Towards A Relational Ontology for Agent-Based Modeling in the Social Sciences

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Abstract

Agent-based modeling is a valuable approach for investigating social systems. We investigate conceptual models of social systems, i.e. structure and agents, in the social sciences including the relationship of systems to their environments. We outline a relational ontology/methodology for constructivist simulation modeling in the social sciences.

Keywords: social systems, agent/structure, agent-based modeling, multi-agent systems, system and environment, relational ontology

Introduction

> **"We adopt the position that conceptual modeling languages should be founded on an upper-level ontology referring to reality in a philosophically justified way. Frequently, the goal of conceptual modelers is not to capture the real structure of some domain but merely to capture some conceptualization of it. It is, however, well-known that not all conceptualizations of a domain are equally suitable. The choice of an adequate upper-level ontology is crucial for achieving an adequate conceptualization." (Guizzardi et al., 2002)**

Agent-based modeling (ABM), or the study of multi-agent systems (MAS), has taken hold in the social sciences. At present, there has been a considerable amount of theory regarding social structure in both political science and sociology but little applied

to formal modeling. What little has occurred has been replete with unquestioned assumptions and undergirded by "thin" models of agent/structure relations and constitution (Axelrod, 1984; Axelrod, 1997b; Epstein et al., 1996; Gilbert and Conte, 1995; Macy and Willer, 2002). As a result, the applicability of such models is far-removed from the complexities of the real social world. What is needed is a more robust methodological approach to conceptualizing agents and structures in MAS for the social sciences.

This is no small feat, however. Unlike purely physical models, social models must deal with a variety of "spaces" in which and with which agents interact. For example, social agents occupy physical spaces, cognitive spaces, social spaces, etc. Understanding and modeling how agents and structures interact relies on an analytically rich description of the entities and processes at work. Given the breadth and depth of academic debate on this topic, a single methodology is not likely to satisfy all scholars. Nonetheless, it *is* possible to construct a methodology that should handle most approaches. Moreover, when theorists assert that certain factors are not relevant, those factors can be ignored and the robust methodology still holds. So for example, a modeling approach where agents' behavior is seen as a function of both material and ideational variables can be of utility even to strict materialists because even as the influence of the ideational variables trends toward zero, the other components of the methodology retain their value and influence.

To reach our objective we will explore 1) a brief look at the "agent/structure problem" as it is conceptualized in the social sciences, 2) an examination of social simulation theory, 3) problematizing the concept of relationality, 4) the proposed conceptual model, and finally 5) conclusions and prospects for extension.

Social Science: Structure and Agents

In the social sciences there have been numerous approaches to the nature and relations of agents and structure. While it would be impossible to review them all herein, a brief overview of the general notions is warranted. Admittedly, such an overview will conflate the important analytical differences between rival theories, but on the whole, these deeper distinctions are not necessary to our primary goal of reaching a robust ABM methodology. After reviewing agent/structure definitions, external and internal relations, and structural monism v. pluralism, we can end with a state-space of possibilities.

Agent/Structure

Agents, quite simply, are units that interact utilizing some form of freewill, or "agency." Agents have agency *only when* their behaviors are *not structurally determined*. Units whose behavior is determined by structural forces can be equated with mechanical deterministic systems such as billiard balls wherein the "reaction" of a billiard ball to being struck by another ball can be rigorously described by means of deterministic equations. These "non-agents" are "reduced to bearers of systemic imperatives" (Wendt, 1987). An agent exhibits autonomy insofar as it is "able to give to itself its proper laws, its conduct, opposite to the heteronomous systems which are drivenby the outside" (Rodriguez et al., 1994).

Structure, on the other hand, is defined as the emergent system-level properties – social, historical, ontological, epistemological, etc. – that *cannot be reduced to or fully explained by the interactions of the agents*. So for example, in political neorealism,

nation-states behavior can be explained entirely based on the material capabilities (weapons, resources, economies, etc.) of the nation-states themselves (Waltz, 1979). In such a configuration, there is no structure acting on the agents. Niklas Luhmann has rigorously differentiated "structure" from "interactions of the agents" to make precisely this point (Luhmann, 1995). Structure is an *independently existing emergent logic* that shapes agents and agent behaviors. Thus, it becomes possible to distinguish analytically between *local and global* influences. Local influences are between agents, whereas global influences are from structure to agent. In swarming and flocking models, for instance, agents react both to each other and to the "center of mass" of the group (which is a system-level property) (Bonabeau et al., 1999; Bonabeau and Theraulaz, 2000; Mach and Schweitzer, 2003). By analogy, voting a particular way because of a friend's recommendation is local influence; voting a particular way because you think that candidate will win is global influence. In addition, a spontaneous riot can be seen as a global influence on the crowd's members (Granovetter, 1978).

