# Collaborative Creativity: A Complex Systems Model with Distributed Affect

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## ABSTRACT
The study of creativity has received significant attention over the past century, with a recent increase in interest in collaborative, distributed creativity. We posit that creativity in distributed groups is fostered by software interfaces that specifically enable socio-emotional or affective communication. However, previous work on creativity and affect has primarily focused on the individual, while group creativity research has concentrated more on cognition rather than affect. In this paper we propose a new model for creativity in distributed groups, based on the theory of groups as complex systems, that includes affect as well as cognition and that explicitly calls out the interface between individuals as a key parameter of the model. We describe the model, the four stages of collaborative creativity and the causal dynamics in each stage, and demonstrate how affect and interface can facilitate the generation, selection, and amplification of ideas in the various stages of collaborative creativity. We then validate our model with data from three field sites. The data was collected from longitudinal studies of two distributed groups involved in producing creative products—astrophysicists studying supernovae and the expansion rate of the universe and children creating multimedia programming projects online—and interviews with staff in a multinational engineering company.

## Author Keywords
Collaborative creativity, distributed affect, distributed groups, computer-mediated communication, creativity model.

## ACM Classification Keywords
H5.3. [Information interfaces and presentation]: Group and organization interfaces–Computer-supported cooperative work.

## General Terms
Theory.

## INTRODUCTION
Creativity is arguably humanity's supreme achievement, the subject of research in multiple domains—including, among others, psychology, computer science, economics, organizational studies, environment and planning, and small group theory. Contrary to the popular belief of the "aha" moment of insight, recent work has indicated that creativity is often a series of incremental steps to discovery [57]. As the discovery/idea is developed, it is amplified over time in its social context/milieu. Ideas that are judged to have positive value are magnified while ideas of lesser value are progressively discarded. This suggests that a dynamical systems approach similar to that used to understand the spread of innovative technologies in the market [7] or the dynamics of small groups [6] may also be applied to collaborative creativity.

Recent technological developments have led to a sudden jump in the ability of humans to collaborate across distance in many types of activity, including creative work [10], resulting in a research focus on collaborative creativity and its underlying cognitive processes [20, 53]. There is also an extensive body of work on the importance of affect or emotion in the individual creative process; and yet more recent work on the socio-emotional processes of virtual teams [53]. We apply the theory of groups as complex systems [6] to synthesize elements of these disparate but interrelated areas of research into a new creativity model.

This paper's primary contribution is a new dynamical systems model of creativity in distributed groups that includes affect as well as cognitive processes, and that explicitly calls out the interface between individuals (mediated communication) as a key parameter of the model. Our work draws upon much previous research in multiple areas, including Poincare's and Wallas' models of creativity [51, 63], Russ's work on affect and creativity [56], work on group creativity by Sawyer [57] and Tatsuno [60], Arrow et al.'s theory of groups as complex systems [6], and Hutchins' distributed cognition [28]. We were additionally influenced by Sutton and Hargadon's work on group brainstorming [59], Girotra et al.'s hybrid idea-generating model [24], Arthur's work in economics on the phenomenon of increasing returns based on assumptions of random processes and on the evolution of technology [7], Benkler's work on networks [10], work on virtual teams by Powell et al. [53], and creativity research by Amabile, Czikszentmihalyi, Harrington and others [3, 4, 16, 27].

We first provide a brief survey of creativity and virtual team research relevant to the topic of group creativity and


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affect as facilitated by computer-mediated communication (CMC). We define key terms, such as creativity, distributed groups, and affect. We then describe the study methodology and the background of the three creative groups to which we applied our model: astrophysicists studying supernovae and the expansion rate of the universe, children creating multimedia programming projects online, and employees in a multinational engineering company.

We next present a new, dynamical systems based theory of collaborative creativity, including the four key stages identified in the collaborative creative process. We illustrate the model's dynamics and stages with examples from our longitudinal studies of the groups. A key strength of our model is that it is based on long-term observation of real-world creative groups. Because creativity is a process that often takes place over a span of time [37] it is critical to understand the temporal aspects of group creativeness, rather than relying exclusively on single-session laboratory experiments.

Arrow, McGrath, and Berdahl argue that groups form complex dynamical systems, and thus our study of distributed creative groups focuses "not on differences in *values* of variables between distinct social entities at a given time but rather on qualitative *patterns* of dynamical variables exhibited by social entities or systems over time" [6].

