Effects of Network Structure on Cooperative Coordination

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Abstract

Coordination and cooperation are often required for satisfactory solutions to social problems. Two factors that affect the ability of groups to solve such problems are the information actors have about other's actions and the costs of taking an action. We utilize a network approach to model the structure of communication between actors and test experimentally how the communication structure affects coordination when actions are costly. We find that the addition of costs causes a significant increase in the amount of time it takes for coordination to occur and that costs cause players to change the strategy they use to resolve the coordination dilemma. Furthermore, the effect of increased costs is not constant across the various network structures. Both more edges (communication) and higher degree variance (leadership) can attenuate the effect of costs to take an action. These results suggest that when designing or studying institutions we will want to account for the communication structures created by the institutions and how this structure may affect coordination and cooperation.

Introduction

Coordination and cooperation are important aspects of many interesting social, political, and economic situations. In general, coordination and cooperation are required in situations where a single solution must be adopted from a set of multiple solutions (which requires coordination) and not all individuals can get their most preferred outcome (which requires cooperation). These settings include a great many allocation tasks, policy solutions, adoptions of new technologies, and social dilemmas, because some players will have to pay a cost to change their action (which creates the need for cooperation) and there exist multiple possible solutions to such problems (which creates the need for coordination).

Scholars, however, have tended to isolate coordination and cooperation from each other in their studies and focused on only one or the other problem (Axelrod 1984). This has occurred despite a long-standing recognition that "Because every ongoing social process possesses a multiplicity of equilibria, opportunities to cooperate and the concomitant problem of coordinating to one of these equilibria are omnipresent (Niou and Ordeshook 1994, p. 210)." Others have also recognized that "Multiple equilibria are a major obstacle to cooperation that was downplayed by the early emphasis on 2X2 games." (Koremenos et al. (2001). Our approach in this paper is to focus on situations in which actors must solve a task that requires both cooperation and coordination.

To study coordination and cooperation among multiple decentralized actors we utilize networks to model the communication between actors and the constraints that they face. Our approach to behavior is consistent with idea that graph theory and game theory are "theories of structure and behavior respectively: Graph theory is the study of network structure, while game theory provides models of individual behavior in settings where outcomes depend on the behavior of others (Easley and Kleinberg 2010)." We turn now to a discussion of how networks can be used to model the structure of communication.

Networks and Communication

One of the key factors that determines the success or failure of decentralized coordination is communication between actors so that they can each learn what the others have done. Much of the prior work has utilized one of the following three models of communication for settings in which there are more than two actors:

1. Simultaneous decision making (Schelling's idea of a focal point)
2. Statement are heard by everyone or anyone who decides to listen (Wilson and Rhodes 1997; Boudreau, McCubbins, Rodriguez and Weller 2010)
3. People receiving information a signal about others' beliefs or actions (DeGroot 1974)

These three models have been very useful in identifying the effect of information on decentralized coordination.

Our work in this paper takes a different approach to modeling information in a multi-actor setting. Instead of adopting one of these three models of communication, we model the communication environment using a network (prior work in this vein include Calvo-Armegol 2001; Choi et al. 2008).

In the network model a node is an individual/actor and a link represents communication or information between them. Using a network approach we can model any pattern of communication among nodes in a network. In our model a link is undirected and implies symmetric information (both nodes see each other) along that link, but in theory links could be directed (i.e. information would be asymmetric) so that only one node could observe the other node, which would increase the number of possible communication structures. It is clear that even with only a small number of nodes and bilateral, undirected links there are many possible communication structures.

Using a network approach provides us with significant flexibility in the type of communication structures we can study. In Figure 1 we display the six different networks we utilize in this paper all of which involve 16 nodes and varying numbers of edges and patterns of connections among the edges

