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Tacit knowledge and the biological weapons regime

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Bioterrorism has become increasingly salient in security discourse in part because of perceived changes in the capacity and geography of life science research. Yet its salience is founded upon a framing of changes in science and security that does not always take into consideration the somewhat slippery concept of 'tacit knowledge', something poorly understood, disparately conceptualised and often marginalised in discussions on state and non-state biological weapons programmes. This paper looks at how changes in science and technology—particularly the evolution of information and communications technology—has contributed to the partial erosion of aspects of tacit knowledge and the implications for the biological weapons regime. This paper concludes by arguing that the marginalisation of tacit knowledge weakens our understanding of the difficulties encountered in biological weapons programmes and can result in distorted perceptions of the threat posed by dual-use biotechnology in the 21st century.

Keywords: tacit knowledge; biological weapons; bioterrorism; Biological Weapons Convention; international security.

1. Introduction

Bioterrorism has become increasingly salient in the security discourse over the last decade partly as a result of the confluence of two events: the attacks of September the 11th and the subsequent anthrax letter attacks. Yet its growing salience can also be attributed to a compelling narrative—premised on the idea that biology and related disciplines are becoming 'easier', more predictable and more prevalent around the globe—in which bioterrorism is somehow inevitable. Thus, against a backdrop of 'new wars' (Kaldor 2006), asymmetrical conflicts and terrorism, a combination of advances in technologies that purport to 'deskill' biological research (such as DNA synthesis machines) and allow greater access to information on the life sciences (including genome information) and a propagation of expertise, are seen to be dramatically increasing the likelihood of bioterrorism (Commission on the Prevention of WMD Proliferation and Terrorism 2008; Toole 2011).

There are a number of manifestations of this narrative, for example the Chinese National Science and Technology Review Paper submitted to the Seventh Review Conference of the Biological Weapons Convention (BWC) stated:

> Developments in biotechnology have come within the reach of some groups and even individuals, and some non-State actors have become more capable of malevolently causing disease, putting international security under great threat. Terrorist groups are improving their mastery of sophisticated biotechnology. With the spread of synthetic biology, some small scale research groups and even some individuals are now able to make the deadly Ebola and smallpox viruses and even some viruses against which all drugs are ineffective, thus making it much harder to counter bioterrorism. Furthermore, it has become much easier to obtain sensitive information. Using publicly available DNA sequences, terrorists can quickly synthesize pathogenic microbes that had previously been eradicated or give existing ones new pathogenic properties. And the means of perpetrating a bioterrorist attack have multiplied. Aerosol and viral vector technology can both be used to spread biological agents and it is highly likely that some terrorist groups will use them to mount a biological attack. (China 2011)

None of the components that underpin this statement are necessarily flawed: DNA synthesis is undoubtedly becoming cheaper and faster (National Research Council 2011; USA 2011); greater amounts of data which could be pertinent to the development of biological weapons is becoming increasingly accessible through the internet; and the life sciences are spreading to the extent that McLeish and Trapp (2011) have begun to speak of a 'post proliferation' agenda in which the:

> . . . life sciences are increasingly globally distributed, with top-notch research and industrial facilities in many countries around the globe.

Nevertheless, this framing of the bioterrorism narrative overlooks the important sociotechnical aspects of biotechnology not least of which is the role of tacit knowledge, which is an important ingredient in 'success' in scientific research and bioweaponeering alike.

Although there have been a number of permutations in the selection of agents and delivery mechanisms in past biological weapons programmes—with more combinations potentially becoming possible in the future—in most cases bioweaponeers aspiring to move beyond the crude efforts to spread disease will likely be required to undertake a number of key steps. Such steps include: obtaining the appropriate strain of the pathogen (either by collecting in nature, acquiring from a laboratory or 'synthesising'), handling the organism correctly, growing it in a way that will produce the appropriate characteristics, storing and scaling up the agent in a stable manner, and developing a suitable mechanism to disperse the product properly (Leitenberg 2004). In order to be 'successfully' achieved without destroying the pathogen (or person undertaking these activities), each of these individual steps are likely to require specific information, expertise and 'know-how' in varying degrees. Moreover, the cumulative process of obtaining, handling, culturing, scaling and weaponising an agent is likely to require a broader and deep 'end-to-end knowledge of the materials and processes needed' (Parachini et al. 2005) and the capacity to effectively manage the research process and ensure continuity and complementarity in different phases of activity.

Historically a number of biological (as well as chemical and nuclear) weapons programmes are understood to have stymied or failed to create or optimise effective weapons in part because of a deficit of 'know-how' (Wheelis and Sugishima 2006; Danzig et al. 2012). This limitation is particularly acute in the weaponisation step which is notably where a number of authenticated instances of bioterrorism (Tucker 2000; Danzig et al. 2012) have collapsed or been rendered of limited utility, leading Vogel (2006) to suggest this step is where:

> . . . critical tacit knowledge for bioweapons development primarily resides.

By weaponisation in this context we are referring to the process of optimising the delivery of a pathogen in a manner that effectively generates a significant physiological effect commensurate with public perceptions of biological weapons as having mass destructive effects. However, the utility of biological weapons is not limited to mass infectivity *per se*, and terrorists or state actors could be attracted to biological weapons for their psychological effects in order to attract attention, create fear and undertake economic or political sabotage (Ilchmann and Revill 2013), objectives that would not necessarily require optimised weaponisation. The 2013 ricin letters emailed to President Obama, Sen. Roger Wicker and Judge Sadie Holland (Lee County, MS) serve to illustrate this point. There is a long history of crude efforts to mail ricin and the 2013 letters are believed to contain a ricin preparation generated through the use of one of a number of recipes available on the internet. However, such recipes frequently fail to optimise the use of ricin and overcome the difficult process of milling the toxin to an optimal particle size (Barnes 2013; Hayden and Wadman 2013), instead generating crude unrefined preparation of ricin. As Leitenberg is reported as saying:

