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Review Article

Ready to Put Metadata on the Post-2015 Development Agenda? Linking Data Publications to Responsible Innovation and Science Diplomacy

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Abstract

Metadata refer to descriptions about data or as some put it, ‘‘data about data.’’ Metadata capture what happens on the backstage of science, on the trajectory from study conception, design, funding, implementation, and analysis to reporting. Definitions of metadata vary, but they can include the context information surrounding the practice of science, or data generated as one uses a technology, including transactional information about the user. As the pursuit of knowledge broadens in the 21st century from traditional ‘‘*science of whats*’’ (data) to include ‘‘*science of hows*’’ (metadata), we analyze the ways in which metadata serve as a catalyst for responsible and open innovation, and by extension, science diplomacy. In 2015, the United Nations Millennium Development Goals (MDGs) will formally come to an end. Therefore, we propose that metadata, as an ingredient of responsible innovation, can help achieve the Sustainable Development Goals (SDGs) on the post-2015 agenda. Such responsible innovation, as a collective learning process, has become a key component, for example, of the European Union’s 80 billion Euro Horizon 2020 R&D Program from 2014–2020. Looking

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ahead, *OMICS: A Journal of Integrative Biology*, is launching an initiative for a multi-omics metadata checklist that is flexible yet comprehensive, and will enable more complete utilization of single and multi-omics data sets through data harmonization and greater visibility and accessibility. The generation of metadata that shed light on how omics research is carried out, by whom and under what circumstances, will create an ''intervention space'' for integration of science with its socio-technical context. This will go a long way to addressing responsible innovation for a fairer and more transparent society. If we believe in science, then such reflexive qualities and commitments attained by availability of omics metadata are preconditions for a robust and socially attuned science, which can then remain broadly respected, independent, and responsibly innovative.

> ''*In Sierra Leone, we have not too much electricity. The lights will come on once in a week, and the rest of the month, dark[ness]. So I made my own battery to power light in people's houses.*''
>
> Kelvin Doe (Global Minimum, 2012)
> MIT Visiting Young Innovator
> Cambridge, USA, and Sierra Leone

> ''*An important function of the (Global) R&D Observatory will be to provide support and training to build capacity in the collection and analysis of R&D flows, and how to link them to the product pipeline.*''
>
> World Health Organization (2013)
> Draft Working Paper on a Global Health R&D
> Observatory

Introduction

Metadata: A science of hows

Meta stems from the Greek word for ''beside,'' or ''along with''. Scholars used it in the past to study what others are studying (e.g., metapsychology). Yet it remained on the fringes of the hard sciences for centuries. This is about to change—with the mainstreaming of ''metadata'' in life sciences.

Metadata refer to descriptions about data, a ''science of hows'' in the pursuit of knowledge, or as some put it, ''data about data.'' Metadata capture what happens on the backstage of science, on the trajectory from study conception, design, funding, implementation, and analysis, to reporting. Definitions of metadata vary, but they can include the context information surrounding the practice of science, or data generated as one uses a technology, including transactional information about the user. Metadata are applicable to any kind of empirical inquiry that deals with data, such as ecogenomics, pharmacogenomics, vaccinomics, or social studies of science and omics technology.

Metadata hold significance in the case of omics science (for a definition, see Box 1). Historically, metadata were not made available in science articles. If reported, metadata would be rarely available under supplementary information, let alone as a stand-alone publication.

In this January issue of *OMICS: A Journal of Integrative Biology*, we are launching an initiative for a multi-omics metadata checklist that is flexible yet comprehensive, and will enable more complete utilization of single and multi-omics data sets through data harmonization and greater visibility and accessibility (Kolker et al., 2014). Moreover, we are publishing, as a stand-alone report, the metadata from the integrative personal omics profiling (iPOP) study at Stanford that introduced a novel, integrative approach based on personalized, longitudinal, multi-omics data (Snyder et al., 2014). We call for the broader use of data publications using the metadata checklist to make omics data more discoverable, interpretable, and reusable, while enabling appropriate credit attribution to data generators and novel forms of practice such as iPOP and citizen science applications of omics technologies.

Box 1. Definition of "Omics" and Its Socio-Technical History (Updated from Ozdemir et al., 2009).

