Physics Imagination Retreat: Exploring the Role of Imagination in the Work of Scientists

June 29 - July 1, 2016

Kings College, University of Cambridge, UK

Participants:

Dr Philip Ball, *Science writer*

Sir Michael Berry, *University of Bristol*

Prof Mike Cates, *University of Cambridge*

Prof Melissa Franklin, *Harvard University*

Prof Herbert Huppert, *University of Cambridge (Physics retreat coordinator)*

Elizabeth Hyde, *Imagination Institute (Research Specialist)*

Dr Scott Barry Kaufman, *Imagination Institute (Scientific Director, lead facilitator)*

Prof Jon Keating, *University of Bristol*

Prof Naomi Leonard, *Princeton University*

Prof Tom McLeish, *Durham University*

Prof John Pendry, *Imperial College London*

Prof Martin Rees, *University of Cambridge*

Dr Rosie Robison, *Anglia Ruskin University (lead report author)*

Prof Martin Seligman, *Imagination Institute (Executive Director)*

Dr Ashley Zauderer, *John Templeton Foundation*

Retreat also supported by Victoria Schwartz (Imagination Institute, Events Coordinator)

Report prepared by: Dr Rosie Robison

"If you can't imagine something marvellous, you are not going to find it. The barrier to discovering what can be done is actually imagination."

Prof F. Duncan Haldane, one of the recipients of the 2016 Nobel Prize in Physics

Reported on 4 Oct 2016, Six O'Clock News, BBC Radio 4

Highlights

- Physicists take questions about imagination seriously.
- Imagination may involve *asking questions* which are new, connect previously unconnected ideas, lead to interesting solutions or stimulate thinking, and are also timely.
- Other forms of imagination however may not center on asking new questions, for example involving practical problem solving, or reformulating the work of others in better ways.
- The act of 'doing' physics involves conjuring up mental images (or imaginings) – which vary considerably by researcher.
- Imagination is not solely a trait of the individual, it may be a product of group interactions or wider scientific culture.
- Imagination in physics (as in all areas) is both constrained and enabled by the methods and languages it uses; this proves both challenging and exhilarating.
- A number of tensions were identified in the pursuit of imaginative enquiry, for example between freedom from tradition, and in-depth working knowledge.
- Senior physicists see themselves as playing a key role in stimulating the imaginations of the next generation of researchers.

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1. Introduction

This report details findings from a two-day event in which a dozen senior theoretical, experimental and mathematical physicists discussed the role of ‘imagination’ in scientific work, and in particular in physics. The event took place over 29 June – 1 July 2016, in the historic surroundings of Kings College at the University of Cambridge (UK) and was devised and coordinated by the US-based Imagination Institute.

The rich qualitative data gathered from two days of in-depth conversations with this group of highly successful physicists offer a rare window into physicists’ own perceptions of the imagination process, including how it actually 'feels' to them. They voiced their understandings of the social and psychological dimensions of both their everyday work and those rarer moments which (when looking back over a career) were felt to have involved profound imagination or inspiration. Through grappling with the notions of creativity and imagination, the conversations also offer insight into how a group of senior scientists relate to each other, and how they explain complicated concepts to both other experts (but who are perhaps outside of their own field) and non-experts.

The bulk of the report which follows describes and discusses six key themes which emerged: imagination as the practice of asking questions; individual experiences of imagination; imagination as a group process; ways to foster imagination; imagination in physics; and interactions at the retreat. A conclusions section then draws together threads from across the six themes. At the end of the report, in an Appendix, brief details are given on the background to the retreat, how it was set-up, and how data was gathered and analysed for this report.

2. Findings and discussion: six key themes

This section is divided into six subsections, illustrated with quotes from participants. First, in subsection 2.1, one potential part of a definition of imagination that developed during group discussions is raised. This centred around asking high quality questions which had various attributes, including novelty, connecting previously unconnected ideas, and leading to new ways of thinking and doing in physics.

Next, attendees were directly asked at several points to relate their own personal experiences, thus there was a strong focus on the individual experience of imagination. One avenue of discussion within this, which the participants showed particular interest in, was exploration of *what went on inside the heads* of other researchers when they were 'doing' physics, or actively using their imagination. Subsection 2.2 outlines findings here.

However, on another level, imagination was also talked about by attendees (both implicitly and explicitly) as a product of group interactions and collaboration. Going further, the wider landscape of science (or indeed society) was seen to play a role in imagination. Subsection 2.3 focusses on the social level of imagination in physics, and suggests limitations of solely looking at the phenomenon on an individual level.

Next, this retreat focussed on physics. It is therefore of interest to try to draw out what aspects of imagination might be particular to the practice of *doing physics*, and might differ from other academic disciplines, or entirely other fields of work or life. Subsection 2.4 is dedicated to this.

As one of the Imagination Institute's explicit areas of interest (explained to participants at the start of the retreat), some of the ideas for developing and fostering imagination expressed by participants are detailed in subsection 2.5. These are divided into those relating to developing one's own imagination, and those relating to developing the imagination of others, for example in one's role as an educator.

In subsection 2.6, the retreat itself is explored in more detail, how participants related to each other and explained concepts to each other as well as the non-experts present. Here, reflections are given on participants' views on the better measurement and encouragement of imagination in physics.

2.1 Imagination: all about asking the right questions?

Rather than simply using imagination to solve given problems, a more critical part of the imagination process (within research at least) was seen by participants as asking, and pursuing, interesting questions; the art of questioning is discussed in this subsection. A core sentiment was illustrated well by the advice that Prof Tom McLeish (Professor of Physics at Durham University and Director of the Durham Centre for Soft Matter Research) gives to newly enrolled PhDs in his department: *"I've got some very bad news for you which is that this finely honed skill [of finding the right answer] will from henceforth be almost useless to you. Almost - not quite - but almost useless. But what really will make you a successful researcher or not is whether you can formulate the creative question or not."* It is at postgraduate (typically PhD) level when one needs to make this switch in focus from problem (or question) solving to problem (or question) finding. In discussion at dinner on the first evening, this differentiation was also made in reference to students solving given 'problems' set as exercises in assignments, and independently recognising unanticipated 'problems' or 'questions' which can arise from anywhere, at any time. As explained by Prof Melissa Franklin (Mallinckrodt Professor of Physics, Harvard University**)** *"Experimentalists want to know if the student has solved a problem, and [if so] what type"* (from field notes at dinner on the first night).

