Innovation Systems are Self-organizing Complex Adaptive Systems

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Abstract

Creativity and innovation can be viewed as Complex Adaptive Systems (CAS) phenomena that occur at different scales, including individual, group, and organization levels. It is conjectured that at the collective level, creativity and innovation can be conceptualized as emergent properties of a system of interacting agents within a CAS. To illustrate the utility of the proposed approach, CAS mechanisms and principles are substantiated in terms of the structure and dynamics of a specific form of user innovation community, called Open Source Software (OSS) development. Specifically, evolution processes that involve variation and selection through professional attention are conceptualized using various organizational design configurations (i.e., network membership, structure) and governance mechanisms (i.e., coordination, conflict resolution, and decision making) to mimic the co-evolution of the project and the community. The paper concludes by proposing a set of proxy metrics that can be used to evaluate emergent system of interactions and organizational structures in OSS communities to measure their innovation output, as well as potential.

Introduction

Creativity is the production of novel and useful ideas by an individual or group of individuals working together (Amabile 1988). Innovation is an extension of creativity, as it is the successful implementation, adoption, and transfer of creative ideas, products, processes, or services (West & Farr 1990). Although the effectiveness of brainstorming in groups has been researched and debated (e.g., (Mullen, Johnson, & Salas 1990)), little is known about how creative minds interact via group processes (Kurtzberg & Amabile 2001). From a process perspective, creativity involves social, cognitive, and technical processes situated in individual, team, and organization contexts that repeatedly produce innovative products. This study aims to answer the call for new methods of studying organizational creativity and innovation (e.g., (Anderson, Dreu, & Nijstad 1990)). For instance, one of the five umbrella research areas identified in the final report of the NSF Innovation and Discovery workshop (NSF 2006) is as follows:

Computational modeling and agent simulations of innovation/creativity that allow for theoretical development across levels of individual, group, and organizational analysis.

The Synergy between Creativity and CAS

Creativity and innovation is a CAS phenomena that occur at different scales, including individual, group, and organization levels. At the collective level, creativity and innovation can be conceptualized as emergent properties of a system of interacting agents within a CAS. Such systems consist of processes that are dynamic, non-linear, path dependent, and self organizing, in which global (e.g., creativity, innovation) properties emerge from the local interactions of actors, which influence one another in response to influence they receive (Miller & Page 2007). As such, the model-based exploratory strategy advocated in this study aims to facilitate revealing the minimal structural and behavioral conditions, that is, the simplest set of assumptions, for the emergence and sustainment of organizational creativity and innovation.

Benefits of the CAS Perspective

The anticipated benefits of abstracting a conceptual model of collective creativity and innovation based on the CAS perspective are three fold:

- A formal simulation testbed improves empirical understanding of creativity by making it possible to explore whether particular types of observed regularities pertaining to creative organizations can be reliably generated via agent-based CAS models.
- The proposed strategy helps investigating if such models can be used as computational laboratories for the discovery of organizational designs that are creative and conducive to innovation. This serves to normative understanding by determining if certain designs proposed for community networks, governance mechanisms (i.e., coordination and decision making styles), and culture result in desirable innovation performance over time.
- Agent-based simulation of organizational creativity also enables theory generation by facilitating better understanding of innovation dynamics over full range of possible configurations and behaviors.

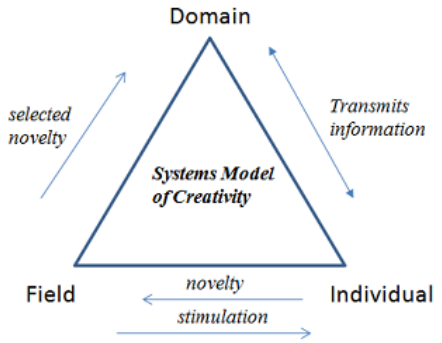

Figure 1: Systems Model of Creativity.

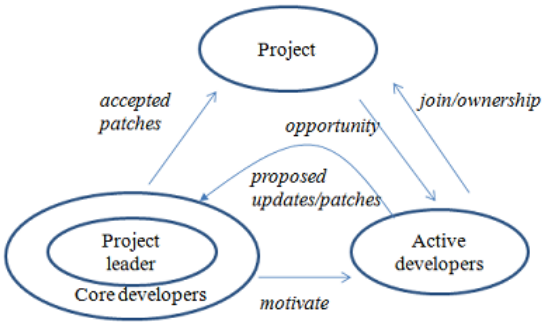

Figure 2: OSS Mode of Production.

