

Classroom learning dynamics using a cellular automata spatiotemporal model comparing peer instruction and traditional instruction

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(Dated: June 2025)

Peer instruction (PI) has recently become one of the popular means of classroom instruction in Physics Education. Such instruction method is vastly different from how classes are traditionally handled where the instructor conducts a lecture for the entire duration of the class. In this study, we model the transfer of knowledge within classes of students as a probabilistic cellular automata model and investigate the effects of different factors such as seating arrangements, class size N , average learning rate λ , and heterogeneity $\delta\lambda$ on the class overall learning efficiency. The learning efficiency of the class is measured in terms of the overall class rate using the initial rate trend and the total learning time t_{\max} for the whole class. PI mode appears to be more applicable with heterogeneous classes (in-class high learning rate max difference $\delta\lambda$). As commonly known TI mode is shown to be more advantageous for large N and homogenous class aptitude (low $\delta\lambda$). We show that the learning curves of highly heterogeneous classes with TI mode have two stages of learning: a fast initial stage and a slow final stage. The slow final state class learning rate is due to the late learners with lower λ -values and have general shape dependent on other model parameters as well. Such curves are absent with PI which consistently shifts depending on the other factors. Differing from a previous empirical data for the PI mode, classes perform best when the best in the class are situated within the inner corner. The model we used for this study currently ignores the actual non-isotropic seating orientation with which students do not share knowledge readily in all neighboring seating directions. Our model simplified the student capabilities to binary values and does not consider the effect of aptitude similarity during peer interactions as described in previous studies. We therefore find that PI performs better than, or similar to, traditional instruction. A mix of TI and PI would be the optimal mode of instruction taking advantage of TI for fast learning in the initial stage and the robust learning curve of PI in the later stages of class learning. Despite these simplifications, our model is able to provide general insights that are in agreement with previous studies and existing practices.

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I. INTRODUCTION

1 Peer instruction (PI)—an increasingly popular method
2 of instruction—attempts to solve a disconnect between
3 students' ability to answer quantitative and conceptual
4 questions, particularly in physics subject matters [1, 2].
5 Such disconnect is said to be attributed to the typical
6 approach of memorizing physics problem patterns and
7 applying the same solution patterns regardless of their
 potential non-applicability. The PI method forces students
 to think critically and to engage with peers guided by the learning material as opposed to simply absorbing the information from lectures given by the instructor as in the traditional mode of instruction (TI). The method's effectiveness has been shown not only in high school physics settings, but also in other disciplines and higher education settings [3–5].

1 The PI method as outlined by Mazur and Somers [1]
2 typically involves an instructor giving a short lecture on
3 the topic, followed by a multiple-choice question (MCQ)
4 that the student answer individually. PI emphasizes on
5 the next phases of instruction which involve repeated cycle
6 of students sharing their answers to the MCQ and discussing
7 them with peers, usually until they get the concepts right. This part makes PI method student centric requiring the instructor to intervene with slightly modi-

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fied steps to adjust to the needs of the class. As long as the same learning objectives are tackled, the instructor can choose variations in the method [6]. The instructor may often decide on: increasing the multiplicity of the peer sharing and discussion phase; having different kinds of requirements and/or levels of evaluation [7]; providing different MCQ sets; or giving another short lecture to ensure clarity of concepts involved [8]. Modifications to the PI method have also been reported to minimize some undesired behavioral patterns such as just copying off each other [6]. The PI therefore contrasts significantly against the traditional method (TI) with which the instructor simply gives a lecture for the entire duration, typically with minimal peer interactions among the students during class time.

Despite the unique approach of de-emphasizing actual problem-solving during the PI lecture phase, quantitative problem-solving skills have been consistently shown to remain not compromised, and in few cases even improved, relative to TI. Several advantages were pointed out in favor of the PI method in relation to the following dimensions: decrease in the number of students with extremely low scores [7–9], improved conceptual understanding [7], as well as being independent of the background knowledge [8, 10].

The dynamics involved during PI is complex resulting from the interacting components during the peer discussion. Existing mathematical models for this are either predictive such as with the case of the artificial neural network (ANN) models [11] or lack the spatial aspect of the process such as utilizing differential equations [12, 13] and those surveyed in Nitta [13]. Somewhat in between these is a generalized Ising model by Bordogna and Albano [14, 15] that considers three sources of information for the student to learn from: teacher instruction, peer interaction, and bibliographic materials (books, lecture notes, etc.). Their model shows that students learn more when they engage discussions with their peers than those who only listen to lectures. They also show that group structure affects student learning, and that low aptitude students may learn at the expense of high aptitude peers—a transmissionist view of PI. We are yet to find mathematical models for learning that compares PI with TI.