External/Internal[1]

Next we turn to the kinds of relations extant in the system. Relations between agents, between agents and structure, and between structures, can be external or internal. External relations are those that are not "essential" to an entity's being or nature. Internal relations, on the other hand, are those that create or influence an entity's identity in the system. So for example, one's telephone number is an external relation, but one's gender is not. External and internal relations have different effects on agents and structures.

[1] It is problematic to dichotomize internal and external relations when relations are "internalized" to a different degree. A normalized continuum of internalization and/or interpenetration is more effective and is addressed in the conclusion of this paper.

External relations are *causal* relations insofar as the two entities are ontologically separate and distinct, and can therefore have causal effects on each other. Internal relations are *constitutive* insofar as the entities are in fact aspects of a larger entity and as such cannot be separated from it or described apart from it. Symbiosis between certain trees and the fungi that live on their roots, and also between certain microscopic organisms, are so tightly coupled that conventional language fails when trying to describe them: it is unclear whether they are two coupled organisms or merely a single organism with radically differentiated components (Margulis, 1998; Ryan, 2002). Such is true of social systems as well.

Monism/Pluralism

Next, there is no typology of agents extant in the system because agents do not have a single overarching identity. Rather agents present "faces" dependent on the interaction in which they are participating at any given moment (Goffman, 1971). In addition, agents consist of multiple identities that they act *in accordance with* at various times, for example: corporate identity, type identity, role identity, etc (Wendt, 1999).

Structural monists advocate a single pervasive world structure, from international anarchy (Buzan et al., 1993; Morgenthau and Thompson, 1993; Waltz, 1979) to global capitalism (Sassen, 2000; Sklair, 1995; Wallerstein, 1979), that affects all agents within it. Pluralists argue that there may be multiple structures in which agents exist. Agents occupy many structures simultaneously and must navigate through their lives and resolve conflicts between various structures and identities as they proceed. As we shall discuss later, these many influences can be conceptualized along a complex proximity continuum (near ←→ far) by their influence on agents. These many variables constitute the "logics

of social structure" wherein agent reproduction of structural properties maintains but also transforms the structure which, in turn, maintains and transforms the agents themselves (Kontopoulos, 1992).

The Constructivist State-space

Finally, we can visualize a continuum of sorts (more accurately, a state space) of agent/structure relations. In one locale, we have structures that entirely *cause* agent behavior. In another region, we have structures that entirely *constitute* agent identities. Complementarily we have two other possibilities, one where agents entirely *cause* structural behavior, and one where agents entirely *constitute* the structure's identity. Elsewhere is the grey landscape of reality where agents and structures both cause and constitute each other in a mutually affective process typically referred to as "structuration" in sociology (Bourdieu, 1977; Giddens, 1993) and "constructivism" in political science (Wendt, 1999).

Another way of looking at this relationship concerns the classical dichotomy between determinism and freewill. Determinism is all structure and no agency, whereas freewill is all agency and no structure. Structural determinists exist primarily among Marxists.[2] Meanwhile, reductive individualists, like Neorealists, often deny any form of corporate or collective agency at all.[3] In reality, of course, both extremes are non-existent. "Individual action neither completely determines (individualism) nor is

[2] Sassen, Saskia. (2001). *The Global City : New York, London, Tokyo*. 2nd ed. Princeton, N.J.: Princeton University Press, Wallerstein, Immanuel Maurice. (1979). *The Capitalist World-Economy : Essays*, *Studies in Modern Capitalism*. Cambridge [Eng.] ; New York: Cambridge University Press.
[3] See Waltz, Kenneth Neal. (1979). *Theory of International Politics*. 1st ed. Boston, Mass.: McGraw-Hill, Wendt, Alexander (2004) 'The State as Person in International Theory', *Review of International Studies* (30): 289-316.

completely determined by (determinism) social forms."[4] Sometimes this distinction is referred to as individualism/holism.[5]

