Cooperation is not enough: The role of instructional strategies in cooperative learning in higher education.

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For several years, scholars have studied cooperative learning and its outcomes in the educational context. Yet, little is known on how different instructional strategies impact the relationship between cooperation and learning. Here we studied how different instructional strategies lead to different social configurations and their differences in academic performance. We set three different experimental conditions for 82 first-year students, where we varied teaching and instructional strategies. The experiment was run in an introductory physics course over two months at a university in Northern Chile. To explore the extent to which students’ social structures facilitate academic performance, we collected data on students’ performance on a physics test designed with well-structured problems, and on an ill-structured problem. In addition, we asked students to respond to an on-line peer-nomination survey related to their social interactions engaged for information seeking to solve problems. We tested the effect of different network structures over academic performance on both types of activities by setting different statistical linear models. Surprisingly, students who actively seek out information on multiple peers are less likely to achieve good performance on well-structured problems, whereas, for ill-structured problems, this effect would depend on the features of the learning environment.

We found that good performance on well and ill-structured problems respond to different social network configurations. In a highly clustered network (which contains highly redundant information), students perform well-structured problems better than ill-structured problems. In contrast, students with access to network structural holes (which enable access to more diverse information) perform ill-structured problems better than well-structured problems. Finally, ill-structured problems can promote creative thinking, but only if instructors guide the solving process and motivate students to engage in the appropriate cognitive demands these problems entail. Our results suggest that teaching and instructional strategies have a key role in cooperative learning; therefore, educators implementing cooperative learning methods have to accompany them with a proper instructional strategy.

I. INTRODUCTION

We focus on creativity and collaboration as important competencies in today’s education [1]. The ability to be creative in a given field of knowledge reflects the level of expertise, to the extent that more and deepest understanding would provide a better base to generate novel and appropriate ideas, both key features for creativity [2]. As suggested by the theory of human adaptability [3], creative thinking depends on one’s ability to build logical connections between previous and new knowledge (i.e., deep learning) in order to overcome daily challenges. The emergence of creative ideas and learning tends to be complex and social phenomena [4, 5], but with important implications for education and professional success. The challenge in education then consists on innovating and enabling appropriate opportunities for creative thinking and collaboration.

The creative and social network literature provide interesting evidence to understand the different individual and social mechanisms that ease collective learning and the emergence of good ideas. In this paper we investigate students’ social networks from three sections from a introductory physics course, and determined the social structures that facilitate good performance on well-structured physics prob-
lems (e.g., textbook problems), and creative tasks defined as ill-structured [6], which consisted on student groups generating physics problems for high school students. Through this analysis we explored whether good performance on both types of problems is predicted by mechanisms associated with creativity and innovation, such as creative combinations [5] or interrogation logic [7]. In addition, we tested the effects of different instructional strategies on performance, and whether the effect of social structures responded differently depending on the learning environment.

II. PROBLEM SOLVING AND CREATIVITY

According to Jonassen [6], well-structured problems are situations that present all possible elements that allow finding a known and unique solution. In physics education, these problems describe a particular phenomena that demands the use of a limited number of rules and principles (e.g. algebra and physics principles). These procedures tend to be wellorganized, constrained to certain parameters (e.g., initial and/or the final conditions on a motion problem in kinematics), and with predictable actions that are frequently used to solve similar problems. In PER, these problems mirror simplified and idealized situations that have little to no connection with students’ real world experience [8], often found on physics textbooks [9] [10]. Educators have assumed the existence of a strong relationship between implementing mathematical representations of physics content and mastering these conceptual principles [11] [12]. Nonetheless, research evidence has found problematic results on this matter, as even after solving over a thousand physics problems, students have yet to develop a conceptual understanding of the physics principles and laws asked in those problems [13] [14]. These results reveal the dangers of mechanizing problems and engaging in superficial use of formulae for finding solutions.

The well-structured nature of these learning activities adds an important limitation for creativity, in connection with 'plug and chug' strategy enacted to solve these problems [10] [11]. Sawyer [15] conceptualized tasks in a continuum governed by their degree of unpredictability. In one extreme one may find highly predictable tasks, such as textbook physics problems, whereas the opposite end would include highly unpredictable activities with no embedded constraints. A predictable and constrained performance implies that the process is highly scripted, and members are expected to perform within the restrictions imposed by the situation. In contrast, unpredictable and unconstrained performances are located in the opposite end of this continuum, where there is room for a diversity of alternative strategies and solutions to succeed on the task. Ill-structured problems, often times associated with real world problems [16] lack the information that individuals would use to find already known and unique solutions, and therefore introduce high levels of uncertainty associated with a spectrum of possible outcomes and strategies on how to proceed in order to create them [17]. The difficulty of ill-structured problems relies on deciding the appropriate constraining conditions that would guide solvers from a scenario with multiple possible responses, to one where solvers decide their unique response [18]. Fortus [16] studied the importance of making assumptions when solving ill-structured mechanics problems on experts and novices. Results indicate that even experts struggled to make the adequate assumptions on the physics variables and principles involved, and on the absolute or relative magnitudes of the variables for deciding and developing a unique solution.

