Interactive Agential Dynamics

Abstract:

The study of active matter systems demonstrates the usefulness of considering how interactions might co-constitute agential dynamics. Active matter systems are comprised of self-propelled independent entities which, en masse, take part in complex and interesting collective group behaviors at a far-from-equilibrium state (Menon, 2010, Takatori and Brady 2015). These systems are modelled using very simple rules (Vicsek at al. 1995), which reveal the interactive nature of the collective behaviors seen from humble to highly complex entities. I argue that the study of active matter systems demonstrates the utility of using a minimal approach to agency in studying interactive agential dynamics in more complex systems. I give examples of how this can be useful for thinking about agency in more complex systems by treating interactions as an ontological category (Longino 2021). The examples of coordination dynamics (Kelso 2001) and participatory sense-making (De Jaegher and Di Paolo 2007) are provided to show how understanding agency requires us to look beyond the individuals to the interactive agential dynamics that can guide, scaffold, or constrain their activity.

1. Introduction

From nanoparticles to penguins, interactions lead to interesting patterns of behavior throughout the natural world. Here, I examine the interactive dynamics within active matter systems to motivate consideration of interactive regularities in looking at agency. Active matter systems are comprised of self-propelled independent entities which, en masse, take part in complex and interesting collective behaviors at a far-from-equilibrium state (Menon 2010, Takatori and Brady 2015). The fundamental force driving active matter systems derives from expenditure of energy at the level of the individual units involved, whether these are living entities (starlings, fish, insects) or non-living objects (Janus particles, microtubules). Collectively, these individual entities, ranging from sub-cellular molecular structures to organisms with complex individual repertoires of behaviour, generate interesting macro-scale patterns of activity such as swarming, flocking, and schooling, responding to environmental features, such as external gradients, and navigating environmental perturbances. Their collective behaviors can often be modelled using very simple rules, regardless of whether the individuals involved are highly complex or simple entities.

Following Helen Longino (2019), I consider how methodological individualism shapes our questions about behavior, with a focus on agency. Using examples from active matter, I argue that in the study of agency, we ought to pay more attention to the agency-shaping properties of interactions. That is, to understand agential behaviors, it is important to look beyond individual agents to the interactive agential dynamics in which they are enmeshed. I take interactive agential dynamics to be mutually dependent, multi-agent processes that scaffold or constrain agency, in which an individual agent directly participates, but does not (wholly) self-produce. These interactive processes are sustained by individuals in a group but cannot be explanatorily reduced to the activities of those individuals nor attributed to any emergent properties of the group as a whole. The agents involved directly participate in the activities that sustain the group behavior, and the interactive behavior is necessary (though not sufficient) for explaining the activity of the individuals. I will show that getting the most mileage out of the explanatory power of interactive agential dynamics comes from understanding individual agency in the broadest possible sense: an individual who is the causal source of asymmetry in differentiating itself from and acting towards its environment. While active matter systems are only one class of collective or complex system in which we find interactive agential dynamics, these systems aptly demonstrate the necessity of paying more attention to the kinds of interactive dynamics shaping individual agency at a number of scales. Getting a firmer grasp on these dynamics takes treating interaction as a viable ontological category.

In the philosophy of cognitive science, there is an increasing focus on understanding the role that interactive dynamics play in shaping or even constituting cognition. For cognitive agents, collective activities are often referred to as providing scaffolding or constraints on individual cognitive processes. Collective dynamics are explored in a number of scientific research programs: coordination dynamics (Kelso 2021, Kelso *et al.* 2014) and collective behavior (Handegard *et al.* 2012, Couzin 2018), for example. Several models have been created to examine and explain the interactions that lead to collective patterns of activity, such as the Haken-Kelso-Bunz model of synchronization (Haken *et al.* 1985) in human dyadic coordination. All of these research programs study interactive dynamics between at least two agents, where explanations of coordination are not thought to be reducible to the agents themselves nor fully captured by examining collective properties. My proposal is to expand the scope of this research in the theoretical cognitive sciences beyond human dyadic interactions, and as a basis for understanding processes beyond social cognition.

The paper will proceed as follows. Section 2 provides some background on active matter systems and the study of collective behavior. In section 3, I examine some ways of taking up interaction as a non-reducible object of research. Section 4 argues that a minimalist approach to agency is most useful for looking at interactive agential dynamics. These dynamics are explored in section 5 in regards to some contemporary approaches to cognition that provide purchase on inter-individual interactions. I then conclude the paper with a brief discussion of how this definition might be useful for thinking about and inter-scale interactions and agency.

2. Active Matter Systems

Active matter systems are “a distinct kind of nonequilibrium system” (Ramaswamy, 2017, p. 2) made up of independently active entities that collectively engage in interesting patterns of activity. A nonequilibrium system is simply a system engaged in activity sustained by energy flow into and out of the system. All living organisms are non-equilibrium systems sustained by metabolic energy processing. Some non-living entities, such as motile oil drops (Hanczyc 2011,

2014) and Janus particles (Meredith *et al.*, 2021), which are microparticles with two physically or chemically distinct surfaces which enable a single particle to have two differing chemical reactions, can also be out of equilibrium due to self-catalyzing reactions.

