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# Meeting the imperative to accelerate environmental bioelectromagnetics research

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ABSTRACT

In this article, the author draws on his experience in the world of geospatial information technology standards to suggest a path toward acceleration of bioelectromagnetics science. Many studies show biological effects of extremely low frequency (ELF) and radiofrequency (RF) radiation despite that fact that the radiation is too weak to cause temperature changes in biological features. Considered together in worst case scenarios, such effects, many of which appear to have long latencies, could have potentially disastrous consequences for the health and safety of humans and wildlife. Other studies show no such effects, and in both cases, often there are significant research quality deficits that make it difficult to draw firm conclusions from the data. The progress of bioelectromagnetics science is retarded by a lack of standard data models and experimental protocols that could improve the overall quality of research and make it easier for researchers to benefit from omics-related bioinformatics resources. "Certainty of safety" of wireless devices used in digital communications and remote sensing (radar) is impossible without dosimetry standards that reflect the effects of non-thermal exposures. Electrical signaling in biological systems, a poorly funded research domain, is as biologically important as chemical signaling, a richly funded research domain, and these two types of signaling are inextricably connected. Entrepreneurial scientists pursuing bioelectronic innovations have begun to attract new funding. With appropriate institutional coordination, this new funding could equally benefit those investigating environmental effects of ELF and RF radiation. The author proposes a concerted effort among both bioelectronics technology stakeholders and environmental bioelectromagnetics science researchers to collaborate in developing institutional arrangements and standard data models that would give the science a stronger bioinformatics platform and give researchers better access to omics data. What is proposed here is essentially a bioelectromagnetics omics initiative.

## 1. Introduction

**"We now realize that the phenomena of chemical interactions, and ultimately life itself, are to be understood in terms of electromagnetism." — Richard P. Feynman** (Feynman, 1963)

Driven by significant public and private investment, an extraordinary amount of knowledge about biological molecular signaling has been acquired in the past two decades (Yao et al, 2015). Much of this has been in the context of omics initiatives that involve collaboration, data sharing, high throughput data collection and powerful bioinformatics computing. Related to this progress, there has been heavy investment in drug research and resultant progress and profits in pharmaceutical treatment of illness.

There has been much less investment and slower progress in learning about the role of electrical signaling in biology and how it might be applied in medicine. However, interest and investment in bioelectrical research and bioelectronics applications is beginning to ramp up (Moses, 2017). Two examples:

- Microsoft founder Paul Allen funds the Levin Laboratory (Levin Laboratory, 2018) at Tufts University. There, researchers study, among other things, electrical signaling in developing organisms, with a focus on morphology. For example, they have analyzed the electrical potentials that give rise to a frog's eyes as a frog embryo takes form. By duplicating those potentials at a point on the frog's emerging tail, they can cause an eye to grow on the tail (Pai et al, 2012).
- Pulse Biosciences, Inc. (Pulse Biosciences, 2018) went public in 2016. The company uses very brief, carefully calibrated electrical pulses to signal cells to go into apoptosis, or natural cell death. By this method, cancer cells and scar tissue cells can be instructed to simply disassemble for harmless reabsorption into the body, without inflammation or other distress (Nuccitelli, 2006).

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These researchers and their funders are at the leading edge of a new biotechnology development cycle. Bioelectronics could bring therapies that are more effective, less expensive, easier to monitor in patients and less prone to side effects than pharmaceuticals. Hybrid approaches involving both electrical and chemical interventions are very likely.

Increased investment in research into the role of electricity and magnetism in life processes could result in a safer electromagnetic field environment as well as important medical advances. Early planning for common standards and protocols, as in the omics sciences (genomics, transactomics, proteomics etc.) would accelerate this dual outcome.

Fields of study in biology that end in -omics apply large-scale bioinformatics to specific types of biological systems to understand how these systems work and interact with other systems. Omics usually involves institutional collaboration to facilitate sharing of data, algorithms, servers and research methods to maximize benefits of scale. Standards support sharing as well as economies of scale that motivate equipment vendors to invest in developing integrated, precise and high-throughput systems for data collection that they can sell to multiple research programs. See Section 4 below.

## 2. Difficulties in environmental bioelectromagnetics research

A key problem with environmental bioelectromagnetics research is that electric and magnetic field exposure conditions are often not reported in sufficient detail or measured with sufficient precision and accuracy to enable reproducible results (Dlugosz, 2013). In vitro studies are necessary to explore natural and induced phenomena, but the energies and induced effects are so small that confounding factors are difficult to avoid. For example, non-homogenous background electromagnetic field environments (1 Portelli, 2017) and temperatures within laboratory incubators (2 Portelli et al., 2013) have been shown to skew results, and this important critique can reasonably be applied to many studies that show or do not show biological effects. Theories of causation based on quantum level effects show great promise (Barnes and Greenebaum, 2016), but also introduce new factors that need to be measured and controlled in experimental protocols. As noted by Barnes and Greenebaum (Barnes and Greenebaum, 2016), it is also the case that organisms have systems for quickly repairing damage and maintaining homeostasis. These natural systems can conceivably make it more difficult to observe and quantify the subtle effects of weak externally applied fields.

