Developing critical being in an undergraduate science course

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This article argues that the development of criticality in the three domains of knowledge, self and the world can and should be a goal for undergraduate learning in the sciences. It presents empirical evidence that this can be facilitated through teaching and learning that places a strong emphasis on the social dimensions of both the exercise and nature of criticality. Given the opportunity to discuss science as both an ongoing process and a human endeavour situated within a social context, students appeared to be able to adopt a hyperopic view allowing for high levels of criticality. When reflecting on their learning, students frequently ascribed developments in their thinking to the interactional, relational nature of the learning environment.

Keywords: criticality, critical being, social learning, hyperopic view, science

Introduction

> Each argument and each discussion has led to a revolution of sorts in the classroom making knowledge flow through debate (Student 1, integrative reflection)

This article presents evidence of the contribution of social forms of learning to the development of high levels of criticality in undergraduate science students.

We start by considering some of the different and potentially conflicting reasons why the development of critical thinking or criticality might be seen as a central aim of higher education. We then describe a recently-proposed model of criticality (Barnett 2015) and some ideas about pedagogy for criticality put forward by both Barnett (2015) and Davies (2015). We draw on these ideas and extend them to include a greater emphasis on the social emergence of criticality, and describe a first year science course which aimed to foster just such an emergence (Howitt and Wilson 2014). We use data obtained through students' reflections on their learning in this course to show how

criticality can come to be developed through social forms of learning, even among students studying positivist disciplines where knowledge is often presented as clear-cut.

Critical thinking or criticality?

Critical thought has long been seen as characteristic of academic work; as such, the development of critical thinking has become what Barnett refers to as a 'defining concept of the Western university' (1997, p2). In this context, it consists primarily of two strands – critical thinking with respect to disciplinary knowledge and practices or methods, and criticality with respect to oneself. When directed at disciplinary knowledge and arguments, academic critical thinking might be considered to be the application of logic to analyse the validity and persuasiveness of evidence and truth-claims. When directed at disciplinary practices or methods, critical thinking might be considered to be the application of logical and diagnostic thinking aimed at improving accuracy, efficiency, potency or intellectual fecundity. When directed at oneself, critical thinking might consist of self-reflection, metacognition and self-regulation. The development of the ability and disposition to engage in such thinking is seen as central to becoming a successful learner, researcher and academic.

However, over the last few decades, significant changes to the higher education sector have occurred in countries such as the UK and Australia. Increased access to higher education, a proliferation of new degree programmes in non-traditional subjects and disciplines, and an increasingly managerial culture of quality assurance have led universities to position themselves as developing the skills needed to succeed in a competitive graduate job market. This has led to a somewhat revised conceptualisation of critical thinking, linking it with the notion of employability as much as (or more than) scholarliness (see, for example, Cox and King 2006; Hinchliffe and Jolly 2011).

In this context, critical thinking is seen as a practical skill allied to problem-solving: the main driver for its development is the production of a well-qualified workforce, able to contribute to a dynamic and profitable economy; it is presented to students as a marketable asset, something that fulfils the needs of employers and sets graduates up for successful careers.

At the same time as contemporary educational policy at the national and institutional level has come to be dominated by instrumental conceptions of the purpose of developing critical thinking abilities, a critical pedagogy movement with strong emancipatory tendencies has arisen in some parts of the educational community. Central to this movement is the Marxist notion of critical consciousness and the conception of critical (and, increasingly, critical global) citizenship (Banks 2008). Authors such as Paulo Freire (1998, 2000) emphasise the need for individuals to be empowered to take on and transform the political and economic structures and strictures of society.

Although the conception of critical thinking deriving from the employability agenda differs markedly from the criticality of the critical pedagogy movement, they share a common factor that is often absent from a purely academic conception of critical thinking – that is, they locate the role of critical thinking in an individual's place within and relationship to a wider society, however differently these places and relationships are envisaged.