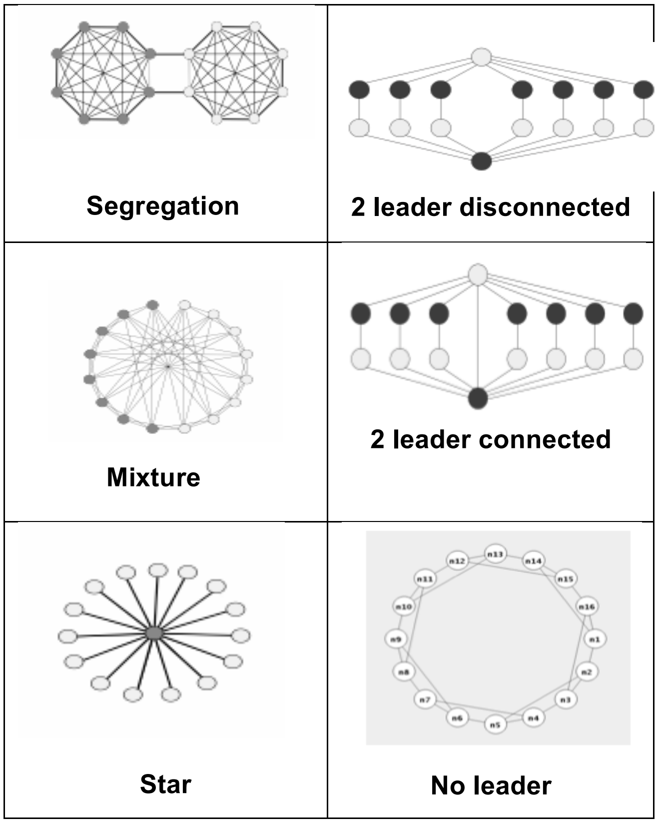

Figure 1: Networks used in experiments

Moving From Coordination to Cooperation

Coordination is required in any situation where there are multiple possible equilibrium outcomes and players must take mutually consistent strategies. In addition, in many coordination games actors must pay a cost to take an action that could facilitate coordination. For instance, to reduce worldwide CO2 emissions countries must all agree to adopt domestic policies (at a cost) that are coordinated with the policies of other countries. This requires both that countries know how to coordinate (which policy to adopt) and be willing to pay the cost of taking the necessary action. In general, actions involve costs either in the sense that it is costly to adopt a new technology/policy or because there is an opportunity cost in taking an action. Either way, real-world actions are not costless, and therefore it is important to understand how costs affect group coordination.

In essence, adding costs to a basic coordination game creates a cooperative coordination game that blends elements of cooperation and coordination. To understand how the addition of costs changes a coordination game consider two different scenarios. First, consider the scenario in which no player has yet taken an action. If taking an action is costly, then players will only have an incentive to pay the cost to take an initial action if they believe that the group can solve the coordination problem (which requires all players to pay at least an initial cost to take an action). If they believe the group cannot reach a coordinated solution, then players will not pay the cost to make an initial choice. If the initial costly choice leads to coordination, then no one has an incentive to deviate. However, if the initial costly choice(s) do not lead to coordination, then successful coordination will require that at least some players pay an additional cost to take another action. In this scenario each player would prefer if the other player(s) paid the cost to change color and facilitated group coordination. This moves the game from one of pure coordination to one that involves both coordination and cooperation. The most important point is that the simple addition of costs to the game creates conflict in the game, thereby infusing the coordination game with an element of cooperation as well and making the game a rich setting to study coordination and cooperation.

Before proceeding, we point out that we do not utilize the standard prisoner's dilemma as a way to study cooperation, because in a game with a dominant strategy (such as the prisoner's dilemma). Recent work has found that network structure had little effect on behavior in a classic public goods game (Suri and Watts (2011). In a public goods game (often modeled as a prisoner's dilemma) players have a dominant strategy not to contribute to the public good and should play that strategy regardless of the connections between players, implying that networks are unlikely to affect behavior in this type of cooperation game. We are interested in situations in which there is an element of coordination among individuals, which is why we utilize a basic coordination game with costs. In this paper we focus on how information structure and the costs of taking an action affect the likelihood a group can solve a coordination problem in which individuals do not have a dominant strategy.

Experimental Design

We turn now to a description of the experiments we use to study how networks affect cooperative coordination. These experiments model a network explicitly by treating individuals as nodes and a link between two nodes allows them to communicate during the experiment. The task facing subjects in these experiments is deceptively simple – they must choose a color for their node that makes them the same as all of their neighbors – this is the constraint the faces the actors. If every node in the network successfully solves their local problem, then the entire group earns a payoff. If nodes are not connected then they do not observe each other, and subjects do not have any information about the global properties of the network other than the number of nodes.

