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EMBeRS: An Approach for Igniting Participatory Learning and Synthesis

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Abstract: Many of humanity's most pressing issues are socio-environmental, and as such, are ill-structured, "wicked" problems. Wicked problems require a participatory process that includes researchers from different disciplines and key stakeholders to collaboratively identify science needs. A key challenge in working on these problems is that the problem scope is typically unbounded, the issues are complex and interwoven, and the modeling approach can be framed in a multitude of ways. Because each wicked problem is unique, there exists a plethora of examples of participatory processes used to gain traction on modeling such problems, along with an equally extensive list of tools and methods used. Unifying frameworks are needed to facilitate understanding of participatory approaches as a whole and to provide guidance for research design in participatory contexts. This article outlines an approach, EMBeRS (Employing Model-Based Reasoning in Socio-Environmental Synthesis), that facilitates collective learning during the early, formative phases of a project based on a synthesis of learning and social theories, including: 1) constructivism, 2) experiential learning, 3) model-based reasoning, 4) boundary objects, 5) epistemic objects, and 6) distributed cognitive systems. A series of EMBeRS-based activities can be purposefully linked to move a collaborative group from vague, ill-defined, heterogeneous understandings of the problem to a co-created, shared framing. Examples from working with stakeholders on water and agricultural systems are provided.

***Keywords**: Collaborative learning; model-based reasoning; stakeholder engagement*

1 INTRODUCTION

In 2015, the United Nations adopted an agenda comprised of seventeen Sustainable Development Goals (SDG) to be achieved globally by 2030, such as clean water and energy, life on land and below water, and climate action (United Nations, 2015). Many of the goals are tightly coupled and achievable only with unprecedented collaboration across diverse perspectives that cross disciplinary, professional, cultural and institutional boundaries (ICSU, 2015). The challenges of achieving this level of collaboration are vast and require more effective approaches to investigate complex problems in inter- and transdisciplinary teams and deliver research findings useful to decision makers (Hamilton et al., 2015; Laniak et al., 2013). Effective participatory work on such ill-defined, 'wicked" problems is often accomplished in ad hoc ways, with lessons learned through experience shared as practices in the modeling literature (Argent et al., 2016). Although there has been progress in understanding the overall participatory modeling process (Belete et al., 2017; Hamilton et al., 2015; Jakeman et al., 2006; Voinov et al., 2016; Voinov and Bousquet, 2010), there is a lack of understanding about how to more effectively engage participants' to better enable collective understanding of the problem (Laniak et al., 2013; Pennington, 2016, 2011a, 2011b, 2008; Pennington et al., 2016, 2013). Because wicked problems are unbounded and ill-structured, they must be framed and structured before they can be solved as part of the scoping, envisioning and goal setting processes (Voinov et al., 2016). The objective of collective problem framing is for participants to integrate their diverse perspectives in meaningful ways so that a shared conceptualization of the problem is generated, based on the belief that this will result in a more comprehensive, synergistic outcome. To achieve this, the team must learn each other's perspectives well enough to discover linkages among their perspectives and use those linkages to generate a new, synergistic view of the problem (Pennington, 2008). Most brainstorming-style activities (e.g. Voinov et al., 2016) were designed for situations where there are diverse, conflicting perspectives on the problem, but those perspectives are not particularly difficult to understand. The assumption is that if participants voice their perspectives, other participants will then be able to build on those perspectives. However, in complex socio-environmental research that intends to combine very different disciplinary perspectives (e.g. social, natural, and computational sciences at a minimum) participants do not hold background knowledge adequate for understanding each other's perspectives, much less building on them. The challenge is to create participatory activities that add elements to the process which are intentionally designed to enable learning vocabulary, concepts and methods fundamental to: 1) understand each other, and 2) leverage new understanding to transform one's own thinking. This form of learning is cognitively intense, yet cognitive struggle is the engine that drives highly creative thinking (Bransford, 2006). Our question of interest is, "How can we facilitate interactions among participants in ways that enable creative, synergistic outcomes while maintaining cognitive struggle at manageable levels?"

In this article, we address problem framing as a collective learning problem and present an approach for purposeful design of participatory activities. We describe the EMBeRS approach that is based on learning theory and it the culmination of a decade of research (Pennington, 2016, 2011a, 2011b, 2010, 2008; Pennington et al., 2016, 2013). We present the process of testing the EMBeRS approach through workshops designed around water and agricultural research and then provide a set of examples where the approach is currently being applied to participatory research involving stakeholders.

