Fantasy Universes: Inquiry Learning in Astrophysics On-Campus and Massive Open Online Courses

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Abstract

Problem based learning, and its variants such as project-based learning and case-studies, is a widely used and highly effective type of inquiry learning. In this paper, I present a case study of applying this method to the teaching of astrophysics. There are two main novelties in my approach. Firstly, traditional problem-based learning gets the students to solve real problems, but my exercises ask them instead to solve fantasy problems. I make up a universe which is interestingly different from our own, but physically self-consistent, for example, a universe with bubbles rather than stars in the sky, that didn't have a Big Bang. The students are given the task of discovering some interesting things about this universe. Each week, the students discuss the data they have in hand, and make proposals for future observations. The data they requested is then generated and returned to them. Week by week, the students learn to analyse their data, formulate hypotheses and propose observations. Because the universe is a different one from our own, the students cannot just look up the answers on Wikipedia. They have to apply the methods and thought processes taught in lectures to this different context. The second novelty is that these exercises were used in a series of Massive Open Online Courses (MOOCS), in addition to more traditional on-campus courses. These online courses have restricted options for assessment, which makes inquiry learning challenging. Student feedback suggests, however, that these exercises were highly effective in driving deep student learning and engagement, for at least a sub-set of the online students.

Introduction

In most astronomy courses, we present the students with information about some topic, and then test their understanding of this topic using problem sheets or essays. Several inquiry-based learning techniques reverse this sequence. Students are presented with a problem first. The problem is usually a real-world one, and is far more complex and open-ended than those normally used in astronomy assignments. Students then have to go out and teach themselves (with the aid of the lecturer and tutors) whatever information is needed to solve this problem.

This family of techniques goes by a variety of names, including the case-studies method (e.g., Herreid 1994, 2007), problem-based learning (e.g., Boud and Feletti 1997), and project-based learning (e.g., Blumenfield, Soloway, Marx, Krajcik, Guzdial and Palincsar 1991; Mills and Treagust 2003). The case studies methodology came out of business-school cases, where a case-study of some real business issue would be discussed in an interactive lesson, but has now been extensively modified and widely applied in the sciences. Problem-based learning came out of medical education, and involves groups of students working for typically a week on a clinical case. Project-based learning is most widely used in Engineering, and once again involves teams, but now working on a larger scale project over a many weeks or months. The common feature is a complex real-world problem that requires students to integrate their knowledge. Most examples also involve group work, but there is an enormous diversity in the timescales of projects, their assessment, and the amount of support and direction provided to the students.

Research has shown that these techniques can improve the ability of students to apply their learning in real-world situations, without degrading their performance in more conventional assessment (e.g., Little, Ostwald and Ryan 1995; Ostwald and Kingsland 1994; Ryan 1993). They force students to learn actively and to integrate their knowledge of different subject areas. They also teach generic skills such as group work, defining problems, and self-directed study. Note however that some research finds the benefits to have been overstated (e.g., Berkson 1993; Bruhn 1997).

For many years, I have been concerned that students in our introductory astronomy course acquired little real feeling for the scientific method. I had used in-class role-playing games to expose students to the scientific method (Francis and Byrne 1999; Francis 2005). These had been very successful, but due to their limited duration, only exposed students to very small scale inquiry and problem solving.

In this paper, I present my attempts to introduce much larger-scale problem-based learning to our astrophysics courses, both on-campus and on-line. To the best of my knowledge, techniques like these have not previously been used in undergraduate astronomy courses, though many related techniques have been applied (e.g., Bailey and Slater 2003; Duncan 1999; Taasoobshirazi, Zuiker, Anderson and Hickey 2006).

The exercises developed here are novel in two ways. Firstly, they are the only attempt I'm aware of to use this type of exercise in a massive open online course (MOOC). Secondly, the problems we get students to solve are fantasy ones – unlike most problem-based learning and case studies, these are not real problems, but made-up ones.