The activities of active matter are often examined through minimal models. Though the individuals that make up active matter systems can range from sub-cellular molecular structures to organisms with complex behavioral repertoires, models of these systems typically ignore the individuals' complexity and material differences. Some models of flocking behaviour can be used whatever the flocks consist of, be it nanoparticles, birds, or bacteria. The most widely-used two-dimensional model of this kind is known as the Vicsek model (Vicsek *et al.*, 1995). Vicsek models are minimal models used to study the phenomena associated with the collective motion in active matter from complex biological to simple inorganic systems. The simple mathematical model has many individual particles which change the direction of their movement depending on the direction of their neighbors (Matsuda *et al.*, 2019). The model, in its simplicity, shows that flocking behaviors can arise from self-propelled particles observing very basic alignment rules. With just the trademark motility of individual units of active matter systems and a mechanism for alignment, Vicsek models demonstrate that a number of different spatiotemporal patterns of activity can be achieved with simple modulations of population density or slight alterations of the alignment mechanisms.

In animal groups, collective motion such as starling murmurations, fish schooling, and wildebeest migrations arises from repeated local interactions (Couzin 2009). Interacting living individuals with local sensing abilities are said to follow a small number of behavioral rules: collision avoidance, velocity matching, and flock centering (staying near to flockmates) (Reynolds 1987) that lead to alignment. This enables collective behaviors such as the amplification and dampening of collective responses, where rapid information sharing is possible through the motions of a few individuals. For example, if a few members of a traveling group perceive a predator and thus alter their motion, that motion quickly ripples through the group, resulting in a relatively quick change in the group's trajectory. Where these kinds of activities in living groups are often thought to rely on various cognitive dynamics, such as memory and anticipation for projecting a course of motion, studies have shown that vision or vision-like perception alone and response to instantaneous cues can produce many of the complex features of flocking (Barberis and Peruani, 2016, Velasco et al. 2018). This means that even without the complex cognitive rule-following attributed to individuals in living active matter systems, we can still find interesting collective activities governed by local interactions.

Another important aspect of the behavior of active matter systems is density. With *E. Coli*, for example, the characteristic motion of individual bacteria is the run and tumble motion. When in large groups, we see interesting collective patterns of motion occur. Well-fed dense collections of *E. Coli* will display turbulent motion, swimming in random or chaotic patterns. However, in less dense starvation conditions, the bacteria will self-organize into bands around the edge of a dish (Budrene and Berg, 1991). Examining how these kinds of changes in density impacts phase transitions or rule-following behaviors is important for researchers theorizing about the functional qualities of collective activities in groups of organisms. Non-living active matter systems, though, have been shown to engage in many similar activities as their living counterparts--such as organizing into bands around a boundary (Thutupalli *et al.*, 2018). Non-living groups have also been shown to be able to follow thermal gradients (Meredith *et al.*, 2021) as well as navigate obstacles (Bechinger *et al.*, 2016). This suggests that though there may be a functional explanation for why living groups take part in these collective behaviors, they are also likely to be exploiting interactive regularities, as we find similar patterns of collective behavior in groups across the phylogenetic landscape.

In contrast, explanations for *how* local interactions lead to collective behaviors are quite different for non-living active matter systems. Collective behaviors are described by appealing to general regularities involving alignment and speed within a defined area (Abaurrea Velasco *et al.*, 2018). Explanations for these behaviors shift away from rules individuals follow and their functionality (e.g. the importance of information transfer or food distribution) to the properties of interactions themselves and the specific laws governing them, such as continuum field theory or Brownian motion (Gompper *et al.*, 2020). Local alignment for some non-living collectives can be evaluated in terms of steric interactions, which concern only the attraction and repulsion dynamics that take place between individuals of certain material or chemical makeups. Interestingly, modeling has shown that even a system with interactions governed only by repulsion dynamics can still engage in interesting patterns of collective behavior (clusters) (Fodor and Marchetti 2018). Local jamming of self-propelled elongated particles can result in alignment, or this can arise from steric interactions due to chemical reactions between materials (Velasco et al. 2018).

We might think, and often do, that to explain the coordinated behaviors of living active matter systems, we will need to draw on an extensive list of internal dynamics (e.g. memory, anticipation, leader-following, and/or rule-following). The study of interactive dynamics in non-living active matter systems shows that we might overestimate the amount of cognitive work needed in order to get interesting collective behaviors, as "[t]he bottom up, self-organized nature of collective behavior means that the group is regulated and maintains coherence without the need for any individual to have global information about the state of the others--and thus serves as a robust model of distributed control with limited communication or information sharing" (Ouellette and Gordon, 2021). Current research through modeling and non-living active matter systems reveal more minimal requirements needed in terms of individual dynamics for the emergence of interesting collective patterns and behaviors. While this certainly raises some interesting questions about when, and to what extent, cognitive processes are needed as explanatory variables to understand some kinds of collective activity, I want to focus on how this research highlights the importance of interaction itself and the role that interactive dynamics might be playing in governing the activities of individual agents.

In order to research these kinds of interactive dynamics in more complex systems, we first have to take interaction to be a viable object of study. In the following section, I support this claim by showing how Viscek models have been used to explore the effects of noise on collective activity, examining how this might be conceptualized as an interactive phenomena that scales up for complexity, and where the interaction itself is treated as an object of analysis.

3. Interaction and Reduction

Helen Longino has recently argued that an ontologically pluralistic approach to behavior is needed, one that includes not only the individual and the collective in explanations, but also treats interaction itself as a suitable object of research (2020, 2021). Longino points out that many of "the questions we ask already presuppose an ontology" (2021, p. 14), which is implied in the way these questions carve out phenomena in need of an explanation. The ontological framing in these questions frequently involves an implicit commitment to methodological individualism, as the questions posed seek answers that emphasize the individual at the exclusion of interactive and collective aspects of behavior. Longino proposes that by treating interactions as a viable metaphysical object of study, we expand the breadth of questions we can pose about phenomena and encourage new types of answers as well. A look at contemporary research on active matter systems demonstrates the value of this kind of ontologically pluralistic approach.