In an attempt to unify the different conceptions of criticality in higher education, Davies (2015) and Barnett (2015) have recently put forward models of the movements within critical thinking research and of criticality itself. Davies's (2015) model shows how academic, social and creative conceptions of criticality relate to each other as parts of a greater whole, rather than as opposing conceptions. He points out that the development of different aspects of this greater whole in students requires different

educational approaches, with the development of academic forms of critical thinking requiring a '*myopic* view' (Davies 2015, p87, emphasis in original) and the development of social forms requiring a '*hyperopic* view' (ibid). That is, academic forms of criticality require close inspection of disciplinary knowledge, and possibly immersion in disciplinary ways of seeing and thinking, while criticality in respect of society's structures, norms and relationships involves an effort to step outside of them and view them "from above" – to make the familiar and unconsciously accepted strange, and to see them as subjects for conscious analysis.

Barnett's (2015) model of criticality draws together critical reasoning, critical self-reflection and critical action. He describes the integration of these three forms of criticality as 'critical being.' Critical being, in this model, operates in three domains – knowledge, self and world – and at four levels – critical skills, reflexivity, refashioning traditions and transformatory critique. In introducing the three domains, however, Barnett stresses their connectedness and interdependence, noting, for example, that 'it is only by being shot through with analytical insight, intentionality, and a wisdom born of the weighing of alternatives that we can talk of action at all' (ibid., p65).

Barnett suggests that the pedagogies that dominate higher education are 'lopsided' (Barnett 2015, p69) and fail to address criticality in a unified way. He argues that conventional academic coursework is overly concerned with criticality in respect of knowledge; performance and competency-based approaches are over-concerned with impact on the world; and the self-reflective approaches that infuse a great deal of learning in professional areas such as education and social work are over-concerned with the dimension of the individual. He proposes reforming approaches to university teaching and learning to directly address the three domains in a unified way. Key to such a reform, according to Barnett, is the need to 'tak[e] students as persons seriously'

(ibid., p65) and to give them 'the space to become themselves, to bring their understandings to bear on situations and, in the process, make them *their* understandings; to understand themselves in relation to situations requiring insight and learning, *including their own limitations*, and to develop the capacity for critical insight in action' (ibid., p69, original emphasis).

So what would such an approach look like in practice? Given that there is some evidence that conventional approaches to teaching critical thinking are mostly unsuccessful in producing lasting, transferable criticality (Arum and Roksa 2011), it seems that alternatives must be sought. Barnett claims that 'academics [must] reveal themselves to their students as the hard-pressed inquirers that they are' (2015, p70). A curriculum for criticality would involve a re-envisioning and rebalancing of traditional academic roles and relationships, so that the authoritative hierarchy of teacher and student is abandoned and a 'genuine openness' is created 'such that students can feel that their own voice and their own existential claims matter' (ibid., p71). Teaching and learning might even benefit from 'the injection of humour: the critical consciousness can be too serious for its own good' (ibid., p71).

Such approaches, when combined with a conscious attempt to develop students' hyperopic views (Davies 2015), may lead to the development of a unified criticality that can be applied to the practices and culture of a given academic discipline as well as to disciplinary knowledge.

The relational nature of criticality

We believe that there is substantial merit in much of what Davies and Barnett suggest. However we would go one step further and more strongly emphasise not just the social dimension of criticality as it is enacted, but also a parallel need to emphasise the social and relational aspects of the *development* of criticality.

Traditional ways of approaching the development of critical thinking in university courses and programmes not only fail to address students as persons, to use Barnett's term, but also largely neglect their existence as persons who are inextricably bound up in webs of social and cultural interaction. While there has been much debate as to whether critical thinking should be taught as a generic skill (Ennis 1989) or within disciplinary contexts (McPeck 1990), both sides have considering critical thinking from an individualist, cognitivist point of view. Critical thought, in these approaches, is perceived as occurring in the heads of individual students, who must master the art of e.g. argument analysis or rational thought.

