Computational Creativity to Design Cyber-Physical Systems in Industry 4.0

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Abstract. The Fourth industrial revolution to be successfully implemented requires higher levels of creativity and innovation in the collaboration, design and composition of its cyber-physical building blocks. Powering industry 4.0 by creativity and innovation triggers efforts for better understanding of human creativity concepts and its intersection with cyber-physical systems in industry 4.0. Since computational creativity is an emerging field of research within AI that focuses on theoretical and practical issues in the study of creativity, the goal of this paper is to motivate a discussion about the application of computational creativity to design cyber physical production systems, which are at the core of industry 4.0. The fundamental research question in the paper is about the applicability of computational creativity in an industry 4.0 context.

Keywords: Industry 4.0 · Computational creativity · Cyber-physical systems · Design · Collaborative network

1 Introduction

The fourth industrial revolution is the information-intensive transformation of industries in an connected environment of data, people, processes, services, systems and IoT-enabled industrial assets which is looking for a way and mean to realize smart industry ecosystems of industrial innovation and collaboration [1]. The term Industry 4.0 refers to the combination of several major innovations in digital technology which includes cyber-physical systems, internet of things, cloud computing, cognitive computing and collaborative networks as its core enabler that can lead businesses to differentiated competitive advantages [2, 3]. According to a survey from 1600 C-level executives in business and government across 19 countries, 87% of these business leaders believe Industry 4.0 will lead to more social and economic equality and stability [4]. Alongside collaboration as the nucleus for all dimensions of the 4th industrial revolution, creativity will be one of the top skills valued in 2020 [5] and collaboration definitely an important aspect [6, 7]. According to the Zion Market Research, the global computational creativity market, which is responsible for finding creative and innovative solutions across different fields, was approximately USD 205 million in 2018 and is expected to generate around USD 1,115 million by 2026 [8]. Collaboration has always functioned as the kernel of creative works [9], but it seems the future of industry and

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digital transformation without creative collaboration and creative collaborative networks will be ambiguous.

As more and more complex and adaptive industrial systems are required, better solutions to design these new systems are needed, that should go much further ahead than just the application of fancy IT solutions such as the cloud or simple IoT approaches. Regarding these systems in a new perspective might be the only way to effectively solve the challenges imposed by industry 4.0. Seeing these systems as collaborative networks of machinery and people and applying all the theoretical framework that has been developed in the last years [6, 10, 11] can be an important contribution, together with a new vision on the importance of applying computational creativity to generate creative solutions to complex problems.

Based on mentioned aspects, the goal of this paper is to motivate a discussion about the application of computational creativity to design cyber physical production systems, which are at the core of industry 4.0.

The paper discussion is centered around the following questions:

RQ1 – Can creativity be implemented by computers?
RQ2 – Is computational creativity appropriate and applicable in an industry 4.0 context?
RQ3 – Is computational creativity appropriate for collaborative tasks?

Hence, this study explores industry 4.0 and computational creativity existing research works to provide better and clearer understanding of their concepts, requirements, nature and processes to answer the mentioned research questions.

Section 2 briefly outlines industry 4.0 and Cyber Physical Systems (CPS). Section 3 discusses about what creativity is and elaborates on how creativity is being introduced to the computer world (computational creativity). Section 4 describes a simple industry 4.0 system that will be used to illustrate how creativity can used to support its design. The research challenges faced by the application of computational creativity to design industry 4.0 systems composed of cyber-physical systems are listed in Sect. 5. Finally, Sect. 6, presents the conclusions for this paper.

2 Industry 4.0 and Cyber-Physical Systems

Economic challenges driven by technological and social development in the twenty first century´s world is provoking industrial enterprises to improve their agility and responsiveness in other to gain ability to manage whole value chain. Hence, enterprises require assistance of virtual and physical technologies which provide collaboration and rapid adaptation for their business and operations [12]. The industrial revolution of the 21st century leads industries to be smarter in decision-making and more flexible in production volume and customization, extensive integration between customers, companies, and suppliers, and above all higher sustainability and better optimization based on environmental variables and available resources [13]. This movement allows much greater agility and mix in a factory without sacrificing quality, cost, or speed. That will allow the company to innovate more rapidly and gain greater revenues. In future manufacturing, enterprises must cope with the need of rapid product development, flexible production as well as complex environments [14], cyber-physical systems, and collaborative networks have to enable the communication/collaboration between humans, machines and products alike [3].