According to one etymological analysis, the suffix ''ome'' is derived from the Sanskrit OM (''completeness and fullness'') (Lederberg and McCray, 2001), underscoring its systems-oriented underpinnings as a form of scientific inquiry. By combining ''gene'' and ''ome'', Hans Winkler created the term genome (Winkler, 1920). Victor McKusick and Frank Ruddle added ''genomics'' to the lexicon as the title for the new journal they cofounded in 1987 (McKusick and Ruddle, 1987).

Omics science aims to characterize individual and population differences in biology. In this sense, the focus of omics science on biological ''variability questions'' is rooted in diagnostic medicine. In fact, understanding and diagnosing individual differences in health and disease have been a preoccupation since ancient times. Some early diagnosticians adopted a systems-oriented thinking, as with omics science. The Babylonians and Sumerians utilized urine to diagnose the general health status of individuals as early as 4000 BCE, whereas Hippocrates (460–ca. 370 BCE, the Island of Cos, Greece) suggested the presence of bubbles in the urine as an indication of chronic kidney disease (White, 1991). Despite these hints of interest in diagnostic medicine in ancient times, until the end of 19th century, variability questions presently addressed by omics science were not a legitimate component of the mainstream science and medicine. In the early 20th century, Archibald Garrod (1857–1936) suggested the chemical individuality of humans as a basis for inborn errors of metabolism such as alkaptonuria (Garrod, 1902).

Omics technologies such as proteomics and genomics were introduced starting with the two-dimensional gel electrophoresis for global protein analyses in the 1970s, and high-throughput DNA sequencing methodologies in the 1990s. They generate observations from successive hierarchies of cell biology from genomics to metabolomics. This multi-layered information helps triangulate, in real time, the system level predictive value of a biomarker test, over-and-above the built-in redundancies preserved in biology during the course of human evolution.

Omics, as a systems-oriented approach, can also be applied to social sciences in the form of sociomics, the data-intensive sociology of life sciences, one of the subject matters of interest to this journal.

Long before the launch of the Human Genome Project and the present popularity of genomics research, Norman G. Anderson and N. Leigh Anderson, a father and son team, attempted to develop an index of all human proteins (the Human Protein Index, HPI) in the 1970s, at a scale that could be considered as one of the very first investigations with an ''omics'' vision (Anderson et al., 2001). The Andersons were ahead of their time; the proposal for the HPI remained unfunded initially. In hindsight, the Andersons provide the following personal account: ''*…because DNA sequencing technology is inherently simpler and more scalable than protein analytical technology, and because the finiteness of genomes invited a spirit of rapid conquest, the notion of genome sequencing has displaced that of protein databases in the minds of most molecular biologists*'' (Anderson et al., 2001). This anecdote on the origins of proteomics science acknowledges that the emergence of omics technology and innovation is not foreordained and subject to socio-political construction. It also underscores the nonlinear and often unpredictable ways in which novel ideas may (or may not) turn into innovations and diagnostic products.

Building on the example of the metadata publication (Snyder et al., 2014) and the checklist (Kolker et al., 2014), we present here a postgenomics innovation analysis on (1) metadata as contextual information that holds strong clues for robust and responsible linkages from data to innovation; and (2) the ways in which metadata play a role as an innovation catalyst, and by extension, in science diplomacy.

Metadata, science diplomacy, and the post-2015 agenda

The UK Royal Society has recently observed that ''*Science diplomacy is not new, but has never been more important. Many of the defining challenges of the 21st century—from climate change and food security, to poverty reduction and nuclear disarmament—have scientific dimensions*.'' (The Royal Society, 2010). Accordingly, there are three ways in which science and diplomacy intersect and interact:

- Science in diplomacy;
- Science for diplomacy; and
- Diplomacy for science.

With the appreciation that science and technology scholarship are invaluable for diplomacy and international relations—fellowship programs have been created by various world governments and their departments of state and foreign affairs. For example, the US State Department and the US Agency for International Development (USAID) have brought in dozens of scientists over the last decade. This capacity building for science-in-diplomacy has served as a force multiplier in favor of a closer proximity of science and diplomacy. Science can advance diplomacy and nation state interests (science for diplomacy), while diplomacy can play an instrumental role for scientific cooperation and innovation among nation states and global regions (diplomacy for science).

As the United Nations Millennium Development Goals (MDGs) agenda is formally coming to an end in 2015, we propose that metadata, as a crucial ingredient for open science and responsible innovation, can help achieve the new Sustainable Development Goals (SDGs) on the post-2015 international development agenda, and serve as a guidepost on the ways in which science and diplomacy can intersect on the new agenda.