Steiner [19] labelled well-structured problems as disjunctive tasks, because when engaged in groups this can be solved by the most capable member of the team, without the necessity of further discussion. Differently, one might expect ill-structured problems to introduce higher levels of positive interdependence [20], and be perceived as additive tasks [19], where performance emerged as the sum of all members’ contributions and relevant abilities. This is coherent with the experience from Heller and colleagues [21], who designed context-rich problems as an alternative to traditional textbook physics activities [8], and found that groups performed better than isolated students. In tasks that require decision making groups are better than individuals because they are more likely to select the right ideas to develop [22]. Yet, individuals are likely to generate creative outcomes, but depending on their dispositions to learn in isolation. Sitar and colleagues [23] found that creativity is predicted by both independent and collaborative dispositions for learning, yet these relationships are mediated by self-efficacy and enjoyment respectively. In more detail, an independent learner would prefer to trust on her/his own learning processes, skills, knowledge and strategies for achieving creative outcomes, whereas collaborative learners would enjoy working and learning with others, leading to higher levels of motivation, social processes and communication with people with different beliefs and background knowledge, enabling them to access valuable information for creativity.

III. SOCIAL NETWORK ANALYSIS FOR KNOWLEDGE DEVELOPMENT

Social network theory has payed attention to the different social mechanisms that enable knowledge development and idea generation. One of this mechanisms consists on creative combinations of information, a process that strongly depends on one’s social position within the network, and the knowledge that could be accessed through such structure. Through this process, the emergence of good ideas would depend on how information is transferred through social ties, from zones of high knowledge redundancy (i.e., high network cohesion), to zones where actors have access to isolated partitions of the network (i.e., structural holes), who may have unique information to share. Actors who bridge connections between two unconnected pairs of individuals or groups, or who span structural wholes through brokerage, would enjoy the advan-
tages of social capital by accessing the resources available in different places of the network [5]. Through this brokering mechanism, individuals may access to novel information that may be utilized for creative combinations and further innovation. The nature of the information that would flow through social ties would depend on the characteristics of the social relationship. For instance, Hansen [24] found that strong ties allow the diffusion of complex and non-codified knowledge, whereas weak ties facilitate the transfer of simple or codified knowledge [25]. This implies that cohesive networks where actors are likely connected through strong ties would ease transfer of complex information. Resources rooted on a cohesive network are less resistant to flow between actors due to the strength of their social relationships, thus easing transactions costs and encouraging collaboration [26]. Conversely, the social investment required to transfer complex knowledge (e.g., time, energy and resources), would make it unlikely for this type of information to flow through weak ties.

Even though brokering, or connecting isolated partitions of the network seems ideal for the generation of novel approaches for solving problems [5, 27], developing creative ideas into real solution demands work and effort, a social investment that cohesive groups are more likely to take. Fleming, Mingo and Chen [28] showed that creative solutions tend to emerge and be developed by cohesive networks, where focal inventors and collaborators have broader experience, or have worked on diverse organizations. Members’ prior experience somehow replaces the value of bridging structural holes, and adds the needed non-redundancy for generative creativity.

From the advantages of brokering new information from sparse networks, groups located in central positions of the networks are more likely to succeed because they are placed in paths connecting two or more teams, and therefore have access to the information that is transferred through those links [29]. In contrast, peripheral groups placed at the end of the information path depend on central groups letting the knowledge flow in their direction, thus making them less likely to take faster advantage of the resources flowing throughout the social system [30]. This highlights the importance of structural positions for idea recombination, however, Rhee and Leonardi [7] found that highly constrained networks afford opportunities for creative ideas, but though different cognitive processes than actors who span structural holes. Accordingly, actors may take advantage of the highly constrained network when their attention is focused on a particular content and its related ideas rather than on the diversity of information flowing throughout the network. The mechanism through which this may happen was defined as interrogation logic [7], and consists of deep examination of the local knowledge managed by the individuals embedded in the cohesive network. Because highly constrained networks are characterized by strong ties [5], it is reasonable to think that actors in such a structural situation would manage a common and well-bounded volume of information. Consequently, the strong ties that connect all members in this cluster may facilitate the collective questioning and reflection over the local knowledge, leading to the emergence of new and complex ideas that are relatively easy to learn and develop through shared strong ties [24, 31, 32].

IV. SOCIAL NETWORK ANALYSIS IN EDUCATION

Education researchers have used network analysis to explore the academic advantages of central position in students’ networks. In coherence with the social advantages of cohesive networks, academic performance is most likely to be enhanced by being immersed in a cohesive network from which students can take advantage of the information, skills, abilities others might share through social ties [53, 34]. Putnik and colleagues [35] found meaningful and positive correlations between centrality measures and performance on project-based course for engineers. Similarly, Bruun and Brewe [36] found that different centrality measures and FCI (Force Concept Inventory) scores as predictors of grades on two subsequent courses (i.e., Newtonian Mechanics and Linear Algebra). Differently, students’ networks have been used to explore the predictable power of social integration on students’ retention [37], as well as the influence of out-of-class relationships on persistence in future physics courses [38]. In both cases, students who are embedded in the network are more likely to enroll in future courses.

Brewe and colleagues [39] took a different approach, as they utilized indicators of participation on a Physics Learning Center (PLC) to predict future centrality. Their findings suggest that subjects have certain degree of control over their centrality in the learning center, where they collaborate with others with diverse levels of expertise, in developing and validating models through participation in inquiry labs, and problem solving. Moreover, the teaching and learning conditions would play an important role in encouraging (hindering) student social interaction [40]. Here, the instructor is likely to meet an important role in fostering effective socialization of information, as well as the nature of the learning activities. Finally, recent evidence has found that the number of social ties is not an unequivocal predictor for academic success, as more ties for collaboration has yielded negative effects, whereas reciprocal relationship enable afford good academic performance [41]. The latter evidence adds an interesting condition over the nature of the ties for success in education.

