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Conversations with Scientists and Science Educators: In Search of the Third Dimension

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ABSTRACT

We have argued that science in general, and scientific inquiry in particular, is a human activity and that current models to describe science (either as Scientific Method or as a Body of Knowledge) tend to underestimate the significance of human beings in the phenomenon. Our earlier paper (Bevins & Price, 2016) suggests a model to correct this imbalance which we call 3-Dimensional science. The current paper used the Storyline Method to look at the lived experiences of nine science researchers and educators for evidence of our third dimension (Psychological Energy). Results suggest that the key features of our third dimension are present, namely: a degree of autonomy, a sense of competence, and a relatedness to significant others. We suggest this further strengthens the argument for a more holistic approach to science education which celebrates these issues rather than simply a technical analysis of isolated teaching techniques.

Keywords: inquiry, nature of science, scientific method, science education

Introduction

Science is broadly-defined in terms of theories, facts and practises. The theories and facts can be described as a single dimension of science which we call Dimension 1 (D1). D1 contains facts (e.g. the melting point of sodium, the atomic weight of hydrogen) and potentially complex, ideally general, theories (e.g. natural selection, kinetic theory) that organise these into productive epistemic structures. Even though the exact contents of D1 are open to discussion there is general agreement, for example, that the melting point of sodium is 'in' while the names of the Kings and Queens of England is 'out'. Over the last 50 years, the growth in D1 has been significant with whole disciplines being created (e.g. the nature and management of genes). This growth in D1 is delivered and regulated by a set of practises that we describe as Dimension 2 (D2). D2 includes rules concerning the collection, and analysis of, evidence by scientific method typically involving generation of predictions and hypotheses which are tested through experiments. Increasingly D2 includes skills like networking and communication required to operate within the modern, global scientific community. In summary, D2 includes enabling skills (e.g. networking, communication), inquiry skills (e.g. control of variables) and mechanical skills (proficiency in specific laboratory procedures). The dimensions, although related, vary independently. It is possible to have a strong D1 (you might know lots of facts and theories) but be deficient in D2 (weak communication skills). Similarly, a strong grasp of the key skills of D2 may not always indicate strong grounding in D1.

Much of the discussion in science education has concerned itself, not always helpfully, with the emphasis placed on these two dimensions with 'knowledge-rich' tradition typically favouring D1 and the adherents of a more process-led approach emphasising D2 (Hmelo-Silver et al., 2007; Kirshner et al., 2006). However, even if the perfect balance could be agreed, the two-dimensional model only covers science as a disembodied, crystallised entity. It produces a portrait of existing science knowledge alongside a statement of the rules of engagement rather than reflecting science as it is practised across the world. We have argued (Bevins & Price, 2016) that a better model of science requires a third dimension. We call this improved model three-dimensional science or 3D science.

Three-dimensional Science

We have described our model for three-dimensional science in detail elsewhere (Bevins & Price, 2016) and so provide only a summary here. 3D science includes three dimensions;

- **D1 A body of knowledge**: this informs scientists' thinking about phenomena and can generate questions and suggestions for inquiry.
- **D2 Evidence-management procedures**: these ensure evidence is generated reliably, interpreted with reference to the underlying ideas and the observed data, and communicated appropriately.
- **D3 Psychological energy**: this provides the energy to create and manage a scientific inquiry.

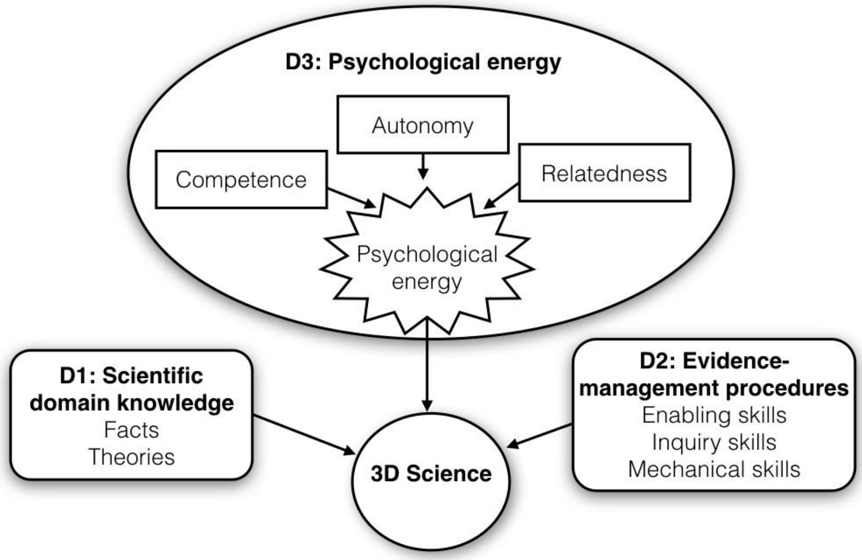
These dimensions have different natures and characteristics and do not link conveniently to each other in a simple sequence. One does not 'lead' to the other nor 'depend' on another in a strict linear sense. All are interrelated but only to the extent that they belong to a system that requires their presence. We have called this model a 'fruit salad' model in that the dimensions are as related to each other as the individual fruits in a fruit salad. They are all essential to the makeup of the salad, but apples are not like bananas and pineapples do not lead to oranges or grapes. The system is more than merely the sum of its parts even though the parts might be externally still recognisable. Figure 1 provides a visual summary of the components of our 3D model.

Understanding D3

Dimension 3 (D3) of our model provides the energy for scientists to operate the machinery of D1 and D2 to drive the further development of the scientific domain. A useful analogy might be to think of D1 as the written-down steps of a ballet, D2 as the ability to complete them through repeated, often formal, exercises while D3 is a feature of the dancers themselves that convert these written steps and practised movements into an actual performance that has meaning and integrity. Without the dancers there is no dance. This sees D3 as a feature of the active scientist, their motivation, commitment and sense of purpose, which drives their engagement. D3 varies from low engagement with limited personal purpose (low energy), through to a clear personal purpose and engagement (high energy). We feel that the 3D model offers a number of advantages when thinking of scientific activity and we describe these in the discussion section that follows.

Figure 1

The 3D Model of Science



Self Determination Theory's (SDT) and the Third Dimension

We draw on Self Determination Theory's (SDT) treatment of motivation (Deci & Ryan, 2012) to inform our understanding of the nature of D3. As Deci and Ryan (2006) explain: "it (the motivation to act) must be endorsed by the self, fully identified with and "owned"" (p. 1561). The endorsement requires a degree of autonomy in the actor since something that is forced upon them cannot be 'owned' - it is, by definition, an imposition 'owned' by an external. Similarly, a person should also feel a degree of competence in the task; in effect the task is appropriate for them and their skills - there is a 'good fit' between act and actor. Finally, the task must in some way be valued by others who are significant for the actor. This is the notion of relatedness central to SDT's understanding of motivation.

Why Another Dimension?

We understand that our use of the 'third dimension' can cause confusion as we are not the first to use the term. The Next Generation Science System (NGSS Lead States, 2013) in the United States talks explicitly of 'three dimensional science', although they mean a particular subset of generally applicable concepts like 'patterns', 'cause and effect', 'structure and function' or 'stability and change' by the third dimension. These are valuable ideas that share some similarities with the concepts of evidence (Gott et al., 2008) and identifying a separate 'third dimension' for these concepts is a useful way to draw attention to them. However, our model assumes they fit more naturally in Dimension 1 where they can impact and inform some of the activities in Dimension 2.

It is important to show how our third dimension links into existing discussion around the 'Nature of Science' (NoS). The understanding of the NoS is not fixed, showing a shift from the notion of science as an external, logical process of justification, producing objective, value-free knowledge to the recognition that all observations are, to some extent, theory-laden (Khalick & Lederman, 2000). An understanding of the NoS is an essential part of science education, particularly with relation to the development of science literacy (Archer & DeWitt, 2016) for citizens and the ability for them to engage with important socio-economic issues raised by technological advances (Tala & Vesterinen, 2015). A review of the elements of NoS in teacher education courses is shown in Table 1 (Noushin et al., 2021).

