Trial of Peer Instruction in an Introductory Phase Diagrams Course

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Abstract

The peer instruction or "turn to your neighbour" approach was trialled in a introductory phase diagrams course in materials science at Imperial College. Notes and videos were provided to students for review prior to the class sessions, along with an online quiz and opportunity to reflect and provide feedback. Lectures were replaced with a facilitated series of conceptual questions answered by student using their own web-enabled devices, followed by small group discussion to review and resolve misunderstanding and then a final review of the correct answer by the lecturer. First impressions suggested that the approach was much more effective than lecturing. Student resistance to the approach was minimal and the cohort concerned were keen to repeat the experience. This was because they felt that, while it required them to review the material in a disciplined fashion, it meant that they came away from the course understanding the material better than in traditional approaches.

1. Introduction

What are the origins of the lecture? In times past, books were expensive and there was only one book in the library and therefore the role of the lecturer was to read the book to students, with the aid of a chalkboard, so that students could take notes. This was the human photocopier method. But now, laser printers and photocopiers are cheap, so it can reasonably be asked if the lecture is required any more. The lecturer might just write beautiful notes for students to read, with perfect copying fidelity, at leisure.

The lecture, a didactic expository monologue, does serve purposes above and beyond that fulfilled by a textbook. It is a visual, auditory and personal presentation of the material that also serves to schedule and sequence students' learning into coherent packages ("lecture courses"). However, many of these purposes can be fulfilled by video presentation online, e.g. via YouTube or iTunesU. At a potential loss in sequencing, these give rise to additional functionality such as the ability to time-shift to a time of convenience and to re-review through the year or for pre-exam revision.

In passing, it is of note that most introductory (1st and 2nd year) material in the sciences is increasingly becoming available online, for free, over the internet, both through freelance efforts by individual academics and through initiatives such as EdX and iTunesU, mostly as lectures but also as lecture notes. This has excited much press comment over whether traditional residential university education, in thousands of lecture theatres around the world, has a future; especially given rampant tuition fee growth. In some sense such Massively Open Online Courses (MOOCs) are just the evolution of the Open University concept. Therefore there is increasingly a burden of proof for universities to demonstrate that their teaching has value over and above that of YouTube plus the purchase of textbooks.

One problem is that school-leavers have no experience of self-study. Therefore the residential university experience provides cohorting (competition, collaboration and peer-norming), sequencing and timetabling into a coherent programme of study as well as certification and credentialling (branding). However, these goals do not, of themselves, require teaching to be structured around the didactic monologue, delivered at 09:00 on Monday to students who are asleep through to 17:00 of a Friday to students who are simply tired.

2. Inside the lecture

To move the discussion on to specifics, lets examine the learning cycle. Beginning with the initial presentation of the material, however interactive, after the lecture students will then ideally review it in the subsequent days. This review will be reinforced by attempting problems, then discussed in tutorials. Subsequently, there will be revision of the material preparatory to the final exam that supports progression to subsequent courses and credential award.

We take it as given that the review step is critical to students maximising their potential in a full-time degree. For example, if there are 10× 1 h lectures a week, plus 4 h of time in labs, then the student is expected to spend a further 4 h writing up the lab, about 8 h preparing tutorial problem sets and another 10 h of review, giving a full-time total of 36 h per week. So skipping the review part, where students review the lecture material, improve their notes and support with textbook reading, is a major loss. But students very often do skip the review, storing up work for the revision period prior to exams (cramming). Enforcing the review is partly the role of tutorials, but especially with larger tutorial groups compliance is often patchy.

Now, where we are going is not to suggest that I don't believe that making one's own lecture notes helps understanding

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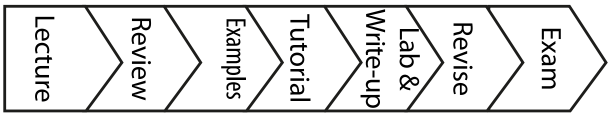

Figure 1: Flow diagram for the learning process in the traditional lecturing approach.

and recollection. It does; the more times, more ways and the more intensively one interacts with study material, the better it is understood. But now we give students slides, they mostly don't make good notes. So that ship has sailed. Now, students must learn in a different way to even those of us who did our degrees in the mid-90s.