Understanding effects induced by ambient fields requires measuring and experimentally controlling those fields, which are complex and highly dynamic. The wireless industry seeks to optimize bandwidth over limited spectrum to meet market demand for ubiquitous mobile access to an ever richer information environment. To accomplish this optimization, communication protocols and the fields they produce become increasingly complex, introducing new permutations of modulated amplitude, frequency, and polarity. Low energy near-field radars in smart cars, drones and other applications are anticipated, and they will have their own narrow frequency bands and patterns. Environmental radiation waveforms thus take increasingly varied and complex pulse shapes, with sharper spikes and perhaps wider dynamic range. As waves propogate on their way from transmitting antennas to receiving antennas and incidental contact with living beings, they interact in various ways with the external physical environment and also with each other, as shown in Fig. 1.

Cell phones and other hand-held wireless devices emit radiation in very close proximity to the body, and in this case the tissue interactions may be a more important issue than geoscale and mesoscale interactions. Each tissue type may have different absorbtion, refraction, induction, capacitance and resistance properties. In-transit interactions at any scale add both complexity and randomness to exposures that shift at their source from microsecond to microsecond or even nanosecond to nanosecond. Radiation impinging upon a studied biological feature or process may be random at some times and markedly pulse-patterned at other times.

Understanding cause and effect will require laboratory studies in which exposures – and also non-electromagnetic parameters characterizing exposed subjects – are carefully controlled in all their parameters. It will be necessary to develop unique test equipment that enables 1) controlled generation of emissions that mimic cell phone and WiFi emissions, creating exposures with varied permutations of frequency, amplitude, polarity and pulsing patterns, with attention to both electrical and magnetic fields, 2) elimination of weak ambient emission background noise and 3) precise control of other factors such as temperature. Development and deployment of this equipment will be expensive. Understanding cause and effect will also require epidemiological studies that document the effects of real world exposures, with their complex mixes of regular and chaotic variations of frequency, amplitude and polarity. Statistical exposure data will need to be accompanied by statistical data about non-electromagnetic characteristics of exposed living subjects This level of detail greatly exceeds the level of detail in previous epidemiological studies. Mobile devices with radiation sensors and bodily function sensors will make this possible, but the studies will nevertheless be expensive.

Overshadowing these research difficulties are controversial business and geopolitical influences that shape funding, regulation and public perception. (Hardell, 2017) The wireless industry's trade group (CTIA) and its member companies advocate before all levels of government to protect their interests with regard to wireless-focused policy issues. Through the industry's heavy investment in lobbying (CIO magazine, 2016), industry statements are frequently echoed in the policy statements of federal agencies. For example, "The FCC's position (FCC, 2018) is that there are no scientific findings that provide a definitive answer to the question of whether cell phone radiation causes cancer." (1 Slesin, 2016) This ignores thousands of studies that provide important evidence of cancer risk, and it ignores very strong evidence of health risks other than cancer, such as adverse effects on membrane function and oxidative stress. It also ignores an international appeal for precautionary measures that has now been signed by more than 230 scientists from 41 nations, all of whom have published peer-reviewed research on the biologic or health effects of electromagnetic fields (EMF) (EMFscientist.org). Local efforts include the CTIA's attempt to stop the city of Berkeley from enforcing an ordinance that requires cell phone retail stores to post basic precautionary advice. Many in the bioelectromagnetics research community point to evidence that industry has hampered the research effort, even while supporting research financially. See, for example, this commentary on the career of researcher N.P. Singh. (2 Slesin, 2017). It should be noted that increased public perception of health risks would also be troubling for governments that seek to promote the economic benefits of wireless communication and that also depend on radar for air traffic control, weather forecasting and national security.

Sources of research funding should be noted and considered in reviewing reported results, and readers should be aware that a papers' abstracts and conclusions may reflect the interests of those who paid for the research more than they reflect the actual experimental results (Huss et al., 2017). There is a need to ensure that all the research is performed with integrity and honesty and without industry influence.

## 3. Bioelectromagnetic data models and dosimetry

The complexity of radiofrequency radiation exposure raises questions about the SAR (specific absorbtion rate), which is the principal recognized measure of exposures' health risks. (SAR is discussed at length by various authors in a recently published book, *Dosimetry in Bioelectromagnetics* (Markov, 2017)). SAR is a measure of average energy absorbtion, typically measured over seconds or minutes across 1–10 $cm^3$ of brain tissue. If exposure is high enough to produce measurable gross temperature rise, the exposure is assumed to be capable of causing adverse effects that are known to be carcinogenic. This measure