## BACKGROUND

Although Guilford's [26] landmark speech to the American Psychological Association led to a flowering of creativity research, much of this work continued, as it had done previously, to focus on the individual [3, 4] and the individual creative process [21, 51, 63]. By the 1990s interest in group creativity was growing, with Tatsuno's [60] organizational group process, Resnick's [55] creative learning spiral, and Sawyer's performance-based studies [57], among others, exploring what happens when creativity develops in a face to face group environment. However, with the growth of electronically-enabled distance working, researchers are now examining what happens when distributed groups of people work on projects explicitly aimed at generating a creative product [10].

### Definitions and types of creativity

Within the field of creativity research there is a consensus [42] that novelty or originality and usefulness or value [11] together with development over time [37] are defining characteristics of creativity. Simonton's definition of creativity incorporates different types or levels of creativity: big-C creativity that contributes to and changes culture and history, and small-c creativity that leads to improved problem-solving in daily work and in life [58]. Simonton concludes that there is a continuous scale of creative activity on which these different types of creativity are graded; and it is this definition that we adopt, studying it across the whole spectrum from small-c to big-C creativity in the context not just of generating big-C ideas and outputs, but also of using small-c creativity to problem-solve challenges facing the group.

We adopt Edwards' and Al-Ani's [20] definition of *distributed groups* as meeting two out of the three following criteria: members occupying more than a single time zone, located in different countries, and from different cultures or speaking different languages.

Additionally, for the purposes of this paper, we utilize Russ's definition of *affect* as "a feeling or emotion as distinct from cognition" [56]. It is a more inclusive term than *emotion*. We use the term *socio-emotional* to refer to relationship-building or affect-laden communication, thought, or behavior—both in terms of content (*"My wife has just had a baby*") and of expression ("*Yayyy production!*"). Finally, we use the term *collaborative creativity* here to refer specifically to creative work carried out by distributed groups. The work of purely collocated groups is beyond the scope of this paper.

## RELATED WORK

Three kinds of creative process are relevant: individual internal or cognitive creative processes, group creative processes within a team or collaborative environment, and contextual processes situating individual creativity within its wider academic and social context. We examine current work that brings together these three creative processes and look at work on affect within creativity, setting the scene for the proposed model.

### Individual creative processes

While it is arguable that each person devises their own unique creative process, the individual creative process has been formalized by Wallas [63], building on Poincaré's [51] examination of his own creative thought processes. Wallas proposed four stages to creative work: Preparation, Incubation, Illumination, and Verification. This firmly established the place of conscious as well as unconscious work in the creative process, laying the foundations for other models [21, 27, 49, 64].

### Affect and individual creativity

A substantial body of work, primarily in the field of psychology, exists to demonstrate the importance of affect in the individual creative process. Russ [56] describes a body of research that indicates that "affective processes influence divergent thinking abilities and transformation abilities." She specifically cites the following affective processes important to individual creativity: access to affect-laden thoughts (e.g. primary process thinking), openness to affect states (e.g. passionate involvement in a task), affective pleasure in challenge or problem solving, and cognitive integration of affective material. She has found that emotion broadens search, and that mood-relevant cognition "triggers a broad associative network" [56].

Amabile [3, 4] found that enjoyment can be taken in the creative process and that creativity is intrinsically motivating. Langley and Jones [33] developed a computational model of scientific insight and applied it to the use of analogy in creative problem solving. Martindale [41] believed that creative individuals have states of "defocused attention," where large numbers of neurons are activated simultaneously, so that the more nodes that are activated, the greater the likelihood that an analogy will be noticed between two different elements. Csikszentmihalyi [15], in his work on *flow*, found that love of the work (autotelic activities) caused one creative act to lead to others over time. Lazarus theorized in "Emotion and Adaptation" that affect plays a major role in the process of *appraisal*, or the quick determination of what action to take to survive, thus demonstrating the value of emotion in adaptation and natural selection [35]. Research by Picard into the development of computing that relates to affect and emotion has shown its relevance in the field of artificial intelligence [50]. This wide array of psychology research into the role of affect in the creative process has mainly focused on the individual rather than the group creative process.

**Group creative processes**

There is a substantial body of work on group creativity, variously described as collective, collaborative, or social creativity. There is a general consensus that as group creativity becomes increasingly significant in the world today, particular attention must be paid to the technologies that support collaborative creativity.