So what <u>is</u> a 'creative' or 'imaginative' question? Classifying a question as particularly imaginative or, as Prof Herbert Huppert (Emeritus Professor, Theoretical Geophysics & Director, Institute for Theoretical Geophysics, University of Cambridge) put it, *"The right"* one, may be impossible out of context. It will depend in large part on the existing body of knowledge which has come before, and thus what is novel (and/or not already known to be wrong) as explained by Franklin: "*The point is they [people who send unsolicited emails to leading physicists about their own theories] don't know physics, so they can't know that their idea is ruled out already*". Further, different audiences may view the same question as either creative, or obvious, in part due to the history of the development in that area and whether the idea is 'new to them'. Prof Jon Keating (Henry Overton Wills Professor of Mathematics & Chair, Heilbronn Institute for Mathematical

Research, University of Bristol) who like several participants works with communities across different branches of physics, explained that "*Quantum information theor[ists] view this [the question of the role of slight disorder in sequences of quantum gates] as a highly creative and insightful question; whereas my friends in condensed matter physics think it's the most blindingly-obvious question"*.

Bringing insights from one field (where they may be 'obvious') into another (where they are not) may exemplify a particular characteristic of the imaginative idea. Prof Naomi Leonard (Edwin S. Wilsey Professor of Mechanical and Aerospace Engineering at Princeton University) expanded on this experience of *"Making connections"* between different fields, concepts, or phenomena, and that this often led to particularly memorable moments of inspiration or imagination[1]: *"You have these kind of 'gee whiz' moments … you feel like your brain has stretched … I think 'Oh my God. This is connected to that'."* Keating also spoke about constantly, deliberately, trying to make connections: *"I have a tube map, I have a map that connects points, those points are the problems [I am focussing on solving]. When I hear something new, I'm constantly thinking: does this create a new link?"*

Of course, an additional 'metric' by which to measure whether a question is imaginative or not only comes later (possibly years later), and is related to whether it led to an interesting solution (or perhaps, further interesting questions). Here the interest the researcher themselves has in a question will play a role, in order to provide the motivation to pursue it. Huppert spoke of how this means rating the imaginativeness of a question must be subjective: "*They [good students] had their own ideas. Sometimes I didn't think they were more interesting, but because* they *thought they were, then they were.*" Choosing well between the multitude of different possible questions to pursue in more depth was mentioned in passing, and was seen as tied up with building a successful career. Here, a certain degree of overt calculation may be undertaken, as explained by Prof Martin Rees (Fellow, Trinity College & Emeritus Professor, Cosmology and Astrophysics, University of Cambridge): "*You have to multiply the importance of the problem by the probability that you will make a big dent*

[1] These moments of inspiration (termed 'claritons' by Prof Michael Berry) are discussed further in an insightful article by attendee Ball: Ball, P. (2016). In search of claritons. *Physics World*, *29*(10), 30.

into it, and maximise that product", although it was not clear how deliberately any of the participants had done this.

It was also noted that imaginative questions might not solely arise through 'thinking', they could equally be stimulated by *"Using skill towards something"* as described by Leonard, such as the active 'doing' (or attempting) of an experiment. The importance of other people in stimulating new questions is also discussed later in this report.

In summary: asking questions was seen as a key part of the imaginative process, and imaginative questions were seen to be those which: (i) were new; (ii) made (new) connections between ideas or areas; and (iii) led to interesting or useful answers.

2.2 Physicists' imaginings

As highlighted in the introduction, participants showed a great deal of curiosity in and fascination with on inside the heads of physicists (including themselves) when they were forming, ruminating upon, or struggling with, an idea as part of their work. In this subsection, there is a discussion of how participants described that it felt to them when in the midst of imagining. This seemed to be something participants had reflected on to some extent previously, but perhaps had not discussed often with others – Prof John Pendry (Chair in Theoretical Solid State Physics at Imperial College London) asked those present, *"Do you replay your invention in your head?"* Here it was implied that the aesthetics of an insightful idea brought an enjoyment one might want to relive. There was variety in the mental representations used, and people switched between different modes when considering different problems, or at different times. In the following paragraphs, these are described.

Participants mentioned how they would often visualise either stationary or moving pictures. McLeish gave a very detailed description of how visual imagination had been involved in a moment of inspiration: *"I heard a series of lectures on protein physics by Robijn Bruinsma who's a wonderful Dutch theoretical physicist … and I fell into a sort of semi-reverie and found myself imagining very* *visually, very concretely, a polymer folding into a protein … so here's a big wobbly protein and it's wobbling because of Brownian motion … and then I saw this other molecule sticking to the side and realised that as it stuck, it would stiffen … the calming influence of binding something to this side of the protein would affect whether other places are fluctuating with the waves of motion so greatly or not … therefore there's some information at these other places on the protein now that the first site is occupied … this is phonon carrier waves."* In this story Tom also deliberately pointed out *"The difference between* my *mental picture of a protein and a molecular biologist's picture"* due to having *"Grown up"* in different areas. This different perspective had helped contribute to his insight. He also went on to expand on the story for the group present, by using an analogy of sticking biscuits onto jelly, a comparison which was both surprising and surprisingly memorable.[2]

Other modes of imagination were also mentioned. Prof Mike Cates (Lucasian Professor of Mathematics & Royal Society Research Professor, University of Cambridge) explained that imagination could involve verbalising in one's head: *"Sometimes you see things by … having a debate with yourself."* Several participants talked about their techniques for imagining mathematical constructs. For example, as described by Pendry, it is very common to relate mathematical objects to physical representations: *"If you can translate [your equation/matrix etc.] into something which is visual, reformulate it, you have a lot of machinery up there which will help."* Keating spoke of doing this for mathematical operations: *"It's a black box. It's a machine. I put something into this machine and some information comes out. I tend to construct sequences of equations that way."*