Yet if some aspects of criticality are embedded in or inherently part of the social or sociocultural, it is arguable that such aspects can only be developed through social interactions. Barnett nods towards this need with a suggestion that students might engage in 'testing their ideas in the critical company of each other' (Barnett 2015 p71); however we believe that criticality is itself a socially emergent phenomenon, constituted in interactions and relations between individuals, individuals and ideas, individuals and social structures, and so on. It is by exposing oneself to the views and practices of others that one can trouble one's own assumptions.

Towards a curriculum for criticality in an undergraduate science course

Science education at the undergraduate level is often associated with a packed curriculum structured around the acquisition of large bodies of declarative knowledge and procedural skills. Unlike in arts disciplines that incorporate the tradition of the studio critique or "crit" (Blair 2007; Percy 2004) in their pedagogies, explicit attempts to develop criticality with respect to the discipline or students' relations to it are rarely included in science curricula. Although many science academics claim that studying their subjects increases students' problem-solving and critical thinking skills (as is

evident from the formal learning outcomes articulated for many undergraduate courses), the underlying conception of criticality is predominantly the academic one described in the introduction. It is also one that tends to operate at the lower levels of Barnett's model: discipline-specific critical thinking skills and reflection on one's own understanding in the domain of knowledge, self-monitoring to given standards in the domain of self, and means-end problem-solving in the domain of the world. The refashioning and transformatory levels of critique, where considered at all, are typically reserved for graduate study or beyond, seen to be requiring substantial expertise within the discipline.

However, there is no obvious a priori reason to believe that sophisticated thinking and high levels of criticality can be achieved only by post-graduate students and experienced researchers. Indeed, an education that focuses on accumulating knowledge and technical expertise is likely to be poor preparation for a future of critical thought, and so may actually undermine the quality of thinking at later stages of learning and professional life. We have therefore sought to explore alternative ways of teaching that allow science students to develop criticality at the highest levels, in all three of the domains of knowledge, self and world, from early in their degree.

In a separate study, we have shown that authentic research projects can offer undergraduate science students an environment in which to develop their criticality to somewhat higher levels, including examples that could be described as refashioning traditions in the domains of knowledge and self (Wilson et al. 2015). However, perhaps because of their immersive nature, the students in that study showed little evidence of criticality at the highest level – the meta-critique of Barnett's earlier work (Barnett 1997) or the transformatory critique of his more recent (Barnett 2015) model. Such critique requires a critical being to envision alternatives to given structures and

relationships, which may be more likely to be achieved if one is able to step outside the structure and view it, and one's relationship to it, from different angles. While it is not impossible that such distancing occur during an immersive research experience, it is probably not a common experience. In addition, although we found that some students engaging in research projects directed some of their critical thinking towards aspects of the research environment, it appeared that their criticality operated primarily in the domains of knowledge and self, with only limited evidence of criticality in the domain of the wider world (Wilson et al. 2015). Both of these limitations may be due to the intensely involved nature of research participation, which inevitably gives rise to a myopic view, rather than the hyperopic view needed to see disciplinary practice as something that is both open to transformation and situated in relation to the social world.

Concerned with creating opportunities for science students to be exposed to and practice higher levels of critique, and to re-balance the curriculum to allow more criticality in the domain of the world, we introduced a cross-disciplinary science course that deliberately aimed to challenge students' thinking about the nature and practice of science (Howitt and Wilson 2014). The course consisted of case studies, group activities and discussions, reflection and question-generating activities. Topics were chosen to highlight aspects of science where issues of evidence, interpretation and bias play a role. They included case studies on fraud, disagreements, communication, disciplinary differences and creativity. Students were encouraged to recognize their own and others' biases in relation to what counts as science, for example through an activity in which they worked in small groups to develop taxonomies for umbrellas. They were also encouraged to recognize their own and others' biases in relation to preferred evidence or preferred authority, for example through a case study based on the Stanford Research

Institute's investigations into the self-proclaimed psychic Uri Geller, and another on the 19th century scientists Pasteur and Pouchet and their conflicting results about the spontaneous generation of life.