Subjects were recruited from large public and private universities via email and flyers throughout campus. Interested subjects were then emailed to sign up for an experimental session and on the day of the experiment we chose 16 people who showed up to participate. The 16 subjects were escorted to a computer lab where they sat at computer terminal with partitions between them to ensure they could not observe each other's behavior. We read aloud instructions to all the subjects to describe the game and ensure they had common knowledge of the game's rules. We also quizzed the subjects throughout the session to ensure they understood how they earned money and the information available to them during the task. Subjects were always given two colors to choose from during a trial, but the colors varied for each trial and the colors differed for each subject to make the development of a focal color difficult. If the trial was solved successfully each subject earned $1, and if actions were costly then the costs are subtracted from the earnings for that session. If coordination was unsuccessful, then subjects lost money for each move they made in that trial. Subjects had three minutes to successfully solve the coordination task, and once the session began subjects could make choices at any time and choices were immediately visible to others (if they share an edge). This makes the game dynamic and asynchronous, not a stage or single-shot game, which is the type of game most of our knowledge of coordination comes from. During the actual experiment subjects know the following information, which is displayed on the screen in front of them.

Number and Degree of Neighbors: Subjects can observe the other nodes to which they are connected and the color of those nodes at all times. They also know how many connections each neighbor has, which is displayed in the center of the node.

Time Elapsed: A bar displays how long until the session expires.

Cost to move: We implement a cost for each choice a player makes, including his first choice and the cost per move is displayed on the screen. We use costs of 0, $0.05, $0.10, $0.20, $0.30, $0.50.

In addition, subjects can determine if the trial was solved successfully because if so the trial will end before the time elapsed bar runs out. They do not know the structure of the entire network at any point during these experiments. We utilize both within and between subject designs. During each experimental session (consisting of 30 to 50 trials) subjects play the coordination game with a variety of different costs to take an action. This allows us to observe, within a single group, how changes in costs affect coordination, but we also pool results from various experiments.

Expected Effects of Networks

In this section we outline our expectations for how the communication structure (modeled as a network) will influence group and individual behavior in a coordination game with costs. It is worth noting that we do not focus on individuals' equilibrium strategies. As others have noted in coordination games that are dynamic and feature communication there are typically so many possible equilibrium strategies that it is not useful to focus on them (Choi and Lee 2009; Choi et al. 2008; Echenique and Yariv 2011). In fact, it is not clear that we could even identify if a player is playing an equilibrium strategy given the asynchronous, dynamic nature of the game.

Although we do not make predictions about individual equilibrium strategies, we can make predictions about the effect of network structure and costs on the likelihood of coordination and the time for it to be achieved. The predictions are based on prior research about how communication, networks and costs affect consensus (see Kearns, Suri and Montfort 2006; McCubbins, Paturi and Weller 2009; Boudreau, McCubbins, Rodriguez and Weller 2010; Choi and Lee 2010). Additionally, we focus on group outcomes rather than individual predictions because our experiments are designed for group analysis and cannot be used to make valid causal inferences about individuals.

Based on prior research about coordination, cooperation and communicate we present the follow predictions:

1. The addition of a cost to take an action will increase time to solve the coordination problem.

   a. The element of cooperation induced by adding costs to the game should make players consider their choices more carefully and be less willing to change colors, both of which should increase the time to coordination.

2. Costs increase the time to the first move because players are waiting to see if someone else will incur the initial cost and attempt to lead the group to a solution.
   a. The action by the first player is a costly signal that at least some person (or people) in the group believes coordination is possible. If this affects the beliefs of people in the network, then it may lead to coordination overall. This is similar to Choi et al.'s (2008) notion of strategic delay in a public goods game.
3. Costs increase efficiency (i.e. players take fewer actions to achieve coordination).
   a. Because each move reduces a subject's earnings, they will be more careful not to make wasteful moves
4. Networks with more edges will be solved faster than networks with fewer edges.
   a. Edges enable communication and therefore we expect that more edges will improve coordination (Kearns et al. 2006; McCubbins et al. 2009; see Enemark et al. 2011 for a more nuanced version of this claim).
5. Networks with higher degree variance will be solved more quickly (variance is a network-level statistic that is computed by finding the variance in nodal degree).
   a. Nodes with a large number of edges can act as a leader in the coordination game, which may improve group performance (Calvert 1992; Wilson and Rhodes 1997).