2 RELEVANT LEARNING THEORIES

All learning requires cognitive change, but not all learning results in the synergistic, integrative outcomes sought in socio-environmental modeling research. Transformative learning theory (Meizirow, 2000) posits that major integrative revisioning of mental models is catalyzed by experiencing a "disorienting dilemma" that forces an individual to critically reflect on deeply ingrained knowledge and beliefs. While the theory was originally developed to explain the impact of life-altering events on worldview it becomes relevant in this context in that individuals involved in participatory modeling are exposed to a deluge of concepts, ideas, vocabulary, and ways of thinking that are foreign to them, creating a disorienting dilemma. They struggle to make sense of this information, and in the process, are forced to make significant revisions to their existing mental models. This transforms their way of thinking, and can enable generation of new, synergistic models of the problem (Pennington et al., 2013).

Transformative learning is one form of constructivist learning theory. Constructivism holds that learning is an active process that occurs when learners interact with each other and with their environment. A key theory within constructivism is experiential learning. Kolb's (1984) model of experiential learning subdivides learning into two phases: 1) grasping, comprised of observation and reflection processes, and 2) transforming, comprised of abstraction and experimentation processes. Grasping processes allow unfamiliar content to be acquired and connected to existing mental models, and transforming processes generate new, creative content from those connections. When unfamiliar content is difficult to grasp, visual and reflective methods can augment learning (Pennington, 2011b). Activities must dynamically afford the flow of information among participants and can be sequenced such that mental models become progressively more integrative among participants (Pennington, 2011a).

A critical enabling component of these interactions is the dynamic production of external representations (Pennington, 2010), including diagrams, charts, concept maps, and any other physical object that is produced within the group, whether created individually or co-created. External representations facilitate cognitive offloading and allow individuals to manipulate more information. Theories from a variety of disciplinary perspectives have converged on the importance of external representations in enabling group interactions, including research in learning and cognitive sciences on model-based reasoning (Ifenthaler and Seel, 2013; Nersessian, 1999) and macrocognition (Fiore and Wiltshire, 2016); in social sciences on boundary objects (Star and Griesemer, 1989); and in organizational sciences on epistemic objects (Ewenstein and Whyte, 2009). Observational studies suggest that people and their tools form distributed cognitive systems that can generate creative capabilities through changes in information representation, inaccessible to individuals alone (Hutchins, 1995).

3 SYNTHESIS OF THEORIES INTO THE EMBERS MODEL

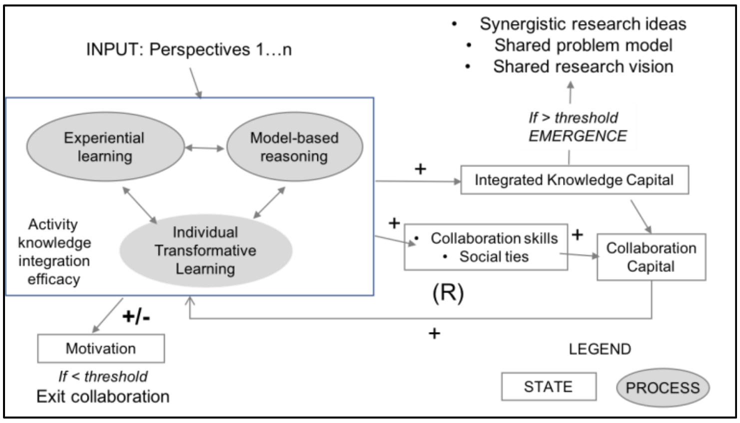

Figure 1.The EMBeRS model of knowledge integration, showing interactions among individual and group learning that occur during collaborative activities. This generates integrated knowledge capital that is the ultimate source of system-level emergence of synergistic research ideas.

