International Society of the Learning Sciences

The *Pivot*: Identifying Emergent Tactics in Distributed Epistemic Games

[Authors blinded for review]

Abstract: The theoretical machinery of epistemic forms and games has been used to describe the knowledge-building processes of individuals. Humanity is faced with challenging problems in an increasingly complex world, and it is clear that productive knowledge-building across domains depends on collaboration. To better characterize this collaborative knowledge-building, we present a framework we call *distributed epistemic games*, in which the activities of knowledge building are carried out by a group distributed across time, space, and expertise. These distributed games are supported through tools such as computing technology and the internet, which allow individuals to connect, communicate, and coordinate their work. We discuss two types of tactics found in distributed epistemic games: those which are deliberately planned in advance, and those which *emerge* as a result of interactions between individuals. Finally, we describe a specific *emergent tactic* and its impact in terms of an increase in interactions and cognitive change.

Introduction

As our world grows increasingly complex, our society is faced with increasingly complex problems. Addressing these problems can be challenging, indeed, some seem impossible to solve.

Isaac Asimov once described a thought experiment in which students were asked "Can you have a relatively small piece of platinum, with handholds affixed, that could not be lifted by the bare, unaided strength of any number of people, no matter how many?" (Asimov, 1989, p. 62). Because the limitation of 'unaided strength' forbids the use of any kind of tools (apart from the handholds) the answer is yes: a cubic meter of platinum weighing "22,420 kilograms under standard gravitational pull" would require too many people to fit around the perimeter of a cubic meter (ibid).

Asimov uses the thought experiment as a metaphor for difficult problems, which are not unsolvable but require more minds around the problem than are possible to fit. The challenge isn't the problem itself, but that "only so many people could gather round the knowledge," so the problem itself remains unsolved (ibid). It should be noted that this limitation is practical, not absolute. There is a possibility of gathering more minds, it just requires a different approach. Constraints of time, space, language, logistics, interest, and expertise must be handled in order for more minds to work the problem together. For some problems, this may be required to find a solution.

The thought experiment implies an opportunity, where the cubic meter of difficult problems could be 'lifted' if we could get enough people gathered around the knowledge. Decades earlier, Vygotsky coined the phrase *Zone of Proximal Development (ZPD)* to describe those tasks which were only possible if a learner received help from someone with more expertise (1981). Using the ZPD as an analogy, we propose a new construct to describe those problems which cannot be solved by individuals but which are possible to solve as a group - something we call the *Zone of Communal Possibility (ZCP)*. In recent decades, "Crowdsourcing" has become a widely used term, thanks to efforts such as FoldIt, Galaxy Zoo, SciStarter, Zooniverse, SETI, and others, who have worked in their own ways to get more people around the problem, with promising results. FoldIt, for example, resulted in creative - and accurate - solutions to a previously unsolved protein folding problem (Koepnick et al., 2019). Though flaws were identified with the process (Madnick, 2022), the DARPA Red Balloon challenge also showed the power of getting more people around a problem. Recently, researchers have used the term "Collective Intelligence" to describe the capacity and capability of a group of individuals solving problems together (see, for example, Malone 2018 and Baltzersen 2022).

We have seen examples of competition (FoldIt), asynchronous individual work (Galaxy Zoo), and collaborative (Idea Connection, cited in Baltzersen 2022) approaches to collective intelligence. The common thread across these examples is the collection of individual minds working together on a single problem. Researchers have demonstrated that groups of humans are able to solve problems which were unsolvable before - due either to difficulty or size - simply by effectively combining or distributing their efforts (Koepnick et al., 2019; Malone et al., 2009; Parslow, 2013; Rutherford et al., 2020).

Some research has investigated the *nature* of distributed knowledge-construction activities (Dunbar, 1997). In this paper, we introduce a theoretical framework for characterizing the nature of distributed knowledge-construction activities and highlighting the impact of interactions between individuals and ideas.