> You could ingest this crude stuff, swallow a couple of tablespoons and you'd probably vomit, but not much more. (Ward 2013)

In the context of weaponisation, tacit knowledge thus potentially plays an important role as a 'barrier to optimising and creating effective bioweapons' and warrants further attention, particularly if one is seeking to make some form of evaluation regarding the extent of threat posed by a perceived bioweapons program or assess the implications of advances in science and technology (S&T). Even where optimised weaponisation is not the strategic goal, tacit knowledge may be an important limiting factor in the ability of unskilled actors to exploit advances in S&T, which has important implications for the way in which threat is assessed. For example, statements such as the Chinese National S&T Review Paper (China 2011) highlight a number of assumptions about the threat, which conflate advances in sophisticated techniques for virus synthesis with increased public access to this knowledge. However, to neglect tacit knowledge and conduct an assessment premised solely on material capacities, such as equipment, facilities and the availability of codified information (in for example scientific journals) alone, is unlikely to be adequate, as it ignores the very real and grounded difficulties experienced in the process of doing science; to paraphrase Walker (2012):

> . . . actual capabilities at any particular point in time are perhaps far less advanced than one might assess by looking in from the outside.

Yet despite its apparent importance, the term tacit knowledge remains poorly understood, disparately conceptualised and often marginalised in discussions on state and non-state biological weapons programmes and assessments of S&T (Vogel 2013). Accordingly, this paper begins by introducing and exploring the concept of tacit knowledge, drawing from the work of scholars of S&T studies, but particularly the work of Professor Harry Collins (2010) who has usefully disaggregated tacit knowledge into a three-way classification. Using this three-way classification,[1] with a minor modification to the third category in order to draw attention to the role of team work and communally synthesised knowledge, this paper looks at: weak tacit knowledge, somatic tacit knowledge, and communal tacit knowledge. Each of these categories of tacit knowledge is introduced with examples from either the historical literature on biological weapons programmes (by State and non-State actors) or in the practice of science to illustrate the importance of each category in the practise of bioweaponeering and biology, respectively. The paper then proceeds to look at the implications of the ongoing revolution in information and communication technology (ICT), particularly the use of visualised experimentation protocols and developments in synthetic biology and the role these advances could play in the partial erosion of aspects of tacit knowledge. The paper concludes by addressing the 'so what?' question and looking at the implications for the biological weapons regime. It argues that advances in ICT are leading to the partial erosion of tacit knowledge of relevance to the BWC. In this context, the paper contends the marginalisation of tacit knowledge weakens our understanding of the difficulties encountered in biological weapons programmes and can result in distorted perceptions of the threat posed by dual-use biotechnology in the 21st century.

2. Tacit knowledge

The concept of tacit knowledge is often understood by reference to its opposite, that is, explicit, fully articulable knowledge that can be conveyed from the knower to a recipient by means of language. In contrast, tacit knowledge is commonly perceived as involving a process of 'learning by example' or 'learning by doing' that can only be acquired through practical hands-on experience (Polanyi 1974). One commonly cited example of tacit knowledge is that of riding a bike, or, more specifically, balancing a bike, an act that requires a certain 'sixth sense' that becomes natural after time, but is difficult to explain in real time to someone trying to balance a bike for the first time. As MacKenzie and Spinardi (1995) have stated:

> Most of us, for example, know perfectly well how to ride a bicycle yet would find it impossible to put into words how we do so.

Yet, while perhaps the most obvious element of tacit knowledge, the bike analogy belies a range of categorically different types of tacit knowledge that could (and should) be considered, particularly when examining the role of tacit knowledge in scientific practice. It is thus an oversimplification to view tacit knowledge solely in terms of the bicycle balancing analogy. Indeed, precisely because different understandings of tacit knowledge and 'tacitness' confuse the debate on this issue, these different categories need to be teased out and separated.

Accordingly, three subcategories of tacit knowledge are outlined and developed in Sections 3–5 using the work of scholars, such as Collins, who has identified a number of different types of tacit knowledge and varying degrees of 'tacitness'. While not accepted homogenously across the S&T studies community where debate continues over the conceptualisation of tacit knowledge, these categories of weak tacit knowledge, 'somatic' tacit knowledge, and communal tacit knowledge, are nonetheless a useful framework to elaborate upon the concept of tacit knowledge in relation to biological weapons and understand the likely impact of the internet on the spread of types of tacit knowledge.

3. Weak tacit knowledge

Weak tacit knowledge is that which could, under certain circumstances, be rendered explicit but either through inability, unwillingness or practicality remains unwritten and implicit. There are a number of specific subcomponents of weak tacit knowledge. Collins (2010) for example, talks of, *inter alia*, 'logistically demanding knowledge', 'concealed knowledge', 'ostensive knowledge', 'mismatched saliences' and 'unrecognised knowledge'.

Concealed knowledge is that which can be 'conveyed in a few words' but is 'deliberately kept hidden' (Collins 2010). In the practice of chemical, biological, radiological and nuclear weapons there are likely to be a number of examples of where competing factions of researchers engaged in the deliberate stove piping of information and knowledge. This is perhaps best articulated in the chemical and biological weapons (CBW) context by Vogel (2006) in her study of bioweapons proliferation:

> Although SNOPB [Scientific Experimental and Production Base] did receive several hundred pages of technical documents involving previous MOD anthrax work, some classified information was not sent to SNOPB. Ken Alibek attributes this to turf issues and competition between Sverdlovsk, the MOD, and SNOPB. As a result, this type of intentionally concealed tacit knowledge . . . would only be conveyed through personal communication with the original developers of the Anthrax 836 weapon.