Anthony Giddens first articulated the "duality of structure", i.e. that structure shapes behavior but is in turn produced and reproduced by behavior, a process he called "structuration."[6] Wendt elaborates, "structuration theory is a relational solution to the agent-structure problem that conceptualizes agents and structures as mutually constituted or co-determined entities."[7] Constitution concerns identities, and as Wendt continues "identities are inherently relational."[8] It is not only the identities of agents in a structure but also their relations that matter: "human beings and their organizations are purposeful actors whose actions help reproduce or transform the society in which they live; and society is made up of social relationships, which structure the interactions between these purposeful actors."[9]

It is essential to understand that constitution does not mean that structures *merely* constrain agents' behavior. Rather, in constitutive systems, behaviors are not given but require the presence of "constitutive rules" that create the possibility for those behaviors to exist.[10] "Social structures, then, constitute the conditions of existence of states and

[4] Bhaskar, Roy. (1982). 'Emergence, Explanation, and Emancipation', In Paul F. Secord (ed.) *Explaining Human Behavior : Consciousness, Human Action, and Social Structure*. Beverly Hills: Sage Publications.
[5] For ex. Kratochwil, Friedrich (2000) 'Constructing the New Orthodoxy? Wendt's 'Social Theory of International Politics' and the Constructivist Challenge', *Millennium, 2000, 29, 1, spring, 73-101*:
[6] Giddens, Anthony. (1979). *Central Problems in Social Theory : Action, Structure, and Contradiction in Social Analysis*. Berkeley: University of California Press.
[7] Wendt, Alexander (1987) 'The Agent-Structure Problem in International Relations Theory', *International Organization* 41(3): 335-370.
[8] Wendt, Alexander (1992) 'Anarchy Is What States Make of It: The Social Construction of Power Politics', *International Organization* 46(2): 391-425.
[9] Wendt, Alexander (1987) 'The Agent-Structure Problem in International Relations Theory', *International Organization* 41(3): 335-370.
[10] Dessler, David (1989) 'What's at Stake in the Agent-Structure Debate?' Ibid. 43: 441-473, Ruggie, John Gerard (1998) 'What Makes the World Hang Together? Neo-Utilitarianism and the Social Constructivist Challenge', *International Organization* 52(4, International Organization at Fifty: Exploration and Contestation in the Study of World Politics): 855-885, Searle, John R. (1969). *Speech Acts: An Essay in the Philosophy of Language*. London,: Cambridge U.P.

state action"[11] Because games are an obvious example – acceptance of constitutive rules must occur before the game can even be played – international relations is often likened to a game nations play. "There can be no mutually comprehensible conduct of international relations, constructivists hold, without mutually recognized constitutive rules resting on collective intentionality."[12] Thus, "constructivists bring to this lack of resolution a systematic communitarian ontology in which intersubjective knowledge constitutes identities and interests."[13] They seek to address the primary flaw of both individualist and structuralist theories that treat their units as "*given and unproblematic*" whether those units are the agents or the structure.

However, "the fact that individual actions, preferences and beliefs are caused – by states, for example, or by any sort of structure – does not make them explanatorily irrelevant. Just as individual actions, attitudes and beliefs are in part the products of and must be partly explained by, amongst other things, structures, so also are structures – or collective action or the origin and evolution of states – in part the products of and must be partly explained by individual actions."[14] Furthermore, David Dessler notes that the agent-structure relationship imposes two demands on our scientific explanations: that they acknowledge and account for 1) the powers of agents, and 2) the relationship of structural factors, i.e. the conditions, or possibilities, of action.[15] Therefore, "the

[11] Wendt, Alexander (1987) 'The Agent-Structure Problem in International Relations Theory', *International Organization* 41(3): 335-370.
[12] Ruggie, John Gerard (1998) 'What Makes the World Hang Together? Neo-Utilitarianism and the Social Constructivist Challenge', Ibid. 52(4, International Organization at Fifty: Exploration and Contestation in the Study of World Politics): 855-885.
[13] Wendt, Alexander (1992) 'Anarchy Is What States Make of It: The Social Construction of Power Politics', Ibid. 46(2): 391-425.
[14] Taylor, Michael. (1987). *The Possibility of Cooperation*. Cambridge [Cambridgeshire] ; New York: Cambridge University Press.
[15] Dessler, David (1989) 'What's at Stake in the Agent-Structure Debate?' *International Organization* 43(3): 441-473.

properties of agents and those of social structures are *both* relevant to explanations of social behavior."[16]