Not everything, of course, can be held at one time in one person's visual imagination – some things are too 'big' or complex. Franklin asked colleagues, *"What would be the equation that doesn't fit in your head?"* Writing things down in conjunction with mental work is common practice in physics, not simply to record ideas but to *have* them. Cates explained, *"I need a piece of paper in front of me and I'm pushing symbols around on the page … so there's this interaction between processing in your head and moving symbols around."* An increasingly important part of physics work

[2] Tom has written up a fuller account of this experience for an upcoming book - *The Poetry and Music of Science* (working title).

is held by computers, which can take over some parts of our 'imaginings' – providing visualisations for us, for example. Rees gave this example, "*If I give you the algorithm for the Mandelbrot set, although that is easily computable, no human being could instantly bring that to their mind's eye*".

There was a recognition that one may make more progress when one finds a topic which, as Rees put it, *"Is suited to your particular style of thinking"*. This is undoubtedly an iterative process; although a degree of innate preference must play a part, one's style of thinking is also shaped by the field one is in, and one trains oneself (actively or subconsciously) through observation of the norms of that field. Sir Michael Berry (Melville Wills Professor of Physics [Emeritus], University of Bristol) explained, "*I wasn't always a visual thinker … I encountered people - senior, older scientists and they always drew pictures … it took time before that became natural to me."*

A related topic of conversation was on subconscious workings of the brain. There were many stories of how ideas had come either in participants' sleep (after working on a problem all day/for several months), when not directly focussing on the object in question (such as in the shower), or even – as described by Berry – eight years after first considering a problem, with little seemingly going on in between. *"I was on a train in January 1985 in Germany, and it was so cold that there was ice inside the windows. I had some insight about the connection between quantum mechanics and chaos and was working this out, [when] suddenly it popped into my head that this is all relevant to the Riemann Zeta function. I remember the exact moment it happened. Of course, I was prepared, because I had read an article about it 8 years before, but I hadn't thought about it since."*

Sometimes this sudden leap in knowledge seems to come, and participants hypothesised about how this is perhaps linked with unconscious workings, and it was only once the leap had been made that it became conscious. McLeish described how this can mean one may live with a certain amount of frustration before a breakthrough: *"I think what is really fascinating here is what is going on in the unconscious … thinking of a problem, 'getting nowhere' and sometimes … the unconscious is actually doing better than our conscious thinking"*.

2.3 Imagination in science as a group endeavour

One's close colleagues, research group, department, university, and the 'science community' at large – these all play a role in both stimulating physicists' imagination, and indeed defining what counts as 'imaginative'. Keating's experience is that: *"[Science] is a team game. It's very rare that people are creative in complete isolation. And we have universities for a very good reason. We are a community, and we work better as a community."* Indeed, the importance of one-on-one or group interactions, as well as what one has read and seen presented by others, was why some questioned the idea of measuring imagination as a trait of an individual at all. As Franklin put it: "*Doing it [measuring imagination] on the individual level doesn't really make any sense … you're gonna have the huge error bars. I mean, Ed Purcell who did the first NMR [Nuclear Magnetic Resonance], … an incredibly creative physicist, might not have done any of that stuff if Bob Pound hadn't been in the office next door, and Norman Ramsey hadn't been down the hall … thinking about this as an individual characteristic is just completely old-fashioned."*

Similarly to this anecdote, several participants spoke of significant others in their own working life who had played an important role in developing their ideas. Berry told the group how, *"Things go back and forth and ideas get sparked which neither of you have individually"*. In this way, dialogue could potentially become more than the sum of its parts. Sometimes these relationships had developed and deepened over long time periods. McLeish spoke of a close colleague with whom he has *"Quite an extraordinary psychological connection with ideas. Once, he even dreamed the same picture that solved an equation the same night"*.[3] McLeish also spoke of how much of scientific endeavour is based on human relationships, and thus that the Royal Society[4] motto – *Nullius in Verba* – often translated as 'take no one's word for it' would be better translated as 'don't swallow tradition'. As he explained, "*Scientists have to take each other's word for things all the time. If we all*

[3] This episode – related to finding the Euler characteristic of a phase-separated binary mixture defined at a set of lattice points in three dimensions – is also discussed in more detail in Ball's article (see footnote 1).
[4] The Royal Society, founded in 1660, is the UK's national academy of science.

mistrusted each other to the extent that we had to do everyone else's experiments and calculations, it wouldn't work".

In talking more broadly about the role of the wider science community, one discussion at the retreat centred on how one distinguishes between 'crank' science and highly creative science, which could also be highly unconventional. This distinction was described as being harder to explain to an outsider than one might think, even when it might seem 'perfectly obvious' to those within the relevant part of the science community. In fact, when one tries to draw a line between crank and creative, much comes back to the consensus view of the wider community. Thus, part of defining an idea as 'imaginative', rather than oddball, has to do with its reception by others, which will also involve the past history of the field and existing body of knowledge.

Recognition from the wider community is, in addition, rather dependent on timing, and what everyone else happens to be concentrating on at the time. As Berry explained: *"There has to be a population of one's colleagues who could* almost *have done the same thing but didn't quite, and so they immediately understand it."* Whether an area is sufficiently 'fashionable' or topical to have other researchers' (or indeed funders' or politicians') attention may affect whether an idea is perceived as imaginative (that is, addressing an interesting and relevant question) or not, and whether that idea gets pursued or dropped. In a similar way, Dr Ashley Zauderer (Assistant Director, Mathematical and Physical Sciences, John Templeton Foundation) talked about the "*Role [that] serendipity and new technology plays in discoveries"* as being significant. One could, therefore add 'timely' to the list of qualities that an imaginative question might have. Further, through the frameworks by which scientists understand 'how science is learnt/done' (e.g. lectures, success in examinations, publications, procurement of funding), one can also see how scientific culture may systematically favour (and therefore reproduce) certain types of imagination over others.

