy Belief Learning (PBL) to model the other agent’s private information and an auxiliary reward to encourage communication by actions. 然而他们需要以有监督的方式进行训练，且需要对奖励函数进行修改。

“Learning to Ground Multi-Agent Communication with Autoencoders”: present a framework for grounding multi-agent communication through autoencoding allows agents to learn non-differentiable communication in fully decentralized settings. assumes that all agents have the same model architecture.

“Learning to Simulate Self-Driven Particles System with Coordinated Policy Optimization”: develops Coordinated Policy Optimization (CoPO), which incorporates social psychology principle to learn neural controller for Self-Driven Particles (SDP). CoPo is based on neighborhood-level coordination, in which agents from the same neighborhood are integrated into a single virtual agent, and coordination occurs only inside the agent's neighborhood, i.e., agents only communicate their actions and observations with their neighbors.

“Neurosymbolic Transformers for Multi-Agent Communication”: proposes an approach for synthesizing programmatic communication policies for decentralized control of multi-agent systems. significantly reducing the amount of communication

“Succinct and Robust Multi-Agent Communication With Temporal Message Control”: proposes Temporal Message Control (TMC) providing significantly lower communication overhead and better robustness against transmission loss.

“COMMUNICATION IN MULTI-AGENT REINFORCEMENT LEARNING: INTENTION SHARING”: proposed the Intention Sharing scheme, a new communication protocol, based on sharing intention among multiple agents. 我们的方法与前述方法的一个区别是，我们使用推断来协作，而不是通讯。

“Learning to Share and Hide Intentions using Information Regularization”: introduced information-regularizer to share or hide agent’s intention to other agents for a multi-goal MARL setting in which some agents know the goal and other agents do not know the goal. By maximizing (or minimizing) the mutual information between the goal and action, an agent knowing the goal learns to share (or hide) its intention to other agents not knowing the goal in cooperative (or competitive) tasks.

多Agent环境被建模为一个图。每个代理是一个节点，代理的局部观察的编码是节点的特征，一个节点和它的每个邻居之间有一条边。

Graph-Based Coordination Strategy for Multi-Agent Reinforcement Learning：引入一个图生成器和基于图的协调策略，以动态地表示基本的决策依赖结构。

Deep Coordination Graphs：DCG通过将所有代理人的联合价值函数按照协调图分解为代理人对之间的报酬，在代表能力和概括性之间进行了灵活的权衡。

Context-Aware Sparse Deep Coordination Graphs：然而DCG专注于预先定义的静态和密集的拓扑结构。研究如何学习动态稀疏协调图，使用成对报酬函数的方差作为指标来选择边缘。

GRAPH CONVOLUTIONAL REINFORCEMENT LEARNING：DGN提出图卷积强化学习适应多代理环境的底层图的动态并捕捉代理之间的相互作用

“TRUST REGION POLICY OPTIMISATION IN MULTI-AGENT REINFORCEMENT LEARNING”: apply trust region learning to multi-agent settings by proposing the first MARL algorithm that attains theoretically-justified monotonical improvement property.

When you open the template, select “Page Layout” from the “View” menu in the menu bar (View | Page Layout), (these instructions assume Microsoft *Word*. Some versions may have  **Fig. 1.** This is a sample of a figure caption.

alternate ways to access the same functionalities noted here). Then, type over sections of the template or cut and paste from another document and use markup styles. The pull-down style menu is in the Formatting Toolbar at the top of your *Word* window (e.g., the style at this point in the document is “Text”). Highlight a section that you want to designate with a certain style, and then select the appropriate name on the style menu. The style will adjust your fonts and line spacing. Do not change the font sizes or line spacing to squeeze more text into a limited number of pages.Use *italics* for emphasis; do not underline.

IEEE will do the final formatting of your article. If your article is intended for a conference, please observe the conference page limits.

This is intended as an authoring template, not a final production template. It is not intended to match the final published format. Differences in final formatting are likely in the final IEEE files. Page count in the template is an estimate. Do not adjust line and character spacing to fit your paper to a specific length.