The above summaries of learning theories together with reported experiences in complex research teams have been synthesized to generate models of the research team as a distributed cognitive system (Pennington, 2016), within which model-based reasoning occurs (Pennington et al., 2016) and transformative, co-created research ideas can potentially emerge (Pennington, 2011b; Pennington et al., 2013). The EMBeRS approach views a participatory group as a human-environment-technical system with emergent properties, including cognition-related properties: synergistic research ideas, shared mental models of the problem to be addressed, and a shared research vision (Figure 1; Pennington, 2016). A participatory research team cannot exhibit system properties until linkages have developed between participants. Participatory activities have some measure of efficacy for discovering and creating these linkages. This efficacy can be augmented by purposeful attention to enabling experiential learning through model-based reasoning, invoking transformative learning. If the efficacy of participatory activities is sufficient, integrated knowledge capital—knowledge that is linked across participants—will increase, and it is from this capital that system properties emerge. Hence, the efficacy with which activities are able to generate integrated knowledge capital is of critical importance. While learning is occurring, other important components are being changed as well, such as collaboration skills and social ties. Increases in knowledge capital, collaboration skills, and social ties all contribute to increased collaboration capital. As this increases the group improves the efficacy of their knowledge integration activities. This forms a reinforcing loop, whereby the group improves its ability to collaborate the longer it successfully collaborates, which has been observed in studies of research teams (Cummings and Kiesler, 2008). However, if knowledge integration activities are not successful at generating integrated knowledge capital, individuals will lose motivation and leave the collaboration.

This leads to the question of how can activities be designed so that they are more effective at integrating knowledge? The EMBeRS approach is designed to: 1) enable experiential learning; 2) invoke model-based reasoning among team members; and 3) allow integrated knowledge capital to accumulate. It posits that purposeful design of activities that accomplish these three things more effectively lead to co-creative emergence (Pennington, 2011b). A given EMBeRS activity typically requires three hours to implement. This includes:

- pre-activity instructions (10-20 minutes);
- a divergent thinking activity where participants work individually organizing their own thinking, representing their mental models with some kind of physical externalization, and explaining their perspective to their team members using that externalization (1 hour);
- a convergent thinking and synthesis activity where participants work together to identify linkages between their individual perspectives and to negotiate a shared problem model by co-creating a boundary negotiating object (1 hour);
- an opportunity to share products across groups (30 minutes); and
- a final question asking participants to reflect critically on the process and products (10-20 minutes).

Activities can be sequenced so that each activity starts with the products from prior activities, and further narrows the problem space under consideration. One set of activities we have developed revolves around a case study of the Rio Grande watershed in southwestern U.S., designed for a multidisciplinary team of researchers to progressively frame an open ended, wicked problem as a more tractable, integrated research project. This case study involves five sequenced activities over three days, each of which follows the three hour format described above:

- **Explore the Problem Space**: Participants individually create a concept map about the case, then co-create a concept map drawing on and integrating their individual mental models.
- **Who are the Stakeholders?**: Participants are assigned a stakeholder perspective. They read a set of articles about that stakeholder perspective then individually create and co-create activity diagrams that represent the objectives and constraints of each stakeholder.
- **Framing the Issues**: Participants are given a set of six frameworks that have been used broadly in the literature to conceptualize socio-environmental systems. They choose one and individually create and co-create a conceptualization that represents the issues of most interest to the group.
- **Model the System**: Participants individually then collectively identify the components and relationships that are most relevant to their framing, using MentalModeler (Gray et al., 2015).
- **Mock Solicitation**: Participants generate a proposal in the form of a presentation that combines all of the above work into a statement of integrated research.

The EMBeRS model is being tested in several contexts, one of which is an eight-day summer workshop for PhD students. The workshop has been held twice at the University of Texas in El Paso (UTEP), in 2016 and 2017 and utilizes the Rio Grande case study to enable in depth investigation of how a team interacting through time uses EMBeRS methods. Students were recruited from large, U.S. National Science Foundation-funded research projects investigating various aspects of water resources. Students selected for the workshop came from different projects, institutions, and disciplinary perspectives, as well as mixed demographic characteristics. Eight selected students together with three UTEP students participated each summer for a total of twenty-six participants. The EMBeRS PhD workshops have evolved into a semester-long course at UTEP, now required for graduate students in our Environmental Science and Engineering programs. The summer PhD workshop will be continued for at least one more summer under a grant from the U.S. Department of Agriculture.