If group processes and the wider landscape play such a critical role, are there ways one might influence these to create conditions for more imaginative physics? Many participants, in tandem with their active research careers, held senior positions within departments or universities;

at an institutional level, areas specifically designed for meeting and discussing (for example, with coffee and places to draw) were seen as critical, as well as the ethos around seminars. At a more fundamental, and longer term, level there are questions about competitive processes such as hiring and funding competitions, and how these might work to encourage, or inhibit, imaginative ideas. Finally, it was noted by Dr Philip Ball (science writer) that many different types of individuals are needed to *"Make the group work"* and thus selecting students or staff on imagination alone may be counterproductive.

2.4 Imagination in physics

"Physics was where you could think about something that was more philosophical than mathematical … and have a chance of being right." Prof Mike Cates

"If someone asks me in the day at what moment am I doing physics, I have no idea."

Prof Melissa Franklin

Although no part of physics is unique to physics alone (overlapping as it does with mathematics, engineering, philosophy, and many other areas), the combination of different elements builds a unique context and tradition. The Imagination Institute describes imagination as a "critically important capacity"[5], but intentionally did not pre-define imagination for the participants of this retreat. Indeed, the series of retreats are in part aimed at exploring the variety in perspectives across different fields. In this subsection, several elements which may help make up the particular form of imagination in physics are discussed: use of mathematics; heuristics (mental shortcuts) in physics; experiment and theory; and how some tools of modern physics might foster imagination through openness.

Maths play a very central role within almost all of physics, and thus formed an important topic of conversation throughout the two days. The boundaries imposed by working within

[5] As described in the invitations to the retreat.

mathematical laws provided considerable challenge in directing imagination towards meaningful results, as Cates explained: *"If you could just completely unconstrain your imagination … you would never get anywhere like that. The fact is you have to imagine … your way through a maze and that isn't easy."* As well as being challenging, these constraints were in fact what made the work enjoyable in many ways. Several participants were attracted to physics/maths at school (more than some other subjects) because from understanding a very few rules or methods, quite complex problems could be solved, or as Cates put it, "*A small amount of knowledge gets you an enormous way".* Interestingly, this use of a specialist language/notation also affects the way group interactions work in physics, as by writing equations on a blackboard, one is able to argue (sometimes quite aggressively) without necessarily taking criticisms personally; as Ball said, communal writing spaces provide a *"Mechanism by which you can bypass the social niceties, because it's 'out there'".* This need to have shared writing space in order to work productively together was described as somewhat unique to maths and physics.

The important role of results provable via mathematics leads to one of the tensions experienced when striving for imaginative ideas in physics. Imagination requires freedom, but this freedom must be tempered by the rigours of the subject, and in physics this often comes back to maths. In order to think differently (creatively, imaginatively) it may be necessary to throw out (possibly only momentarily), or question fundamentally, what has come before. However, there is then an important 'editing' stage, and it is here that one's expertise, and depth of knowledge, is so vital. These two stages of imagination were described by Pendry as follows: "*It's a two-step process, isn't it? You have to go through the imagining and then after you've done that, you go through the editorial process and say well … is this really right?".* Or, as put more colourfully by Cates: *"You have to have a way of undoing the valves and letting your brain run riot, but then you also have to have the self-censorship to not publish crap."* The depth of knowledge in a particular area needed to do the 'self-censorship' only comes from years of repeated, frequent attention which is highly valued in an academic career. Pendry felt that, *"Creativity is, I am sure, hard work"*. Thus creativity was not seen to be simply about freeing oneself. The deep, active, knowledge needed (which involves constant questioning) is qualitatively different from the knowledge which comes through *memorising*, with too much of a focus on the latter seen as a way of stifling imagination.

A second, related, theme was that of the particular mental shortcuts (heuristics) developed as a practising physicist. Over time, and with experience, one develops heuristics in any field. In physics, this can mean that certain equations come to feel *"Hard-wired in"* (as put by Berry). Notation (mainly mathematical notation) was seen here as key. For example, Cates explained, *"Good notation … allows you to develop a heuristic which involves an informal manipulation of these symbolic things in your head"*. Indeed, this was aptly illustrated with the following personal anecdote from Berry: *"I remember once we had a lecture … and [the lecturer] deliberately used completely unfamiliar notation … We have h which means Planck's constant, he put q." [Laughter]* The fact that the message here was so immediately understood by all shows how deep notation runs. Similarly, Keating talked of how a great deal of care is sometimes taken over coming up with: "*One very apt word or one very apt description, and people do spend a lot of creative energy … 'Black hole' conveys so much ...";* as Prof Martin Seligman (Director of the Positive Psychology Center, Univeristy of Pennsylvania; Executive Director, Imagination Institute) pointed out *"it [a phrase like black hole] becomes everyone's heuristic"*.

As one's depth of knowledge increases and one becomes more expert, intuition (or perhaps greater faith to *follow* intuition) may play more of a role. One begins to have moments when, as Ball put it, "*You know the idea is true, and the proof will come later"*. Such intuition is far from infallible (indeed, those who have experienced significant 'success' may be somewhat vulnerable further in their careers to placing undue faith in their later ideas) but a feeling that the solution is just around the corner may help in deciding what to focus attention on. Cates spoke of how this may feel: *"Something … ma[kes] you want to check that in a way that you probably don't check everything."*

Another theme which generated discussion was the differences between experimental physics and theoretical physics. Although of course not black and white, this dichotomy was described as somewhat particular to the field. Many physicists (including workshop attendees) certainly cross the boundaries, but there did seem to be recognition of differences between the two 'cultures' including how imagination was viewed. For example, when selecting graduate students to take on, experimentalists may particularly value imagination used in 'doing' whereas theorists may value that used in 'thinking'. Indeed, asking questions – as described in detail earlier – is not all there is to imagination. When considering the more practical side of physics (for example, experiment design), imagination might look quite different, and involve the solving of numerous (small and large, ad hoc and systematic) problems to just *get something to work*. Franklin, one of the few dedicated experimentalists at the event explained that: *"There is a lot of imagination that goes into how you do the experiment which is not [answering the question which stimulated the experiment in the first place]. I don't think it's actually divorced at all."* A complaint was made that, through perhaps an over-emphasis on hands-off education, sometimes students ended up thinking that physics *is* theory and equations, but that this is not in fact the case. There was also interesting discussion of the different psychologies of experimenters and theorists, for example regarding their attachment to particular ideas. Rees provided interesting insights here: *"If you are an experimenter, you have a far greater investment in your work than a theorist … to be motivated to put that effort in [years and years developing a technique or piece of equipment], you've got to perhaps have a slightly exaggerated perspective on how important the result's going to be."*