Cyber-Physical Systems (CPS) which has been perceived as the core foundation of industry 4.0 [15], are systems of collaborating computation entities, that have an intensive connection with the surrounding physical systems and their ongoing processes through collaborative networks is the core foundation of Industry 4.0 [16].

CPS in the 4th industrial revolution can pursue different goals under different industrial and manufacturing circumstances. New smart CPS can drive innovation and competition in different sectors such as agriculture, energy, transportation, building design and automation, healthcare, and manufacturing. Small and medium-sized enterprises (SMEs), particularly start-up companies in the IT industry, are key participants in the development of the innovation and value creation potential of cyber physical systems.

Even though CPS strongly rely on technological advancements, the creativity, flexibility and problem-solving competence of human stakeholders is strongly needed for their operation [17].

Since CPS involves transdisciplinary approaches, merging theory of cybernetics, mechatronics, collaboration, design and process science [18], creative computation might be crucial in the design of cyber physical production systems to reduce creativity dependency from human stakeholders. This type of CPSs based on creative computation can support agile creative production to increase customer satisfaction and improve extensive integration between customers, companies, and suppliers, and above all sustainable creative economy. Hence, computational creativity-based CPS support, generate and/or evaluate creative solutions.

To achieve its basic goals industry 4.0 production systems should be basically cyber physical production systems, whose inherent collaborative and complex nature calls for highly creative designs.

3 Computational Creativity

The intersection of artificial intelligence, cognitive psychology, philosophy, and the art fields is on the basis of a multidisciplinary endeavour that is known as Computational Creativity. Mechanical Creativity, Artificial Creativity and Creative Computing are other names for this fascinating new field [19]. It uses computer and artificial intelligence-based technologies to study, emulate, motivate and enhance human creativity to reach one of various aims [19]:

- to develop and design models, methods and computer-based programs that can stimulate and enhance human creativity without necessarily being creative themselves;
- to develop and design models, methods and computer-based programs that can generate human-level creative ideas;
- to better study and understand the nature and processes of human creativity and apply a computer perspective about the human creative behaviour.

In summary, Computational Creativity is the capacity of finding, creating and developing solutions that are novel, interesting and appropriate for computational technologies. These aspects should go beyond human-level intellectual and computational capacity, which is far above the current state of the art in Artificial Intelligence, especially in what respects the high level cognitive functions [20, 21]. One important issue is clearly identifying the two different approaches for computational creativity: (1) using computers to stimulate human creativity, and (2) using computers to generate creative works. In this paper we are focused on the second approach.

Computational creativity cannot be achieved without a clear understanding of human creativity. Therefore, it is needed to investigate the most important cognitive models of creativity developed by psychological and behavioural scientists: (1) Psychodynamic Models, (2) Personality Models, (3) Psychometric Models, (4) Problem-Solving Models, and (5) Constraints Model of Creativity.

Psychodynamic Models of Creativity: Psychodynamic Models consider creativity an unconscious process. The unconscious mind allows creativity because it is less rigid and less specialized than the conscious mind [22]. Some researchers find these models of creativity unsettling because they give very little credit to individual or self-creativity.

Personality Models of Creativity: Personality Models of Creativity recognised the role played by individuals during the creative process. Garlick states that differences in an individual's ability to process information depend on brain differences [22]. Based on this approach people with higher level of Neural plasticity can have higher level of creativity. Some find these models of creativity oppressive because they give little credit to the thought base creativity.

Psychometric Models of Creativity: Psychometric Models consider creativity as something that can be taught [23]. Divergent thinking and Free Association thinking empower creativity and creative idea generation that brainstorming, followed by convergent thinking transform into valuable and appropriate solutions for the problem. For Psychometric Models creativity involves three major phases: (1) Problem Consideration; (2) Thinking of possible solutions; (3) Testing or evaluation those solutions to determine whether they are useful or not [24].

Problem-Solving Models of Creativity: In these models, creativity is about finding new and original solutions for problems. All searches for these novel solutions take place in a problem space. The problem space consists of the: (1) Initial state; (2) Search space and (3) Goal state. According to Weisberg, creative problem solving is a gradual development from initial knowledge to a final goal state [24].