3. Flipping the Lecture

In the Peer Instruction (PI) approach, we flip where the lecture class session sits in the learning sequence. First students review the initial presentation of the material, using notes supplied by the lecturer and/or textbooks and/or videos of the expository monologue. Then, the class session serves to support students in the review step, helping them to overcome cognitive roadblocks and misunderstandings. This is done by asking students simple conceptual questions, algebraically simple enough to be solved in 60 seconds. We then ask for their answers, using flashcards, clickers or web-enabled devices and software. But the magic is what happens next.

Often, there will be several misunderstandings that lead students to be unable to answer the question or to be incorrect. The lecturer cannot possibly understand and answer all of these in the time available. Or to put it another way, say a student asks a question, which the lecturer answers. Only a few of the other 80+ students in the class will have the same question. So even in a smaller tutorial, the 1-to-many Q&A process is a very inefficient use of time (lectures cost on the order of £5,000 /hr)

Instead in Peer Instruction, we then ask the students to turn to their neighbour and, in groups of three of so, contend for and explain their answer to their peers. And the student who gets the right answer will convince their neighbour of the correct answer, and resolve their problem. Both students benefit; the student who is wrong gets their misunderstanding resolved, and the student who is right will improve their understanding and recall by explaining it; its only once you can explain something that you really understand it.

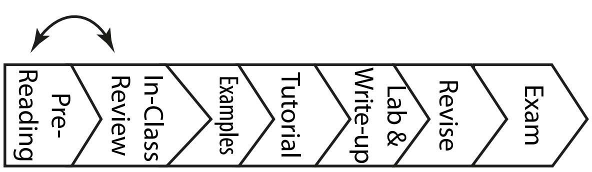

Figure 2: Flow diagram for the learning process in the peer instruction approach; the class session is 'flipped' from the initial presentation of the material to the review, consolidation of understanding of that material, similar to the Socratic approach.

The students then re-vote; for good conceptual questions the fraction of students getting the right answer will increase from 50% to 80%. The lecturer will then do a whole-class review, explaining the answer. The question cycle then repeats.

The advantage of this approach is that the initial presentation of material is taken out of the class, freeing time to actually resolve people's problems, focussing on the concepts rather than solving exam questions. Cohorting and sequencing are preserved; if students don't do the review before the class session they quickly learn that to get anything out of the course they have to comply with the requirement to do the pre-reading and video review, or risk falling terminally behind. In this approach the review step after initial presentation is the focus rather than information transfer, so students end the lecture course much more uniformly at the desired state. Or at least, so goes the theory.

4. Teaching for Understanding, Not Plug-and-Chug

In the US in Physics 101, it is often found that even students who perform well in problem-solving exams often perform very badly at answering even the simplest conceptual questions. So in basic electric circuits and mechanics problems based on Newton's Laws, 'Concept Inventory' type of multiple choice tests often given startling, and alarming, results.

The problem is that students get quite good at plugging numbers into equations and memorising how to take the problems presented in class and apply those to the problems presented in exams. Asking wholly unseen mathematical exam questions tends to lose too much of the class to consist of 100% of an exam, and the median student often really struggles at these, because they have learned to plug in the numbers and then chug through to a solution. Even Feynmann commented on this in the 60s.

But whilst we want students to be confident at problem solving using mathematics, we also want then to understand the concepts. That is, when they fail, we don't know that its because they can't do the maths or because they don't get the concepts. In fact, the above suggests that sometimes they can get a solution even if they don't get the concepts.

So the thing about this approach is that it is vital to focus on the concepts; we should ask simple questions that help students to get to the point of understanding the physical ideas we are teaching. Then, having got the ideas sorted out, students are prepared for the longer and more mathematically arduous tutorial questions that then prepare them for the exam.