The rest of the paper is structured as follows. In section 2, the synergy between systems model of creativity and the mode of production of OSS development communities is discussed. In section 3 the basic elements of CAS are laid out and interpreted in terms of the structure and process of OSS mode of production. Section 4 extends on this interpretation to propose a conceptual model of OSS development dynamics. Section 5 proposes a set of proxy metrics that facilitate measuring innovation potential of user innovation communities involved in OSS development. Finally, in section 6, we conclude by discussing potential avenues of future research.

Systems Model of Creativity

The systems view of creativity (Csikszenthmihalyi 1999) advocates the role of cultural and social environment, as well as psychological dimension in defining creativity. According to the model, for creativity to occur, a set of domain-specific rules and practices must be adopted for an individual to produce a novel and appropriate contribution. The contribution results in a variation in the domain, and it must be selected by the field that represents the society for inclusion in the domain.

Csikzentmihalyi's systems model of creativity shown in Figure 1 captures this phenomena. The model considers *domain* as a critical component of creativity because it is impossible to introduce a variation without reference to an existing pattern specified in the domain knowldge. The technical contributions made by *individuals* that produce creative solutions to domain-specific problems. Such technical contributions induce novel variations in the domains that constitute the context. However, acceptance of variations and innovations in a domain requires the community of scientists and engineers of the *field* to confirm the appropriateness of the contribution. Hence, it is useful to view the evolution of a specific domain in terms of interactions between the individual, domain, and field components.

The mode of production in OSS development as shown in Figure 2 presents structural and behavioral similarities to the systems model of creativity. *Active developers* in such communities freely join and aim to gain ownership of the *project* by proposing patches to existing source code. The project presents to developers opportunities to make contributions and enable them to adjust their actions based on the evolving code base that defines the domain knowledge. The proposals are evaluated by the *project leader* along with a small group of *core developers* on the basis of technical merits and elegance of the contributions. Selected contributions are then reflected on the project. The actions of the leader and the core group influence the intrinsic motivation of the participants of projects by affecting the joy and reputation they gain in the process. This strong similarity between the systems model of creativity and OSS mode of production suggests OSS community dynamics and software development process as a useful testbed to study organizational creativity and innovation.

CAS Principles and User Innovation Communities

In his seminal work on adaptation and its role on complexity, Holland (1995) presents four common properties and three universal mechanisms: aggregation, tagging, nonlinearity, information flows, diversity, internal models, and building blocks mechanism. Next, we interpret these principles in the context of user innovation communities (von Hippel 2001) such as OSS development groups.

Aggregation

Aggregation refers to composition of primitive and basic elements of a system into a composite unit. In addition to this structural view of composition, aggregation is concerned with the emergence of complex large-scale behaviors from the aggregate interactions of less complex agents. Aggregates can be viewed as meta-agents at a higher level of abstraction. The structure of OSS communities exhibits a layered architecture. The project leader is often the person, who initiates the project. Core developers are responsible for collective guidance and coordination of the project. Active developers regularly contribute new features and fix bugs. Peripheral developers occasionally contribute new functionality or fix bugs. Their contribution is irregular and the period of involvement is sporadic and short. OSS systems and communities co-evolve through the contributions of large number of participants.

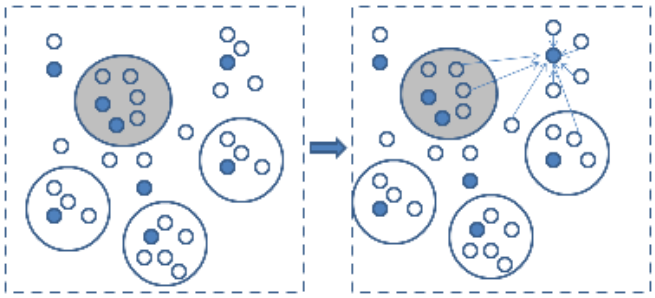

Figure 3: Reputation - Tagging Mechanism.