Simulating Social Science

> **"The notion of an agent is meant to be a tool for analyzing systems, not an absolute characterization that divides the world into agents and nonagents" (Russell and Norvig, 2003).**

Next, we turn to the question of modeling these complex social phenomena. Agent-based modeling, or social simulation, has a solid interdisciplinary standing as a new "third way" of performing inquiry:

> **"Simulation is a third way of doing science. Like deduction, it starts with a set of explicit assumptions. But unlike deduction, it does not prove theorems... induction can be used to find patterns in data, and deduction can be used to find consequences of assumptions, simulation modelling can be used as an aid to intuition" (Axelrod, 1997a).**

> **Clearly, agent-based social science does not seem to be either deductive or inductive in the usual senses. But then what is it? We think generative is an appropriate term..." (Epstein & Axtell 1996).**

Modeling is "generative" in the sense that it takes certain variables and rules of interaction and allows us to observe the dynamics of those theories *in action* in a virtual

[16] Wendt, Alexander (1987) 'The Agent-Structure Problem in International Relations Theory', Ibid. 41: 335-370.

world (Epstein, 1999). Moreover, "bottom-up" modeling is in sharp contrast to years of "top-down" social modeling which ignored both local agent interactions and non-linear effects (Johnson, 1998; Johnson, 1999). As a result, modeling is most effective when micro-level interactions are known and when the research aim is to observe the patterns that emerge at the macro level under various conditions and assumptions (Page, 1999) . For social scientists, for whom "experiments" are routinely out-of-the-question, the computer thus becomes a social laboratory.

In agent-based modeling, computer agents occupy "states" within the model with accompanying rules that describe how agents "transition" from one state to another in response to *both internal and external forces*. In fact, in some social models, such as panicked crowds, internal forces almost entirely vanish and the resulting mob can be well-described using the language of particle physics and "Brownian motion." In such situations, agent-behavior is entirely structurally determined. More to the point, the structure has provided the "default" or "panic" mode which agents revert to in certain contexts.

There are four basis sociological ways in which structures can constitute agents: norms, values, ontology, and roles (Guye-Vuilléme and Thalmann, 2000). Constitution contrasts with typical Bayesian rationally-calculating agents insofar as structural influences determine what counts as "rational" behavior.

Norms: There are two types of approaches to modeling norms (Conte and Dellarocas, 2001: 5). The first is to take the presence of a norm as an aftereffect of behavior, but this explanation doesn't explain normative behavior when outcomes are sub-optimal under typical rationality assumptions, i.e. the traditional problem of accounting for collective action (Olson, 1971; Ostrom, 1990). The second approach is to

treat norms as responsible for constructing part of an agent's internal identities. This constructivist approach focuses on how constitutive norms make certain kinds of behaviors possible. For example, norms of reciprocity provide the foundation for trust, thus making cooperation possible (Ostrom and Walker, 2003). Also, norms can affect private versus communal payoffs, thus altering the rationality matrix (Sartor, 2001). Finally, norms need not be taken as given, and some attempts have been made to model norm evolution and dynamics (Hoffmann, 2002; Hoffmann, 2004).

Values: Values affect the rank-ordering of individual and group preferences. The very definition of rationality depends on the presence of values. Values are rarely fixed however and in many cases rank-ordered preferences are inconsistent and unstable.

Ontology: The agent's world-view, or ontology, determines what "is" in the world. Because an ontology defines the very boundaries of what does and does not exist, it acts as a profound filter on perception and categorization (Bourdieu, 1977; Bourdieu, 1990; Lakoff, 1987).

Roles: As we noted earlier, Wendt discusses a "role identity" that agents act in accordance with during encounters (Wendt, 1999), and Goffman suggests agents display different "faces" when acting in accordance with various roles (Goffman, 1971). Recently, some attempt has been made to formalize how we might model agents acting in multiple roles (Guizzardi et al., 2004).

Furthermore, all of these structural influences are extant simultaneously. The compound influence produces "information fields" that agents occupy. "In order for an agent to act coherently in such an environment, it must first identify the information field that supports the role it is playing in each situation" (Filipe and Liu, 2001: 143). Thus, as Ian Lustick notes, the challenge for constitutive theorists is to "somehow probe the

multiplicity of identities available to individuals, the range of 'identity projects' available within a population or across overlapping or intermingled populations, and the relationship of those identities to changeable sets of preferences and changeable institutional circumstances" (Lustick, 2000).