Fischer and Shipman call for careful design of technologies and socio-technical environments to support social creativity and cultures of participation [22]. Aside from the use of technological interfaces, much research on the group creative process itself has focused on verbal communication between individuals. Sawyer's studies of improvisation in music and theater focus on the value of group creativity from a linguistic and cognitive point of view [57]. Dunbar [19] studied biologists collaborating. He found that conversation was a driver of collaborative creativity as the biologists spoke, argued, and came up with analogies and collaborative insights in meetings. In a comparison of four labs, he found that the ones that used analogies in conversation came up with more important discoveries. Markman et al. [40] found, in a Lego-building experiment, that talking about their work caused the group to create richer and more complex categories. John-Steiner [30] introduced the concept of "integrative collaboration" and described the profound bonding within a group that leads to shared vision and radical innovation. Within the context of Japanese manufacturing, Tatsuno [60] described five group creative process stages (*recycle, search, nurture, breakthrough, refine*) that, while echoing Wallas' four stages of an individual creative process, are all collaborative.

Since Janis' work on *groupthink* [29], there has been an implicit assumption that groups must be less effective than individuals at creative thought. The cliché "designed by committee" has served to solidify that impression. However, recent work by Nemeth et al. [47] argues that dissent and diversity play an important role in avoiding groupthink. They cite studies showing that social inhibition also reduces creativity. Their study focuses on dissent as a stimulus of creative thought. "[D]issent, even when wrong, serves to liberate the individual from a tendency to conform" [47]. This value of dissent is echoed by a study by Uzzi and Spiro [62] on musicals and creativity, finding an optimal level of interconnection between individuals for creative success. More connections can expose a team to a wider variety of source material, but if a network moves towards complete connection, there is less diversity and conflict, and ideas may become more conventional.

In many of these studies of group creativity, examples are given of processes where affect is clearly present. Sutton and Hargadon discuss the role of affect in how brainstorming allows designers to "experience skill variety" [59]. However, in most studies, affect is usually not called out explicitly for its role as a group creative process driver.

**Contextual creative processes**

As well as research on individual and group creative processes, work has also been done on contextual creative processes. These examine how social, socio-political and domain environments impact on the creativity of those working within them.

Csikszentmihalyi [16] describes a domain theory of creativity in which creativity is situated in the interaction between an individual, the domain (a subject's organized body of knowledge) and the field or 'gatekeepers' of the domain. Sutton and Hargadon [59] position creative brainstorming firmly within organizational contextual processes. Harrington [27] proposes an ecological model of creativity where "acts of social creativity must be viewed as the products of a human ecosystem as well as the products of an individual or two" [27]. As early as 1990, Harrington's work identified the need for a creative process that describes and underpins what he calls *social creativity*. In this paper, we apply dynamical systems theory to construct a new model that does just that.

In his seminal work "Cognition in the Wild" [28] Hutchins introduced the concept of distributed cognition. We see this as a precursor to our theory of collaborative creativity, describing as it does cognition as a process that includes the formation of knowledge outside any one particular individual. It depicts a cognitive ecosystem (echoing Harrington [27]) where information and cognitive processes exist as interactions between individuals and between individuals and their environment. The distributed cognition framework is now used widely in multiple areas such as computer-supported cooperative work (CSCW) and computer-supported collaborative learning (CSCL).

It is interesting that the seminal event leading to this research was a crisis on a naval vessel that generated high levels of emotion and stress. Hutchins noted the emergence of collaborative cognitive processes that accumulated a combination of knowledge that did not exist within any individual human brain. However, he did not explicitly call out the emotional states that drove the collaborative problem-solving process that led to the solution of the vessel's mechanical problem and enabled them to avoid crashing into the shore. It is this area of emotional states in distributed groups that we explore in our research and present here.

Finally, from the extensive literature of team development we reference Tuckman and Jensen's work [61] as important in bringing forward the balance between the team's task and its socio-emotional needs and states. As we set out our four-stage model of collaborative creativity we refer to the five stages (*form, storm, norm, perform* and *adjourn)* in their more detailed original form [61].

## METHODOLOGY

The theory developed in this paper arose out of the authors' longitudinal studies of multiple long-term collaborations exhibiting creativity across the continuum from small-c to big-C. One author works with organizations supporting their creative processes and studying in depth the physical environments necessary for organizational creativity. The other has studied scientific and technical online collaborations in detail, with a focus on distributed creative technical work. In the course of our work, we both had come to see facets of group creativity that were not fully explained by previous creative models. This research emerged from our desire to find a model that could more effectively capture the commonalities in the group creative process that we observed time and again across widely dissimilar groups, and that could lead to a deeper understanding of collaborative creativity in the networked world of today. New technologies facilitating mediated communication over distance have contributed to our work by making previously hidden content more explicit; thus the evidence driving much of our research is online from chat logs and other persistent modes of CMC. It is also supplemented by a rich data set of interview and observation.