Tagging

The formation of aggregates requires mechanisms for attracting agents toward each other. The notion of tagging is proposed by Holland (1995) as a strategy used by agents to perform selective interaction. The evolution of the community occurs as a result of entrance of new members, exit of old members, and role transformation of existing members. In our model, the internal dynamics of an OSS community will be patterned after variation and selection through preferential attachment mechanism presented in (van Wendel de Joode, de Bruijn, & van Eete 2003). The notion of project leader *reputation* as a tag for attracting active and peripheral developers and the mechanism of *imitation* (van Wendel de Joode, de Bruijn, & van Eete 2003) explain which projects developers direct their efforts. In Figure 3 small dark circles represent the developers with high reputation. When a developer with high reputation and outside a specific cluster develops a new application or thread of development, others are attracted based on the degree of reputation. This may result in one or more independent threads of development. If one development line receives highly respected developers, while the second one has fewer and less reputable developers leading the effort, the signaling effect of the reputation tag results in preferential attachment to the project with more reputable developers. This reputation-based tagging notion, along with the imitation mechanism, leads to positive feedback through which one application or development line becomes the dominant one.

Nonlinearity

A numerical property of a system is linear, relative to values of the parts that constitute the property, if the property is a linear function of these values. However, the elements of a complex system interact with each in a nonlinear way, making simple arithmetic through differential equations to algebraic topology ineffective, as they rely on the assumption of linearity. For instance, in an OSS development community, cumulative contributions of active developers to the project can be defined in terms of the contributions accepted so far, proposals generated during the last time period, the acceptance rate of proposals, and the reputation of the developer. More specificaly, we can define cumulative contribution using the following nonlinear equation:

$$C(t+1) = C(t) + (\alpha \times P \times r(t)) - (\beta \times C(t)) \quad (1)$$

In this equation $C(T)$ refers to contributions at time t, P defines the number of generated proposals, α indicates the acceptance rate by the leader, $r(t)$ is the current reputation level of the developer, and β refers to the overriding of prior contributions by new developments. The proposal generation can be more specifically defined as

$$P = ln(1-p) \quad (2)$$

where p is a stochastic variable between $(0, 1]$. As the probability p increases the amount of contribution decreases, indicating that smaller efforts occur with high probability.

Information Flow

In CAS, information flows are are considered over a network of nodes and connectors. The flows through these networks vary over time; moreover, nodes can appear and disappear as the agents adapt of fail to adapt. Viewing an OSS community as a social network of developers facilitates the definition of information flows in terms of knowledge mobility. Contributions from one group may solve the problems of another, if connections between existing solutions can be made across boundaries. When such connections are made, existing ideas appear new and creative as they change form, cobmbining with other ideas to meet the needs of users of another project.

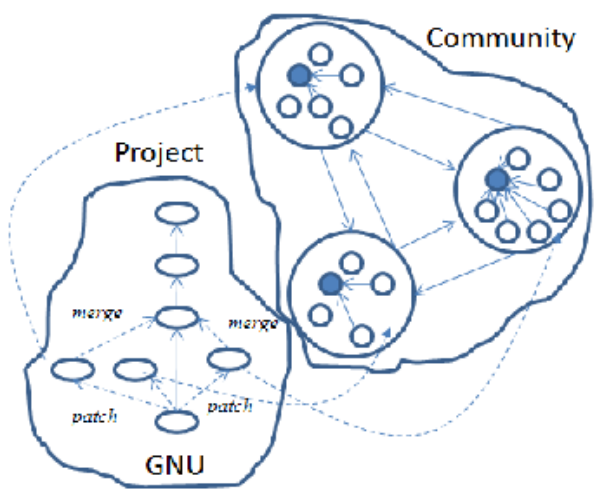

Figure 4: Information Flow in OSS Communities.

The evolution of the project can be viewed as a bottom-up generative process whereby the core software goes through multiple iterations that improve over time. A plausible perspective is to consider the project to be organized in a tree form, which grows as new subprojects are initiated and patches are created. Figure 4 depicts the evolution style of a popular OSS community, called GNU. To simulate the growth of a project, it is necessary to model the effort of individuals along with the evolution of versions (releases) according to a mechanism that mimics the reputation-seeking behavior of individuals. Corresponding to each subproject, a community of developers grow as new participants join and contribute by submitting their inputs to the project leader. In

addition to such contributions at the subcommunity level, skills and knowledge flow across community boundaries, as developers contribute to multiple threads of development within the same project.

