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Groupwork as a Complex Adaptive System: a Methodology to Model, Understand and Design Classroom Strategies for Collaborative Learning

1. Introduction

Agent-based modeling (ABM) has been increasingly used by scientists to study a wide range of phenomena such as species in an ecosystem or molecules in a chemical reaction (Bonabeau, 1999; Wilensky & Reisman, 2006). Such phenomena, in which the elements within the system have multiple behaviors and a large number of interaction patterns, have been termed complex and are studied in the field called complex systems (Holland, 1995). Typical of complex phenomena is that the cumulative ('aggregate') patterns at the macro level are not premeditated by the "lower-level" micro-elements. For example, flocking birds do not intend to construct an arrow-shaped structure (Figure 1), or molecules are not aware of the Maxwell-Boltzmann distribution. Rather, each element ("agent") follows its local rules, and the overall pattern *emerges* as epiphenomenal to these multiple local behaviors. In the mid-nineties, researchers realized that ABM could have a significant impact in education ((Resnick & Wilensky, 1993; Wilensky & Resnick, 1995). To study the behavior of a chemical reaction, students would observe and articulate only at the behavior of individual molecules — the chemical reaction is construed as emerging from the myriad interactions of these molecular "agents."

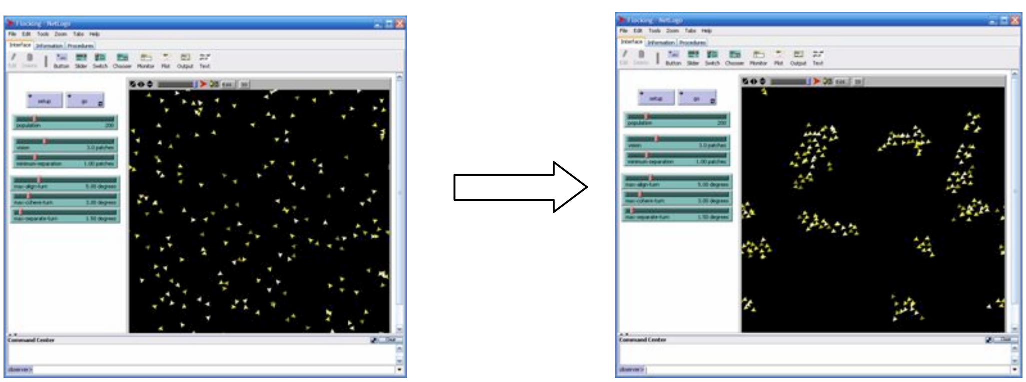


Figure 1. An agent-based model of the flocking behavior of birds.

Complex-systems methods and perspectives are also highly relevant to research in the social sciences. R the recent decades have seen a surge in social-science studies employing ABM (Epstein & Axtell, 1996; Diermeier, 2000; Axelrod, 1997). Recently ABM has been used to illustrate aspects of cognitive development (see Abrahamson & Wilensky, 2005, Blikstein, Abrahamson, & Wilensky, 2006; Blikstein, 2006a) – also juxtaposing simulations with real classroom/clinical interview data (Blikstein, Abrahamson, & Wilensky, 2006).

We argue that ABM has potential to contribute to the advancement of theory in multiple ways that we illustrate in this paper: (a) **explicitizing**—ABM computational environments demand an exacting level of specificity in expressing a theoretical model; (b) **dynamics**—ABM enables the researcher to mobilize an otherwise static list of conjectured behaviors and witness group-level patterns; (c) **emergence**—investigate individual and collaborative learning as a collection of emergent, decentralized behaviors and (d) **intra/inter-disciplinary collaboration**—the lingua franca of ABM enables researchers who otherwise use different frameworks and methodologies to understand each others' theory.