First, though, while using physics to get a better understanding of collective behavior might seem to be a boon for other fields, there may be hesitance because of lurking concerns about reduction--especially since active matter physics has been characterized as aiming "to bring living systems into the inclusive ambit of condensed matter physics, and to discover the emergent statistical and thermodynamic laws governing matter made of intrinsically driven particles" (Ramaswamy, 2017, p. 3). Identifying, modelling, and creating synthetic active matter systems has been thought to hold the promise of a theory of living active matter dynamics that can utilize the same formulas used to understand the physics of systems, such as those from mechanics and statistical mathematics, as those used for understanding the collective activity of non-living particles.

However, this does not mean that the study of active matter should be viewed as reductive in spirit. Like other research into complex systems, the study of active matter treats collective and interactive phenomena as underexplored and subject to some regularities--and at least some of those regularities can be described through formalizations commonly used in physics. Green and Batterman (2017) have addressed similar concerns about explanatory reduction (Mayr 1988) between physics and biology. While many philosophers have wrung their hands about the possibility of reduction through "bottom-up" explanations, Green and Batterman point out the serious limitations of any serious threat of reduction given the scale dependency of physical behaviors (Batterman 2012). The multi-scale models in physics and biology used for capturing specific phenomena or behaviors are not intended to capture all details at every scale of explanation. Instead, they establish a minimal baseline to achieve a certain phenomena (e.g. fluid flow) by averaging or establishing boundary conditions for activities which have an effect on or produce that phenomena. In doing so, multi-scale models demonstrate how a "bottom-up" approach using explanations from physics will "often reveal the importance of macro-scale models and explanations" (2017, p. 1), or the need for a pluralism about explanatory scales, rather than attempting to reduce the macro-scale to the micro-scale. Green and Batterman discuss this in terms of tissue modeling: "[W]hen modeling cell motion at tissue scales or at that of the whole embryo, developmental biologists often rely on coupled partial differential equations that ignore the stochastic properties of interactions between individual molecules and cells. Similar to mean-field approaches in physics, they study the collective dynamics of the population of cells rather than the individual components (Lesne 2013)" (2017, p. 23). Where looking at the macro-scale collective activity of cells enables developmental biologists to understand tissue generation, elaborating on the stochastic properties of individual interactions would give them no explanatory purchase.

To draw again from Longino, what we want to know will determine which characteristics at each scale will be valuable (2021). To study the collective properties of cell movement at the tissue scale, only a generalization over interactions is needed, not details about the properties of individual cells. That is, in doing multi-scale modeling, we are not trying to answer all possible questions on all scales at once. Rather than making a case for reduction, where the theories governing the inter-scale dynamics of the target system can be reduced to statistical or mechanical explanations, it is more appropriate to think of these as establishing individual, interactive, and collective regularities whose effects can be tested within the broader system. The formalizations derived can also be helpful for understanding the additional variables that need to be included when we scale up to more complex systems (McGivern 2020). These assist in determining what formalizations and behaviors are scale invariant and which are scale-specific.

In the above example we see that finding formalizable regularities, whether scale-specific or scale invariant, need not have anything to do with reducing macro-scale explanations to the micro-scale. This is also the case for inter-individual interactions, where the worry is that interactions are often thought to reduce to individual contributions (Longino 2021). Researchers studying active matter have to be very precise about the difference between individual, collective, and interactive variables and explanations, as well as their limitations. For example, Sinhuber et al. (2021) have developed a thermodynamic descriptive framework for collective group activity, which provides state equations for midge swarms in order to investigate the collective function of group behaviors. While their descriptive framework provides some purchase in explaining the functions of group activities, they are careful to avoid implying that the characterizations of interactions utilized to do this work would also apply on other scales, in other models, or in other contexts in the same way as the state equations of the collective will: "Extracting interaction rules by observing group behaviour is a highly nontrivial inverse problem that can typically only be solved by assuming a modelling framework a priori. Appropriate model selection is made more difficult given that interactions may change in different contexts" (Sinhuber et al. 2021, p. 1). Thus the interaction rules that are useful for understanding a specific behavior are in some cases only useful for a specific model or framework, and model selection is highly dependent on both the type of behavior itself and in what context that behavior is occurring.

Viscek models provide a simple example of how inter-individual interactions can be given a distinct treatment. The model factors in alignment of individual units' velocity with the average velocity of its local neighbors and alignment with the angles of its local neighbors. One of the important variables in looking at collective behaviors is the effects of noise on collective activities of a system. In Vicsek models, each agent in the model averages its current heading in accordance with its local neighbors at regular intervals. At a certain level of noise, an active matter system following these rules will go through a phase transition wherein the orderly (aligned) system will become disorderly (random movement) or vice versa. Noise can be divided into two kinds: intrinsic noise, which disrupts the internal alignment mechanism, and extrinsic noise, which causes difficulties in the alignment process itself (Chepizhko and Kulinskii 2010). For models of living active matter systems, such as a fish school or starling murmuration, extrinsic noise represents factors that affect conspecifics' alignment interactions, such as fog, or murky water; for bacteria or particles, it might be a chemical interference introduced into the colloidal medium. Noise might also involve physical interferences such as topological defects or vibrations, such as sound waves.

By altering noise, both intrinsic and extrinsic, researchers have interventions which allow them to test the strength and variability of the interactions that lead to flocking behaviors. Because "the motion of flocking organisms is usually controlled by interactions with their neighbors" ((Czirók and Vicsek, 2000), p. 18), noise is used to test interaction variability and strength. Put simply, an agent does not align or match velocity with itself, though these factor into averaging. It is the interaction that supports both the individual and collective behaviors. The interactions are under examination, as universal features of collective behavior , and can be adjusted to examine how active matter will move in different mediums or under different boundary conditions "when the level of *pertubrations* or the mean *distance* between the individuals are changed" (Czirók & Vicsek 2000, p. 17). This can reveal aspects that are important for understanding how these interactions underpin macro-scale behaviors at another scale, including some of the fundamental processes of cellular life (Doostmohammadi *et al.* 2018). Variables and inputs can be altered to test the scale-specificity of interactions, as "such models represent a statistical approach complementing other studies which take into account more details of the actual behavior" (Czirók & Vicsek 2000, p. 18).