Table 1

Elements of the Nature of Science (NOS) Covered in the Teacher Education Programs

	Example of NoS Elements covered in the teacher education programs
1	Scientific knowledge is based on *empirical* evidence.
2	*Society and culture* influence each other with respect to science.
3	Scientific investigations are influenced by theory and by scientists' backgrounds, and therefore, *subjectivity* is part of science.
4	*Creativity* plays an important role throughout scientific investigations.
5	Both *observation* and *inference* are important in the construction of scientific knowledge.
6	Scientific knowledge is durable yet *tentative*.
7	Science uses *shared methods* and there is not a single scientific method.
8	*Scientific theories and laws* serve very different and not interchangeable functions.
9	A scientist works within the *scientific community* to evaluate and contemplate the work of other scientists.
10	The evidential part of science is strongly advanced by the *technology* available at the time.
11	Science and *religion* are different ways of knowing.

While the NoS elements may not concern themselves with the melting point of sodium or the theory of evolution, they are claims based on evidence in the same way as Newton's claim that for every action there is an equal and opposite reaction. They are a valuable part of science and science education but they do not require a new dimension - they can be accommodated with Dimension 1 in our model.

Reviewing issues concerned with the teaching of the NoS, Bell (2009) identifies three domains which contribute to the creation of science, these are a body of knowledge (equivalent to our D1), a set of procedures (equivalent to our D2) and what he calls 'a way of knowing'. The 'way of knowing' includes a set of statements (e.g. 'Scientific knowledge is based on evidence', 'Creativity plays an important part in science' which help to describe science as it is practised). These statements give rise to a set of what he calls 'key concepts' (e.g. the tentative nature of scientific knowledge). Taken alongside the other domains these concepts describe the NoS. Again, these can be sufficiently described in terms of concepts and procedures, although these concepts and procedures may not, at first glance, appear in traditional content lists for science courses or be unique to science.

A Testable Claim for D3

In comparison to NGSS' third dimension or even the material on the NoS, our D 3 is not a selection of valuable concepts, insights or attitudes or even habits of mind (Gauld, 2005). It draws on many of the concepts mentioned in the discussion of the NoS and will be manifested in some of the activities that fit easily into D2. Our D3 is concerned with the psychological energy to drive the processes of D2 which generate, and apply, the concepts of D1. In physics education, energy is a notoriously difficult concept to teach, perhaps because the many 'forms' of energy (e.g. sound, light, heat) are not energy itself but are the *effects* energy creates as it transfers within and between systems. The energy itself is invisible. In the same way, our psychological energy is invisible but manifests in activity, and in the context of science this means scientific research. Again, as in physics lessons, a key issue for energy is where it comes from and what happens if the supply runs out? The energy that resides in D3 comes from the individual scientist and we explain below how Self Determination Theory has helped to inform our thinking on this. A collapse in energy supply (D3) means scientific research stops; the body of knowledge (D1) remains intact but static, the skills and procedures (D2) pristine, but unused.

So, if D3 is both real and necessary for a complete description of science, we should be able to find evidence of it in the way scientists describe their scientific activities. Our model predicts that when there is clear evidence of all three dimensions present the scientist should be engaging in work that is demanding but rewarding, objectively significant and personally satisfying. A gap in any of our three dimensions should inhibit this productivity. This provides us with a clear testable claim which we explore in our data collection: if people are actively engaging in scientific activity there should be some evidence of their D3 needs being met.

This claim generates two related research questions:

- Can we find any evidence of D3 needs being met in scientists' accounts of their educational careers and professional lives?
- Is there any suggestion that D3 is not merely helpful but essential, i.e. when D1 and D2 needs are met but D3 is absent does the science slow down or stop?

To explore the experiences of scientists over their lives and to look for evidence of the three dimensions we developed an approach using Storyline method (Beijaard et al., 1999)

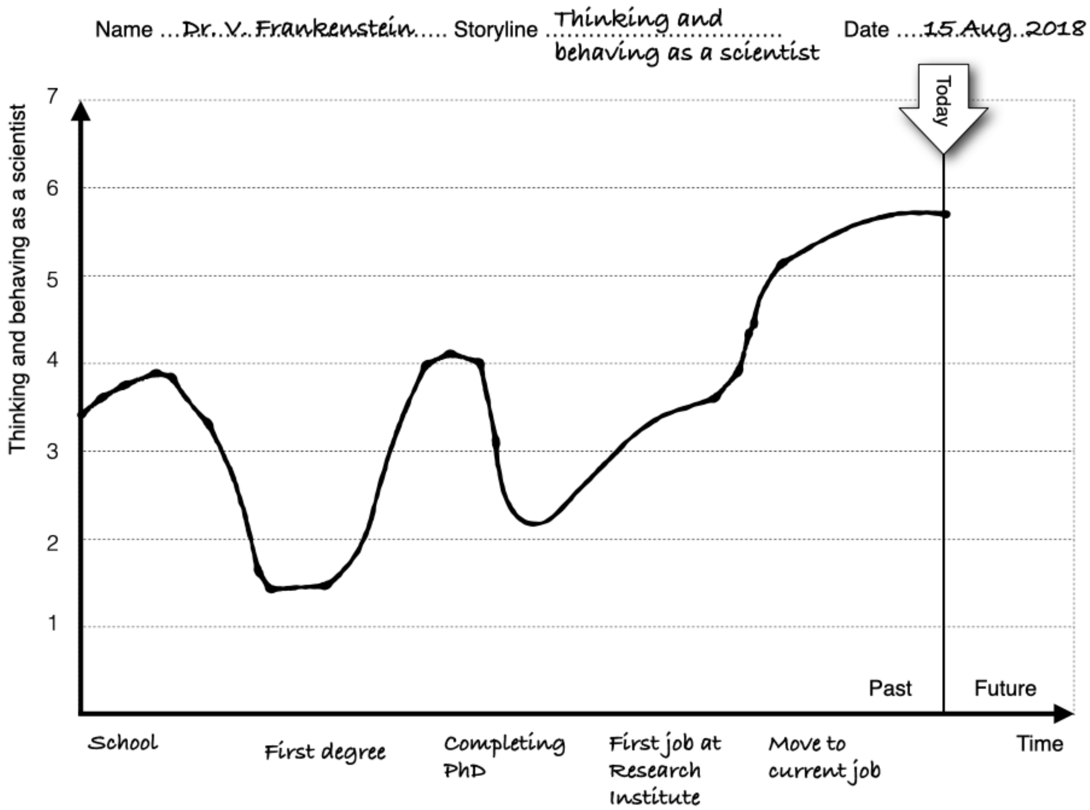
Methods

We used the storyline method (Beijaard et al., 1999) to stimulate and frame conversations with practising scientists. The participants were given a chart containing a pair of axes with the present day fixed at the far right of the x-axis. Each participant was then asked to score their current level of 'thinking and behaviour as a scientist' and mark it on the line labelled 'Today'. They were then asked to draw a line backwards through time showing rises or falls in their scientific activity. Labels could be added to the x-axis to identify significant events or periods. Figure 2 shows a typical storyline plot.

Once participants completed their storylines, we engaged them in a conversation to explore reasons for these rises or falls. This focus on their own story places the participants in a relatively powerful position and, from experience, they are both motivated and skilled in their analysis as they explore their understanding of what behaving as a scientist means to them.

Figure 2

An Exemplar Completed Storyline Form



Data Analysis

Each conversation was audio recorded and transcribed. We used thematic analysis (Braun & Clarke, 2006) to identify patterns and themes within our transcriptions. Themes represent something important about the data related to our original research focus (e.g. the factors impinging on their lives as scientists) and provide some level of meaning (e.g. obtaining research funding, designing an experiment). The three dimensions became our superordinate categories in which we housed themes. The transcribed conversations were read and re-read as we developed notes prior to agreeing on themes to be placed in each superordinate category. Throughout this process we engaged in reflective discussions to ensure the specifics of each theme appropriately represented a feature from one of the dimensions. This 'theoretical' approach framed our analysis in contrast to a purely inductive approach more typical of Grounded Theory (Charmaz & Belgrave, 2015). Thus, by asking the participants to explain what they meant when they said they were 'acting as scientists' we could analyse their perceptions of the nature of science which in turn, allowed us to identify references to the three dimensions that we claim our 3D model of science presents (see Table 2).