2. Exploration vs. Exploitation: A Tradeoff of Collaborative Inquiry?

Axelrod and Cohen (1999) discuss *exploration versus exploitation*, a tradeoff inherent in *complex adaptive systems*, such as human organizations. For instance, in allocating resources, an organization must determine which strategy will maximize its benefits—"mutating" to check for a better fit. Typically, "the testing of new types comes at some expense to realizing benefits of those already available" (Axelrod & Cohen, 1999, p. 44). We submit that a classroom, particularly when students work in groups) can be seen as a *complex adaptive system* (Hurford, 2004), at least in terms of students' within-group free-range agency in engaging in different phases of problem solving. Despite students being initially explorative, once a functioning coordination scheme evolves, and groups progress towards completing a task with positive feedback from facilitators, an implicit quietus is set on any further exploration or task rotation, and the group achieves dynamic stability. From that point on, the individual cogs in the production mechanism hone their skills and produce.

Such arrangement would be fitting for a workplace, but its instantiation in a classroom presents teachers with the dilemma of group output maximization harming individual learning, especially for students with lower ability in more mathematized tasks. When students are given the freedom to explore a problem collaboratively, both remarkable and undesirable group behaviors may emerge. The methodology introduced in this paper may provide education researchers and practitioners tools for understanding these classroom dynamics such that they can identify points of leverage for working *with* students' to achieve equitable participation.

3. The Combinations tower: A Combinatorial-Analysis Collaborative Project

The current investigation uses classroom data from a design-based research study of middle-school students' mathematical cognition pertaining to the topic of combinatorial analysis (Blikstein, 2006; Abrahamson & Wilensky, 2005b). Central to the study was an implementation of a challenging classroom collaborative project—the construction of the *combinations tower*, the sample space of a 3-by-3 grid of nine squares that can each be either green or blue (for a total of 512 distinct "9-blocks"). The classroom, working in groups, created all the 9-blocks and assembled them into a "histogram." Data analysis revealed unanticipated participation patterns. Namely, individual students operating within groups assumed restricted roles that we named: (a) "number crunchers"; (b) designers; (c) producers; (d) implementers; (e) checkers; and (f) assemblers. In previous work, we demonstrated the descending mathematical challenge of the *a*-through-*f* roles, and that students' individual roles were related both to their mathematical achievement, as reported by the teacher, and their demographics. We argued that these roles were emergent and that they affected the students' learning opportunities and self image and that therefore it is important to understand how some students landed up on the lower rungs of the production line—how a **stratified learning zone** emerged.

4. Implementing a Theoretical Model with Agent-Based Procedures

In this section, we demonstrate the applicability of ABM for simulating the emergence of a *stratified learning zone* (Abrahamson & Wilensky, 2005b) in a 'virtual' classroom. For this model, we chose a simple numeric puzzle task (see Figure 2). This linear puzzle consists of set of numbered pieces which should be concatenated in ascending order (1, 2, 3, 4…). Necessary activities within this task are retrieving pieces (simplest task), verifying if pieces are already present in the puzzle (intermediate demand), and connecting pieces in the correct order (most demanding task). Thus, the roles that students might specialize in are piece-retrievers, piece-verifiers, and piece-connectors. In the beginning, puzzle pieces are scattered in the classroom. Retrievers wander around and, upon finding a piece, grab it and go back to their group's table, delivering it to the piece-verifier and then returning to retrieve more pieces. Upon receiving a piece, the piece-verifier evaluates if it is already present (the puzzle cannot have repeated pieces). If so, the piece-verifier orders the piece-retriever to discard the piece and bring a new one. If the piece is suitable, the piece-verifier delivers it to the piece-connector, who will check if the piece fits the puzzle in its current state, and connect it to the puzzle. For each successful micro-task, students get positive feedback by means of an increment in their skill (speed and/or accuracy). Overall group performance is evaluated by the time-to-completion divided by the number of correct pieces. Our independent variables are: (a) pedagogical style (with or without mandated role rotation); (b) students' initial skill level for each task and distribution of skill levels within students; (c) task difficulty.

