European Commission

JRC SCIENCE FOR POLICY REPORT

Bridging Across Methods in the Biosciences

-BeAMS-

Joint Research Centre

EUR 29852 EN

This publication is a Science for Policy report by the Joint Research Centre (JRC), the European Commission's science and knowledge service. It aims to provide evidence-based scientific support to the European policymaking process. The scientific output expressed does not imply a policy position of the European Commission. Neither the European Commission nor any person acting on behalf of the Commission is responsible for the use that might be made of this publication.

This report has been produced within the context of a scientific collaboration between the JRC (Directorate for Health, Consumers and Reference Materials, Chemicals Safety and Alternative Methods Unit) and **Annamaria Carusi** (Reader in Medical Humanities, Honorary Reader in Philosophy & Co-Director Medical Humanities, University of Sheffield Medical School, Beech Hill Road, Sheffield, S10 2RX, United Kingdom) who received financial support through a JRC Expert Contract (#EX2017D310935).

Contact information
Maurice Whelan and Clemens Wittwehr
European Commission JRC, Chemicals Safety and Alternative Methods Unit (JRC.F.3)
Via Enrico Fermi 2749, TP126
I-21027, Ispra (VA), Italy
Email: JRC-F3-ENQUIRIES@ec.europa.eu

EU Science Hub
https://ec.europa.eu/jrc

JRC116305

EUR 29852 EN

PDF	ISBN 978-92-76-11181-8	ISSN 1831-9424	doi:10.2760/190697
Print	ISBN 978-92-76-11180-1	ISSN 1018-5593	doi:10.2760/41124

Luxembourg: Publications Office of the European Union, 2019

How to cite this report: Carusi A., Whelan M., Wittwehr C., *Bridging Across Methods in the Biosciences – BeAMS,* EUR 29852 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-76-11181-8, doi:10.2760/190697, JRC116305.

Abstract

Crossdisciplinary research is essential if science is to properly address societal needs. In spite of several policy initiatives to foster such research across sectors, there is still a high level of compartmentalisation in the biosciences. The European Commission is preparing for a Missions based science and innovation strategy in which it will be important to consider how the goal of meaningful crossdisciplinarity can be achieved. This report aims to raise the question of crossdisciplinarity again, and to suggest specific actions to further the understanding, achievement and evaluation of crossdisciplinarity in the biosciences.

Bridging Across Methods in the Biosciences

-BeAMS-

Contents

Acknowledgements

The findings presented herein draw on previous studies and on the outcome of a BeAMS Workshop organised by the JRC in June 2018 which solicited views on crossdisciplinarity from representatives of a wide variety of societies, associations and agencies. The valuable contribution of the workshop participants is gratefully acknowledged:

Toni Andreu, European Advanced Infrastructure for Translational Research (EATRIS)

João Barroso, European Commission JRC

Sofia Batista Leite, European Commission JRC

Elisabet Berggren, European Commission JRC

Ivana Campia, European Commission's Joint Research Centre

Annamaria Carusi, University of Sheffield Medical School

Eero Castrén, Federation of European Neuroscience Societies (FENS)

Anne-Marie Coriat, Wellcome Trust

Christian Desaintes, Directorate-General (DG) for Research and Innovation (R&I) of the European Commission

Nicolas Dudoignon, European Federation of Pharmaceutical Industries and Associations (EFPIA)

Paul Friedemann, Alliance for Biomedical Research in Europe (Biomed Alliance)

Liesbet Geris, Virtual Physiological Human Institute (VPHi)

Patrícia Gomes-Alves, European Society for Animal Cell Technology (ESACT)

John Kendrick, European Federation of Pharmaceutical Industries and Associations (EFPIA)

Susanna Louhimies, Directorate-General (DG) Environment (ENV) of the European Commission

Heather Patisaul, Endocrine Society

Francesca Pistollato, European Commission JRC

Andrea Richarz, European Commission JRC

Mathieu Vinken, European Society of Toxicology in Vitro (ESTIV)

Maurice Whelan, European Commission JRC

Clemens Wittwehr, European Commission JRC

Andrew Worth, European Commission JRC

The valuable feedback received from JRC colleagues, Guy van den Eede, Paolo Castello and Andrew Worth during their review of the report is also gratefully acknowledged.

Executive summary

Crossdisciplinary research is essential if science is to properly address societal needs. In spite of several policy initiatives to foster such research across sectors, there is still a high level of compartmentalisation in the biosciences. The European Commission is preparing for a Missions based science and innovation strategy in which it will be important to consider how the goal of meaningful crossdisciplinarity can be achieved. This report aims to raise the question of crossdisciplinarity again, and to suggest specific actions to further the understanding, achievement and evaluation of crossdisciplinarity in the biosciences.

The focus here is BeAMS (Bridging Across Methods in the Biosciences). This is an initiative of the European Commission's Joint Research Centre (JRC) that emerged from the recognition that entrenched compartmentalisation of methods, disciplines and sectors is a major obstacle to changing approaches to toxicity testing. The silos that result from compartmentalisation are endemic across the sciences; the BeAMS initiative focuses on the biosciences as one starting point. We aim to show how Bridging Across Methods in the Biosciences can support Missions based research, in making it clearer how meaningful crossdisciplinarity can be achieved. The aim is to contextualise BeAMS in current policy initiatives and in the history, philosophy and sociology of the biosciences. The report suggests that disciplines can sometimes be an arbitrary demarcator of scientific activity and knowledge, whereas methods are at the heart of what scientists actually do. Methods can be usefully analysed at the micro level of Research Practices and also the macro level of Research Systems. This report summarises the key themes of a workshop held to explore the idea of "bridging across methods" with representatives of some major bioscience societies and organisations. It suggests that policies on crossdisciplinarity could make better use of existing social science and humanities based science studies; further, that it is useful to focus on one of the elements that is most frequently named as a challenge to crossdisciplinarity, that is, the absence of a common language. 'Systems of equivalences' and 'grounds of comparability' are suggested as tools that scientific teams can use to facilitate the formation of translatable or hybridised languages at the level of Research Practices. Finally the report suggests that large scale research and innovation policies that seek to leverage crossdisciplinary and cross-sector collaboration, such as a Mission centred strategy for Horizon Europe, would be more successful in harnessing these collaborations if they used clear criteria, indicators and assessments of meaningful crossdisciplinary and cross-sector research.

Two main ongoing actions for the BeAMS initiative are identified:
Action One: Put into practice insights about the social dimensions of the biosciences and crossdisciplinarity from social, historical and philosophical studies of science.
Action Two: Address the most commonly cited challenge to interdisciplinarity: the absence of a common language.

The main recommendations are:

- Gain a better understanding of cases where scientific methods do succeed in becoming bridgeable across disciplines and sectors, through analysis of historical and current paradigm cases, and extract lessons from these;
- Create new opportunities to facilitate and experiment with ways to bridge across methods;
- Analyse existing policies and initiatives regarding open access, open science and others, and see what gaps there are between data and method complementarity;
- Include more explicit criteria for crossdisciplinary research and bridgeability across methods in funding calls, and in assessments of research and innovation projects.

1. Background: Why BeAMS?

The biosciences are at a critical point of development, with new innovative technologies constantly emerging, making possible new methods and techniques. Currently, we see many emerging technologies: such as stem cells, organ-on-a-chip, gene editing, and an ever increasing capacity for bioinformatics and computational modelling to name but a few. All of these technologies have their associated methods and techniques, which demand high levels of specialisation and expertise on the part of researchers. Each innovation demands significant investment, both financial and in terms of researchers' time and effort, in order to ensure that it reaches its full potential and yields useful scientific results. However, there is also a risk that each will evolve within silos with little connection between them, and that opportunities to fully exploit the potential of methods and their integration will be lost. BeAMS – Bridging Across Methods in the bioSciences – is an initiative that aims to support greater connectivity between methods. In particular, we focus on how knowledge sharing can play a useful role and what form it should take.