Logistically demanding knowledge has been illustrated using the example of the 'old warehouseman', and covers individuals who knows where everything is and maintain a mental database of the warehouse contents, yet for pragmatic reasons of cost/benefits to the business, this information is not articulated. Such a concept at first may appear far removed from the world of CBW, however, in the process of obtaining agents, for example, logistically demanding knowledge could be useful and certainly a RAND study highlighted the role of:

> . . . administrative and security personnel who are likely to possess sensitive information about the facilities or institutes in which they work. (Parachini et al. 2005)

Indeed, there are a range of aspects of logistically demanding tacit knowledge that could be employed in the acquisition of chemical and biological materials, including: knowledge of security procedures to facilitate theft; knowledge of customs and/or police procedures; knowledge of the pharmaceutical sector or other industrial structures to facilitate purchases of materials and equipment; and a knowledge of fixers and individuals who can make arrangements and links between sets of people. None of these is fixedly tacit, on the contrary all these could be written down. Nor are they sufficient to generate functioning weapons alone. Yet they are elements which could facilitate the acquisition of materials and/or their transfer.

Perhaps of greater significance is the concept of ostensive tacit knowledge, defined by Collins (2010) as:

> . . . knowledge that can be learned only by pointing to some object or practice because the description in words . . . would be too complex to be spoken.

Again, the work of Vogel (2006) in relation to bioweapons proliferation is useful in this regard:

> Solving various engineering problems related to the unique infrastructure at SNOPB involved a trial-and-error process that deployed knowledge obtained through previous hands-on experience from working with fermentation, biosafety, drying, and milling equipment. Again, transfer of the 65 experienced MOD staff likely contributed to deciphering these types of ostensive tacit knowledge and adapting existing MOD protocols to work at SNOPB.

Two final, closely linked, examples of weak tacit knowledge identified by Collins are those of 'mismatched saliences' and 'unrecognised knowledge'. In the case of the mismatched saliences, these are argued to occur when:

> . . . person A, who wants to convey everything they know to person B, assumes that person B is in possession of some essential piece of explicable knowledge . . . when in fact they are not. (Collins 2010: 95)

It is not difficult to imagine how mismatched saliences can confuse. In the world of biological disarmament diplomacy mismatched saliences can (and do) occur frequently through the use of acronyms, the use of which is not a necessarily a deliberate effort to conceal knowledge, but rather a shorthand which can become inadvertently inaccessible to those new to the field.

To provide an example, experts in the CBW field may agree or disagree with the suggestion that:

> . . . the BWC needs an OPCW style SAB supported by the ISU and the IAP to build on the new ISP's S&T SAI discussion in the MX.

However, most in this small community would be able to decipher what is being proposed. Yet those outside would not immediately interpret this as a suggestion that:

> . . . the Biological Weapons Convention needs an Organisation for the Prohibition of Chemical Weapons style Science Advisory Board supported by the (BWC) Implementation Support Unit and the Inter-Academy Panel to build on the new Inter-Sessional Process's S&T Standing Agenda Item discussion in the Meeting of Experts.

The same types of obstacles also apply to biology, as one introductory guide to biology states:

> . . . the biological literature is filled with acronyms, terminology, jargon, and references to kits and reagents with obscure trade names. (Nadeau 2012)

The concept of unrecognised knowledge is perhaps of even greater significance and something illustrated with the seminal tale of the transversely-excited atmospheric-pressure (TEA) laser, which is worth quoting at length to illustrate some of the practical challenges posed by unrecognised knowledge:

> H knew that the leads from the capacitors to the electrodes had to be short, and the glass tubes flat, but had not given any quantitative consideration to these matters . . . These leads were about eight inches long in the laser as first built, which, as H remarks, is 'short by any standards'. When H got to Whitehall, he found that their capacitor leads were considerably shorter than his, and there was 'no limit to how short they should be, just as short as possible'. (Collins 2010)

The examples illustrate an important point on communication or lack of between disciplines and even within disciplines wherein specific communities develop their own dialects:

> . . . loaded with arcane terminology, acronyms and tribal jargon that bind members of one group together but are unintelligible to outsiders. (Restifo and Phelan 2011)

This suggest that weak tacit knowledge is rendered tacit, in part, because of the limits of discursive abilities of individuals, as Collins (1992) notes:

> . . . the general rule is that we know more than we can say, and that we come to know more than we can say because we learn by being socialized, not by being instructed.

4. Somatic tacit knowledge

Somatic tacit knowledge or 'somatic-limit tacit knowledge' refers to things that our bodies can do which we cannot articulate, transfer and replicate as knowledge without the recipient learning by doing. As Collins (2007) points out, it relates to the 'limitations of the human body and brain'. Here the example of riding a bike or, more specifically, balancing a bike becomes appropriate, although any number of activities from curving a football, catching a ball or touch typing could be equally valid. Of course, instructions for all these skills or activities are written down and articulated in various media and there are techniques employed to aid individuals' skills in these areas. Even so, they are not capabilities which can be achieved from instructions alone, rather they require 'learning by doing' in order to be successfully achieved. As Collins (2010) notes:

> When we ride our bikes we do not self-consciously use any physical or mechanical models; somehow, with practice and training, the ability to balance on a bike becomes established in our neural pathways and muscles in a ways that we cannot speak about. We do not learn bicycle riding just from being told about it . . . or reading about it, but from demonstration, guided instruction, and personal contact with others who can ride – the modes of teaching associated with tacit knowledge.

In this context, somatic tacit knowledge is harder to render explicit than weak tacit knowledge. Indeed, it is something which often takes place—at least after significant practice and experience—without conscious thought at all. For example, as this paper is being drafted the authors are able to write text without consciously seeking the specific keys that would be pressed to form words, but rather in an automated manner through touch typing, not (hopefully) without significant thought, but without conscious selection of the keys pressed to form the words used.

Although somatic-limit tacit knowledge may at first glance appear far removed from the laboratory setting, this learning by doing matters in biology, as Nightingale (2003) has stated:

> . . . many forms of memory can only be recalled by doing . . . and these include many scientific and technical procedures.