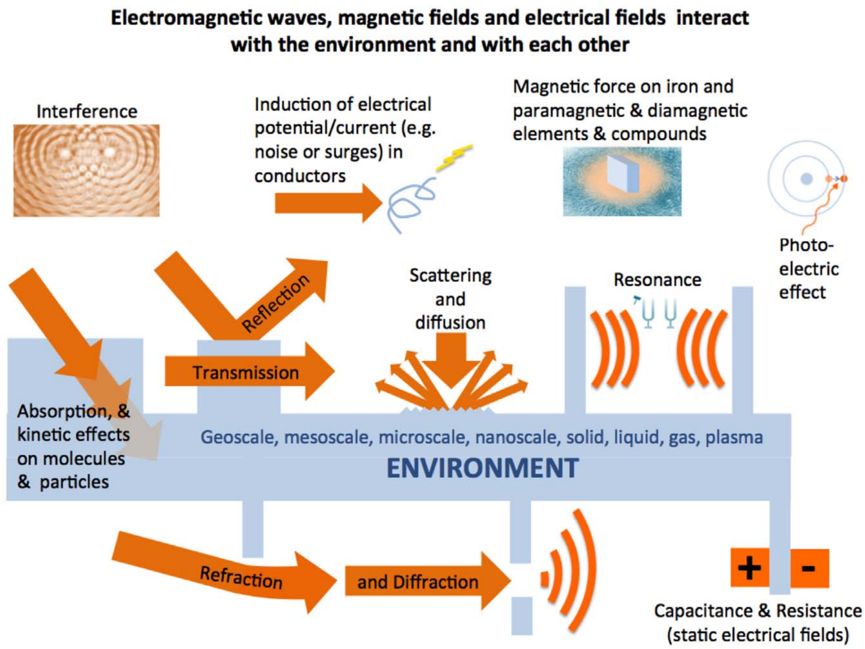


**Fig. 1.** Electromagnetic radiation interacts with the environment in complex ways.

of thermal effects has provided the sole basis for exposure guidelines and regulations in many parts of the world. Brief interspersed high energy pulses lasting milliseconds, microseconds or nanoseconds may not average out to levels high enough to produce gross thermal effects. Yet at a microscopic or nanoscopic scale they can potentially influence electrical signaling, chemical reactions and thus the functioning of nerves, cells, membranes, organelles and molecules that comprise links in larger functional networks.

Indeed, many laboratory studies suggest that subthermal exposures affect blood/brain barrier, calcium transport across membranes, and other intracell and intercell phenomena (Sage and Carpenter, 2018). In epidemiological studies, too, subthermal exposures have been shown to affect health outcomes. (Sage and Carpenter, 2018) And yet, as mentioned above, often there is counter-evidence. Many scientists believe that the questionable evidence and poor repeatability of many laboratory and epidemiological bioelectromagnetic studies, including those that show no effects, make it impossible to draw sound conclusions. There is an increasingly obvious need for more rigorous consensus-derived standard dosimetry protocols that account for dynamic exposures at microscopic or nanoscopic scales, and perhaps over periods ranging from nanoseconds to years.

Dosimetry refers to the calculation and assessment of a radiation dose received by a living organism. The term was first applied and is perhaps still most often used in reference to human exposure to ionizing radiation, such as that encountered in nuclear power plants and nuclear medicine. Dosimetry for non-ionizing electromagnetic radiation is far more complex. Researcher Henry Lai wrote in 1998, "I think the main barrier in understanding the biological effects of RFR (radiofrequency radiation) is caused by the complex interaction of the different exposure parameters in causing an effect. An independent variable of such complexity is unprecedented in any other field of biological research." (Lai, 1998) The non-reproducibility of the results of many studies has slowed the progress and lessened the policy impact of bioelectromagnetics. This can be attributed in many cases to inconsistent or incomplete reporting of factors that might affect the results (Duglosz). Computers are absolutely essential in working with "an independent variable of such complexity", which is what dosimetry involves. For this reason it would be a serious mistake to embark on a project to develop new dosimetry protocols without the expertise of experienced data modelers.

Science depends on effective communication, and today this includes communication between computers. In the age of networked computers and the "cloud", researchers in many fields increasingly depend on consensus-derived standard data models that structure data used to model complex things (CODATA, 2018). Data models help researchers to develop and express their ideas and observations consistently within their disciplines and across related disciplines.

"Data model" is a term that pertains to management of complex digital data. Computers typically require very specific ordering and naming of data elements. The requirement for data model standards has grown along with the growth of network-based computing because network nodes — different individual computers — must be able to communicate with each other. A consensus-derived open data model standard provides an agreed-upon way to name and organize a data domain's data elements. The model is not merely a list of parameters or lexicon of terms, but a diagram that reflects the relationships between different parameters and data elements, relationships such as "includes" or "may include". Data models typically refer to formally defined lexicons. (The discipline of data modeling involves careful distinctions among terms such as lexicon, vocabulary, domain semantics and metadata.)

An abstract data model for bioelectromagnetics exposures would provide a formal conceptual structure for the organization and representation of all of the exposure parameters that need to be accounted for in a dosimetry protocol. Variables and their names, units of measure, data types (floating point, integer, ascii, etc.) would be specified. Relationships between parameters would be explicitly represented. The Unified Modeling Language (UML) is a widely used method for visually representing such relationships. Relationships are visualized in UML as various types of arrows, as in Fig. 2.

Bioelectromagnetic data models will need to model details of both endogenous fields and charges and also introduced electrical fields and magnetic fields. They probably will also need to model details of the biological entities involved. Accommodation for ultra high-rate time series sampling will be important. These data models will need to characterize such things as location, extent, direction, frequency, amplitude, polarity, duration, etc. Locational mapping along established anatomical coordinate systems will be important to specify precisely where the fields and the features and phenomena are located in multicell organisms.