Why the need for BeAMS?

While on the one hand there is a proliferation of new ways of conducting research in the biosciences, the use of any particular technological apparatus requires a high level of specialisation and expertise. Research careers often have at their core specialisation around particular methods and techniques, as well as around particular research disciplines, problems and questions. Social scientific research on science shows that scientists tend to cluster around technological apparatus for conducting research, and identify strongly with specific methods and practices (Knorr-Cetina 1999, Rheinberger 1997; Pickering 1995, Keller 2003)[1]. There are many different reasons for this, both scientific and institutional. The naming of disciplines, and the academic institutions such as departments and institutes, is contingent on many different factors, and can be quite arbitrary as domain demarcators (Burke 2016) – thus the reason any particular individual finds themselves in a particular department with a disciplinary label is not necessarily a strong indicator of where their scientific identity lies. Technologies for conducting research, and the associated methodology, play an important role in identifying research questions and setting standards of evidence within research communities. They are a central part of the *epistemic cultures* of scientific communities: that is, the way in which different communities (often arranged around disciplines and sub-disciplines, but not completely overlapping with them) think about evidence, quality, validation, and what counts as credible and useful research (Clarke and Fujimura 1992, Becher and Trowler 2001). A high degree of expertise with a method and methodology yields greater robustness and depth of knowledge. However, it also limits the potential for different technologies, techniques and methods to travel across scientific communities, and to help to address questions in other communities. For example, the potential for experimental, mathematical and computational studies to support each other in systems biology and systems biomedicine has been extensively written about, both by scientists and social scientists (for example, Calvert and Fujimura 2011, Carusi 2011, Green and Wolkenhauer 2012, Macleod & Nersessian 2013, Vermeulen et al 2013), yet there is still only patchy uptake

[1] The term 'methods' is used in a broad sense, and encompasses practices relating to implementing specific techniques, as well as the methodology in which they are embedded: that is the system of research design, hypotheses, objectives, standards of proof or acceptability, assessment and validation, and related theories.

and collaboration across these communities. Another good example is non-animal (alternative) methods. Although they are gaining ground, they are often still localised within particular communities that focus precisely on developing these methods, while their uptake in mainstream basic and translational research can be limited. History also shows that the uptake of particular approaches is dependent on many factors besides scientific merit. For example, molecular biology is now a mainstream form of biological enquiry. Its widespread acceptance, however, is due not only to scientific results, but also to the convergence of several organisational, institutional, disciplinary and technological factors that enabled it to obtain those results. (Fujimura 1996, De Chadaravian and Gaudilliere 1996, Garcia-Marquez 2012). We are currently seeing the same forces at work in the rise of data-centric biology (Leonelli 2016).

The biosciences continue to be rich in innovation. Technologies, tools and methods jostle alongside each other in what can be healthy competition. But frequently, co-operation and integration of efforts work better than competition, especially for bringing basic science to effective translation (see below, Box 1 on penicillin). For example, the CIPA initiative, couples in vitro stem cell and in silico computational studies of cardiotoxicity, and is on its way to obtaining FDA approval[2]. Rodriguez et al (2015) point out the benefits of mutual support among a range of different human based approaches in the domain of pharmacology and cardiology. However, in order to achieve this, a deeper level of crossdisciplinarity is required than is currently attained. While ever greater quantities of data and information become accessible through Open Data, Open Access and other policies, there is a lack of skills in integrating data gathered from different studies and approaches. This too requires potential co-operation among disciplines to be taken into account at early stages of the research life cycle. Better integration often depends on better contextualisation of data throughout the lifecycle of data. The contexts in which data are produced are mostly implicitly shared among researchers producing the data, while effective integration often requires that more aspects of the context be made explicit. As yet the skills for knowing what to make explicit, and how to do this, are still only in embryonic stages of development.

The catalyst for BeAMS is the recognition of the prevalence of both the need for co-operation and deep crossdisciplinarity on one hand, and the challenges to achieve these across the biosciences on the other.

[2] CIPA (Comprehensive *In vitro* Proarrhythmia Assay). See www.cipaproject.org.

2. Current trends in 21st century science

The need for crossdisciplinarity[3] has been recognised for a long time in all major European funding programmes, and it has been factored into Horizon 2020, through the structuring of funding around Societal Challenges that specifically call upon crossdisciplinary approaches. A good example of the overall ethos of current trends in the research environment is the European Commission Report 'Open innovation, open science, open to the world—a vision for Europe (European Commission, DG Research and Innovation' 2016), which delineates the importance of overcoming the boundaries of science, be these disciplinary, sectoral, economic or national. The Missions programme that will inform Horizon Europe similarly calls for greater deployment of transdisciplinary approaches, that cut across disciplines and sectors[4] and produce research for relevant missions that is implementable and actionable (European Union, 2018a).

At the same time, the difficulties of crossdisciplinary research are also recognised. For example, a recent study of interdisciplinarity by the UK Higher Education Funding Council for England (HEFCE) notes that despite the existence of strong incentives for interdisciplinary research, the barriers are significant. It is interesting to note that although the scholarly community broadly recognises interdisciplinary research as more likely to have an impact beyond academia in addressing social and other challenges, they also perceive it as more likely to have a negative impact on researchers' career prospects, on successful publication, and on attracting funding (HEFCE 2016: 9). With this understanding of interdisciplinary research, for example, a senior academic would advise early career researchers to stay away from interdisciplinary research until they are sufficiently established for this not to matter; this however loses the opportunity to lay down the ground for successful interdisciplinarity in the habits and outlook of young researchers.

2.1 Openness

These calls for greater crossdisciplinarity are also part of other deep transformations that are currently occurring in science. *Open Access and Open Science* are being pursued through several different avenues. While the value of openness is increasingly evident, achieving it requires a major and systematic effort across the whole science system, as evidenced by the 'Open Science Policy Platform Recommendations' (European Union, 2017a).

2.2 Reproducibility

The inability to independently generate the same published research result in a different lab by a different team is of great concern in bioscience communities not only because of the implications for scientific progress, but also for the potential impact on health. While the scale of the problem is controversial (Baker

[3] The main terms for crossdisciplinary research are multidisciplinary (research involving more than one discipline, but without significant crossover between disciplines), interdisciplinary (research involving more than one discipline, where the disciplines co-operate and collaborate, but maintain their disciplinary identity), and transdisciplinary (research where the boundaries between disciplines become blurred, and which may also cut across sectors: eg governance, academia and industry). In this document, the term 'crossdisciplinary' is used as the more general term, except where one of the particular forms is being discussed.

[4] 'Sector' can mean different things; here it refers mainly to academic, government (research and policy), public (including non-governmental), industry sectors. Other sectors to which this report may also be relevant are, for example, clinical, health, and environmental sectors.

2016), in a Comment published in *Nature*, the directors of the US National Institute of Health announced a concerted effort to address this issue (Collins and Tabak 2014). There are several reasons for the lack of reproducibility, but one of these is that methods are not fully explicit, including what Collins and Tabak call the 'secret sauce' that some scientists use to make their experiments work. Given the competitiveness of research, secrecy may well be deliberate; however, much more likely is that it is simply not clear how much of the experimental process is implicit, and not explicitly articulated. A greater awareness of how to make methods more explicit is one of the measures to address reproducibility, and this fits in with BeAMS objectives.