Why did I use made-up problems? I wanted the students to try to solve large-scale problems, initially in cosmology. Normally, one would pick a real scientific problem in the field and turn it into a case-study for the students. Unfortunately, there is only one universe, and vast amounts of on-line resources about it. If I had set the students a problem about the origin and fate of our real universe to solve, they could and would have simply looked up the answer on Wikipedia. This led to the idea of making up a universe different from our own. It should be physically self-consistent, and the students would need to apply all the techniques used by real cosmologists to figure out what was going on, but they couldn't just look up the answer.

In this paper, I explain what I did, how it worked, and the lessons learned. The simulated universe exercises were first tried out in an on-campus course, but more recently have been applied to a set of massive open online courses (MOOCs). I will describe how they worked in both.

A Fantasy Universe Exercise in an On-Campus Course

I first tried a simulated universe exercise in a first-year on-campus astrophysics course taught at the Australian National University. This exercise was used as a major assessment item for a six week module on cosmology. About 30 students were enrolled. These students were required to have a reasonable high-school maths and physics background. Students were required to do the exercise in their own time: little class time was made available for it. Lectures continued throughout the running of the exercise.

Prior to running the exercise, I invented a detailed, fictitious but mathematically self-consistent cosmology. Early in the course, I took about 30 minutes out of a lecture to present the exercise to the students, as follows:

> *'I would like you to imagine that you are all inhabitants of the planet Zog. Zog is remarkably similar to the Earth in every way. For example, the astronomers of Zog have all the same telescope facilities that we have.*
>
> *There is only one difference: the universe of Zog has a quite different cosmology to our universe. Your task, over the next few weeks, will be to figure out what the cosmology of Zog's universe really is. I've invented a detailed, self-consistent cosmology for Zog. Your task is to discover it.'*

I then show a computer presentation (Figure 1), describing the night sky of Zog. This has no Milky Way and no galaxies. Instead it has such novel features as the Greater and Lesser Milkstains, the Northern and Southern Blue Spots with their jets, and the fuzzballs. All these are features of the fantasy cosmology I had devised. This presentation was made available to the students on the web.

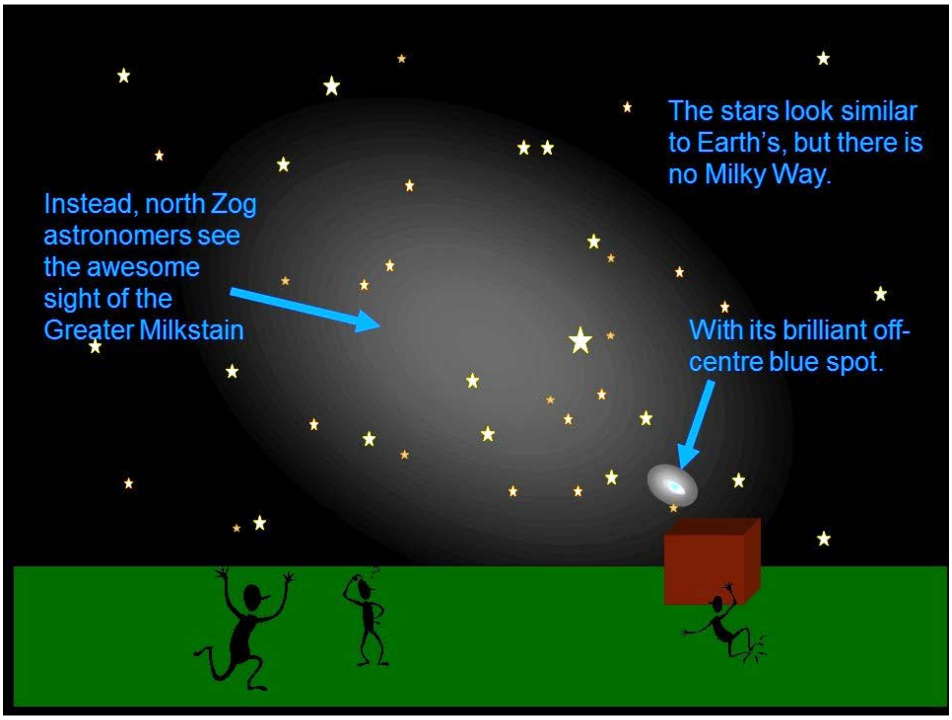

Figure 1. One slide from the introductory presentation describing the night sky of Zog