We revisited existing data sets to derive the model we put forward in this paper, then tested and refined it within the context of the various distributed groups that we have studied closely (astrophysicists' collaboration, children creating multimedia projects online, and engineering company employees).

The groups we focus on all meet the criteria for distributed groups [20], and all possess the following key characteristic: they are performing creative technical work that requires both a degree of specialized knowledge (astrophysics, programming, or engineering) and the generation of a range of creative ideas. The astrophysicists are working all the way from small-c to big-C (e.g. trying to solve a grand challenge problem about the nature of the universe, but also needing to build novel software tools to solve practical telescope engineering problems), while the children and engineers, although not attempting foundational societal change, nevertheless exhibit boundless amounts of creativity across the small-c to big-C spectrum in their daily work. A description of the three groups and the study methodologies follows.

### Scratch

Scratch [39] is a programming language developed by Mitchel Resnick's research team at the MIT Media Lab, designed to enable children to create programmable media such as games, interactive stories, animations, music and art. The Scratch Online Community (scratch.mit.edu) [45] was developed to be a source of inspirational ideas, to provide an audience for children's creations and to foster collaboration among its members.

Since scratch.mit.edu went online in May 2007, a number of "companies" or collaborative groups have been formed spontaneously on the Scratch web site by the children themselves, with the main goal of creating projects together. We studied one such company that has been relatively successful in terms of producing several finished video games which were "published" to a gallery on the Scratch web site. The company, referred to here as "Green Bear Group" (GBG), was active for over two years from 2008 to 2010, and produced seven complex, polished projects during this time.

Three children, ages 8, 13, and 15, were the "founders" of the company, and it had a membership ranging from 12 to 18 children over the period studied. The active participants in Green Bear Group have, for the most part, never met one another, live in different time zones, and do not even know each other's real names. The 8-year-old "owns" the GBG gallery and the founders collectively make decisions on company membership. The members then vote on which games to develop. Each member has a specific skill, such as art, music, programming, or storytelling, which they contribute to the game by downloading an unfinished version, editing the program, and re-uploading a new version. This process is called "re-mixing" and is iterative. Each finished GBG game has had on average 17 remixes [5].

### The Nearby Supernova Factory

The Nearby Supernova Factory (SNfactory) [2] is an international astrophysics collaboration studying supernovae (exploding stars) in order to address a physics grand challenge problem about the expansion rate of the universe. The collaboration consists of about 30 members; about half of the scientists work at several different locations in the U.S. and the other half in three research institutes and universities in France. Collaboration members develop software to aid the collection and analysis of supernova data, remotely operate a telescope in Hawaii, and collaborate on scientific research and publications. The scientists are in different time zones from each other (France, California, the US East Coast) and from the telescope itself (Hawaii). Some team members have never met and come from differing cultures with dissimilar assumptions; some are not native English speakers.

Collaboration scientists use chat (augmented by a virtual assistant [52]) and VNC (virtual network computing) as their primary means of communication during telescope observation.

### Multinational Engineering Company (MEC)

Interviews conducted with senior staff in the engineering company [name withheld by request] formed part of a wider post-graduate research program and focused specifically on collaborative creativity with distributed groups across the company of 80,000 employees.

### Study Methodology and Group Demographics

The examples used to illustrate the model are derived from longitudinal studies of the collaborations described above. The SNfactory was studied over a period of five years, and GBG over a period of two years. Study methods were participant observation, semi-structured interviews, and chat log analysis. More detail on the studies can be found in [5].

At the end of one study period (July 2009), the SNfactory had a membership of 28 scientists, including 14 senior scientists (permanent or tenured positions), eight junior scientists (post-doctoral researchers), and six graduate students. Each level had an even distribution of personnel between the US and France, satisfying Edwards and Al-Ani's criteria for distributed groups [20].

Within MEC, separate interviews were conducted in April 2010 with two network leaders of distributed groups comprising, respectively, 150 people in 90 transglobal locations and 12 people across the three global areas of AsiaPacific, the Americas, and EMEA (Europe, Middle East and Africa).

As of July 2010, Green Bear Group had 18 members ranging in age from 8 to 17 (self-reported). 11 of the members were located in the US, three in the UK, two in Canada, and one each in Poland and India.

All quotations in this paper use pseudonyms.