2.3 Data science

Another factor feeding into the demands for openness characteristic of 21st century science has to do with the digital transformation of all scientific research which is enabling data bases and data platforms of all kinds that are accessible to high performance computing. This is profoundly reshaping what scientific outputs are considered to be, with new modes of publication, new kinds of connectivity between publications, and a wide range of different kinds of output compared to the traditional peer-reviewed stand-alone publication. These include the publication of data, metadata, research processes and protocols, workflows, and others (see for example Clarke et al 2015). Internet enabled databases and their related capacities and research technologies (such as computational means of processing, analysing and modelling data), have led to the upsurge of *data* intensive biosciences (Leonelli 2016); to a new wave of standardisation within and across scientific communities; and to other initiatives to ensure that scientific data are accessible to both humans and machines. This is the aim of the FAIR principles (Findability, Accessibility, Interoperability and Reusability (Wilkinson et al 2016)). The FAIR principles show the extent to which achieving the ideals of openness in science can only be achieved through reconfiguring science as an enterprise that attends carefully to both social and technological dimensions of science.

The demand for openness and for reproducibility, the increasing datafication of all aspects of the scientific process, with the associated standardisation, and development of initiatives such as the FAIR principles: all of these strive towards various ideals of science. This is the ecosystem of the calls for crossdisciplinarity in all its forms that we are responding to, and finding a way forward to support crossdisciplinarity by way of bridging across the methods that are typical of sub-disciplines, has to be sensitive to its place in the ecosystem. All have in common a tendency to create greater awareness of the research process and to make more of the process explicit. They all face challenges that can be distinguished at two levels[5]: the macro level of the research system and the micro level of the research process. The macro level of the research system includes the social, economic and institutional factors that shape research: funding and publication structures, reward systems and incentives, education, career pathways, organisation of research institutions, legal and governance frameworks, technological infrastructure and so on. At the micro level are the research processes enacted in the daily working lives of researchers as members of research laboratories, teams and networks.

The BeAMS agenda, aiming to create greater support for bridging across methods in the biosciences, must therefore work synergistically with these major trends and initiatives in 21st century science.

[5] This is not meant as an exhaustive analysis of science, but is merely a pragmatic distinction for discussion in this context. See Frickel et al (2016) for discussions of the complex contexts of which crossdisciplinarity.

3. Defining a BeAMS Agenda

The major trends discussed in the previous section are fundamentally reshaping the way that science is carried out, organised, accessed and communicated. There are also regularly calls for greater crossdisciplinarity in all its forms. For example, the need for inter- and transdisciplinary research was a central tenet of 'Societal Challenge' research of the European Commission Horizon 2020 research programme, and of other 'Grand Challenge' based funding strategies (De Grandis and Efstathiou 2016). While frequently invoked, meaningful crossdisciplinarity is less often accomplished, even more rare are explicit descriptions of how it is actually accomplished. The BeAMS initiative aims to address this lack, and suggests that bridging across methods is a good place to start the articulation of successful crossdisciplinarity. First, we discuss the different contexts of methods, at the broad 'macro' levels, and the more specific 'micro levels'. We then go on to discuss how bridging across methods can be facilitated and supported.

3.1 Methods at the Micro and Macro levels: Research Practices and Research Systems

We focus on the methods characteristic of bioscience disciplines and subdisciplines because methods are often what scientists cluster around when it comes to the evidentiary standards that they are most likely to trust and to find convincing. So for example, biologists used to working with the observational methods of microscopy might be resistant to mathematical and computational methods, because they do not meet the same evidentiary standards as are yielded by microscopes, may not address the same research questions, and do not participate overall in the same epistemic culture (Keller 2002). Methods are highly dependent upon available tools and technologies, which means that research practices are often organised around typical technological equipment and apparatus around which the life of a scientific setting, such as a laboratory, is arranged. In addition, methods are also closely related to the type of research questions scientists are likely to be pursuing, which in turn are a strong indicator of their scientific curiosity, a strong motivator for most scientists. There is much about the actual use of methods that is implicit or tacit, which is shared among a community of scientists, and which is not formally written up into the methods sections of research articles. Finally, carrying out methods in daily routines and practices shapes most scientists' immediate experience of science in their own lives, while also acting as strong connectors to other scientists in their communities, hence being a kind of social 'glue' (Knorr-Cetina 1999). Therefore methods are a key aspect of the 'lived experience' of scientists, and are important for the *micro level* of scientific practices.

Methods are also very closely interconnected with the broader ecosystem of science, the Research System at the *macro level*, as this both enables and constrains which methods can be pursued and how. For example, the overall use of methods, and the crossover between different methods is also affected by how resources are distributed via funding systems (for example, do different approaches and methods compete for funding in the same broad research area?), by reward systems (for example, do journals favour some methods over others?), by career pathways (for example, are researchers who follow a clear line of continuous research in a constrained area more likely to be promoted?), or by any number of other factors in the broader research system. Combinations of these factors, at macro and micro levels, can lead to methods developing in silos, with very little cross-fertilisation between them. Silos, shaped by different factors, can spring up between disciplines and sub-disciplines, but also between different sectors: academic, industry, clinical, regulatory, policy-making and other.

Big and important shifts in the sciences can often come about when methods are forced out of their disciplinary or sectoral silos. Two examples illustrate these levels: Shifts at the micro level of research practices can be seen in an example of bridging across methods that has fundamentally shaped current biosciences, discussed by the historian of life sciences Miguel Garcia-Marquez. In his book on the history of sequencing and bioinformatics, Garcia-Marquez (2012) gives a detailed account of how sequencing, which is now entirely established as a technique and method of molecular biology, evolved as a 'form of work' borrowing from practices of different researchers across disciplinary boundaries, and cutting across categories ‘such as technical and scientific work; biology and chemistry; experimentation and computation, or academia and commercialisation’ (Garcia-Marquez 2012: 14). The second example of bridging across methods that was made possible by interventions at the macro level of Research Systems is the production of penicillin in a form that could be used to treat infections on a large scale, during World War II. (See Box 1).

Box 1: Penicillin: a very short translational history (based on Schwartz Cowan, 1997)

Even though Alexander Fleming published his observations of the effects of penicillin in 1929, the publication remained largely ignored despite Fleming’s attempts to get others interested in it. It was only in the 1940s – with Europe in the midst of a major war – that the Florey Institute began serious research to attempt to develop penicillin into a drug that could be used to treat infections effectively. The collaboration included biochemists, pathologists, physicians, technicians and chemists, among others. While researchers made some progress in extracting the active substance from the mould, the numbers treated were still extremely low, and it was clear that collaboration with industry was needed to develop a form of penicillin that could be used for the very large numbers of patients, specifically, at the time, soldiers with war wounds. An obstacle to further development in the UK was the UK Medical Research Council’s refusal to fund research that might lead to patents. The research was shifted to the US, where political events, specifically the attack on Pearl Harbour, finally pushed the state to intervene to facilitate industry-academia collaborations, through new competition and patent laws. Only through this combination of actions – involving collaboration among multiple *research practices* of the different disciplines and sectors involved, facilitated by interventions on the level of *research systems*, did the quantities of penicillin rise – from 6 patients treated through the efforts of the Florey Institute in 1941, to 7,5 trillion units of penicillin by 1945, the end of World War 2.

The story of penicillin continued through the production of synthetic forms of the drug, and still now continues. The grand challenge of producing a drug able to treat the large numbers of patients suffering from infection during WW2 has given way to another grand challenge, of microbial resistance. Can we get any better at the foresight that might have alerted developers to this unintended outcome?

3.2 Building bridges

Crossing over between different methods and the knowledge economies in which they are embedded demands reflection on existing models of knowledge sharing around methods, and on the framework that could support and scaffold change. Here we discuss four interconnected aspects of research on such a framework.

3.2.1 Trust and confidence

Trust comes into play whenever researchers are asked to accept evidence from the data, models, practices or findings of others, and it brings into play the different evidentiary standards or criteria of different methods. Understanding a method includes understanding how it is carried out, and the rationale for adopting it (why it is considered a 'good' method, by whatever criteria). In crossdisciplinary research, problems relate to the understandability of evidence of different research communities, and their rationale for adopting methods or prioritising some forms of evidence over others. How do researchers make their method or approach more understandable beyond their own immediate community, so as to instil trust and confidence in their data and findings? This is an issue that arises across disciplines and subdisciplines, but also across sectors, and can be a major stumbling block in translation.