This is illustrated at some length in Vogel's account of the process of 'douncing' in Wimmer's high-profile polio synthesis experiment which was described by one US Congressional Resolution (Library of Congress 2002) as:

> . . . a blueprint that could conceivably enable terrorists to inexpensively create human pathogens.

This 'blueprint', required the careful preparation of HeLa cell-free extracts using a Dounce homogenizer (a round glass pestle that is manually driven into a glass tube) in order to 'break the HeLa cells open gently and release the cytoplasmic extract'. Difficulties in the 'art' of douncing identified by Vogel (2013) through interviews with researchers working on this experiment are worth quoting at length:

> When you pull on a piston part of the Dounce homogenizerm, that creates a vacuum, and the cells explode because they swell . . . If you pull really slowly on that you don't create much of a vacuum and so you don't break the cells very efficiently . . . [but] you can actually pull on the piston part so hard that you can actually break the bottom out of the Dounce out . . . There is definitely some technique in that, in terms of learning how many strokes do you do and how hard you pull . . . but that is something that is harder to read from the text of a paper and really appreciate.

As this example illustrates, public accounts of science can differ considerably from informal accounts of how science actually takes place, and these public accounts frequently conceal the importance of tacit knowledge. One of the reasons that scientists have difficulty in discussing the role of tacit knowledge could be that reproducibility is considered a key principle of the scientific method and the existence of forms of knowledge that cannot easily be codified and replicated sits uncomfortably with this principle of reproducibility. This is potentially significant for the way in which advances in S&T are assessed in the context of the BWC. Relying on accounts of science that are based purely on publications in journals or in grant portfolios may conceal important aspects of tacit knowledge that are relevant to assessments of how 'easy' or 'accessible' some of these techniques really are.

Since the 2002 polio synthesis experiment, there have been a number of advances in techniques that have made the synthesis of DNA faster, cheaper and easier. For example, the Gibson Assembly technique, which uses enzymes to join two or more sequences of DNA that have overlapping end sequences, is a relatively recent development in *in vitro* DNA assembly methods that has the potential to simplify the construction of large DNA molecules (Gibson et al. 2009). Yet even this technique, as in many areas of molecular biology, requires specific skills such as using equipment like polymerase chain reaction (PCR) machines and general 'good laboratory practices' which are typically not evident in published accounts of scientific experiments.

The importance of developing specific mechanical techniques is, of course, not limited to douncing. Many aspects of life science research require the development of 'tricky' mechanical techniques, whether 'pipetting' (which requires using the correct pipetting angle, using the correct immersion depth, pipetting with a constant rhythm, using the pre-rinsing technique (Mettler-Toledo 2013), cloning the constructs of adenovirus, micro-injection of neuronal cultures, or cell lysis (Nadeau 2012). Developments in high throughput and automated lab capacity could potentially reduce the requirement for human skill, but even the operation of machinery requires a certain level of tacit knowledge in order to ensure that the equipment works, and works consistently. For example, a member of a synthetic biology research laboratory has repeatedly joked that their automated pipetting system will not work for anybody else and that it took him about two years to get it to work at all.[2] Like touch typing or catching a ball, many such activities require practice to master the technique and develop the muscle memory necessary to undertake such activities successfully.

This is particularly evident in some of the experiences of amateur or 'DIY' biologists, who conduct biological experiments as a hobby rather than a profession. The growth of an amateur biology community has been attributed to advances in synthetic biology and the de-skilling of techniques such as DNA synthesis, with concerns being expressed over potential biosecurity implications (Zimmer 2012). However, in practice, the types of projects being conducted by DIY biologists tend to be far less sophisticated than experiments involving genetic design:

> The amateur activity right now is at the seventh- or eighth-grade level . . . We're making $10 microscopes and all of the discussion around us is about weaponized anthrax. (Ledford 2010)

While the majority of truly 'amateur' activity is at this level, some DIY biology groups are beginning to conduct significantly more sophisticated experimentation that draws on advances in synthetic biology. For example, members of BioCurious, a community lab in Silicon Valley, are seeking crowdsourced funding through Kickstarter to bioengineer a bioluminescent plant (Pollack 2013). However, in examples such as this, the individuals involved are professionally trained scientists working on a specific enterprise. The extent to which 'amateurs' are, or could be, involved is therefore questionable.[3]

Rather, the experiences of the amateur biology community serve to illustrate the considerable challenge of mastering the necessary techniques and skills to perform even basic biological experiments. For example, the London Biohacker group, who comprise a mixture of complete novices and some trained or student biologists, have noted the challenge of overcoming 'pipetting errors' when trying to optimise techniques for DNA extraction and PCR process (London Hackspace 2013a). MadLab, a bio group based at the Manchester Digital Laboratory (2013), experienced similar difficulties during their 'PCR challenge', in which they pitched their home-made Arduino-based PCR machine against the open-source OpenPCR kit and the commercial PCR at Manchester Metropolitan University:

> . . . the hardest part of the process was getting our samples into the gel using a micropipette. It turns out there is a bit of an art to pipetting . . . The more experienced pipettors claimed that it took them weeks to get the proper technique. (Manchester Digital Laboratory 2013)

Even the use of equipment for PCR requires a certain level of learning by doing in order to master the 'dark art' (EGlowi Cambridge 2013), and reading a manual alone is not always sufficient:

> After spending some time with the manual I think I have it figured out, *but it's definitely something that's going to need training and/or practice to learn to use* . . . The interface [of the thermal cycler] is quite logical and comprehensible when you're used to it, but it's bafflingly opaque to first-time users! (London Hackspace 2013b) [emphasis added]

The development of these necessary techniques often requires guided instruction and practice, something that is built up over the course of a biologists' academic career and is not always readily accessible to an amateur. This was noted by the 2012 University College London iGEM (International Genetically Engineered Machine competition) team who collaborated with the London Biohacker group to develop a 'public biobrick' (a standardised, interchangeable biological device):