Sample

We identified eight scientists (three female, five male) from India and the UK, working at university level, who had experience as practising scientists and educators. The participants formed a convenience sample (Etikan et al., 2016) and were identified through ongoing project links.

Table 2

Indicators of the Presence of the Dimensions

D1: Scientific domain knowledge	D2: Evidence-management procedures	D3: Psychological energy
References to scientific domain knowledge (D1's facts and theories). Conversations should also emphasise increasing levels of scientific understanding (e.g. new subjects, higher levels of treatment).	References to practical work (mechanical skills are part of D2) but also the notion of designing experiments, the 'control of variables strategy' (Schwichow et al., 2016) which appears in D2 as inquiry skills and working in teams (D2's enabling skills).	References to having a degree of control over the work both in terms of its purpose and implementation (autonomy). This offers the option to engage and develop it because it is in harmony with the scientists' views, values, and perceived abilities (competence). There will also be references to significant others who have contributed to the scientists' choices (relatedness).

Ethics

Each participant was briefed about the research purpose, potential outcome and dissemination. They were informed that all data would be anonymised and stored on an encrypted drive within the university. All participants were made aware of their right to withdraw from the research at any point and that their data would be destroyed immediately. Consent forms were gathered from all.

Findings

This section describes the interviewee's understanding of the nature of scientific endeavour based on data gathered through conversations and storyline graphs. Background information not directly related to science (e.g. family history, strong peer group friendships) from the interviews is included where relevant. Reproductions of the storylines drawn are included with markers [numbers in square brackets] to indicate where during the interview a particular point was emphasised. We also offer specific quotes with the relevant timecode. The data are presented by individual conversation and general observations covered in the discussion section which follows.

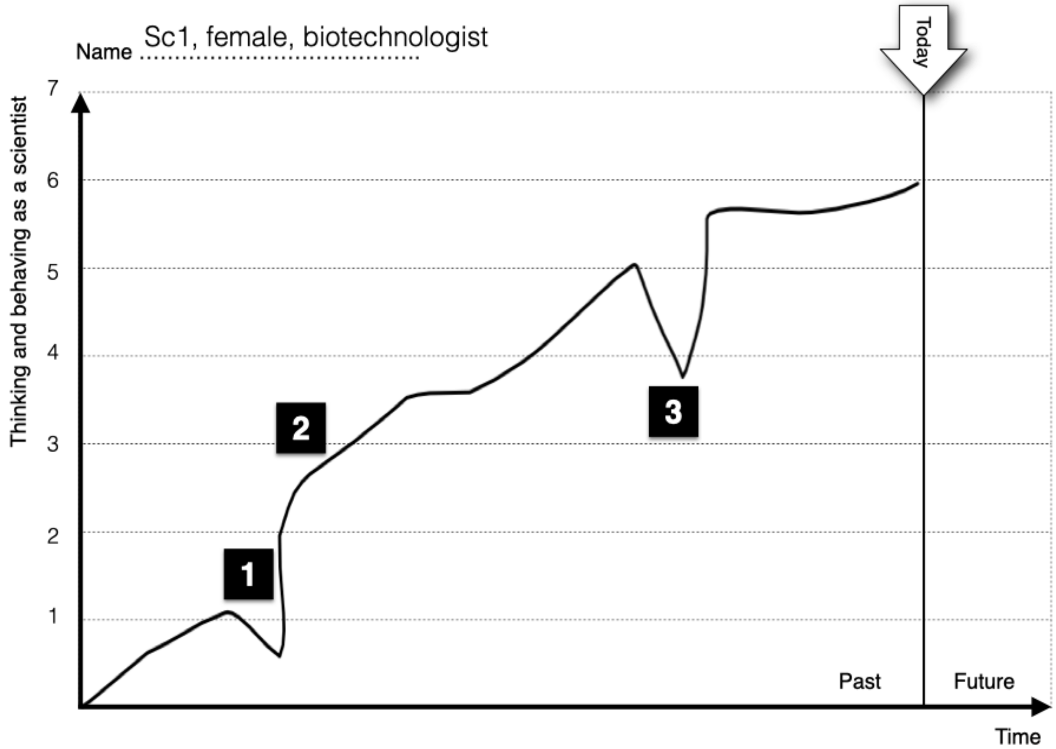
Sc1, Female, Biotechnologist

Much of Sc1's conversation concerned her experience of learning and little was positive, the first dip on her Storyline [1] was as she entered college (age 18), where science was being taught in a very didactic manner:

basic biology was very good but mode of learning was not … (Sc1/ 9:52)

Figure 3

Sc1's Completed Storyline Form



Afterwards she joined a new course that involved much more practical work and decision-making by the students [2]. The references to 'practicals' and 'we were doing it ourselves' correspond to D2 while her personal involvement in the process (D3) is clearly referenced in her explanation that when they made mistakes they felt bad about it:

> In our Masters we were given a lot of practicals to do… a lot of exposure to hands-on training. The teacher would not demonstrate the practical…we were doing it we were making mistakes and feeling bad about it. (Sc1/12:50)

The centrality of practical competence (D2) was emphasised in talk of 'good hands' (practical skills) which she enjoyed (D3):

> In scientific research people say that she or he has very good hands … technical hands … so a lot of technical skills were imparted to us … which we enjoyed. (Sc1/13:02)

However, the lab activity began to pale as it became more repetitive and focused around a small, technical problem. She explained that she was not happy finding an unknown protein and working on that for the next ten years. She talked of work becoming a mundane trudge for more data. This disenchantment with the routine of lab work produced a significant fall in her storyline trace [3]. In these comments we see the effects of a relatively low D3 - Sc1 had felt purposefully involved and doing something of substance early on in her career (high D3) but as the work became more mundane and repetitive (low D3) it lead to her leaving the profession and moving into a full time teaching role.

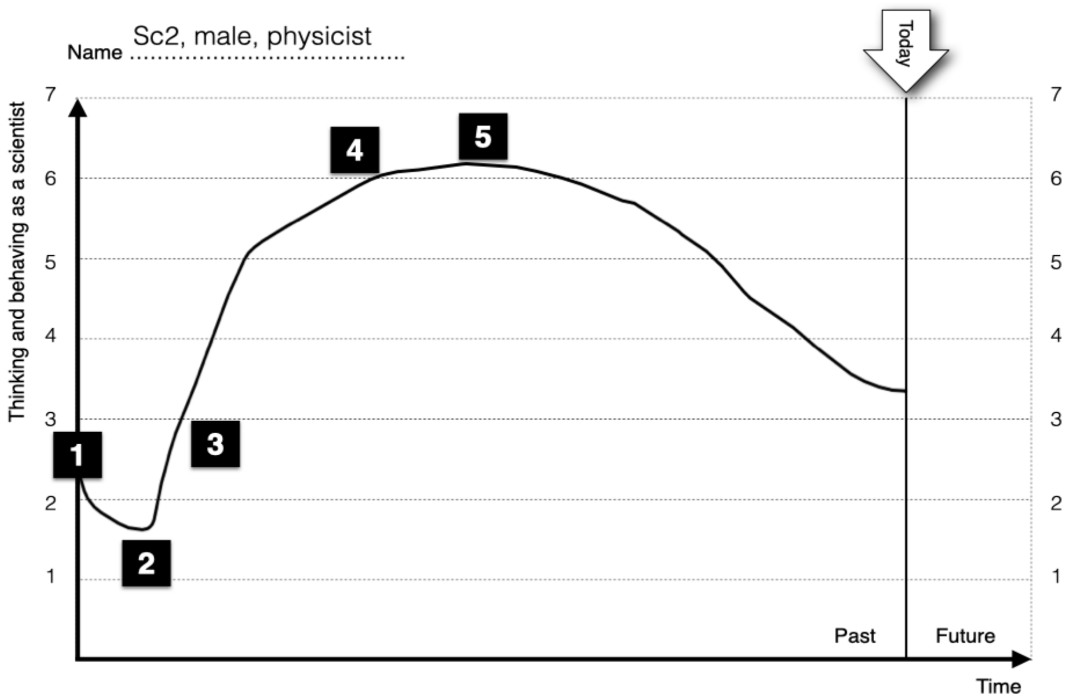
Sc2, Male, Physicist

Sc2's obvious warmth when recalling his friendship with other students at his school [1], who were also interested in science, resonates with D3's emphasis on 'relatedness'. The subsequent lack of similar enthusiasts at first degree led to a fall [2] in his feelings of being a scientist:

> I was very unhappy with that (no friends who were similarly enthusiastic) … during my BSc … even the teaching methodology was more memory-orientated than problem-solving … that was very disappointing (Sc2/9:23)

Figure 4

Sc2's Completed Storyline Form



The situation improved dramatically during his MSc [3] where the emphasis was on him personally taking the initiative to solve problems - another aspect of D3:

> There was no memory-oriented tests it was all problems … so, the teacher will teach you concepts and you'll work on it, try to understand it more on your own and the exams would be completely new problems. (Sc2/10:00)

He described his BSc as 'training to do science' not 'doing science', whereas in his MSc work and post as a Project Assistant [4] he was working with new ideas, (D1) exotic materials and lasers (D2). There was a strong sense that high levels of domain knowledge at the edge of evolving theory (D1) and the use of complex equipment and sophisticated techniques (D2) were essential for his sense of 'being a scientist' [4]. The peak of this storyline was during his PhD [5] when he had much more personal control (D3) over his work. Sc2 reflects the experience of other participants who felt that they can only do what many call 'real science', in distinction to merely following instructions, when they have control (D3) of their work during their PhD years or when working on a project with a team that can make its own decisions. Typically they will also be deploying sophisticated skills (D2) and using complex ideas (D1) at this time.

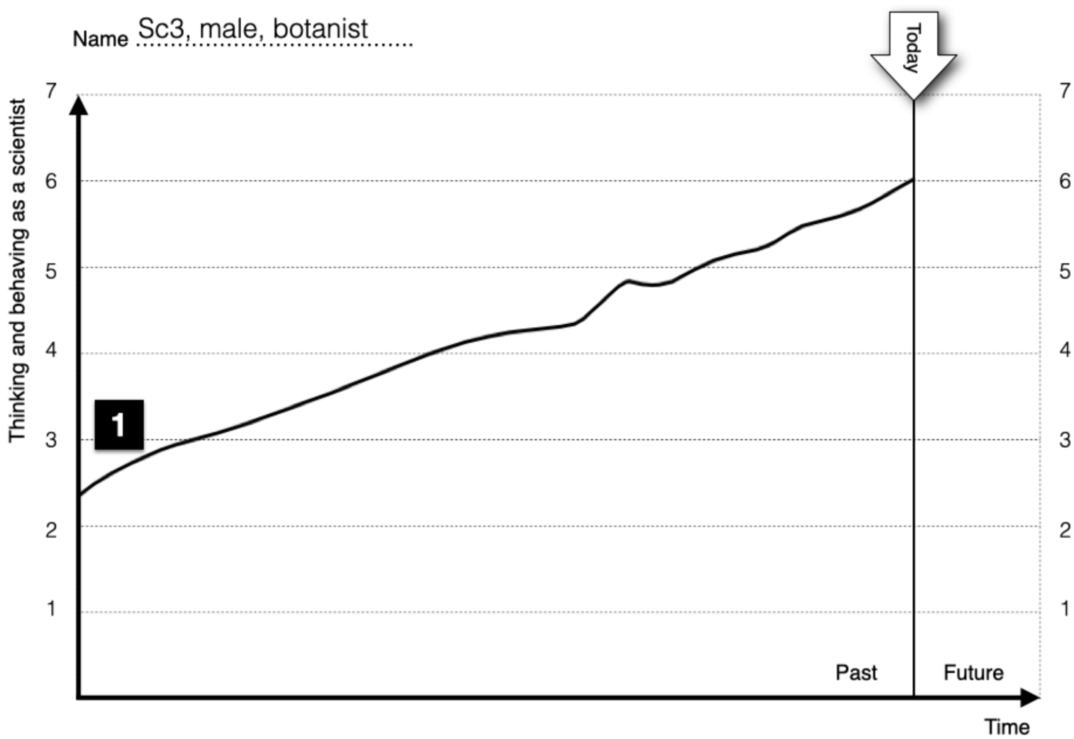
Sc3, Male, Botanist

Sc3 discussed his choice to become a research scientist in terms of finding solutions to 'help society' [1].

> That was a time when I had to decide if I was going to continue with my higher studies or if I was to go for a job. … I decided I could continue and look for certain problems and solutions which may help society itself. (Sc3/2:15)

Figure 5

Sc3's Completed Storyline Form



He explained scientists as people who find solutions to societal problems - because they are able to think systematically and scientifically:

> I think it was thinking as a scientist … you have to look at the problems in a scientific manner…they can be solved in a better way…in a scientific manner. (Sc3/3:07)

These two anecdotes contain evidence for D2, 'looking at the problems in a scientific manner' but also show a strong involvement of D3 in talk of doing something to help 'society itself'. The importance of working in a way that makes a contribution to a range of people (SDT concept of relatedness) is strong evidence of the existence of D3, referenced again later in the conversation:

> I thought that was necessary for the survival of everyone on this planet because if you do not work in a scientific manner the system may collapse. (Sc3/5:15)

Returning to the issue of the gradual rise in his storyline trajectory we asked what was different in his 'scientific thinking' at 16 years of age and now that he was 20 years older. His response was of a gradual increase in knowledge and skills - developing D1 and D2:

> I think its the constant learning…because when I was at school I was not exposed to many things there…I think its the exposure… how you have been exposed to problem-solving capabilities. (Sc3/7:18)

He saw his progress in terms of being more autonomous and more 'self guided' (Sc3/11:49) and when he added this to his storyline he claimed this extra capability developed during his MPhil and subsequent PhD studies.

Sc4, Male, Biologist

Sc4's storyline covered his whole life which gave him a chance to describe the difference between knowing 'how science works' (D2) and a sense of science as an approach to life in general, which he referred to as 'scientific temperament':

> I am a teacher, I am post-doc who knows how science works. I do know the components that some sort of observation is there, then we do have some sort of hypothesis…we do test these things, and then we draw some conclusion and theory. (Sc4/6:50)

However, his personal curiosity, and drive to ask questions, which seems more like D3, was also active. He makes this clear when he compared his PhD [2] with his preschool life [1], where he knew none of the mechanics of scientific method, but felt he was much better at thinking like a scientist:

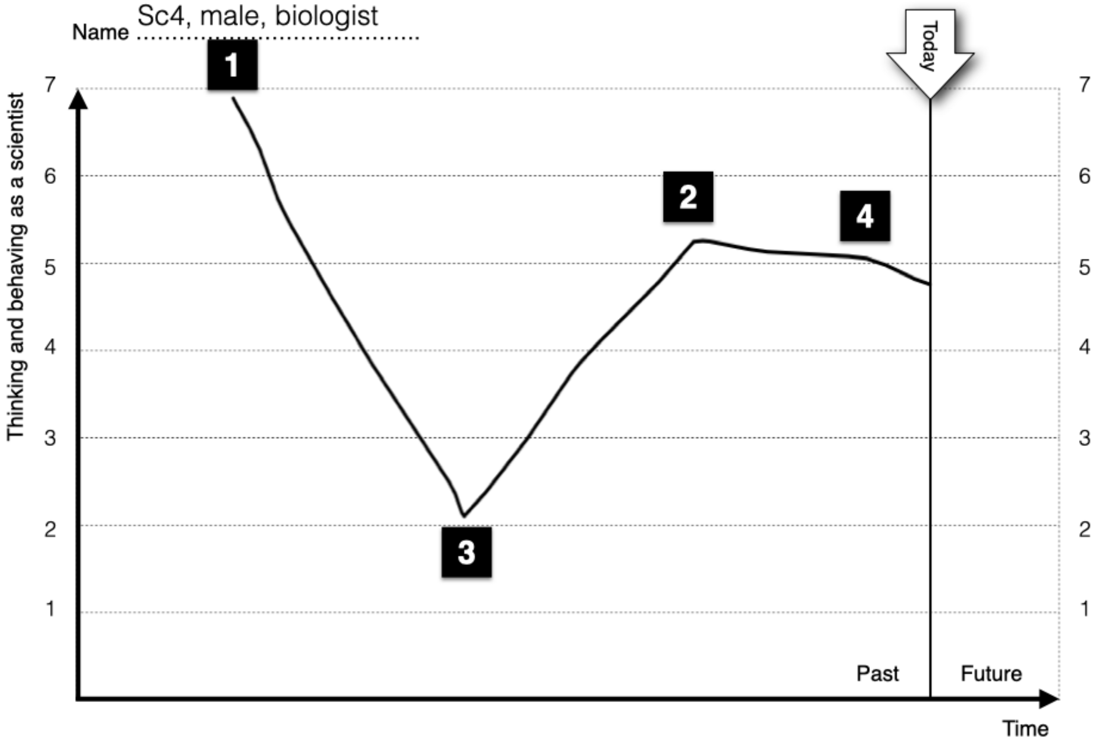
> If I compare this phase [2-4] to preschooling or the first five years of my life it was not taught to me these are the components of science as such…my observation power was more. I was questioning each and everything, no matter what resources were available or not but I was testing it right? (Sc4/6:57)

