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SYSTEMS BIOLOGY, INTERDISCIPLINARITY AND DISCIPLINARY IDENTITY

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Introduction

While waiting in the entrance hall of an impressive new building for the interdisciplinary biosciences in the UK I watched a monitor set up on a constant loop with a slide show for guests. One of the images which flashed up was a picture of six students standing in front of the new building and smiling. The title was "some of the first new systems biologists". The extent to which these students associated themselves with this title is something that I will investigate in this chapter, which focuses on interdisciplinarity in the new field of systems biology, and its implications for individual disciplinary identity.

I start by exploring various different understandings of interdisciplinarity, and describing how I am using the term. I distinguish between individual and collaborative interdisciplinarity, and then examine two types of motivation for an interdisciplinary approach: the question and the object. Both of these motivations are found in systems biology. But despite the strong motivations for interdisciplinarity in systems biology, practical problems result from attempts to institutionalise this interdisciplinarity, and battles have to be fought in setting up systems biology institutes. Even when these institutes have been set up, cultural barriers still exist between people in different disciplines, exacerbated by the fact that not all disciplines have equal status in systems biology (as is indicated by the name 'systems *biology*'). There is also much discussion of communication difficulties, which focuses particularly on the widely-used metaphor of language. But all of these discussions are based on the assumption that the interdisciplinarity is *collaborative*. Once we start talking about interdisciplinarity in an *individual* sense, this gives rise to new issues, particularly concerning scientists' own conceptions of, and struggles with, their disciplinary identity, which, as I will show, vary depending on the seniority of the researcher. An analysis of individual interdisciplinarity leads to discussions about the best way of training new systems biologists. In the conclusions I suggest that systems biology is presently best understood as an emergent phenomenon resulting from the coordination of multiple sets of expertise, and that interdisciplinarity at an individual level is going to require structural changes and policy interventions.

This chapter draws on 35 interviews with systems biologists in the US and the UK, selected on the basis of their location in systems biology institutes.[1] The interviews were conducted between late 2005 and early 2008. A subset of the interview questions were specifically focused on interdisciplinarity and disciplinary identity, and it is these answers which are analysed here. The interviews were taped, transcribed and coded. Recurrent themes were extracted from analysis of the interview transcripts following the principles of grounded theory (see Glaser 1965; Strauss 1987; Strauss and Corbin 1988). Interviewees are cited here using anonymised code-names which refer to their original discipline of training and their country of work.[2]

The chapter is also based on attendance at systems biology conferences and workshops, extended stays in three systems biology laboratories in the US and the UK, and two discussion meetings with systems biologists (with approximately 40 people at each meeting). Additionally it draws on three consecutive years of two day long teaching sessions on social and philosophical issues in systems biology at one of the few Doctoral Training Centres in the field in the UK.

Understandings of interdisciplinarity

The term 'interdisciplinarity' is not defined consistently in the literature, so it is necessary to clarify how I am using it here. I am defining interdisciplinarity as the integration and synthesis of perspectives from different disciplines (see Barry et al. 2008), in contrast to multidisciplinarity, which I am defining as the combination of several different disciplines, in an additive, rather than integrative manner (Thompson Klein 1990), i.e. "where each discipline works in a self-contained manner with little cross-fertilisation among disciplines" (Tait and Lyall 2007). A further distinction is particularly relevant to studies of collaboration. This is the difference between interdisciplinarity at the level of the *individual* researcher, where one person integrates perspectives from different disciplines in their work, and interdisciplinarity as the result of a *collaborative* endeavour, were different disciplines come together to bring their insights to a problem. Collaborative interdisciplinarity fits well with Hackett's (2005) definition of collaboration as "a family of purposeful working relationship between two or more people, groups, or organizations" (p.671). Individual interdisciplinarity, in contrast, requires that one person has multiple skills.

This is a very simple distinction but it is one that is not widely discussed.[3] As a result, when people talk about 'interdisciplinary research' it is often not clear which one of these is being referred

[1] Systems biologists visiting the UK from France and Japan were also interviewed.
[2] For clarity, interviewees are classified as either 'biologist', 'computer scientist', 'physicist' or 'mathematician'. How they personally identify themselves is a topic that is explored below.
[3] Some exceptions are Collins et al. (2003), who distinguish interdisciplinarity at the individual, collaborative and disciplinary level, and Evans and Randalls (2008), who reflect on their personal experiences of doing doctoral research which spanned the social and the environmental sciences.

to. As I will show, the distinction is not hard and fast, because research that starts off being interdisciplinary in a collaborative sense often affects the behaviour of the collaborating researchers, who then may become increasingly interdisciplinary in an individual sense as a result of being exposed to different disciplinary perspectives.