It is important to recognise that this is a research-based approach that has been shown to be effective at improving student conceptual understanding and test performance, over more than a decade, in large cohort randomised testing. US introductory physics classes are very large, and often taught multiple times by the same instructor, over multiple cohorts and years, so large cohort testing is possible using randomised questions. It is not about the technology! The technology is only an enabler.

5. Teaching Introductory Phase Diagrams by PI

So, in autumn 2012 I trialled this approach for an introductory phase diagrams course of nine lectures to a group of 82 students starting their Materials Science degree programme. About half the students were overseas and half home/EU; about a third of white ethnicity and about 30% female. The course composes introducing unary and binary phase diagrams and their interpretation and use; eutectics; mass and atom fractions and the lever rule; thermodynamic quantities, Entropy and Gibbs Energy; the regular solution model; the connection between Gibbs energy curves and phase diagrams; Scheil (fast) solidification; nucleation kinetics and TTT diagrams; steels and martensite. It is supported by two tutorials, given by the lecturer, to students in groups of 20 and takes place over the first five teaching weeks of first year. A couple of labs reinforce and apply the lecture material. The first lecture is also an introduction to structural metallurgy and mechanical properties (stress, strain, stiffness and stress-strain curves).

I began with a good set of notes for the course, in effect a mini-textbook, and a set of slides from previous years' delivery of the course. Then, as an aid to the students, I broke the lectures up into 16 video segments of about 20 minutes duration each and delivered these using a whiteboard in my office during the summer; a summer student did the videography and video editing (about 100 man-hours). As far as possible, I avoided using slides in the videos; sketching the graphs and writing the derivations forces you to explain these properly and forces the viewer to understand what you are writing. This approach also avoids consent and IP issues. These were placed on YouTube, to go along with the notes and problem sets which were placed on my (public) webpage. The purpose of the videos was to deflect any criticism that I wasn't 'lecturing properly,' and to support those people who prefer add on a personal exposition to the reading. All the materials can be found through www.imperial.ac.uk/people/david.dye/teaching.

The decision to go public was not only less hassle than dealing with the institutional VLE, it was also both pragmatic and idealistic. If universities are there for public benefit, we can at least make materials available when the incremental cost is zero. And, I know well that even our own students use others' YouTube lectures as study aids; if the classical lecture is to be disintermediated by the internet, people may as well be watching me as some guy on the other side of the planet. It does give me some pause to know that I am publicly able to be wrong, live and in technicolour, on the open internet, but that just gives one an incentive to do a good job!

I then used a trial set of licenses on Learning Catalytics LLC's website to deliver the questions both as (i) pre-session review and feedback and then (ii) for the class sessions. Students used their own web-enabled devices to answer the questions, anonymously, during the lecture. They used a mixture of Blackberry's, Android phones, idevices and laptops, and were enthusiastic about doing so. No student did not / could not interact in this way. This software allows the students to be shown histograms of the class response (individual and group feedback), after both single or dual rounds of voting. I made extensive use of a visualiser to explain the answers. The software also allowed the students to be grouped according to their answer and where they were sitting into groups with dissimilar answers, gaining socialisation benefit in a class new to university and breaking up collaborating groups of friends. Using such polling software isn't a requirement, but it is less hassle to administer than clickers and more anonymous than flashcards. It effectively manages the administrative overhead of the Q&A interactive approach. Paid licenses cost US$ 10 per student per year, which isn't too expensive to contemplate.

The pre-session review questions help frame the questions in the class session ("what didn't you understand"), prompt reflection on the reading material and gave me an idea of how many people were completing the pre-reading. Doing this is suggested to be best practice when using the PI method. Four days before the first session I introduced the website and showed students how to access the notes and videos, and asked them to create their logins and do the pre-reading for the first class.

I began trialling this approach with a first year course on the basis that this seemed to be the point at which it would best fit the students, albeit at highest risk. At the start of first year students have not yet developed coping strategies for lectures, so it seemed to fit best there. Everything is new compared to school so there is reduced resistance to change; and, its actually closer in style to interactive high school teaching than the traditional lecture. Also Phase Diagrams are quite conceptual and 'hands-on,' so fit the conceptual question style quite well.