## A. Abbreviations and Acronyms

Define abbreviations and acronyms the first time they are used in the text, even after they have already been defined in the abstract. Abbreviations such as IEEE, SI, ac, and dc do not have to be defined. Abbreviations that incorporate periods should not have spaces: write “C.N.R.S.,” not “C. N. R. S.” Do not use abbreviations in the title unless they are unavoidable (for example, “IEEE” in the title of this article).

# III. Preliminaries

Use either the Microsoft Equation Editor or the MathType plugin, which can be obtained from <https://store.wiris.com/en/products/mathtype/download>. For help with formatting and placing equations, refer to the *IEEE Editing Math Guide* at <http://journals.ieeeauthorcenter.ieee.org/wp-content/uploads/sites/7/Editing-Mathematics.pdf> and the *IEEE MathType Tutorial for Microsoft Word Users* at <http://journals.ieeeauthorcenter.ieee.org/wp-content/uploads/sites/7/IEEE-Math-Typesetting-Guide-for-MS-Word-Users.pdf>.

TABLE I

This is a Sample of a Table Title



## A. Equations

Number equations consecutively with equation numbers in parentheses flush with the right margin of the column, as in (1). First use the equation editor to create the equation. Then

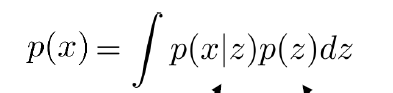
select the “Equation” markup style. Press the tab key and write the equation number in parentheses. To make your equations more compact, you may use the solidus ( / ), the exp function, or appropriate exponents. Use parentheses to avoid ambiguities in denominators. Punctuate equations when they are part of a sentence, as in

*Bp* + *H*2 = 40. (1)

Be sure that the symbols in your equation have been defined before the equation appears or immediately following. Italicize symbols (*T* might refer to temperature, but T is the unit tesla). When referring to an equation or formula, use simply “(1),” not “Eq. (1)” or “equation (1),” except at the beginning of a sentence: “Equation (1) is ... .”

# IV. MULTI-AGENT Coordination LEARNING Via inference

## A. Generative Intention Network

在部分可观测环境中，每个智能体只能通过自己的观察进行行动，无法感知全局状态。这里，我们假设在多智能体稳定协作的情况下，将其他智能体的意图与当前观测结合，可以重建或部分重建全局状态。因此，在协作稳定情况下的状态可表示为：

人类合作者具有社会感知方面的能力，被定义为根据基本行为信号解码另一个人的心理状态的能力，由于其反射性和高效的性质，在进化上是适应性的。

当人们理解他人的行为时，还有一种机制在很大程度上依赖于感知者的自我认知：为了理解他人的行动，感知者必须首先观察该行动，然后形成对该行动的心理模仿。在人类中，镜像神经元网络允许在观察和模仿的行动之间进行比较。

因此，根据以上理论，我们提出了一个有条件的深度生成模型来建模人类的社会感知能力，并为每个代理人编码潜伏代码来代表代理的意图。

在每个场景中，我们有N个跨T步的代理。用X 属于 R N\*T表示这个场景中的所有轨迹数据，xti表示第i个代理人在第t步的位置。给定Tobs T为历史帧的数量，我们有观察XP = X1:Tobs，任务是根据观察结果预测XF = X(Tobs+1):T。

我们的动机根据过去的动作轨迹进行意图建模。因此，我们用条件生成模型对数据进行建模，潜变量zI描述代理人意图。这个模型可以通过最大化证据下限（ELBO，[35]）来训练，ELBO通常被用作难以解决的对数似然的替代物。在训练过程中，当收集到一整幕的动作轨迹后，我们将数据分为过去和未来部分，我们使用给定XP和XF的编码器推断潜势，并用SGD优化ELBO。在预测过程中，我们不需要编码器，而是使用给定XP的生成模型来建模意图。我们的模型，GIN，如图1所示。我们在下面的小节中描述细节。