In the context of collaborative interdisciplinarity, one further distinction that it is helpful to make is between an 'integrative-synthesis' mode of interdisciplinarity and a 'subordination-service' mode (Barry et al. 2008). In the 'integrative-synthesis' mode the contributing disciplines all make equal contributions to the knowledge produced. In the 'subordination-service' mode the different disciplines do not play an equal role, but one discipline, such as computer science, performs a service for another discipline, such as biology (Barry et al. 2008).

Both types of interdisciplinarity are driven by similar motivations, one of which is the question or the problem being addressed, which will often demand that resources and skills are drawn upon from many different disciplines. As Eddy (2005) says in respect to interdisciplinary work: "you want to go where a question takes you, not where your training left you" (p.3). This question-driven interdisciplinarity is often seen where research takes place outside academia, because the issues that are important to society and the economy (such as climate change) often transcend the barriers of traditional disciplines (Barry et al. 2008). This is the kind of interdisciplinarity (or, to use their preferred term, 'transdisciplinarity') described in Gibbons et al.'s (1994) discussion of Mode 2 knowledge production.[4] They talk about how this type of knowledge, which cuts across different disciplines, emerges from a specific context of application in order to solve a particular problem. However, it would be misleading to assume that all interdisciplinarity work is by definition 'applied' or problem-oriented (see Evans and Randalls 2008). As we will see below, systems biology is highly interdisciplinary, but most systems biologists are concerned with fundamental biological questions, rather than real-world applications.

Aside from the question being addressed, another motivation for interdisciplinarity is the object. A new object of study can give rise to an interdisciplinary approach, or conversely, interdisciplinarity itself can "lead to the production of new objects and practices of knowledge" (Barry et al. 2008:42). Here we see that there can be a close relationship between disciplines (or interdisciplines) and the objects that are considered to be legitimate foci of research.

Systems biology

Systems biology is a new approach to biology which started attracting funding and attention in the late 1990s. Over recent years many governments have prioritized systems biology in their budgets and a

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[4] Gibbons et al. (1994) use the terms 'transdisciplinary' and 'interdisciplinary' interchangeably (see for example p.29).

growing body of literature identifies itself as systems biology (Powell et al. 2007). Although there were attempts to apply systems theory to biology in the 1950s and 1960s (see for example, Bertalanffy 1950), these did not take off because of their perceived lack of relevance to biological questions (Kitano 2002). Systems approaches to biology have flourished more recently because of the vast amounts of genomic, transcriptomic and proteomic data that have been made available by the human genome project and other sequencing projects, along with the development of advanced computational and mathematical tools necessary to analyse this data (Powell et al. 2007, Vermeulen 2009). It has now become possible to pursue the main objective of systems biology: to integrate molecular data to produce dynamic computer-based (or '*in silico*') models of biological systems (Ideker et al. 2001). To do this, systems biology requires the skills of physicists, computer scientists, engineers, mathematicians, statisticians and biologists, which makes systems biology a purposely interdisciplinary approach to biology, to such an extent that some define the field as "a new culture of interdisciplinary work" (Biologist3, UK). At the moment, systems biology is mainly interdisciplinary in a *collaborative* sense, although this may change in the future, as discussed below.

The emphasis on integration and synthesis of disparate types of molecular data that we see in systems biology contrasts with earlier periods of biological research. The development of the biological sciences in the nineteenth century has been described by historians as exhibiting increasing specialisation, with disciplines such as natural history bifurcating into botany, zoology and bacteriology, for example (Ben-David and Zloczower 1991 [1962]; Lemaine et al. 1976). After this period of specialisation, we are now seeing a period of synthesis, where new fields are crossing existing disciplinary divides. Powell et al. (2007) suggest that this may be due to the recognition of "deep underlying commonalities in biological organisms, for example regarding cellular mechanisms or biochemical processes" (p.25).

Why be interdisciplinary in systems biology?

There has been a great deal of policy pressure for interdisciplinarity across all areas of research in the last decade, both because "creativity is seen to lie in the ability to combine elements from many sources" (Strathern 2006: 192), and because of the supposed practical relevance of interdisciplinary research. But rather than interdisciplinarity being a trend or something imposed by funding bodies, in systems biology it is often argued that the motivation for interdisciplinarity is that it is the only way of understanding and integrating the data and solving the problems that are being raised by the field. For example, during my fieldwork I interviewed an astrophysicist who had been hired to apply his skills in the simulation of galaxies to systems biology.