6. Impressions and Student Feedback

I was very concerned that there would be significant student resistance to this approach and/or that they wouldn't do the pre-reading. Therefore I asked them for their feedback before and after lecture 1, at the start of lecture 4 and after the end of the course at lecture 9. On the contrary, the feedback was astonishingly positive, from the start.

The students really loved the videos, even though only about 60% claimed to watch them before each session (Table 1). Being on YouTube, its difficult to track as these videos now get about 3000 views per month; the spike in views from my students wasn't that obvious above the background level. They liked being able to go back to them for clarification, on demand, for just the point at issue. Indexing the videos would be useful, but they seem to cope without it; it helps that the videos follow my old slides and therefore the notes very tightly.

On the notes, I increased the margins, font and figure size in order to create the space to make marginal notes and to aid clarity, so they were 60 pages long (in LaTeX), compared to 30 in two-column format with smaller figures previously. Some people found them a bit long, but if anything, I would say they were too brief. Overall, they liked them, Table 2.

So in summary, making the videos and the notes, the tutorial problem sheets and model answers, and doing a good job with them, is absolutely key to the successful introduction of this approach. Making the students still feel supported in the initial presentation of the material is the driver that creates consent to then focus on understanding in the review part.

n=60/82	Worthwhile	Wasted Effort	No opinion
Videos	58	0	2

- The videos were good and backed up the notes well. They were also easier to follow than the notes especially when doing calculations/deriving equations.
- Quality transitions, top notch explanations combined with professional equipment (board rubber).
- While they were all extremely helpful and well presented, it was sometimes difficult to find the self-discipline to watch them before the lectures. It is also possible that some people may not have watched any, and therefore miss out on essential knowledge.
- I found most of the videos very useful to properly understand the notes. Many points from the notes only made sense when I went over them a second time with the explanation in the videos.
- They are much more helpful than the notes as you can see how the derivations are done step by step and the diagrams also become clearer.
- Very helpful! Though they are time consuming (even to watch) they help a lot. I find it much easier to understand new things when someone explains them rather than reading from a page.
- I admit I haven't seen many of them. The problem is that in the first month we spend a lot of time on lab reports and tutorials sheets and not always we have time or brain-power to watch a 20 minutes-video in which you must pay attention to understand something.
- Everything is good. I really enjoy the video. Thanks a lot for making the videos.

The videos were useful for...	n=57/82
I could skip lectures	3
Useful for revision	53
I could pause and replay to come back to points	52
It means we can do something else in class	23

Table 1: End-of-course feedback on the videos from the course.

n=61/82	Positive	Prefer slides	No opinion	No answer
Notes	56	3	2	21

- I think these were the best notes we have received in any lecture course so far.
- More effective than slides. Some lecturers have a random picture on a slide, and an analogy/explanation in their head...... with notes the diagrams are well explained.
- I think the videos were more helpful when learning new things. However the notes are better for revision.
- The notes gave useful information and useful for revision. However, they are not standalone. They have to be understood/revised in tandem with the videos and of course, going for the lecture.
- They too complicated. Can we have shorter version.
- Extremely instructive and sufficient in itself, although Chapter 8 needed the lecture in addition. The other lectures were subsequently not absolutely necessary, but were useful for ensuring complete conceptual understanding.
- Very well done. In addition to the videos, there are no excuses not to pass your subject.
- They are good coupled with the videos. It would have been much harder to follow the class with just the notes.
- The notes were very clear and informative, especially when coupled with the videos. Maybe some example questions would be useful to be embedded within the notes, in order to get to grips with the problems before the lecture.

Table 2: End-of-course feedback on the notes from the course.