Finally, from within the field, participants did feel that overall, physics was more open to imagination and new ideas, and maybe less *"Combative"* (as Huppert put it) than some disciplines. One particular way this was exemplified was the, now widespread, use of the arXiv.[6] This online repository allows physicists to share their papers (and thus their ideas) at very early stages, and very quickly respond to developments in the field. As one example, given by Ball: "*This blip that CERN*[7] *had … a little bump in their data, had what, 200 papers within a couple of weeks speculating on what*

[6] Pronounced 'archive': https://arxiv.org/
[7] CERN, the European Organization for Nuclear Research based in Geneva, runs the largest particle physics laboratory in the world which includes the Large Hadron Collider.

that might be? That would never happen in another field. Everyone would sit back for a year very cautiously." Of course, one can view this prolific output as either collaborative or highly competitive, but it serves to illustrate how the particular historical trajectory of a field (the move towards using certain tools rather than others), and how its work is structured, may fundamentally impact upon the possibilities for imagination.

2.5 <u>Developing imagination in physics</u>

There are a number of wider influences on imagination which may be out of the individual's control, and/or take a rather long time to evolve. However, the group suggested there *were* things individuals could try to develop their own imagination, or that of their students and peers, in the shorter term. McLeish saw this as a valuable potential output from the retreat: *"It would be a huge contribution if we can suggest to aspiring researchers 'you might like to try …'".* Interestingly, several of these 'tips' came in the form of anecdotes about how esteemed scientists apparently did their work. Of course, it is hard, within one career, to really know whether such techniques *did* contribute to an increased imagination, but certainly the commonality of experience of some of them suggest at the very least, senior scientists would have respect for the attempt.

First, as already mentioned, hard work and **depth of knowledge** was seen as a pre-requisite for developing imagination in physics. However a degree of disappointment was expressed by Ball if this was found to be the key to imaginative enquiry: *"Wouldn't it be a bit sad if we found out that we could solve it just by working hard enough, rather than discover[ing] something extraordinary that we never knew about? We'd kind of want the second to be the case."* It will be interesting to see whether hard work features across all the sectors surveyed by this set of retreats, or whether in some areas the freshness of a totally outside (non-expert) perspective can bring revolutionary new insights.

A second key ingredient was **perseverance.** Pushing the boundaries of physics is hard, and can involve days, weeks, months, or even years of frustration and seemingly slow or non-existent progress. In order to keep going, one needs to develop the ability to keep at it, and not give up. Franklin explained further: *"If I'm working on a problem, then I can usually solve the problem before I lose interest … there are many students who don't or can't do that and they get very frustrated".* One might then ask about the techniques senior physicists use to deal with this sort of struggle; undoubtedly there are some. As one example, perseverance can be exercised by resisting the temptation to look at the work of others before having a go at a problem yourself. Pendry mentioned this technique in an anecdote about the scientist Barnes Wallis: "*The idea being if he put these things into his mind, he would block his creative juices."* This approach is also likely to alter how the work of others becomes incorporated into your own mental maps, as you have built your own frameworks to hang new ideas off. In contrast to perseverance though, **knowing when to take a break** may be important. After intensive working, breaks (from deliberate work on that problem) may help the subconscious make progress. In one story, Cates recounted how John Edensor Littlewood realised he was having his best ideas on a Monday morning, after the break of the weekend. Apparently, he ultimately took this to rather an extreme level, so that:*"As soon as he had a great idea, he took the rest of the day off. (But that doesn't mean he wasn't working)."*[8]

Franklin again brought her experimental experience to bear when explaining that, *"There are cases where you build an entire accelerator and nothing, no physics come out of it, but you can learn a lot"*. Thus, **a focus on process as well as outcome, and learning from failure,** may help keep one open to imaginative ideas. This can be hard in an output-driven culture where every project is expected to 'achieve', but Leonard felt that *"Knowing that even if your original idea ends up with a negative result, it might lead to something positive"* can help in being open to new ideas and less set back by 'failure'. A question posed by Franklin to the group was: *"Let's say there was a God, and God told you the answer to the question you were working on, would you still do the experiment? Would you still do the calculation?"* This highlights fundamental aspects of the identity of 'being a scientist': working to satisfy one's own curiosity; the work *itself* being part of the point, rather than just the

[8] This story comes from the book *Littlewood's Miscellany*, edited by Bela Bollobas.

‘answer’; but also the fact that the formulation of the question is as, if not more, important than the finding of the answer.

As already mentioned, constantly **asking new questions** was in some senses the group’s definition of imagination. Imagination produces questions, as well as being stimulated by them: they go hand-in-hand. Training oneself to ask more (and potentially better) questions was seen as key. As related by McLeish *“[Einstein] said, look, if you gave me a problem [and] an hour to solve it, I would spend the first 55 minutes … just asking questions about it and looking at it from different angles.”* When one identifies good questions (by one’s own, continually evolving, measure of ‘good’ – which may be closely related to a question which ‘nags’ at you), **keeping those questions in mind semi-continually**, and not letting them go, may be important. Keating in particular deliberately uses this technique: *“[I] have a certain set of problems in my mind and … whenever I go to a talk or I discuss with somebody and they say anything new … my first instinct is to think ‘Does that help me with any one of the eight problems I’ve got in my head?’”*

As was discussed in subsection 2.3, science is rarely a completely solitary pursuit (although those who are more collaborative in nature may be more open to attending an event such as this!). Therefore, **finding others you can work with**, who may be at different stages in their career, both more junior and more senior, helps provide both inspiration and motivation. Many participants felt that mentors had played a very substantial role in their own careers, thus Pendry explained: *“The third thing [along with developing in-depth knowledge and learning to collaborate] I'd advise the student to do is to find a mentor”.*

Lastly, Huppert talked about: *“Tak[ing] your own route, don't just follow others and do what others are doing”*. However, **developing your *own* passions** was not seen as automatic (and therefore something that if you don’t have, you never will). Indeed, it was pointed out by Leonard that: *“When students come in there’s a lot of nervousness about how do you even find this passion?”* It is perhaps something which also develops with expertise, as one gets more ‘comfortable’ in one’s position within the field.