These models can also be adjusted to evaluate the density of individuals needed to obtain the kinds of interactions that lead to collective behavior. For some models this will involve a confined area, as certain active colloidal systems--some bacteria and cells--will only exhibit active turbulence when unconfined, but will exhibit flocking when enclosed (Thutupalli *et al.* 2018). Material topography, boundaries, and flow interference can also contribute to interactive dynamics. Thutupalli and colleagues used different boundary conditions to test the collective behavior of oil droplets in hydrodynamic flow fields (Thutupalli *et al.*, 2018). They found that within a tight boundary, the oil droplets would briefly form into unstable bands and then scatter. When the boundaries were farther apart, the oil droplet formed into stable bands that not only maintained their coherence, but could travel through other bands traveling the opposite direction and re-form. They then removed one boundary completely. The oil droplet continued to form into collectives, and depending on whether the wall was replaced with water or air, they would engage in a schooling-like behavior or would form small semi-stable two-dimensional groups. Stokes flow equations are used to calculate the force of flow fields exerted by swimmers in these boundary conditions, providing a picture of the ways that the hydrodynamic flow operates around individuals. However, to understand how the individuals engage in the collective activities they do, the pair interactions have to be mapped out in terms of flow-induced phase separations. In simpler terms, understanding the collective behavior involved not only treating the interactions as the focal point of interest, but also treating the material design of the surroundings (boundaries) as a parameter of the interaction rather than as a parameter of the individuals involved.

Interactive dynamics are important for understanding behaviors of active matter groups comprised of both complex and simple individuals. And as discussed in the last section, the cognitive dynamics that contribute to collective behaviors can often be quite minimal. This opens up a space for thinking about how interactions might contribute to some phenomena we generally think of as only involving individual contributions. In the next two sections, I'll argue that one area worth thinking about is how interactions contribute to shaping agency.

4. Agency and Interaction

Many of the conceptions of agency we find in the philosophical literature are generated with a specific kind of system in mind, namely humans, and thus capture a limited range of capacities. If we are looking to understand or make claims about rational agency, moral or legal responsibility, or other concerns relevant to human forms of life, then using human agency as a baseline seems appropriate. However, there is a growing shift away from the androcentric criteria usually encountered in philosophical literature on agency, with more foundational physical or organizational criteria instead pointed to as hallmarks of an agentive system. Several developing research programs, such as basal cognition (Lyon et al., 2021), minimal cognition (Beer, Randall, 1996), and autopoietic enactivism (Varela et al., 1991, Barandiaran et al. 2009) for example, present compelling reasons that agency should be thought of as inherent to all living systems.

Regardless of the recent shift away from intellectualism about agency, looking at how interactive dynamics can be used to understand agency is tricky, as definitions of agency are still highly framework-specific. That is, definitions of agency are generally intended to be useful within a specific framework for understanding behavior and/or cognition. The methodological individualism we find in definitions focused on demarcating agential from non-agential individuals is thus not necessarily problematic given the types of questions we usually want to pose--as Longino explains it: "[I]n any particular inquiry researchers have particular aims and particular characterizations of the phenomena to be explained. The appropriate characterization of the phenomena will depend on what we want to know about it" (2021, p. 14). However, getting a firm grasp on what exactly an agent is (or is not) by means of a criteria involving cognitive capacities is, for the project of looking at regularities in interactive dynamics, neither necessary nor especially useful for establishing inter-individual interactive regularities that give us some explanatory purchase on agential behaviors. In the previous section, I have provided examples to show that these interactive answers do not always reduce to the contributions of individual agents, and that looking at interactions can reveal important inter-individual regularities inexplicable in terms of collective properties as well.

In this paper I leave it an open question what kinds of individuals are agents, as this is a framework-specific question. I will also not argue for any special relationship between agential dynamics and cognitive dynamics. The more one would like to load up a definition of agency with cognitive criteria in order to shave off this or that kind of entity (plants, bacteria, artificial intelligence), the more difficult it will be to establish on what scales we find regularities in interaction. A suitable starting point might be with a pre-theoretical definition of agency, such as the one provided by Stapleton and Froese (2016): "At the very least the term 'agent' implies (1) an individual, and (2) a capacity for action" (p. 221). Similarly, we find the terminology of "Brownian agents" (Schweitzer, 2003) or "particle agents" (Ebeling and Schweitzer, 2001) used in modeling of collective dynamics, and which at the very least have the ability to initiate or maintain activity through the expenditure of their own energy.

What makes the dynamics *agential* rather than *cognitive* is that the individuals do work using their own energy, satisfying a pre-theoretical definition of agency to which variables can be added as interactions grow more complex. Another good pre-theoretical definition comes from Stuart Kaufmann, who defines autonomous agency as "a self-replicating system that is able to perform at least one thermodynamic work cycle" (Kauffman 2003, p. 1090), optimistic that his definition "gives the minimal physical condition for a physical system about which the language game of doing, acting and value becomes natural" (*ibid.*). What I propose here is that a slightly more deflated definition--a non-autonomous approach--proves useful for looking at the interactions in which "doing" and "acting" sometimes takes place.[1] Pre-determining what must belong to the individual risks putting too much at the individual level before even beginning to investigate the role of interactive dynamics, as we saw above with the over-attribution of cognitive processes to explain collective patterns of activity. The pre-theoretical definition of agency proposed is useful for looking at interactive regularities on all scales because it does not involve drawing a hard line between behavior and mere activity, as the important factor is that the agent is energetically responsible for its own movement. As we see with active matter systems, there is an interesting grey area here precisely because of the interactive dynamics that can make collective activity non-random even for non-living systems. In this way, looking at interactive dynamics can be an altogether different (though supplemental and supporting) project from determining agential capacities and determining to which organisms or systems they belong.