Also, the object of study in systems biology (biology as a system) is different from the object of study in biology as traditionally practiced (e.g. the gene or the protein), so it seems as if this new object of study in the biological sciences has itself given rise to an interdisciplinary approach. This is an example of how new objects of study are created by interdisciplinary practices, and resonates with Mattila's (2005) idea of 'object oriented interdisciplinarity', where objects are themselves the "carriers of interdisciplinarity" (p.533). In fact, Mattila defines interdisciplinary research in this manner, as "the form of research collaboration in which the shared object is defined and new tools and practices for collaboration are developed" (p.537). Systems biologists are increasingly finding that their objects of study are not well suited to traditional biological approaches, and they have to draw on diverse types of disciplinary expertise. However, it may also be the case that the interdisciplinarity approach has itself allowed the biological system to become a legitimate object of study. In this way systems biology is an example of how new objects can create (and simultaneously be created by) interdisciplinary practices.

Keller (2007) interestingly makes a direct link between the object of study in systems biology and the social arrangements that have been formed around it. Describing the changes that we are witnessing in systems biology she says:

> "we are beginning to see a shift in focus as the search for biological function turns to the cellular processes responsible for regulation, and to the cross-talk between and among all the players of the cellular orchestra. Communication has become the new buzz word in biology, and it captures the discovery by traditionally reductionist life scientists of the powers of sociality" (Keller, 2007: 107).

The communication and interactions that the scientists find in the cells they study are being mirrored by the collaborative arrangements that they are developing in their own research. We see a similar parallel in a document from the UK's Biotechnological and Biological Sciences Research Council (BBSRC) which states that a systems biology approach must "take into account the organisation of individuals into interacting networks and communities" (BBSRC 2006: 26). What they mean by 'individuals' and 'communities' here are molecular interactions, but the point is that interacting *social* networks are required to study the molecular ones.

Setting up collaborative interdisciplinarity

Even if systems biology's collaborative interdisciplinarity is the product of necessity, this does not mean that the institutionalisation of interdisciplinarity has been easy. Many leaders in the field talk about the obstacles they have faced in trying to set up systems biology within normal academic structures, and how they have had to fight against the constraints of academic bureaucracy. Scientists, lab managers and centre directors all pointed out how traditional academic environments make interdisciplinary work difficult and how "new ideas need new organisational structures" (Biologist1, US). This quotation shows that the kind of interdisciplinary collaboration that people are instigating in systems biology is primarily face-to-face. Co-location is considered to be a crucial ingredient in systems biology, despite the *in silico* nature of much of the work. All the institutes of systems biology I studied had already or were working to bring together biologists, mathematicians, statisticians, physicists and computer scientists under the same roof. For this reason new buildings are often required, such as the Institute for Systems Biology in Seattle and the Manchester Interdisciplinary Biocentre – which required "an enormous struggle" (Biologist4, UK) to set up.

Such new "gleaming temples to interdisciplinary bioscience" as Thrift (2006: 292) describes them, have interdisciplinarity purposely built into the design, often with no walls between the laboratories, and specially designed social spaces which mean that the 'wet' experimental and 'dry' computational people will easily come across one another. Because of the attempt we see in structures such as these to "socially engineer the process of scientific discovery" (Thrift 2006: 294), buildings of this type have been described as examples of 'performative architecture' (see also Stephens et al. 2008). Performative architecture does not determine scientific interactions, but it can be understood as both "the object of human agency and as an agent of its own" (Gieryn 2002: 36), which facilitates and enables certain types of interdisciplinarity.

Attitudes of people in different disciplines

After setting up institutes and centres for systems biology there are further difficulties to contend with. The first is overcoming the initial assumptions different groups of scientists have about other fields. My US interviewees drew my attention to an article in *Science*, which they thought summarised their experiences well: "Biologists think of themselves as wise, sagely knowledge banks, and they see computer people as keyboard jockeys. The computer guys think of themselves as mathematics-driven scientists. They think of biologists as lab technicians." (Kling 2006: 1306). A UK interviewee made a similar observation in describing how, in their preliminary interactions with biologists, computer scientists "tend to walk in and say 'right! I've got all these tools, show me your tedious little problem and I'll solve it for you'" (Computer scientist4, UK).