V. METHODS

This work consists on a descriptive case study conducted in three sections of introductory physics courses designed for engineer majors in a University in Northern Chile. The research goal was to investigate problem solving and network features of students when they solve well and ill-structured physics problems. For this purpose, in collaboration with course instructors, we designed a battery of ill-structured
problems grounded on real-life situations for a weekly administration during problem solving sessions for a period of 2 months.

A. Research Context

The research settings consisted on three undergraduate sections from an introductory physics course in a Chilean University over a period of two months in 2018. The course dedicated 3.0 hours each week to lectures-based instruction, 1.5 hours per week to lab practices, and 1.5 hours per week to problem solving sessions.

On course section A (Traditional section), instructors used ill-structured problem only the day of data collection (week 7 of the semester), while using well-structured math-based problems every week. On course section B (Mixed section), instructors implemented ill-structured problems every other week alternating with well-structured activities. On course section C (Treatment section), instructors used ill-structured problems every week. In addition, instructors in sections Traditional and Mixed guided problem solving session by behaving as sources of information in the face of students problem related questions. Whereas, instructor in section Treatment responded to students questions by directing their attention to other classmates who may have either asked similar question, or responded it already. The constant used of ill-structured problems in Treatment section was accompanied by the instructor highlighting the importance of assumptions and creativity for solving the open-ended activities. We perceive these different approaches to either facilitate information or guide them towards multiple sources of ideas, as having an effect over collaborative mechanism, and the effectiveness of these social processes for academic performance. Table I summarizes the types of problems engaged by the different sections before the day of data collection on week 7, as well as the role enacted by the respective instructor during the problem solving sessions.

Students were engineering majors in their first or second year of college education, pursuing a careers on either Industrial Civil Engineer or Software Civil Engineer. A total of 82 participated in the study (Traditional = 33; Mixed = 23; Treatment = 26).

B. Data Collection

During the data collection session we tasked students with the activity of designing a physics problem for high school students addressing the concepts and principles of circular motion. At the end of the session we gathered students’ problems, and asked them to respond an online peer-nomination survey to identify the social network structures that enable good performance on both well and ill-structured problems. The survey consisted on two questions:

a. Information Seeking: From whom had you sought information for solving the physics problem addressed in this session?

b. Good Students: Who is a good physics problem solver in your class? (i.e., a student you believe is good at understanding physics content and solving physics problems).

To facilitate students’ responses on each of these questions, we included the roster of students enrolled per section. Consequently, subjects responded by selecting the individuals in their sections from whom they sought information, and the ones that are perceived as good students. Both questions led to directed (i.e., ties are not necessarily reciprocal) and binary networks (i.e., links between nodes either exist (1) or do not exist (0)). The network of information seeking was designed to reveal whether students engaged on social interactions with the goal of finding resources and ideas for solving the physics ill-structured problem. Because flow ties are difficult to obtain, social interactions such as ‘seeking information’ may be perceived as proxies of information flow [42,43]. Using good student network is thought to enable an additional dimension to reveal what type of students engaged on information seeking, to then explore whether this perceived prestige is a valuable contributor to the social processes that affect academic success.

Physics grades consisted on students’ scores to a test designed by instructors over three well-structured physics problems. Physics grades were shared by the instructors three weeks after the day of data collection, without the possibility to review the assessment instrument, nor students’ solutions to these problems.

Perform elaboration is a variable constructed to assess the degree of elaboration of student generated problems. Because creative tasks and their respective outputs may deviate from the standard solutions, analyzing performance on ill-structured problems was conducted through the identification of embedded features and characteristics. A total of 26 problems (Traditional = 10; Mixed = 9; Treatment = 7). In order to conduct the analysis, we translated these problems from Spanish to English, which were revised by a native English speaker knowledgeable in physics. The analysis of these solutions (i.e., physics problems) was conducted on NVivo 12 plus, a software for qualitative data analysis. This qualitative description comes from the identification problems’ attributes and characteristics, such as physics concepts used as data and/or questions, type of information, contextual details, word count among others variables shown in Table II. A first wave of problem coding was conducted by the lead author, which guided to an initial version of the code-book, who was revisited in collaboration with a trained graduate student in qualitative analysis and physics content. After agreement, an independent wave of coding was performed, where both covered 40% of the data (10 problems), obtaining an inter-rater reliability of 92%.

The network measures used for this analysis were computed from the network of information seeking (i.e., response to survey question a). This set of social structure variables
TABLE I. Sections, problems and instructor’s role.

| Section     | Problems worked before day of data collection | Instructor’s Role                                      |
|-------------|---------------------------------------------|-------------------------------------------------------|
| Traditional | Well-structured physics problems             | Source of information                                  |
| Mixed       | Alternate between well and ill-structured physics problems | Source of information                                  |
| Treatment   | Ill-structured physics problems              | Guided students towards different sources of information & emphasized the importance of assumption making and creativity |

TABLE II. Code description of problem characteristics.