Small group and class discussions, both in class and online, were central to the course, with discussions and group interactions taking approximately 50% of class time. The bulk of the assessment (both formative and summative) involved reflective writing in response to prompt questions regarding the case studies and group activities/discussions. The course thus combined a highly social space with a more private, reflective space, both of which provided opportunities for students to express themselves as individual persons, and to develop their ideas and opinions in relation to those expressed by others.

Research design

As indicated earlier, we believe that since criticality is relationally constituted, it must also be relationally developed. This is not to suggest that there is no introspective component to its development, as the relations that constitute it include those between individuals and ideas, and individuals and their (physical) environment. However, it is to suggest that critical being can only be fully developed, in all its domains, if a social dimension is included in learning.

We therefore sought to evaluate the impact of the social learning elements of the course on students' development of criticality. Following approval from the university's ethics committee, permission to use students' written submissions as research data was gained from all those taking the course. In the analysis, we focused on students' accounts of their learning as reported in an integrative reflection written at the end of the course and incorporated into the assessment process. Students were asked to use this piece to reflect on if, how and why their views of science and scientific practice had

changed during the course. We also interviewed ten students (all those who responded to a call for volunteers and with whom suitable times could be arranged) between one and two years after completing the course, with the aim of understanding whether students' continued to believe they had developed criticality in the module, and attribute that development to the same activities, some time after the course was completed.

The integrative reflections and interview transcripts were read in full by both authors. The analysis was guided by Barnett's (2015) model, seeking examples of criticality in the three domains of knowledge, self and world, at the higher levels of refashioning or transformatory critique, and examining whether these were accompanied by references to class discussions or other forms of social learning. The analysis was informed by the ideas and approaches of phenomenography (Marton 1981), which looks for variation in student thinking and associates expanding focus with increasing sophistication.

The data presented below are drawn from the work of the 105 students who undertook the course between 2010 and 2012. The course was run at a research-intensive university which offers 'elite,' research-focused variants of its science degrees to high-achieving school leavers alongside its standard programmes. Approximately half of the students in the cohorts under study were enrolled in such programmes; they might thus be described as highly academically able. However, we would note that students from these degrees did no better in the course than those enrolled in standard programmes.

Within this context, the data are further limited in two ways: self-selection among the students, and self-reporting. The course was an elective module, likely to be taken by those who already had an interest in thinking about science at a meta level; those students who were interviewed were doubly self-selecting, having responded to a

request to participate in this follow-up research. However, it is not the intention of this article to claim that all students participating in such a course would develop high levels of criticality – rather it is to focus on the social emergence of such criticality where there is evidence it is developed, particularly in the domains of the self and world.

Results and discussion

The reflections and interviews provided evidence of the development of both persons with a hyperopic view and criticality in the three domains of knowledge, self and world. As the analysis proceeded, it became evidence that ethicality was intertwined with criticality, as judgments were made on ethical as well as rational and emotional grounds. We explore different degrees of ethical awareness and nuance in detail in a separate publication (Howitt and Wilson 2016). In the following, we present and discuss excerpts illustrating the development of a hyperopic view and criticality, highlighting the reliance of this development on interactions and discussions between students. We have selected excerpts which illustrate this relationship with relatively concise and focused examples, but similar patterns were evident in almost all integrated reflections and all post-course interviews.

Persons with a hyperopic view

Comments made by some of the students strongly suggest that their experiences in the course encouraged a hyperopic view: for example, one student described the unusual experience of 'thinking about the discipline you were doing' (Student 2, interview).

They also suggest that the combination of discussions and reflections created a sense that the students were being treated as persons. The same student described how in the classes 'we were given the space to discuss the ideas and discuss how *we* thought

about them' (Student 2, interview). Another contrasted the course with her other science courses:

> no one in science wants to know your opinion, not until you're a post-doc somewhere important. So I found it difficult at first to really want, know my opinion and to vocalise it in a way that was acceptable, because it's *so* not acceptable everywhere else. I found it was a lot easier to reflect on content and analyse content a lot more after [the course] (Student 3, interview).