* 1. **Encoder**  
     编码器将基本行为信号解码另一个人的心理状态。

编码器计算出一个近似的后验q(zjXP;XF)，样本z = [zI 以XP和XF为条件。

人类具有时间整合的能力，即构建和整合一段时间内信息的过程和能力，使之成为一个连贯的整体，从而能够理解和预测随着时间推移发生的事件。因此，我们沿时间维度串联XP和XF，并使用递归神经网络（RNN）来计算每个代理的全长轨迹的特征.并使用层归一化进行特征正则化

假设z遵循多变量高斯分布N(; I)，利用重参数化技巧[31, 16]，我们对N(0; I)进行采样，得到z = + ，其中和是由多层感知器（MLP）预测的。

* 1. **Prior**  
     先验p(zjXP)表征了仅给定XP的z的条件分布。在我们的实现中，先验与编码器共享模型权重。在这种情况下，编码器和先验只是在公式1中的RNN的输入数据方面有所不同。通过权重共享，同一个RNN可以看到不同长度的输入，而损失中的KL-分歧项会强制编码器和解码器从输入中提取类似的信息。因此，RNN被鼓励学习从XP和[XP;XF]中编码相同的信息。此外，权重共享减少了其内存成本。
  2. **Decoder**  
     形成对该行动的心理模仿，并在观察和模仿的行动之间进行比较。对互动伙伴的预测和实际行动进行比较，可以帮助个人调整自己的行动，以适应互动伙伴的行动。

解码器p(XF jzA; zG;XP )产生以随机变量z和过去轨迹XP为条件的未来轨迹。按照[18]，我们假设潜伏的z是对距离历史的充分总结，并将似然定义为p(Xt+1jz;X1:t) = p(Xt+1jz;Xt)。因此，给定z和Xt，解码器可以预测^X t+1。对于t > Tobs，解码器的输入是它自己的预测^X t。

在这里，我们采用预测下一个观测值与当前观测值之间差异的动力学函数，即oi t+1 oi t，而不是（Nagabandi等人（2018））提出的下一个观测值oi t+1，以减少学习早期阶段的模型偏差。

## B. Casual Inference

在此有理由提出这样的问题。如果参与者已经在跟踪和预测他们自己和互动伙伴的意图，为什么还需要一个推断他人意图的因果关系，而不是直接将所有意图整合？在我们看来，简单的意图整合会导致信息冗余，甚至可能影响学习过程。而因果推断则将使代理能够捕获高阶关系，甚至形成有共同的目标和意图的动态即时团队。

现在人们普遍认为(Interactive brains, social minds: Neural and physiological mechanisms of interpersonal action coordination)，大脑间的同步化是人际行动协调和社会互动行为的重要和必然的机制。虽然社会知觉涉及感知和解码他人的外部行为信号并推断他们的潜在意图，但知觉者的自我作用相对来说是沉默的。然而，当人们理解他人的行为时，还有一种机制在很大程度上依赖于感知者的自我：感知者可能试图理解其他智能体的意图对感知着智能体的策略的因果效应。

与协作相关的行动理解需要感知者超越单纯的解码，努力将自己的行动与观察到的行动成功匹配。

一个代理人对另一个代理人的影响是由该代理人的意图对另一个人的政策的因果效应来体现的。对于任何能够引起对方政策剧烈变化的代理人，该代理人被认为是相关和有影响力的。

直观地说，一个代理人更有可能与那些可能对其战略施加更多影响的人进行协作，希望获得关于他们倾向于如何行动以及如何作出合作反应的线索。因此，其他代理人的因果效应可以被看作是以其他代理人的意图为条件进行决策的必要性。

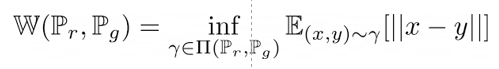
这里，我们通过以不同意图为条件生成的策略分布来测量和量化代理人之间的因果效应来确定代理人-代理人的协：

\documentclass{article}
\usepackage{amsmath}
\pagestyle{empty}
\begin{document}

$ KL\left [ \pi \left ( a\mid o,[z_{intention}^m, z_{intention}^n, \cdots z_{intention}^k] \right )\parallel \pi \left ( a\mid o,[z_{intention}^n, \cdots z_{intention}^k] \right ) \right ]  $