I then tell the students:

> *'You should divide yourselves up into groups of about three people, and talk through what you have just learned. At present, you do not know anything like enough to figure out the cosmology of Zog's universe. Just as earthly astronomers did, you will have to make some new observations to figure things out.*

> *Once you are in your groups, try and figure out some observations that will help unravel the mystery of this universe. The techniques you are learning about in this course, by which we learned about* our *universe, should give you somewhere to start. Remember: you have all the telescope facilities of Earth at your disposal. You can coordinate your observations between groups to avoid overlaps, if you wish.*
>
> *One week from now, you should send me your proposed observations. If they are technically feasible, I will calculate what you would observe, generate the appropriate data and put them on-line for the whole class to see.*
>
> *You will then have two weeks to mull over this data, and come up with a second set of observations. I will generate the data from these new observations, and once again place them on-line.*
>
> *You will then have a further two weeks to consider all this data, work out a cosmology for this universe, and write it up in your groups. Your write-up should describe both the cosmology you have deduced, but more importantly the process whereby you arrived at this conclusion.'*

The students were very enthusiastic about this assignment, and almost all worked very hard at it. I was bombarded with questions after every lecture. Whenever the lectures covered some issue of direct relevance to the assignment, students perked up in class, began furious discussions and peppered the lecturer with detailed questions.

To make progress with the mystery, then needed to interpret spectra, measure redshifts, integrate multi-wavelength data and construct a three-step distance ladder. There were a number of surprises hidden in the data – in particular, this universe had the topology of a cylinder (so you could see multiple copies of each galaxy by looking around the circumference of the cylinder, analogous to being between two parallel mirrors), and was contracting rather than expanding (which the students could determine by measuring the distances and redshifts of several galaxies).

The exercise ran for six weeks, and at the end of this, each group had to write-up what they had deduced. Typical write-ups were around ten pages in length, and were worth 20% of the total course mark. Several colleagues warned me that this assignment was too difficult for any of the students, but in the event all made substantial progress (albeit sometimes with substantial help from me), and two groups essentially cracked the mystery.

Student Evaluation of the On-Campus Exercise

Students were asked to complete a questionnaire after the end of the course. One item on this questionnaire asked them to list the best and worse features of the simulated universe assignment. All students completed the questionnaire.

Best Features

38% of the students commented that the best feature was that it forced them to thoroughly learn and understand the course material. Typical quotes include:

> *'You pretty much learned the course material to complete the task.'*

> *'A very original assignment - led to some of the most interesting conversations I've had. Gave me a great understanding of the course.'*

> *'Though provoking, motivational. Tied in nicely with the lectures. Very challenging. Interesting, exciting in the context that it was constructed along the lines of real-world astronomy.'*

31% of students commented that one of the best features of this exercise was that it forced them to think hard. Typical quotes include:

> *'I lay awake every night for a week thinking about it.'*

> *'The only assignment that made me think, rather than reach for a text book.'*

> *'Real life situations where you have to think as real astronomers do. I thought this was very good and very important.'*

> *'I was compelled to do the assessment task especially early because it was so goddamn interesting.'*

No other best features were raised by more than 10% of the class. I conclude that the exercise succeeded in making students thoroughly think through and learn the course material.