| Code                               | Description                                                                 |
|------------------------------------|-----------------------------------------------------------------------------|
| Physics Concepts Asked             | Physics concepts used as problem items (e.g., angular speed, tangential acceleration). |
| Type of Information                |                                                                             |
| Ready-to-Use Info                  | Data is explicitly presented in the problem and with appropriate units for its use. |
| Conversion of Units                | Physical quantities that need conversion to respect the IS of units (i.e., m and s). |
| Text to Math                       | Physics information is presented in written form and needs translation into mathematical expressions (e.g., “begin its motion from rest” or “uniform motion”). |
| Algebra Transformation             | Physics information for solving the problem needs algebraic steps for accessing and using it. |
| Information Research               | The problem requires researching appropriate magnitudes to solve the problem. |
| Assumptions                        | Problem forces students to assume particular characteristics of the problem, such as constant acceleration, or the position of the ‘particle’ that describes the circular motion. |
| No. Phys. Concepts Asked           | Number of physics concepts used as problem items.                          |
| No. Equations Needed               | Number of equations required to solve the problem.                         |
| Contextual Details                 | Elements from real-life activities, and/or actors witnessing or engaging in actions. |
| Word Count                         | Number of words used on the problems’ description.                          |
| Cognitive Demand                   | Taken from a taxonomy of introductory physics problems [44].                  |

consisted on different metrics of network centrality (degree, in-degree, out-degree, betweenness and eigenvector), as well as network density and constraint. Following we describe each of these variables:

- **Degree**: a network measure of centrality that counts the number of edges (i.e., social ties) connecting the focal actor.

- **Out-degree**: on directed networks this measure of centrality counts the number of outgoing edges or social ties for a given node, that is, the number of links directed from the focal actor towards other individuals within the network.

- **Gatekeeper**: a brokerage measure that counts the number of times node $i$ bridged connections between $j$ and $q$, being the source node $j$ a member of a different group than $i$ and $q$, which in turn are members of the same group. A gatekeeper broker is an individual that spans non-redundant ties with nodes outside its own group, has connections with its own group members, and engages in bringing information from the outside ties, while the destination of that information is a members within its own group. On Fig. [1] nodes C, D and F display such type of brokerage as they display ties with nodes outside their own units (sources), but at the same time engaged with teammates, and therefore, may have access to novel information from these outside sources and bring it to the group.

- **Eigenvector**: network centrality measure that regards to social influence within a system, as it depends on whether the nodes tied to the focal actor shows social ties to other well connected nodes.

Accounting for the connectivity of one’s friends is key for flow processes [42], to the extent that friends with social relationships outside one’s social domain might boost chances of receiving and sharing valuable information for learning, innovation and social status. The algebraic representation of eigenvector is as follows: $e_i = \lambda \sum_{j} x_{ij} e_j$. Here, $e_i$ is the eigenvector centrality of node $i$, and $\lambda$ the largest eigenvalue of $e_i$. Moreover, $x_{ij}$ can take values of 1 or 0 depending on whether nodes $i$ connected to $j$ or not respectively. That is, eigenvector centrality of node $i$ is proportional to the sum of its neighbors’ eigenvector centralities.

- **Constraint**: Constraint is network measure that accounts the number of redundant social ties, that is, the degree to which a node spans ties with others who are also connected to each other [45]. This is an inverse measure of social capital, as high constraint means low access to structural holes.

This is an inverse measure of brokerage, or the node
that bridges isolated portions of the network, thus accessing structural holes. High constraint will indicate that a node is totally invested in a group of already connected others, and will therefore have access to zero structural holes. The definition introduced by [45]:

\[ C_i = \sum_j c_{ij}, \quad i \neq j; \quad c_{ij} = (p_{ij} + \sum_q p_{ij}p_{jq})^2, \quad q \neq i, j, \]

where \( C_i \) is the constrain of node \( i \), and \( c_{ij} \) an index that indicates \( i \)'s investment on its relationship with \( j \), counting direct (\( p_{ij} \): proportion of tie strength between \( i \) and \( j \), relative al all of \( i \)'s ties) and indirect (\( \sum_q p_{ij}p_{jq} \); proportion of tie strength through indirect paths connecting \( i \) and \( j \) via \( q \)).

Network constraint is a variable negatively associated with brokerage, that is, the investment in social interactions that bridge connections between previously isolated portion of the network, known as structural holes. For instance, on Fig. 1 node F has access to a structural hole because it shows non-redundant ties between groups green and blue, and may access to new information and ideas from both groups, which may provide unique opportunities for creative combinations. Consequently, node F would have lower network constraint than, for instance, nodes G and H as these have redundant ties, and therefore are unable of brokering beyond their close network.

Finally, we accessed to data on students’ scores on a nationwide standardized testing (University Selection Test or UST) to access higher education, type of high school from where students graduated, city where they lived before entering university, engineering major and gender, which were utilized as control variables in our analysis. These control variables aim to account for the homophily mechanisms that drive social networks configuration in higher education. [46-48].

**FIG. 1.** Network diagram of constraints and structural holes. Node F has access to different sources of information from blue and green communities.

After removing missing cases, the number of students remaining for analysis was \( N = 67 \). We used ordinary least square multiple regressions (OLS) on the continuous dependent variables (i.e., physics grades and problem elaboration) to explore the effect of network structures, as well differences in performance by sections.

First we tested the effect of network measures over problem elaboration and physics grades. For this we regressed physics grades on network predictors. The models for grades and problem elaboration include interaction terms between class sections and the investigated network measure, which enable a comparison and interpretation on whether the network variable has a similar effect over the whole sample, or its effect over students’ outcomes depends on the learning environment defined by the type of problems and teaching strategy. In order to ease interpretation of regression coefficients, all predictors were standardized. For interpreting the regression coefficients of categorical variables such as academic sections (as), school type (st) and engineer major (em), readers must consider that the coefficient emerges as the difference between the variable in the model and the baseline categories (here as: Traditional, st: Industrial civil engineer, and em: public schools).