Metadata to Responsible Innovation

Context and reflexivity matter

Context and reflexive thinking are everything when it comes to linking science and technology to responsible innovation. This applies in particular to the case of Kelvin Doe, aged 16 and native of Sierra Leone, and the youngest ever ''visiting practitioner'' with the Massachusetts Institute of Technology (MIT) International Development Initiative (Global Minimum, 2012). Equipped with a deep understanding of the local resource-limited context, and of basic human needs in that situation, Kelvin built homemade batteries from scrap material such as metal, soda, and acid collected from local garbage. He then went on to develop a community FM radio station in his country. Kelvin, who goes by the name ''DJ Focus,'' is inspired by the desire to empower other youth, and to help them innovate reflexively, with a view to responsible development in rural communities. Had it not been for his keen understanding of the local context in which his innovations would be applied, not to mention of the veritable need for electricity and extended public space for youth in Sierra Leone, Kelvin's inventions and radio station might have taken an entirely different trajectory, or not have materialized at all.

Kelvin's story is not merely one about a teen prodigy. It is a telling example of how scientific knowledge and innovations are co-products of forces beyond technology: the choice of experimental supplies and methods, funding, how and by whom data are processed, analyzed and reported, and the human values, imaginations, and motives that shape the scientific ends (Özdemir, 2013). We should not place blind faith in the epistemic convictions (Collins and Evans, 2002), or life science knowledge, engineering, medicine, social sciences, law, ethics, or philosophy; none of them can guarantee responsible oversight of science and innovation (De Vries, 2003; Dove and Özdemir, 2013a; Jasanoff, 2013; Law, 2004; Özdemir, 2010; Wynne, 2006). Instead, if we aim to help to create solutions for society's greatest challenges, we need to be thinking attentively about how our values impact the societal outcomes of research. That is, being a reflexive thinker for omics science is as important as the technological drivers of innovation (Bauman, 2000; Dove and Özdemir, 2013a, 2013b; European Commission, 2007; Guston, 2004; Jasanoff, 2007).

Without the reflexive capacity—and will—to question his own purposes deeply, Kelvin might have produced a very different set of goods that are still innovative, but not necessarily reflexive enough to address the local community needs. If we believe in science, reflexive qualities and commitments are preconditions for a robust and socially attuned science, which remains broadly socially respected, independent, and responsibly innovative.

Understanding the Backstage for Science

Metadata is closely allied to ''scientometrics'' (i.e., the field of measuring and analyzing science research), which was developed by Yale University Professor of the History of Science, Derek J. de Solla Price, in the 1960s (de Solla Price, 1963). An example of scientometrics is analysis of the trends in scientific citations over time; the United Kingdom and Germany have recently overtaken the United States in terms of articles cited per scientist (Marshall and Travis, 2011). Another is the new metrics tab for every new article published in the PLOS (Public Library of Science) that allows viewers to follow trends in article downloads over time. Such metadata are critical for shaping informed science policy and advocacy (Priem et al., 2010).

OMICS will devise mechanisms to put the omics metadata checklist in action for selected, relevant, and priority omics research in a phased approach, thus building bridges to knowledge-based innovation from studies and datasets. The checklist can be used as part of a larger publication or as a standalone metadata publication (Snyder et al., 2014) to inform the community of an available data resource. This will give credit to data producers, harmonize different omics data sets, and use research resources more effectively for advancement of omics science and innovation. Importantly, the checklist will allow for appropriate attribution and due credit to data generators, infrastructure science builders, and scholars who study omics science in its socio-technical context in the postgenomics era.

Metadata: What would Frederick Soddy say?

It is interesting to note that since the Age of Enlightenment in the 17th century, science has by and large been preoccupied with data, rather than metadata or data provenance (Parker et al., 2003). Wet bench laboratory data prevailed as a narrow measure to benchmark scientific progress and performance, often bracketing out the socio-technical context in which data are generated. Social and political scientists who worked to understand the context in which data came into existence challenged the supremacy of data over metadata. Yet even fewer scientists, such as Brian Wynne in the field of science studies, took the study of context to heart, and had the courage to examine their own trade (science, engineering, and medicine), situating data and innovation trajectory with the tools of social and political sciences (Wynne, 2009).