The Constraints Models of Creativity: Constraints models of creativity consider creativity as an activity in creative problem solving [25]. Reitman argues that incremental problem-solving technique is a matter of constraints. Externally imposed and self-imposed constraints help the individual to reach a creative solution by narrowing the search space and guiding him or her towards the goal state [26].

These models can be used to understand better how the cognitive process of creativity is developed. All this work can be used to support the development of computer models that can be the basis for the development of creating creative computer programs. Computational creativity researchers from the AI area have already developed important work in creating computer programs that produce creative work [27], although not to generate industry 4.0 creative designs.

Psychologists and artificial intelligence (AI) scientists such as Boden [28], believe that there are three different processes to generate creative ideas: combination, exploration, or transformation [28]. These processes, if properly applied can be the genesis for novel and valuable ideas. They may be differentiated by the sort of psychological and cognitive processes that are involved in generating the creative and useful ideas in the human brain [29].

Combinational Creativity: involves generating unknown, surprizing and valuable combinations of known and usual ideas. Sometimes, the combinational creative outcomes can be unexpectedly novel, and extremely appropriate. In short, startlingly creative. Combinational creativity relies on a shared conceptual foundation and it happens by creating recognizable associations between ideas that were formerly only indirectly linked together. Combinational creativity outcomes require a fraught and valuable store of knowledge in the person′s mind, and numerous different paths to move between this knowledge. It is combinational creativity that is usually mentioned in the definitions of "creativity" and is studied by experimental psychologists and neuroscientists specialized in creativity [29]. Combinational creativity is the most difficult for AI to model. Computers do not have any problem in making new and novel combinations of familiar concepts that are already stored or even accessing them. But there are two important problems. The first one is that the process of combining familiar concepts can continue for ever. The second problem is how to make these new combinations valuable and significant, which requires deep world knowledge, such as cultural knowledge. Human brain has a treasure trove of world knowledge which includes cultural knowledge. This is the missing element in generating many novel and valuable combinations by computers. However, artificial intelligence has this ability to generate novel and significant combination within a stoutly constrained context. But currently AI systems, including CPS, has no access to a rich and tightly structured storage of concepts that normal adult human has made in his/her life [29].

Exploratory Creativity: it rests on using the existing stylistic rules or conventions to generate novel structures (ideas), whose possibility may or may not have been realized before the exploration took place. Usually, these rules are largely, or even wholly, implicit. Style-defining rules should not be confused with the associative rules that underlie combinational creativity. Style-defining rules are normally called "generative rules" by AI scientists. Every structure produced by following them will fit the style concerned. Most artists and scientists spend their working time engaged in exploratory creativity. It can produce higher valued structures, or ideas. This type of creativity can often offer surprises that are rather deeper than merely seeing the previously unseen. The premise of exploratory creativity is that the new idea is not in your head yet, but that ideas already in your head would only lead you to explore beyond them [28, 29]. AI can model the exploratory creativity by enough clarifying the rule of relevant thinking style for putting them into an artificial intelligence program. Experts in the different styles spending their lifetimes to immersion into one style and give a verbal description for them which is not suit for computer implementation. Nevertheless, modelling exploratory creativity is much more possible for AI experts then earlier processes [29]. In many exploratory models, the computer comes up with results that can be compared with even professional human results [30].

Transformational Creativity: Boden defined transformational creativity ideas as “impossibilist surprise”. In transformational creativity, the space or style itself is transformed by altering (or dropping) one or more of its dimensions. As a result, ideas can now be generated that simply could not have been generated before the change. The resulting change is so marked that the new idea may be difficult to accept, or even to understand. Sometimes, many years will have to pass before it can be valued by anyone outside a small group of aficionados. Boden believes that transformational creativity generates the most radical ideas, the ones that have the likelihood of winning a Nobel prize. The premise of transformational creativity is assuming (or hypothesizing) that an idea (or a few) in your head are actually wrong, and exploring the possibilities that result from accepting it [29]. Some people believe previous processes of creativity can at least be simulated by computer, but no computer could ever achieve transformational creativity because this processes not just producing new and significant idea, it also involves in producing new way of thinking based on new generated rules. They believe computer performance is based on their specified and determined rules and cannot go beyond these rules. Boden [31] criticizes this issue and argues that what is ignored by other researcher in this matter is that the program may include rules for changing itself. She suggests programs that contain evolutionary algorithms such as genetic algorithms can make random changes in the programs own task-oriented rules [31]. Insofar as computer´s performance is caused by its program, everything it does was somehow implicit in the instructions provided by its programmer. As soon as computer programs are affected by unforeseen internal or external events than genuinely new types of results can emerge [32].