For many of the ideas outlined above, stating the intentions may be the easy part. The next question is 'how?' Here one perhaps also needs imagination, in order to develop techniques which will work for oneself. Thus, having enough imagination to successfully work on developing one's own imagination is perhaps a key (if somewhat circular) ingredient. In addition, one can read all of the above advice as relating to 'succeeding in physics' rather than solely developing one's imagination. One might therefore ask, is it possible to do all of the above and yet still *not* be imaginative?

The question of fostering, or encouraging, imagination in others was also considered in some detail. The participants of this retreat were almost all working in universities, and they all certainly played a role as educators. Participants were clearly very interested in working to develop the imaginations of their students, and had given considerable thought and effort to some version of this question of how to foster imagination. Here some of the key elements they recognised are detailed. Of course, much of what follows can apply equally to working with peers as students.

Giving confidence through respect was described as possible to achieve in three different situations. First, Ball talked of not dismissing the 'stupid' question: *"It does seem to me that increasingly within educational systems, asking a question shows you don't know the answer and that's dangerous."* Secondly, taking a genuine interest in students' work, and bothering to spend the time to do that was seen by Cates as vital: *"It makes an enormous difference for the junior scientist … when senior scientists are genuinely … interested in … what they have to say".* Part of this, Leonard explained, was the art of being able to find something interesting in any discussion *"People who are inspiring [are] those who can find something interesting about just about everything."* Thirdly, being (more) ok with failure was discussed by Keating: *"[How can we] encourage people to make them feel more comfortable with the failure that comes with most creative and imaginative ideas?"*

Giving students freedom from, for example, aims and targets was a second strand of thought. When talking about a pilot, interdisciplinary class she had taught, Leonard related how, *"A lot of students said this was the first time, even if they were fourth year students, that they had been not given an objective, not given some constraints."* In order to open things up, it may also be helpful to introduce ways of **doing things which are very different** to what the student has experienced before. Franklin had tried this *"I taught a class on introduction to quantum mechanics in which, without any equations, we did all of the demonstrations of physics necessary to get to quantum mechanics."* This raises the interesting question: how might imagination be related to confusion (and frustration)? When doing things in markedly different ways to before, one may well feel both lost, and unsure where one will end up. And in most of these cases, one does not end up with a ground-breaking new result.

It may also be important to recognise the context-dependent nature of other people's imagination, in order **not to pre-judge others.** In a very honest 'confession', Berry recounted how he had advised a past student not to continue in academic life, because he *"Hadn't been very creative"* during his PhD. But when that individual (contrary to his advice) moved to a different academic group, he started *"Doing very original, very creative work … after [having] left me" [chuckles].* In this way, having the humility to recognise that you may not be the best mentor for everyone, is important.

Finally, you might aim to **exemplify working to develop your own imagination.** Berry wondered whether: *"The bottom line with imagination is basically you can't really teach it, but you can exemplify it and you can try to encourage it."* In this way, explaining the tools you yourself use/used (whilst recognising they may not suit all) may be helpful. It will be interesting to see, across the range of retreats, whether others see imagination as a quality which can be taught, or not.

2.6 Interactions at the retreat: physicists talking about imagination

Participants gave their views explicitly and implicitly on the idea of measuring imagination, and the motivations for doing so. Some wondered whether measuring imagination would actually help facilitate it or not. In the context of a competition-based academic system, a measure of individual imagination (one of the core interests of the Imagination Institute – i.e. an 'Imagination Quotient') was mainly discussed in the context of hiring (e.g. graduate students or junior faculty staff) and funding decisions. The former was described by Cates as culminating in "*Hav[ing] a conversation with them on enough of a scientific topic and see if the sparks start to fly*" rather than via quantitative measures, perhaps in part as the element of group interaction/fit is so important. In addition, the possibility of measurement raises questions about how this might influence, for example, students' or job applicants' strategies, and ultimately how people would then work to improve their 'Imagination Quotient'. As raised elsewhere, some wondered whether measuring the imagination of one individual may be missing the wider picture, and the importance of group context.

A further reflection is that, ultimately, the group was very willing to engage on the issue (of course, all had accepted an invitation to do so), and seemed to feel discussions of imagination had relevance to their work. Relatedly, they were very happy to engage in (and were knowledgeable about) discussion which concerned the fundamental ontological and epistemological questions of physics: what exists and how knowledge is constructed.

In this final section, a brief reflection is given on how members of the group interacted at the retreat. Attendees used a number of tools to describe or explain physics concepts to each other. The power of the anecdote was clear, and these were used very often, in relation to well-known physics or science personalities (Einstein, Hoyle, etc). In this kind of conversational setting, science and past research is often invoked, without detailed referencing (however it may well be these were sought after the event for ideas which participants wanted to follow up on). The importance, and use, of narrative has been explored in the fields of science education and philosophy of science. Interestingly, when reading the transcript during the data analysis for this report, it was also clear how much intonation plays a role in conveying understanding of complex concepts, which is harder to infer simply from words on a page. It is also perhaps unsurprising that issues of everyday relevance to senior physicists were often picked up and generated ready dialogue (the UK's Research Excellence Framework, peer review, applying for funding etc.). As one might imagine, from the starting point of imagination, conversation spilled over into inspiration, creativity, curiosity, and general discussion of how to 'be an effective physicist'. Overall, the mood was generally constructive and interested, with several funny moments (as Victoria Schwartz, Imagination Institute Events Coordinator, commented: *"Who knew that physicists could be so funny?"*). There were arguably high levels of trust (as displayed by the sharing of personal stories) and respect, however it is worth noting that people did not agree all the time.