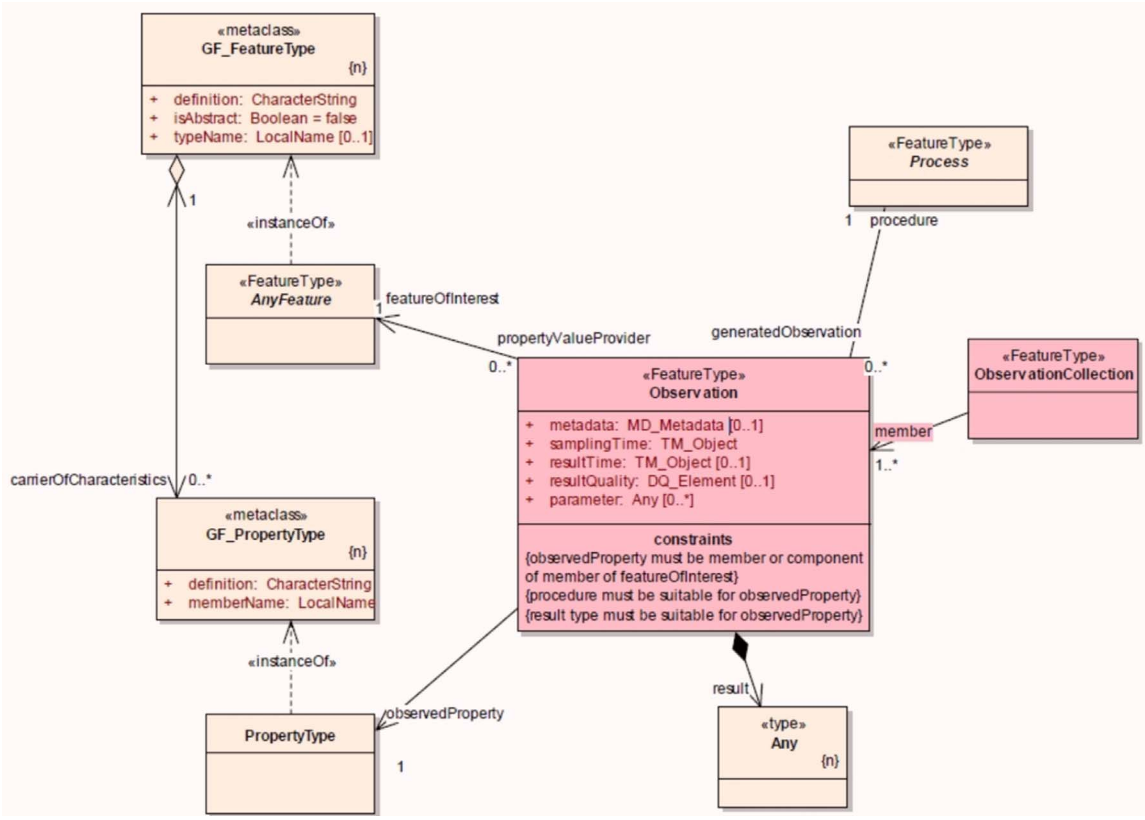


**Fig. 2.** An example of an abstract data model represented in a UML diagram. This UML diagram is part of the the OGC and ISO Observations and Measurements (O&M) conceptual model (ISO, 2018), a standard for modeling scientific observations and measurements.

The purpose of beginning with an *abstract* model is to enable structuring of data in a standard way for use across different fit-for-purpose database systems and digital encodings. This makes it possible to easily share and integrate data developed using those different database systems and encodings, with as little loss of information as possible. Various digital encodings can be derived in an automated way from abstract models implemented in UML. Some encodings, such as eXtensible Markup Language (XML), which can be directly processed by a wide range of Web services, are chosen for maintenance of semantic richness. Others, such as javascript and HDL, are chosen for conciseness to accommodate rapid data acquisition, high-throughput computation and ease of programming. A biolectromagnetic data model might be encoded in a relational database that can be accessed using SQL. If it were simple enough (not likely), the model could be encoded as a comma separated value (CSV) file that could be exported from and imported to a spreadsheet and accessed in various ways, including linked data approaches based on direct URIs pointing to data elements. It is quite likely that graph databases, the engines of social networking sites like Facebook, will play an increasing role in bioinformatics, as they are suited to account for known or predicted network-like interactions and relationships such as those among molecules. Decisions by researchers regarding the most appropriate mathematical and statistical approaches will be an important factor when researchers make decisions about encodings. For the abstract standard electromagnetic field data model, it is quite likely that UML would be used as a means of ordering the data model elements and visualizing their relationships.

Abstract data models lend themselves to design strategies that maintain backward compatibility while giving users ways to make ad hoc additions or changes for inclusion in future updates. This will be important in bioelectromagnetics, where new measurement technologies, theories and experimental designs will continually require updates to protocols or variations of protocols. The abstract standard should be designed to accommodate the development of abbreviated profiles and application schemas to accommodate the different needs of different subdomains.