\end{document}

Kullback-Leibler（KL）散度被用来衡量这两个条件概率分布之间的差异。Ij i的大小表明，如果考虑到代理人j的意图，代理人i会对其政策做出多大的调整，也表明代理人j的战略与代理人i的政策有多大的关联。如果Ij i>阈值δ，则将该智能体加入到协作集中，delta是一个超参数。

我们同时也提出了使用Wasserstein Distance直接比较自身意图分布与其他智能体意图分布的距离，以此作为每对代理之间的相关性。基于此，代理人之间的强、弱相关性定义如下：

代理人之间的强关联性。对于任何一对代理人i和j，如果相关系数ci;j大于阈值G，那么这两个代理人就处于彼此的强相关状态。

代理人之间的弱关联性。对于任何一对代理人i和j，如果相关系数ci;j小于阈值G，那么这两个代理人之间就处于弱相关关系。

如果为强相关关系，则加入到协作集中。

阈值G设定为0.5，实验中分析了不同阈值G的性能

每个智能体根据部分其他智能体的意图进行决策，产生的新的决策被智能体感知后，意图也会随之更新，从而进一步更新策略，这样便形成了无限嵌套的信念。

## C. Long Short Term Intention Clip

我们工作中的其中一个主要技巧是使用裁剪的意图重要性比率--这试图限制意图在迭代之间的急剧变化。剪切的强度由超参数控制：大的允许更大的意图变化。

我们认为对意图进行剪裁，在一定程度上控制了由变化的多代理政策引起的非平稳性。如第5.4节所示，我们观察到，虽然较低的数值减缓了学习速度，但它们对应的是更一致的政策改进。另一方面，较高的数值会导致较大的方差和较大的性能波动。



此外，智能体的探索可能会产生不符合宏观意图的动作从而干扰意图的建模，在非合作情形下，对手可能在短时间内做出假动作（与长期意图相反）。因此，为了学习更稳定的意图，我们提出了一个短期意图来消除干扰性动作。

短期意图网络与GIN中**Prior**网络共享参数，和先验只是在公式1中的RNN的输入数据方面有所不同。具体地，先验使用整个历史动作轨迹作为输入，而短期意图网络使用长度为n的动作轨迹作为输入，长度n设定为3，实验中分析了不同n的性能。根据先验和短期意图网络输出的意图，我们比较了他们的KL散度，如果KL散度大于delta，则将n个动作进行masking，否则保留。

## D. Action Mask

在多智能体环境中，每个单元由一个独立的代理控制，该代理只对以该单元为中心的有限视域内的局部观测进行控制(如，smac),智能体不可能在每个时刻都可以观察到其他所有智能体的动作，因此在智能体观察的动作轨迹中会存在缺省值。对这些缺省值进行意图建模，无疑是毫无意义的，甚至会对策略训练造成巨大影响，我们的建议是简单地使用一个特定于代理人的常数向量，即一个带有代理人ID的零向量，作为代理人动作缺省值的输入。我们称这种技术为 "动作屏蔽"。

## E. HAPPO with Intention Ratio

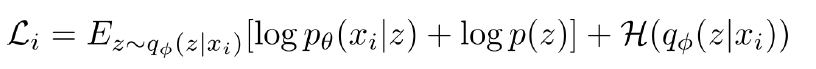
TRUST REGION POLICY OPTIMISATION IN MULTI-AGENT REINFORCEMENT LEARNING开发了异质代理近端政策优化（HAPPO）算法。与许多现有的MARL算法不同，HATRPO/HAPPO不需要代理共享参数，也不需要对联合价值函数的可分解性进行任何限制性假设。最重要的是，他们在理论上证明了HAPPO的单调性改进特性，建立了新的技术水平。