Actual assessment results by Roxas *et al.* [11] is used to train their ANN to predict expected second assessment scores of students depending on seating arrangements. Using this neural network, they were also able to characterize information transfer and investigate the effects of group homogeneity. Their study revealed that an optimal seating arrangement for students under PI methods based on their final aptitude. In their paper, the measure of students' improvement was calculated via the Hake gain as follows [16].

$$\langle g \rangle = \frac{\langle 2^{\text{nd}} \text{ assessment} - 1^{\text{st}} \text{ assessment} \rangle}{\langle 1 - 1^{\text{st}} \text{ assessment} \rangle} \quad (1)$$

They also used the output/input ratio (O/I), which was the ratio of second assessment scores vs first assessment

scores, to gauge student improvement.

The results of their study show that the outer corner seating arrangement (SA) performed the best using both the Hake gain (Eq. 1), followed by inner corner, then random, then center (see Fig. 1 for SA visualizations). In simulated classrooms, each with 64 students and 10 classrooms in total, they found that homogenous classrooms with low aptitudes have significantly higher O/I values. This means that low aptitude students benefit the most from being grouped together.

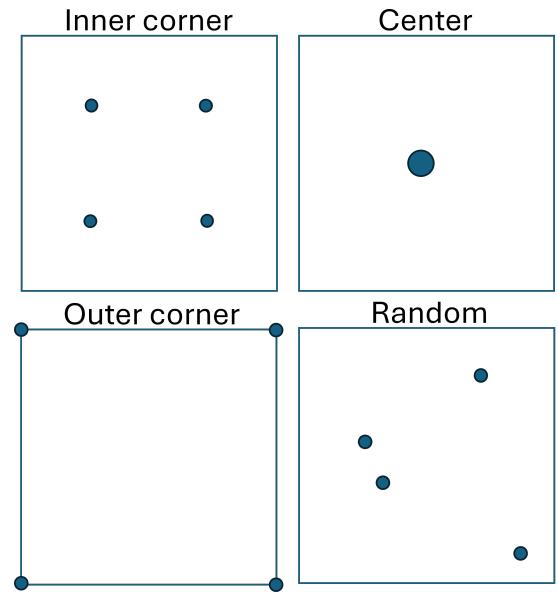


FIG. 1. Seating arrangements considered for PI. Dots represent position of high aptitude students.

Nitta [13] also presented their own model of PI:

$$\rho_2 = \rho_1 + \rho_1(1 - \rho_1) \quad (2)$$

where ρ_1 and ρ_2 are the normalized number of students who answered the first and second MCQ correctly respectively. Combining Equation 2 with their formulation of gain similar in form to Equation 1, the gain is equal to ρ_2 .

$$g = \rho_2 \quad (3)$$

There are others whose gain are derived from their own models like that of Pritchard *et al.* [12] where the equation is much more complicated.

Despite the diversity of the models that we found, current models of PI lack some aspects of PI that we would like to incorporate together like seating arrangements, students' learning rate, and aptitude heterogeneity.

II. A PROBABILISTIC CELLULAR AUTOMATA MODEL

Here, we show that a probabilistic cellular automata (PCA) model can be used to study the spatiotemporal

dynamics of both PI and traditional instruction when incorporating these different aspects into the model. We previously used a probabilistic cellular automata to model the classroom [17], the results of which were presented in the 42nd Samahang Pisika ng Pilipinas Conference in July 2024. The findings presented in the paper are also presented in this study as part of the results.

For the PCA model, each cell in the automaton represents a student where each student is assigned a learning rate $\lambda_{i,j}$ to describe how fast they learn as an individual. The state of each cell represents their aptitude $s_{i,j} = \{\text{unlearned, learned}\} = \{0, 1\}$. We assign the neighborhood to be an outer totalistic Moore neighborhood of radius $r = 1$ and define the boundary conditions to be fixed wherein the grid does not wrap around itself and $s_{i,j} = 0$ for $i, j \notin [1, L]$. For each time step, we find the probability of a student to learn and update the state of the student based on this probability. The probability of a student to learn is calculated differently for traditional instruction and peer instruction.