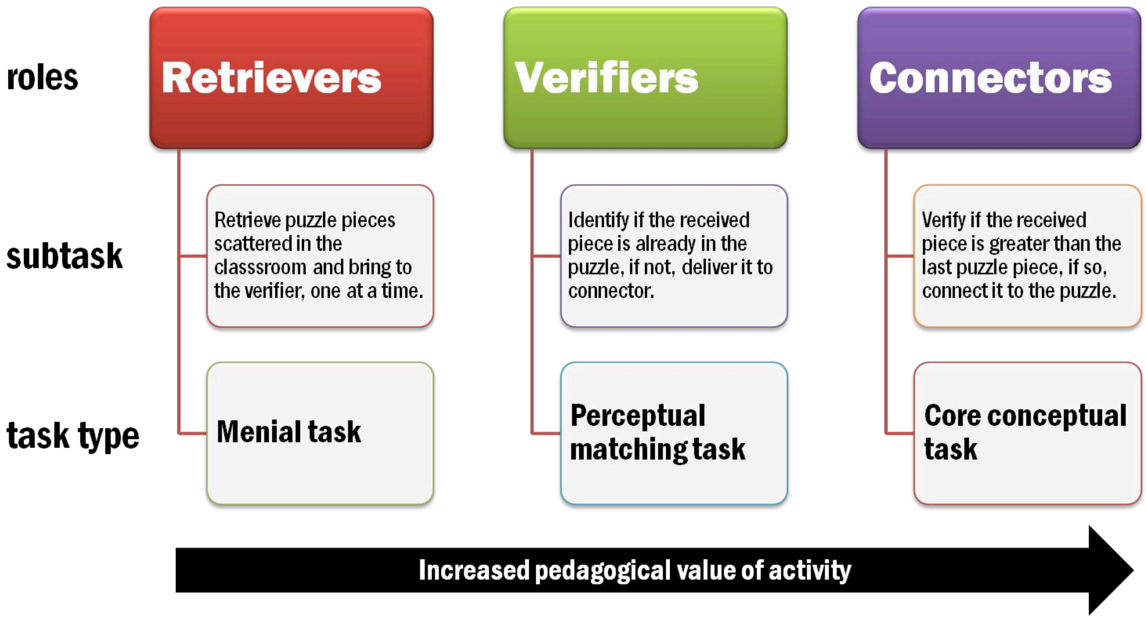
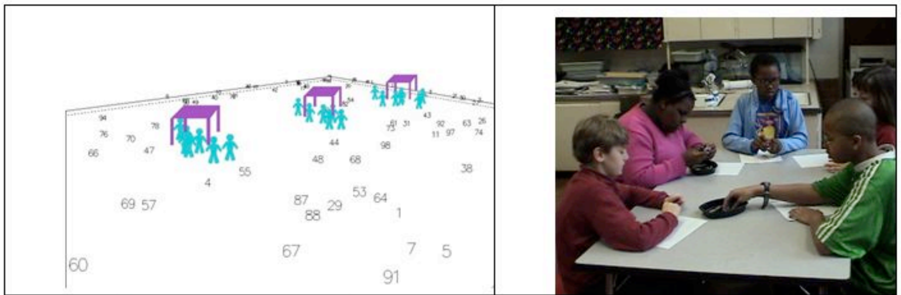


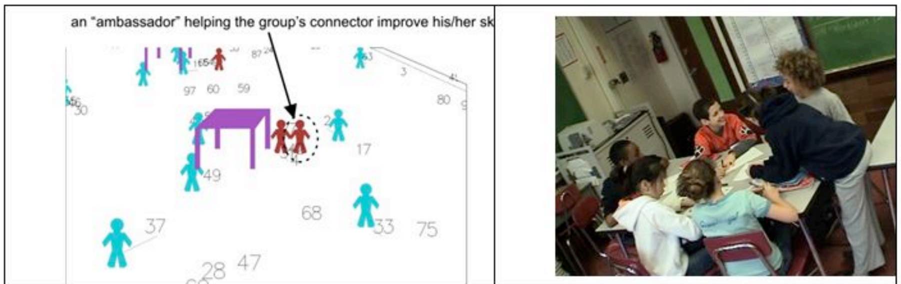
Figure 2. Design rationale for the Stratified Learning Zone agent-based model.