Problems with the Exercise

The simulated universe was time-consuming to prepare and run. Initially devising the exercise took three days, and simulating each set of data another two days. This was a highly skilled job requiring an intimate familiarity with the tools used by astronomers to generate synthetic data.

The exercise can, however, be re-used. When re-using it, we rely on the students making very similar data requests from year to year, which seems to be what happens. This greatly reduces the lecturer workload. It does, however, make cheating possible, as students may be able to get hold of model solutions from previous years. We found one case in which students had gone to extraordinary lengths to cheat in this way.

From the student point-of-view, by far the biggest problem was time management. Despite repeated warnings, most groups left the detailed analysis of the observational results until the last moment, and then found that the assignment was more difficult than they had anticipated. When I repeated the exercises, I put in an intermediate deadline, with students required to show evidence that they'd started serious work on this exercise. This partially solved the time management problem, but also reduced the open-endedness of the whole exercise.

The other major problem as seen by the students was group meetings. Most student groups found it logistically impossible to meet outside of class time. This problem was resolved by allowing time in lectures and tutorials to discuss the assignment, at some cost to other aspects of the class.

14% of students commented that they would have liked more observations, and 7% felt that the exercise was too difficult and baffling. Solving the time management problem reduced but did not eliminate this problem.

Simulated Universe Exercises in Massive Open Online Courses

In 2013 the Australian National University joined the edX partnership and started to put out a series of Massive Open Online Courses (MOOCs), purely online and open for free to anyone in the world. They started with a series of four astrophysics courses taught by me and Brian Schmidt, which were loosely based on our first-year on-campus course described above. The courses first ran in 2014 and 2015 and have been taken by tens of thousands of students, ranging in age from 11 to 92, and coming from over 170 countries around the world. Students were expected to have high-school level mathematics and physics knowledge.

In the early planning stages for this course, it became clear than many people across the university believed that an on-line course had to be inferior to an on-campus course, because it could not stimulate discussion and deep thinking (though there is some evidence that on-campus courses are pretty poor at teaching critical thinking, e.g. Willingham 2007). They felt that the limitations inherent in fully automated assessment meant that the course could only convey facts, and not critical thinking. Eager to prove them wrong, I decided to adapt the simulated universe exercises to this new environment.

Once again, simulated universes were invented for each course. More time was spent on the development of these universes, due to the larger number of students expected, and the desire of the university to make a good impression with their first MOOCs. The resulting exercises were larger, more complex, and had better production values.

The courses were divided into nine weekly sessions, each containing a lesson (a lecture equivalent, made up of short videos interspersed with questions), reference notes, webcast worked examples (Citation removed for anonymity), practice questions, homework assignments and the “Mystery”, which was the simulated universe.

18649 students enrolled in the first course, but only 5679 of them (30%) ever logged in. Most of those who logged in only watched the first five-minute video: only 1812 students attempted and passed the first week’s homework. Once the students had progressed this far, there was a very good (75%) chance of them continuing on and passing the entire course. These trends are broadly similar to those seen in other MOOCs (e.g., Breslow, Pritchard, DeBoer, Stump, Ho and Seaton 2013). Around 50% of those who passed the course posted at least once on the discussion forum, and a small group of around 50 students accounted for over half of all discussion forum posts. In the later courses in the series, the fraction of students actively engaged in the class similar but modified by a cohort of around 1000 students who were working their way through all the courses, who had very high completion rates.

In the first section of each course, the universe was presented, using simulated graphics to make it exciting and perplexing (Figure 2).