II.1. Update Rules for Traditional Instruction (TI)

For traditional instruction, the probability of a student to learn in each time step ($P_{i,j}$) is given by:

$$P_{i,j} = \lambda_{i,j} \rho_0 \quad (4)$$

where $P_{i,j} \in [0, 1]$ is the probability of student $c_{i,j}$ to learn in each time step, $\lambda_{i,j} \in [0, 1]$ is the learning rate of student $c_{i,j}$, and $\rho_0 \in [0, 1]$ is the probability of $c_{i,j}$ to learn from the teacher based on their relative position from the teacher.

We consider the case that students have heterogeneous learning rates $\lambda_{i,j} = \lambda_0 \pm \delta\lambda$ where $\lambda_0 = 0.5$. This allows us to investigate the effects of student heterogeneity on the classroom's learning dynamics.

Having a positional learning coefficient $\rho_{i,j}$ allows us to model a classroom where students closer to the teacher in front learn faster than those farther away or vice versa. However, for this research, we only consider the case such that $\rho_{i,j} = \rho_0 \forall i, j$.

The numerical procedure is outlined in Figure 2. Each simulation for the TI model starts with all students unlearned.

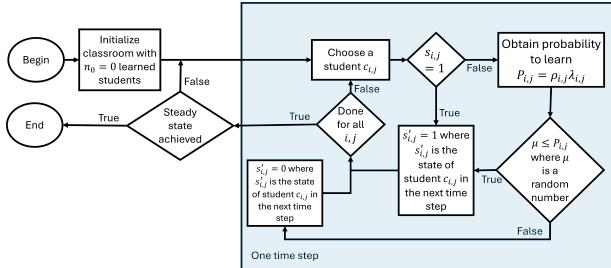


FIG. 2. Numerical process for simulation of 2D BPCA for traditional instruction.

II.2. Update Rules for Peer Instruction (PI)

In contrast to TI, the probability of a student to learn in each time step for PI is additionally dependent on the student's neighbors and their states. The probability of a student to learn in each time step ($P_{i,j}$) is given by:

$$P_{i,j} = 1 - \prod_{\forall \delta i, \delta j} [1 - (\lambda_{i,j})(\rho_{\delta i, \delta j})(s_{i+\delta i, j+\delta j})] \quad (5)$$

where $P_{i,j} \in [0, 1]$ is the probability of student $c_{i,j}$ to learn in each time step, and $\lambda_{i,j} \in [0, 1]$ is the learning rate of student $c_{i,j}$. We consider the case that students have heterogeneous learning rates $\lambda_{i,j} = \lambda_0 \pm \delta\lambda$ where $\lambda_0 = 0.5$. The variables $\rho_{\delta i, \delta j} \in [0, 1]$ is the probability of $c_{i,j}$ to learn from their neighbors in seats $\{c_{i+\delta i, j+\delta j} \forall \delta i, \delta j \in \{-1, 0, 1\}\}$ solely based from their relative positions with each other, and $s_{i+\delta i, j+\delta j} = \{\text{unlearned, learned}\} = \{0, 1\}$ are the neighbors' aptitude level.

The numerical procedure is outlined in Figure 3. Each simulation for the PI model starts with only four learned students $n_0 = 4$.

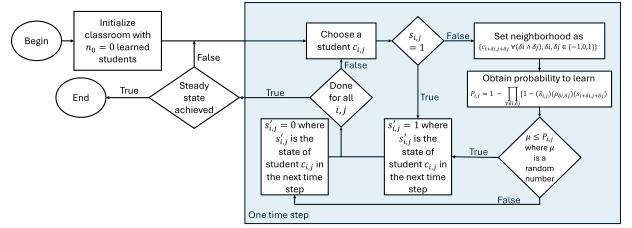


FIG. 3. Numerical process for simulation of 2D BPCA for peer instruction.

II.3. Model parameters

The values of the model input parameters we considered for the class size $N = L^2$, the positional learning coefficient ρ_0 , and the learning rate heterogeneity $\delta\lambda$ are as follows:

- $L = \{32, 48, 64, 96, 128\}$
- $\rho_0 = \{0.1, 0.2, 0.3, \dots, 0.8, 0.9, 1.0\}$
- $\delta\lambda = \{0.0, 0.1, 0.2, 0.3, 0.4\}$

To assess how well the class performed, we used the time it took for all the students to learn t_{\max} . For both TI and PI, the simulation ends when all students have learned. Each set of parameters was run 5 independent times to get the average and standard deviation of t_{\max} for each set of parameters.