In the first section, I gave an example of how some collective behaviors thought to involve a number of individual cognitive capacities still emerged in even very simple, non-cognitive, non-living systems through very simple inter-individual interactive dynamics. This might also be the case for the inter-scale interactions that support other kinds of capacities. For instance, actin filaments play an important role in separating the chromatic materials (DNA) in nuclei during cell division. Here, microtubules form a network across the body of the cell, a spindle apparatus or

[1] For some kinds of individuals, this might include behavioral modulation that doesn't appear to be active, as with a bird gliding on a breeze (Baradiaran et al. 2009).

mitotic spindle, that acts to separate the cell itself during cytokinesis (when a cell divides into two daughter cells). When extracted from cells, these same cellular components, actin and myosin filaments, will exhibit flocking behaviors in high density conditions (Schaller *et al.*, 2010, Butt *et al.*, 2010). Active forces have also been shown to play a role in collective behavior of cells in processes such as morphogenesis and collective chemotaxis (Balasubramaniam *et al.*, 2021, Hughes and Yeomans, 2020).

Understanding how micro-scale non-living active matter can support macro-scale biological processes is going to require substantive work on not just collective properties, but interactive regularities. Taking a non-autonomous approach to agency as a means to look at interactions does not restrict us to using the same baseline at all scales. Other aspects of agency may be important at particular scales, and we might consider how or whether the inclusion of additional agential dynamics for individuals affects the scale-dependency of interactions at that scale (e.g. basal agency, rational agency, collective agency). The utility is in setting aside unnecessary questions about individual capacities when we are looking specifically at interactions. For example, investigating *why* an *organism* engages in a behavior might involve establishing fundamental processes of self-organization, positing internal dynamics, situating the organism within its environment, looking at the organism's adaptive learning capacities, and so on. We might take into account whether the system is goal-directed, or can be thought of as having intentions. And, of course, each scale-specific definition of agency will also be subject to debates about the most suitable theoretical framework.

For looking at interactions, our operationalization of agency ought to reflect its utility across a variety of research programs, rather than tracking our metaphysical commitments or intuitions. I have argued that for this project, agency is a productive concept in a deflated form that can be scaled according to what is needed to understand the interactions in which agents engage. All that we need be concerned with for looking at interactive regularities is that an agential entity generates its activity rather than being fully at the mercy of external forces. The advantage of this terminology is that it carves out an interdisciplinary space for looking at interaction, and second, that it does not posit any cognitive capacities to the individual agents that make interaction a more appropriate phenomena of study for one discipline over another. To look at how they influence agency, interactions are treated as contracting or expanding degrees of freedom for action, thus facilitating the undertaking of actions that would otherwise not be available or limiting actions that would otherwise be available. The aim is to understand agency better, where agency involves energy exertion within a limited range of degrees of freedom, by asking what degree-of-freedom-establishing forces belong to the interaction itself. Simply by asking a question in this manner, by treating the interaction as a property-bearing entity, we are afforded the opportunity to operationalize and empirically test the interaction itself (coupling strength, density thresholds, etc.) in obtaining an answer.

Importantly, this does not require that we commit to the existence of an interaction in a metaphysically robust sense, just that we treat it epistemically as such. In the following section, I offer some examples from theoretical and empirical cognitive science that treat interaction itself as a viable ontological proprietor of cognition-shaping processes. These illuminate how we might approach formulating questions about agential scaffolding and constraints.

5. Interactive Agential Dynamics

In this section, I offer some suggestions for formulating questions on interactive agential dynamics in studying agency and cognition. Interactive agential dynamics can be defined as mutually dependent, multi-agent processes in which individuals directly participate that may guide, scaffold, or constrain agency. To clarify, this is not about describing activities that individuals engage in together (e.g. joint action), but about understanding how interactive properties or forces between individuals establish scaffolding and constraints for behaviors. I consider these to be mutually dependent in the sense that they are sustained by individual agents but cannot be explanatorily reduced to the activities of individuals nor attributed to any emergent properties of a group. The agents involved directly participate in the interaction, and the interactions are necessary (though not sufficient) for explaining the activity of the individuals. In order to understand the kinds of internal dynamics involved with agential behaviors in biological agents, the previous section argued that we start with individuals with a capacity for action participating in activities that involve interactive dynamics, but in which there is no need to posit any further internal dynamics to the system (regulation, decision-making, or goal-directedness). Internal dynamics can be accounted for as they become explanatorily necessary for more complex interactive behaviors.

In previous sections, I have provided some examples of how interactive dynamics are taken up in the study of non-living active matter systems. What might we learn about agency from looking at the interactive dynamics of these kinds of systems, and how might we similarly ask about interactive agential dynamics for more complex or cognitive agents? There are several areas of cognitive research that utilize theories or models to look specifically at interactions, of which I will go over but a few. There is the burgeoning field of interaction studies itself, for example, but the field is united topically, not as a unified research program. More specifically within cognitive science, there is Bickhard's interactivist approach to the study of the mind (Bickhard 2009), which reimagines mental representations within an interactive view of process metaphysics. There is also work by Seibt (Seibt 2009) on how we might logically schematize types of emergent interactions.