He made this distinction between knowing technique and intrinsic curiosity very clear with the statement: "It was not a formulated science but I was doing it." (Sc4/7:23) Since Sc4 recognised the attitudes of science in himself even prior to school it might have been hoped that when he went to school the formal rigour of scientific method would increase his ability and opportunity to think like a scientist. In fact, as he explained, this went down dramatically:

> When I came to the schooling phase [3] it dropped down tremendously because I was not given or provided that autonomy to think or question things….It dropped off because what has to be taught was fixed and how it has to be taught was also fixed so there was no autonomy for me so I stopped questioning. (Sc4/8:01)

Figure 6

Sc4's Completed Storyline Form



Significantly when Sc4 felt his autonomy (D3) was denied he did not feel he was behaving like a scientist. Indeed, much of Sc4's conversation suggested that science was an attitude of mind, he called it a 'scientific temperament' which revolved around making observations, asking questions, and trying things out without fear of censure in a methodical and organised manner (D2). His complaint about school science was that it offered no chance to question. Here he draws a distinction between a technician who follows procedures designed by others and a scientist who has the right (D3) and capability to ask novel questions and explore ideas and fields that are personally important to them:

> If you don't have the capability of observing, questioning, and analysing I don't think that person can be a scientist. There's a difference between a technician and a scientist I think. (Sc4/13:24)

During the last few minutes of the conversation he remarked about the slight fall in his scientific research as he took on more responsibility for teaching [4] - a common remark amongst other participants indicating a degree of loss of control of his personal timetable (D3).

Sc5, Male, Botanist

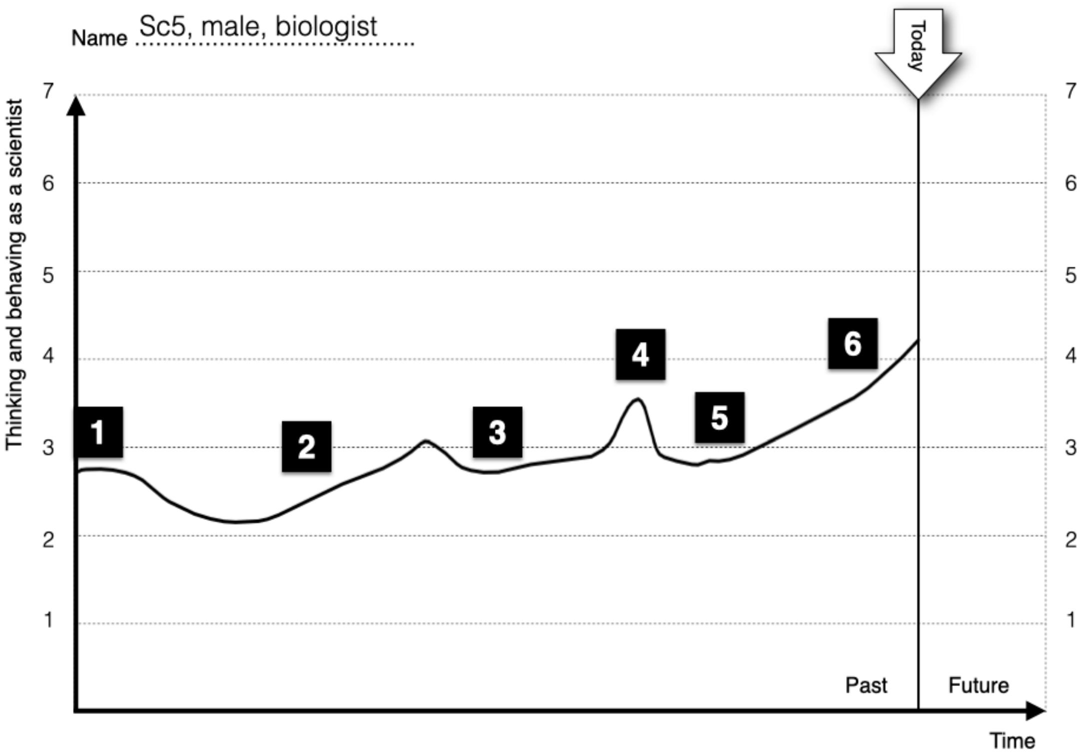
Sc5 started his conversation with his personal history:

> My parents are involved in agriculture…he (his father) would always tell me 'mangoes come this season' and I would ask him 'why? Are there mangoes which come in all seasons?' So this type of behaviour was there when I was young [1]. So he would get different types of mango plants and say 'Let's see which one comes first' and then the first ones would not be

> tasty … that would make me wonder why these ones were not tasty but after rain they get tastier. (Sc5/5:00)

Figure 7

Sc5's Completed Storyline Form



Sc5 equated inquiry with curiosity and asking questions - with a real purpose behind the questions - even if only for a good supply of tasty mangoes! Notably his father helped him as he tried to grow different types of mangoes. His school also seemed supportive:

> …this kind of thinking (questioning and experimentation) was there. So it would connect to us when school projects [2] were made and then you could very easily take five mango plants and explain in school why this is sour and this plant is sweet. (Sc5/5:30)

Sc5's storyline shows only a small increase over time - largely based around original research. In his comments it is possible to see D2 (trying different mangoes and testing a hypothesis about mango and rains) and strong D3 (his supportive father providing a powerful 'relatedness', while his school offered options for projects) at his earliest age. The preparation for university [3] was more fraught with greater emphasis on D1 capability (the main feature of the assessment systems that controlled his entrance to university) coinciding with less laboratory work (D2) and, to some extent, others setting his career goals (low D3):

> So, the push (to agriculture) was good by the parents but in that time they (the schools and university-preparation institutions) were giving me no hands on in the lab. (Sc6/7:14)

In university [4] he spent more time in the lab (D2) and working on projects that were important to him. He got in well with his supervisor who was active in research. This illustrates an aspect of D3 - the need to work with significant others, the SDT idea of 'relatedness'. He explained any small dips in his storyline [5] by 'other pressures', he implied the need to complete assessments (including practical assessments) and exams, interfering with his time to do research in the lab:

> Inquiry was still there in terms of what you were doing (in the lab) but not something you would necessarily enjoy doing in terms of subject (the background knowledge and 'textbook work' he had to complete to gain his final degree). I am given a problem where I know I will get the result but in research I feel you have to take a topic and search for answers and not be given them. (Sc5/9:11)

The distinction he makes between lab work and constructed problems that are 'just a test of technique' and research emphasises the centrality of D3 in his feelings about behaving like a scientist. Lab work (D2) alone is insufficient, there has to be an element of autonomous control (D3) if the activity is to be real 'research'. When asked to explain this he again identified the notion of 'constructed' work by which he meant activity where the key decisions had already been made:

> Because my research here was all constructed. I was told 'this is the parameter. This is the variable. (Sc5/15:17)
> But there was a time when we were just told, 'this is it. You are just doing this. This is your spectrophotometer. I give you the samples. You're processing this. You're giving me the results. So most probably I was mostly a technician. (Sc5/16:00)

This did not feel, to Sc5, as if it was research. The missing component appeared to be D3 - the chance to engage as an active researcher pursuing his own agenda rather than simply following instructions from others. However, he did claim that his position at university now allowed him some responsibility for driving research projects across his department, more widely shown as a rise in his trace [6]. This was unusual as most interviewees reported a fall in research activity as they were embedded in the day-to-day work of university teaching.