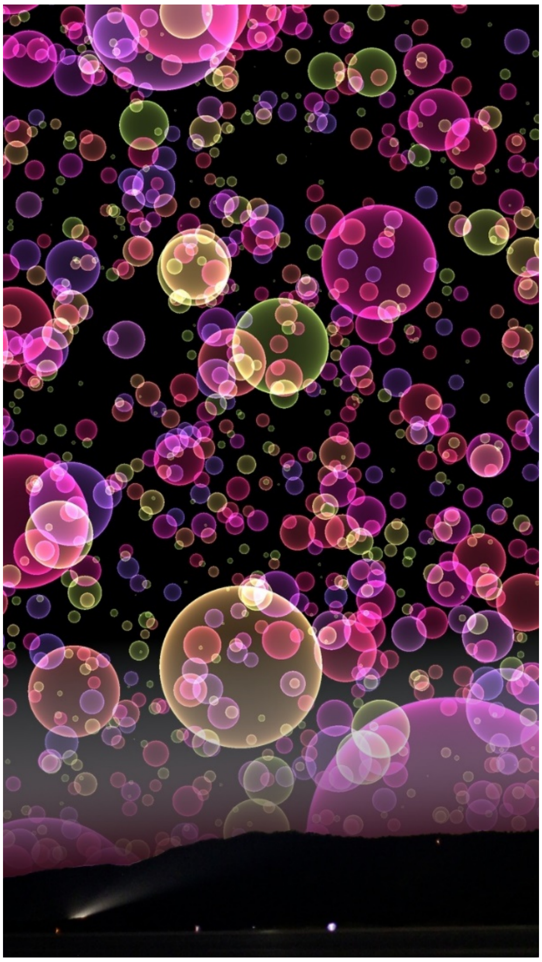

Figure 2. Simulated image of the night sky with bubbles rather than stars, from the introduction to one of the MOOC simulated universe mysteries

The students were urged to discuss what they could deduce from this initial set of data on the course discussion forum, and to then request new data. Each week, as the course ran, I would generate the requested data and post it for the students. The data might include images, spectra, photometry or tables for data. In addition, I would post simulated TV interviews and a number of simulated research papers. These interviews and papers would sometimes contain deliberate flaws or misinterpretations of the data, to teach students a healthy skepticism.

The students would post on the discussion board what they had deduced, and make requests for more data. For example, they requested spectra of the bubbles. Once these spectra were provided, the students spent a considerable amount of time interpreting the spectra, working out what the bubbles were made of (a wide range of elements), and using the Doppler shifts to investigate the dynamics of the bubbles. Students would post their analyses and hypotheses, and other students would critique them. After a few days, a consensus would normally emerge, and based on that, new observations would be requested. In this case, the students were able to deduce that the bubbles were expanding shells of gas, presumably coming from some central explosion. They would then request detailed observations of the centres of the bubbles, looking for the remnants of whatever caused the explosion. And they could also use the Doppler and transverse expansion rates of the bubbles to measure their distances and redshifts, and hence investigate whether this universe was expanding, and whether it contained dark energy.

At the end of the course, the students were taken step-by-step through the solution to the mystery, by a series of multiple choice, symbolic entry and numerical entry on-line questions. So for example, they might be asked to measure the wavelength of a spectral line, then asked to identify what element it came from and what velocity the gas was moving at. Using the results of this, they might be asked to determine the redshift of the galaxy and hence the expansion rate of the universe.

The mystery generated a vast number of posts on the discussion forum almost immediately. An extremely lively discussion emerged in each of the four courses, with many students deeply involved in a virtual community, trying to solve the puzzles. Indeed, the number of posts generated was so large that navigating all the various data requests and theories became a major challenge.

It rapidly became clear that the on-line students were making much faster progress through the mystery than the on-campus students had ever done. This was partially because many of the on-line students were mature age learners, often with higher degrees, and partially because all the active students shared ideas and theories online (whereas in the on-campus course, sharing was only internal within the groups of students). Part of this, however, was undoubtedly because of the class size – we had a critical mass of top-end students that you wouldn’t get in a small on-campus class, and it was this top end who drove much of the progress in solving the mysteries.