In research systems, trust and confidence needs to be built up between the different levels or domains of the research system: between the biosciences, life sciences and society[6], with science management, publication and funding operating across all of these. Trust is the major issue in sharing knowledge across these sectors, and linked to understanding as the main goal to be achieved. There is a need for understanding or at least 'understandability' among groups or communities who do not necessarily share outlooks or approaches or even goals.

3.2.2 Common language

The need for a common language is a recurring theme in discussions and studies of all forms of crossdisciplinarity. But what is the nature of this common language? Is it some sort of special communication skill, or is it similar to the skill that some people have in natural languages of being bilingual or polylingual? The need for a common language is most often invoked when issues about understandability are raised, or the broader aim of 'bridgeability'. The answer seems to be in the suffix: '-ability'. We do not all need to speak the same language, or actually to be bilingual or polylingual. Rather we need skills that make these in principle possible. We need the skills that make it possible to translate or interpret across languages. We need translatability, or communicability across research cultures and *bridgeability* across methods.

3.2.3 Circular pathways for change

Change is not a linear process, and cannot be imposed unilaterally by any of the actors in the system. Instead, change can be brought about through an iterative process of co-formulation, co-definition, co-creation and co-production, whereby the problems, issues or challenges to be addressed, how to address them, and the criteria for deciding whether they had been successfully addressed, need to be negotiated and agreed by the relevant actors, rather than imposed on them. Recognising therefore the importance of the prefix: 'co-', this approach to *co*llaboration builds trust and confidence, and also establishes a common language and the understandability that is so important for working across science borders.

3.2.4 Time

Time comes into play in two different ways: firstly acting in good time to achieve bridgeability, taking steps to ensure whichever forms of bridging are appropriate given the goals of a research programme, from the outset of the programme, and not adding it on in a *post hoc* fashion, after other activities that are taken to be more basic or closer to immediate interests. For example, validation that is open to, or accessible to the evidentiary criteria of other disciplines, subdisciplines or sectors, needs to be thought about from the very beginning of research design, and not as an afterthought, if translation is the goal. Secondly, bridging takes time. It is not something that can be demanded to be in

[6] Biosciences: science concerned with biological mechanisms. Life sciences: more broadly, biosciences that take into account health objectives. Society indicates the social stake in scientific knowledge, but also, how bio and life science knowledge circulate in broader society too. These three levels of the research system have different approaches to knowledge, but also make use of knowledge with very different goals and purposes. The full range of knowledge 'for curiosity', knowledge for health, for economic or political ends, for social or personal ends, all come into play.

place all at once; it is a process that needs several iterations, and the time for collaborations to develop.

3.3 Actions

There are many actions that are being undertaken by various organisations such as scientific societies, funding agencies and public-private partnerships to support crossdisciplinarity. Here we raise three questions about interventions in this domain:

3.3.1 Who do actions address?

Generally many actions are focused on post-docs and early career researchers. However, this then needs to be further supported by actions in the broader research system. For example, developing a better reward system for collaboration, or including a criterion in the evaluation of funding applications relating to a measurable or otherwise demonstrable outcome of collaboration is one way this can be supported.

The role of funders also comes to the fore in terms of requirements on the dissemination of research projects, since even though cross-fertilisation could occur through funding streams such as the ERC (European Research Council) and the MSC (Marie Slodowska Curie) fellowships, they often also disappear with the researcher at the end of the project. However, many crossdisciplinary research projects do not get funded because the reviewing process is geared towards disciplinary panels, and there has still not been sufficient improvement in the way that crossdisciplinary projects are reviewed. Funders therefore play a key role in supporting any other action that is taken to enhance collaboration across (sub)disciplines and sectors; through the calls, the criteria of evaluation and reviewing of research applications, and the requirements made on research outputs and dissemination.

Another group that needs more attention are patients, as well as other stakeholder groups in broad society. For example, clinicians frequently act as spokespeople for patients in shaping clinical trials and other biomedical research. However, they may not fully appreciate what the priorities and values of patients actually are (for example, see Rothwell et al 1997). In the cycle of communication and collaboration between biosciences, life sciences and society, ways to ensure the collaboration of patients – and other members of the public – need to be found. Social media platforms have an important role to play here, but cannot be fully relied on.

3.3.2 What do we talk about and what do we not talk about?

In any particular research setting, there are conversations and topics that are common, and others that are not. This is not because some topics of conversation are prohibited or anything like that; there simply are not conversations about these topics, or very few, or only in a very marginal way. It is impossible to give a list of where the silences might be in any particular domain. In the report ‘The Biomedical Bubble’, Jones and Wilsden (2018) write about the way in which research funding is overwhelmingly targeted at finding biomedical solutions to a very wide array of conditions, disorders and diseases, because there is an over-riding assumption that it is through biomedical means that solutions can be found. Biomedical research so dominates the domain of health, that other solutions, such as environmental or social solutions, do not get much attention in comparison. We might say that there is a silencing of other solutions. In each research context, some conversations are easier and more common than others. Which conversations are easier, and which are more difficult, which topics are raised and which are not, reveals a great deal about the assumptions of a research domain, and where its blindspots are. Thus, we need to get better at reflecting on what we do not talk about, as much as on what we do talk about, if we want to realise what we simply take for granted, without test or evidence.

3.3.3 Who standardises and how?

Standardising instruments are immensely important in creating common criteria for defining, describing and evaluating research processes and outcomes. In the biosciences, prominent examples are Standard Operating Procedures, Test Guidelines and Good Laboratory Practice. Each of these has a standardising role, designed primarily for industry, aiming to produce an auditable research process in order to increase trust and confidence. However, these mechanisms are often very difficult for academic scientific laboratories to implement, thereby creating an even greater rift between the kind of basic research mostly carried out in academia and its translatability beyond academia (See Fujimura 1996 for an historical example of standardising practices). Standards are never neutral, they always come from somewhere, serve some purposes better than others, and are more accessible in some places rather than others: institutions, disciplines or whole geographical areas may find themselves on the 'wrong' side of standards. Depending on the aims of a domain, the source and reach of standards is a very important factor in shaping how much common ground there is likely to be.

4. A framework for a BeAMS agenda

As outlined in Section 2, policy and other initiatives have been focused on openness of research, in particular, data and publications, in terms of developing the technologies and infrastructure for openness, and fostering the attitudes and scientific virtues or best practices that will encourage openness. Alongside these, there are also frequently calls for greater inter, or transdisciplinarity.

In 1970, the OECD hosted a workshop to discuss how interdisciplinarity should be defined, and how it could be encouraged. The report that issued from the workshop in 1972, one of the many progenitors of the BeAMS workshop, concludes that 'there is real need not so much to eliminate any of the disciplines but to teach them in the context of their dynamic relationship with other disciplines'. The report, with chapters by leading experts of the time, is rich in insight about disciplines and interdisciplinarity. Yet, despite the fact that the topic of multi, inter-, and transdisciplinarity has by now accumulated a very substantive literature, there is still little agreement about what it is, or how it can be assessed or evaluated, for example, in learning and teaching programmes (Morrison 2015). While the European Commission has made a concerted effort to encourage interdisciplinarity in funding structured around societal challenges rather than around discrete disciplines, a study of interdisciplinarity in the Framework Program 5 (FP5) round of funding found:

> *'disappointingly few projects among those funded in the early calls of the FP5 Programme that seemed by our criteria to be clearly inter-disciplinary, particularly in terms of crossing the boundary between natural and social sciences. Although FP5 sets ambitious targets for a step change in the amount and quality of interdisciplinary research, there have been formidable constraints to the delivery of these targets. Even where projects were interdisciplinary, the degree of interdisciplinarity varied. It tended to increase with time and with learning among the partners.'* (Bruce et al 2004: 468).