The written reflections that students undertook throughout the course were also seen as spaces in which students could follow their own lines of thought. One student described how, for him, the reflections opened things up: 'it didn't limit you … It's not like you were limited to a question. They were purely just guiding questions. You'd start with that and, by the end, you'd be – I don't know – take it where you want really ... you can think what you want' (Student 4, interview). Another student described reflection as 'a personal experience with the subject … a reflection is what did I just experience, what have I not learned, but what have I seen, what have I experienced really? … How do I relate this to me? How do I relate it to my view?' (Student 5, interview).

All of these excerpts suggest a strong sense of ownership, with students acting as persons and taking charge of their thinking. These findings are not altogether surprising – reflections are, of course, often perceived as personally owned spaces. There is often a tension, however, between creating a space for genuine introspection or unconstrained speculation and creating a space that is surveilled (and known to be so by its inhabitants), resulting in an unwanted level of performativity. The very tentativeness of the students' comments above – 'you'd be – I don't know' etc. – indicate an authenticity that makes such performativity unlikely.

The possibility of adopting a hyperopic view through the experience of being treated as, and treating each other as, persons is also evident in excerpts such as the following:

> The topics for discussion each week were designed to evoke thought on different aspects of science, however I believe they contribute to one main underlying question that I found significant throughout the course. Each topic has allowed the students (and quite possibly the teachers too) as individuals to develop our own answer to the question 'what makes a good scientist?' ... The most important quality of this course is that it does not have the intention of giving a definition of what it means to be a good scientist, but instead allows us to decide and analyse this for ourselves. (Student 6, integrative reflection)

This student has been able to take a step outside her discipline and consider the larger question of what makes a good scientist – a question that only arises when a hyperopic view is possible.

Comments such as these were a common feature of the integrative reflections. Almost all suggested that, by the end of the course, the student had developed the confidence to express his/her own thoughts, opinions and doubts, often in creative ways including drawings and on one occasion a graphic novel. Around two-thirds of the integrated reflections directly related class discussions to an expanded or changed sense of science or specific scientific disciplines, suggesting that the course was relatively successful in helping students adopt a hyperopic view.

Criticality as a socially emergent way of being

Our analysis suggests that many students substantially developed their criticality in all three domains of knowledge, self and the world. In the domain of knowledge, students became much more aware of the contingent nature of scientific knowledge and the roles of accident, uncertainty and interpretation in its production. In the domain of the self,

some students underwent quite profound transformations, in some cases leading to them changing their majors. In the domain of the world, some students developed more nuanced understandings of the role of science in society; a small number went further, aiming to transform how science operates. The frequency with which students attributed these developments to class discussions and relationships with their peers and the class facilitators was striking, with (as indicated above) around two thirds of the integrated reflections and all of the interviews referencing discussions with peers. In the following, we provide excerpts from the integrative reflections and interviews that demonstrate criticality and its association with social forms of learning.

The domain of knowledge

Although a minority of students indicated in their final reflections that they continued to adhere to a black-and-white view of science as being purely objective truth-seeking, most students referred to changed understandings of the status of scientific knowledge or the rigidity of scientific method. These changes were regularly attributed to exposure to other perspectives during the class discussions, as in the following excerpt:

> During [this module], I have seen many different perspectives on right and wrong in relation to science, and have developed an understanding … that there really is no precise definition as to what 'right' and 'wrong' actually mean, in relation to scientific fraud or otherwise. It really seems to vary depending on the situation. (Student 7, integrative reflection)

Here, the student describes becoming critical of the idea of scientific absolutes, showing a criticality that goes beyond the level of her own knowledge, changing her understanding of the epistemology of the field. She explicitly links this development to the way the class structure exposed her to many different perspectives.