Later, we explored whether engaging on problem elaboration enabled good performance through the moderation of social engagement on information seeking. In other words, we investigated the degree to which creative problems foster students’ ability to answer well-structured problems in interaction with students’ network structure. For this purpose, we fitted OLS multiple regression models with an interaction term between problem elaboration and network measures.

**VI. RESULTS**

**A. The Effect of Social Structures over Problem Elaboration**

Plots on Fig. 2 summarized the multiple regression models on problem elaboration, with main predictors in academic section, gatekeeper brokerage and eigenvector centrality. In addition, we include the interaction between network metric and academic section to explore whether there are differences in problem elaboration due to differences in instruction.

The first results worth mentioning is observed in Fig. 2 B, with a significant differences in problem elaboration between Mixed and Traditional section, while such differences are not significant between Treatment and Traditional. This result may be explain due to differences in the learning conditions and motivations to create problems with diverse levels of complexity. An instruction based on ill-structured problems but without appropriate guidance over the importance of decision-making and novel ideas may have had a negative
A constraint*Treatment interaction term is negative for Mixed compared to Traditional section and statistically significant at a level of p-value < 0.05 (Fig. 2A). Moreover, students seeking out information from peers from other groups, and sharing it with their team members (i.e., gatekeeper brokerage) is a positive predictor of problem elaboration above and beyond instructional differences (Fig. 2B). The interaction term is negative for Mixed compared to Traditional section and statistically significant at a level of p-value < 0.05, and less negative for Treatment relative to Traditional, but at .1 level of significance. Figure 2B depicts the relationship between problem elaboration and gatekeeper by section. Accordingly, Mixed section depicts a negative slope, while being a gatekeeper in Traditional and Treatment sections yield to higher problem elaboration.

Finally, eigenvector centrality showed to be negatively related to problem elaboration, that is, students who are linked to well-connected others in the network of information seeking do worse than those who do not enjoy of such social prestige. However, this significant coefficient gets closer to zero when including the interaction between eigenvector and sections (Fig. 2C). Consequently, the direction of this coefficient would depend on the classrooms where these social interactions take part. In detail, having well-connected peers within the network of information seeking would yield to negative effect over students’ motivation to engage in creative thinking. In contrast, due to the task required students to generate a well-structured physics problem, students from the Traditional section may have used the repository of physics problems worked in their class, and be more effective in selecting the right variables and characteristics to include in their problems. The elaboration of problems from Treatment section was likely a consequence of the constant practice on solving ill-structured problems, along with a positive narrative for creativity enacted by the instructor.

Being a member of a cohesive network where most actors seek out information from each other (i.e., redundant ties) shows a null effect effect over problem elaboration (Fig. 2A). Moreover, students seeking out information from peers from other groups, and sharing it with their team members (i.e., gatekeeper brokerage) is a positive predictor of problem elaboration above and beyond instructional differences (Fig. 2B). The interaction term is negative for Mixed compared to Traditional section and statistically significant at a level of p-value < 0.05 and two stars (**) indicate significance at a level of p-value < 0.01.

![FIG. 2. Graphic depiction of OLS multiple regression models for Problem Elaboration regressed on network predictors, controlling by confounding variables (see table 1 on the supplementary results section). Red color indicates a negative effect and blue color indicates a positive effect. One star (*) indicates significance at a level of p-value < 0.05 and two stars (**) indicate significance at a level of p-value < 0.01.](image)

![FIG. 3. Linear regression for interaction between gatekeeper and sections for predicting physics grades.](image)

**B. The effect of social structures over physics grades**

Fig. 3 depicts classroom networks for information seeking. The network diagram informs outdegree centrality as the size of nodes, whereas color shades indicate the grade obtained in the physics test. In relation with the regression coefficients shown on model (2) for outdegree centrality, darker colors indicating good grades tend to be smaller (i.e., lower outdegree centrality).
FIG. 4. Classroom networks for the three analyzed sections: Traditional, Mixed, and Treatment. Node color represents physics grades (being dark red the highest), and the node size represents the out-degree centrality, i.e., the number of times that a student seeks for information in the classroom.

gree) and located at the periphery of the system. In contrast, higher outdegree shown in larger nodes displays light color, thus indicating lower physics grades.

Fig. 5 summarizes the multiple regression models fitted using gatekeeper, log(outdegree), network constraint, log(degree) and eigenvector. These models allowed us to explore the effect of network structures over physics grades, and whether such effects are invariant of the teaching conditions enacted on each section.

Taking all the models, university selection test (UTS) has a positive and significant effect on physics grades in the students sample. Moreover, the regression coefficient for Treatment section is positive and significant with a large effect over physics grades. This result indicates that, after controlling for confounding variables, students under the Treatment condition are likely to increase almost a point in their grades, compared to what students in Traditional section would score under similar conditions. This result suggest important effects of the learning environment generated in Treatment section, based on ill-structured problems, along with guidance over socialization of information.