It would certainly be interesting to discover whether the number of genuinely interdisciplinary projects increased in subsequent EC funding frameworks, or whether they remain at the level of multidisciplinary, side-by-side cooperation without integration. Unfortunately, subsequent analyses are apparently not available in the public domain. However, if it did increase, the skills relating to interdisciplinarity have not been disseminated, seeing as the European research community still seems not to have moved a great deal from the recognition of the need for interdisciplinarity, and repeated attempts to articulate what that consists in.

There is a wealth of knowledge about scientific processes, across micro and macro levels, in the sociology, history and philosophy of science and technology; similarly, there are many studies and reflections on interdisciplinarity. This knowledge could be drawn upon to gain a better understanding of how science works, particularly how 'crossover' science – that is, science that crosses disciplinary or sectoral boundaries – operates. This is another form of silo-ed knowledge that mostly fails to inform thinking about science, or science policies. This knowledge could be made more applicable to policy formation regarding how to create a climate for genuine interdisciplinarity, to education about interdisciplinarity and to assessments of success, failure and all the gradations between. Social sciences and humanities have a valuable input to make both in policy formation, and as interdisciplinary partners in projects. They have a role to play not only where there are social and ethical factors, but also as mediators of interdisciplinarity in projects.

In proposing BeAMS, we do not propose to reinvent the wheel on crossdisciplinarity in its various forms. Rather, we highlight two potential actions.

ONE: Put into practice insights about the social dimensions of the biosciences and interdisciplinarity coming from social, historical and philosophical studies of science.

TWO: Address the most commonly cited challenge to interdisciplinarity: the absence of a common language.

5. Bridging knowledge cultures through common languages

The absence of a common language is frequently named as *the* obstacle to crossdisciplinarity. In this section we go deeper into considering what common languages in the sciences can be, and how they can be powerful supports for bridgeability across methods. We look at how common languages are embedded in knowledge practices and knowledge systems.

5.1 Knowledge practices

While the increasing emphasis on open data and open science are hugely important in shaping future research, crossdisciplinary research needs more than accessible data; it needs the contextualisation of data in the knowledge practices that produced it. Research practices are a lot like cultural practices, which are closely associated with shared languages, objects and technologies in everyday life. They are the stuff of daily lives and experience and form the basis for community. What is needed for cultures not to become too insular is not necessarily an existing common language across cultures, nor even that everyone should speak each other's language. Rather, we can draw on two analogies with language in its most common sense (or natural languages) to build up two ways of facilitating a dialogue across research cultures.

The first is the analogy of the bilingual dictionary, through which languages are translatable one into the other, and make it possible to learn the language of another culture. A bilingual dictionary comes in many different forms from the simple holiday vocabulary, for example, to much more elaborate dictionaries, but their basic principles are always the same: stating for words or expressions in one language what is the equivalent in another language. Bilingual dictionaries are not made all at once, but usually have taken significant time to develop. They're an ongoing project, and along the way, the languages that the dictionaries map may even cross-pollinate each other, through the stronger cross-cultural links that having the translation system brings about. Words and phrases travel across language boundaries, are adopted or modified.

The second useful analogy comes from the long evolution of languages, and how they develop, influence each other, or hybridise. Common languages (or at least the ones that people actually use), are not enforced in a top-down way, and do not come into being all at once. Sometimes in the long history of languages, hybrids of different languages are formed, new common languages – such as the creoles that emerged from trading encounters between different cultures. This is an analogy that was proposed by the historian of science, Peter Galison, who argued that hybrid languages – scientific pidgins (definition) and creoles (definition) – were a feature of the emergence of modern physics (Galison 1996, 1997).

Both of these analogies underscore that translatability across languages, and forging common languages takes time, and concerted effort. The wish for a readymade common language for bridging across sub/disciplines/sectors is misplaced. The productive effort to bridge across languages goes into the production of something like bi-lingual dictionaries, or into producing, together, a hybrid language. These 'dictionaries' can take many different forms, and are not necessarily glossaries of linguistic terms; the skill that goes into producing them is that of identifying which are the terms or other items (for example, aspects of images or other visualisations, data ranges, parameter values, etc.) that require definition, and how to define them in such a way that someone not familiar with the term or item but who does have a specific interest in it, is able to grasp its meaning. Much of this skill is that of making explicit assumptions of a discipline or research area that are normally implicit and in the background. The skill of creating pidgins or creoles that are useable by people coming from different backgrounds or cultures is that of hybridising existing terms (or other items) so that they bridge across different meanings, but with an understanding of which terms can by hybridised most usefully in the context.

When it comes to scientific methods becoming complementary to each other, the effort of the collaboration initially goes into the production of something akin to bilingual dictionaries: that is, setting out a *system of equivalences* between the methods and approaches of the different disciplines, that can then function as the grounds of comparability between them. Supported by a system of equivalences, it is possible to compare the data and outputs of the methods in a way that is meaningful for all the collaborators (Carusi et al 2012; Carusi 2014; Carusi 2016). Standards and ontologies are forms of advanced systems of equivalences. A famous example in the biosciences is the Gene Ontology[7]. In interdisciplinary research, new systems of equivalences have to be forged. A system of equivalences does not exist independently of collaborations, but emerges from them, and is possibly one of the most useful outputs of collaboration as it enables further research. Systems of equivalences ground comparisons; they are the basis for a common understanding of standards of evidence of the different methods, and the grounds for evaluating their outputs in ways that are understandable by all. In this way they anchor discussions about quality of evidence, which so often makes crossdisciplinary dialogue difficult, as each side has no context for evaluating the evidence offered by the other. They function as *epistemic norms*, that is, standards of knowledge. The sharing of epistemic norms in turn builds *trust*. Importantly, they do not pre-exist crossdisciplinary encounters or collaborations, but emerge from them. This is illustrated in Figure 1 and an example is outlined in Box 2.

[7] See the Gene Ontology Resource (http://geneontology.org/): the stated aim is to build a computational model of biological systems: that is, an overarching equivalence between a computational model of some specific biological system on one hand, and the biological system in question on the other. One means of achieving this is through the ontology, that is a controlled vocabulary. This operates like a dictionary to strictly map the terms of one system onto another, that is to make them equivalent; and thereby to stabilise meaning, so that comparisons can be made, and evidence built up.