Sc6, Female, Chemist

Sc6's storyline shows a significant jump in her ability to think and behave as a scientist when she took a job in a professional pharmaceutical lab [1]. She explained that at A-level (a 2 year course followed in many UK schools prior to university) [2] she was learning *about* science and mainly D1 whereas in her job she was actually thinking and behaving like a scientist. When asked what 'thinking like a scientist meant' she explained:

> Thinking like a scientist…well, I'm looking at what is in front of me in the lab, thinking about why it's happened, what I need to change to make it happen the way I want it to happen… or what's gone wrong … um any other different ways I could get to the same result… or experienced colleagues that could contribute to the experiment. (Sc6/5:00)

When asked if she had done any practical work in school at A-level she said 'not really' and when further questioned about her A-level lab work experiences she was clearer:

> I wouldn't count that (practical work at A-level) as 'being a scientist' because it's very much following a recipe…knowing what I now know about teaching , it's very much following a

> recipe…and that's very different (to science)… science is very much unknown territory. (Sc6/7:42)

Her A-levels emphasised D1, the content required for passing the examination, and D2 in terms of recipe-driven practical work. Only when she reached the professional lab did she experience the range of D2 and any aspect of D3 - a chance to engage with significant others in a task that involved her making a contribution to a real research project.

The Storyline then jumped downwards [3 to 5] which corresponded to changes which reduced her personal control including routine work and teaching and [5] when she took time out to have children:

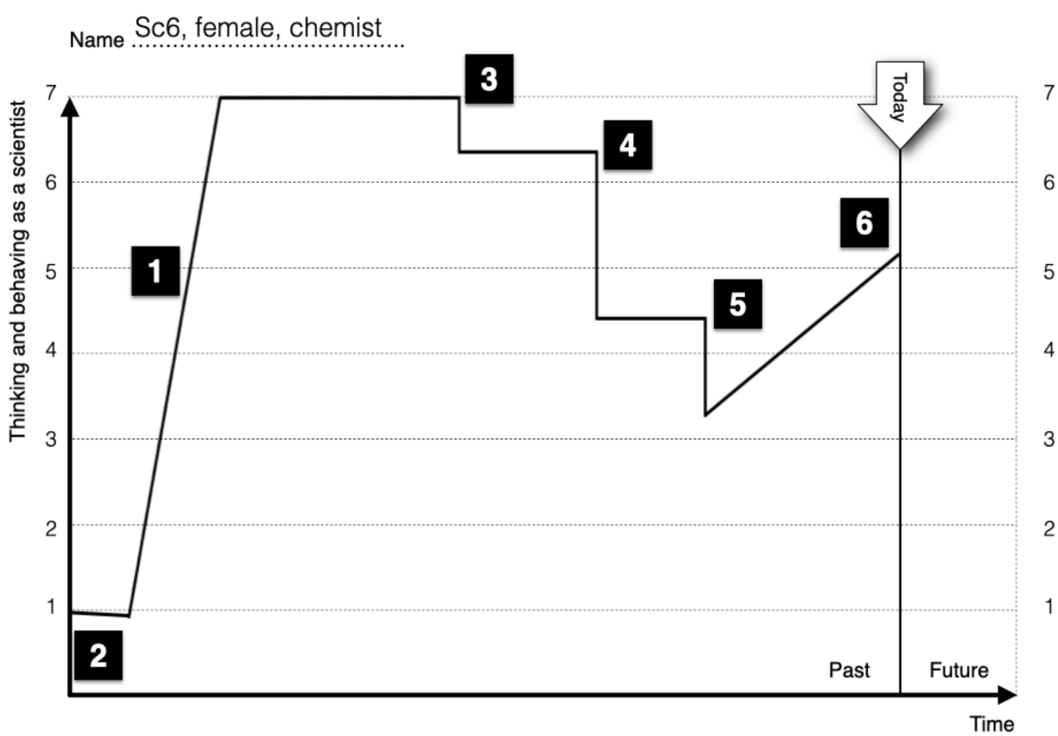
> I was very much on a treadmill of routine analysis and though I did have to use my brain … most days… but sometimes there were times when I just had to tap numbers into computers and things like that …so it drops off there … [3] (Sc7/9:00)
> I got a lectureship … and my priority there became teaching, preparation of teaching, assessment …getting to grips with that type of role and my research, what I call the real science, my research, dropped off to almost one day a week. [4] (Sc6/9:35)

When we asked what she meant by 'real science' she explained:

> Real science is trying to find answers to things broadly…or finding the methods, new methods to find answers to things. (Sc6/10:30)

Figure 8

Sc6 Completed Storyline Form



She went on to explain that she was not really doing any 'real science' - that had been delegated to her students:

> At this point I'm thinking the only science that is happening here is in my … three PhD students. (Sc7/10:45)

Clearly, she feels limited at this time [3 to 5] because her personal opportunity to do 'real science' directly (i.e. conducting the research *herself*) was limited not by D1 (she is at the peak of her field) or D2 (she has contributed to significant laboratory projects) but because her autonomy (D3) has been severely reduced by the time demands of management. However, as she reflected further, she saw herself acting as a 'consulting scientist' by which she meant that she was involved, admittedly at one step removed, from the physical research by offering high level and strategic advice and support to her PhD students [6] playing to her strengths in D1, D2 and D3 explaining the rise in her storyline trace.

Sc7, Female, Physiologist

Sc7 was keen to be a scientist from an early age influenced by a talk given by Heinz Wolfe at her school. Sc7 described her home as being supportive with high expectations. This illustrates a significant feature of D3 in science. To opt to become a scientist, a decision often taken at a relatively young age and largely mandated in the UK prior to age 16 where choices about A-levels can effectively rule out later ambitions to pursue science, involves issues of personal choice (autonomy) that includes emotions, values and a sense of self. In the case of Sc7 the significance of important others (relatedness in SDT terms) was clear. Interestingly, she was not obviously 'good' at science - she volunteers that at school she was only tangentially involved in the practical work central to D2:

> I went to a really awful school [1] where girls weren't really encouraged to do science … I was in a physics class with 5 girls and 35 boys and we weren't allowed to do experiments because we were girls. But sixth-form college was very different, much more academic so that's how I managed to get to university. (Sc7/4:52)

However, when she arrived at university [2] the disappointment was considerable:

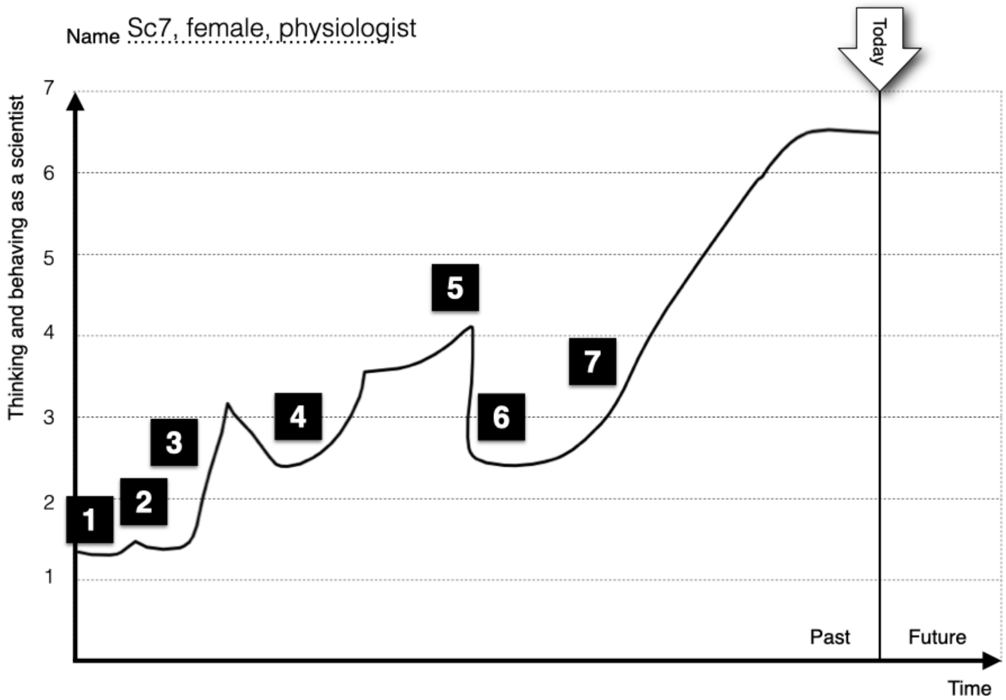
> I found it (the university course) the most boring thing on earth. I did biochemistry and I remember sitting in the first lecture, I was so excited to go to university and it was so boring and I just thought … "Oh no! Why am I here?". (Sc7/5:40)