- Makes more sense than conventional teaching, we will see if it has better effects.
- it seems much more efficient time wise, as it utilises the contact time with lecturers much better as they can help you with questions rather than talking at you for an hour.
- I understand how it can be a more efficient method of teaching, but if we are split into small groups and we teach each other, there is the possibility of someone completely misunderstanding the subject matter and then trying to teach it to the rest of the group. Personally I prefer the traditional style of teaching.
- I want to try. It sounds pretty good.
- I feel it is better than classic lecturing, it gives me a chance to attempt the work first, and it means that I can access notes and videos at any time
- It seems much more sensible for larger classes than a one-size-fits-all provision of information.
- Good, discussions with each other will give a better understanding of the theory.

Table 3: Pre-course responses on the peer instruction concept.

Then the key question: how did the class sessions go? From the beginning, I had better attendance than in previous years. Previously, attendance would run at about 75%; I had attendance run at 82/78/74/70/78/78/72/73/60 out of the 82, so an average of 73/82 or 90%. Of course, I don't know if they were simply a good cohort, but this was exceptional. I also had 60 and 72 in the two tutorials, which again was much greater than in previous years.

I did a pre-session review on about 5/8 of the sessions and had about 60% of students engage with those questions. At the beginning of lecture 4 I asked the students if these were useful and ALL of the 46 who answered said they were. At the same time 41 said they had done the pre-reading and 6 said they hadn't. 36 said they had watched the video and 11 said they hadn't, but 42/45 said the videos were useful - so even those who hadn't watched it, liked it.

Before the course began, 36/42 expected the sessions to help them understand the notes, i.e. I had achieved consent to try the approach. 4/39 students who made a comment were cautious, mostly concerned about misunderstandings propagating from one to the next. Some responses are given in Table 3.

Following advice, I started each session with a quick overview of the key ideas. This is very comforting, and if you aren't careful you can spend too long on this and lose time for the PI part of the session. This reversion to lecturing sends the students very mixed messages; it makes the students who did the reading feel cheated and dampens the incentive to do the reading. So while its probably OK to introduce the main concepts as an aide-memoire, this should be limited to $\sim$ 10 min.

In the sessions, it takes about 5 minutes to pose and have them answer a question. So for two rounds of voting, plus a discussion of the answer, takes about 12 minutes. This means that the method works optimally with about 4 questions in the session - but then they need to be really well-posed questions. I tended to have more, then make the explanation very fast and skip second round if they got the idea. So in my trial, I made more questions than I would need, and then adapted as I went in the session. Still, I asked too many questions and spent too long on the introductory review, so I struggled with time.

The sorts of questions you can ask are quite flexible. One problem students struggle with is that they don't understand that in a two phase region, the compositions of the phases are given by the boundaries of the two phase region. So, for instance, in one question, I asked them to point to the right answer on a graph (Figure 1) - to make sure that we are all getting the idea of how to read the phase diagram. Its not actually important to read the number off the graph, its that you are trying to calculate the correct number in the first place. So it is possible to ask more than simply numerical, many choice or multiple choice questions.

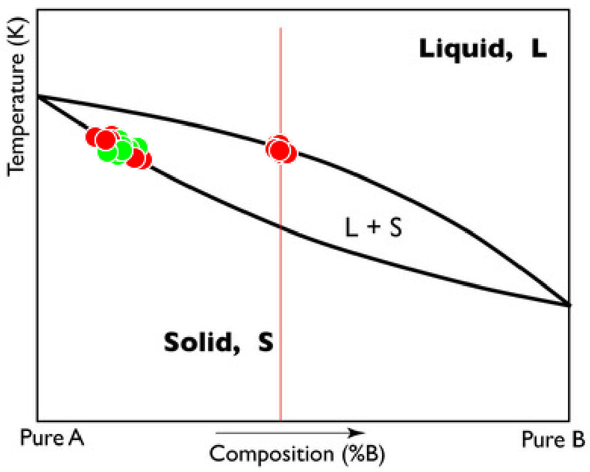

Figure 3: Example of a graphical question; the green and red dots show student's answers; a tolerance box (in this case drawn a bit small) is drawn to define 'correct' answers, in green.