Diversity and Internal Models

Diversity and heterogeneity of agents in a CAS enables specialization for adaptation to emergent states. For instance, the notion of convergence in biology facilitates fulfilling the role of a replaced agent through cascading adaptations, so that a new agent with requisite skills can emerge and fill the role. In OSS communities, developers possess diverse skills, which enable selective attention of agents to project features that are consistent with their skills. Furthermore, agents make decisions based on perceptions and anticipations, which require internal predictive models that specify self, others, and the environment. As suggested by Kanter (1988) and Amabile (1996), intrinsic task motivation plays a critical role in creativity and organizational innovations. Credible models of innovation in OSS communities require a level of fidelity that captures individual differences and preferences, as well as their incorporation into the project growth model depicted above. The use of an agent-based model of an OSS community, in which agents that represent developers have autonomous decision making capabilities facilitate seamless integration of human behavior. A widely accepted approach to motivation is the expectancy model, also known as expectancy theory (Vroom 1964). Motivation is defined as a product of three factors: how much one wants a reward (valence), one's estimate of the probability that effort will result in successful performance (expectancy), and one's estimate that performance will result in receiving the reward (instrumentality) (e.g., acceptance of a developer's contribution by the project leader or the core members). This relation is stated in the following formula.

$$M = Valence \times Expectancy \times Instrumentality \quad (3)$$

The range of valence, expectancy, and instrumentality can be dynamically updated to revise the motivation level of an agent (i.e., developer), which then influences his/her participation frequency and performance. Figure 5 depicts plausible variation ranges for a baseline agent. Motivation will be used in the OSS community model as the strength of the drive of individuals toward making contributions.

The feedback from the community (e.g., core members or the field in systems model of creativity) will either stimulate or hinder motivation by updating the values of valence, expectancy, and instrumentality. Alternative personality traits and roles can be represented by varying the upper and lower bounds of these ranges.

Building Blocks

The (re)use of building blocks to generate internal models, as well as objects in the environment is a pervasive property of CAS. Combining basic elements in different ways to generate novelty is also an important part of the creative process. In the OSS development domain, possible features of

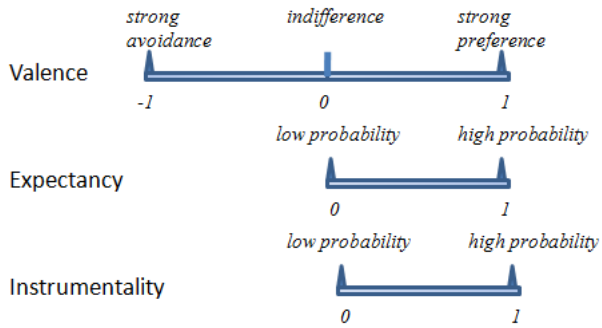

Figure 5: Model of Motivation.

the software sytem can be considered as the building blocks. More specifically, a project can be speficified over a space of binary strings of length n, where n is the size of the largest set of possible features for the application of interest. For instance, the project specified by the binary string

$$< 0100101 \ldots 101 >$$

that depicts those projects that combines features $f_2, f_5, f_7, \ldots, f_{n-2}, f_n$. Note that, diversity of agents in terms of skill variation dictate that only those agents, whose skills match features of a given project can contribute to that particular project.

A Conceptual Framework for Exploring Creativity and Innovation in OSS Communities

Figure 6 depicts the components of our theoretical model that is used for the study of organizatioal creativity and innovation in OSS communities. It depicts community structure (social network) design, network generator (synthetic community generator), the governance processes, community culture, individual characteristics, and project evolution processes.

One way to investigate the structure of an OSS community is to view the organization as a social network. Powell et al. (1996) stated "A network serves as a locus of innovation because it provides timely access to knowledge and resources that are otherwise unavailable, while also testing internal expertise and learning capabilities (p. 119)." Organizational networks can be characterized along several dimensions such as network design and their process components (Dhanaraj & Parkhe 2006).

Network Structure

The information presented in this section is concerned with the network design components (i.e., network membership and network structure).