## THEORY

Abrahams has explored the mathematical fields of dynamical systems theory and complexity theory in the context of psychology [1]. This, along with recent work by Arrow, McGrath, and Berdahl on a theory of small groups as complex systems [6] and our observations of creative practice across three field sites, has led us to apply similar principles to the process of group creativity.

As we construct our model of collaborative creativity, we focus primarily on the nature of creative groups as open, adaptive, complex systems, and on the causal dynamics in the group that facilitate the creative process on local, global, and contextual levels. We describe the role of affect and interface in facilitating these dynamics to foster creativity, and use analogies from complex systems to develop our model. In our previous work with distributed creative groups [5], we have repeatedly observed a phenomenon akin to the physical behavior of resonance, or driven harmonic motion, where key ideas begin small and grow and are elaborated over time. We hypothesize that, as in physics—where for an impulse to be amplified and for the system to oscillate at the resonant frequency, the system must easily be able to store and transfer energy between two or more different modes (e.g. a pendulum and the case of kinetic and potential energy)—the same phenomenon can be observed as creative ideation flourishes across a distributed group. We term this process *creative resonance*.

This model of incremental development leading to apparent discontinuous growth is consistent with previous theories of the individual creative process [17, 21, 56, 57, 63].

Key ideas of our model are based on group creativity research in psychology that shows that the creative process is much less of a "spark" or "leap" and much more incremental than commonly believed [57]. The nature of dynamical systems, similarly, is that local dynamics of the incremental type plus feedback loops can lead to nonlinear/discontinuous global dynamics (e.g. the "sudden insight"). We postulate that group interactions, specifically those of affect, facilitate these feedback loops. The 'sudden leap' appears to happen in the individual creative process only because many of the incremental stages are hidden in the 'intelligent unconscious' [13]. In the group process the interface makes it overt.

Finally, we hypothesize that affective, social or technological factors may act to damp the phenomenon of resonance. These three factors are consistently identified across disciplines: Quershi and Vogel [54] working with virtual teams, identify technology, work, and social adaptation issues as key within a virtual team environment. The social psychology of creativity [3, 4] identifies social and affective inhibitors to creativity, as does the literature of creativity in collocated teams [43]. Research into virtual teams [53] identifies trust, relationship building and cohesion as key socio-emotional aspects of successful virtual teams. We hypothesize that the obverse of these aspects acts to damp creative resonance in the system: e.g. low levels of trust which lead to an inability to establish a shared knowledge base [14]; poor relationship building resulting in negative conflict [46] and consequent lack of group cohesion [61].

Technological issues include poor quality technological interfaces [65] or overly-complex ones [48]. Our finding, that group members will adapt inadequate technology to their specific needs [5], is confirmed by Majchrzak et al. [38]. We postulate that recent technological developments have both reduced the damping factors inherent in the means of communication and decreased those present in human behavior. We suggest that communicating affect between members of a distributed group increases the level of energy and engagement between them, and hence the resonance of ideas in a distributed group. "A system needs access to itself. It needs to understand who it is, where it is, what it believes, what it knows. These needs are nourished by information" [66]. The study of resonance-damping and -enhancing factors specific to distributed creative groups is an area for further research.

Our model includes four key phases of collaborative creativity: *focus*, in which the group's rationale is explored and discovered, *frame*, in which the group forms within its context, *create*, when the group does just that, and *complete*, when the final idea or ideas converge and are tested and consolidated. This model is based on our observations of distributed groups; a topic for future study may be to explore its possible application to collocated groups. While we set out our model linearly for clarity, we suggest that it in fact works iteratively within each of its four stages, and across the whole model, nearer to Resnick's spiral model than Wallas' linear one.

***FOCUS*** is concerned with *problem-finding* (as distinct from *problem-solving*) creativity [18]: a problem, curiosity, or area for exploration emerges with greater or lesser force. Where a group is already working together *focus* typically explores an issue arising from, or impacting on, the context within which the group and its members are based. In team development terms [61] this is the first stage of *testing and dependence* in which the activity is *orientation to task*. In dynamic systems terms, a *founded group* emerges from an internal, planned context whereas when an issue or opportunity arises in a wider field a *concocted* group may form specifically to explore it within an external planned context [6]. The process is the same in each case: one person (or small node) notices an anomaly, issue or opportunity and begins an iterative process of sharing their awareness. The wider group opens to the information and builds a picture of the anomaly or issue, collaboratively determining its level of importance and urgency and hence whether or not to proceed; an *extrinsic collective goal* [57] is identified and described. For one MEC team a small issue identified in one site and then shared across the distributed group was found to be present in all sister sites: "so the awareness builds from one or two of us seeing something, discussing it, crystallizing what the problem is, [to] testing it with the extended group in an extended discussion" (MEC engineer).