Each of these predictions is drawn from the existing work on decentralized, networked coordination and the idea that coordination with costs creates an element of cooperation in which players will try to determine if coordination is possible before paying to take an initial action and will also try to minimize the total number of moves they make.

Costs Change Games and Behavior

We turn now to the results of our experiment. We have a total of 514 observations at the group level. The most basic result is to compare the average time to completion for free choices to costly choices. The addition of costs makes the task take significantly longer ($p<0.001$) when we examine the effect across all networks and cost structures; additionally, coordination is achieved successfully less often when it is costly to take an action. This comports with our primary prediction. However, in Figure 2 we display the average time to completion broken out by the cost for action, and surprisingly it seems that the relationship between costs and time to coordinate is non-. The results suggest that costs initially significantly slow down coordination but as costs continue to increase coordination occurs more quickly, although never as quickly as when costless. To determine if this was related to subjects learning how to complete the task (i.e. developing strategies for the task), we have varied the order of the treatments in the experiments (sometimes starting with low costs and sometimes with high costs) and we have also completed multiple blocks of the same cost within an experimental group. We have not been able to identify any effects of the order of the treatments in the research so far.

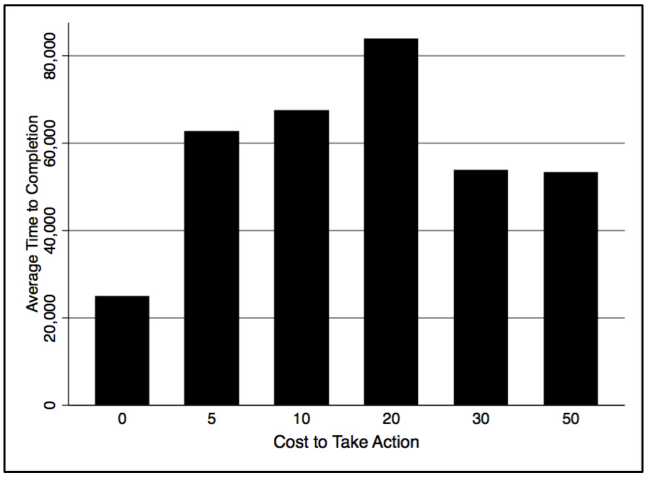

Figure 2: Non-monotonic effect of costs on coordination

This non-monotonic effect was unanticipated, and it suggests that as the cooperation element of the game becomes more significant players change their behavior. Earlier we discussed that the first choice players must make is if they are going to pay an initial cost to adopt a color, and they will only make this move if they believe the probability of solving the game is sufficiently high that it is cost-effective to choose an initial color. To that end, we investigate the time it takes for the first choice to be made in the game under each different cost condition. As the cost to make a choice increases it becomes more important to ensure that if one makes a choice coordination will result, and will occur with as few moves as possible because each move is costly. Accordingly, in Figure 3 we examine the time between the beginning of an experimental trial and the first time someone selects a color. Clearly as the cost to take an action increases subjects wait longer before making the first move. This is consistent with the idea that costs make the initial decision more important and subjects want to wait to let someone else make the initial move.

One way to interpret this result is that players are attempting to turn the game in to one of sequential action rather than an asynchronous game. Prior research finds that sequential cooperation games are more easily solved, so this change in approach may help to explain the success in solution even as the costs increase. In fact, the results we