Earlier, other scholars like Frederick Soddy, the recipient of the 1921 Nobel Prize in chemistry, took similar interests in study of science in its socio-political context (Sclove, 1989). Still, the idea of socio-technical integration remained as an afterthought, rather than a forethought or an integral part of 20th century science. In an analysis of Soddy, Sclove (1989) provides the following account:

> Many scientists shared Soddy's scientific knowledge, but none became as committed as he to investigating the social implications of that knowledge (…) The story of Frederick Soddy thus provides dramatic evidence for the role of so-called 'nonscientific' factors within the content and social organization of science. But it goes further, suggesting that nonscientific knowledge, social context, emotion, and imagination contribute—and in this case fruitfully—not only to the development of scientific knowledge, but also to the interpretation of its social consequences.

Things do change with the sands of time, and occasionally for the better. A collective cognizance is now emerging with appreciation of the dual architecture of 21st century science, comprised of both *actors* (e.g., scientists) and *narrators* (e.g., innovation analysts and observatories) (Dove and Özdemir 2013b; Jasanoff 2013; Özdemir 2013; WHO 2013). We need the actors and practitioners (e.g., scientists, engineers, and medical doctors) who are trained in science and technology, contributing to the *making* of science and knowledge-based innovation. Innovation narrators and observatories play an essential role to *stimulate*, and *steer* science to responsible and robust innovation, attuned to societal values and priorities. Far from an abstract and esoteric academic interest, the idea of innovation observatories is gaining momentum, acknowledging a co-productionist view of scientific knowledge and collective innovation. Moreover, such observatories, rather than merely describing the linkages between science and its social context, are also aiming to intervene on the innovation trajectory to steer it towards responsible innovation. The World Health Organization (WHO) has begun a process for the laudable proposal to establish a Global Observatory for Health Research and Development (R&D), with a draft working paper published in May of last year (WHO, 2013). An important focus of the proposed observatory will be new ways to link R&D flows to product pipeline(s).

Science and technology trajectories are never pre-ordained and thus, face multiple possible futures. Innovation observatories can bring about much needed adaptive, responsive, and creative flexibility on the part of the innovation actors. They also build capacity for reflexivity to imagine alternatives (e.g., as products and the ends which they intend to serve) in the pursuit of knowledge-based innovation. In relation to reflexive innovation, a definition of reflexivity and its difference from reflection are provided in Box 2. An example of the importance of local situated context knowledge to realize innovations is provided in Box 3.

Box 2. Definition of Reflexivity in Relation to Knowledge-Based Innovation

The concept of reflexivity has been debated extensively in the field of sociology of scientific knowledge. For our purposes in this article, reflexivity can be understood as a ''capacity to bend back on oneself,'' and being cognizant of the context-sensitive and -responsive nature of knowledge-based innovations, for example, through context information embedded in omics metadata. A reflexive scientist thinks attentively about how her/his values impact the course of scientific inquiry, and the attendant broader societal outcomes. Scholars have noted that reflexivity applies symmetrically (*tu quoque*) (i.e., equally well) to the works of scientists and social scientists alike (Ashmore, 1989; Bourdieu, 2001; Thoreau, 2011; Thoreau and Delvenne, 2012).

Frederick Soddy has advocated for what is essentially a reflexive understanding of science in the 20th century. Similar advocacy is necessary for reflexive social science practice in the early 21st century (Dove and Özdemir, 2013a; Thoreau and Delvenne, 2012).

Reflexive governance of science and innovation relates to ‘‘the organization of recursive feedback relations between distributed steering activities’’ (Voss et al., 2006). Such recursive feedback mechanisms can be more readily brought to life, if omics metadata were made available, particularly for data sets that have broad community-wide significance, or those that are likely to pave the way for disruptive innovation.

Stirling (2006) has distinguished ‘‘reflexivity’’ and ‘‘reflection’’. Reflection is a mode of representation whereby attention is diverted to everything that ‘‘lies in the field of view.’’ On the other hand, reflexivity goes beyond reflection, by firmly acknowledging the intrinsic uncertainties and epistemic plurality, with a view to transformation of the self, through self-awareness of context-sensitivity and -responsiveness of science, technology, and innovation.

Box 3. The Empty Soap Box—Japanese Case Study on Context-Sensitive Innovation

One of the most debated Japanese engineering case studies is the *Empty Soap Box Problem*. In brief, a large-scale company received a complaint that a consumer had bought a soap box that was empty.