III. RESULTS AND DISCUSSION

III.1. Different Dynamics of Traditional and Peer Instruction

For TI, varying the different model parameters yield different dynamics. As shown in Figure 4, the progression of the fraction of learned students was not affected with increasing class size N . The time to learn t_{\max} , however, increased with class size N . This is expected as TI is set up such that the students can all learn at the same time from the teacher — so the dynamics are independent of class size N . Positional learning factor ρ_0 changes the initial number of learned students and the rate at which students learn throughout the simulation (Figure 5). Upon initial inspection of Figure 6 for the effects of learning rate heterogeneous, we see that it has a similar effect to that of positional learning factor ρ_0 without changing the initial number of learned students. However, we notice that the effect is on the rate of which students learn is not linear. The difference between $\delta\lambda = 0.4$ and $\delta\lambda = 0.2$ is greater than that of $\delta\lambda = 0.2$ and $\delta\lambda = 0.0$. This is consistent with the non-linear effect of ρ_0 on the learning rate. Upon further inspection, we notice that TI classes with high learning rate heterogeneity $\delta\lambda$ have a two-stage learning process. The first stage is characterized by a sharp increase in the number of learned students caused by the majority of fast students ($\lambda = \lambda_0 + \delta\lambda$) learning in the first few time steps. The second stage is characterized by a much slower increase in the number of learned students caused by waiting for the slower students ($\lambda = \lambda_0 - \delta\lambda$) to learn. An example case where this phenomenon is observable is shown in Figure 7. In this case, we see at $t = 2$ that majority of the students that are learned are fast students and at $t = 13$ the slower students have started to learn, but the rate of learning has slowed down significantly. Despite the promising-looking start to this simulation, it will spend up to $t = 232$ waiting for all the students to learn.

As for PI, varying the different parameters do not lead to as varied dynamics as TI. The progression of the fraction of learned students are affected the same way when varying class size N , positional learning factor ρ_0 , and learning rate heterogeneity $\delta\lambda$. Generally, there is a time delay before the learning starts to speed up. As shown in Figure 4, Figure 5, and Figure 6, increasing class size N and learning rate heterogeneity $\delta\lambda$, and decreasing positional learning factor ρ_0 all increase this time delay. A combination of these factors may affect to the slope of classes' progression over time once learning speeds up, but these factors individually do not noticeably affect the progression. Additionally, we see in Figure 8 that different SAs perform differently even with the same set of parameters with the inner corner SA performed the best. The random SA may outperform the center and outer corner SAs in the middle of the simulation but still ends up having the highest time to learn t_{\max} .

The plots in this section show that classes under TI

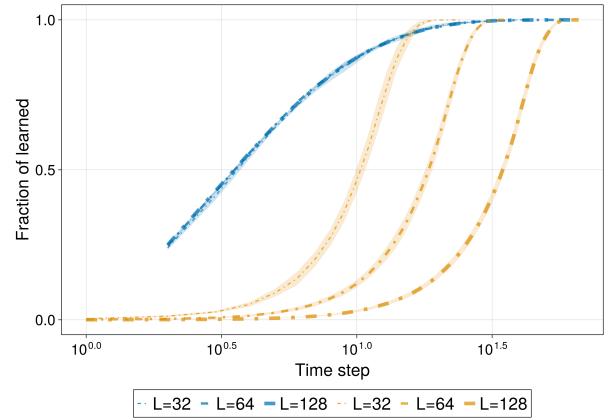


FIG. 4. Comparison of time to learn t_{\max} and fraction of learned students for class size N . Each SA corresponds to a different color — blue for traditional, orange for inner corner. Different class sizes correspond to different line widths where bigger classroom sizes are represented by thicker lines. The bands around each line show the standard deviation of the data over 5 trials. Higher fraction of learned students indicate better learning.