The requirement for such updates, profiles and application schemas illustrates the importance of having a well-supported ongoing consensus process for data model maintenance. This requirement underscores the need for stakeholder groups to commit to ongoing organizational representation and participation in the standards development and maintenance process. Stakeholders whose interests are environmental need to stay engaged with stakeholders whose interests are bioelectronic. Data models can be shaped to favor or deprecate the interests of particular stakeholders; thus the need for an open process.

A standard data model and its derivatives would help experiment designers ensure that their experiments account for all pertinent independent variables and controls. The model would also support rigorous reporting of critical parameters as well as explanations of omitted parameters. Use of the standard data model would make experimental results readily publishable, discoverable, assessable, accessible, comparable, aggregatable, analyzable, and, very importantly, usable with other omics databases. This is critically important for a more collaborative "open science" omics future for bioelectromagnetics.

## 4. The omics path

Omics sciences depend on high-throughput experimental technologies that generate massive and complex data sets. Often the phenomena are probabalistic. These data sets are analyzed using sophisticated computational techniques that provide biological insight based on statistical inference (Hasin et al, 2017).

The original omics sciences were genomics, transcriptomics, proteomics and metabolomics. There are now also omics initiatives focused on epigenomics, lipidomics, glycomics and microbiomics. The initiative called for in this paper falls in the category of "exposome informatics" (Sanchez, 2013). The US Centers for Disease Control (CDC) exposomics page (CDC) suggests there is already a field called "exposomics". What is proposed in this paper is essentially a new omics discipline that might be called something like "*spectrum*omics", a subset of exposomics.

Omics does not only involve numerical data. Some omics systems include text mining capabilities that exploit textual data consisting of thousands of research papers that can be searched for patterns and correspondences (Raja et al, 2017). These systems might be described as highly automated literature review tools aimed at producing large numbers of promising hypotheses for experimental exploration. The research papers can be drawn en masse from the literature collections of diverse sciences.

A key objective for the proposed new research initiative would be to provide online access to multi-omics analysis tools that would be available for querying one or more large databases of research data and literature (Hasin). These would include bioelectromagnetics studies focused on endogenous electrical potentials and ion fluxes, as well as multiomics databases pertaining more generally to biology, chemistry and physics. Large databases can be and are being aggregated into multi-omics data sets to expand the range of data that can be explored at once through queries. Omics data exploration is being offered as a service (Iomics, 2018). This is quite likely an early indicator of an expanding and diversifying sector of biotechnology.

Collaborative planning and funding of data collection and system development, common in omics programs, introduces important efficiencies. Scientists concerned about health risks of EMF need to collaborate with scientists studying not only bioelectronics but also Body Area Networks (Clinical Leader, 2010) and perhaps other domains. The standards and omics tools to be developed will be useful in multiple domains of research.

Collaboratively developed and rigorously applied standard operating procedures and standard data models are part of collaborative science. The flow of biological information among the omics disciplines is bidirectional, so the disciplines need to “speak the same language”, digitally. Data collection, publishing, discovery, assessment, verification, sharing, comparison, aggregation, and analysis all benefit from data model standards and associated data encodings that reduce or eliminate the need for tedious and error-prone manual or semi-automated data conversion. “Big data” analysis can produce meaningful results despite diversity in data models, but speed and accuracy both improve with the use of consistently structured data.

The idea of using omics approaches in bioelectromagnetics is not new: In April 2001, Nature Genetics published "Proteomics: New way to determine possible biological effects of mobile phone radiation" (Leszczynski and Joenväärä, 2001). In 2004, Nylund and Leszczynski used the high-throughput screening techniques of transcriptomics and proteomics to show that mobile phone radiation might alter gene expression as well as expression and activity of proteins (Nylund and Leszcynski, 2004). Following that, in 2006 *Proteomics* published a special issue titled "Application of Proteomics and Transcriptomics in EMF Research", edited by Leszczynski et al. (2006). In 2012, *Proteomics* published a review of all the research in this field through 2010 (Leszcynski et al, 2012). This review, funded by European Cooperation in the Field of Scientific and Technical Research (COST) Action BM0704, provides, in addition to an analysis of that research, a set of recommendations for future study. (COST, 2018) The first recommendation was: "Research efforts using proteomics and transcriptomics, aimed at determining whether EMF exposures affect gene and protein expression, should continue, but they should be more synchronized between research groups and should consider as close as possible replication of key positive findings as of paramount importance for reliably establishing the effect."

That recommendation describes the institutional ethos that should inform the work to develop a new bioelectromagnetics informatics platform. Collaboration has become a byword in biological and health sciences. The new approach values communication and the sharing of data, strains, reagents, algorithms and other resources, including, in our case, both data involving in situ potentials and gradients and data involving exposures to external electromagnetic fields.

The data deposit internet site offered by *Bioelectromagnetics*, the journal of the Bioelectromagnetics Society (BEMS), through the journal's publisher, Wiley Periodicals, provides authors free hosting for tables or files too massive for inclusion in an article. These datasets can be accessed online by subscribers, and authors are able to provide a link to the data for inclusion in a number of Internet data banks, including the Genome Database (GDB), Protein Databank (PDB), and European Molecular Biology Laboratory (EMBL). This is an important first step, but its use needs to be enforced and more needs to be done to meet Leszczynski et al.'s recommendation.