Student evaluations

Many students commented on the simulated universe mysteries, both in the discussion forum and in a survey we conducted at the end of the third course. Most comments showed that the students enjoyed the mysteries, and felt that it was giving them a sense of research in action:

> *‘Not only did the course present us with the wobbly, complex and frustrating world of research astronomy; it also gave us the chance to feel what this was like for ourselves, through the mystery. If the goal of the mystery was to learn what it was like to be a research astronomer, then high marks shouldn't go to the student who gets all the answers right first time. High marks should go to a student who looks at the data, then suggests a theory, then gets proved completely wrong, then swears profusely, then devises another set of observations, gets the results, refines the theory, then notices something quite similar in a wholly other branch of astronomy, tries a refinement of the theory on that basis, checks the data again, and ends up with - not the "right answer", but with at least a model that is close enough to be feeling quite encouraged.’*

> *‘This isn't a course that teaches us "what real astronomers know about the universe". We can get most of that on Wikipedia, to be honest. Rather, this course teaches us "how real astronomers behave in the face of what they don't know about the universe". Much more interesting!’*

> *‘I have been trying to self-study these topics in the past months, and this process of trying to apply what I've learned in a critical manner has forced me to really try to not to just know the material, but understand it. There's a huge difference. […] There's also*

a tremendous amount to gain in going through a process that gives some insight into the scientific method in this field. To me, this is really a unique opportunity.'

'Working with the material in this way also makes you realize which parts of it you have misunderstood and which parts you got right. Participating in the discussions let you get different angles on the material as well - when you see how others interact with it. For example, I working with the spectra in the mystery helped me understand how to interpret them a whole lot better. I also learned a whole bunch of things that were not in the course, that I or someone else would look up to try and understand some part of a theory better. It also made me more confident in formulating my own ideas and figuring out what they would imply. As for the formulas and relations in the reference material, I got a whole lot better feeling for what they mean, how and when to apply them. I learned how fun it is to try and figure these things out, I hope that working as an astronomer is something like it. How complex analyzing the meaning of measurements are and placing them into a framework for understanding. It is fascinating, and instructional, to watch the more advanced students grapple with the information and try to make sense of it. Ideas that flow out aren't always right, but that's how it is in physics, and one should be able to face being wrong as much as being right, as learning comes from both scenarios. Over time, ideas coalesce, and new information adds to or contradicts conclusions. THIS IS A GREAT PART OF THE CLASS!!!!!'

The mystery was thus working as hoped for a substantial number of students. It was not clear, however, that these comments were representative of the whole student body. To gauge this, we asked the students who completed the third MOOC to do a short survey, part of which focused on the simulated universe mystery. Around 25% of those who completed the course filled out the survey (220 students). They were asked how much they had engaged with the simulated universe mystery during the course: (Table 1)

Table 1. Student self-reported engagement with the mystery

I ignored the mystery	10%
I occasionally looked at the mystery but did not take part in the discussions	30%
I followed the mystery and read some of the discussions about it	25%
I read the mystery each week and also read most of the discussions, but did not post anything myself.	23%
I followed the mystery and participated in discussions about it	8%
Other (please explain below)	4%

The major reason why some students reported low levels of involvement with the mystery was lack of time:

'I would've liked to participate in the mystery more but time did not allow it. The one I was most engaged in was for the first course and it was hugely beneficial, but I'm afraid I only read it weekly and did very little with it this go around'

'I liked the way it was used in the exam, but did not have time to spend much time on the mystery throughout the course'

A feature of MOOCs is that students can engage in them at different levels: for example, many students would watch the videos but not do the homework. Clearly a fraction of students chose not to participate fully in the mystery, while many more were “lurkers”, following the mystery in detail but not actively participating in the discussion. Most of these people who participated in a limited way were happy to do so:

> *‘I did not mirror all the calculations as done by others this time. (In the first course I used the data provided to make my own charts to satisfy myself that I could understand what was happening). I am perfectly happy lurking. I did make one comment […]. It was a rather silly idea but I enjoy imagining outlandish scenarios and in fact posted this one in a brainstorming thread. I'm glad the "anything goes" philosophy was encouraged. I think the universe designer has achieved the goal of putting the participants in a situation analogous to real research. I greatly admired the intelligent requests from the participants and wondered if I actually could have worked in a scientific field myself, given that I didn't come up with anything original! I had no trouble with the exam, so I think I'd have to say that the most important thing I learned is that original research is HARD - kudos to those with the patience and intellect to perform it.’*

> *‘I enjoyed the process of developing hypotheses and thinking in new ways about material presented in the course. I like the "application" mindset. What do we know and how can we apply that to what we are seeing here? It is good real-world training for problem-solving. I think it was good training for thinking like a scientist. While I could not participate as much as I wanted toward the end due to job requirements increasing with the Christmas season, I still read every post and did the thinking part. It also led to interesting discussion around the dinner table as my husband got involved in the speculation I was doing and helped me think through things as well. In the final, I really like that it focuses on the mystery and walks you through the solutions. The methodology for answering the questions came from the coursework, but applying that to problems involving the mystery was interesting and challenging to me. I know some do not like that way of doing it, but I certainly did.’*

Some students, however, were intimidated by the small number of very able students who contributed most of the forum posts. Here are two representative quotes:

> *‘The mysteries are a BRILLIANT idea. I love them. But what seems to happen in each course is very quickly the discussion gets dominated by a handful of very competent people that effectively intimidate others from participating. I don't think this is intentional on their behalf, but it is the outcome. I don't know how this can be avoided, really. It's just a function of the mix of students we have right now.’*

> *‘Well, sometimes the level of a group of participants and their extensive knowledge prevented me to be more participative. I felt sometimes overwhelmed. Anyway I think this is how science works. Many information+noise coming everywhere. Nonetheless one can participate and people is fair and respectful with others opinions and inputs Anyway I think the Mystery Part is very interesting and allows me to keep in track and engaged during the whole course’*

The simulated mysteries did, however, have an unexpected benefit that flowed on to all the students in the class, even those who did not participate. It brought the top end students back to the discussion forum on a regular basis. And while they were there, discussing the mystery, they would often discuss other aspects of the class, and answer questions from the weaker students.

Before running the courses, I had been worried that the fictional nature of the simulated universe mysteries would be off-putting to some students, who wanted to get the actual facts, not some made-up facts. This was not, however, mentioned by any significant number of students.

There were a few disparaging comments about the open-ended, unstructured nature of the mystery:

> *'Having said that, in my opinion, the Mystery drags the rest of the course down. It lacks the structure that is my entire reason to take a course like this in the first place. Apparently, the reason that it is offered is to give students "the chance to experience what it is like to be a research astrophysicist". The fact is, I do not want to be a "research astrophysicist"; I just want to learn (more) astrophysics, and they are actually very different things. I also find the discussion aspect of the Mystery to be not very helpful; most posts (not all) are rather poorly organized, and many have incorrect information as well. Frankly, having taken many online courses, I have almost never found the discussion forums to be really helpful except when diagnosing errors. Anyway, that is just my opinion. I appreciate that the instructors have put a lot of effort into the Mystery, and I just wish it were a less integral part of the course.'*

> *'I really did not know what to look for. So I found the mystery unuseful. If at the beginning it was clearly stated the goal of it, i would know what to search for and be interested to be a part of the search'*

Writing the mysteries

Writing the mysteries is hard. You want a puzzle that is interesting enough to grab the students in the first set of clues, physically plausible, self-consistent, challenging and yet simple enough that you can simulate things without a supercomputer, and so that the students can solve it given the knowledge they acquire in the course.