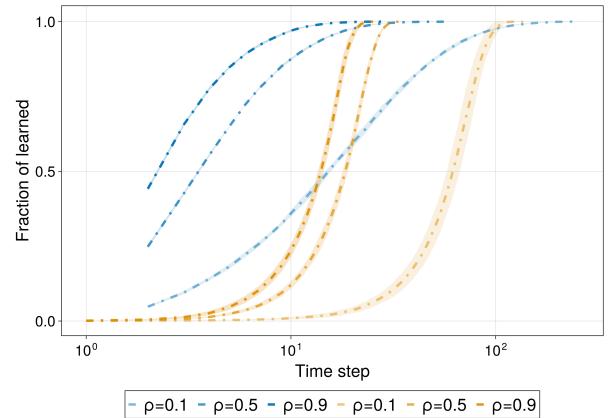


FIG. 5. Comparison of time to learn t_{\max} and fraction of learned students for positional learning factor ρ_0 . Each SA corresponds to a different color — blue for traditional, orange for inner corner. Different ρ_0 values correspond to different line transparencies where darker lines represent higher ρ_0 values. The bands around each line show the standard deviation of the data over 5 trials. Higher fraction of learned students indicate better learning.

have more students learning in the earlier time steps, but has lower time to learn t_{\max} when compared to classes under PI with the same set of parameters. These findings suggest that to optimize the learning in the classroom, it would be best to perform TI at the start of the class to take advantage of the fast initial learning stage, then switch to PI where having learned students spread throughout the classroom benefit those who have yet to learn. This is consistent with current practices [1, 6, 8, 11], where the students are expected to have read up on the material in advance and the instruc-

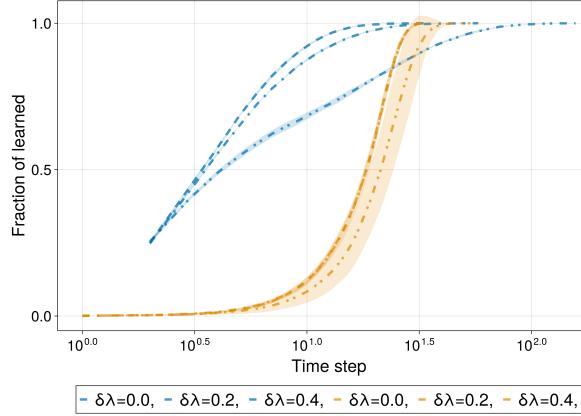


FIG. 6. Comparison of time to learn t_{\max} and fraction of learned students for different learning rate heterogeneity $\delta\lambda$. Each SA corresponds to a different color — blue for traditional, orange for inner corner. Different $\delta\lambda$ values correspond to different line styles where $\delta\lambda = 0, 0.2, 0.4$ are represented by dashed lines, alternating dots and dashes, and two dots and a dash respectively. The bands around each line show the standard deviation of the data over 5 trials. Higher fraction of learned students indicate better learning.

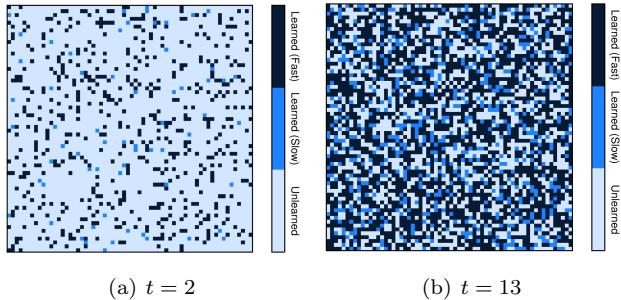


FIG. 7. Example classroom evolution for TI with $L = 64$, $\rho_0 = 0.3$, and $\delta\lambda = 0.4$ at different time steps t showing a two-stage learning process. Dark blue cells represent learned students with learning rate $\lambda = \lambda_0 + \delta\lambda$, blue cells represent learned students with learning rate $\lambda = \lambda_0 - \delta\lambda$, and light blue cells represent unlearned students.

tor gives a short lecture before the students engage in peer discussion.

III.2. Summary of effects of class size N , positional learning factor ρ_0 , and learning rate heterogeneity $\delta\lambda$

As we vary the different parameters, as shown in Figure 9, we are able to identify which cases are more favorable for TI or PI. We find that PI suffers more than TI when handling larger class sizes N , and that TI suffers more from increased learning rate heterogeneity $\delta\lambda$ compared to PI. However, low positional learning factor ρ_0 affects both TI and PI similarly.

The same figure also shows us the magnitude of the advantage of one method of instruction over the other.