I was engaged in many discussions about the difficulties of altering ingrained attitudes such as these. Even small differences in behaviour can have consequences. For example, a biologist said that he had recently realised that his computer scientist colleagues deleted all emails in capitals, which explained to him why his email messages were not being read. These apparently insignificant habits or practices can have implications for interdisciplinarity, to such an extent that a UK computer scientist insists that "You must not under-estimate the importance of culture in blocking interdisciplinary advances" (Computer scientist1, UK).

Problems are sometimes exacerbated by the fact that there is not necessarily a democratic balance between the disciplines that are coming together. The field is called systems *biology* and many senior scientists stress the centrality of biology to the scientific work. For example a US biologist says:

"I think biologists need to drive systems biology, because if it's driven by computation or engineers, without a depth of training in biology, they lose that sense, they tend to treat molecules as nodes and edges without a sense of how they're performing their functions" (Biologist7, US). A UK biologist also emphasises how systems biology cannot be conducted without biological "intuitions" (Biologist10, UK).

So does this mean that biology dominates in systems biology? Are the computer scientists and mathematical modellers merely providing a service for the biologists? This would tie in with Barry et al's (2008) definition of interdisciplinarity as the subordination or service of one discipline to another. When I put this point to one mathematician he reflected thoughtfully that rather than working for the biologists, he was working for the biological *problem* (Mathematician1, UK). Here the biological problem becomes the 'master' rather than one discipline or another, which ties into the ideas about the motivation for interdisciplinarity coming from the problem focus, rather than from externally imposed demands. What we see here is the mutual dependence of different experts in addressing a shared problem.[5]

Communication problems

Another issue which arises in bringing people together is the difficulty of communication. Talk of different disciplines almost inevitably leads to talk of languages and of translation among systems biologists. The idea of language is sometimes used metaphorically, as in the case of a biologist who says: "we all have to speak a common language which is biology, but at the same time we have to also speak with an accent of mathematics" (Biologist9, US). The idea of mathematics being an 'accent' is interesting, but what exactly does 'language' mean here? On closer interrogation, another biologist explained "It's not only the words, it's also the logics behind it, the syntax if you like, so it's really the way that thinking is structured" (Biologist8, UK). This is arguably the case for the kinds of 'languages' we are more familiar with (such as French and English): they do not just require different words, but also subtly different ways of thinking (see also Lewis, this volume).

Others, however, use the idea of language more literally to mean the actual words that are used. A mathematician explains, "If you didn't know any biology it might as well be in Japanese" (Mathematician1, UK). In this case he mentioned the word 'telomerase', which someone outside of biology would simply not be able to use if they did not understand its meaning. Here we see that the idea of language is straightforwardly to do with the meaning of technical terms. An example of the differences caused by terminology was given by a computer scientist who explained how a colleague

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[5] This is a phenomenon which Law (1973) also notes, and explicitly connects to Durkheim's notion of organic solidarity. He distinguishes collaborations based on mechanical solidarity (where there is consensus about theories and methods), to those based on organic solidarity (which make use of a variety of theories and techniques in order to address a particular problem).

who was a biologist came into his office and "started ranting on about how *in silico* people are using all these bloody acronyms. And we were all looking at him like 'what are you talking about? Have you ever seen a paper, a molecular biology paper full of PPLK2AX?'" (Computer scientist3, UK, see also Penders et al. 2007). When it comes down to terminology, jargon and acronyms, language becomes much more than a metaphor.

Scientists working in systems biology talked about how they have developed a kind of shared language where they have learnt to use some of the words from other disciplines in a way which facilitates communication. Here they could be understood as developing 'pidgins', as Galison (1997) has described in branches of physics. Whether it is in terms of a broader culture and way of thinking, or the down-to-earth use of words, languages are key in understanding collaborative interdisciplinarity.

It is necessary to do more than just develop a shared language, however. It is also necessary to have a particular 'mind-set', and even a particular type of personality, according to some interviewees. In systems biology there is much discussion of the type of person who is best suited to interdisciplinary collaboration. It is said that they must be willing to learn about many different topics, and even to plunge into a new area that they are not familiar with. This is described as "kind of exciting but also kind of scary" (Biologist7, UK), because scientists have to put up with being uncomfortable and not having full command of all the contributory knowledge-bases. As one biologist jests: "being ignorant and incompetent isn't a curse any more" (Biologist1, France). The willingness to be ignorant has to be accompanied with a kind of humbleness: "Arrogance is the bane of systems biology, so you need to be humble and recognise that what other people are doing is just as valuable" (Biologist3, US). (Although others pointed out that it was necessary to posses a certain level of confidence in order to express this humility).