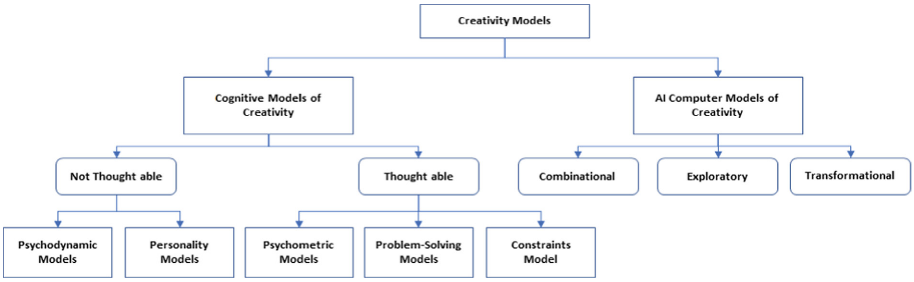

Fig. 1. Creativity models

Figure 1 classifies the different types of creativity models discussed in this section. The Cognitive Models of Creativity are those models developed by psychologists and behavioural scientists that explain how the creativity is processed in the brain, while AI Computer Models are those developed by computer scientists to support the implementation of creative based computer tools. So, computer scientists are developing new computer-based models that are inspired on the Cognitive Models of Creativity. Considering all that was discussed in this section the Research Question “RQ1 – Can creativity be implemented by computers?” is answered.

4 A Production System Illustrative Example

To answer RQ2, a simple assembly production system is described to illustrate how computational creativity can used to support its design. This example was previously used to demonstrate a different concept [33], but it is still very valid for the current case. The assembly of an adhesive tape roller dispenser (see Fig. 3) is the task to be considered. This product consists of the Part 1 and Part 3 joined together by a screw (Part 4), and Part 2 (tape roll). The assembly operation is going to take place on top of the work-piece carrier that are transported by the conveyors [33].

The choice of available system modules, for simplicity reasons, is limited to a small set (examples in Fig. 2) such as: a vertical and horizontal moving axis (Z and X), and a bulk feeder for screws. What is being considering here is the different digital twin modules following the RAMI 4.0 that may be available from different suppliers, and which can be considered as candidates for creating different possible layouts to answer a customer problem or order. Figure 4 illustrates how the two robotic axis (Z and X) are combined together with a 2-finger gripper to make a two axis pick and place robot. This created pick and place unit is used to execute all the required assembly operations for the Tape Roller Dispenser [33].

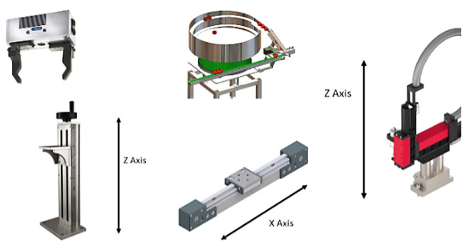

Fig. 2. Modules to be selected

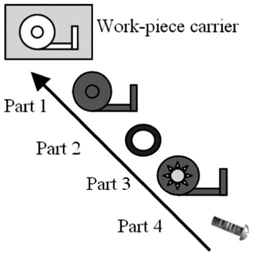

Fig. 3. The adhesive tape roller dispenser. From [33]

Layout. The computational creativity-based design tool can generate many new and significant layouts and choose the one that best answers the end-user defined constraints and available modules.