Wagner's agent-object-relationship (AOR) model enhances the standard agent model by including both active agents *and* passive objects in the model (Wagner, 2003), but fails to tackle the issue of multiple identities. Some work has been done attempting to examine collective identities (Axelrod, 1997b; Cederman, 1997), as well as investigating the dynamics of how cultures evolve and change in the past and present (Boyd and Richerson, 1985; Taylor, 2001). The primary mechanism by which information is transmitted between structures and agents is the "meme," or unit of thought – a concept, an idea (Dawkins, 1989; Dennett, 1995). The profound implication is that the meme may in fact be an agent of its own. This raises the question of the locus of agency, which is the essential problematique which we will investigate in the next section.

To this end, Lustick has made considerable progress with the "PS-I" framework.

> **"PS-I (Political Science-Identity) is an agent-based computer simulation platform originally developed to operationalize, refine, and test competing versions of constructivist identity theory. Based on an earlier prototype, the ABIR (Agent-Based Identity Repertoire) model, agents with repertoires of identities (or other potentialities) interact in localities of specifiable size and are influenced as well by cross-landscape values attached to particular identities" (Lustick, 2002).**

Because Lustick's work begins with a constructivist ontology in which "individuals and groups maintain not one identity, but repertoires or portfolios of possible identities – ways of presenting themselves to the world" (Lustick, 2002), the resulting models have

demonstrated patterns typical of complex adaptive systems – thresholds, cascades, lock-in, etc. (Lustick, 2000). Unfortunately, Lustick's work extends traditional cellular automata models like Schelling's (Schelling, 1978), and is therefore not a multi-agent system per se.[17] Nonetheless, there is a problematique buried in all of these models, and indeed, in the very conceptual foundations of multi-agent systems and agent-based modeling, namely, the nature of relationality. It is to that issue that we now turn.

Problematizing Relationality

Ontologically, all of these systems are comprised of objects and relations. The problem with all of them is that by asserting the primacy of objects over relations, they are thus methodologically individualistic (Kontopoulos, 1992). The individual is taken as the locus of identity. The primacy of objects in current programming and information systems parlance is a function of the recent fascination with object-oriented design (OOD) (Booch, 1994). It is an interesting, if "chicken and egg," question as to whether the programming methodology is flawed because it was informed by previous philosophy of science object-oriented ontologies, or whether we are constrained into doing object-oriented social science by the lack of alternative programming ontologies.[18]

A glimpse towards a solution involves reconceptualizing relationality. An ontologically sound methodology would treat objects and relations as ontologically equivalent, i.e. neither is prior to the other. Relations are not something that objects "have" or "enter into." Relations are intrinsic to an objects identity, not extrinsic.

[17] For an excellent comparison demonstrating the improved utility of multi-agent systems over older cellular automata models, see Benenson, Itzhak and Paul M. Torrens. (2004). *Geosimulation : Automata-Based Modelling of Urban Phenomena*. Hoboken, NJ: John Wiley & Sons.
[18] To be fair, procedural languages offer one alternative, but they are 1) archaic, and 2) obscure.

Rather, networks of relations make possible certain objects very existence. Unlike recent formal attempts to define relations as something which merely connects relata (Guizzardi et al., 2002), in a relational ontology the relata change; the relationship remains. In this view, identity is inherently relational, i.e. the locus of identity is diffuse and communal rather than focused and individual. To be concrete, Eric Raymond has pointed out that one becomes a "hacker" by being accepted into the hacker community by other hackers (Raymond, 2001), and political theorists have made the point that political hegemony also requires social recognition as such (Taylor, 1996). Similarly, the value of real estate depends on the properties of both it and its neighbors, as well as global properties like the location of the entire neighborhood, city, state, nation, etc. For deep constructivists, this should be self-evident, but, even so, no models to date implement a relational ontology.

Programmatically, current simulations implement either entity-relationship models (ERM) or object-oriented design (OOD). ERM defines entities as real-world phenomena separately from the relations between them, and object-oriented design utilizes hierarchies of object "classes" which contain further objects lower in the hierarchy. In constitutive social relations however, the object in question cannot be defined or considered apart from the relations that constitute it. Moreover, it doesn't matter whether the entity is a species (Seegert, 1998) or a person or state (Wendt, 2004).