Individual interdisciplinarity and disciplinary identity

As this discussion illustrates, the type of person who is well-suited to interdisciplinary collaboration is the kind of person who is willing to learn new things and to venture into new areas. We can see how this kind of person would be well-suited to becoming interdisciplinary in an individual sense. But one of the consequences of becoming interdisciplinary as an individual is that disciplinary identity becomes problematic.

The importance of personal disciplinary identity struck me during my fieldwork when I spent a couple of weeks at one of the leading institutes for system biology in the USA. During my stay I was asked to hold a discussion group on my ongoing work, and, encouraged by one of the junior scientists I had previously interviewed, I asked the group as a whole (40+ people), to say if they identified themselves as a 'systems biologist' by a raising their hand. To my surprise not one of them volunteered. After a pause, this led someone to quip that being a systems biologist was an emergent property.

This initially appears surprising in a context where, as we have seen, there have been immense efforts to establish new interdisciplinary facilities and to bring people together, and to enable them to communicate and overcome ‘language’ barriers. However, these efforts are all directed towards increasing interdisciplinarity in a collaborative sense. Does this trickle down to interdisciplinarity in an individual sense? To answer this question, I look more closely at the different dimensions of the responses systems biologists gave me when talking about their own disciplinary identity.

Senior scientists

Rather than identifying themselves as systems biologists, most of the senior scientists self-identified along disciplinary lines, usually referring to their own training by saying ‘I was trained as an X’. For some, X is a straightforward disciplinary identity such as biologist (Biologist4, US) or physicist (Physicist1, US), while others preferred a more specialised sub-disciplinary identity such as molecular biologist (Biologist7, US), biochemist (Biologist9, US) or geneticist (Biologist10, UK). A few added that they no longer saw themselves as members of their original discipline. For example, one of the scientists who was trained in physics said he had been working in experimental biology for the last 30 years, and another who had trained as a computer scientist said that he now described himself as a bioinformatician (Computer scientist1, US). A keynote speaker at one systems biology conference summarised some of the feelings of fluctuating identity within the field in saying "I don't know what I am, some kind of purgatory between mathematics and biology" (Jeremy Gunawardena, Manchester systems biology conference, 2006).

After initial reticence to self-identify as a systems biologist in the US discussion group, one faculty member did eventually volunteer, and a couple of others then plucked up the courage to do so. Wider discussions show that some senior scientists based at systems biology institutes do describe themselves as systems biologists, probably because they feel secure enough in their position to assert their identity in this way. For example, Hiroaki Kitano, the leading figure in Japanese systems biology, is a notable self-proclaimed systems biologist (see Fujimura 2003).

Those with greater experience talked about how they could bring skills from different disciplines to bear on a particular research problem. A senior US scientist says that there are “a relatively large group of senior scientists and experienced people like me who carry the experience that you need in a discipline that’s not your own” (Computer scientist1, US). In this way, seniority gives advantages because it gives one a choice about the field in which one wants to strategically position oneself. For example, the head of a systems biology institute in the UK said “I've got 50 papers and I can pick any subset, and I could go into chemistry or biology or even at a pinch computing” noting that “for the younger people this is much harder” (Computer scientist1, UK). He emphasised that research evaluation procedures, such as the Research Assessment Exercise in the UK, since it works along established disciplinary lines "is absolutely an anathema to this multi-disciplinary kind of stuff", and worried that it may be discouraging younger people to identify with a field such as systems biology. Here we see how a shift from collaborative interdisciplinarity to individual interdisciplinarity requires an accompanying shift in reward structures, which has not yet occurred. This is also a problem in the US. One biologist even argued that "The whole sociology of tenured positions has to change" (Biologist3, US) in order to adjust to new fields such as systems biology. This may involve re-thinking what constitutes an achievement and what is recognised as research quality (Biologist5, UK). These points resonate with ideas found in Gibbons et al. (1994) and Nowotny et al. (2001) about how the shift to inter/transdisciplinary Mode 2 science will require new ways of evaluating research.[6]

Junior scientists

Despite these concerns, I found that junior, less well established scientists were generally more comfortable with identifying themselves as systems biologists (although not in a public forum such as a discussion group in front of their senior colleagues). They were less mono-disciplinary in training (for example a postdoc at ISB described her training as "geo-bio-cogno"), and more influenced by demands for interdisciplinary skills.