Data from the workshops were collected by an external evaluator and a team of learning scientists, reported in detail elsewhere (Pennington and Vincent, 2018; Kate Thompson et al., 2017; K. Thompson et al., 2017; Wheeler et al., 2018). Briefly, surveys and interviews found that students believe the workshop provided them with skills and tools unattainable elsewhere, greatly improving their ability to contribute to interdisciplinary research projects. Pre- and post-workshop surveys show dramatic changes in their attitudes toward transdisciplinary research and their confidence in their abilities to engage in such research. Learning analytics suggests that EMBeRS activities contribute to students' abilities to synthesize information across perspectives. As we monitor students over time they consistently remark that they are finding the workshop methods and tools gained extremely useful.

We are now beginning to explore how these methods can be used in participatory research *with* stakeholders. This is significant because stakeholders involved in socio-scientific policy decisions express three concerns about their participation in research: 1) stakeholder participation is minimal, passive, or an afterthought (Simmons 2008; Gaventa 1980; Lacogano, Moore & Goltsman 1990; Katz & Miller 1996); 2) stakeholders do not have access to technical information to inform their decisions (Potts & Salvo 2017; Hart-Davidson 2001; Simmons 2008); and 3) different perspectives among stakeholders are lost in public participation processes because researchers dismiss differences among them (Ross 1996; Wills-Toker 2004; Young 1990; Flower 2002; Flower 2008; Higgins, Long & Flower 2006; Simmons 2008). How, when, and on what terms stakeholders are included in research are important factors to consider (Voinov and Bousquet, 2010). We envision that the EMBeRS method might fruitfully address some of these well-known and costly problems by working with stakeholders to: 1) elicit stakeholder concerns that inform emergent cognition-related properties; 2) engage stakeholders in considerations of power relations; 3) elicit stakeholders' priorities in relation to nested individual, community, and institutional commitments; 4) conduct culturally attuned and technically accessible usability studies to inform simulation modeling; 5) consider how different adaptation strategies might affect their communities; and 5) design data-driven processes for reasoning about scientific models about possible scenarios, courses of action, constraints, and outcomes for those involved.

4 APPLYING EMBERS IN WORKSHOPS WITH STAKEHOLDERS

Several EMBeRS workshop participants work with stakeholders in their research, and have reused the EMBeRS approach. Aaron Shew and colleague Bradley Wilson are currently preparing for an invited two-day May workshop for a non-profit organization in Swaziland to inspire collaboration among employees. The organization works on economic policy and sustainable development initiatives, spanning economics, political science, and public health with a goal of providing actionable public policy research to governments and stakeholders. The two-day workshop will introduce the EMBeRS approach, stakeholder analysis, and designing actionable research plans. Information on current projects will be provided in advance by the host organization to help design the workshop. Stakeholder analysis activities, for example, will be designed so participants think about 1) their own obligations and perspective as an employee, 2) the obligations of the organization, 3) stakeholders outside of their institution (i.e., governments, NGOs, etc.), and 4) the potential tradeoffs between and across the various stakeholders at each level. The workshop's activities will encourage individuals to develop their own analysis and rank different aspects in terms of importance before synthesizing their own understanding within small groups. This reflective process will be discussed in detail as a large group, with particular emphasis placed on the critical role that importance rankings played in the synthesis process.

Alex Killion is also using the EMBeRS approach to design a workshop as part of his dissertation research investigating the social processes of human-wildlife interactions to identify how ranchers in the American West make decisions when presented with risks posed by large carnivores. To categorize different types of decision making, he will present a variety of risk scenarios in a computer-based model landscape to stakeholders and record how they make decisions. The research relies on experts and diverse local stakeholders, including ranchers, biologists, wildlife managers, and policymakers, to develop a computer-based model and co-create large carnivore risk scenarios. In the EMBeRS-based workshop, to be implemented in 2018, stakeholders will iteratively map their conceptual model of the human-wildlife conflict, reflect on those created by the other stakeholders, and update their model until their conceptual distance is decreased and a shared model is agreed upon (Pennington et al., 2016). Risk scenarios will be identified using a similar process. Stakeholders in attendance are expected to gain integrated knowledge of the issue and have an increased likelihood for future collaborations.