The following excerpt shows how discussions led a student to value the role of creativity in science:

> One of the final discussions we had in the course was about whether or not science required creativity, and this gave me completely new ideas to think about. I'd never really considered the role of imagination and creativity in science before, and I found it very interesting … To me … thought experiments represent the way some science can move forward before experimental data catches up, which I would consider parallel to artists painting a picture of an imaginary scene. It was one of my highlights in the course to hear people who had an almost completely opposite reaction to the comparison (Student 8, integrative reflection)

This excerpt shows that the student has come to understand science as a sequence of transformations of understanding, suggesting critique in the domain of knowledge at the refashioning and possibly even transformatory level.

For some students, the act of arguing led to a transformation in their understanding of scientific knowledge, including an embrace of its inherent contingency and of the potential that knowledge can and will be transformed:

> One such argument was of comparing art to science: when a new art work is created it is art but when science is created in can be wrong. The opinion of the majority was that a piece of art is still a piece of art whether people like it or not but when a new scientific theory comes along it could be wrong and discarded. This led me to a realisation that science is not 'black and white' as I argued desperately against the majority … Science is as much a work of art as art is an extrapolation of science. (Student 1, integrative reflection)

This student's critical enlightenment regarding the nature of scientific knowledge prompts him to action in the form of desperate argument against what he felt to be the hegemonic understanding of scientific truth of his peers. Thus we can see substantial movements towards sophistication regarding views of the nature and practice of science, development of criticality towards knowledge and even, occasionally, steps

towards critical action in the form of resistance, attributed to discussion and the opinions of others.

The domain of the self

All students in the three cohorts reported how exposure to other ideas and beliefs had led them to become more critical of their own thinking. For example, one student's final reflection included the statement that 'I understand my own stance far better now that the class discussions and debates have forced me to put a great deal of thought on matters that I once saw as black and white' (Student 9, integrative reflection). Another linked their improving capacity to make judgements to the discussions:

> Subjective opinion allows for creativity and ideas that become testable hypotheses. Opinion encourages discussion. In [[the course], by soliciting others' opinions, my own judgement was improved. (Student 10, integrative reflection)

Some students explicitly valued the variety of background knowledge that their peers brought into the class:

> I arrived laden with preconceptions, as did everyone else. I noticed this most acutely between myself and another classmate …who grounded many of his opinions in mathematics and physics. This is a considerably different approach to any that I could take, and I was surprised by some of the analogies he was able to draw. (Student 11, integrative reflection)

> … more powerful to me was the discussions, where people studying e.g. law or psychology (subjects I haven't studied) would bring up examples and ways of looking at a problem or situation that I would never have thought of. (Student 12, integrative reflection)

The key point here is not simply that our students recognised both the possibility of other perspectives, but that they genuinely appreciated this, rather than being troubled

by it.

Another student described becoming more aware of her own critical thinking processes:

> over the course of the writing and class discussions and forum posts, I learnt a lot about how I formed conclusions on a topic. I learned that I formed my opinions in many ways, and they never actually stopped forming. They kept on evolving, slightly tweaking, and these ideas came at very different times. They started out simple, naïve…then came some outburst, comment or a situation someone in our class would mention, the idea would get unsettled. Then, when on the can, walking to uni, or doing some other subject, I'd find a better way of putting it. Slowly, slowly, the ideas would grow more complex, more refined. And an opinion worth sharing would emerge.(Student 13, integrative reflection)

Here, we see an example of criticality in the domain of the self that is clearly at the level of reflexivity. However we also see several examples of criticality in this domain at higher levels. For example, the following excerpt shows how one student became aware of her own biases:

> As the course progressed I tried to be more discerning with ideas and evidence I accepted, looking more critically at things even if they were said persuasively, by someone more comfortable in their scientific identity. The effect of the discussions was complex and had a number of paradoxical outcomes. The debates often got highly polarised and tense, and I sometimes found myself really drained after the longer classes. This was on the one hand because some of the views professed were quite absolutist and inflexible … but it was also due to the extent of my own defensiveness … I often went into class poised to defend things from biology to the public, which was unhelpful, and perhaps said more about me than the debate in question. However, the polarised nature was also helpful as it exposed me to different perspectives and allowed me to either argue against them or see how both sides withstood a debate. In this way the discussions were like an informal peer review, a microcosm of the scientific method which helped me formulate and change my opinions along the way. (Student 2, integrative reflection)