5. A Bifocal Model of Emergent Collaboration Practices in a Mathematics Classroom

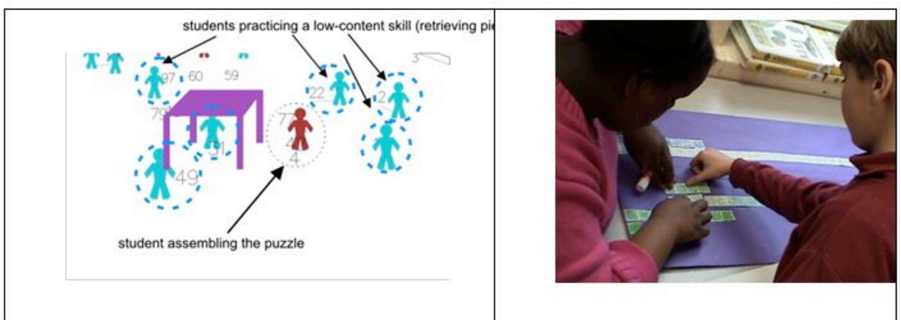
Figure 3, below, shows three examples of real-data (on the right) and simulated data (on the left). Note that our choice to model a generic collaborative activity, rather than modeling the precise activity, makes for surface differences between the real and the simulated data. The comparison is thus analogical: the real sample space corresponds with the linear puzzle, and six roles in the original data have been simplified to three. In introducing such simplification, one must adopt a skeptical stance, because in any act of modeling lies the inherent possibility that some critical aspect of a situation has been overlooked. And yet, this challenge of modeling is certainly not unique to agent-based modeling but is typical of any scientific endeavor.



Onset of group work: before the assignment of individual roles emerge.



Student (standing) whose role is to help other groups improve on a specific skill.



Students whose emergent role involves conducting a mathematically trivial skill

Figure 3. Bifocal modeling of collaborative learning: Three samples of paired states in student collaborative practice—computer simulation (left) and classroom data (right).

6. Implications for educational practice

After many sets of experiments with our model over a large initial parameters set, and comparison with the classroom data previously collected, we were able to plausibly demonstrate relations between pedagogical practice and student learning, given the simplifications of the model, as follows:

a) For an external observer, groups with mandated role-rotation have their overall performance decreased to 40% (see Figure 4, top). Hypothetically, those groups would be regarded as low-performers and possibly, the non-rotated scheme would prevail.

b) When 'student–agents' receive positive feedback only for group performance and not for their individual learning, they become entrenched within skills (speed of piece-retrieval, or accuracy of piece-connection, for example) reflecting their initial skill-level distribution and increase their personal level only in those skills.

c) However, when role rotation is mandated, even though production slows down, more skill-improvement occurs for individual students, in both high- and low-level skills.

d) Initial skill disparity between students in the same group has a significant impact on the outcome of role-rotation. High initial skill disparities generate high differences between the role-rotation and role-specialization scenarios – when students' initial skills are similar, the two scenarios result in similar performance, which could suggest that role-rotation would be especially effective for heterogeneous groups or classrooms (see Figure 4).