> Academics build their knowledge step by step, but a biohacker may not have that structure of knowledge – they have gaps here and there, so their knowledge isn't so well organised . . . I think the Biohackers gained a lot of experience [from the collaboration] in terms of structure because within science, the steps to achieving a specific goal can sometimes be very hazy. (UCL iGEM team 2012)

Heralded as a form of 'extreme citizen science', the iGEM collaboration also provided members of the London Biohacker group with the opportunity to work in an academic laboratory and learn the skills and techniques that their own trial-and-error methods alone could not provide. This collaboration served as a type of master-apprentice relationship to promote the transfer of tacit knowledge from the iGEM team to the amateur biologists. As was stated by members of the London Biohacker group:

> We needed some outside input to improve our techniques and experiments . . . I was interested in getting a grasp on the professional techniques, taking [my skills] to the next level. (UCL iGEM team 2012)

Thus aspects of life science research require the development of certain mechanical techniques that, much like riding a bike, can only be learned through guided instruction and practice.

5. Communal tacit knowledge

Finally, communal tacit knowledge is the combined knowledge that is developed through interaction between experts with different disciplinary backgrounds working together. Very few people are likely to have all the skill to master all the steps needed to do something serious with biological weapons: rather, serious activities are the product of teams that integrate different disciplinary expertise.

Communal tacit knowledge can be conceptualised in two distinct ways. On the one hand, it can be interpreted as the bringing together of different disciplinary experts that are greater than the sum of their parts but, nonetheless, can still be separated out into their respective individual parts. This view emphasises the importance of close working relationships and the social process of learning required to fit in a particular community of practice (McNamara 2001) but implies that communal tacit knowledge is simply the addition of different types of expertise to a community, which operates to achieve a shared goal (MacKenzie and Spinardi 1995). Although this appears to be a simplified interpretation, the failure of an organisation to foster this form of communal tacit knowledge can hinder the development of the weapons production process, as demonstrated by the limitations with biological weapons experienced by the millenialistic Aum Shinrikyo cult that was responsible for the chemical weapons attack on the Tokyo subway in 1995. Despite being well resourced and having significant time, the cult categorically failed with biological weapons, partly because of weak and somatic-limit tacit knowledge barriers, but also because:

> Aum was obsessed with secrecy . . . the organisation limited its opportunities by predominantly confining the development of its biological and chemical programs to the leadership group. (Danzig et al. 2012)

On the other hand, communal tacit knowledge can be understood as a form of 'communally synthesised tacit knowledge' (Vogel 2006) that comes from the ongoing interactions between different types of expertise. In this sense, these interactions create new forms of knowledge that become integrated in the community, rather than residing in particular individuals. This view of communal tacit knowledge is akin to what Collins (2010) has termed 'collective tacit knowledge', that is, the embedded nature of knowledge in the social and infrastructural environment. This form of knowledge is located in 'human collectivities' wherein:

> . . . the changes in the content of the knowledge belonging to communities is beyond the control of the individuals within the communities. (Collins 2007)

Both forms of communal tacit knowledge emphasise the importance of expert interaction and assimilation of knowledge at the institutional level, but also raise the question of the significance of communal tacit knowledge in weapons programmes. As Vogel (2006) argues, these different conceptualisations of communal tacit knowledge could have implications for the way in which proliferation threats are assessed:

> Since much of the work carried out at SNOPB was done in a communal and interactive setting, one could argue that the tacit knowledge related to 836 [anthrax] was distributed across its R&D, production, and testing communities . . . However, if communal tacit knowledge does not degrade with disruption, or if it can be easily reconstituted from its individual components, then this has worrisome implications for proliferation.

In other words, communally synthesised tacit knowledge would be much more difficult to reconstitute if it was dependent on the institutional memory of the community, compared to expertise that is distributed a community of weapons scientists but could be easily reassembled in another institutional context. However, even major bioweapons programmes require a level of improvisation and adaptation at an institutional level that might not be replicable in another context (Leitenberg 2004: 36).

6. The partial erosion of tacit knowledge

The advance of ICT over the last two decades has been profound in terms of its global reach, but also the amount and the nature of information available. In terms of global reach, it has been estimated that world internet usage has grown by 480.4% over the course of a decade from an estimated 360,985,492 internet users in December 2000, to an estimated 2,405,518,376 users in June 2012 (Internet World Stats 2013). This increase is particularly strong outside of the western world (Royal Society 2011; Cortada 2013).

There have been parallel changes in the consumption of data through the internet and as of 2011 one website, YouTube, consumed the 'same bandwidth as entire internet in 2000' (Meadway 2011). This is coupled with a change in the nature of ICT and the internet in which there has been a shift from a passive consumption model (so-called Web 1.0 model), in which for example users read a static documents; to the more interactive model characterised by 'user-generated content'. This Web 2.0 concept is evident in the emergence of 'webs of social participation' and interactive websites, such as YouTube, Facebook, Twitter and Wikipedia where users can actively engage with the content. It has been suggested that the next step will be Web 3.0, which is:

> . . . about representing meanings, connecting knowledge, and putting these to work in ways that make our experience of internet more relevant, useful, and enjoyable. (Davis 2008)

Advances in ICT have generated a number of practical applications, not least in terms of collaboration in science and the enhancement of knowledge transfer. In terms of collaborative science, the Royal Society (2011) has reported that:

> . . . over 35% of articles published in international journals are internationally collaborative, up from 25% 15 years ago.

Several sources attribute the growth in collaboration to the increasing availability and utility of ICT. Olson et al. (2008) noted that:

> . . . cost-effective and reliable ICTs have made it possible for scientists to put together more long-distance collaborations

> than ever before. Whereas in the past it would have been deemed necessary to bring colleagues together in a single laboratory, more such partnerships are now conducted at a distance thanks to technologies such as e-mail, videoconferencing, shared whiteboards, and centralized databases.