- **Network membership - Size:** With regard to network size, the research is fairly consistent in that there is a positive relationship between network size and innovation such that as the size of the network increases, innovation performance also increases (**?**). However, it should

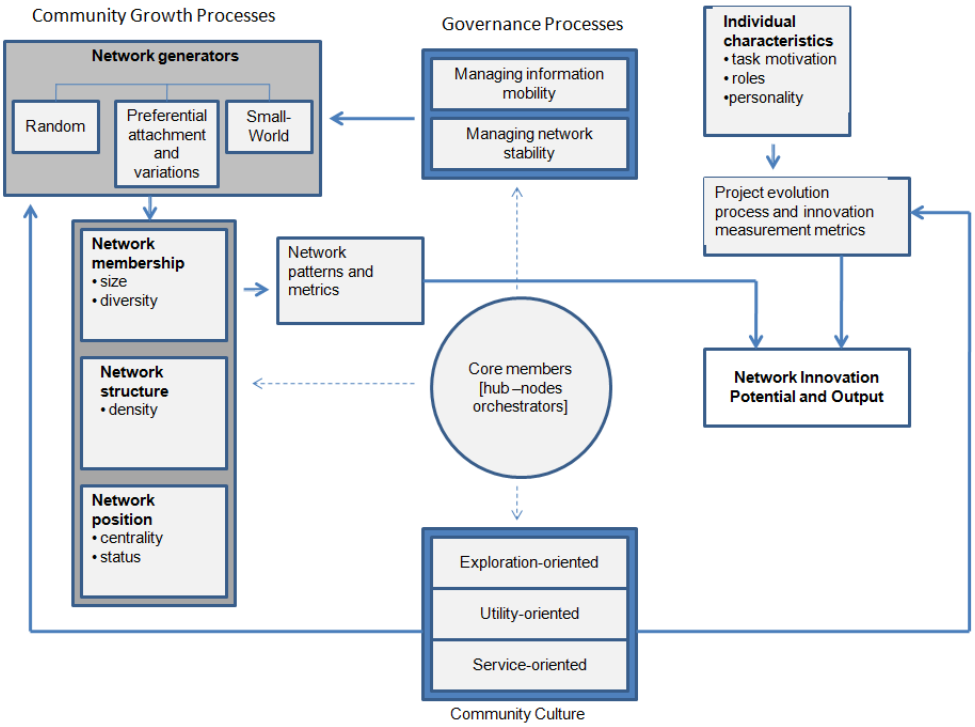

Figure 6: Theoretical Model.

be noted that this relationship likely asymptotes at some point. That is, there is likely some critical point at which adding new members to the network does not increase innovation.

- Skill Diversity: (Powell, Koput, & Smith-Doerr 1996) assert that diversity of sources of information leads to innovation. In addition, (Dhanaraj & Parkhe 2006) state "Innovation networks thrive as organizational forms when sources of expertise are widely dispersed and knowledge base is complex and expanding (p.661)." Based on this more recent research, diversity of knowledge sources is believed to increase creativity and innovation.
- **Network structure - Density:** Density refers to the level of interconnectedness between the ties of various members within a network. Density is a characteristic of the entire network and measures the relative number of relationships within the network that link agents together. Network density can be computed as a ratio of the number of relationships that exist to the total number of possible relationships that would exist if every agent was tied to every other agent (Rowley 2001).

On the one hand, higher density networks leads to information sharing (or mobility) which is expected to enhance innovation. On the other hand, higher density networks may lead to the creation of shared norms and conformity and thereby less diversity, which hinders innovation. We manipulate both density and diversity, so that we can track the effects of the interaction between these two factors on innovation.

Community Culture

The culture of an OSS community can have a significant impact on the evolution of the project and the innovation potential of the community (Furst, Blackburn, & Rosen 1999).