In this excerpt, the student has recognised the unhelpfulness of her own stance in class to the furthering of her opinions about the status of biology among the sciences. She may not actively seek to transform these opinions, but is likely to seek to move away from an overly defensive stance, and it appears that she recognises herself as sometimes changing her opinions. This is a good example of criticality, in the domain of the self, at the level of refashioning. Equally clear is how this criticality emerged through discussion and debate – that is, as an effect of relational interactions with her peers.

Sometimes criticality spanned domains of both self and knowledge, as with this reflection on class discussions around paradigms:

> It did make me think deeper about what we were doing and whether we had a lot of paradigms assumed in what we were doing … how much of it were we getting the 'right' answer because we were asking the 'right' questions and channelling ourselves along the same thing? (Student 14, interview)

Here, a student's reflexive critique of her own and her peers' thinking leads to a desire to refashion that thinking.

In some cases, this criticality in the domain of the self led to a critique that might be considered as refashioning or transformatory – that is, to changes in how students saw themselves, their possible futures and their motivations. One student described how class discussion had led him to a transformed view of his own practice as a scientist:

> As a good science student, in several occasions, I have manipulated the data that I got from my laboratory practicals. I remember in a discussion session it was mentioned that there is no difference between scientists and us, in terms of being fraudulent with our experimental results. After a little bit of pondering, I realised that this was indeed true. All I had gained from such manipulations was me getting used to a bad science practice, and thus making my scientific training useless (Student 15, integrative reflection)

While this student does not explicitly expression an intention to change, his description

of his actions as rendering his scientific training ‘useless’ suggests he will refashion or transform his practice in future.

Other students described how the course had led to action in the form of changed academic directions, sometimes with the intention of changing their own experiences and sometimes with the intention of transforming the understanding of others:

> I think it was also a big influence in me changing towards more philosophy and art, because you don’t get given that opportunity in science … you learn things, instead of deeply think about them or think about what relation they might have to bigger picture things. (Student 4, interview)

> It really made me want to look at fundamentally why science is the way it is. That kind of threw me into a world of science communication … and how the public perceives science and where the disparities lie … I changed my major. (Student 3, interview)

In a related fashion, a student who had only recently changed to science from an initial arts major described how the class discussions had contributed to her growing self-confidence and a change in her identity as a scientist:

> Deconstructing science has not only helped me feel more comfortable with discussing science, as in our classroom context, but has also changed what it means to me as a discipline. My motivation to switching to science, was primarily to use it as a ‘means to an end’ … However I find myself thinking about pursuing science for its own sake … This is also due to my increasing understanding of what it means to be a researcher; from [the teachers’] own stories, to analysing the process behind journal writing. My scientific identity then, was not only being shaped with being able to talk more authoritatively about each issue by the end of each session, but by a change in my personal focus. Crucially, this helped alleviate the changeling or ‘interloper’ sense that I had in my other courses; I felt like I was actually sitting in the lecture theatres that I was supposed to be in. (Student 2, integrative reflection)

These last examples show how opportunities for social learning, and the emergence of criticality amid the relations produced between students, teachers and ideas, that had the potential to transform students' intended pathways and even their sense of self, resulting in critical action to take more control of their own futures.

The domain of the world

In the limited context of a classroom, there may be few opportunities to engage in transformatory critical action in the domain of the world. However, several students expressed views that indicated a desire to engage in such action, particularly in regard to changing the culture of science, or its role in the world. This was already hinted at in Student 3's comment above, where she indicates that she has embarked on a path of science communication because of what she perceives as disparities between reality and public perceptions.