我们在HAPPO的基础上，引入了意图重要性比率，这使得每个代理人的目标都不仅考虑到所有先前代理人的更新，还考虑到意图的更新。

## F. Training

* 1. GIN

对于训练，我们从编码器中取样z = [zI]，q(zjXP ;XF)，然后优化ELBO：



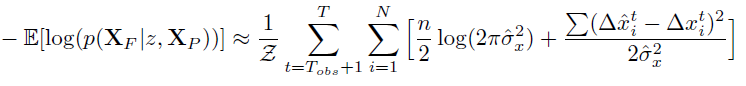
可以从另外一个角度看待ELBO：



最大化对数似然的同时，尽量缩小编码模型和先验分布的KL divergence



由于我们的解码器预测[^xti ;^x]为代理人i在步骤t，并且它遵循高斯分布。我们用样本平均数对期望值进行近似。



其中Z是归一化项，n是xti的维度。由于先验和编码器的输出是高斯的，所以第二个项可以用分析法计算。



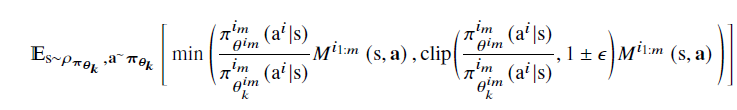
优化的目标为最大化ELBO：

此外，我们使用首次更新和延迟更新：

不准确的意图估计可能会导致糟糕的策略和Critic更新，这特别有问题，因为会产生一个反馈回路，错误地意图导致Critic产生有偏差的状态估计，从而造成策略朝着错误地方向更新，而有偏差的意图也会直接对策略改进造成影响，进而改变后续的意图更新。

此外，在训练的内循环中对意图进行优化，计算量很大。相反，我们在优化Actor-Critic的k个步骤和优化意图的一个步骤之间交替进行，同时在多个ppo-epoch中，只在首次更新意图。这样做的结果是，只要意图的变化足够慢，策略和Critic就会被维持在其最优解附近。这种策略类似于GAN的训练方式。该程序在算法1中正式提出。

* 1. HAIPPO



## G. Color Space

The term “color space” refers to the entire sum of colors that can be represented within the said medium. For our purposes, the three main color spaces are grayscale, RGB (red/green/blue), and CMYK (cyan/magenta/yellow/black). RGB is generally used with on-screen graphics, whereas CMYK is used for printing purposes.

All color figures should be generated in RGB or CMYK color space. Grayscale images should be submitted in grayscale color space. Line art may be provided in grayscale OR bitmap colorspace. Note that “bitmap colorspace” and “bitmap file format” are not the same thing. When bitmap color space is selected, .TIF/.TIFF/.PNG are the recommended file formats.

## H. Accepted Fonts Within Figures

When preparing your graphics, IEEE suggests that you use one of the following Open Type fonts: Times New Roman, Helvetica, Arial, Cambria, or Symbol. If you are supplying EPS, PS, or PDF files, all fonts must be embedded. Some fonts may only be native to your operating system; without the fonts embedded, parts of the graphic may be distorted or missing.

A safe option when finalizing your figures is to strip out the fonts before you save the files, creating “outline” type. This converts fonts to artwork which will appear uniformly on any screen.

## I. Using Labels Within Figures

1. **Figure Axis Labels**
   1. Figure axis labels are often a source of confusion. Use words rather than symbols. As an example, write the quantity “Magnetization” or “Magnetization *M*,” not just “*M*.” Put units in parentheses. Do not label axes only with units. For example, write “Magnetization (A/m)” or “Magnetization (Am−1),” not just “A/m.” Do not label axes with a ratio of quantities and units. For example, write “Temperature (K),” not “Temperature/K.”
   2. Multipliers can be especially confusing. Write “Magnetization (kA/m)” or “Magnetization (103 A/m).” Do not write “Magnetization (A/m) × 1000” because the reader would not know whether the top axis label means 16000 A/m or 0.016 A/m. Figure labels should be legible, approximately 8- to 10-point type.
2. **Subfigure Labels in Multipart Figures and Tables**

Multipart figures should be combined and labeled before final submission. Labels should appear centered below each subfigure in 8-point Times New Roman font in the format of (a) (b) (c).

## J. Referencing a Figure or Table Within Your Article

When referencing your figures and tables within your article, use the abbreviation “Fig.” even at the beginning of a sentence. Do not abbreviate “Table.” Tables should be numbered with Roman numerals.