One explanation for this may be that these junior scientists are usually embedded in institutes for systems biology. This requires a commitment of some sort to the goals of the institute (Biologist7, US), it temporarily shields them from the mono-disciplinary pressures of research evaluation, and affects their understanding of their own disciplinary identity. The head of a systems biology institute, for example, says that a mathematically trained scientist who comes into his institute has to be "happy to portray himself or herself [as some] sort of biologist" (Physicist1, Japan). He thinks that without this kind of commitment then they should not be engaged in systems biology. This point was echoed by a young UK mathematician moving in to systems biology who recognised that he could not remain a mathematician and work in systems biology.

A postdoctoral researcher from the US says he would primarily describe himself as a systems biologist, particularly if talking to someone from outside his institute (which shows that one's disciplinary identity often depends on who is asking). However, he says that in graduate school he would have called himself a bioengineer, with the added rider that he works in the field of systems

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[6] A similar point about the measurement of research quality is made by Funtowicz and Ravetz (1993) in respect to 'post-normal' science.

biology. He said he still thinks of himself as a bioengineer, showing that he maintains two disciplinary identities simultaneously.[7]

For this younger group, identifying as a systems biologist does seem to be a relatively recent phenomenon. A postdoc from the UK who had recently been awarded his PhD explained how during his graduate training his supervisors told him not to use the term 'systems biology' because it was regarded as a 'buzz word', which would not necessarily catch on. However, in the last couple of years this policing has relaxed, and he now happily calls himself a systems biologist.

First year PhD students in training at a centre for systems biology in the UK did hope to be able to call themselves 'systems biologists' in the future, but they felt that they could not take on this identity until they had accumulated the requisite skills, which would be at the end of their training. One of them said he was "clinging to the fact that I'm going to be a systems biologist in the future", showing that acquiring this type of disciplinary identity is becoming particularly crucial for those scientists who are being trained in the field, particularly since jobs for 'systems biologists' are starting to be advertised in globally. What is important here is that identity has a trajectory – it is connected to the past and the future (Wenger 2000). An emerging field does not yet have an established past nor a secure future, but as it develops it starts to accumulate a past, and young trainees can then start investing in the future by identifying with the field.

Even among these junior scientists who were more willing to call themselves systems biologists there was a tendency to associate themselves with either the 'wet' or 'dry' side, probably to ease everyday interactions and expectations about the set of skills they possess. A postdoc explained: "lot of times when I'm talking to people here I'll say I'm a computational person" (Computer scientist4, US), while other people will say they are primarily experimental. However, the language of an in-between state was starting to be adopted, and interviewees talked about being "moist" (Computer scientist1, UK) and even "soggy" and "damp" researchers (Systems biology teaching 2009), implying that a there was a spectrum of 'wetness', along which an individual could be placed.[8]

Where interviewees placed themselves along this wet-dry spectrum could change over time. A self-declared 'dry' mathematician who I interviewed two years ago recently told me that he had started to do a few 'wet' experiments (Computer scientist3, UK). This is a clear example of how collaborative interdisciplinarity can lead to individual interdisciplinarity. This interviewee was initially a specialist in particular mathematical imaging techniques, but over the years of working with biological scientists he has started to expand his own skill set and adapt his identity.

We may not be seeing complete symmetry between 'wet' and 'dry' researchers here, however. When I turned my question of disciplinary identity on to a group of UK systems biologists, it was

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[7] This resonates with the point made in the organization studies literature that most people usually juggle multiple identities (Wenger 2000).

[8] Penders et al. (2008) in their study of nutrigenomics also posit the 'moist zone' as a liminal space between wet and dry science, but in this case 'moist' is an analyst's category, whereas in my interviews the term was introduced by the actors themselves.

those trained in mathematics and computation who were more willing to identify as a systems biologists. One mathematician remarked on this difference, saying of the biologists: "I suppose it's because they've always been working in their labs, they don't feel things have changed, whereas the mathematicians and computer scientists are coming to the biology" (Mathematician2, UK), and as a result their experience is more dramatically different.

Training

There is disagreement about the best way to train the systems biologists of the future, and whether individual interdisciplinarity should be encouraged at all. Some think that radical changes in science education are necessary, reaching down to undergraduate or even high school level. Princeton is one of the few places that has an undergraduate training programme in what it calls 'Integrative Genomics'. The co-director of the programme explains that they consider undergraduate training necessary because they want to bring computation and mathematics "to the biologist at a time early enough when they're not afraid of it, and can really incorporate it into the way they think" (Biologist9, US). He continues on a track which shows his clear support for individual interdisciplinarity: "the next generation that we would like to see trained are ones in which the biologist and mathematician is one and the same person". This view is also held by the director of a UK systems biology centre who says "you have to train a new generation of people that think differently" (Biologist1, UK).