Mutual constitution is not limited to agent-structure relations, but also includes structure-environment relations. There are times when "dynamics and environmental interaction are so fundamentally interrelated that a modeler cannot satisfactorily represent one without the other" (Box, 2002: 60). Organism and environment are mutually constituted by the boundary formation that occurs when the system comes into being by the very act of differentiating it from its environment (Luhmann, 1995). This way of

conceptualizing relational systems parallels developments in the theory of complexity (Lewin, 1999; Waldrop, 1992). A complex adaptive system is "a system which is *neither* totally determined by its environment…, *nor* solipsistic (i.e. totally isolated or independent of its environment" (Stewart, 1992: 479). Because the system and environment are mutually constituted, "*agent society and its spatial environment are coupled*" (Epstein et al., 1996: 19). Structure, then, is the *interface* between the system and its environment, shielding it from determination and making it possible for information to flow in and out (Stewart, 1992: 480).

If the goal of constitutive model- and theory-building is to be able to investigate the structural coupling that occurs over time between system and environment as agents interact and evolve (Kauffman, 1993; Kauffman, 1995; Kauffman, 2000), then the challenge for modelers and programmers is "elevating the landscape to an equal player" (Box, 2002: 78). Ian Horswill has noted that making environmental properties explicit enables us to better observe how they facilitate some relations at the expense of others (Horswill, 1992: 63). For constructivist modeling, we want to observe how the landscape of constitutive relations creates possibilities for structure and behavior. Thus we should consider, as Patrick Jackson puts it, "relations before states"(Jackson and Nexon, 1999).

Towards a Relational Model

The key problem, then, concerns how to model the information transfer that occurs across the the semi-permeable boundaries between environments, structures, and agents. First, information transfer can occur over two axes: time and space. Second, the information transferred has to be stored somewhere, in the agents, structure, or environment. Agents

can access stored information via memory or culture, including institutions (Balzer, 2001; Hammerstein, 2003; Magnenat-Thalmann and Thalmann, 1994). Networks of relations provide the structure through which information is transmitted across social and conceptual spaces (Scott, 2000; Watts, 2003). In addition, modern telecommunications improves the process by which information is transferred with effects on the social as well (Katz and Aakhus, 2002; Katz and Rice, 2002). Creating a framework that encompasses these facets is exceedingly difficult to say the least.

The framework I am proposing is essentially this: agents occupy states within multiple structures in both space(s) and time(s). Space can be further disaggregated to include virtual/cognitive/social and physical spaces. The effects of entities and relations on each other is a function of their "proximity" to each other in a given space. Measures of proximity are entirely dependent upon the space in question. Multiple measures of proximity are often the case, and may in fact be necessary. Tobler's First Law of Geography is instructive:

> **"Everything is related to everything else, but near things are more related than distant things" (Tobler, 1969)**

This tenet has been used as a heuristic for calculating degrees of influence. Paradoxically, it is tautological. What things influence? Those that are near. What things are near? Those that influence. The escape from this conundrum lies in recognizing that geographers have an absolute physical measure of "nearness" that is often absent in social science. In social networks, for example, there are numerous measures of "nearness" between entities (Scott, 2000). The value of Tobler's Law is that it holds regardless of

the measure being used. Moreover, things that are "near" and influential by one measure *may also be "near" and influential on other scales*. Thus it is entirely appropriate to define an influential "neighborhood" using the metaphor of a spatial "topology" (as social network theorists do) even in the absence of an absolute "geography" (Gimblett, 2002). Therefore, "movement" or "change" for an entity (agent or structure) can be realized as the transition from one set of coordinates in a state-space to another set of coordinates in the same state space.[19]

Thus, the formal statement for our model looks like this:[20]

$$\mathbf{E} \sim (\mathbf{I};\ ((\mathbf{S}, \mathbf{R_S}),(\mathbf{N}, \mathbf{R_N}))_{\text{time-1 ... time-n}};\ ((\mathbf{S}, \mathbf{R_S}),(\mathbf{N}, \mathbf{R_N}))_{\text{space-1 ... space-n}})$$

A long explanation follows, but first let us define our terms:

- **E** – the entity in question. This can be a structure or an agent.
- **I** – the "identity" of the entity in question at the moment, i.e. the identity that the entity is *reproducing*, or acting in accordance with.
- **S** – the set of states associated with E
- $\mathbf{R_S}$ – the transition rules for those states
- **N** – the neighbors of the entity
- $\mathbf{R_N}$ – the transition rules for relations and thus neighborhoods

[19] It is conceivable that transitions could include movement from one state-space to another, i.e. changing the state-space altogether, but as this step would constitute a new "meta" state-space orthogonal to the first two, consequently leading to an infinite regress. The original two state spaces could therefore be reduced to a single state-space.