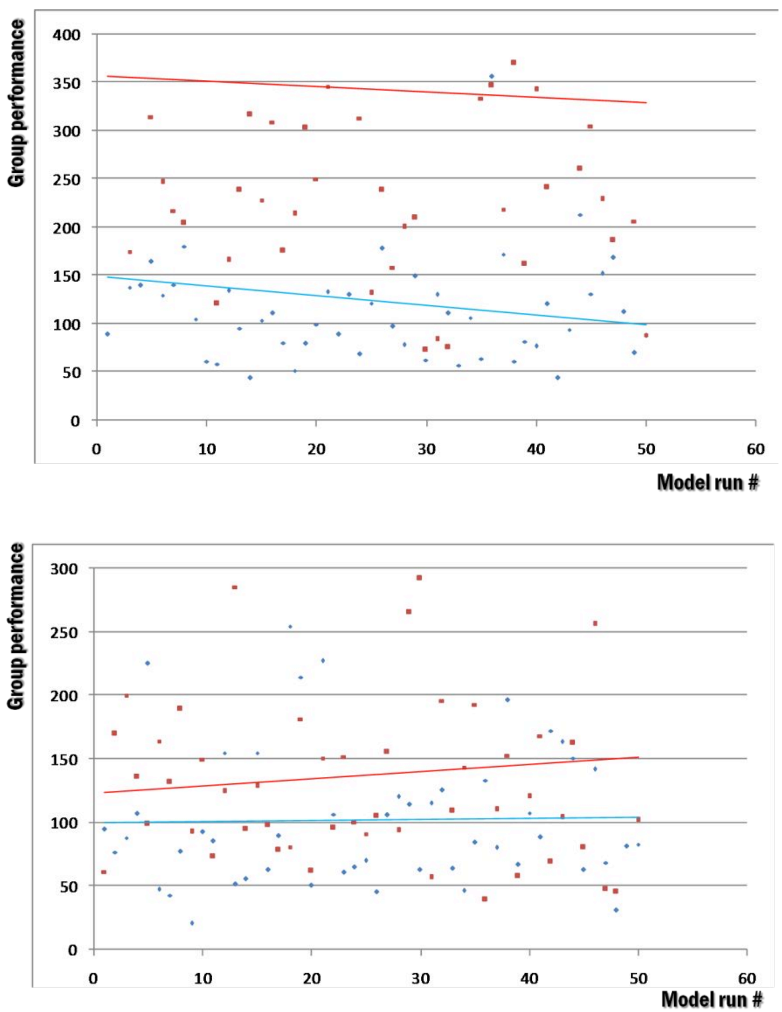


Figure 4. Comparison between non-mandated (blue line) and mandated role-rotation (red line) for two scenarios: high initial skill disparity between students within a group (top) and low initial skill disparity (bottom).

e) An analysis of the impact of each task on group performance is necessary for a causal explanation of our results. Increasing a low-level task skill (i.e., increasing the number of puzzle pieces a retriever–student can bring to the group per time tick) appears to improve group performance **linearly** (see red line in Figure 5). Increasing the high-level task skill (i.e., increasing the probability of the connector–student choosing a correct piece) effects a non-linear trend (blue line, in Figure 5).

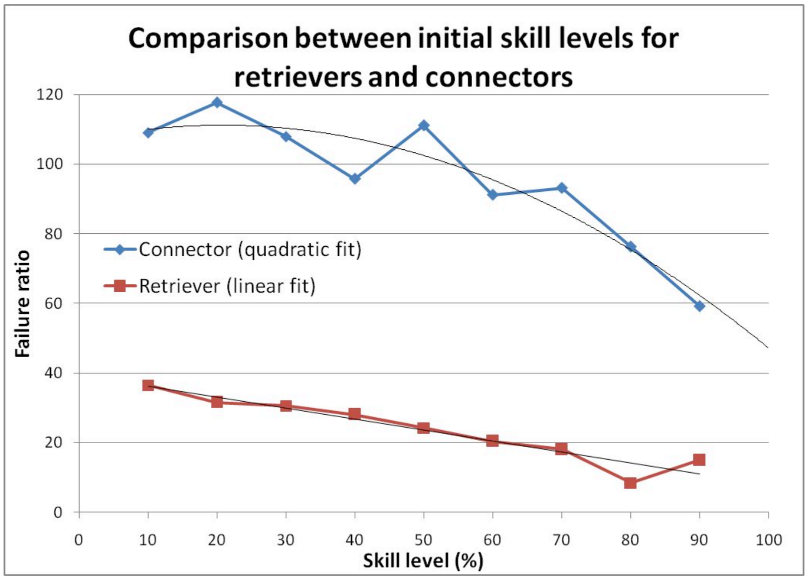


Figure 5. Comparison between initial skill levels for retrievers and connectors.

Interaction between different effects of low- and high-level tasks might indicate that the multidimensional combinatorial space is not a smooth surface, but might contain discontinuities and multiple local minima and maxima (see Figure 6, below). In some regions, slight improvements in connecting skills may significantly impact group performance. Within the same region, improvement in low-level skills renders negligible impact on group performance. This could correspond to a classroom scenario in which one heterogeneous group of students suddenly improves its performance, while other groups, perhaps more homogeneous, still struggle to solve the task at hand. The gain in performance could be attributed to a single student who advanced on a high-level task. Group mates may not have learned the new skill at all, but the group performance, as observed by the teacher, would have improved greatly.