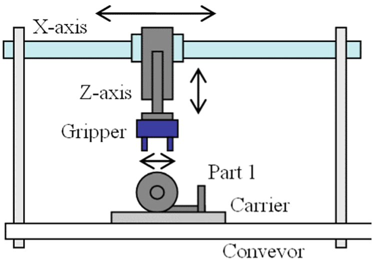

Fig. 4. Robot with one gripper and Part on a work-piece carrier. From [33]

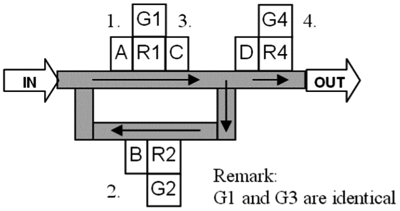

Fig. 5. Circular layout with Robot 1 Part 1 and Part 3. From [33]

The layout shown on Fig. 5 is produced, which is characterized by having all robots with identical topology, as indicated in Fig. 4. The loop shown in the layout of Fig. 5 make the system more flexible and adaptable. Another interesting characteristic is the fact that work piece carriers are allowed to execute two differentiated tasks, any time they are visiting robot 1 (R1). In this especial example, Robot R1 works faster than Robots R2 and R4, and thus assembles Part 1 as well as Part 3. Empty work-piece carriers are input in the indicated 'IN' point, while 'OUT' represents the point where the finished product and its assigned carrier leaves the system. The letters A, B, C and D on Fig. 5 are the feeders for all Parts. Part 4, the screw, can be fed by any feeder type, for instance a bowl feeder as indicated in Fig. 2 that can be picked up by a magnetic screwdriver. The tape roll might be fed using a simple tubular gravitic feeder, and the main body parts can be store on pallets [33].

5 Computational Creativity Research Challenges in Designing Cyber Physical Production Systems

The problem described in the previous section is a typical manufacturing design problem which represents one type of industry 4.0 problem that could benefit from the application of computational creativity. In this type of problems, the goal is to autonomously and intelligently generate the best layout and configuration that answers the requirements by the application of computational creativity. Hence, computational creativity-based design tools can be a new generation of tools adequate to develop Cyber-Physical based Industry 4.0 systems in which collaboration between components are an important issue. Despite the application of computational creativity being not ended on design tools, this paper is focused on this class of problems as they are enough to illustrate its basic goals.

To motivate discussion and point out research directions in developing these new generation of computational creativity-based design tools (CCBDT) a sketch of a possible building blocks for such a tool is described in Fig. 6.

This proposed building blocks main goal is to support the development of a new generation of design tools whose main decision process is based on computational creativity, and therefore support the development and implementation of industry 4.0 based cyber physical systems. Novel and valuable creative layouts can then be generated by machines.

The most important components or parts of this building blocks are:

1. The digital twins of the manufacturing components that can be candidates for the possible generated layouts. Essentially, the most important characteristic to be considered here is the description of the operating parameters, and their functionality or basic skills that are relevant for the considered problem;
2. The objectives that are the products to be produced (for instance, the adhesive tape roller dispenser);
3. The basic operational modules, such as the Collaborative network module, User interface, Knowledge intelligence module, and the Supervision Module that orchestrates the functionality of the tool, interacting with all the main components;