Surprisingly, and contrary to research evidence in the literature of social networks in education, centrality metrics showed to have a negative effect over grades. These effects are observed for log(outdegree) (A), log(degree) (D) and eigenvector (E). Because outdegree refers to the number of outgoing ties, that is, the activity of seeking out information, one may interpret that students with high outdegree are less knowledgeable in physics. Yet, the seeking out information process is engaged by students with diverse levels of previous knowledge given by the low and non-significant correlation with UST ($r = .12, ns$). The same can be said for being perceived as a good students in the classroom ($r = .15, ns$). Consequently, in the three sections, seeking out information to different peers is not a social process that enables good results. One may think that good students may not need to engage in such processes in order to get good results, the fact is they do participate in such process, yet this social engagement does not allow them good physics grades.

Further, we found a high correlation between good students and indegree centrality ($r = .72, p < .01$), defined as the number of incoming ties in the network of information seeking. Not surprisingly, students who are perceived as good students tend to be sought out for information more often than the rest, and are more likely to obtain good grades. In general, having high number of social ties, either incoming or outgoing, shows to be negatively related to physics grades, as seen on model D for log(degree).

For eigenvector centrality (Fig. 5E) we observe a negative regression coefficient at 0.1 level of significance. Because eigenvector accounts for how well connected are the nodes connecting a given actor, it is associated with social prestige. This position in the network would enable access to multiple others who themselves are well-connected. Again, this negative result would indicate that social prestige within the network of information seeking does not afford good grades. This coefficient is consistent with the latter results, as having numerous different social ties in the pursuit of information for solving physics problems is detrimental for academic success. We extend our interpretation of these results in the discussion section.

Fig. 5B shows a negative effect for gatekeeper brokerage for physics grades. Consistent with our previous results, connecting other outside one’s group for information does not afford academic success in well-structured problems. In addition, network constraint (Fig. 5C) measures the extent to which someone’s social connections are connected to each other, that is, high constraint would suggest low access to
structural holes and its consequent lack of inflow for novel information. Different from other models, regression coefficient is positive, yet not statistically significant. The direction of the coefficient is of interest, as this would support the evidence found by [7] in regards to interrogation logic, and the fact that more redundant social ties would enable success on tasks grounded on well-bounded bodies of knowledge, such as algebra-based physics problems. The significant interaction emerges between Traditional and Mixed sections with a negative coefficient, thus indicating that the relationship between grades and network constraints is more positive in the Traditional classroom.

To disentangle this relationship, Fig 6 shows the interaction between network constraint and sections in predicting physics grades. According to the plot, both Traditional (red) and Treatment section (green) show positive and rather similar slopes, whereas the effect of network constraint is negative for the Mixed section. In both classrooms (Traditional and Treatment), less access to structural holes (i.e., high constraint) is likely to afford good grades, whereas, low constraint is a positive predictor of grades only for the Mixed section. Both contrasting evidence have been found to be related to different social processes for learning, with idea recombination [5, 32, 49] benefiting from low constraint, while interrogation logic [7] being possible on highly constrained social systems.

To interpret what it means for network constraint to predict physics grades, one must consider the nature of the social network measured, the type of information flowing though these ties, and more importantly, the features of the task. First, the test given to students reflects the content and information introduced into the social system, as a common practice to assess the extent to which students are capable of utilizing physics concepts and principles for solving learning activities, such as math-based problems. The test and ultimately, students’ grades would illustrate the degree to which they are capable of manipulating a well bounded volume of information. Now, having high constraints in the network of information seeking implies that the targeted others are themselves connected to each other through incoming and/or outgoing ties, thus generating a dense network of peers through which the redundant content would flow. Moreover, and because the volume of knowledge needed for success in the test is well-defined and established, student may enjoy the benefits of re-
flecting upon the content with others within a cohesive net-
work without experiencing the need of brokerage for creative
combination (i.e., negative coefficient on gatekeeper broker-
age). According to the coefficient, being immerse in such a
highly knitted network with no structural bridges connecting
other partitions of the network would affords good grades.

### C. The Moderated Effect of Social Structures over Physics Grades

In this section we explore whether network variables moderate the relationship between problem elaboration and physics scores. Because having designed an elaborated physics problem has shown to be statistically insignificant in predicting physics grades (see Fig. 5), we considered the possibility that this relationship to be moderated by students’ structural position within the network of information seeking. Here we present multiple regression models with moderators in log(degree) and eigenvector centrality (Fig. 5D and E respectively). Given that regression coefficients for network centrality such as log(degree) and eigenvector are negative, it may not be surprising to see that a negative interaction, thus suggesting that students with high network centrality and who scored high in problem elaboration may not necessarily bene-
fefit by getting good physics grades. In addition, we tested the moderating effect of perceived good students over the rela-
tionship between problem elaboration and physics grades (Fig. 5F), by following the rationale that different levels of problem elaboration may have enabled differences in concep-
tual understanding and abilities for solving well-structured problems (i.e., physics grades), at different levels of perceived status (i.e., good students).

Both models D and E showed negative interaction be-
tween degree and eigenvector centrality, with problem elab-
oration in predicting grades. The same result is also found for the moderated effect of good students nomination, with a negative coefficient. To interpret the moderated effect of these variables, Fig. 7 depicts the interactions at different levels of the moderator (Low in red; and High in green). First, for log(degree) (Fig. 7A), students who show low degree centrality (red) would benefit from developing problems with high elaboration as this would afford them good grades. However, for students with high degree centrality (blue), creating problems with high elaboration would not enable them good grades. In simple words, scoring high in problem elaboration would ease good grades only for those who engage in lower social interactions for information seek-
ing (i.e., low log(degree)), while having average (blue) and high (green) log(degree) seems to be detrimental for obtaining good grades, which is coherent with our previous results. Finally, the interaction between good students and problem elaboration in predicting good grades (Fig. 7B) show that students who are not perceived as good in physics would ben-
efit from creating well elaborated problems, as this process would enable them good grades, while ‘good students’ are better off creating simple problems.