***FRAME*** describes how "a sense of family" (MEC interviewee) is created in new or existing groups, building a complex system that can deliver the extrinsic collective goal. Component parts are: behaviors, interfaces, and structures. Information and affect have begun to flow around the system in the *focus* stage, and are made explicit and consolidated in the *frame* stage; the group undergoes a process of enculturation and the establishment of group cohesion [61]. This observation is supported by studies identifying group norms of individual expertise, collective achievement, open communication and interpersonal trust [12, 31, 43] as key to a flourishing creativity. "[Never having met] we just talked as if we had known each other for 20 years. And it always happens when somebody inside the company rings up to discuss something, there's never any kind of tension or difficulty about getting going. I suppose it's because you've got this very strong shared attitude – that is what enfolds it all" (MEC interviewee). Similarly a GBG member, age 13, expressed comfort with sharing her work specifically because of her trust in other members [5].

Group members are able to share information safely and freely within the group norms, to absorb external information, data, ideas and intellectual nourishment, and at the same time to filter out potentially harmful environmental pressures. Trust is a key affective component of open systems [44, 66], building the relationships that include rather than exclude group members and the knowledge they bring. This *affective integration* is experienced as emotional as well as cognitive strength, bringing people closer together [6]. In this *frame* stage group norms are established and interfaces are built enabling affect, cognition and information to be distributed across the system. It is worth noting that trust and affective integration does not mean consensus. Nemeth et al. are clear that creative ideas are unlikely to be generated by consensual thinking, but instead "there is evidence of greater creativity in response to minority dissent" [47]. Intragroup conflict or emotional response to task demands [61] is an integral part of distributed and collocated group development. Montoya-Weiss et al. [46] find a positive impact on performance from *competitive and collaborative conflict* (as opposed to *avoidance and compromise conflict)*. Framing creates a supportive affective environment within which dissent and positive conflict is encouraged and productive.

Framing is also the stage at which interfaces that facilitate affect-laden communication are set up or consolidated: collaboration relies on a free flow of information unrestricted by censorship or gatekeeping [66], requiring efficient and easy-to-use interfaces [48]. For example, the chat environment the supernova scientists used and modified was deliberately designed to have a very low barrier to entry and to facilitate communication of all types [52]. Measurements of the amount of socio-emotional or affective content in the chat room confirmed that relatively high levels were present (32% of total content, as opposed to 16% in an earlier collaboration) [5].

For an existing group *frame* is a continuation or re-energizing of an existing state; with a new group the optimum state for collaborative creativity is established at its inception during *focus*, and developed in the *frame* stage with growing group cohesion [61]. In individual group members there may be a level of resistance to or rejection of ideas as evidenced in Evans and Russell's *frustration* stage [21]. *Framing* parallels Tatsuno's nurturing stage, setting out the ethos and parameters for the ongoing collaborative creative process: creating through the social environment the possibility of "discussing offbeat ideas [...] tossed about, expanded, picked apart, and playfully combined with other ideas" [60]. Framing starts early in the process, but is consciously maintained and grown throughout the life of the group or project.

***CREATE*** By the *create* stage the distributed group has established cohesion through open exchange of perspectives [61]. The group uses iterative, incremental ideation steps, leading to non-linear discontinuities that are experienced as ah-ha! moments of insight [57]. The group shares the raw material of ideas – cognitive information, data, experiential knowledge from internal and also unrelated fields – generating ideas randomly as this divergent [49] process opens the possibility of unexpected juxtapositions [32] in Einstein's 'combinatory play'. As yet more raw material enters the system and is shared through the affective interfaces, so it sparks yet more ideas and a systemic resonance emerges. The system becomes more able to store and easily transfer energy between two or more different storage modes, in this case from individual minds to external representations. As the relative chaos of the initial divergent thinking moves towards complexity and order we see the emergence of structure which becomes the scaffolding for attaining the extrinsic collective goal. In this process we see emerging aspects of Resnick's [55] five-stage spiral process of *imagine, create, play, share, reflect, imagine*, and Laseau's [34] iterative model of creative revision in which "the more often the information is passed around the loop [eye to brain to hand to paper], the more the opportunities for change."