The collaborative process generates a number of benefits for science and scientific output. The Royal Society report usefully identifies a number of such benefits. First, it enables scientists to 'seek to work with the most outstanding scientists in their field'. Secondly, it allows for the 'benefit of scale' as the Royal Society (2011) notes:

> . . . the International Space Station and the Large Hadron Collider are instances where the scale or scope of research is too great for a single nation, even if that nation is scientifically advanced.

Thirdly, it allows the burden of research activity to be shared:

> . . . breaking down complex tasks into manageable pieces, can be invaluable.

Perhaps of greater significance is the role collaboration plays in mobilising scientists around the globe to deal with a shared global challenge:

> In 2002 and 2003, Severe Acute Respiratory Syndrome (SARS), presented a very real and immediate epidemic threat. Over 8,000 people were infected, with over 770 deaths. Within a very short period, clinicians, epidemiologists, microbiologists and many others had joined the international effort. This was a global public health emergency, for which large scale global commitment and collaborative research were essential, to ensure a rapid and effective response. The global challenges of the 21st century look to be drawing researchers together to combat broad issues, which require a collaborative approach. (Royal Society 2011)

In this context, the advance of ICT cannot and should not be stopped or stymied any time soon given the range of expectations pinned on the internet and the clear benefits derived from ICT. As much has been stated in the Deauville G8 Declaration (G8 Summit 2011), which suggests the internet is 'a major driver for the global economy, its growth and innovation'. Yet ICT and the internet can be seen as a double-edged sword. On the one hand, advances in ICT and the growth of internet usage are likely to bring tremendous benefits, not least to the process of scientific collaboration. Yet on the other hand, the convergence of ICT, particularly with biology, has the *potential* to generate a number of new ethical, legal and social challenges, including in the sphere of the CBW regimes and weapons knowledge.

First, advances in ICT have the potential to 'unlock the master's secrets', or at least make these easier to discover. Despite some initial scepticism regarding ICT and the transfer of types of tacit knowledge, more recently, some academics have suggested changes in ICT will make the exchange of tacit knowledge possible. Certainly, Foray and Steinmueller (2003) have suggested that:

> . . . the next generations of ICTs will enable efficient storage and long distance transfer of a greater variety of knowledge (including knowledge that has previously been regarded as 'inherently tacit').

Whereas Hildrum (2009) has posited that:

> advanced e-learning systems—particularly remote laboratories—make possible efficient sharing of tacit knowledge between internationally dispersed technicians. However, successful knowledge-sharing depends crucially on the degree to which the users are motivated to acquire new knowledge online

Scientific websites, such as the *Journal of Visualised Experimentation* (JoVE) enable actors to follow the methods and techniques used in experiments systematically, using visual demonstrations of the protocols and processes employed. *Journal of Visualised Experimentation* (2013a), which is a 'peer reviewed, PubMed-indexed video journal', contains more than 2,000 video protocols on a number of different experiments, and purports to address:

> . . . two of the biggest challenges faced by today's life science research community: i) low transparency and poor reproducibility of biological experiments and ii) time and labor-intensive nature of learning new experimental techniques.

Indeed, testimonials (such as those given below) and further discussion with those that use this open access internet tool indicate the website variously serves to aid the learning process, save time and money and reduce the trial-and-error process required to replicate results.

- I have not yet used the mouse olfactory recording video you allowed me to download today, but I have used links to other JoVE videos on several other occasions. I find them to be very effective ways to communicate different concepts to students - a picture may be worth a 1000 words, the videos save me millions.
- You can't figure out how to do this stuff just from reading the literature, you have to have somebody show you . . . this is amazing!
- By having the video protocol . . . as the ones in the *Journal of Visualized Experiments*, anybody can quickly learn the technique whenever it is convenient for her/him saving them lots of time, money and frustrations.
- Thank you for your wonderful website; we just used it at this lab and you saved us hours of trial and error!! (*Journal of Visualised Experimentation* 2013b).

In this context, internet tools, such as the *Journal of Visualised Experimentation*, which visualise the methods employed in the experiment, can be seen as a new means of laboratory sharing and exchange which, perhaps under certain conditions enable the transfer of certain aspects of tacit knowledge but particularly the categories identified by Collins (2010) and others, as 'mismatched saliences', 'hidden knowledge' and 'ostensive knowledge'. They can do this precisely because visualised experimentation facilitates the more complete transfer of knowledge in circumstances that require you have somebody to show you.

There is, however, a need for caution in overstating the implications of tacit knowledge transfer through visualisation and the process of viewing only gets you so far. First, because video protocols only reveal as much as the editors deem necessary, it is possible that some information is lost in the editing process, not least because completely following every single step in the process would make a rather boring video. Secondly, while visualised experimentation may aid knowledge transfer, it does not aid the development of somatic-limit tacit knowledge and researchers are still required to develop the physical skills and muscle memory required to execute certain actions: watching an Eric Clapton guitar solo, for example, still leaves most viewers a frustrating distance from being able to replicate such a solo. Thirdly, in relation to biological weapons, there are no available video protocols (at least publicly in the open-source literature) which go through all the processes required to develop a serious biological weapon. Sections of different visualised experiment may help achieve certain tasks, but it would require a great deal of dedicated effort to identify and assimilate all the necessary steps required to do something serious, a factor which may drive aspiring bioweaponeers in search of other, more conventional, options.

Thirdly, yet related to the point above, while somatic tacit knowledge remains difficult to transfer, this may be rendered less important as biology becomes more predictable and better understood through a process of 'digitisation' and the purported transition of biology into a predictive, engineering discipline. As the website of the Craig Venter Institute (2010) notes:

> Sequencing genomes has now become routine, giving rise to thousands of genomes in the public databases. In essence, scientists are digitising biology by converting the A, C, T, and G's of the chemical makeup of DNA into 1's and 0's in a computer.