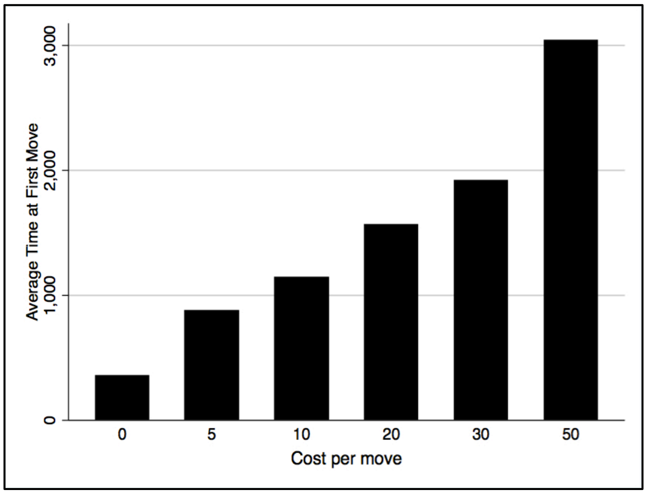

Figure 3: Costs to move lead to a delay in first move

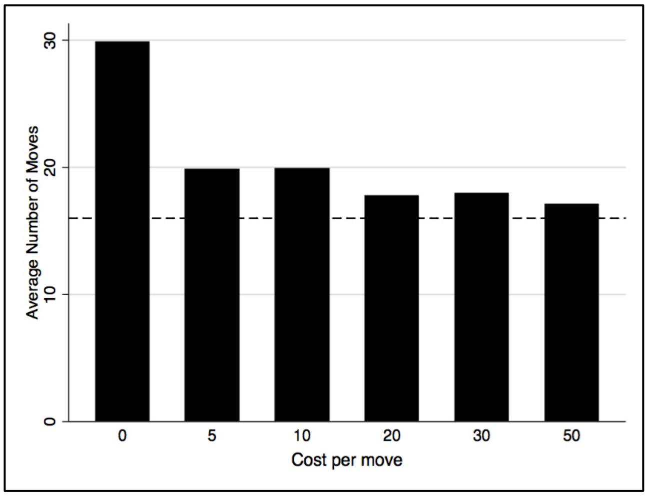

Figure 4: Costs lead to more efficient coordination

find are generally consistent with Potters, Sefton and Vesterlund (2005) who find that in a public goods game where subjects have different information about the good being provided they endogenously choose a sequential contribution mechanism and it is associated with larger donations to the public good game.

We also note in Figure 4 that the introduction of costs causes a significant decline in the number of moves per player, which again is consistent with the idea that players have an incentive to minimize the number of times they change colors. The dashed line represents 16 total moves, which is the minimum required for successful coordination. When taking an action is free groups averaged about 30 moves per trial, but when action was costly groups averaged just over 18 moves per trial, a difference that is significant at the 0.001 level. In only 1 of the 84 free action trials subjects took the minimum number of actions (16), but when actions were costly subjects took the minimum number of actions in 142 of the 323 total trials and in 137 of the 265 successful trials subjects took the minimum number of actions. In the 54 costly action experiments that were not solved successfully subjects made an average of 19.7 decisions and in the 238 that were solved subjects took an average of 17.9 actions (p=0.08). This suggests that very few subjects are willing to pay costs multiple times for coordination to occur, which means that when coordination is costly it is mostly likely to be successful with only a small number of choices per player. If subjects fail to achieve coordination after an initial move it may be that they believe coordination is unlikely to occur, and therefore may not be willing to pay the additional cost to move again. Overall, the costly treatments cause an increase in the time to move and a decrease in the total number of moves, which as the cost increases seem to be related to more rapid coordination.

We have not been able to observe any learning or order effects within the experiments, which suggests that increases in costs causes subjects to adopt a different strategy to solve the game than they use in the free and low cost trials. In addition, we do not find that subjects must "practice" at the higher costs to adopt this strategy, which we take as evidence that they are all tapping in to a strategy for solving problems like this that they possess prior to arriving at our lab.

We turn now to a discussion of how the different network structures affect the time to coordinate. We expect that both greater numbers of connections and higher degree variance will make coordination occur more quickly. To examine this we need to look at networks where other structural characteristics are held as constant as possible. Therefore, to examine the effect of number of edges we focus on the mixture and no leader networks, which both feature no variance in degree. The mixture network has 56 edges and the no leader network has only 24. Consistent with our expectation about the effect of more edges, the mixture network is completed significantly more quickly (p<.001 in a two-tailed t-test) than the no leader network when we examine all the network trials when taking an action is costly, as shown in Figure 5.