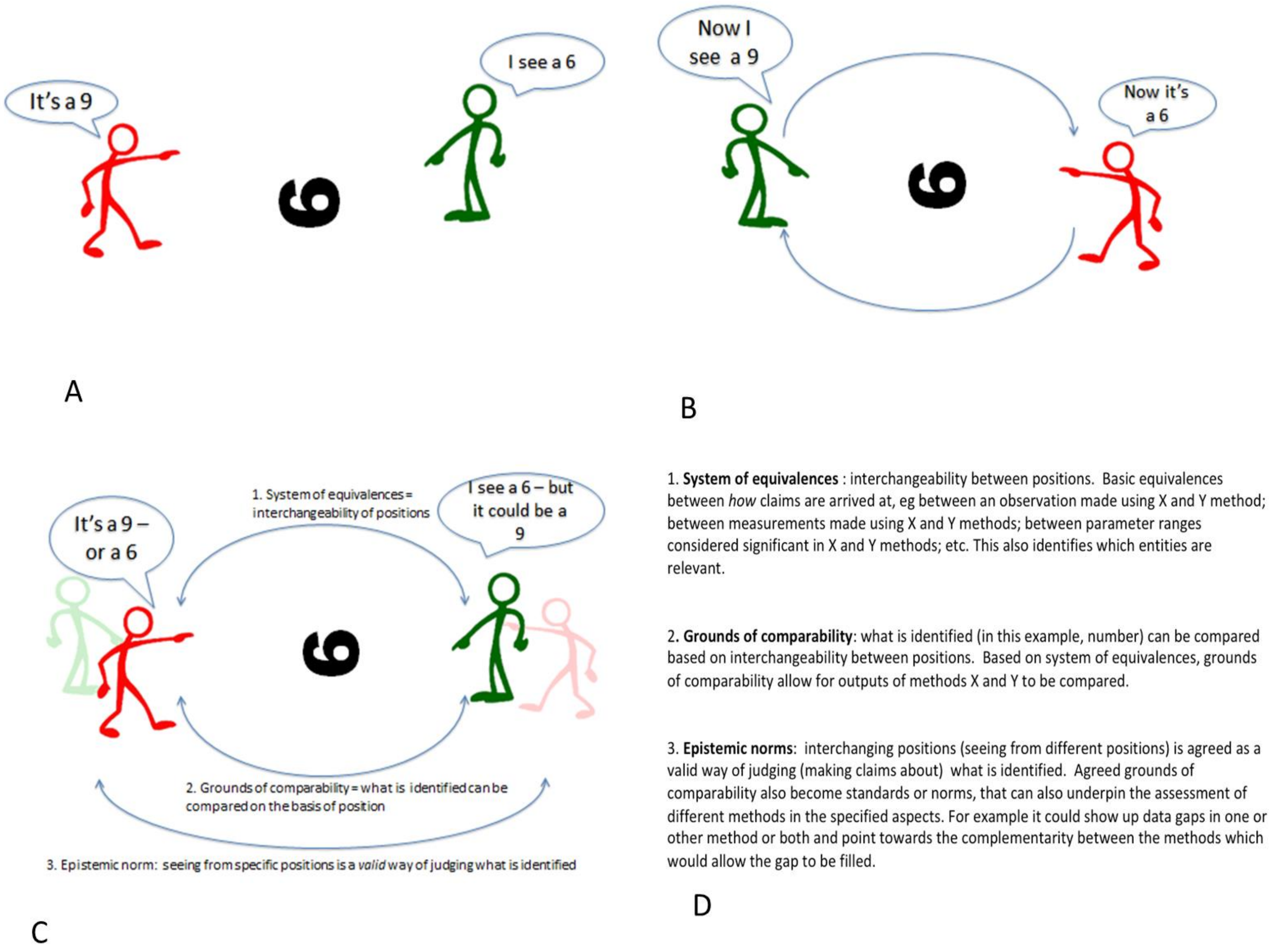

Figure 1: The relations among systems of equivalences, grounds of comparability and epistemic norms.

Box 2: Systems of equivalences in toxicity testing

The overarching system of equivalences that has dominated in toxicity testing for many decades is that between the effects of substances on non-human animals and humans, which licences the use of animals for testing the safety of chemicals and other substances. This overarching equivalence between humans and other animals is supported by a network of equivalences, for example, between specific effects (endpoints) on animal organisms and specific outcomes for humans, and the whole panoply of conventions associated with upholding it. This equivalence is the basis for comparing the effects of substances on humans and other animals, and for extrapolating from non-human animals to humans.

The sub-net of further equivalences, for example, between specific endpoints, supports further comparisons between different studies. Epistemic norms identify what are the valid ways of carrying out these studies and deriving evidence from them. Sometimes these are entrenched in explicitly articulated standards, such as Test Guidelines and Good Laboratory Practice. New methods coming into the domain need to establish new systems of equivalences, anchoring themselves in existing ones: for example, between the outputs of an in vitro test, and the outputs of an existing animal test, or between mechanisms and endpoints. The challenge is that systems of equivalences are seldom one-to-one mappings, but wide networks with a variety of bridging points with established systems. Which are the appropriate bridging points for making new equivalences, and the details of how to do this, emerges from the community of practitioners in the domain.

The work done by systems of equivalences is often implicit, but using this as a scaffold encourages scientists working across domains to come to a mutual agreement about bridging points, and to get better at making these explicit, along with the methods, comparisons, norms and standards that are associated with them. Importantly this process must include regulators, who stabilise the epistemic norms and standards in an applied science of social concern, such as regulatory toxicology, and also the public, whose acceptance of risk and hazard, and expectation of safety, plays a very important role in constraining the whole domain. Therefore, at some level, the system of equivalences has to be acceptable to the public as well as to scientists.

The most important aspect of this process, however, is that it should be conducted together, by the relevant disciplines and communities, and that the system of equivalences and norms should be co-produced. This is not an alien process to science, it is happening all the time, but it is usually implicit and tacit, not documented or made explicit. It happens by serendipity, and may be highly dependent on the right people and circumstances happening to come together. Can we become better at creating the right conditions for this to happen, rather than leaving it to chance?

Our suggestion is that *bridgeability* between methods is achieved through a form of knowledge sharing that supports or scaffolds the construction of systems of equivalences and grounds of comparability. These in turn allow methods to enter into a meaningful dialogue with each other: to compare, to see what they have in common, what they do not, what they might borrow from each other. BeAMS could play a role in developing ways of supporting and facilitating the type of knowledge sharing that scaffolds the construction of systems of equivalences between the knowledge practices associated with specific methods. At the same time, this form of knowledge sharing will make the processes of constructing systems of equivalences more explicit, so that they can be passed on and reutilised.

Essentially, the knowledge sharing that supports bridgeability between methods works to make explicit the assumptions around the use of methods in specific research contexts, so that key terms or other items in the different practices of research cultures can be compared. A key ability in this form of knowledge sharing is the ability to take a ‘meta’ stance on one’s own practice: that is to stand back from it in order to describe it and what it is based on.

Ways of achieving this are through:

- Describing examples of past or current research where this has been achieved and show the different forms that systems of equivalences can take, and how these relate to the research of the interacting groups of scientists[8];
- Creating opportunities to develop systems of equivalences/grounds of comparability simultaneously with the skills of being able to articulate what the systems are; at workshops, conferences, summer schools, etc., through for example facilitated structured dialogues, tables, activities to arrive at a 'dictionary', or to an embryonic hybridised common language, visualisation or diagrams, co-designed experiments, talk-aloud methods (where participants carry out tasks while at the same time describing what they are doing out loud), conceptual analysis, scenario building;
- Incorporating reflection work packages in funded crossdisciplinary projects, that make explicit how systems of equivalences/grounds of comparability are arrived at or what obstacles are met.

5.2 Knowledge Systems

Knowledge practices are embedded in knowledge systems; knowledge systems are, on one hand, productive for practices in setting in place the structures that allow them to flourish, and on the other, constraining because they do not enable all practices to flourish, and may indeed suffocate some. There was overall agreement at the BeAMS workshop, as there is in broader research stakeholders as evidenced in the different initiatives already discussed in Section 1, that the current knowledge system needs to change: reward, incentive, publication mode and platform, authorship, ownership, career structures, research institute organisation, all need an overhaul in order to deal with the demands of current trends in science. There are already a number of important initiatives to tackle several aspects of Research Systems (see Section 2), and whatever BeAMS does at this level should support those strategies, and bridge between them.