My impression was very strongly that students were actually getting their misunderstandings resolved in the sessions. I have been teaching this course for a number of years, so I have an idea from exams and tutorials what things students struggle with. For instance, when we teach bct martensite formation from fcc austenite, we often don't really emphasise in first year that there must be distortion in the cell (towards the bcc cell) in order for martensite to differ from austenite at all, so the c/a ratio of bct martensite must be slightly less than $\sqrt{2}$. I didn't put this in the notes because its a complication to get into the interface misfit and so on, but if you don't, the thoughtful student will then find it really confusing! So I asked it as a question. Initially it really flumoxed them but over two rounds, they got from 1/3rd getting it to 2/3rds by PI, without needing me. So PI really does work, and it helps them develop their insight.

- I prefer this approach as it gives me more time to go over the material and make sure I understand it before the lecture and it highlights weak areas in my understanding.
- Once we get it more organised I do believe it can work.
- It is a good way to test yourself, it makes you think more than you would normally
- I still prefer it to the classic style of lectures as it gives me a chance to attempt the work myself and refer to other books and the given notes if I need to.
- I personnally prefer lecture, but I still think this is a cool way of learning.
- Aboard.
- I love this style of teaching. It makes more smooth to understand the syllabus clearly.
- I think its a really good way to learn!
- It's the lecture I remember the most about so far so definitely a good method!

Table 4: Student responses on the peer instruction concept after the first session.

So, I really felt that it worked. It seemed a lot more satisfying than lecturing, anyway.

After the first session, as part of the self-paced review for lecture 2, I asked for comments on how they felt about it, Table 4. They were generally still evangelical after first contact, at least, the 38 who answered were.

Then, at the end of the course, I asked them for their feedback one last time. I asked them about its effectiveness, the PI questions, whether I should do it next year for the succeeding cohort, and whether they would like me to do this again with them in the second year course that I teach. Finally I asked for their overall feedback. The quantitive data are in Table 5 and the comments in Table 6.

Their answers were quite absurdly positive! So much so, that even if all the people who didn't answer were uniformly negative, around 2/3rds would still want to do it this way. To put it another way, over 90% of those responding thought I should do this again and asked for me to do this again, with them, in their second year course with me.

The students were also very thoughtful in their written responses (Table 6). They were very aware that it was essential to do the pre-reading to get much out of the class sessions, but they were much more confident about their understanding than either previous cohorts or in their other courses. And, they enjoyed it. Some wanted more start-of-session review, some wanted less. So there is a balance to be struck.

Some might be concerned that this approach takes more time. On the contrary, it doesn't take more time for students that work at the material properly, but in this approach we are scheduling their learning to happen during the degree programme rather than cramming at the end. So in the UK, where high school exams have been modular and sat in January and June, many bright students are used to being able to cram for individual exams, studying in bite-size chunks. The result is a lack of deep

n=61	Overall, I this this approach is...
39	More effective than lecturing
0	Less effective than lecturing
3	Just the same
19	Different - some pluses, some minuses
n=60	Did the questions in the lectures help improve your understanding?
42	Mostly
18	Sometimes
0	never
n=55	I think I will do better in the January test and June exam than I would have done had you lectured this material like everyone else
46	Agree
9	Disagree
n=57	You should do this again next year for the next group of MSE104 students.
53	Agree
1	Disagree
3	No opinion
n=57	My lectures in MSE203 on stress tensors are very mathematical and are about solving problems. Would you like me to do this again for that course (in Jan 2014)?
55	Yes
2	No

Table 5: End-of-course quantitative feedback on the PI approach.

understanding and recall, rather a transient surface memorisation that is the product of strategic revision. As demonstrated earlier in this paper, it doesn't take more time, but it does require the students to spend the time in review at the correct time in the degree.

Another question would be what sorts of courses this approach will work for. Starting out, I was quite worried that while it might work for algebraically easy but very mathematical Physics 101 courses at Harvard, it might not work so well for a quite conceptual and graphical course that is still mathematical. But, it seemed to actually work very well - you just have to think up good conceptual questions that have multiple possible answers. I'm still unsure how this would work for advanced courses in Masters degrees, where the material is very discursive, like my Ni, Ti and Zr lectures.