Synthesis techniques have the potential to enable the reverse; that is the conversion of digitised data into the A, C, T, and G's of the chemical makeup of DNA. New enabling technologies are argued to make this process easier to the extent that it has been suggested that DNA synthesis is now 'equivalent to operating an espresso machine' with the process of 'ligating base pairs' described as being 'as easy as making a milkshake' (Workshop Discussion 2012).[4]

Such claims, which emanate from experienced laboratory professionals, remain contested and 'easy' remains a relative term, as one interview participant in a Harvard Sussex Program project on the future of the S&T reviewing process in the Biological and Toxic Weapons Convention (BWC) pointed out:

> . . . people who say things are easy often come from labs, have support and if required can go and ask others. (Participant 28)

Indeed, the ease through which individuals can synthesise life remains contested and certainly scratching beneath the headlines of various synthetic biology success stories suggest the process of engineering biology remains more complex and costly than sometimes presented in scientific publications (Kwok 2010; Voosen 2013). This is not to belittle the potential of emerging fields like synthetic genomics, nor is it to dismiss the significance of emerging platform technologies, but rather to inject a note of caution and draw attention to the complexity that frequently lies behind the gloss. Moreover, synthesis of a potential agent is a far cry from weaponisation, and there is perhaps a need for caution in conflating the acquisition of strands of DNA with the acquisition of a weapon. As Vogel (2012) has stated:

> . . . the way science is done – its troublesome, contingent, and messy means of production – often differs from the clean and orderly public representations of scientific work codified in scientific publications and other written accounts.

Despite the hidden complexities in doing science, the human race has a history of innovation and once the pace of innovation begins to gather momentum, technologies can evolve in spectacular fashion under certain circumstances (Rogers 2002), something evident in the evolution of ICT and the home computer (Cortada 2013). Moreover, one only has to look at the achievements of undergraduate biologists competing in iGEM to see how 'people are resourceful and work to solve problems and constraints' (Participant 43). In this regard, concepts such as 'biobricks' may become particularly important over the coming decades. Although synthetic biologists are still struggling to develop the requisite interoperability and reliability of standardised parts, the pace of progress suggests these could become a very real prospect in the coming decades. This could result in a 'game changer' that would simplify aspects of biology and moves the life sciences away from trial-and-error to rational design and engineering approaches, at the same time placing biology in the hands of mathematicians, engineers and computer experts rather than experienced biologists, potentially reinventing the discipline and practise of biology. This is not that same as the erosion of the somatic skills required for success in biology. Nor does the ability to design pathogens necessarily entail the ability to animate, culture, stabilise and weaponise pathogens. Yet it does perhaps suggest that some of the somatic tacit knowledge required in research in biotechnology could be less important in the future.

7. So what: implications for the BWC regime

Under Article XII of the BWC, it has become established practice to conduct a quinquennial review of the Convention which takes:

> . . . into account any new scientific and technological developments relevant to the Convention.

This process of monitoring developments in S&T and 'tending' to the BWC is important, as advances in S&T—along with a number of other factors—have the capacity to undermine (or reinforce) the norm embodied in the BWC. Advances in science which, for example, could increase the capacity of individuals to create and control biology may enhance the utility—and by implication the appeal—of biological weapons thereby undermining the norm. As the Stockholm International Peace Research Institute (1973) noted:

> The more a proscribed weapon gains in military attractiveness, the more likely is its proscription to be ignored.

In contrast, advances in detection technologies could contribute to the process of investigating alleged violations and thus reinforce the norm or could be used for identifying potential threats in a more rapid and effective manner.

With a number of other means whereby S&T can influence the BWC, the process of reviewing and responding to developments in S&T of relevance to the BWC is important. However, historically developments in S&T have been marginalised in the review conference process and there is little evidence of substantive discussion on this topic beyond debate on whether or not to include lists under the additional understanding agreed under Article I. This deficit has led some States Parties and non-governmental organisations (NGOs) to question whether the established practice of reviewing S&T remains fit for purpose. Certainly in the run up to the Seventh Review Conference in 2011, longstanding calls from NGOs and States Parties to do something about the process of reviewing S&T intensified, with proposals from countries as diverse as:

> . . . Australia, Japan and New Zealand; India, the UK, the US, South Africa and China, as well as in meetings, such as the Wilton Park Clingendael workshop in September 2011. (Revill et al. 2011)

In an effort to rectify some of the limitations in the quinquennial S&T review process, the Seventh Review Conference established a SAI on review of developments in the field of S&T in order to formally inject an S&T component in the intersessional discussions. The purpose of the S&T SAI is 'to discuss, and promote common understanding and effective action' on the following on an annual basis (Biological Weapons Convention 2012):

- new S&T developments that have potential for uses contrary to the provisions of the Convention
- new S&T developments that have potential benefits for the Convention, including those of special relevance to disease surveillance, diagnosis and mitigation
- possible measures for strengthening national biological risk management, as appropriate, in research and development involving new S&T developments of relevance to the Convention
- voluntary codes of conduct and other measures to encourage responsible conduct by scientists, academia and industry
- education and awareness-raising about risks and benefits of life sciences and biotechnology
- S&T-related developments relevant to the activities of multilateral organisations such as the World Health Organization, the World Organisation for Animal Health (OIE), the Food and Agriculture Organization, the International Plant Protection Convention and Organization for the Prohibition of Chemical Weapons
- any other S&T developments of relevance to the BWC

With additional topics identified for each year, there is potential within this agenda item to generate an ongoing process of review and to 'fill a perennial lacuna in scientific discussion under the Convention'. However, a number of challenges remain in maximising the potential, including overcoming the limited time available for discussion (effectively 45 minutes per sub-agenda item) and the limited resources available to the Implementation Support Unit (ISU) (Revill 2012). Moreover, to date the outcome of the intersessional processes has been disappointing, with some useful discussion but limited promotion of common understandings and even less effective action.