Major policy strategies play a key role in shaping research, and the flows of researchers between domains. Horizon 2020, for example, is a funding policy that is structured around societal challenges rather than around disciplines or research domains in order to encourage crossdisciplinary cooperation[9]. Horizon Europe is the next major research funding framework for Europe, and it will be informed by the idea of Missions (European Union 2018a). Missions are policies to improve the capacity of research and innovation to have an impact on societal challenges. They are aimed at specific problems or challenges. The historical example given is getting a person onto the moon; another example is penicillin discussed above. Missions integrate different projects, in order to ensure that through their combined efforts, a specific problem is effectively tackled. They are policies that inherently recognise that no societal challenge or problem can be addressed through science and innovation alone, but also requires an understanding of the interplay between science, technology, and socio-economic and political factors, and the engagement of actors across sectors. Crucially, Missions are transdisciplinary in the strict sense of the term: they cut across disciplines, institutions, sectors, and nations, attempting to harness and integrate opportunities across these. Missions give combinations of projects directionality, that is, a mutually recognised objective. Missions cannot be imposed in a unilateral way, but have to be agreed by all stakeholders. They integrate bottom-up and top-down forces, with the overall mission providing a direction for research and innovation, while leaving a lot

[8] For example, three pojects are mentioned as best practice examples in this Horizon Europe presentation, and could be studied further: https://ec.europa.eu/info/sites/info/files/horizon-europe-presentation_2018_en.pdf

[9] Social Sciences and Humanities were however still separate; and although nominally included in Societal Challenges, it would be interesting to see how many of these projects actually included SSH and in what capacity.

of scope for bottom-up creativity of the projects and participants in them. A Missions-informed research and innovation strategy would set the scene for the emphasis on circular pathways for change, and thinking in terms of co-production, co-creation, co-formulation and co-definition of science, methods and aims, which was a theme throughout our discussions at the workshop. The vision for Missions-informed research and innovation is ambitious and progressive; however, there is a great deal of detail still to be filled in, specifically relating to how this strategy would be implemented, how the top-down and bottom-up drives will meet, and how the different projects, actions and strategies will be integrated in order to ensure that they are all pulling in the same direction (European Union 2017b, 2018a, 2018b). The success of the implementation of the missions-informed strategy will depend on this important detail. In well-implemented missions-informed research and innovation, knowledge practices and knowledges systems will cohere and mutually support each other rather than cutting across each other.

This is where BeAMS aims to make a contribution: to gain an understanding of how bridging across different inputs and contributions can be supported and facilitated rather than left to chance; how bridging can be explicitly encouraged as a criterion for projects participating in the Missions research and innovation, how it can be assessed and evaluated, and how can bridging know-how continue beyond the life of a project and be passed on. See Figure 2.

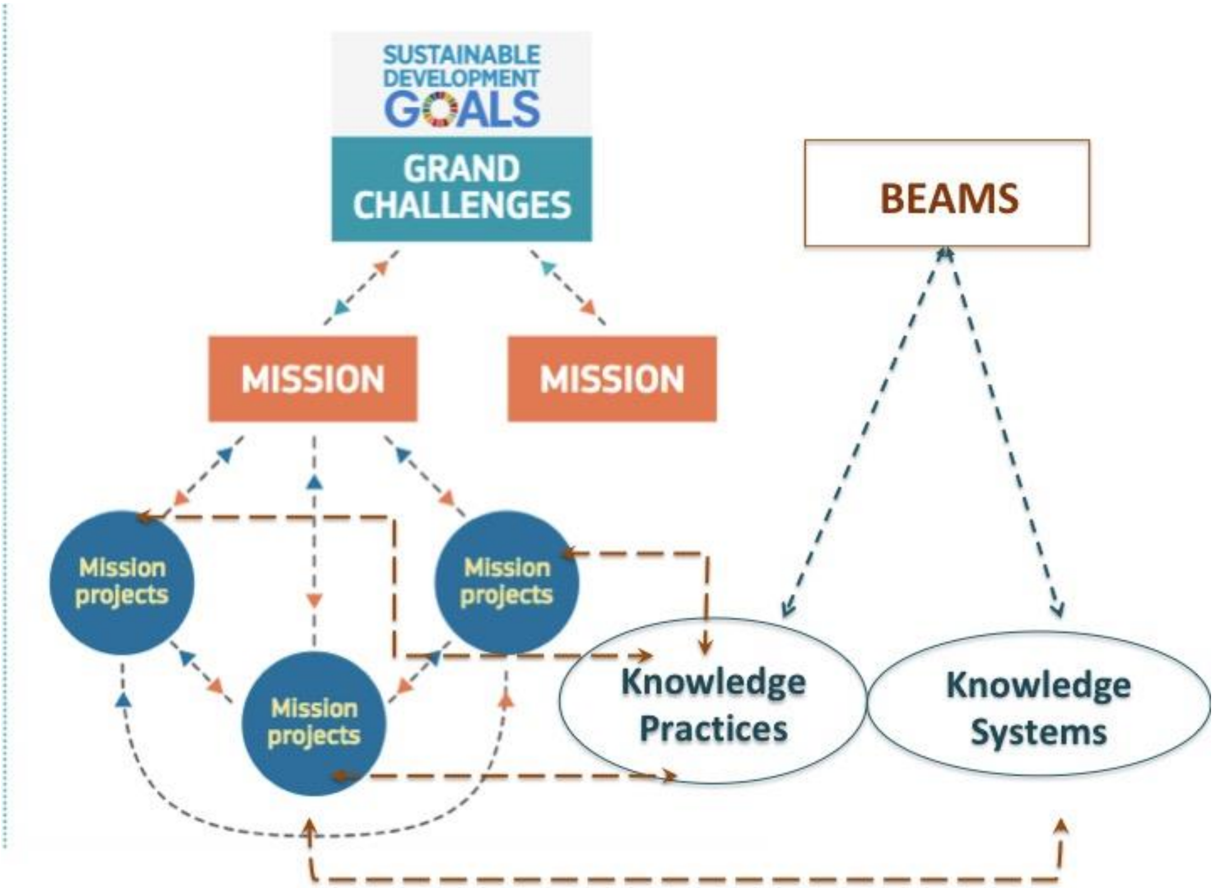

Figure 2: How BeAMS could support Missions centred Research and Innovation (adapted from EU 2018a).

6. Recommendations

Sometimes successful bridging happens by serendipity and produces novel results and new ways of tackling problems. Most times it does not, even when funders invest in grand crossdisciplinary projects or programmes. We need a concerted effort by the research communities, across science, social science and humanities, to gain a better understanding of how research practices can be bridged or made bridgeable, how this could be implemented in practice, and how it can be replicated, especially when scientific knowledge is being deployed to tackle complex societal challenges.

In order to achieve this, we need a combination of approaches and initiatives:

- Gain a better understanding of how scientific methods become bridgeable across disciplines and sectors, through analysis of historical and current paradigm cases;
- Create new opportunities to facilitate and experiment with ways to bridge across methods;
- Analyse existing policies and initiatives regarding open access, open science, and open data, and see what gaps there are between data and method complementarity.
- Include more explicit criteria for crossdisciplinary research and bridgeability across methods in funding calls, and in assessments of research and innovation projects.

References

Baker, M. (2016). Is there a reproducibility crisis in science? *Nature,* 533, 26 May 2016 https://www.nature.com/polopoly_fs/1.19970!/menu/main/topColumns/topLeftColumn/pdf/533452a.pdf

Becher, T. and Trowler, P.R. (2001). *Academic Tribes and Territories: Intellectual enquiry and the culture of disciplines*. Buckinham: Society for Research into Higher Education and Open University Press.

Bruce, A., Lyall, C., Tait, J., & Williams, R. (2004). Interdisciplinary integration in Europe: the case of the Fifth Framework programme. *Futures, 36*(4), 457-470. doi:10.1016/j.futures.2003.10.003

Burke, P. (2012). *A Social History of Knowledge. Vol II. From the Encyclopedie to Wikipedia.* Cambridge, UK & Malden, US: Polity Press.

Calvert, J., & Fujimura, J.H. (2011). Calculating life? Duelling discourses in interdisciplinary systems biology. *Studies in history and philosophy of biological and biomedical sciences, 42*(2), 155-163. doi:10.1016/j.shpsc.2010.11.022

Carusi, A. (2011). Computational Biology and the Limits of Shared Vision. *Perspectives on Science, 19*(3), 300-336.