Immediately, the authorities isolated the problem to the assembly line, which transported all the packaged boxes of soap to the delivery department. For some reason, one soap box went through the assembly line empty.

Management asked its engineers to solve the problem. The high-ranking expert engineers devised an X-ray machine with high-resolution monitors staffed by two people to watch all the soap boxes that passed through the line to make sure they were not empty.

But then a worker found another solution. S/he did not get into complications of X-rays, but bought a strong industrial electric fan, and pointed it at the assembly line. After switching the fan on, and as each soap box passed the fan, the fan simply blew the empty boxes out of the line.

Metadata for OMICS

Why now, and why should we care?

With the proposed WHO Observatory on Global Health R&D, and other observatories monitoring innovation contexts at country and regional levels, there is now a real opportunity to bring about legitimacy for metadata in life sciences. While other sectors like meteorology, environment, and physics are historically schooled in the importance of metadata, life sciences, and health R&D in particular, have worrisomely lagged behind. The time is ripe to move forward to remedy the metadata gap in OMICS science and post-genomics integrative biology.

Metadata is important for at least three reasons. First, metadata is a *conditio sine qua non* for transparent, reproducible, and thus, accountable omics data provenance (Kolker et al., 2013). In the age of Big Data (Higdon et al., 2013), the open source movement that has stemmed from the advancement of newly developed and available softwares and technologies, integrated Personal Omics Profiling (iPOP) and personal genomics (Prainsack and Vayena, 2013; Vayena and Tasioulas, 2013a), metadata are crucial for robust open science (Snyder et al., 2014).

Second, the context information embedded in metadata provides powerful clues to link data to knowledge to responsible innovation. Consider, for example, the spectrum of OMICS data-intensive biotechnologies (e.g., genomics, proteomics, metabolomics) (Bragazzi, 2013). Their intersections with distinct application contexts such as vaccines, nutrition, and drugs create novel innovation fields, as featured in this journal recently—fields such as nutri-metabolomics (Bondia-Pons et al., 2013), omics-in-ecology (Weng et al., 2014), and vaccinomics (Huzair et al., 2011).

Third, metadata can serve as a veritable catalyst for innovation diplomacy. For example, in the European Union (EU), the Europe 2020 economic reform and growth agenda placed one of the five EU-wide targets as R&D and knowledge-based innovation (European Commission, 2011). Crucially, however, this commitment can only be fulfilled if it is accompanied by an equally consistent commitment to connecting the salient research to real contexts of need, and resources and constraints, as illustrated for Kelvin Doe. This requires institutional innovation, with attendant new channels of influence and communications, and a commitment to ‘‘walking the talk.’’ In this vein, the Sixth High-Level Symposium on Global Health Diplomacy held in Geneva in November 2013 underscored the proximity and emerging intersections of health diplomacy and science diplomacy (Graduate Institute and the Swiss Academy of Medical Sciences, 2013). Both health and science are viewed as catalysts for diplomacy (and vice versa). The nation states and other diplomacy actors would gather around their common denominators more effectively when health and science are closely and effectively coupled with innovation. Metadata provide the missing context information to link data to science diplomacy, and knowledge-development to human needs. For example, a metadata analysis of the global distribution of neglected disease reveals—paradoxically—that many of these diseases disproportionately occur among the poor living in a group of twenty (G20) countries (i.e., the poor among the wealthy), rather than exclusively in the poorest sub-Saharan African countries as one might expect (Hotez, 2013). This finding contests the traditional global health views that tend to subscribe to a binary narrow vision as developed *versus* developing countries. As suggested by Peter Hotez at the Sabin Vaccine Institute, science and global health diplomacy might focus on responsible advocacy to pressure the G20 countries, including the United States, to take greater responsibility to treat and prevent neglected diseases among its poorest and disenfranchised populations (Hotez, 2013). A related metadata analysis from the Institute of Medicine identified several G20 nations as ''underachievers'' in terms of their contributions to global health R&D. Global health diplomacy needs to focus intervention efforts on these nations to ''elevate their game'' in terms of financial or scientific contributions to the proposed WHO Global Health Observatory (Hotez et al., 2013).

Some difficult questions, however, remain to be addressed. Tensions emerge when metadata, on one hand, increases knowledge about and sensitivity towards contexts of knowledge-development and uses, and the social needs that such knowledge is supposed to be meeting. This is in contrast to the possibility that metadata frameworks might do the opposite, as aggregated metadata from multiple studies can nullify context, by cancelling out significant individual context-information. That is, challenges to the much talked about Big Data phenomenon could also emerge for ''Big Metadata'' in their founding architectures, and are deserving of attention and reflection now, as to the very purposes that metadata are intended to serve: genuinely learning, practicing, and enculturing context-responsive and context-sensitive responsible innovation.