### VII. DISCUSSION

Based on the types of problems worked on the Mixed sec-
tion, it is a surprise that the Mixed section had lower elabo-
ration than the Traditional section. The learning conditions, problems and instructional guidance on how to solve prob-
lems engaged on each section may have influenced students’ motivation for creating problems with various levels of elabor-
oration and complexity. For instance, the learning goal of the task (i.e., design a physics problem for secondary students) may have motivated students in the Traditional section to uti-
lize characteristics from textbook problems that were in their repository of activities to design problems in an effective way. The Mixed section worked on ill-structured problems, but the instructor did not emphasize the importance of assumptions in the face of ill-structured activities. Consequently, high-
lighting the role of assumption making when addressing cre-
ative tasks we believe had positive effects over students’ ex-
pectations and motivation for generating problems, as sug-
gested by the high problem elaboration found on problems from Treatment section, whose instructor engaged in such a positive narrative for creativity.

Interestingly, being a central actor within the network of in-
fomation seeking does not afford good grades. This evidence is redundant and observed for variables such as outdegree, degree and eigenvector centrality, and consistent with the evidence found in Candia and colleagues [41]. The directionality of the relationship between centrality and grades contradicts the research evidence found on other studies [35, 36, 50]. To understand this contradictory results, one could focus on the nature of the social networks mapped on this and other stud-
ies, and argue that the social processes these different systems entail as one of the reasons why we obtained contradictory evidence. Studies in physics education had asked students to
write down the names of their peers with whom respondents had meaningful interactions inside the classroom [37, 51]. Under such survey question, students are likely to remember interactions with friends [52], or useful interactions related to the learning goals of the session [36]. Consequently, it may be reasonable to argue that not every friendship-based interaction would bring meaningful outcomes in the learning context, and therefore accounting for such relationship as a confounding variable may clean the evidence over the effects of meaningful interactions on performance. The survey question used in this study aimed to determine students’ social engagement in the process of seeking out information in the classroom. For this, we facilitated the roster of students rather than having them report the names of their connections. Under these conditions, students are also likely to report useful as well as friendship-based social interactions for information seeking, yet, both types of relationships may not necessarily overlap as the nature of the network does not account for the effectiveness of the social tie. That is, students may have interacted and reported ties with friends and others not considering friends for information for solving the problem, regardless of the meaningfulness of the interactions. Consequently and according to the negative coefficients of centrality over physics grades, students are either not capable of requesting appropriate information for solving physics problems due to ineffective communication, or it may be that engaging in such processes for information seeking is irrelevant in the learning context described here. If the former were true, this would be evidence for the need to engage students on the social processes linked to effective communication and collaboration. Yet, if the learning context were blind to social interactions and sharing information, then this would call for a reflection over the teaching and learning practices involved in this context of university education. Alternatively, it may be the case that students approximated effective social interactions, yet the actors reached lacked meaningful information to share, or rather provided misconceptions regarding the content and/or the goals of the task. Consequently, having nodes with reduced knowledge of the content is not an ideal scenario for students to engage in socialization of information for collective growth. This calls for remedial strategies that prepare subjects for proper learning before putting them in positions to collaborate.

We found no effect in the interaction between network centrality and sections, where the single effect of network structures is stable across multiple measures in predicting physics grades. Yet, the models fitted for predicting problem elaboration would suggest that there are differences on the effects of eigenvector centrality depending on the type of instruction. In detail, eigenvector centrality, or having well-connected peers does not enable problem elaboration on students from the Mixed section, while it does predict positive outcomes on the Traditional class. The radical difference between Mixed and Traditional may be attributed to the combination of problems, and the need to invest on either strong and/or weak ties for accessing information. Based on these results, engaging on well and ill-structured problems without a narrative that highlights the importance of alternative ideas and creative processes (i.e., Mixed section) may have limited students’ motivation to engage on effective socialization of information for creating a highly elaborated problem, or due to the absence of appropriate ideas to share. Moreover, working on distinctive problems every other week may constitute an inconvenient learning strategy in the absence of appropriate guidance, as this may add confusion over the nature of ideas required for solving each problem, as well as the nature of the relationships students would need to develop in order to access it. In contrast, a consistent practice on well-structured problems is suggested to have helped students in transitioning from weak to strong social ties, under the assumption that the information shared for generating the problem is more complex than the one needed for well-structured activities. Fur-
ther, an instruction motivated by ideas of creativity and social interaction afforded students from Treatment sections to experience effects of centrality to be less negative compared to Mixed section, and less positive compared to Traditional. The negative effects may be attributed again to ineffective mechanism of communication and lack of clarity associated with the nature of the information needed for generating a problem, a phenomenon presumably moderated by the instructor every time he guided students to connect others for information.