One theory that has stressed the importance of viewing agency through an interactive lens is Latour's Actor-Network Theory (ANT) (Latour 1996). ANT is too complex to detail here, but the relevant aspect is that it is a sociological approach to agency in which individuals are taken to emerge from interaction, a radical shift from treating interactions as taking place between pre-given individuals. As Latour describes it, one of the preoccupations of ANT is "an ontological claim on the 'networky' character of actants themselves" (1996, p. 373), where actants "can literally be anything provided it is granted to be the cause of an action" (*ibid*). Rather than involving methodological individualism, Latour's theory goes to the opposite extreme in espousing methodological reduction to local networks (1996). On his view, agency must be viewed through a metaphysical lens in which interaction is the only viable category for underpinning explanations. Bennett (Bennett 2010) and Malafouris (Malafouris 2013) have both expanded on ANT in ways that include the material environment in the networks from which agency emerges.

Decades of work now in enactive, extended, and embedded cognition, as well as ecological psychology, likewise argue that an exclusive focus on internal dynamics keeps us from appreciating how cognition is structured by (or constituted within) the agent-environment relationship (Clark, 2016; De Jaegher, 2018; Gibson, 1979; Paolo et al. 2017; Thompson 2007; Varela et al. 1991). In the enactivist approach in particular, cognition is conceptualized as a dynamic interactive process involving the agent-environment system. Enactivists are committed to the best explanation of cognition involving processes across the agent-environment system, though this doesn't necessarily require committing to a robust metaphysics involving these categories (Chemero 2009).

While the environment has been taken up as co-determining the realm of possibilities for a particular agent, ultimately it is not clear why stressing the agent-environment relation in this way is not still utilizing a kind of methodological individualism. The inclusion of interaction is intended to flesh out the story of individual cognition, perception, and/or subjectivity, through looking at cognition as an environment-inclusive process. That is, enactivism as a framework does not necessarily view interactions as an object of investigation, though cognition is expanded *interactively* beyond the individual. For the most part, the cognitive agent (or agency) is conceptualized in a situated, active sense--but the goal is still to provide answers to questions about cognition at the individual scale. In this way, "proponents recognise the need for a perspective change that does proper justice to the situatedness and embodiment of the social subject, [but] often remain themselves methodologically individualistic" (De Jaegher and Di Paolo 2007, p. 486). While the enactive approach moves away from treating cognition as internal to the system to conceptualizing it as an (inter)active process spanning more than the individual organism, it is still at its core a methodological individualism in that the explanandum involve cognition at the individual scale. The interaction processes themselves in which individuals engage are simply part of the explanans.

One exemplary exception is the enactive theory of *participatory sense-making* (PSM), which holds that a social interaction involving two or more agents can itself be considered an autonomous process (De Jaegher and Di Paolo 2007; see also De Jaegher and Froese 2009). PSM was developed in response to the limitations of the pervasive methodological individualism for understanding social cognition. Briefly, social cognition is the ability to understand what another is feeling, wanting, thinking, or intending, and the cognitive underpinnings of these abilities are a hotly debated topic in the philosophy of cognitive science. In introducing the theory, De Jaegher and Di Paolo criticize the commitment of other approaches to explaining social cognition through appeal to individual mechanisms alone:

> "...as long as there is no explicit and focused attention to [the] relational domain ... this emphasis on interaction remains vacuous. In many of these approaches, the interaction

> seems merely an addendum to a position that departs from what is really still an individualistic perspective. In our opinion, any approach that mentions interaction, but fails to go into the relational dynamics of the interaction process in detail, is simply not an interactive account and probably not even a social one, despite the goodwill driving it." (2007, p. 494)

In contrast, De Jaegher and Di Paolo clearly specify that "[i]nteractions depend on individual contributions, but are not fully determined by them. They depend also on the relational dynamics between subjects, and other factors" (De Jaegher and Di Paolo 2012, p. 1; see also Auvray et al. 2006, Di Paolo et al. 2008; Di Paolo and De Jaegher 2012). Elsewhere, they offer a clear definition of an interaction as "the mutual interdependence (or bidirectional, co-regulated coupling) of the behaviors of two social agents" (Di Paolo et al. 2010). They point out that coordination between individuals has been demonstrated not to require much in the way of cognitive capacities, which I have shown above to be the case in the study of collective behavior in active matter systems. Moreover, they note that interactive coordination is "often hard to avoid" (2007, p. 490).

De Jaegher and Di Paolo specify that a PSM interaction emerges when "social encounters acquire [an] operationally closed organization" where "the agents sustain the encounter, and the encounter itself influences the agents" (*ibid.*, p. 492). Now, unlike some of the examples above of how physical or chemical coupling can lead to interesting patterns of behavior, at the more complex organismic levels the individuals have to exert energy to maintain some kinds of interactions. Efforts to understand why organisms do so thus tend to look for functional explanations at the individual or collective level. In the case of what might be considered a social interaction, there are additional considerations, such as maintaining individual autonomy and sustaining motivation to perpetuate an interaction. What De Jaegher and Di Paolo stress is that what makes this particular kind of interaction *social* is the preservation of the autonomy of the interacting agents--the agents must be actively contributing to the interaction *and* maintaining their autonomy for it to be considered its own autonomous process (2007).