7. Student Evaluations and Exam Performance

In December, the students completed their student online course evaluations (SOLE). Converting the responses to a numerical scale of 1-5 and taking the average, they gave this course a score of 4.7, which is substantially higher than I have ever received before. Mostly my courses are in the 4.0-4.3 range, which is slightly above average for the Department but barely so. 4.7 is exceptional. Again, the written comments were very positive, with some students noting that the content was quite hard in comparison to other courses.

In January they had a progress test in which I asked probably a slightly harder - and very insight-driven - question. It was about the salt-water phase diagram, the use of salt in snow in the UK and Canada, salt in salt shakers and in ice brine quenching, none of which had been taught directly. This was generally well answered, with an average mark in range for the test in past years. Because the question was quite different to previously, its difficult to compare with previous years.

In the June exams I asked a question about solidification under both equilibrium and Scheil conditions. Compared to previous years, the vast majority of students clearly understood what all the terms in the Scheil derivation were and how to apply the equation to solve a real problem, whereas previously the idea of solute partitioning at the interface was understood by only a minority of students. Therefore the mean mark was about 10-15% higher than in previous years. This was in spite of a rubric change to the exam that meant that students had much less choice. It was also noticeable that nearly every student answered this question in the exam, compared to about 60-75% in previous years.

Of course, given the year-to-year variations in our exams and cohorts, direct statistical comparisons are not possible. But, both in terms of my impression when marking and in the numerical scores, it seems to be clear that students understood very more clearly - in both conceptual and quantitative terms - how to apply binary phase diagrams to solidification problems. Therefore it seems that this approach resulted in qualitatively more learning and better outcomes.

8. Conclusions

The Peer Instruction or "turn to your neighbour" approach, supplemented by full lecture notes and YouTube videos, was trialled using learning catalytics to deliver the in-lecture questions in a first year phase diagrams course in Materials Science with a class of 82 students. The following conclusions are drawn.

1. The approach was well received by students and appeared to result in greater student understanding of the underlying concepts. Above all, it appeared to be an *effective* method of teaching.

2. It is important in using this approach to support the initial pre-reading step very fully; I gave them full lecture notes and videos, broken into small 20-min segments. I also gave them a pre-session quiz to get feedback for the class sessions and to help them figure out what they did and didn't understand.

3. It is important to ask good questions that will develop insight and diagnose problems, supporting discussion by the students. To an extent, the lecturer becomes a facilitator. The initial review should be kept short.

4. Learning catalytics helped support the in-class and self-paced reviews, and provided data on how students were getting on. It particularly helped avoid the technology taking up time in the interactive sessions. Students liked being able to use their own web devices.

It seems clear that the traditional lecture exposition is going to be overtaken by technological and social change; this approach to teaching seems to both improve outcomes and provide an answer to ‘why the university’ in the age of the internet.

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References

1. E Mazur. Farewell, Lecture? Science 323(5910):50–51, 2009.
2. MK Smith, WB Wood, WK Adams, C Wieman, JK Knight, N Giuld, TT Su. Why Peer Discussion Improves Student Performance on In-Class Concept Questions. Science 323(5910):122–124, 2009.
3. E Mazur. Peer Instruction: A User’s Manual. Prentice Hall, NJ, USA 1997.
4. CE Crouch, E Mazur. Peer instruction: Ten years of experience and results. Am. J. Phys. 69(9):970–977, 2001.
5. J Watkins, E Mazur. Just in time teaching and Peer Instruction. in “Just in Time Teaching Across the Disciplines”, Ed. S Simkins and M Maier, pp. 39-62. Stylus Publishing, Sterling, VA, 2009.
6. WB Wood, KD Tanner. The Role of the Lecturer as Tutor: Doing What Effective Tutors Do in a Large Lecture Class. Cell Bio. Ed. 11(1):3–9, 2012.
7. L Deslauriers, E Schelew, C Wieman. Improved Learning in a Large-Enrollment Physics Class. Science. 332(6031):862–864, 2011.
8. J Nelson, DF Robison, JD Bell, and WS Bradshaw. Cloning the professor, an alternative to ineffective teaching in a large course. Cell Bio. Ed. 8(3):252–263, 2009.
9. TM Andrews, MJ Leonard, CA Colgrove, and ST Kalinowski. Active Learning Not Associated with Student Learning in a Random Sample of College Biology Courses. Cell Bio. Ed. 10(4):394–405, 2011.