Genomics and the other omics disciplines have benefited from standards, and they would undoubtedly have benefited from earlier and more open, collaborative, cross-domain standards development. Without collaboration, different standards for the same entities become entrenched in neighboring research communities who ought to be able to easily share their data. Subsequently it becomes difficult to harmonize those standards and make best use of legacy data. The standards initiative proposed in this article would build on standards already in use in the omics world and benefit from participation in the working groups that maintain those standards. Participants interested in environmental effects would need to work with those interested in bioelectronics, and with those interested in such things as the role of magnetism in animal navigation (Prato, 2015). The goal is to develop a basic open standard electromagnetic field abstract model that will be useful in multiple domains, but also adaptable.

## 5. Larger data sample sizes needed

Large sample sizes tend to reduce margins of error. Large array data collection techniques have been important in the development of omics sciences (Hasin) and they will also be important in the proposed collaborative bioelectromagnetics omics initiative.

Technologies and basic principles underlying current large array biological data collection equipment will likely be adapted for in vitro and in vivo bioelectromagnetics environmental exposure studies. A special requirement would be rigorous and spatially fine-grained isolation and control of complex electromagnetic exposure sequences in arrays of closely spaced experimental enclosures. This could be accomplished by employing recent advances in miniature signal generators (UCI News, 2010) and electromagnetic interference (EMI) shielding (Kato et al, 2017). It is not difficult to envision specialty laboratory equipment manufacturers offering to researchers an array of products that would provide the necessary capabilities.

The pioneering work of the Levin Laboratory (Levin Laboratory, 2018) involves manipulation of cell membrane voltages at cellular scale. This work is sure to figure importantly in bioelectronics and in understanding how environmental exposures are having their effects.

Innovative means of studying brains have been and are being developed, and some of these, such as optogenetics (Guru et al, 2015) may be adapted for bioelectromagnetic research. Nanobots may have a role in data collection in coming decades. For in vivo studies, land in relatively radio-free deserts or mountain valleys could be set aside for development of shared large scale radiation-controlled test facilities.

As noted in "*Exposome informatics: considerations for the design of future biomedical research information systems*" (Sanchez, 2013), "The panoply of miniaturized sensing devices now accessible and affordable for individuals to use to monitor a widening range of parameters opens up a new world of research data." This certainly applies to bioelectromagnetics and bioelectronics. There are wearable biosensors and there are sensors embedded in mobile devices to monitor, for example, ozone or carbon monoxide. Mobile apps that publish to the cloud technical details of personal mobile devices’ emissions and receptions, along with location, motion and orientation, could provide vast amounts of environmental EMF exposure data. Linked to wearable biosensors or device-embedded sensors, or location-aware sensors mounted in buildings or cars, such apps could similarly provide even richer EMF epidemiological data.

One area in which bioelectromagnetics research will benefit from "exposomics" (NIOSH, 2018) will be in the study of electro-hypersensitivity (EHS), which is similar in some respects to multi-chemical sensitivity. EHS may also be functionally related to chemical hypersensitivity (Belpomme et al., 2015). In those who are electro-hypersensitive, symptoms are frequently nonlinear with respect to exposure, as symptoms often are in those who are chemically hypersensitive (Goldsmith and Kordysh, 1993).

## 6. Lessons from the geospatial standards world

Geographic information – or more precisely, geospatial information – is essential in a wide range of human activities. In the 20th century, geospatial information management functions – data collection, storage, publishing, discovery, assessment, verification, sharing, comparison, aggregation, display and analysis – were achievable mainly in closed, monolithic GIS systems. The 21st century's global transition to internet and web-based distributed computing introduced a requirement for open software interface standards and associated encoding standards that would enable these functions to be provided independently by different providers. Communication between diverse software systems provides opportunities for automation of tedious and error prone manual steps. The standards, developed jointly by providers and users in an open process, offer users more options and provide significant cost savings. Vendors, even the dominant vendors who previously benefited from "vendor lock-in", have benefited from greatly expanded markets.

OGC owes its success to a culture of cooperation and a system for collaboration. OGC members include more than 500 private sector geospatial technology providers and data providers, major computer platform companies (e.g. Google, Microsoft and Oracle), federal and national agencies, NGOs (e.g. the UN and GEO, the intergovernmental Group on Earth Observations), research institutes and universities. The members work together in OGC to discuss and work toward common goals that serve the members' diverse purposes. Guided by bylaws devised by a diverse and visionary founding board of directors and with the help of a small staff, OGC member organizations developed and continue to evolve a set of policies and procedures for an inclusive and open process of standards development. OGC *domain* working groups review particular interoperability requirements; OGC *standards* working groups develop and maintain standards. Active liaisons with other standards organizations contribute to a high level of consistency of geospatial information and geoprocessing approaches across the information and communication technology universe. The organization provides staff-supported online and face-to-face venues and resources for sharing information. The OGC Innovation Program provides mechanisms for sharing requirements and funding for testbeds, pilot projects, interoperability experiments, etc.

Like biological data, geospatial data are complex in many respects, and the data models frequently must evolve to accommodate technological innovations. Different application domains create and use geospatial data in diverse ways. Within those domains, there are communities and sub-communities with different missions and incentives.