The framework can ultimately be used to build computational models to help us understand the structure and dynamics of knowledge-construction activities, which are widely distributed and span long periods of time.

Theoretical Foundations

Our theoretical framework is a synthesis of two existing theoretical frameworks, one characterizing the nature of knowledge-building activities, the other characterizing the collaborative nature of cognition.

Epistemic forms and games

Epistemic forms and games is a theoretical framework developed by Collins and Ferguson (1993) to characterize the knowledge-building work of scientists and scholars in non-scientific domains. The general idea is that scholars build new knowledge through epistemic games and that these games are guided by epistemic forms. In the same way that the game of Tic Tac Toe is constrained by the crosshatch form on which it is played, a scientist's knowledge-building game is constrained by a particular epistemic form. The epistemic form is a template the scientist "fills out" as they play their epistemic game, the empty template slots guide the moves they make in playing their game. An epistemic form might be something as simple as a list of critical elements, as in the case of diSessa's list of p-prims (diSessa, 1993). It might describe the structure of something in space or time, such as a cross-product table (e.g., the periodic table of the elements; Bensaude-Vincent, 1986), or a stage model (e.g., Piaget's model of cognitive development; Inhelder & Piaget, 1964). It may describe a process or causal relationships, as would an agent-based computational model (e.g., an ABM model simulating the complex dynamics of murmurations in a flock of birds; Wilensky & Rand, 2015).

Epistemic forms and their associated games correspond with particular research questions. For example, a list of critical elements is a common epistemic form produced in response to the question: what is the nature of X? A scientist answering the question, "What is the nature of the clay-colored sparrow?" might list characteristics including "lives in North America," "belongs to the New World Sparrow family," "migrates south for the winter." A list is a simple template with a sequence of blank slots that must be filled with items, which constitute answers to the question at the heart of the inquiry. The inquiry is driven by the goal of filling the template slots and governed by the general rules of the list-making game, which are determined by the constraints of the list form. Constraints include that the list should feature items that are similar yet distinct and cover all possible answers to the question yet be as brief as possible. In playing the game, *scientists enact moves*, such as adding or removing items, combining or splitting items, or substituting one item with another. In the example given above, the scientist looks for distinct characteristics of a clay-colored sparrow, adding, modifying, and removing characteristics according to the constraints of the list form.

The epistemic forms and games framework has been described in terms of the moves made by an *individual* scholar to develop new knowledge, yet research has shown that knowledge construction can be a very distributed process (Dunbar, 1997).

Distributed cognition

In his (1995) seminal work, Edwin Hutchins described cognition as a distributed phenomenon, dependent upon not just an individual brain, but upon other individuals, tools, and the environment in which cognition happens. Hutchins describes two different styles of navigation, the first aboard a U.S. Naval vessel, the second in the ocean travels of Micronesian sailors.

In both environments, features external to the individual mind play a critical role. Sailors for centuries have been concerned with the location and phase of the moon, and its influence on the water through which they are traveling. Sailors use maps in some form - paper, digital, or mental - to situate themselves against/within their environment.

In both environments, there is a distribution of cognitive work across time - most noticeable in the co-evolution of tools or artifacts. The tools used in navigation from maps to sextants have changed over time and serve as repositories of knowledge. For learners today, as for the sailors in both ships and canoes as described by Hutchins, the tools we use embody cognition and reduce the amount of work required to solve problems. As Baltzersen (2022) points out, information travels with artifacts. Even working 'alone' we can distribute the work across time by preparatory work - such as doing calculations in advance. In everyday life, many people nowadays offload cognitive tasks to our devices, for example, asking Siri to remind us about an appointment or a task that needs completing.

To distribute work across time - and especially across individuals - requires a common substrate. It's not enough for two individuals to share the same language, they must use the same terminology, and understand the same references, in order to have a distributed cognitive work.