It is worth paying attention to the significant interaction between network constraint and sections for predicting physics grades. Here, both Traditional and Treatment show a positive relationship with grades, whereas for Mixed section this relationship is negative. This evidence suggests that the social systems created under Traditional and Treatment conditions take advantage of highly constrained networks, where subjects presumably engaged on deep analysis and reflection of ideas, or as [7] called interrogation logic. Consequently, within such a cohesive network it is easier to learn complex information, as well as to develop good ideas [28]. This process is evidence that the nature of well-structured problems does not benefit from the mechanism of creative combinations, but rather engaging in such efforts brings negative effects. Access to unique connections is related to inflow of novel ideas, which here does not afford better outcomes, likely because the well-bounded nature of the physics information for solving well-structured problems does not need novelty, but rather conventional knowledge. Further, the negative effect of constraint on the Mixed section suggests the opposite, where students benefit from connecting structural holes. Surprisingly, students on the Mixed section displayed higher network constraint relative to students from Traditional section (Fig. 3). Consequently, not taking advantage of it for scoring higher grades may be due to ineffective communication for collaboration.

Moreover, and even though the models did not yield to significant coefficients, constraint show null effect for problem elaboration compared to the negative physics grades, while gatekeeper brokerage shows to be a positive predictor for problem elaboration, and negative for physics grades. These results add interesting evidence to the contrasting nature of both types of performance, as well as the shape of learning objectives and the measurement instruments design for such purpose. Generating problems may be close to benefiting from creative combinations [5] compared to well-structured physics problems, provided students engaged on effective mechanisms for information seeking in a context that rewards creativity, and with subjects showing appropriate knowledge and skills [53]. Both mechanism resemble network oscillation proposed by [54], where individuals may oscillate between periods of intense socialization within a cohesive cluster, here appropriate for well-structured problems, and periods of intense brokerage for connecting ties with structural holes, found positive for ill-structured problems. This evidence supports the creative dimension surrounding ill-structured problems, as well as the role of social processes for learning and academic performance, but beyond well-structured problems.

The interactions between problem elaboration scores and degree, eigenvector centrality and good student for predicting physics grades are consistent with the single effect of network structures over physics grades. Low levels on degree and eigenvector centrality are related to good grades when students show high problem elaboration. This results is an alternative evidence of the detrimental effect of socialization and seeking out information, presumably through ineffective mechanisms. Surprisingly, students who are not perceived as good students would get better grades if they score higher on problem elaboration. In simple words, the complexity of generating a physics problems shows to have negative effects for the students who enjoy the social recognition of being proficient in physics. The physics education tradition grounded on mathematical physics problems [9, 10, 13, 14], and its consequent belief that a good physics performance respond to solving well-structured problems has clearly encouraged students to recognize proficient others based on their own ability to solve such math-based problems. Yet, this hierarchical position has not afforded ‘good students’ higher chances of developing more elaborated problems as a proxy for creativity. As mentioned, generating an elaborated problem requires an alternative set of capabilities and skills nonexistent in the case of well-structured problems. The literature on creativity provides a plausible explanation for why such a negative effect was observed on good students. According to [23], both independent and collaborative oriented individuals are likely to be creative, provided they show high self-efficacy and enjoyment respectively. Because well-structured problems are disjunctive tasks [19] that can be solve without the need to collaborate, then one may presume that perceived good students are likely to enact on independent styles rather collaborative, and are capable of creative ideas as long as they show strong believes over their own abilities to perform accordingly. The lack of significance and sometimes negative coefficient of good student nomination over problem elaboration may suggest that perceived proficient students lack the required self-efficacy for creativity. Alternatively, students that do not enjoy such recognition could enjoy more collaborative oriented tasks, like ill-structured problems, and therefore may be more capable of creating highly elaborated problems like the interaction would suggest.

VIII. LIMITATIONS AND FUTURE RECOMMENDATIONS

We recognize the limitations of this study associated with the reduced sample size, and the lack of alternative variables that would have strengthen the analysis of students’ responses and social experience. Further control and observation over instructional strategies would also facilitate a deeper understanding of the nature of the social system generated on each academic section. In addition, short term activities like the
mands these problems entail. In addition, having students motivate students to engage on the appropriate cognitive de-

This is true when instructors guide the solving process and outcomes and interesting chances for creative thinking, yet, ill-structured problems in education brings positive learning implications over effective strategies for collaboration and interdependency. Using such principles would support the need to introduce pedagogical innovations that respond to creativity and collaboration in university education. However, and in coherence with the dichotomy between independent versus collaborative oriented students, having access to whether students are comfortable in the face of collaboration and social interactions would add valuable information to understand the appropriateness of pedagogies grounded on socialization of information, as well as to think about the roles independent students are likely to meet within such learning context.

Based on this results, educators must be cautious in implementing teaching strategies grounded on principles of collaboration and interdependency. Using such principles would demands intense attention on students’ interactions, and appropriate guidance over effective strategies for collaboration and communication of information. In addition, introducing ill-structured problems in education brings positive learning outcomes and interesting chances for creative thinking, yet, this is true when instructors guide the solving process and motivate students to engage on the appropriate cognitive demands these problems entail. In addition, having students developing appropriate content knowledge before attempting to introduce activities that require intense knowledge transfer may induce richer dialogues.

IX. CONCLUSIONS

Having students solve ill-structured problems within a learning environment that highlights the importance of creativity and socialization of information (i.e., Treatment condition) is likely to make students obtained better grades compared to traditional classrooms. Yet, socialization of information would be detrimental for getting good physics grades, or solve well-structured problems. The nature of the well-structured problems and the features of the learning context tend reward individualized performance, or collective efforts that emerged from highly cohesive clusters of students. Moreover, well and ill-structured problems respond positively to different social structures, and therefore, social positions that afford good grades may be detrimental for solving ill-structured problems, where the learning environment plays an important role in enabling appropriate knowledge distribution across members, as well as effective communication.

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