Beyond these procedural challenges a much deeper issue is the apparent limitations in understandings of S&T among delegations to the BWC. This is perhaps not surprising; many individuals on delegations to the BWC in Geneva remain so-called 'generalists' on comparatively short-term postings and, in many cases, covering several very different issue areas. As Johnson (1998) has noted:

> As ambassadors and their staff are subject to rotation every 3–5 years, and most foreign ministers work on the principle of diplomats as non-specialists, the likelihood of a significant proportion of ineffective representatives being engaged in the multilateral forum is high.

The limitations in scientific capacity mean that expectations of the extent of scientific discussion possible in the two or three weeks of a review conference process—or 45 minutes of an intersessional meeting—needs to be tempered. As one interview participant mused:

> . . . some policy people have some technical training but if the challenge is to understand the science and have a scientific conversation is that enough? (Participants 33).

This factor, on the one hand, further dampens expectations of what can be achieved in the process of reviewing S&T

within the BWC, something compounded by reluctance on the part of some states to get into detail on S&T in the BWC because of security concerns. On the other hand, it perhaps underlines the importance of bringing an understanding not just of the substance in relation to advances in science but also the process of research and its 'doability'. If things really are getting 'easier' and:

> . . . the availability of web-based technologies is facilitating the transfer of tacit knowledge through the creation of worldwide formal or informal learning communities or partnerships. (National Research Council 2011)

There may then be requirements to 'tend' to the regime accordingly in order to ensure its continued suitability. In other words, if states are going to do S&T in the context of the Convention, then they need to address not just the 'recipes' and the availability of ingredients and equipment, but also the contingent and complex process of cooking, and thereby pay heed to the sociotechnical dimension in which biotechnology evolves. Thus there is a need to look at how:

> . . . technologies emerge within social, natural, economic, and political contexts. (Vogel 2013)

This is not to suggest that tacit knowledge has been entirely ignored in the process of reviewing S&T of relevance to the BWC. Drawing on a workshop in Beijing hosted by the Inter-Academy Panel, section II of the 2011 background material which was produced by the ISU (Implementation Support Unit 2011), stated:

> Although first class research continues to rely heavily upon tacit knowledge, the availability of web-based technologies is facilitating the transfer of tacit knowledge through the creation of worldwide formal or informal learning communities or partnerships . . . The report notes a number of current examples, and also suggests that an area for future in-depth analysis is the changing nature of tacit knowledge, of which intangible technology is a subset, as kits and other resources make it easier for less skilled individuals to carry out work that once required significant training.

Yet there is little evidence of this issue being raised within the Review Conference (or since) and given the significance of tacit knowledge in understanding the threat posed by biological weapons, this topic surely warrants further attention because of its potential to: undermine our understanding of biological weapons programmes, generate distorted perceptions of the threat posed by dual-use biotechnology in the 21st century, and generate a myopic focus in the process of reviewing S&T. As Ouagrham-Gormley (2012) has stated:

> To more accurately identify the nature and evaluate the pace and scope of future proliferation threats, and consequently develop more efficient nonproliferation and counterproliferation policies, scholars and policymakers must include the intangible dimension of proliferation in their assessments. They must also understand the factors that determine the mechanisms and the conditions under which scientific data and knowledge can be efficiently exploited.

Indeed, the role of tacit knowledge and its potential partial erosion suggests that the area of know-how warrants broader and deeper attention by delegations in reviews of S&T, particularly if, as has been suggested by some, these developments in S&T have the potential to become 'game changers'. As Carlson (2011) put it more bluntly:

> If it were easy to write pathogen genomes . . . from scratch, we would quite frankly be in deep shit.

Greater attention to the role of tacit knowledge and the sociotechnical dimensions of S&T—that is, the recognition of the socially embedded nature of technology—could help to unpack concepts such as 'game changers' when used in the context of biosecurity concerns.

In order to progress in this area one first step is surely building a greater understanding of what tacit knowledge is and how it is acquired in the life science context. A second step is to work out, through sociotechnical discussion, the extent to which this form of knowledge matters and how easy 'easy' is in relation to certain key activities. There is surely a significant role for academics, NGOs and learned societies, such as the National Academies or the Inter-Academy Panel's Biosecurity Working Group, working in conjunction with those in the security forces, intelligence agencies and disarmament specialist in this interdisciplinary process. Specifically, such interested parties could address the difficulty involved in, for example, the weaponisation process of biological weapons or the creation of functioning organism through synthetic components. Related to the above it could be useful to look at the extent to which new enabling technologies reduce the tacit knowledge 'barriers to bioweapons', 'or whether they require the development of new skills' (Ouagrham-Gormley 2012).

Realistically, there are limitations as to what can be raised in fora such as the BWC and it remains unlikely that a detailed, useful and open exchange on tacit knowledge barriers to biological weapons could take place between the 170-odd state parties to the BWC, not least because of national security sensitivities of such a discussion. However, sociotechnical discussion on the assembly of synthetic organisms could provide a less sensitive yet useful route to generating a greater understanding of whether and how tacit knowledge matters. Alternatively, this is something that could be dealt with in depth among a smaller collective of actors who could begin a process of building a more significant understanding of the complex reality of the scientific research process, which could be presented within the BWC forum. Such steps could go some length to advancing thinking about S&T in a more meaningful way and counter oversimplified understandings of the process of research which neglect the social factors that are involved in, and influence, developments in S&T generally, and biological weapons specifically.

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Notes

1. The original three-way classification developed by Collins is based around three categories: 'relational tacit knowledge'; 'somatic tacit knowledge' and 'collective tacit knowledge' (Collins 2010).
2. Based on evidence from author's participant observation over several months in a synthetic biology research laboratory at the Centre for Synthetic Biology and Innovation, Imperial College London.
3. In the case of BioCurious (2012), while community projects are open to anyone, participation in projects that involve considerably more wetlab work is only open to members who have taken safety training.
4. Statement by participant and a workshop held under Chatham House rules hosted by the University of Bath on 8–9 November 2012 as part of the UK FCO Strategic Programme (grant number: SPF 000211).

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