Distributed epistemic games

In the present work, we introduce the idea of *distributed epistemic games*. As the name suggests, we view epistemic games through the lens of distributed cognition. Distributed epistemic games are defined as epistemic games which are played collectively by members of a group differing in expertise, location, and time/duration of interactions. Because these games are not bound by any of the constraints discussed above, they allow for a larger number of participants and interactions. In the interactions between the members of the group, we can see the process of "computation itself" (Hutchins, 1996, p. 283). Like the interactions of an individual with their environment, the interactions between individuals are the thinking process itself (Hutchins, 2008, p. 2011). Following this reasoning, a larger number of interactions (as we see in a distributed epistemic game) means we have a larger amount of computation or thinking happening around the problem.

These distributed epistemic games (DEGs) have a critical relationship to the zone of communal possibility (ZCP). A DEG is a way to work *within* the ZCP, to coordinate efforts across individuals, time, and space in order to increase both the size of the ZCP, as well as the knowledge available within it. DEGs are how groups of individuals work *within* the zone to solve problems through collaborative effort.

Our framework can be used to model distributed epistemic games, identifying, for example, the moves of which they are composed and the organization of the moves across players, time, and space. For this paper, we introduce the idea of a *tactic*: a collection of moves made in an epistemic game. In chess, masters will play multiple tactics, each of which is intended to add a threat to the opponent and advance the player toward victory. In distributed epistemic games, the intent is not to threaten an opponent, but to take multiple paths towards the goal of the larger game. While some of these tactics are deliberately planned, others emerge as a result of the interactions between individuals.

We illustrate the power of our framework below, using it to identify moves and tactics in the distributed knowledge-building work of a network of individuals (n> 39), as they collaborate to solve a complex mathematical problem.

Methods

We use our distributed epistemic games framework and a grounded theory approach to model the collaborative knowledge-building of individuals who have come together in a unique way to solve a complex problem known as *polymath1*.

The first Polymath Project was proposed by Professor Tim Gowers on his blog ("Is Massively Collaborative Mathematics Possible?," 2009). He posed the question of whether a group of individuals could engage in massive and collaborative problem solving. The initial problem was creating a proof for the density Hales-Jewett problem (Polymath, 2012). The group's attempt at collaborative problem-solving was both mediated by and recorded in a temporal sequence of blog posts. Some of the contributions were meta comments, summarizing existing threads or discussing the tools/processes in use – such as blog posts, Google docs, and wikis. While these comments provided useful tracking and discussions, they did not make novel contributions to the proof itself. The practice of numbering comments caught on fairly early in the process. The numbering allowed for multiple concurrent threads (since there was a limit of 100 comments on each thread). It also made referring to other comments – building on other ideas – more concise and clear. This was especially important as the number of comments was well over 700 within a few weeks, and over 1500 by the project's end. Early in the process, posts were not only numbered but author-tagged with the thread or approach. These tags included author tags like *Varnavides*, *Sperner*, and approach tags such as *Lemma Removal*, *Pair Removal*, to name a few. Tags are used by authors to reify different *deliberate tactics*, or the multiple planned approaches directed at the goal of solving the problem.

Participants

Earlier research used the number of numbered comments as a measure of individual contributions, finding that a total of 39 distinct users contributed at least one numbered comment to the overall process (Cranshaw & Kittur, 2011). The 29 users who could be linked to 'real' profiles were homogenous in several respects, including gender (28 male) and field (mathematics or computer science backgrounds). Interestingly, however, there was a large range of expertise in their field as measured by the number of refereed publications. Several participants had no published work before engaging with the Polymath project, while a handful had hundreds. According to Cranshaw & Kittur, the spread in publications resulted in a median of 35 and a mean of 65.2, even with a number of participants with 5 or fewer publications (2011). This means that we would be looking at a histogram with a very long tail, or, to put it another way, it means that there were a handful of experts working with a larger group of engaged novices. In spite of the large difference in seniority, Cranshaw & Kittur noted that even users “who commented very infrequently” had “a large impact on the proof” (2011, p. 8).