The iterative process of creative revision occurs in product design: Sutton and Hargadon observed designers calling physical prototypes "solidified intellect" [59]; these external representations enabled them to easily transfer and remember creative ideas. We observed analogous processes in the groups we studied; for example, the children created intermediate artifacts on the Scratch website which they used for the same purposes (remixing). These artifacts served as both a reminder of their intellectual work and a source of positive affect. Group product creation was greatly facilitated by the ease with which the Scratch interface allowed this type of idea transfer. As the group experiences success (progress towards creative outputs, small quick wins etc.) and acknowledges it, this enhances the distributed affect in the group. The affect within the system makes the connections between ideas and between people stickier. Sawyer [57], in examining group creativity among performers, suggests that in performance, creativity consists of the parallel processes of ideation and evaluation, both processes done collectively by the group as the performance is underway.

In *create* we observed a similar (if less instantaneous) process taking place: ideas generated by individuals, then shared and built upon by the group members from the perspective of their particular knowledge bases, adding aspects of information and data that may not have been apparent to the idea's originator. Girotra et al. [24], in their comparison of the effectiveness of group structures for idea generation, also conclude that a hybrid model where individuals work both independently and then together has advantages over to group brainstorming.

Three system dynamics are at play in the *create* stage: local, global and contextual [6]. Each of these dynamics contains the key components of information, affect and norms, and interfaces. *Local dynamics* comprise interactions between group members, and how their varying needs are taken into account by the behaviors and structures of the group. Arrow et al. posit that group members have a need to 'tune' the interactions between them, focusing on *affiliation* where they develop socio-emotional links with other group members, needs for *achievement* and power where their skills in specific areas are acknowledged and encouraged, and *agreements* that cover benefit and resource needs [6]. When these local dynamics are tuned, there is a greater possibility of distributed affect creating the resonance that drives and grows ideation.

In the longitudinal study of the Scratch group, affect magnified as each group member shared their excitement about the game they were building: their productivity rate went up, and with each new version the others were excited in their turn. This is borne out by Russ who conjectures that affective experience serves as a cue for problem-finding as individuals experience "tension, pleasurable anticipation of challenge in a problem [and] the ambiguity of a situation" [56]. Csikszentmihalyi's work on *flow* explores this phenomenon in depth and links it to creativity [16, 17]. This process is enhanced where there is high horizontal differentiation in the *global dynamics* (across the group as a whole) allowing members to specialize deeply, and low vertical differentiation so that group members are not inhibited and the resonance not damped by a task-based hierarchical status [6].

Throughout the *create* stage the group is also responding to changes in its external environment. These *contextual dynamics* are mediated by the group's *frame*. Adaptation to the external environment (proximal and distal) can be either undirected (emergent) or directed (driven by goals). For example, the junior supernova scientists were constantly driven by the need to publish and establish a positive reputation in the wider astronomy community so that they could obtain a permanent research position upon leaving their postdoctoral appointment. This led to emotional content in their communication with group members, with junior scientists pressing for goals valued by the wider community, such as open data release. This is a prime example of contextual dynamics driving the end products of the *create* stage.

This stage is characterized by multiple interactions: socio-emotional interaction between people, and between people and information, mediated by the affective interfaces; interaction between ideas, driven by resonance through the system; and interaction between the three system parameters (local, global and contextual). These interactions can be visualized as spirals and feedback loops and are the point where dynamical systems processes such as bifurcation and nonlinear development occur [1]; ideas may resonate with the group, grow wildly, or be damped out.

We hypothesize that the means of communication between individuals can be likened to a physical conductor. The higher the conductivity, the less the resistance, the less the damping/dissipative force. We suggest that the information to be transferred must include the two strands of cognition and affect. Thus we have not only distributed cognition but also distributed affect. New technologies, plus a new generation growing up with the new technologies and co-evolving along with them, have, we hypothesize, led to a decrease in the resistance along these communication channels; thus the reduced resistance of the interface is a local parameter that can have profound effects on the global state. As one GBG member commented, "Scratch is simple, so that made it easy and fun to use and people kept coming back." Affect of various types will also modify the resistance, and can be considered another local dynamic parameter.

The process is about the growth of the idea, the growth of the individual through learning about themselves and others and how to work in collaboration, and the growth of the distributed group as a productive entity. So in the same way as people and technologies co-evolve, so the ideas and the group co-evolve through changing technologies. As a result the process must be seen as a dynamic one, with complex interacting subprocesses rather than simple cause and effect.