## K. Submitting Your Graphics

Because IEEE will do the final formatting of your article, all figures, figure captions, and tables can be placed at the end of your article. However, if you do place your figures within the article, they should be placed at the top of the page, closest to the first mention in the text. Figures should be submitted as individual files, separate from the manuscript in one of the file formats listed above. Place figure captions below the figures; place table headings above the tables. Do not include captions as part of the figures, or put them in “text boxes” linked to the figures. Also, do not place borders around the outside of your figures.

## L. Color Processing / Printing in IEEE Transactions, Journals, and Letters

All IEEE Transactions, Journals, and Letters allow an author to publish color figures on IEEE *Xplore* at no charge, and automatically convert them to grayscale for print versions. In most journals, figures and tables may alternatively be printed in color if an author chooses to do so. Please note that this service comes at an extra expense to the author. If you intend to have print color graphics, you will have the opportunity to indicate this in the Author Gateway and will be contacted by PubOps to confirm the charges.

# V. EXPERIMENTS AND RESULTS

## 我们考虑两个最常见的基准--StarCraftII多Agent挑战赛（SMAC）（Samvelyan等人，2019）和多Agent Mujoco（de Witt等人，2020b）--用于评估MARL算法。所有的超参数设置和实现细节都可以在附录中找到。

星际争霸II多Agent挑战（SMAC）。SMAC包含一组《星际争霸》的地图，其中

一组盟友单位旨在击败对手的团队。IPPO（de Witt等人，2020a）和MAPPO

(Yu et al., 2021)被认为在这个基准上取得了最高的成绩。通过采用参数

共享，这些方法在大多数地图上实现了100%的获胜率，甚至包括有异质代理的地图。

有异质性代理的地图。因此，我们假设，不一定需要非参数共享，共享政策就足以解决

需要，共享政策足以解决SMAC任务。我们在两张硬地图和一张超硬地图上测试了我们的方法。

图2的结果证实，SMAC的难度并不足以展示HATRPO的能力。

与参数共享方法相比，SMAC的难度不足以显示HATRPO/HAPPO的能力。

多Agent MuJoCo。与SMAC相比，我们认为Mujoco环境为我们的方法提供了一个更为

为我们的方法提供了更合适的测试案例。MuJoCo任务要求机器人学习一种最佳的运动方式。

多Agent MuJoCo将机器人的每个部分都建模为一个独立的代理，例如，蜘蛛的腿或手臂。

例如，蜘蛛的腿或游泳者的手臂。随着身体各部分的种类越来越多，建立模型

异质性的政策变得很有必要。图3表明，在所有情况下，HATRPO和

HAPPO享有比参数共享方法更优越的性能。IPPO和MAPPO。

并且在奖励值和方差方面都优于非参数共享的MADDPG（Lowe等人，2017b）。

奖励值和方差。还值得注意的是，HATRPO和它的竞争对手之间的性能差距，随

其竞争对手之间的性能差距随着代理数量的增加而扩大。同时，我们可以看到，HATRPO

在几乎所有的任务中都优于HAPPO；我们认为这是因为HATRPO的硬KL约束。

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1. E. P. Wigner, “Theory of traveling-wave optical laser,” *Phys. Rev*., vol. 134, pp. A635–A646, Dec. 1965.
2. P. Kopyt *et al., “*Electric properties of graphene-based conductive layers from DC up to terahertz range,” *IEEE THz Sci. Technol.,* to be published, doi: 10.1109/TTHZ.2016.2544142. *(Note: If a paper is still to be published, but is available in early access, please follow ref [5]).)*
3. R. Fardel, M. Nagel, F. Nuesch, T. Lippert, and A. Wokaun, “Fabrication of organic light emitting diode pixels by laser-assisted forward transfer,” *Appl. Phys. Lett.*, vol. 91, no. 6, Aug. 2007, Art. no. 061103.
4. D. Comite and N. Pierdicca, "Decorrelation of the near-specular land scattering in bistatic radar systems," *IEEE Trans. Geosci. Remote Sens.*, early access, doi: 10.1109/TGRS.2021.3072864. (*Note: This format is used for articles in early access. The doi must be included.)*
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