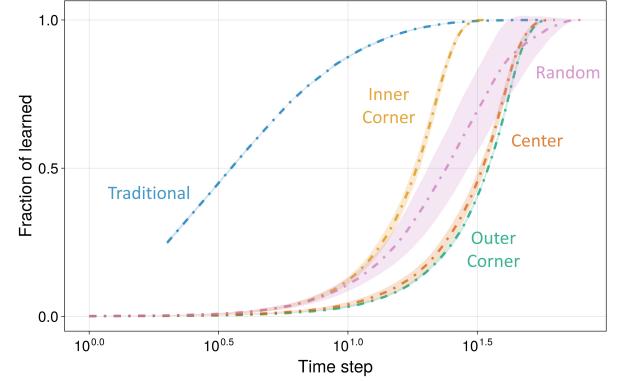


FIG. 8. Comparison of time to learn t_{\max} and fraction of learned students for different SAs. Each SA corresponds to a different color — blue for traditional, orange for inner corner, green for outer corner, orange for center, and pink for random. The bands around each line show the standard deviation of the data over 5 trials. Higher fraction of learned students indicate better learning.

We find that when TI is advantageous, like in cases of big classrooms and low learning rate heterogeneity, the advantage over PI is not that large. However, in cases where PI is advantageous, like in cases of small classrooms and high learning rate heterogeneity, the advantage over TI is very large. This suggests that PI can be a safe option — never performing much worse than TI, but can perform much better in certain cases.

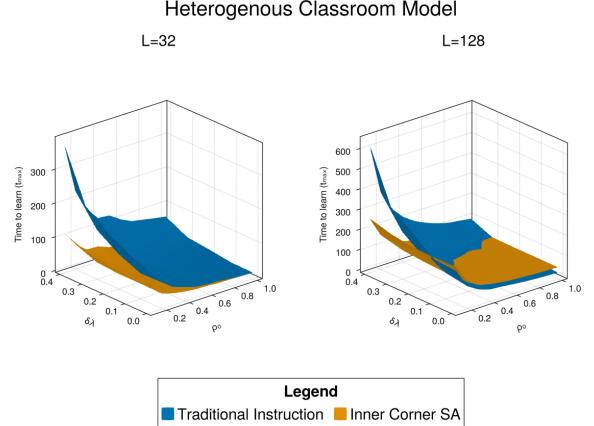


FIG. 9. Time to learn t_{\max} as a function of positional learning factor ρ_0 and heterogeneity $\delta\lambda$ of PI (inner corner SA) and TI for different class sizes $N = L^2$. The blue surface represents TI and the orange surface represents PI. Lower time to learn indicates better learning.

III.3. Comparison with existing research/data

Comparing our data to Nitta's model (Equation 2) [13], as in Figure 10, only our data for PI approaches their model — this is expected since their model

is for PI and not TI. Furthermore, PI only approaches their model when the conditions are favorable for PI (Figure 10(b)). Considering that their model has been shown to agree with experimental data, it suggests that real world students' behavior and learning dynamics are better represented by the values of high positional learning factor ρ_0 and small class sizes N . It should also be noted that Nitta's model and data tracks individual students' learning while our model tracks the class's learning as a whole. We chose to track learning this way because there is not much insight to be gained from tracking individual students' learning in a binary-state model. Nevertheless, the agreement of our model to theirs and to experimental data suggests that our model can be a good approximation of the real world with further improvements.