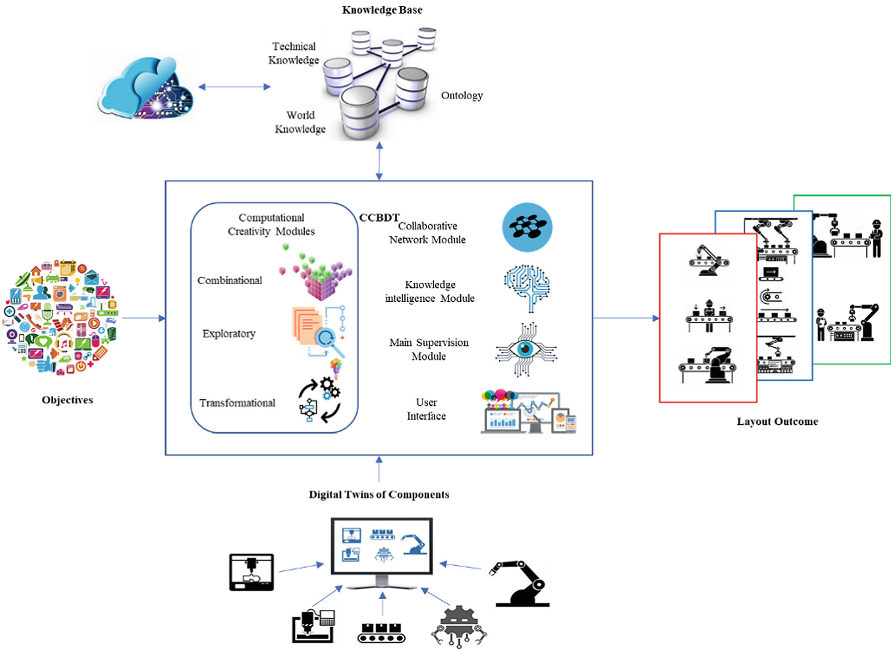

Fig. 6. Possible building blocks for a CCBDT

4. The knowledge management module that is responsible to manage and interact with all the different knowledge bases that are fundamental in a computational creativity process or system. As it was mentioned during the discussion of creativity and computational creativity, there is no creativity without different type of knowledge. So, technical knowledge is very relevant and fundamental, but common-sense knowledge (world knowledge) is also an important player to implement the different creative approaches (combinational, exploratory, and transformational). Ontology is included to indicate that concepts and their relations are fundamental. Of course, technical and world concepts will also be part of the ontologies. Technical and World KBs are more related to rules or set of rules that are important in the creative process. It must be noted that learning will be an important process to be included in the architecture to update the different knowledge bases;
5. Finally, the most novel part of this architecture the modules that will support the computational creative process. The idea is to have three different modules, each one responsible for one of the creative processes: combinational, exploratory, and transformational. The intention is to create a modular system that can accommodate a stepwise approach in which the system can be enriched with modules as they are being developed. If no modules to support transformational or combinational creativity are available, but exploratory modules are already available, then the system will only apply exploratory creativity. If all modules are available, then different solutions will be considered applying all the different three processes.

The proposed building blocks is much more to raise new questions than an answer to the problem. The authors' goal is much more to motivate discussion by raising some initial research challenges. Hence, the following research points might be considered as a starting point:

- Structure the work about creativity (non-computational). It involves working with psychologists, behavior scientists, cognitive scientists, artificial intelligence scientists, and neuro scientists and really understand what has been done until now and how it can be applied to computer-based systems. The study of the existing Cognitive Models of Creativity (Fig. 1) needs to be understand and better studied about how they can be adapted to computer models.
- Getting a good review and structure about all the computational creativity work. What Computer Models of Creativity exist, where they have been applied and how they can be used in our domain. Moreover, what new models are needed and what new field of applications in the Cyber Physical Production Systems computational creativity can be applied.
- Refine and work on a more elaborated architecture for CCBDT (Fig. 6).
- Understand and explore how computational creativity can be used and applied to facilitate collaboration in collaborative networks.

6 Conclusion

This paper is a very preliminary work but novel in terms of proposing a new approach for the application of computational creativity in the development of computer based supporting tools for the design of Cyber-physical based Industry 4.0 systems. The novelty is therefore proposing that creativity is not a magic but a type of Artificial Intelligence that can emulate the three basic types of human creativity: combinatorial, exploratory, and transformational. It is hoped that this work can motivate strong discussions and raise new research challenges based on what has been discussed and proposed on this paper.

The RQ1 was positively answered in Sect. 3, and the most important research question about the appropriateness of creativity to industry 4.0 (RQ2) is believed to be supported by what was described in Sects. 4 and 5. The answer to the research question 3, (RQ3) about the application of creativity in collaborative networks is also believed to be positively answered for two main reasons: (1) collaboration is an important part of the solution for industry 4.0, and (2) creative based computer tools are needed to implement and support collaborations.

A lot of work is still needed to be done in terms of implementing these three basic types of computational creativity processes, but what is important for now is that industry 4.0 can really get advantage from the application of computational creativity techniques, that have been essentially used in the areas of art, music, and literature generation. Its application in this domain, can be an important novelty and helping to bring the issue of creativity to different application areas rather than just design tools.

Another important conclusion is related to the implementation that the proposed building blocks left open. The most important challenge is how to really implement computer combinations, explorations, and transformations. A lot of work has been done in other areas (music, art, literature) that can be the starting point. Another implementational aspect is the learning that needs to be integrated in the architecture in order to keeping real time update of the knowledge bases, and all the knowledge modelling issues behind the representation of common knowledge.

The authors really look forward to having the possibility to continue proceeding this very challenging and innovative work of applying computational creativity in the world of industry 4.0 and integrate it with the collaborative networks work that has been done.

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