Finally, the organisers of this retreat are psychologists, which of course participants knew. This certainly played a role in the conversations, both in terms of the topics explicitly chosen by the facilitators and those which arose and were seen as worthy of more discussion. There was discussion of a number of pieces of psychological and neuroscientific research during the retreat. As might be expected from a group of senior figures within higher education, they were clearly reasonably well-informed on a range of scientific issues, including within psychology and neuroscience. In line with the questioning spirit of 'imagination' perhaps, participants often asked many questions ("how is it measured?", "what mechanism is at work?") of some of the concepts invoked in this area.

3. Conclusions

In this final section, the six themes above (described in subsections 2.1 to 2.6) are first summarised, before outlining a number of ideas which draw together threads from across them. These include one reason why advice on developing imagination may be harder to follow than it is to state: the balance necessary between potentially competing elements. There is then a reflection on a few of the conclusions from the retreat which were perhaps more unexpected than others. A number of possible follow up questions this work raises are highlighted, before a final question is posed: what is imagination for?

To summarise the six findings subsections: first the central role that *asking questions* plays in imagination was discussed, and three elements of 'imaginative' questions were proposed: novelty, connections, and outcomes (a fourth, timeliness, was suggested later). Second came a description of the variety of mental imaginings physicists experienced and deliberately cultivated when doing their work. Third was a discussion of how one-on-one or group interactions within the context of the wider scientific community play their part in imagination. Fourth was a reflection on the ways in which imagination in physics might be particular to that subject; here the role of mathematics, heuristics, differences between experimental and theoretical work, and new tools being used were all covered. Fifth, ways in which the group suggested imagination could be developed and encouraged were outlined. Finally came a brief exploration of the generally interested atmosphere at the retreat, including discussion of the idea of measuring imagination. Key conclusions from across the report are given in the highlights on page 2.

When talking of the pursuit of imagination, some tensions and trade-offs were mentioned, often implicitly. First, it is interesting to note that imagination was not seen to be the only skill needed (for example, to build a successful research group in physics), thus of course it is not necessarily sensible to be pursue imagination at the cost of all else. But in addition, there were different elements which seemed to contribute to imaginative ideas, but which may be tricky to balance. This may be in part why there is no fool proof advice to follow in order to generate an imaginative idea – and indeed why this area is so interesting to explore. The most recurrent of these tensions was mentioned in several related ways: freedom versus structure; hard wiring of existing knowledge (heuristics) versus breaking from tradition to imagine things differently; developing depth of knowledge in one area versus making connections with other areas. One can imagine a number of other trade-offs which must be negotiated and may give rise to choices for the researcher. One example would be calculating whether to pursue the seemingly more 'useful' or more 'creative' question. Another, as mentioned, might be taking work by others on trust whilst keeping a questioning spirit. Or indeed, fostering an 'imaginative scientific culture' versus encouraging individual progression. How such trade-offs are practically negotiated by researchers and institutions could be an interesting next question; findings from this retreat would suggest these negotiations develop and change over time.

Further, one can see how there may be tensions *between* different types of imagination itself. That is, conditions which favour one sort of imagination may inhibit another. It was clear from discussion that the group felt there to be many different types of imaginative person, and imaginative activity. Such differences are seen not only in the way imagination is *experienced* by individuals (as discussed in subsection 2.2) but also in how apparent that imagination is to others. As Berry put it: "*There's a difference between a brilliance on the surface … and an acquired ability just to focus exactly right and get something that works."* Huppert also described how imagination can occur on different timescales for different researchers: *"[An] extremely capable colleague of mine was hopeless on the short timescale and when he gave seminars, if you asked him a question, he'd make a complete fool of himself. The next day, he'd blow you out of the water because he'd had time to think about it."* Greater value may be placed on some types of imaginative activity over others; the highly imaginative technician who has contributed to numerous experiments may be less likely to receive community recognition than the professor who solves a long-standing theoretical problem. In addition, there is a great deal of important work which does not involve coming up with entirely original ideas, but rather involves translating them in an original way, so they can better be understood and used by others. For example, as recorded in field notes from discussion at dinner on the first night, the physicist James Clerk Maxwell wrote an *"Incomprehensible"* paper on his famous equations describing the rules governing magnetic and electric fields. It took another researcher, Oliver Heaviside, to reformulate them in a more useable format. Is this type of imagination any less valuable?

At dinner on the first night, Seligman asked Ball what might be an interesting outcome from the retreat, that he could imagine wanting to write about. Ball replied that he might want to write about something particularly surprising. Whilst it is left to the reader to decide what, if any, of the findings of this report are surprising, in this paragraph ideas are raised which certainly the lead author did not have in mind prior to the retreat. First, we observe that, interestingly, mental visualisations (a core part of imagining and indeed undertaking physics) seemed to be primarily developed 'on the job' without any formal attention in teaching, or even perhaps much discussion between colleagues. Some had certainly noticed what more senior physicists seemed to do and tried to emulate this, thus 'training' themselves. It would be interesting to track this process of development over a period of time in a research career. Secondly, imagination was not all about thinking in one's head, it was also described as being produced through using skill, and through conversations. Perhaps this variety is unsurprising, but by trying to define imagination one will inevitably focus attention on some types more than others. As imagination depends in part on your point of view (e.g. whether something is 'obvious' or creative) then the labelling of something as imaginative is in some senses what makes it so. Thirdly, both 'aha' moments and slower burn development of imaginative ideas were described by participants. The former was perhaps easier to pin down and talk about in the form of anecdotes, but both were recognised (as well as instances when imaginative ideas 'failed' for one reason or another). It is interesting to reflect on whether this variety is present in other areas – one might think the 'Eureka' moments would be less usual in the art world for example, but are they? Finally, it was interesting to hear about the multi-step process of imagination. Reflection and refinement was an important second step in the imaginative process, following the first seeds of an idea.