Looking at the theory of PSM draws attention to three important facets of theorizing about interactions for more complex cognitive systems, as discussed in previous sections. First, attribution of properties at the individual level only need to include what is absolutely necessary for the purposes of delineating the type of interaction. Second, the nature of the interaction--in this case, its self-organizing autonomous nature--is articulated in such a way that offers possibilities for empirical analysis of the interaction itself (whether or not the means are currently available). Third, the interaction is sustained by the energy output of the individuals involved and their degrees of freedom are limited or enabled through engagement in or maintenance of the emergent interaction. In some ways, sustaining an interaction constrains the agency of the individuals involved, but the interaction can also enable possibilities for group activity and coordination that were not previously available.

Since we are concerned here more broadly with interactive agential dynamics, there are certainly other examples of interactions between individuals that can shape the degrees of freedom of those involved. De Jaegher and Di Paolo give the example of the transfer of body heat between people at a bus stop as one example of non-social, non-autonomous interaction, where "there is coupling between the agents, but the coupling is not actively regulated by the agents involved so as to affect this coupling itself" (2007, p. 493). This might be considered to be on the lesser constraining-or-enabling end of the interaction spectrum. Nearer the other end, we find other kinds of complex social interactions, where we might need to posit cognitive capacities at the individual scale to explain regularities, such as with interactive synchrony (Varga 2016). This term is used to describe infant-caregiver interactions where there is "an emergence and maintenance of non-predetermined synchronic interaction patterns over time, in which caretaker and infant complement each other's states and moderate the level of positive arousal in cooperation" (Varga 2016, p. 2474), which leads to "organization of social behaviour into rhythmic sequences" (*ibid.* p. 2475).

For an example of why it is important to establish minimal criteria at the individual scale when looking at interactions, let's look at a counter-example. Satne (2021) has criticized what she views as the insufficiency of PSM in that it does not specify what kinds of agents can enter into a PSM interaction. One of the flaws in taking PSM interactions up as explanatory, Satne claims, is that "the concept of [interaction as an] 'autonomous system' does not yet draw differences between agents, including biological organisms and artificial ones, and persons, to whom we apply the enriched idiom of mental predicates" (2021, p. 511-512). Satne argues that interactions alone cannot constitute social cognition, and that in order for PSM to do so, it requires more demanding cognitive elements at the individual scale: an understanding of both one's own and their interactor's goals, as well as a shared goal of maintaining the interaction, "constituted by interactants targeting and keeping track of each other's goals and in such manner, being attentive to other's goal directed attitudes" (Satne 2021, p. 523).

First, where PSM is making claims about how interactions can play a constitutive role in social cognition, Satne conflates the explanatorily relevant aspects of social cognition that exist at the individual and the interactive scales, treating the interaction as though it is intended to do individual-scale work. De Jaegher and colleagues are clear that interactions are a constitutive element in understanding social cognition, not the full explanation (2010, p. 443). They specify that interaction dynamics might, in some cases, play explanatory roles that have traditionally been ascribed solely to individual mechanisms (*ibid*., p. 445). It is not clear how Satne understands interactions as being able to do all of the work at both individual and interactive scales, without understanding interaction in the more methodologically individualistic sense of being merely an extension of the individual scale. Either the PSM interaction is not being treated as an autonomous process or the process is being reduced to individual-scale explanations.

Second, the non-specificity about types of agents is clearly highlighted in PSM as a feature, not a flaw: "We do not restrict social interaction to the human species. As long as the terms of the definition can be verified, they can apply to cross-species interactions or interactions with robots that are autonomous in the sense intended" (De Jaegher et al. 2010, p. 443). No motivation is given for why we would want to clearly delineate types of participants along these intellectualized or anthropocentric lines. If our focus is the PSM interaction itself, these individual-scale demarcations are outside of the scope of relevance. In fact, the broader field of interaction studies is highly interested in all kinds of interactions, including human-robot interactions, and the study of human-robot interaction provides a lot of practical information about how, for example, elderly people and autustic children can form unique and satisfying bonds with some kinds of robots (Soares *et al.*, 2019; Wang *et al.*, 2019). Pre-emptive exclusion of these as PSM interactions closes off what might be very fruitful research avenues unnecessarily:

> "Indeed, interaction with complex, but not fully autonomous systems (such as virtual characters or some social robots) can provoke an experience of engagement. It is also true that engagement can occur without aclear experience of there being another person... The reasons for these phenomena deserve examination, but the phenomena would remain obscured if we integrated the subjective element directly into the definition. Thus, although these subjective aspects are important, our definition needs to focus on objective aspects, because only then can the link between interactive patterns and the experience of interacting be scientifically examined instead of assumed." (De Jaegher *et al.*, 2010)

Rather than trying to get an explanation that covers all scales at once by inflating criteria at a single scale, PSM demonstrates the use of treating interactions as separate, although enabling, constraining, and/or constitutive elements, worth taking into account when formulating full explanations. I have also argued in Section 3 that trying to collapse interactions to individual scale phenomena is not an empirically practical approach to a multi-scale process (see Dumas *et al.* 2014 for more on social cognition as a multi-scale phenomena).

Satne's scale equivocation, though, draws attention to a broader concern about how we delineate between processes at the individual, interactive, and collective scale. Pamela Lyon (2006) has made a similar point regarding concerns about the difficulty of demarcating cognitive processes from biological processes. She stresses the salience of this problem for organizational approaches, where operational closure of the system understands self-organizing biological processes as dynamically interwoven and co-sustaining: "What an observer designates as an organism's 'cognitive subsystems' will always have substantially linked, if not shared, molecular pathways with other systems usually considered to be non-cognitive—just as the brain, so often equated with mind, supports 'physical' functions as well as 'mental' ones, and it is difficult to determine where one sort ends and the other sort begins" (Lyon 2006), p. 25). For understanding interactive agential dynamics, we have a comparable demarcation problem if we try to isolate the cognitive or biological processes that constitute agency to either the individual or interactive scales, not to mention macro- or micro-scales. This likewise closes off potential research avenues for understanding how molecular sub-systems self-organize and support biological processes, how interactions between non-autonomous individuals can themselves become autonomous or lead to collective behaviors, how these processes break down, and so on.