Putting Metadata on the Post-2015 Agenda

Metadata and the study of omics innovations in their socio-technical and political science context are becoming centerpieces for sustainable robust science, and responsible knowledge co-production in the early 21st century (Özdemir, 2013). Such responsible innovation, as a collective learning process, has become a key component of the European Union's 80 billion Euro Horizon 2020 R&D Program from 2014 to 2020. These global shifts in scientific practice are not emerging in a vacuum. After the Earth Summit 2012 on sustainable development in Brazil (Rio+ 20), a new set of Sustainable Development Goals (SDGs) are being developed by the United Nations, governments, civil society, and key partners (Hotez, 2013; United Nations, 2013a). The SDGs will address significant environmental issues not currently covered by the 2000 Millennium Development Goals (MDGs) (United Nations, 2013b). In the post-2015 agenda for development, open science and novel ways to link data to responsible innovation will attain greater urgency, both in relation to SDGs and across various sectors of life sciences. As the linkages among metadata publications, responsible knowledge production and science diplomacy gain strength through the proposed omics checklist, it might create a domino effect by legitimizing metadata and its study in other sectors of life sciences and social sciences as well.

Historically, the study of science, technology, and innovation context has been pioneered by social scientists. But life scientists, medical doctors, and engineers, too, can play an important role together with social scientists, philosophers, and historians in the study of their own trade (i.e., knowledge co-production), under a socio-technical and co-productionist lens (Fisher et al., 2012). Metadata connect data to their production context, and thus to responsible innovation, and is important to address in the current climate of the post-2015 science, development, and diplomacy agenda, for all the reasons listed above.

In low and middle-income countries (LMICs), the emphasis to connect technology and development through science diplomacy is growing (Colglazier, 2012; Dereli et al., 2014). Thus far, the conceptual framework for such linkages has been technology transfer in many LMICs. It is conceivable that with better recognition of metadata and socio-technical context in which data come into being, technology transfer efforts might evolve into a broader integrated approach for Networked Innovation Observatories (NIOs) at country, regional, or global scales, as catalysts of social change and development, and responsible science. Reimagining global priority concerns in R&D and innovation, as well as reimagining who salient stakeholders and knowledge-actors might be, would be a key dimension of this. Studying the context of technology via metadata might even hold out the biggest prize of all—enabling OMICS science, postgenomics medicine, engineering and the life sciences overall to become global leaders in science diplomacy, as part of the post-2015 development agenda and SDGs.

Risk, uncertainty, and ignorance are inherent in all technological change (Wynne, 1992; Jasanoff, 2007). In terms of unplanned or unanticipated consequences, work is needed for reflexive foresight and systemic governance. In particular, we need to understand how technological systems that produce innovation can be responsibly managed for systemic risk mitigation (Hellstrom, 2003), as well as for more inclusive and sustainable benefit-generation, for the most needy as priority. Each country, society, and technological system presents a different context with different unknowns and possibilities for the development of technologies and innovation. The context in which research for omics technologies is produced, and the generation of metadata that capture this very context, are massively important for reflexive and efficient knowledge-based innovation.

Each LMIC faces a different set of issues in terms of societal needs, environmental constraints, and opportunities, funding availability, research capacity, availability of expertise, and possibilities for public engagement and effective governance. On the other hand, LMICs do not suffer from the hyper-specialization endemic in more developed countries. Hence, LMICs in global regions like sub-Saharan Africa are well poised to avoid the ''innovator's dilemma'' (Christensen, 1997), and instead appreciate the importance of science and technology context across the transdisciplinary knowledge silos for effective linkages with innovation. Seen this way, LMICs might be particularly keen to adopt metadata for responsible innovation while investments in omics science escalate in resource-limited settings, for example, through the H3Africa Project and many others around the globe (Dalal et al., 2010; Aklillu et al., 2014). Parallel study of science and its socio-technical context through metadata should start early for the young generation of scientists, be they in LMICs or not.