Carusi, A., Burrage, K., Rodriguez, B. (2012). Bridging experiments, models and simulations: an integrative approach to validation in computational cardiac electrophysiology. *American Journal of Physiology, Heart and Circulation, 303*, H144-H155.

Carusi, A. (2014). Validation and variability: dual challenges on the path from systems biology to systems medicine. *Studies in history and philosophy of biological and biomedical sciences, 48 Pt A*, 28-37. doi:10.1016/j.shpsc.2014.08.008

Carusi, A. (2016). In Silico medicine: Social, Technological and Symbolic Mediation. *Humana.Mente, 30*, 67-86

Clarke, A. and Fujimura, J. (1992). What Tools? Which Job? Why Right? In *The Right Tools for the Right Job: At Work in Twentieth Century Life Sciences*. Princeton, NJ, and Oxford, UK.: Princeton University Press, pp. 3-45.

Clarke, T., De Waard, A., Herman, I., Hovy, E., (2015). The Future of Research Communication, DagstuhlReports, Vol. 1, Issue 8, pp. 29–52. doi 10.4230/DagRep.1.8.29

Collins, F.S. and Tabek, L.A. (2014). NIH plans to enhance reproducibility. *Nature*, vol 505, p. 612-3.

De Chadarevian, S. and Gaudillière, J.P. (1996). The tools of the discipline: Biochemists and molecular biologists, *J Hist Biol*, 29: 327.

De Grandis, G. and Efstathiou, E. (2016). Introduction – Grand Challenges and Small Steps. *Studies in the History and Philosophy of Science. Part C. Studies in Biological and Biomedical Sciences*, vol 56, p. 36-47.

European Commission, DG Research and Innovation. (2016). Open innovation, open science, open to the world—a vision for Europe. Brussels: European Union. doi 10.2777/061652.

European Union. (2017a.) 'Open Science Policy Platform Recommendations'. Luxembourg: Publications Office of the European Union. doi 10.2777/958647.

European Union. (2017b). Towards a Mission-Oriented Research and Innovation Policy in the European Union – An ESIR Memorandum: Executive Summary. Luxembourg: Publications Office of the European Union. doi 10.2777/0956.

European Union. (2018a). MISSIONS. Mission-Oriented Research & Innovation in the European Union. A problem-solving approach to fuel innovation-led growth. Luxembourg: Publications Office of the European Union. doi:10.2777/360325

European Union. (2018b). Mission-oriented Research and Innovation Policy: A RISE Perspective. Luxembourg: Publications Office of the European Union. doi:10.2777/426921

Frickel, S., Albert, M., Prainsack, B. (2016). Investigating Interdisciplinary Collaboration: Theory and Practice across Disciplines. Rutgers University Press.

Fujimura, J. (1996). Standardizing Practices: A Socio-History of Experimental Systems in Classical Genetic and Virological Cancer Research, ca. 1920-1978, History and Philosophy of the Life Sciences, 18, 3-54.

Galison, P. (1996). Computer Simulations and the Trading Zone. In P. Galison, Stump, D.J. (Ed.), *The Disunity of Science: Boundaries, Contexts, and Power* (pp. 118-157). Stanford, California: Stanford University Press.

Galison, P. (1997). *Image and Logic: A Material Culture of Microphysics*. Chicago & London: University of Chicago Press.

Garcia-Marquez, M. (2012.) *Biology, Computing and the History of Molecular Sequencing*. Basingstoke and New York: Palgrave Macmillan.

Green, S. and Wolkenhauer, O. (2012). Integration in action. EMBO Reports, 13 (9) 769-771.

Jones, R. and Wilsden, J. (2018). The Biomedical Bubble. Why UK research and innovation needs a greater diversity of priorities, politics, places and people. NESTA.

Keller, E.F. (2002). *Making Sense of Life: Explaining Biological Development with Models, Metaphors and Machines*. Cambridge, Mass. & London, England: Harvard University Press.

Keller, E. F. (2003). *A Feeling for the Organism*. New York: Henry Holt and Co.

Knorr-Cetina, K. (1999). Epistemic Cultures: How the Sciences Make Knowledge. Harvard University Press.

Leonelli, S. (2016). *Data-Centric Biology: A Philosophical Study*. Chicago and London: University of Chicago Press.

Macleod, M. and Nersessian, N.J. (2013). Coupling simulation and experiment: The bimodal strategy in integrative systems biology. Studies in History and Philosophy of Biological and Biomedical Sciences, 44(4), 572e584.

Morrison, David (2015). *The underdetermination of interdisciplinarity: theory and curriculum design in undergraduate higher education.* PhD thesis, University of Glasgow.

Pickering, A. (1995) *The Mangle of Practice: Time, Agency and Science.* Chicago and London: Chicago University Press.

Rheinberger, H-J. (1997) *Toward a History of Epistemic Things: Synthesizing Proteins in the Test Tube*. Stanford University Press

Rodriguez, B., Carusi, A., Abi-Gerges, N., Ariga, R., Britton, O., Bueno-Orovio, A., Burton, R.A., Carapella, V., Cardone-Noott, L., Daniels, M.J., Davies, M.R:, Dutta, S., Ghetti, A., Grau, V., Harmer, S., Kopljar, I., Lambiase, P., Lu, H.R., Lyon, A., Minchole, A., Muszkiewicz, A., Oster, J., Paci, M., Passini, E., Severi, S., Taggart, P., Tinker, A., Valentin, J.P., Varro, A., Wallman, M. and Zhou, X. (2015). Human-based approaches to pharmacology and cardiology: an interdisciplinary and intersectorial workshop. *Europace*. doi:10.1093/europace/euv320

Rothwell, P.M., McDowell, Z., Wong, C.K., Dorman, P.J. (1997). Doctors and patients don't agree: cross sectional study of patients' and doctors' perceptions and assessments of disability in multiple sclerosis. *BMJ* May 31, 314 (7094): 1580-3

Schwartz Cowan, R. (1997) *A social history of American Technology*. Oxford University Press, chapter 13

Vermeulen, N., Parker, J. N., and Penders, B. (2013) Understanding life together: a brief history of collaboration in biology. *Endeavour, 37*(3), 162-171. doi:10.1016/j.endeavour.2013.03.001

Wilkinson, M.D., Dumontier, M., Aalbersberg, I.J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.-W., Bonino da Silva Santos, L., Bourne, P.E., Bouwman, J., Brookes, A.J., Clark, T., Crosas, M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C.T., Finkers, R., Gonzalez-Beltran, A., Gray, A.J.G., Groth, P., Goble, C., Grethe, J.S., Heringa, J., 't Hoen, P.A.C., Hooft, R., Kuhn, T., Kok, R., Kok, J., Lusher, S.J., Martone, M.E., Mons, A., Packer, A.L., Persson, B., Rocca-Serra, P., Roos, M., van Schaik, R., Sansone, S.-A., Schultes, E., Sengstag, T., Slater, T., Strawn, G., Swertz, M.A., Thompson, M., van der Lei, J., van Mulligen, E., Velterop, J., Waagmeester, A., Wittenburg, P., Wolstencroft, K., Zhao, J. and Mons, B. (2016). The FAIR guiding principles for scientific data management and stewardship. *Sci Data*. 3:160018.

List of boxes

List of figures

KJ-NA-29852-EN-N

The European Commission's science and knowledge service

Joint Research Centre

JRC Mission

As the science and knowledge service of the European Commission, the Joint Research Centre's mission is to support EU policies with independent evidence throughout the whole policy cycle.

EU Science Hub
ec.europa.eu/jrc

@EU_ScienceHub

EU Science Hub - Joint Research Centre

EU Science, Research and Innovation

EU Science Hub

Publications Office of the European Union

doi:10.2760/190697

ISBN 978-92-76-11181-8