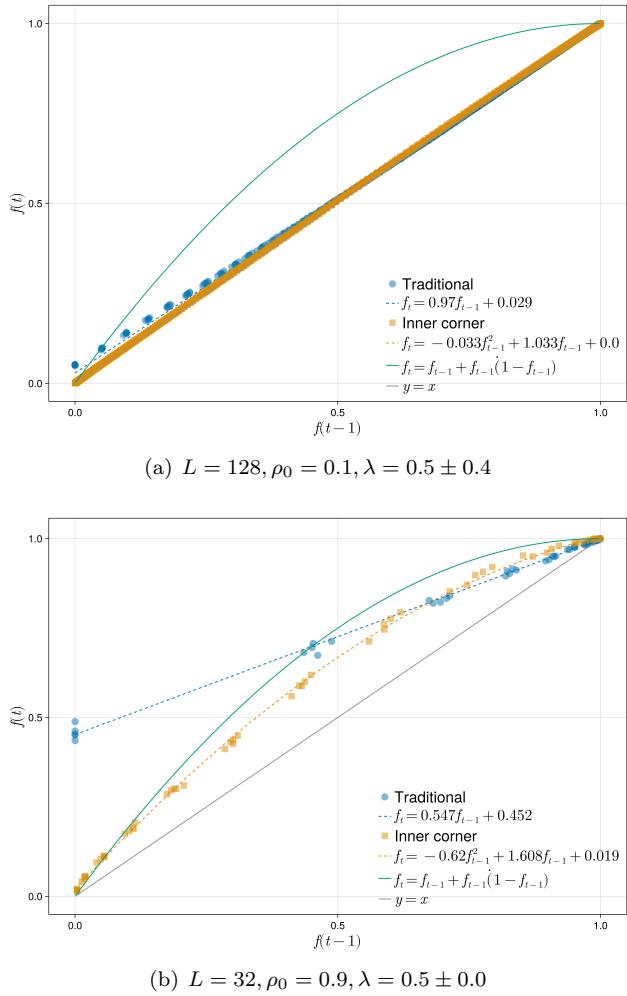


FIG. 10. Return map for selected parameter sets for both TI and PI. Blue circles represent the data points for TI and orange squares represent the data points for PI. The corresponding best-fit quadratic function obtained using the Levenberg-Marquardt algorithm for each set of data points are shown in blue and orange dashed lines respectively. The green line represents Nitta's theoretical model (Equation 2) and the gray line represents $y = x$.

Following Nitta's model and equation for gain (Equa-

tion 2 and 3), we can see for our PI model where

$$f_{t+1} \approx a + bf_t + cf_t^2 \quad (6)$$

b is expected to be $b = 1 - c$ and the gain g is

$$g \approx a + cf_t \quad (7)$$

Doing the same for our TI model which was best modeled by a linear function

$$f_{t+1} \approx f_t + g(1 - f_t) \approx m_0 + m_1 f_t \quad (8)$$

and noting that the coefficients m_0 and m_1 approximately sums to 1 (Figure 10) gives us the equation for gain:

$$g \approx m_0 \quad (9)$$

These values for gain g shows us that gains for TI are constant while gains for PI are linearly proportional to the fraction of learned students f_t . We find these values reasonable since TI is set up such that all students learn at the same time from the teacher while PI is set up such that students learn from each other.

Compared to Roxas' work [11] which found the outer corner SA to perform the best, we found the inner corner SA to perform the best. This difference can be attributed to the simplifications made in our model. We were not able to consider the aptitude similarity effect that happens where students of similar aptitude learn better when grouped together regardless of their actual aptitude level [6]. The implementation of this phenomenon is better suited for a continuous-state model rather than a binary-state model. Additionally, we did not consider the orientation of the students in the classroom, resulting in an isotropic system. In addition to the findings regarding seating arrangements, our model also agrees with their findings that homogenous classes find better improvements compared to heterogeneous classes.

IV. SUMMARY AND CONCLUSION

We propose a probabilistic cellular automata model as a new way of investigating learning dynamics in the classroom. Through this model, we can investigate how different factors can affect students' learning in the classroom for both traditional instruction (TI) and peer instruction (PI).

We found that TI performs better in larger classes and when the students have low learning rate heterogeneity. On the other hand, PI performs better in smaller classes and when the students have high learning rate heterogeneity. To be more precise, class size, heterogeneity, and low positional learning factor affect both TI and PI negatively, but TI is not as affected by class size compared to PI and PI is not as affected by heterogeneity compared to TI.

We also found that when a highly heterogeneous class is under TI, the class exhibits a two-stage learning process where majority of the fast students learn in the first

few time steps and the rest of the time is spent waiting for slower students to learn. Our findings regarding class heterogeneity are in line with those of Roxas, et al. (2010) [11]. However, our findings regarding seating arrangement differ from theirs where they found that the outer corner seating arrangement perform best while we found that the inner corner seating arrangement perform best. This difference is likely because of the simplifications made in our model — namely learning isotropy and non-implementation of an aptitude similarity effect. These simplifications are from the limitations of having a binary-state model.

Another limitation of having a binary-state model is that there are not much insight to be gained from track-

ing individual students' learning. Hence, we chose to track the class's learning as a whole. Despite having a different way to assess the methods of instruction effectiveness, our findings are consistent with the existing works like that of Nitta, et al. [13] which is backed by real-world data.

While our model can be a good approximation of the real world, there are still improvements that can be made. The current model only considers the peer discussion part of a whole PI session. A mixed model that considers the whole session with a mix of TI and TI would be a better representation of the real world. Additionally, transitioning to a continuous-state model would allow us to incorporate more real-world phenomena like aptitude similarity and orientation effects.

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