Data collection

For this project, the authors contacted Professors Gowers (whose blog hosted the lion’s share of the problem-solving work) and Tao (who also hosted several threads on his blog) to request permission to export and analyze the comments on their posts. Both professors gave their permission, and the data were extracted on September 23rd, 2022. Data were in pdf format - one document per primary post - with all comments for that post included at the end.

Data analysis

Building on Hutchins (2008), we are particularly interested in the interactions between individual contributors, which are captured by the comments and responses on the blog posts. For analysis, the posts and comments were transferred to a single file, with data for the author, timestamp, text, and (perhaps most importantly) the comment or post being referenced by the new post. During this process, the authors noted comments and interchanges of interest to review as a team.

A subset of the larger data was selected for a closer analysis based on the authors’ noting a particular section of interest. This section - initially identified by the phrase “I can’t see a flaw in your reasoning. If it’s correct, then it shows something rather interesting” - was expanded as the authors worked backwards and forwards from that phrase to isolate a section of interactions. One of the characteristics of an emergent tactic is the importance not of *time* but of *timing*, so we wanted to get a good set of comments leading to and from the point of interest.

Ultimately, the authors ended up with a set of 21 comments to review and code as moves within our framework of a distributed epistemic game of mathematical problem-solving. A microgenetic grounded approach was applied to the data (Glaser & Strauss, 2017; Siegler, 2006). Individual posts were analyzed for potential moves. Identified potential moves were named and the larger structure of the temporal and inter-individual relationships between the moves made during the discussion segment was analyzed to provide insight into the way moves responded to previous moves to generate new knowledge.

Findings

We identified a collection of these interactions as an *emergent tactic* (one which is not planned but emerges through interactions), which we have named the *Pivot*. In the *pivot*, a monologue is interrupted and then interaction increases as a result of the interrupting participant’s contribution.

Within the *pivot*, we have identified the following moves:

- *Monologue*
  - In this move, there is a consistent, relatively undisturbed, progress along a train of thought. It can also be described as a ‘stream of consciousness.’ While this comes from a single author in our selected example, it is possible to have this process carried out by multiple participants. The distinguishing characteristic is that it is consistent (or very nearly so) progress along the same trajectory of thought.
  - Due to space limitations, the full monologue (over 3,400 words across 10 posts/responses) is not included here. The monologue in question serves to summarize the discussion up to that point, calling out promising suggestions and defining several deliberate tactics in the form of named threads to pursue. Two of the named threads (Pair Removal & Triangle Removal) have several responses each in the monologue process.
- *Interruption*
  - In the interruption, an engaged participant poses a question which interrupts an ongoing thread. The interruption problematizes a part of the thinking to which no one had thus far paid attention. Even though the interruption may be uncertain, by problematizing a previously-overlooked section it challenges assumptions.
  - This interruption is shown below (see Figure 1). Several things about this interruption are striking.
    - First, the author labels it a ‘dumb question.’ Humility aside, this suggests that the author is questioning something which might seem obvious to a more experienced

participant. They expect that the answer is known, perhaps known well enough to make the question seem silly to more knowledgeable collaborators.

- Second, the author is not responding to the most recent previous post. It is not a continuation of the monologue by voice, topic, or trajectory. This question is specific to Pair Removal, which the monologue left behind several posts earlier. Finally, in addition to the self-applied label of 'dumb question,' the tone of this post is uncertain and questioning, rather than challenging.

Figure 1
The Interruption

Can someone help me with this dumb question?

Suppose $A = B$ are the family of sets not including the last element n. Then A and B have density about $1/2$ within $KN_{n,n/2-k/2}$. (We're thinking $k(n) \to \infty$, $k(n)/n \to 0$ here, right?) It seems that the fraction of Kneser graph edges which are in $A \times B$ is about k/n, which is "negligible". So we should be able to delete any small constant fraction of vertices from $A = B$ and make it an intersecting family. But A is 100% of the Kneser graph $KN_{n-1,n/2-k/2}$, and doesn't the largest intersecting family inside such a Kneser graph have density only around $1/2$?