Participatory sense-making provides an example of how we can treat interactions as an ontological category in the study of cognition, and how we can do so in a way that is deeply linked with the empirical side of cognitive science, by drawing on dynamical systems models (DST). One type of DST model appealed to often in discussing interaction are coordination models, which have been used for understanding how coupled systems, living and non-living, engage in synchronization patterns without appealing strictly to hierarchical mechanisms. The Haken-Kelso-Bunz (HKB) model of coordination is one of the most widely used applications of nonlinear dynamical laws being used to explain behavioral coordination in biological systems (Haken et al. 1985). Briefly, the HKB model is a model of motor coordination that tests the metastability of interactions. Though originally developed to study bi-manual coordination in individuals, the model was partly inspired by the self-organization of collective groups (e.g. bird flocks and fish schools) that we see in active matter systems (Kelso 2001).

One of the guiding aims behind the development of the HKB model was to understand how collective behaviors can shape degrees of freedom within the collective, where the full range of activity of individuals is limited to a smaller set of dynamical variables (Kelso, 2001). The HKB model tracks phase transitions (between in-phase and out-phase patterns) of coordination, as well as multistability, through the use of synergetic concepts. Kelso describes this in terms of the relation of events on different timescales: "the faster individual elements in the system may become 'enslaved' to the slower, emergent pattern or collective variables, and lose their status as relevant behavioral quantities (Haken 1977)" (2001, p. 13846). To explain the relationship between these slower emergent behaviors at the collective scale and the individual behaviors, we have to understand how the collective behaviors create boundary conditions, or constraints, on the faster-timescale individual behaviors. The individual behaviors might have control parameters, which involve the range of possibilities of the individual as determined by its composition and energetic output, and these control parameters are what become limited by collective coordination. With the emergence of stability at the collective scale comes restriction at the individual scale; these collective scale constraints are order parameters.

The HKB model and its many adaptations provide means for testing coupling strength and a language for conceptualizing how local interactions can constrain and enable degrees of freedom. These models have been applied to understanding interactive phenomena, such as the sensing of coordination instabilities (Granatosky et al. 2018), coordination strength and social memory (Nordham et al., 2018), remote synchrony in motor coordination (Alderisio et al., 2017), increase in coupling strength with mechanical coordination (Cuijpers et al., 2019), and multi-agent coordination in medium-sized human ensembles (Zhang et al., 2018). Other empirical work has confirmed and/or supplemented this work, demonstrating inter-brain synchronization is social interaction (Dumas et al., 2010) and music improvisation (Müller et al., 2013).

To summarize, HKB models give us but one example of the resources available now in the cognitive sciences to provide explanations for the shaping of agency at multiple scales that do not solely rely on individualistic mechanisms. These and other models have shown that interactions themselves can play both causal and constitutive roles in establishing possibilities for action

(Meyer 2020). Some of these interactive agential dynamics are explicit, evaluable cognitive phenomena, but many are pre-reflexive, implicit, and even biological: "In short, for biological coordination, concepts from physics such as order parameters and their essentially nonlinear dynamics were shown to rule at both collective and component levels" (Kelso 2021, p. 3). This is important for moving away from treating interactions in the cognitive sphere as purely individual mental phenomena, or even as conscious mental phenomena, and makes it clearer how framing questions differently can open us to understanding how interactions situate agency by establishing some constraints and enabling conditions.

How interactive dynamics shape individual agency, whether at the cellular or social level, still remains largely underexplored, and the relationships between these scales are an additional concern which is reaching a critical point in cognitive science: "The question is what kind of framework could be put in place which will allow us to make sense of the relationships between these different scales – recognizing their differences and systematically addressing their interactions" (McGann 2020, p. 5). While this paper has focused mostly on providing motivation for asking questions about inter-individual interactions, we might also think about how inter-scale interactions could be similarly treated as a viable ontological category. To do so, I suggest, would also require that we consider interactive agential dynamics in the minimal way I have advocated for in previous sections. Locating agency at a particular scale or threshold of cognitive capacities limits our ability to understand the interactive agential dynamics that can help us make sense of the behaviors of individuals, collectives, and the scaffolding and constraints between scales. Consideration of the scale-specificity of some kinds of behaviors, as well as the scale-specific manifestations of scaffolds and constraints, will point to the kinds of disciplinary resources that will be helpful for getting some answers.

6. Conclusion

In sum, I have argued that changing our ontological framing of questions around agency to treat interaction as a viable ontological category can generate new kinds of questions and answers. This includes both inter-individual and inter-scale interactions. In treating interactions as a category for inquiry, we can look at the boundary conditions of interactions themselves, we can establish how interactions scaffold and constrain activity, and we can think about how to test interactive coupling. I have also argued that this will help us solve problems in which a single-framework or phenomena-specific definition of agency is unlikely to give us much purchase.

Agents, even human agents, are enmeshed in all kinds of low-level and high-level interactive dynamics that shape their behavior. Though using formulations from physics is often thought of as being a reductive approach to understanding cognition, decades of work from coordination dynamics demonstrate that this is not the case. Looking at non-living active matter to understand interactive agential dynamics provides infields to grasping even more interactive phenomena that shape behavior, and thinking in terms of agency rather than cognition helps us in formulating questions about constraining and enabling conditions at a multitude of scales. As

Longino has proposed, treating these interactions as causally relevant ontological categories can reveal explanatorily relevant intermediaries between individual and group scales. The first step is just to start asking the right kinds of questions.

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