Again, an event with clear D3 references changed things. She found herself working in a lab [3] and 'doing research' with people who she valued and who valued her:

> I really scuffed my way through university until I got to the final year and then … you had to pitch for a final year project and I applied for the professor's project … so I ended up in the PhD lab and it was fantastic! Doing research and it was amazing! And I just thought "This is what it's all about!" And I went from being bottom of the class to getting a 2:1. (Sc7/6:08)

Figure 9

Sc7 Completed Storyline Form



After graduation she got a job as a part time technician [4] and was later asked if she would like to do a PhD. Her research explored the immunological basis for recurrent miscarriages and eventually produced a significant contribution to knowledge and a step towards treatment for this condition. This was significant and important work that matched her skills and her values showing clear D3 links. At [5] she took some time out to have children. Over subsequent years, a teaching post at a university [6] led to research opportunities [7] and then supervision of PhD students until she was running a department with her own research grants. At this point she was acting as an advisor in a range of research and teaching projects. This fed D3 in terms of the personal significance of the work (she chose to do this) and the value ascribed to her work (D3 competence) by significant others (D3 relatedness):

> The Head of research encouraged me to apply for some funding for a PhD student …so I got that student and she was successful and then I acquired another one … and another one … and then I got a grant … and then because I'd now got people in the lab and because I was becoming more senior I was seen as someone who knew how to do it and so other people invited me to be on their supervisory teams… I now spend most of my time thinking like a scientist … both in my teaching and my research. (Sc7/14:52)

When asked if her teaching interfered with her research she was clear: 'most of my psychological time thinking about research' (Sc7/16:40). She talked about mentoring her PhD students, reviewing papers for a journal and analysing data for an internal project at the university as examples of her 'thinking about research'. She explained that her brain was 'always thinking about analysis really' (Sc7/19:08) which she equated with 'thinking scientifically'. Most D2 references amongst other interviews were to practical work, whereas, in Sc7's case, she was doing no practical but working with others in terms of the aims, variable control strategies, and interpretation of the results rather than handling the equipment. However, when asked to talk about the time, early in her career when she was working in the PhD lab in London [3], and why she felt that was a time of growth in her thinking as a scientist she was clear that it was not simply about control of variables (D2). The references to personal autonomy and the opportunity to make decisions (D3) are very clear:

> It was weird … it's a combination of fun as in, the PhD students were having such a laugh, they were just enjoying doing science so much. They were working really hard … get in really early and go home really late and what they were doing was really complicated, interesting and complicated. Whereas all my experience of lab classes up to then was essentially cooking …. essentially taking ingredients, putting them in a pot, heating them up and seeing what happened and, you, following a protocol is not exciting. (Sc7/20:10)

Sc8, Male, Chemist

Sc8 recognised very clear threshold points related to growth in skills (D2) and personal autonomy (D3) concerning an 'independent research project':

> 'There are very definitely threshold points … some of the more significant ones were at the start of my degree [1] … I did a four year integrated Masters program, I think the first two years were very different to the second two years and so Year 3 [2] was a big step up in scientific methodology because we got to do an independent research project during the third year of my degree. That made a significant difference. In the fourth year [3] we did a larger scale independent project so again that contributed largely to that development which was built on during the PhD. (Sc8/2:58)

Returning to his years at A-level [4] he complained that they were stressful and did not contribute to his developing as a scientist because of assessment pressures:

> A-level was mostly targeted at exam performance, so there wasn't much scope for designing experiments, testing hypotheses…seemed to be a lot of practising for the exam questions. (Sc8/5:08)

He found that at degree level there were changes, in both educational philosophy and educator desires, towards encouraging students to develop their own ideas (D3) and 'the thought processes of a professional scientist' (Sc8/5:58). When asked what these 'thought processes' are, Sc8 was very clear and provided a summary of the typical scientific method that sits largely in D2 but with references to theories from D1:

> So, it is based on a cycle largely making an observation of a phenomenon in the real world, developing an idea or hypothesis that rationalises why that observation can be made in the way it is … then design an experiment to test that hypothesis… evaluating the results. (Sc8/6:05)

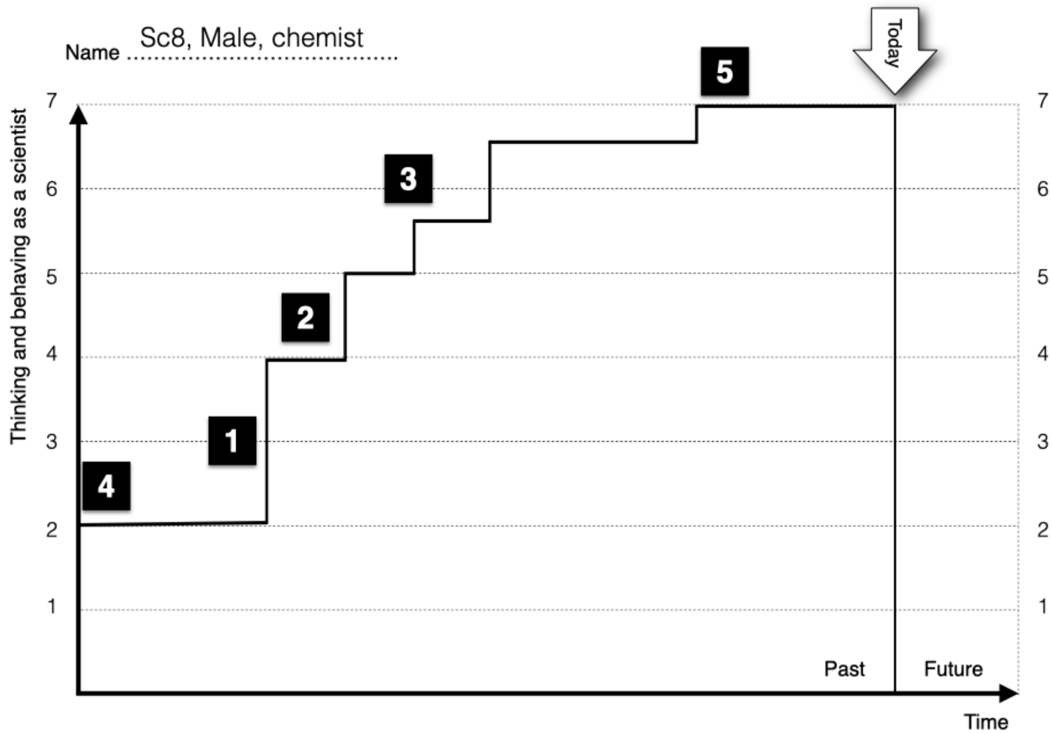
Despite his description of 'the scientific method' (D2) as a simple, almost personal process he emphasised collaborative working in teams as a key part of being a scientist:

> I think it (team work) is an important part of science. If you look at any of the major research challenges they are all interdisciplinary in nature. In order to form a productive

> research team you need contributions that span the conventional discipline boundaries … it requires that close level of collaboration. (Sc8/8:03)

Figure 10

Sc8 Completed Storyline Form



Sc8 also distinguished between training in formal skills and independent research:

> A lot of the formal training that was put into place in the first year and the second year of the degree helped bring out those skills (research skills involving scientific method and collaboration) but I really think it was going into the lab and putting a lot of that into practice in independent research that brought it up to almost where it is now. (Sc8/9:45)

The conversation then moved on to discuss the Problem-Based Learning (PBL) curriculum used at Sc8's university. When it was introduced he identified lack of student engagement with their science courses as a significant issue - almost a nervousness about even discussing chemistry with their peers and tutors in case they displayed a lack of understanding in their answers. When asked how they solved this problem he did not reach for better teaching on scientific method (D2) but in a shift towards supporting student autonomy (D3):

> The only way we've been able to solve that problem is to give students almost complete control of that type (PBL) of learning experience. (Sc8/18:44)

His storyline trace finished at the maximum indicating he was thinking and behaving as a scientist more now than at any other time in his career [5]. This was unusual as most of the storylines tend to dip slightly as participants took on more teaching or administration duties. Sc8's rise seemed to be linked to his active involvement in the research his students were initiating and doing, a component of the department's PBL approach. When asked if there was anything he would like to add about his experience of becoming a scientist he was very clear - it was about personal control and the degree of autonomy available (D3):

> I think it's entirely down to being put in control of situations to develop as a scientist is to be given that responsibility … plan, design, carry out and reflect on your own experiments … the overall message is that it's got to be something that you're in control of, something that isn't scripted, something that there isn't a fixed end point to … unlike some of the early level educational experiences people have.' (Sc8/23:44).