A leading US systems biologist recognises that when training systems biologists it will not be possible to teach all the details. Instead "you have to do teaching in a much more conceptual way than is generally done", with less emphasis on memorising facts (Biologist1, US). This point is echoed by senior UK researchers and also by a US policy maker who hopes that we will see a movement from *specialists* to *integrators* in the future (Policy maker1, US).

There is an acknowledgement that training a fully-fledged systems biologist is potentially very time consuming. A senior US systems biologist thinks that in the future all scientists should have a dual major (Biologist1, US), but a head of a centre in the UK doubts the desirability of being "bilingual" (returning again to the language metaphor). A student who had been through interdisciplinary PhD training in mathematical biology was more positive about the prospects for interdisciplinary training, although he did say that: "half the people turned into interdisciplinary people, at the end of it, and half of them pretended to" (Mathematician1, UK).

In one new UK doctoral training centre for systems biology they are adopting a two-pronged strategy. On the one hand, they are training their students to have a specific interdisciplinary expertise. As one of the course developers explained: "the students will still become the world's expert on something, this is not chemistry, it's not physics, not mathematics but it's a new something, somewhere in between them" (Biologist11, UK). But "at the same time the students must be trained to be able to talk to other people that are interdisciplinary or mono-disciplinary…to be able to understand what they do". In this way they are also training their students to have interfaces, to be "the broker in between" (Biologist11, UK) different disciplines, so they have skills in facilitating communication, and knowing which are the appropriate questions to ask. This is described as being "a light expert in the other disciplines" (Biologist11, UK).

Hood (1992) argues that interdisciplinary researchers will become leaders in biology and medicine in the twenty-first century. But interviewees stress that in order to do this, they will have to "find new ways of speaking and to be able to communicate across different conceptions of the world" (Computer scientist2, US). This is placing considerable demands on these young people. Some of the literature on interdisciplinarity points out that the kind of person suited to interdisciplinarity is someone who must have "a high tolerance for ambiguity" (Tait and Lyall 2007:3), since "one knows one is in an interdisciplinary context when there is resistance to what one is doing" (Strathern 2005:130). Eddy (2005) interestingly reflects that "People who gravitate to the unexplored frontiers tend to be self selected as people who don't like disciplines—or discipline, for that matter." (p.4). It will be interesting to see whether these are characteristics of those become involved in systems biology in the future.

Others think that we should not aim to introduce undergraduate programmes in systems biology, partially because of the requirement that a young scientist needs a specific disciplinary background in order to grow their own career. Some people feel strongly about this issue: "you can't be trained interdisciplinary, because a discipline requires training, so interdisciplinary training can't exist" (Biologist10, UK). However, if we follow this scientist and define a discipline as a place where training is done, we are effectively defining away the possibility of interdisciplinary training.

Even those who do not advocate systems biology training at undergraduate level do think that the training of biology undergraduates in mathematics needs to be radically improved (Biologist5, UK). Another point on which there is wide agreement is the necessity to have "people that speak the same language" (Biologist10, UK) since "very few physicists speak biology and very few biologists speak mathematics" (Biologist9, US). In summary, there is no consensus about the best way to train systems biologists, and this is something that is currently the subject of heated discussion at many systems biology meetings.

The future

So how will scientists working in systems biology self-identity in the future? A Director of a UK institute argues that "a self respecting biology department in the future won't put out someone who doesn't know bioinformatics and modelling" (Computer scientist1, UK), and we do see a widespread hope that systems biology will become the dominant approach to biology. This point is made by a UK biologist who says "every biologist is a systems biologist, just a proper biologist" (Biologist10, UK). Others agree that biology will become systems biology, and if it does then the career path will become clearer (Biologist11, UK). The head of an institute says that scientists trained as systems biologists should not worry about not having a particular disciplinary identity because they "will maintain their career trajectory much better by becoming systems biologists with a huge number people willing to hire them at the end" (Computer scientist1, UK). One senior scientist expands this point in saying that there is too much concern about disciplinary identity. He complains "I think there's a lot of fuss made about this business of an identity, I mean, first and foremost you're a scientist" (Biologist4, UK). Perhaps this is how the systems biologists of the future will identify themselves.