Table 1 depicts the classification of community cultures based on decision making and coordination styles. In exploration-oriented communities (e.g., GNU community) the product evolves mainly at the hand of the project leader. Direct contributions are not frequent as they have to be incorporated only if the project leader finds the contribution consistent with his or her architectural vision. Most community members collaborate with the leader, and since the decision making and coordination is cathedral style as opposed to bazaar, it is more difficult for community members to move toward the center. In utility-oriented OSS communities (e.g., Linux), centralized control is minimal, and developers frequently create new projects to meet personal needs. The projects that receive interest grow, while others diminish due to lack of interest. The evolution pattern can be viewed as a tournament style. The decision making for contributions is also decentralized. In service-oriented communities (e.g., PostgreSQL and Apache), the goal is to provide robust and stable services to the user community. In accordance with its conservative nature, the contributions are evaluated by several core members (not just the project leader), and the decision making is distributed across the members of the core group. The majority of the core group needs to confirm proposed changes before a contribution is accepted. The coordination is achieved via a centralized scheme, where contributors need to communicate their im-

Decision-making style	Coordination Style	
	Centralized	**Distributed**
Centralized	Exploration-oriented	
Distributed	Service-oriented	Utility-oriented

Table 1: Community Cultures

provement suggestions and contributions to the core group. As such, the control and decision making mechanism can be viewed as council style. Recognizing the potential impact of community cultures on innovation and project growth patterns, the above formulation of the bottom-up growth of the project tree needs to be further refined to take into account the styles of growth suggested by alternative cultures.

Measuring Innovation Potential

By far, the most widely used measures of innovation and creativity are (a) the number of nonredundant ideas, (b) ratings of idea or product quality, and (c) information mobility, and stability.

Measuring Innovation Potential: In (Dhanaraj & Parkhe 2006), it is shown that network innovation output will be greater the higher the level of (1) information mobility and (2) network stability orchestrated by the hub members. Our preliminary investigation reveals that network resilience and structural holes may be used as dependent variables to measure stability and mobility, respectively. The resilience of a graph is a measure of its robustness to node or edge failures. Many real-world graphs are resilient against random failures but vulnerable to targeted attacks. There are at least two definitions of resilience. Tangmunarunkit et al. (2001) define resilience as a function of the number of nodes n: The resilience R(n) is the minimum cut-set size within a n-node ball around any node in the graph (a ball around a node X refers to a group of nodes within some fixed number of hops from node X). The minimum cut-set is the minimum number of edges that need to be cut to get two disconnected components of roughly equal size. Intuitively, if this value is large, then it is hard to disconnect the graph and disrupt communications between its nodes, implying higher resilience. For example, a 2D grid graph has R(n)= $\sqrt{n}$ while a tree has R(n) = 1, thus, a tree is less resilient than a grid. Resilience can also be related to the graph diameter: A graph whose diameter does not increase much on node or edge removal has higher resilience. The knowledge mobility in a social network depends on information benefits that are defined in terms of who knows about opportunities for contribution, when they know, and who gets to participate in them. A developer with a network rich in information benefits has (1) contacts established in places where useful bits of information are likely to surface and (2) a reliable flow of information to and from those places (Burt 2001).

Structural holes (Burt 1992) in networks is proposed as a social structure for competition, as well as a basis for network entrepreneurship (Burt 2001) via measuring nonredundancy between members of a network. There is an ongoing debate in the social networks literature about the relationships among density, structural holes, and innovation (i.e., whether more density or less density in organizations leads to positive innovation outcomes). On one side, the logic is that developing multiple relationships with disconnected structures (high centrality and low density) leads to more structural holes which results in more unique sources of information/knowledge-thus, higher levels of innovation. However, the low density also means there is less trust, less shared knowledge, and less shared resources (i.e., more structural holes), more trust, more shared knowledge, and more resources seem to be important for innovation in a collaborative system. Thus a competing hypothesis is that the interconnectedness of the partners in a network connected to the leader or hub (i.e., high density and fewer structural holes) is believed to facilitate innovation by other researchers (e.g., (Burt 1992)). Thus, we will test these 2 competing hypotheses regarding the relationship between structural holes and innovation. It is established that cohesion and structural equivalence (Kilduff & Tsai 2006) are empirical indicators, the absence of which indicate presence of structural holes.

Concluding Remarks

To illustrate the utility of the proposed approach, CAS mechanisms and principles are substantiated in terms of the structure and dynamics of a specific form of user innovation community (von Hippel 2001), called Open Source Software (OSS) development. The synergy between such communities and innovation systems are established, and it is posited that OSS development exhibits the characteristics of self-organizing complex adaptive systems. The premise of the proposed model is based on the observation of similarities between the systems model of creativity and the mode of production in such communities. The paper concludes by proposing a set of proxy metrics that can be used to evaluate emergent system of interactions and organizational structures in OSS communities to measure their innovation output, as well as potential.

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