Mechanisms for extended peer-review and novel forms of public engagement in omics science (e.g., through micro-grants for Big Data, as proposed previously in this journal) might be considered by omics technology developers and funders in order to capture the crucial metadata that may otherwise be lost (Özdemir et al., 2013). The generation of metadata that shed light on how omics research is carried out, by whom and under what circumstances and to what ends, will go long way to addressing responsible innovation for a fairer and transparent society (see Snyder et al., 2014 in this issue).

Concluding Remarks and the Way Forward

Postgenomic knowledge is produced in a highly 'distributed' manner—extending well beyond the hallways of academia and the laboratory bench space, and by new stakeholders such as citizen scientists, developing countries, and patient advocacy groups (Özdemir et al., 2013; Prainsack, 2014; Terry et al., 2013; Tutton and Prainsack, 2011; Vayena and Mauch, 2012). Generation or collection of omics data can also come from less traditional sources, for example, from crowd-sourced omics research, citizen scientists, or others engaging with participant-led-research (PLR) (Prainsack, 2011; Vayena and Tasioulas, 2013b). While PLR is a relatively small segment relative to traditional academic and industrial research at this moment, it is rapidly growing, and should be included in discussions over metadata and its broad availability (Kolker et al., 2014; Terry, 2013; Vayena and Tasioulas, 2013a). In this vein, a further argument to embrace metadata is that the open innovation paradigm is gaining acceptance (Dandonoli, 2013). We will need new ''rules of engagement'' so harmonization of data is facilitated through governance instruments such as the proposed omics metadata checklist.

Metadata do not apply to technical data only. Theory-driven knowledge domains related to robust science, such as normative philosophical and bioethics analyses of emerging technologies, and their policy recommendations (e.g., statements such as ''ethical/unethical technology'', etc.), have attendant—and often unchecked—metadata. Such analyses, too, are subject to influences and social construction by the socio-political milieu where they are conducted, the sources of funding and personal career motivations of the innovation narrators (e.g., social scientists, humanists, bioethicists) (Bourdieu and Wacquant, 1992; Dove and Özdemir, 2013a; Thoreau and Delvenne, 2012). Recognition and utilization of metadata can help achieve transparent, reflexive, and thus accountable and robust social studies of omics technologies as well. This will contribute towards maintaining the essential analytical distance between social science and scientific practice, and ensure the innovation narrators maintain blue skies pan-optic thinking, remain truly independent, and are not co-opted by the subject matter of their analysis (Petersen, 2013; Solbakk, 2013).

Responding to change, and recalling Bertrand Russell

At a time when a human genome can be sequenced in about 24 hours for what is now less than $5000 (Collins and Hamburg, 2013), omics science offers tremendous opportunities for novel diagnostics and therapeutics for human diseases, not to forget the possibility to realize the full potential of new postgenomic fields such as pharmacogenomics, vaccinomics, agrigenomics, and ecogenomics. Sociomics, too, is a much-needed field that is rapidly rising, to advance reflexive and responsible social science scholarship that can then accompany (and not lag behind) the growth of omics science and technologies (Box 2).

Science and its conclusions have long relied solely on data. It is time data meet their long forgotten soulmate, metadata, without which we cannot link data to knowledge to innovation (and to science diplomacy) in a robust, reflexive, and responsible manner. Adopting metadata as part of scientific practice will require some change in the postgenomics innovation ecosystem. But change does not always come easy. In this regard, we should recall Bertrand Russell who has once aptly reminded us, ''*Do not fear to be eccentric in opinion, for every opinion now accepted was once eccentric*''—that all conventional views were at one time unconventional (Russell, 1988). We need to act now, to better appreciate and utilize metadata for strengthening omics innovations and 21st century life sciences. If we truly intend to remain on the cutting edge of knowledge-based innovations, and invest in science in an enduring trans-generational capacity, rather than immediacy or self-interest and personal careers, Russell's insight is a guidepost to treasure. It will set us on a sustainable trajectory of science that is both innovative and reflexive, and will thus stand the test of time to benefit global society. At a time when much is being anticipated from 21st century science to address the pressing needs in medicine, environment, ecology, and life sciences broadly, the twin scholarship of data and metadata is timely and essential.

As we welcome the New Year in the January issue of the journal, stay with OMICS for the advances in the field in 2014 and beyond! The journal will continue, independently, to peer-review, analyze, and catalyze progressive socio-technical research for knowledge-based, context-sensitive, and responsible innovation in the field. We welcome global inputs with an eye for local outputs that are meaningful both for the local and global communities.

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