Consider the communities of water: The oceanography and meteorology communities have worked closely together for many decades, and in the OGC they work together in the MetOcean working group to adapt and develop standards that conform to the OGC (and OGC/ISO) standards for modeling vector data, data arrays, point clouds, coordinate reference systems and so forth. Similarly, the international hydrographic, or ocean navigation, community has worked together since the 19th century. They have a special set of data standards that predates OGC and doesn't address MetOcean requirements. Hydrography stakeholders work toward their shared goals – and interoperability with MetOcean data – in the OGC's Marine DWG. The Hydrology Domain Working Group (Hydrology Domain Working, 2018) is a Joint Working Group of the World Meteorological Organization (WMO) and the OGC. This group provides "a venue and mechanism for seeking technical and institutional solutions to the challenge of describing and exchanging data describing the state and location of water resources, both above and below the ground surface."

OGC working groups in domains such as aviation information systems, disaster management, 3D urban models and geology have overlapping interests with the MetOceans, Marine and Hydrology standards communities. Their applications are different, but there is only one Earth and it is the single stage onto which all human and natural features and phenomena map. This reality provides the inescapable logic that drives collaborative development and maintenance of OGC's self-consistent set of open and international standards. This logic also drives OGC's efforts to liaison with other standards organizations to find paths toward consistency with the location elements within their standards.

Just as the Earth is a single stage shared by many domains, life is a single electrochemical stage onto which all of biology maps. Biology, chemistry and physics share standard units and measurements, taxonomic systems for chemistry and for life forms, and so on. Within these fields, as knowledge expands new specialized scientific domains emerge with their associated special vocabularies.

The diagram below illustrates progressive variegation of climate science domains (Fig. 3).

## 7. The way forward

The main lessons to learn from comparing the life sciences with the geosciences are these:

1. The author is not aware of an omics data standards hub that provides a robust central organizing function like that provided by OGC in the geospatial world. although there are resources in the omics domain, such as The Omics Discovery Index, Expression Atlas and FairSharing.org, and in various domains there is an ethos of cooperation and collaboration. The bioelectromagnetics community would benefit from working closely with the larger omics community in any effort to develop a cross-omics organization that would provide services like those provided by OGC in the geospatial world.
2. The bioelectronics community and environmental bioelectromagnetics community have much to gain from a collaborative standards initiative dedicated to providing what's necessary to understand bioelectrical signaling and bioelectromagnetic processes as well as susceptibilities to environmental electrical, magnetic and electromagnetic fields.
3. Data modeling expertise is a key requirement for developing a

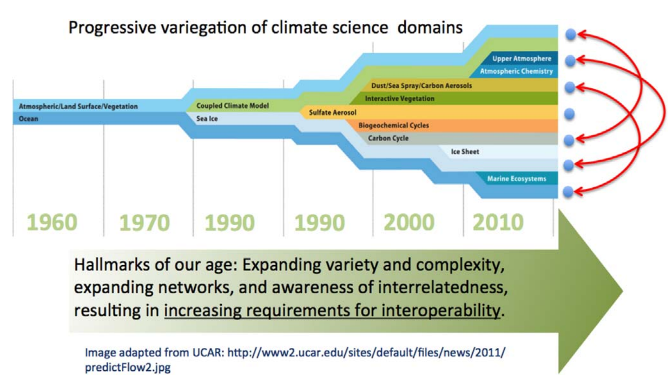


**Fig. 3.** In 1960, there were only two main data domains that figured importantly in climate science. According to the chart from the University Center for Atmospheric Research (UCAR), dated 2011, there were, in 2011, 13 distinct data domains. A similar progression is obviously happening in the life sciences.

successful standards regime.

A chapter in a book titled *Bioinformatics for Omics Data - Methods and Protocols* is titled "Data Standards for Omics Data: The Basis of Data Sharing and Reuse" (Chervitz et al., 2011). It provides this introduction: "To facilitate sharing of Omics data, many groups of scientists have been working to establish the relevant data standards. The main components of data sharing standards are experiment description standards, data exchange standards, terminology standards, and experiment execution standards. Here we provide a survey of existing and emerging standards that are intended to assist the free and open exchange of large-format data." That survey and any updates or subsequent surveys on this subject would be useful to bioelectromagnetics research community members interested in building an omics platform for bioelectromagnetics.

The bioelectromagnetics standards work should be done in communication with other standards organizations such as IEEE (especially the International Committee on Electromagnetic Safety (ICES) – TC95 and TC34), ITU and OGC that already have related standards or standards processes involving electromagnetic fields. Incorporation of the OGC's standard macro-scale and meso-scale spatial and temporal location data model elements would enable easy integration with other types of environmental spatial and temporal features, such as mobile device locations, geomagnetism, animal migration paths, 3D city models, terrain, atmospheric conditions, radars and cell towers. Such data integration will likely become important in epidemiological studies, assessment and design of spaces and facilities, and, very importantly, EMF monitoring and regulation.