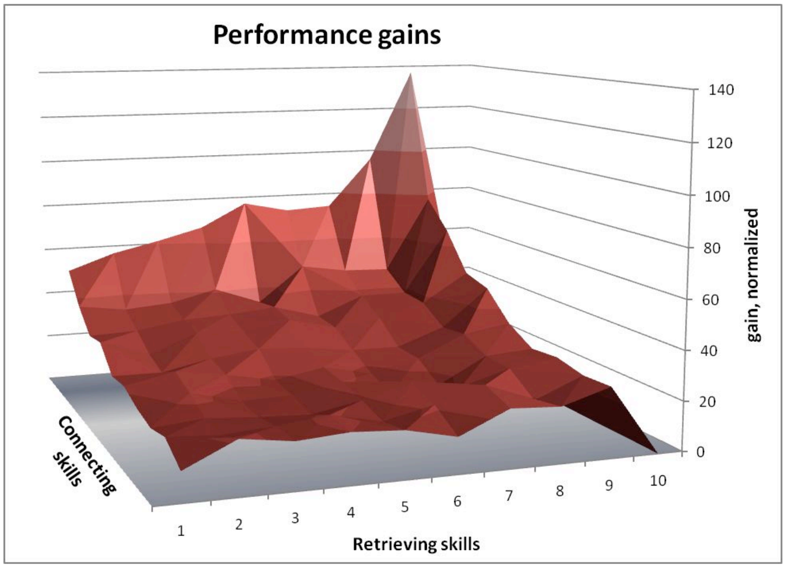


Figure 6. A multivariable experiment, in which both connecting and retrieving were varied, revealing local minima and maxima, and patterns of performance gains.

We are improving the model in two main directions. First, we are incorporating non-linear "learning curves" – improvements in skill which do not increase linearly over time (figure 7), as to investigate the existence of optimal opportunities for role-rotation (see Figure 7, right, with the highlighted area). Also, to further examine relations between pedagogy and equity, we are interested in simulating pedagogical practices (e.g., Aaronson, Blaney, Srephan, Sikes, & Snapp, 1978; E. G. Cohen, 1986) so as to understand their underlying mechanisms and gauge their potential.

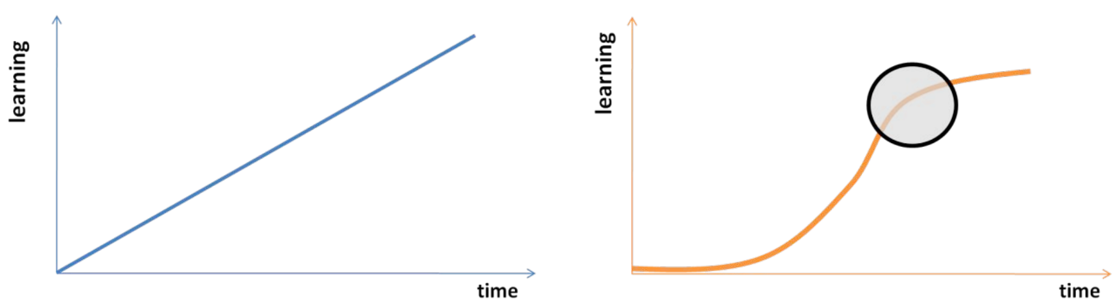


Figure 7. Schematic representation of a linear vs. non-linear learning curve, with the optimal moment for role-rotation highlighted.

7. Conclusions

We have presented a computer-based methodology for research into collaborative learning. We described the design and implementation of an agent-based model for studying the emergence of inequitable participation patterns observed in a middle-school implementation of a collaborative-inquiry activity. Based on the functional resemblance of the simulated and real behaviors and on interviews with the teacher and students, we conclude that the model constitutes a viable explanation for the emergence of the observed patterns. For our full paper and presentation, we will explain in detail the newest results from our modeling experiments, model validation using classroom data, limitations, as well as indicating how the results can inform practitioners in the field.

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