I would typically follow the same process that Agatha Christie did in writing many of her mysteries (Curran 2010) – I would start out with some extreme idea, such as a planet kept warm by explosions rather than stars, or a universe with bubbles and not stars in the sky. I would then try to work out what could cause such a universe – in the case of the planet kept warm by explosions, there would clearly need to be a very large number of extremely luminous supernovae. Perhaps if stars never sat on the main sequence but liberated all their energy in a single cataclysmic detonation, would that do it? But what changes to the composition of stars, or the physics of fusion, would I need to get them to do this?

Eventually I would come up with the smallest possible number of changes I'd need to make in order to get the extreme idea to work. Usually I'd try to only change things that we don't understand anyway (such as the exact explosion mechanism of Type 1 supernovae). I would then work backwards, asking what effect these changes would have on the observable universe. Often these changes would be very profound, far beyond the initial extreme idea (such as precluding the existence of planets with life), or would produce results that would be too hard to simulate, or too hard for the students to figure out. I would then go back and forth between the changed fundamental astrophysics and its conclusions, trying to tweak things until we had a mystery that met my goals.

I would then try to anticipate the types of data the students would request, and generate it. In some cases, I would take real astronomical data and re-purpose it, or edit it slightly. In some cases, Photoshop was used to massage images. And in other cases I'd write programs to generate tables of simulated data, simulated images, light curves and spectra.

If there was a clue I wanted to reveal but which the students were unlikely to request, I'd write a fictional scientific paper, or record a mock TV interview. I would generally put in some valid data but incorrect interpretation in these, to teach the students a critical approach to reading papers, and to look at the numbers, not the conclusions reached by the authors.

All of this is very time consuming – it would take 2-3 weeks for on-line courses. And roughly a day a week while the courses were running to generate the exact data requested and put it online. For the on-line courses, however, this level of complexity was essential, due to the large number of very able students who would scrutinize the mysteries in great detail. For example, some of the students would take the simulated images and run them through image analysis profile to measure colours and brightness profiles.

One way to reduce the workload is to re-use the exercises. I did this for three years in the on-campus course. Students tended to request the same data each year, so the revisions required were not great. This only works, however, if the exercises are not used for high-stakes assessment, as otherwise it is too easy for the students to get hold of answers from previous years.

One way around this is to randomly generate part of the mystery (for example, have the students try to find planets around a star, but write a program to randomly generate the planetary systems and the associated data). I wrote several such randomized exercises, which allowed me to give every student their own personalized problem, so they couldn't swap answers with other students (though they can still discuss methods with each other). They certainly worked, and as they reduced copying, were a more rigorous test of an individual student's ability. These algorithmically generated exercises were not, however, as exciting for the students, as they did not address big picture issues (such as "was there a big bang in this universe?") and didn't have the surprises, plot twists and narrative thrust of the human-written exercises.

Conclusions

It is clear that these simulated universe exercises were an extremely powerful experience for at least some students. They reinforced the course content, and gave the students a sense of real research. They led to many fascinating discussions between students about the nature of science, and helped develop a real sense of class community. On the other hand, many students found these exercises to be intimidatingly difficult, while in the MOOC, some students simply chose to ignore it.

With the on-campus students, the main problems were student time management and the unwillingness of the students to get together outside of class time. For the on-line students, the main problem was the diversity of students, some of whom did such a good job of working with the mystery that they intimidated the others.

The fantasy nature of these exercises is not appropriate in courses teaching detailed techniques, for which real-world problems are preferable. For example, if you were teaching an environmental management course about the trade-offs between the economy and nature, there are abundant real-world examples you could and should use. But for courses teaching really big foundational concepts, such as the Big Bang in astrophysics, evolution in biology, or plate tectonics in Geology, fantasy exercises could help students to critically evaluate the evidence for these theories, and their profound effect on the world. One could imagine, for example, a fantasy biology exercise with students investigating a planet on which complex life had come about in quite a different way (for example Lysenko's theories might be correct on this world, rather than natural selection). As the students figured this out from observations, they would acquire a deep understanding of the evidence for and logic behind Darwinian evolution.

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