The head of one UK systems biology centre agrees that biology will become systems biology, and it will be so pervasive and widespread that simply describing yourself as working in systems biology will not be sufficient. He explains:

> "now people will say that they're a molecular biologist, but that in a way isn't enough, you need to know what they're working on as a molecular biologist, and I think the same will be true of systems biologists. So people will say 'I'm a systems biologist' to describe the kind of biologist they are, but that, in itself, only tells you what kind of biologist [they are], and you need to know what their area of focus and application is" (Biologist5, UK).

Conclusions and implications

There are two possible routes for the systems biologists of the future. On the one hand we may see the development of all the skills necessary for systems biology in the same person, who will become interdisciplinary in an individual sense. If this occurs perhaps an appropriate metaphor for a systems biologist would be a multi-headed and handed creature like the Hindu God Krishna in his Vishvarupa form.[9] On the other hand, systems biology may remain a distributed activity, with perhaps a greater mutual understanding of different disciplinary 'languages'.

At the moment systems biology is primarily interdisciplinary in a collaborative sense, with the research that results being the 'emergent property' of the skills of different experts. Collaboration, with its attendant difficulties of bringing people together and of facilitating communication, is currently the most important challenge in systems biology research. Individual interdisciplinarity is currently more of an aspiration than a reality, although we have seen examples of training which attempts to produce students who are 'integrators' or 'brokers', and have a 'light expertise' in a discipline outside their core area of work.[10] There are also cases where individuals who engage in

[9] "With many faces and eyes, presenting many wondrous sights, bedecked with many celestial ornaments, armed with many divine uplifted weapons; wearing celestial garlands and vestments, anointed with divine perfumes, all wonderful, resplendent, boundless, and with faces on all sides" (Campbell 2008, p.198).

[10] This is similar to what Collins and Evans (2002, 2007) call interactional expertise.

collaborative interdisciplinarity change their behaviour, and as a result become more interdisciplinary in an individual sense. In these situations their individual disciplinary identity may become problematic.

As briefly mentioned above, Galison (1997) famously draws on the anthropological notions of pidgins and creoles to discuss communication across disciplinary boundaries in physics, but I think his discussion can also help elucidate our understanding of the transition from collaborative to individual interdisciplinarity. Galison describes how a pidgin is initially just a basic tool for communication between two different groups (primarily in the interests of trade), but

> "As the pidgin expands to cover a wider variety of events and objects, it comes to play a larger linguistic role than merely facilitating trade. Eventually, as children begin to grow up 'in' the expanded pidgin, the language is no longer acquired to solve specific functions but now must serve the full set of human demands" (p.833).

Once this situation is reached the language becomes a creole. The way Galison describes this shift makes it seem as if it is almost inevitable. We may well see an analogous situation in systems biology, where the trainees in new centres 'grow up' with a working pidgin that they then transform into their own creole, as they become fully-fledged systems biologists. However, the implication of this analogy is that once collaborative interdisciplinarity has been transformed into individual interdisciplinarity, systems biology will then itself become a discipline, and so will, by definition, no longer be interdisciplinary. This tendency of interdisciplines to congeal into disciplines over a period of time is noted in the literature,[11] and could, according to some criteria, be considered to be the measure of success of a (previously) interdisciplinary field. However, the contention over the training of systems biologists shows that there is no guarantee that individual interdisciplinary will result, or that systems biology will, as a consequence, become a new discipline. Perhaps this should not even be an aspiration. Instead of establishing a new discipline, maybe those who describe themselves as 'systems biologists' in the future will be integrators rather than specialists, as some of my interviewees hoped, and will be in this sense 'post-disciplinary' (Sayer 2003).

In order for this to happen, however, there will need to be substantial structural changes at the level of science policy, in order to address "the problem of establishing a post-disciplinary identity in a highly disciplinarised modern academy" (Evans and Randalls 2008: 589). Not only will teaching and training have to be transformed, but, importantly, academic reward structures will have to change to reflect these developments (McCarthy 2004). As discussed above, measurements of research quality have shown themselves to be poorly equipped for evaluating work that transcends disciplinary

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[11] For example, Gibbons et al. (1994) talk about how transdisciplinary research is likely to lead to the institutionalisation of a new discipline (p.29).

boundaries (Tomlinson 2000, Gibbons et al. 1994, Nowotny et al. 2001 and Funtowicz and Ravetz 1993). And the conservativism of the peer review process in the face of interdisciplinary research was something that frustrated many of my interviewees.

Whatever the future holds, systems biology is a fascinating integrative post-genomic approach to the life sciences which is likely to set the course for the biology of the future. Its interdisciplinarity is not only interesting in itself, but it can also inform studies of collaboration in other scientific fields by helping us think about how collaboration can have consequences for individual researchers.

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