- *Response*
  - In an almost recursive or retrospective way, the response creates the interruption. If the monologue continues without acknowledging the interrupting move (as we see at other points in the larger project), then the *pivot* tactic doesn't emerge (the cognition doesn't pivot and focus on a new direction). In this case, the interruption is acknowledged, so the moves continue in the *pivot*.
  - The tone of the response (see Figure 2 below) by Gowers shows the cognitive impact of the interruption. He is pondering the reasoning and the implications of what was thought (by the author) to be a dumb question. His assumptions were challenged by an unassuming question.

Figure 2
The Response

[redacted] all I can say is that I can't see a flaw in your reasoning. If it's correct, then it shows something rather interesting. I couldn't get [redacted] argument to work unless I assumed that degrees were very small rather than just small, and your example suggests that it's actually false when you merely assume that the degrees are a negligible fraction of the maximum possible. In your example, the degree of a vertex in A is still large, even if it's proportionately small, so there's still some hope that [redacted] argument is correct and adaptable to DHJ.

Now I must stare at the argument that I produced in 308 and try to work out what's going on.

- *Increased Interactions*
  - After the *pivot*, we see an increase in interactions between individuals and a branching of thought processes.
  - One of the ways to measure this increase in interactions is to look at the difference in voices before and after the interruption. Before the interruption there is a long monologue (10 distinct posts/comments) with a single voice. After the interruption the voice changes eight times in the next ten comments - the interactions have increased drastically (from 1 voice in 10 posts to 8 voices in 10 posts). Due to space limitations, screenshots of these posts are not included here.

Discussion

This paper introduced a new framework for making sense of collaborative knowledge-building processes. The framework integrates ideas from two existing frameworks: *epistemic forms and games* and *distributed cognition*. The resulting framework, which we call *distributed epistemic games*, can be used to model collaborative processes through which new knowledge is generated. We illustrate how the framework can be used to model the joint intellectual work of mathematicians focused on solving an “unsolvable” problem. The work of this group is preserved in threads of individual blog posts made over a handful of weeks. We identify two types of tactics (collections of moves) - both planned or *deliberate,* and *emergent*. We also look closely at the effect of a specific emergent tactic - *the pivot* - in terms of the individual moves and its resulting impact of increased interactions. It is important to note that the increase in interactions, rather than the setting of a stable direction, is the beneficial effect of the pivot tactic. Like a turn during a murmuration, the productivity is not in producing a new and stable heading, but in producing an increase of movement and change. Tying into the theory of distributed cognition, these increased interactions represent an increase in cognitive growth or knowledge building. Put another way, it is the movement of the group that accomplishes the communal knowledge-building goals.

Our work makes a theoretical contribution to both literature concerned with characterizing the nature of expert knowledge building and literature concerned with characterizing the nature of cognition as distributed across time, space, and minds.

Future work includes qualitatively analyzing more of the threads in the Polymath project to identify more moves, such as the *interruption*, and meso-constructs like tactics such as the *pivot*. As the moves and constructs are identified and described, their characteristics can be used both for modeling (in which we create agent-based computational models of collective cognitive change) and for scaling the research process by automating the scanning of large text corpi of the Polymath Projects and other collective problem-solving initiatives. Analysis of move frequencies and structure (relationships to other moves in time and space) are expected to reveal insights into aspects of distributed epistemic games such as which moves/tactics are most fruitful.

Without the affordances of computers, internet, and blog posts, the *distributed epistemic game* enacted in the Polymath Project would not be possible, and the problem may have remained unsolved. By understanding this game, we can design environments, exercises, and games to solve more of the unsolvable problems by working together and extending our collective *zone of communal possibility.*

References

Asimov, I. (1989). *Prelude to Foundation*. Random House Worlds.