This work raises a number of questions, and potential avenues for future research. In this paragraph eight such questions are highlighted. Recognising that talking about experiences 'in the abstract' is different from the lived experience, what might be learnt from *observing* collaborative meetings between physicists in-situ? This retreat was deliberately carried out with senior physicists, what differences might there have been with those in early or mid-career? As highlighted earlier in this report, will 'hard work' be seen as a prerequisite to imagination in all areas? And, across the range of retreats, will imagination be seen as a quality which can be taught, or not? When considering physics in particular, do heuristics in the two broad areas of experimental and theoretical physics develop differently? What techniques do senior physicists use to deal with the tensions which must be negotiated to develop imagination, and how did they learn these? How might imagination be related to confusion (and frustration)? And how do structural components of physics, such as funding and hiring mechanisms, impact on imagination?

One final question which was not explicitly raised is: what is imagination for? Apart from a short comment at dinner on the first night – on the imaginativeness of terrorists – imagination was described in overwhelmingly positive terms. As such, it was intertwined with 'success' throughout conversation. Thus the moments most often (but not always) deemed most imaginative were those associated with coming up with ideas which felt like great achievements: ideas which took hold more widely, and had the potential to revolutionise the field. However it was also recognised that sometimes it is when one is not deliberately aiming for 'success' that imagination comes. Zauderer illustrated this as follows: *"A really cool story is Vera Rubin, who discovered observational evidence for dark matter. I remember her speaking when I was in graduate school, and saying she didn't want to be working on a hot topic in a hyper-competitive environment. She said just 'put me in a corner - I want to just do science because I enjoy it', so she worked on these rotation curves of galaxies … In the process, she discovered observational evidence for dark matter which is still a huge open question in astrophysics."* Thus, a final idea to reflect on might be the purpose of developing imagination, and indeed how aiming overtly for more imaginative ideas interacts with progress towards thatgoal.

Appendix: background and methods

For those unfamiliar with the Imagination Institute's programme of work, a little background is presented here. The Imagination Institute is a US-based organisation founded in 2014, funded by the John Templeton Foundation, and headed by Prof Martin Seligman and Dr Scott Barry Kaufman (both of the University of Pennsylvania). The Institute is *"dedicated to making progress on the measurement, growth, and improvement of imagination across all sectors of society".*[9] To this end, they are currently funding two main streams of work. Firstly, in 2015 they released nearly US$3m across 16 different projects aimed at exploring whether imagination can be measured, and if so how. These 'Imagination Quotient grants' are supporting the development of a range of quantitative measures of imagination, as well as interventions aimed at fostering imagination of different groups. Second, they are exploring the experiences of imagination across a number of different areas (from comedy, to spirituality, to physics - the focus of this report) and how one might encourage greater imagination in these fields. To this end, several 'Imagination Retreats' have been organised.[10]

Invitation of attendees was coordinated between Imagination Institute staff and the subject-specific expert, Prof Herbert Huppert of the University of Cambridge. Attendees were particularly selected on the basis of demonstrated creativity, and thus there was an emphasis on senior figures from world-leading universities, above, for example, those earlier in their careers. In addition to Huppert, 10 physicists took part for either both days (8 of the 10) or the second day only (2 of the 10). Other attendees were the Imagination Institute staff leading the event (Seligman who was there until lunchtime on the second day, Kaufman and Elizabeth Hyde), the author of this report (Dr Rosie Robison), and the logistics coordinator (Victoria Schwartz) who participated in (non-recorded) discussions during refreshment breaks and dinners.

All participants worked at UK or US academic institutions (with the exception of Ball, an independent science writer based in the UK, and Zauderer, a director at the Templeton Foundation,

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[9] http://imagination-institute.org

[10] Reports from future retreats will be made available, as this one is, freely on the Imagination Institute website.

both with backgrounds in Physics). Participants' travel, accommodation and time was covered by the Imagination Institute.

In advance of the retreat, participants were sent a substantial list of preparatory 'questions for discussion' across a number of different areas. During the event itself, a number of these questions were used as initial prompts (which each participant was often invited in turn to answer); discussion was then allowed to flow fairly freely, and many additional topics arose spontaneously.

Qualitative data collected included: (1) Field notes taken by the lead author during all sessions, and also the evening dinners, together with reflections after the event. (The notes taken during dinner were much more significant on the first night, when one conversation was maintained through the group for the majority of the time); (2) Full video recordings of all the sessions (not refreshment breaks), which were then transcribed by a third party and sent to the report authors.

In the months following the retreat, participants were invited to undertake a battery of cognitive/personality tests, but these data do not form part of this report.

Ultimately, this was a piece of qualitative research undertaken with a focus-group type methodology. Analysis undertaken for the preparation of this report involved several stages:

1. First, the written field notes were re-read, and from this, seven initial broad themes were noted, some with several sub-themes.
2. The full transcript was loaded into the software tool nVivo where it was coded for themes (that is, sections of text were 'labelled' with key words/phrases). Not every piece of text was coded (however, over time more and more were, and longer chunks). This was done fairly descriptively, however at the same time ideas were noted down in a separate document relating to ideas which didn't have specific text associated with them; these were less descriptive and more interpretive. From two days' worth of conversation there was a substantial amount of data, and this coding generated in excess of 150 key words/phrases.

3. These key words/phrases were then revisited and merged/nested, to form a hierarchical structure. From this, the five subthemes emerged.
4. All of the quotes within each of these themes were then re-read and the most representative quotes were pulled out. At that point, quotes were cut down as far as possible whilst still retaining the essential idea.
5. These quotes were then used to inform the writing of the subsections of this report.
6. Following feedback from the Imagination Institute, minor revisions to the report were made. This work included emphasising some of the themes which the Imagination Institute advised were less apparent at other retreats.
7. Participants were contacted to check they were happy with the use of the quotes attributed to them, prior to publication of the final report.