Emily Bondank successfully led a team of sustainability civil engineers in a workshop engaging water and power infrastructure managers and city planners. The workshop solicited feedback from stakeholders regarding researchers' conceptual understanding of water and power systems and their interdependencies, shared with stakeholders the possibilities of cascading failure given interdependencies and extreme weather events, and identified best practices for mitigating and becoming more resilient to events that could cause service losses. Two external representations were used—1) a board game and 2) a simulation environment. The board game established an experiential and model-based representation of water and power distribution networks, a suite of possible management strategies, and the relative success of strategies under extreme events. Participants first role-played as infrastructure managers and took turns in rounds of managing their network of assets. Participants had to choose their investment strategy in the face of increasing probability of extreme events, which determined whether or not they were able to stay in business. Then, participants engaged in a simulation of the networks that incorporated greater detail in real-time response actions to mitigate the propagation of failure between infrastructure systems. Focusing the workshop around external representations created a shared experience that encouraged participants to share their thoughts and provided a common point for discussion. As a result, participants challenged the model explicitly, expanding the researchers' view of all issues involved in decision-making. Their insights will now be used to reorganize the researchers' mental models of the system to provide more realistic scenarios.

Similar to Emily, EMBeRS thinking has influenced Kelley Sterle's reflection on iterative engagements between local stakeholders and researchers in the highly regulated snow-fed Truckee-Carson River System located in the Sierra Nevada of western U.S. The collaborative modeling research design developed for this case study systematically and iteratively convened water managers and interdisciplinary researchers to 1) develop plausible climate scenarios; 2) review the results of hydrologic and operations model simulations under these climate scenarios; and 3) identify viable strategies to adapt (Singletary and Sterle, 2018, 2017). Key local water managers, identified and selected through a stakeholder analysis (Prell et al., 2009; Reed et al., 2009), represent diverse urban, agricultural, environmental and regulatory water use communities (Sterle and Singletary, 2017). Researchers also bring diverse perspectives on how to model the system, and what strategies are most viable to adapt to climate change. Conducted prior to the EMBeRS workshop, Kelley has observed that EMBeRS thinking helps explain how activities led to convergence of these perspectives and a shared understanding. Iterations have allowed time and space to form relationships and build trust, familiarize with hydrologic and operations modeling tools and capabilities, and revise research objectives accordingly. Incorporating managers' representation has advanced understanding of climate-induced water supply variability in the case study area, guiding researchers to refine model simulations to present results in which managers are most interested. Researchers and managers continue to prioritize simulations through iterative information exchange, assimilating a collective assessment of the most viable strategies and model simulations needed to support understanding. Kelley is striving to use this experience to develop a case study teaching tool for navigating adaptive water management strategies in snow-fed river systems.

Kat Salas and Deana Pennington are currently designing another activity for the Rio Grande case study, involving hands-on work with a new watershed modeling interface developed for the region (Garnica Chavira et al., 2018). The interface enables easy execution of an economic and agricultural optimization model linked with a hydrologic model. The objective is to facilitate participatory development of future scenarios affecting water sustainability with stakeholders. This activity will first be tested within an ongoing graduate class that incorporates the activities from the workshop, then will be used with stakeholders in the Rio Grande region. In the class students are assigned to teams. For the stakeholder analysis activity, each team member is assigned a different stakeholder role. Students will with others assigned the same role to run simulations based on their assumptions about what scenarios their stakeholder might be most interested in, first as individuals then within their stakeholder group. They will co-create a set of scenarios they believe captures the key questions of interest to their stakeholder role. Then the students will return to their team and share these scenarios across stakeholder roles. They will revise their MentalModeler diagram from the previous activity to incorporate components and relationships relevant to different stakeholders. The initial stakeholder meeting will be designed to use student-generated scenarios and questions of interest as a starting point for guiding stakeholders through a set of activities that consider water sustainability from different stakeholder perspectives.

6 CONCLUSIONS

Integrating knowledge across researchers and stakeholders to generate a more comprehensive, synergistic understanding of the problem is often a goal of participatory modeling, but can be a complicated, difficult undertaking for many reasons. To be successful, participants must learn each other's perspectives well enough to transform their own thinking about the issues. Application of a variety of learning theories, including experiential learning, model-based reasoning, and transformative learning show promise for guiding the design of activities that are better able to generate synergistic outcomes. The EMBeRS project has tested this approach in interdisciplinary training workshops for PhD students with excellent outcomes, including building their competencies for teaching these methods to their own research teams. We, along with the trained PhD students, are now beginning to formulate approaches for applying these methods in working with stakeholders.

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