Discussion

Given the obsession with D1 and D2 in the research literature about science education we anticipated that the storylines would have shown a gradual rise as participants mastered more of the theoretical background (D1) and gained more skills (D2). However, the emphasis for the eight participants seems to be much more around D3, and high levels of D3 always seemed linked with high levels of scientific activity, while low levels of D3 always indicated a lack of what the participants called 'real science'. This corresponds with our contention that D3 includes 'psychological energy' (Bevins & Price, 2016) which is an essential factor in driving scientific activity. Psychological energy, as we conceive of it, is produced by a combination of autonomy, competence and relatedness in the same way as intrinsic motivation as described by SDT. (Deci & Ryan , 2006; 2012). Our 3D model moves scientific activity from a process to be completed by implementing aspects of prior knowledge (D1), alongside relevant skills (D2), into a conscious strategy adopted by an autonomous individual (D3) using aspects of D1 and D2 to achieve a personally valuable goal.

References to autonomy and being 'in control' appear regularly (Sc2; Sc5; Sc6) and are always related to high points in participants' sense of 'doing real science'. This autonomy brought responsibilities, participants talked about working harder, seeking to understand issues more deeply and 'feeling bad' when things did not work out (Sc1; Sc2). Participants also expressed the opposite perception - that the lack of autonomy reduced the activity to meaningless techniques or procedures (Sc4; Sc5; Sc8). The participants made a number of comments about increased competence with some identifying teachers (Sc5) or changes in courses (Sc2; Sc7) as significant. Participants distinguished between simple 'rule-following' and 'thinking like a scientist' implying that their sense of competence was more deeply-seated than being simply a high mark in an assessment (Sc3; Sc6; Sc7). Reviewing the conversations, there are many references both to the notion of relatedness concerning being part of a scientific team or even group of friends (Sc4, Sc6) with shared interests and capabilities, a relationship with a particular teacher or mentor and even, in some instances, a relatedness linked to a sense of the planet and the natural (Sc3; Sc5), or family and friends (Sc6; Sc7). Sc8 simply claimed that scientific research is inevitably collaborative.

Reviewing the 3D Model

We argue that the conversations and our analysis supports our claim that science is best thought of as an activity that has three related but independent dimensions. Our second claim is that a deficit in any of these dimensions will lead to activity that is not perceived as 'behaving like a scientist'. If D1 or D2 are weak the activity is not 'science' since it does not draw on scientific domain knowledge or scientific method. It may be a valuable activity but it is, by definition, not science. Our data shows that a deficit in D3 has a more subtle effect. People using scientific ideas and employing scientific method can be engaged in what some of our interviewees (Sc2; Sc8) described as, 'training for science' where an absence of D3 meant authentic science, which they often refer to as 'real science', was not happening - both in terms of their comments and the, sometimes dramatic, falls in their Storyline traces. In some instances a weakness in D3 led to the scientist absenting themselves (in the case of Sc7 to travel the country with a student rock band!) whereas in others it led simply to continuing to work hard, but with little sense of purpose or achievement (Sc3, Sc4). Arguably this second, larger group of 'willing conscripts' were still motivated sufficiently to continue their 'science' courses and activities but they felt it was not authentic. The motivation had been lost but something more significant to the discipline had also been lost. The message is repeated in other conversations: science without strong D3 is not just boring or un-motivating, it is not authentic science in a very significant sense: it is not experienced as the 'genuine article' by the people engaged in it. So, while D3 shares some commonalities with motivation (whether for science research or studying history or practising skateboarding) it is not exactly the same.

Implications for Science Education

We believe that we have provided evidence to support the idea that D3 is a critical part of scientific activity and suggest that this has serious implications for science education and the relative amounts of time spent on different activities within it. When we explore approaches to teaching science we notice that much of it, particularly in England, focuses on gathering more knowledge (D1) and practising routines and skills described as 'scientific method' (D2) in preparation for high-stakes assessments. Further research from the US and Australia report the curriculum cramping effect of heavy assessment instruments (Jones, 2007; Polesel et al., 2013). Even ignoring D3 for a moment, teachers in the UK regularly report the pressures on them to deliver large amounts of material in a limited time and that this prevents them from doing investigative work (a possible incarnation of D2) outside the limiting demands of the assessment regimen (Bevins et al., 2019). Having spoken to teachers from both the US and India, it seems that many of them share a similar perception that the science curriculum is already content heavy and the assessment regimen is dominated by D1.

But if we argue that D3 is an essential part of scientific activity surely there must be some shadow of it in the curriculum? In our study of the National Curriculum Science Orders for England (Department for Education, 2013) we can find no overt references to the components we anticipate fitting into D3 (autonomy, relatedness, competence) and even the references to the nature, processes and methods of science refers to it as 'working scientifically', reducing it to a sort of *cognitive mechanism* with no reference at all to society more widely until students reach the age of 14. While versions of the NoS from the US (see Table 1 earlier in this article) may contain some connection to some aspects of our D3 (the notion of 'a scientific community' and that 'society and culture influence each other', has shadows of D3's references to relatedness), any references to a scientist as a person rather than as a kind of biological and cognitive mechanism following a set of shared rules to produce an agreed understanding of a topic are not front and centre.

Similarly, problem-based learning and socio-scientific approaches can provide opportunities for the 'scientist as a person' with a social context to be revealed and communicated to students in lessons. However, these approaches are still relatively rare, despite the fact that a range of meta-analyses (Minner et al., 2010; Schroeder et al., 2007; Schwichow et al., 2016) show that emphasising the real world context of the science and allowing collaborative working not only increases motivation but improves performance. Indeed, it may be that the enlivening of otherwise boring material by an exciting or dramatic context may be the sole motivation for including aspects of D3 in the teaching and learning strategies rather than to reflect the nature of scientific activity itself. However if D3 is present as an integral part of scientific research, as claimed by the researchers quoted in this article, then supporting it is not simply a possible teaching strategy or a way to make material about electricity 'sexier' but a fundamental requirement?

Possible Ways Forward

The researchers and educators quoted in this paper are amongst the most successful of their years, they are the people who make it through to research and teaching posts, and they are clear on two issues. The first is that no D3 means no 'real research' (Sc8) with only 'constructed' (Sc6) problems on offer. The second is that their science education did not always provide the necessary third dimension in their studies and, in some instances, almost drove them from a career in science. If we are to help students to develop into 'real' scientists we have to accept that D3 is not a desirable extra, any more than D1 or D2 is, but an essential requirement. To avoid D3 or maintain that it is less worthy of a place in our, admittedly crowded, curricula may mean that most students have a limited experience of 'real science' and are unlikely to become the research scientists and technologists we need to solve some of the global problems we now confront as a species.

But how can one 'teach' students 'autonomy', 'competence' or 'relatedness'? These are not simply facts and theories or skills and capabilities and cannot be 'taught'. Maybe they are 'caught' by students as they work in classrooms that support student autonomy, that allow working in collaborative groups and aim for mastery rather than the performative goals of traditional public examinations? Researchers working in SDT have been looking at environments that support, or reduce, student autonomy and other related D3 factors for a number of years (Hyungshim et al. 2016) and have published useful advice on these matters.

In our previous paper (Bevins & Price, 2016) we suggested D3 existed. In this paper we present evidence that it is familiar to scientists who have actually engaged in research. We now propose to create D3-friendly science materials and approaches and evaluate their impact in terms of student motivation, perception of the nature of science, and eventual achievement.

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