Similarly, following class discussion, one student postulated that scientists are fulfilling a biological imperative to manipulate nature. This led him to a critique of science education:

> This however brings up the question, why isn't everyone a scientist if it is a biological imperative and the only answer I could think of to that question is the education system where science is taught as a block of facts that one must memorise, not as a way of obtaining that block of facts in the first place. (Student 16, integrative reflection)

Although not explicitly expressed in the excerpt above, such a critique may lead to a desire to transform current education systems. Similarly, one student was critical of the influence of commercial interests on science:

> Unknown to me before [this course], I became aware of how influential my mother's job in the health sciences was on my views regarding drug companies and

> commercial interests in science. Seeing her receiving free lunches, dinners, flights and gifts from various companies and industries, I was subconsciously critical of the tremendous waste of money. (Student 17, integrative reflection)

Again, in the limited context of the classroom there may be no room for critical action, but the judgmental tone suggests a desire for change.

The following excerpt from a final reflection shows a student becoming aware of an aspect of scientific culture that she would like to transform – an overly-strong reductionism – a critical stance she articulated and refined in response to being challenged in class:

> I do stand by the comment I made in the class discussions that purity and reductionism in scientific disciplines, particularly those with a higher level of maths, can tend to make people more closed-minded to the possibility of new ideas and changes in scientific thinking. Something I hadn't thought of that [Student 2] pointed out was perhaps that disciplines normally dominated by men; physics, engineering, maths, and to some extent chemistry are the ones considered 'hard' sciences whilst those with more woman; psychology, biology, science communication are the ones generally considered 'soft' (Student 18, integrative reflection)

Some students described becoming more aware of the social and cultural factors that influence how science is conducted. For example,

> Even discussing science in [the course] showed that science is a social activity, as it can spark conversations and discussions. Science is shaped by thought, history, beliefs and values, all of which are influenced by opinion. Culture shapes a scientist's approach to scientific problems, and they are further restricted as the values of their individual societies determines what topics will be financially supported. Scientists bring their own perspective to their work and bring subjectivity and opinion to their research – what topics they perceive as important, how they conduct their research and in their interpretation of the findings. (Student 10, integrative reflection)

Going beyond a transformed understanding of science, the following excerpt shows how a student came to see science itself as transformational:

> At the opposite end to cooperation, yet powering the growth of thought maybe more, are the arguments between scientists. Disagreement will drive scientific progress in a way that complacency cannot. Through the challenging and criticising of assumptions we are forced to reconsider our own thought process… conflict will widen our perspective and spur on advances that would otherwise have happened at a much slower rate. I came to these conclusions in the discussions of some particular noteworthy disagreements that have occurred … arguments can prompt critical reflection on the evidence we have and how it is interpreted, leading to greater fertility of theories. I believe this social aspect is incredibly important to what science is for these reasons. Science ignites arguments because people do become personally invested, their passions and creativity entwined with their work. Marx's macrosociological views highlighted to me that our humanity could be rooted in the acts of creation and discovery. (Student 15, integrative reflection)

Thus we see how critical discussions and interchanges contributed to emerging desires to act on and within the worlds of science and humanity, and to act so as to change.

Conclusions

The excerpts and discussion above show that first year science students can engage in high levels of critique of science, including in the domains of the self and the world, in ways that may not normally occur in conventional coursework or immersive research experiences. By taking a hyperopic view of their discipline and scientific research in general, they are able to deconstruct science and scientific knowledge. Throughout the data presented above, the importance of interactions and discussions among peers, and the telling of stories by texts, the course facilitators and peers, is evident. When given the opportunity, students easily and enthusiastically ascribed shifts, entrenchments, refinements and transformations of their understanding and sense of self to these

interactions and relations.

Whilst not all students exhibited such sophisticated levels of criticality, the data illustrate the importance of a social dimension to teaching and learning when trying to develop criticality. Such a dimension not only provides opportunities for students to be exposed to perspectives and beliefs that differ from their own, but also encourages the situation of disciplinary knowledge and practices within a wider world. We suggest that, if the development of critical being is a goal of higher education in science, it can be triggered and facilitated through courses and activities such as those described here.

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