[20] This formula is entirely adjusted from Benenson and Torrens' excellent work on Geospatial Automata Systems in Geosimulation Benenson, Itzhak and Paul M. Torrens. (2004). *Geosimulation : Automata-Based Modelling of Urban Phenomena*. Hoboken, NJ: John Wiley & Sons.

The first set of states and neighbors are applied on the temporal axis. The number of such influences ranges from time-1 up to time-t because there can be many temporal events exerting influence at the moment. Events that are distant in time may be near in a temporo-spatial neighborhood as regards their effects, such as childhood trauma or historical events. Conversely, events that are near in time may be distant in terms of their effects, such as what one had for lunch last Tuesday. The second set of states and neighbors are applied on the spatial axis. The number of such influences ranges from space-1 to space-n because their can be many spatial influences operating at the same time. Again, influences vary according to measures of proximity. As Paul Torrens explains, exploration "then becomes an issue of qualitative and quantitative investigation of the spatial and temporal behavior of [the entity]… given all of the components defined above" (Benenson and Torrens, 2004).

A modeling framework requires definitions and rules regarding 1) location, 2) neighborhood, and 3) change (Benenson and Torrens, 2004: 25). In this case, the location method depends on the physical or conceptual space in question, using either either direct (absolute coordinates) or indirect (relative coordinates) referencing (Benenson and Torrens, 2004: 28-29). Future states and neighborhoods are a function of current states and neighborhood influences as the agent moves through a state space (Benenson and Torrens, 2004: 26). As a result of multiple spaces, or "information fields, that agents occupy, "neighboring" agents in one space may or may not be neighbors in another space. For example, agents could be neighbors in a physical space (e.g. citizens), or neighbors in a conceptual space (e.g. ethnicities). This affords us two particularly salient avenues of study: 1) observing the effects of the topology of relations in the system such as the "small-world network" (Watts, 1999; Watts, 2003), and 2) observing the intersection

between conceptual and physical spaces, such as the impact of a "shrinking" physical world on populations inhabiting shared conceptual spaces.

So what of structure? Structure acts in the model as a mediator between its internal agents and its external environment. Given our earlier distinction between local and global influences, structure manifests in agents as **influences of omnipresent proximity**. This is a necessary but not sufficient condition, however, as near-agent influences could also be omnipresently proximal but not necessarily structural. This is, to my knowledge, notably different than current approaches to the problem of persistent relationships in social modeling (Peckham et al., 1995).

It should be useful to normalize all relations. A typical 0 to 1 scale would demonstrate proximity by level of influence – 0 is none, and 1 is total, i.e. deterministic causal influence. A scale of -1 to 1 could be used if the "direction" of influence were needed – -1 being total repulsion and 1 being total attraction. It should be noted that for constitutive relations 0 carries no constitutive influence and 1 would be completely constitutive, i.e. the individual's absolute identity.

A final clarification is in order at this point. Many of the agents in social systems are corporate, or collective, agents. A few tenacious individualists notwithstanding, the debate over whether or not corporate agency exists has been resolved with a resounding "yes" in the social sciences. Even so, this fact is entirely irrelevant to the value of our methodology. The choice to admit corporate agents or not belongs to the researcher, not the model, and the model works equally well with our without corporate agents. Similarly, the question of monism v. pluralism is at issue. Again, because the model *allows* for multiple structures of influence does not mean it *demands* them. Structural monists should find equal utility herein.

Conclusion

This minimal conceptual framework offers the first steps towards a robust methodology for investigating complex causal and constitutive social systems. The next step is for motivated practitioners of MAS to transfer the concepts herein into a software environment. As a social and political theorist, this is admittedly entirely outside the scope of my expertise, and I welcome with open arms any and all attempts to refine the model on offer by actual implementation. Subsequent implementations could provide the possibility of an emerging *simulation language* for MAS in the social sciences which would provide transferability and incremental progress of MAS research. In addition, being able to perform both causal and constitutive modeling within the same framework would provide a modicum of commensurability as regards the outcomes of the models. Reflecting on the philosophy of science for a moment should serve to illuminate the need for inter-paradigmatic comparisons, however difficult (Kuhn, 1996; Lakatos and Musgrave, 1970).

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