Baltzersen, R. K. (2022). *Cultural-historical perspectives on collective intelligence: Patterns in problem solving and innovation*. Cambridge University Press.

Bensaude-Vincent, B. (1986). Mendeleev’s periodic system of chemical elements. The British Journal for the History of Science, 19(1), 3-17.

Collins, A., & Ferguson, W. (1993). Epistemic forms and epistemic games: Structures and strategies to guide inquiry. Educational psychologist, 28(1), 25-42.

Cranshaw, J., & Kittur, A. (2011). The polymath project: Lessons from a successful online collaboration in mathematics. 1865–1874.

Dunbar, K. (1997). How scientists think: On-line creativity and conceptual change in science.

Glaser, B. G., & Strauss, A. L. (2017). The discovery of grounded theory: Strategies for qualitative research. Routledge.

Hutchins, E. (1995). Cognition in the Wild. MIT press.

Hutchins, E. (2008). The role of cultural practices in the emergence of modern human intelligence. Philosophical Transactions of the Royal Society B: Biological Sciences, 363(1499), 2011–2019. https://doi.org/10.1098/rstb.2008.0003

Hutchins, E., & Klausen, T. (1996). Distributed cognition in an airline cockpit. In Y. Engeström & D. Middleton (Eds.), Cognition and Communication at Work (1st ed., pp. 15–34). Cambridge University Press. https://doi.org/10.1017/CBO9781139174077.002

Inhelder, B., & Piaget, J. (1964). The early growth of logic in the child (EA Lunzer & D. Papert, Trans.). London: Routledge & Kegan Paul.

Is massively collaborative mathematics possible? (2009, January 27). Gowers’s Weblog. https://gowers.wordpress.com/2009/01/27/is-massively-collaborative-mathematics-possible/

Koepnick, B., Flatten, J., Husain, T., Ford, A., Silva, D.-A., Bick, M. J., Bauer, A., Liu, G., Ishida, Y., Boykov, A., Estep, R. D., Kleinfelter, S., Nørgård-Solano, T., Wei, L., Players, F., Montelione, G. T., DiMaio, F., Popović, Z., Khatib, F., … Baker, D. (2019). De novo protein design by citizen scientists. Nature, 570(7761), 390–394. https://doi.org/10.1038/s41586-019-1274-4

Malone, T. W. (2018). Superminds: The surprising power of people and computers thinking together (First edition). Little, Brown and Company.

Malone, T. W., Laubacher, R., & Dellarocas, C. (2009). Harnessing Crowds: Mapping the Genome of Collective Intelligence (SSRN Scholarly Paper No. 1381502). Social Science Research Network. https://doi.org/10.2139/ssrn.1381502

Parslow, G. R. (2013). Commentary: Crowdsourcing, foldit, and scientific discovery games: Crowdsourcing, Foldit, and Scientific Discovery Games. Biochemistry and Molecular Biology Education, 41(2), 116–117. https://doi.org/10.1002/bmb.20686

Siegler, R. S. (2006). Microgenetic Analyses of Learning. In D. Kuhn, R. S. Siegler, W. Damon, & R. M. Lerner (Eds.), Handbook of child psychology: Cognition, perception, and language (pp. 464–510). John Wiley & Sons Inc.

Polymath, D. (2012). A new proof of the density Hales-Jewett theorem. Annals of Mathematics, 1283–1327.

Rutherford, A., Cebrian, M., Hong, I., & Rahwan, I. (2020). Impossible by Conventional Means: Ten Years on from the DARPA Red Balloon Challenge. https://doi.org/10.48550/ARXIV.2008.05940

Vygotskij, L. S., & Cole, M. (1981). Mind in society: The development of higher psychological processes (Nachdr.). Harvard Univ. Press.

Wilensky, U., & Rand, W. (2015). An introduction to agent-based modeling: modeling natural, social, and engineered complex systems with NetLogo. MIT Press.