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- The class sessions allowed me to apply what I had learnt from the notes/video and picked up weak areas that I need to go over.
- One criticism. You spend too long on the first question, then you have to power through last questions.
- Useful questions to reinforce learned material and good revision session at the start, with useful questions to test the concepts as well as the equations.
- The pace of class sessions could be a little faster. Although the questions were useful in addressing fundamental concepts, I think it would be helpful to show how the concepts may be used in exam problems. Even if we could get the questions during class sessions right, tutorial questions are on a whole new level. There is a large gap in difficulty.
- I really enjoyed your class sessions and thought they were quite helpful. It is always fun to have a bit of theory and questions, instead of just having long theory lectures. However, sometimes I thought the theory part was a bit too less. I think some of the difficult concepts should be elaborated a bit more in class.
- The class sessions helped me to understand and solve problems which are based on the videos.
- Class sessions were very useful as long as the work had been done beforehand. I skipped some videos and read the notes only for a few sessions and this wasn’t enough to understand what was happening in the class.
- learning catalytics is a good thing, and this group discussion approach makes it more user-friendly and interesting.
- They were helpful! I liked the feedback when we could ask questions over this website
- Haha all the stuff you did is just amazing.
- Overall good, it meant that the lectures held my full attention for the whole hour because of the interaction, and it gave me more understanding of how the information in the lecture notes would relate to problems and questions in an exam.
- While your method involved a mountain of work to be done before lectures, I think it has helped our learning by allowing us to figure out what we don’t know before coming to lectures and addressing them during the lecture. I think it’s a fair trade to better understand the topic.
- On your lectures I really had to think how the physics actually work instead of just memorising as on ”traditional” lectures. I think this helps me understand and actually learn it better.

- I find this technique is a bit like communism; it works very well on paper. However, in practice, it comes with a few problems. If for what ever reason you have not been able to do the groundwork before a session, I found it was very difficult to then try and catch up and, at the very least, it would have been one wasted session. You did warn us of this, but it is very difficult to make sure you read the notes/watch the video EVERY time beforehand and it seems that missing one unfortunately had a bit of a knock on effect for the remainder of the course.
- For first year students it might be a little bit hard to begin with this kind of teaching in the first month of university. It is hard because it implies reading the notes and watching the videos twice a week and with lab reports taking so much time, it isn't easy. However, I think this is a much better method of lecturing and I enjoyed it. It allows students to have a more active role in their learning, and this means using their brains. The only thing I would suggest is make sure everybody understands, because the course is not very easy and is totally new.
- Overall, the notes were rather complicated and if I didn't want to watch the videos I wouldn't be able to understand. As one of the first courses the motivation to work hadn't yet sunk in entirely and so a few lectures were wasted. Adding examples in the notes as in the videos could go a way to help and adding more in the notes to help us understand - 5 pages of notes corresponded 40+ minutes of video for example, but the videos were useful and will be great in revision.
- Sometimes if we did not review fully the materials before we go to lecture, it does result in a bit of a wasted lesson, but that totally depends on the students.
- Overall, very good. I don't want to sound cheesy, but I'm sure this will have great impact on our future exam marks. It is basically two lectures for the price of one! (but twice the work for you...)
- The courses were engaging. The use of learning catalytics kept the class active and engaged in the lecture.
- You are the best lecturer i had so far in imperial. Very engaging. Its the only lecture i never sleep halfway through class.
- Overall I think this is worth doing and is a better way of learning
- I'm still undecided on which method I prefer. I like normal lectures, and this technique a swell.

Table 6: Student comments on the course and class sessions at the end of the course.