Our other expectation is that higher degree variance will facilitate coordination because actors with high degree have more information about the network and can lead the group to a solution (Calvert 1992; Wilson and Rohdes 1997). One might also argue that high degree actors are a focal point (Schelling 1960) to which others might defer. To investigate the effects of degree variance on coordination we would prefer to have networks that are identical in all parameters except for degree variance. For now we have to compare networks that differ slightly in their number of edges, but rather significantly in their degree variance. The most obvious comparisons in that regard are the star and no leader networks. The no-leader network has zero degree variance, but more total edges than the star network. Therefore, if number of edges is

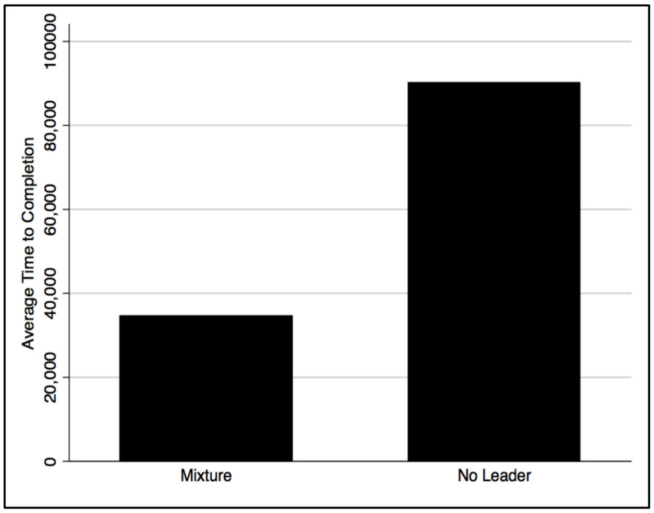

Figure 5: More edges can improve coordination

more significant than degree variance, then we would expect the no-leader network to be completed more quickly. Figure 6 shows that the star network is completed more quickly than the no-leader network on average ($p<0.001$, two-tailed t-test), which suggests that degree variance is an important factor in time to coordinate. However, the networks differ in other parameters, too, so we cannot identify degree variance as the sole cause of the different times for coordination.

One limitation of these results is that it is very difficult to modify the network structure without changing multiple structural parameters in the network, i.e. a change in number of edges changes that factor and may also change degree variance, clustering, distance or other (perhaps unmeasured) characteristics that affect coordination. As such, in these results we are hesitant to identify a single structural parameter as the mechanism that leads to different coordination behavior between networks.

An important note about these experiments is that subjects' behavior changes very quickly with the introduction of costs. We do not have to train subjects how to play the game and subjects do not have to learn a new strategy during the experiment. This is a subtle point but it is important because it suggests that subjects have pre-existing strategies for playing games such as the ones we ask them to complete. This gives us greater confidence in the ecological validity of the experimental and the effects we identify.

Discussion

We demonstrate in this paper that network structure can have significant effects on collective action when the underlying problem involves elements of both coordination and cooperation. Given that many (most?) social situations involve elements of both of these problems it seems clear that network structure is likely to affect whether groups can resolve such problems. The findings are consistent with the idea that both communication and leadership can be important in helping groups to solve collective action problems.

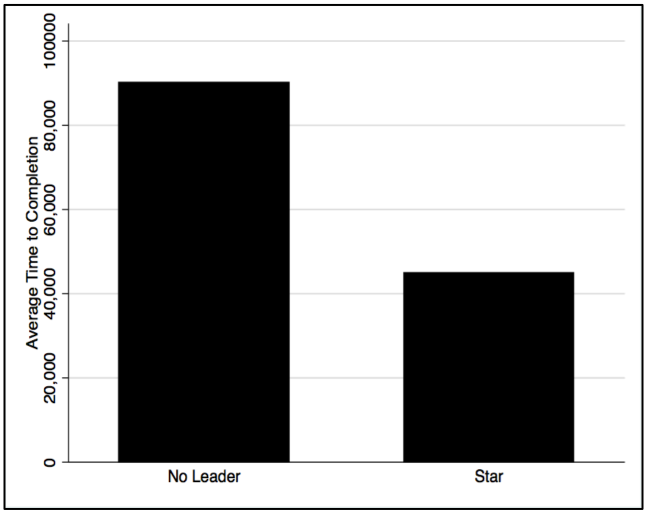

Figure 6: Highly connected nodes facilitate coordination

Theory and experimental results suggest that both the number of edges and the presence of highly-connected nodes can facilitate solutions in this type of problem. In our experiments subjects have some basic information about the number of connections that another node has, which may be crucial for highly-connected nodes to improve cooperative coordination, but as of now we lack the data to know what information is necessary for the structure of the network to affect group behavior.

Our results in this paper show clearly that the structure of communication can affect decentralized tasks that feature elements of coordination and cooperation.

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