***COMPLETE*** The resonance within the group drives the ideas from chaos towards order in the *create* phase, and as the system moves towards order the ideas converge, a final idea coalesces and other ideas fall away. In the *complete* phase the emergent idea is evaluated and, where appropriate, elaborated [57], cycling back for as long as necessary into the *create* phase. As discussed earlier, this is part of the continuous iterative process within as well as between the four stages of the model. This final phase parallels previous creative processes models as, variously, *refine* [60] *reflect* [55], *verify* [63], or *working it out* [21]. This *completing* evaluation is different from the *create* phase's synchronic interaction [57] ideation/evaluation loop; rather this evaluation is done within the external context of the group, when an idea is aligned with the extrinsic collective goal. Researchers have also identified the skills needed at this phase: Belbin [9] in his study of team roles identifies the need for a *monitor/evaluator*, Foy's [23] adaptation of Belbin calls for a *critic*, and Luther and Diakopoulos [36] identify *analyzers* 'who provide feedback and evaluation' engendering further iterative improvement loops. Foy adds the caveat that critics are best kept away from the *create* phase lest they damp the resonance and the ideas converge too early.

## DISCUSSION

Our empirical observations suggest that designers of interfaces should focus on building to facilitate distributed affect across group systems, concentrating on ease of use, simple access and intuitive process. The networking tools used by MEC employees permit simultaneous document access, electronic chat logs, and voice, enabling groups of varying sizes to communicate easily at and between on-line meetings. Our observations also suggest the key role of how these interfaces are used; for example, MEC's explicit rule set for working on-line "means that people are better at waiting and listening" supported by a "careful moderated approach to chairing." This encourages strong horizontal and low vertical systemical differentiation with its resultant rise in creative resonance. It also supports the ability to engage all the group participants, an important element where distributed groups include a wide geographical area with a concomitant range of expertise, cultural perspectives and personalities.

For the children on Scratch, the primary motivating factor keeping the kids coming back to communicate on the site is, in the words of one founder, "because it's fun. We're not getting paid for this." In an interview, one GBG member said, "If one person is excited about a project, other people will see that excitement and it'll motivate them to be excited too. They'll say, this is an exciting project and I want to contribute." The sheer joy and excitement of the children in creative production is evident from the site logs.

> *Yib: Yayyy production! Sounds like this Claw Game may actually go somewhere. Now as for the name...Retro Claw Capture?*
>
> *King: Yes! Yes! It is called Retro Claw Capture, looking at the recent remixes… I'm going to add to the game today.*

The importance of feedback to the group creative process is also clear. This resonance was described by one member as "a friendly version of peer pressure." We see similar examples of creative contributions in the astrophysics projects, where a positive feedback loop encouraged members to contribute new software:

> *Kevin: Ah, OK. I made a "sooper looper" for the SNIFS processing like I did for the search automation, and at least the first part of that pipeline seems to be working.*
>
> *Sam: :)*
>
> *Kevin: Since you are at home with your roomba, I am sure you are on your mac, but I wanted to mention I made some hacks to the tightvnc unix viewer handy for summit watching. ... I can toggle the bell off and on in the menu for one! ... I can also make 1/2 and 1/3 sized thumbnails of the desktops.*
>
> *Sam: oh, nice ... I think ultravnc (for windows) had a feature like that; I always missed it on Unix and Mac.*

Kevin's pride in his work and Sam's encouragement led to the development of more novel software tools to facilitate the group's work. Conversations of this type were rampant throughout the scientists' chat logs, indicating the importance of affect in accelerating local, global, and contextual dynamics over time across a range of creative endeavors.

Affect can be hard to measure, especially in face-to-face interactions, where body language, facial expressions, and tone of voice convey a wealth of non-cognitive information. However, we suggest that with the increasing prevalence of computer mediated communication in group work, that communication of affect is both being facilitated and made more overt. At the same time, our research has shown that people can feel freer to express emotion online, and the lack of non-cognitive information can be a positive benefit: "When you can't see the body language, the ideas stand more strongly in their own right" (MEC engineer).

## CONCLUSION

Our long-term work with distributed creative groups gave us the impetus to develop a new model for collaborative creativity that includes the importance of *distributed affect* and carefully designed *affective interfaces*. We built upon a large body of research in multiple domains to devise a model based on complex systems theory, a tool that has been useful in numerous areas. It is often counter-intuitive to express affect in professional circumstances, and arguably, many are wary of what designer Jean Muir called "the messy bits." In facilitating the resonance that helps drive ideas around a distributed group and in the dissent that can spur them in the first place, affect is, we posit, at the heart of the collaborative creative process. With the escalating quantity of persistent data available from online collaborations, we hope to see further study of this important aspect of group creativity.

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