The potential of bioelectronics to reduce the cost of health care alone provides an important reason to accelerate and publicize bioelectromagnetic science, bringing additional funding and more young scientists into the field. It would be prudent to begin developing standards early on because of downstream efficiencies and because communications from the standards initiative could be used to gather support for the larger collaborative initiative. Also, quite importantly, almost immediately the standard or standards could provide a basis for comprehensive and consistent reporting of the details of electromagnetic fields used in studies. The cost to make early progress in standards development would be small and the immediate and long-term return would be great.

A few members of the bioelectronics and bioelectromagnetics communities could immediately take initial steps toward realizing the vision put forward in this article:

- Private discussions among scientists and potential funding sources would be an important early activity, reviewing possibilities and developing strategies for collaboration. Planning for development of a significant funding stream must begin at the outset. First, it will be necessary to compensate the collaborating research planners. Then, it will be necessary to assemble data sets in multiomics computing environments to begin proving the concept. Research grants will be offered and proposals submitted. Grants will need to provide for development of the special equipment that will be developed to collect complex data about wavelength mixes, modulations and power, as well as other factors that must be controlled in studies. The funding stream will need to be maintained.
- Planning sessions at conferences could be organized.
- Existing data reporting protocols required by publishers and professional associations should be reviewed, with an eye towards standardizing data models and protocols that would be adopted by these institutions.
- Dialog with standards groups such as IEEE, ITU and OGC should begin.
- Available omics databases and their associated analytical tools need to be reviewed. Work should begin on aggregating bioelectromagnetics literature collections and preparing them for upload into a multiomics database.

At the outset and as an ongoing activity, thought should be given to new dosimetry protocols that reflect what has been learned in the decades since the World Health Organization and governmental regulators established their current and now badly outdated guidance and limits based on thermal effects.

The Bioelectromagnetics Society (BEMS) and the European Bioelectromagnetics Association (EBEA) have a tremendous opportunity at this juncture. It is not too late for the associations (which are in discussions about merging) to undertake the initiative described above, and it is not too early. No scientific associations have more to gain. Bioelectromagnetics is positioned to transform its image. It could be characterized now as a little known field whose image in the public eye is tainted by historical association with pseudoscience, whose image in the scientific community is tainted by questionable research quality and irreproducible results, and whose image among many who are knowledgeable or interested in the science is tainted by the obvious difficulty of working in the field without facing endemic conflicts of interest. It is extremely important at the outset that the journals and associations establish rigorous rules for funding transparency and consideration of funders' motives. There needs to be a new level of scrutiny regarding the funding of research and the funding of international conferences.

Bioelectromagnetics is now poised to become a well-funded high-profile science leading to exciting medical applications. Bioelectromagnetics is also the science needed to provide a scientific basis for mitigating what could, in worst case scenarios of adverse biological effects of electromagnetic radiation, become a global health catastrophe that would limit humanity's ability to deal with other higher profile crises.

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## Conflict of interest

None.

## Background and disclaimer

The author has made a career of promoting collaborative development of open standards that support sharing, integration and use of spatial and temporal data. In 1994 he helped found the Open Geospatial Consortium (OGC), an open international standards organization. He retired from his OGC staff position in 2016. Electromagnetic phenomena are inherently spatial/temporal. They interact in complex ways with each other and with the solid, liquid and gaseous spatial/temporal features and phenomena that are modeled in OGC's open standard data models. The electromagnetic spectrum is a locally limited civilization-critical resource without a standard data model to facilitate sharing, integration and reuse of data. For this reason, and because of his concerns about biological effects of such radiation, he became an OGC member to initiate and chair (now co-chair) the OGC Electromagnetic Spectrum Domain Working Group (EM Spectrum DWG) (OGC, 2018). This group is exploring the feasibility of developing either an open standard data model for electromagnetic fields (EMF), or, more likely, a set of shared location elements to implement in diverse EMF data models. The other group members' interests are principally in applications that do not address biological effects but that are of interest in the geospatial technology world.

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## Glossary

*Bioelectromagnetics:* The study of the interaction between electromagnetic fields and biological entities.

*Bioelectronics:* Field of research in the convergence of biology and electronics.

*Bioinformatics:* An interdisciplinary field that develops methods and software tools for understanding biological data. It combines computer science, statistics, mathematics, and engineering to analyze and interpret biological data.

*Data model:* A systematic abstraction of data, defining how the data elements are connected or related to each other.

*Dosimetry:* The calculation and assessment of a radiation dose received by a living organism

*Exposomics:* The exposome can be defined as the measure of all the exposures of an individual in a lifetime and how those exposures relate to health. An individual's exposure begins before birth and includes insults from environmental and occupational sources.

*eXtensible Markup Language (XML):* A flexible way to create information formats and electronically share structured data via the public Internet, as well as via private networks.

*Extremely low frequency (ELF) radiation:* Alternating current (AC) fields and other electromagnetic, non-ionizing radiation from 1 Hz to 300 Hz.

*Ionizing radiation:* Radiation consisting of particles, X-rays, or gamma rays with sufficient energy to cause ionization in the medium through which it passes.

*JavaScript:* The programming language of HTML and the Web

*Lexicon:* the vocabulary of a person, language, or branch of knowledge.

*Multiomics:* a new biological analyses approach where the data sets are multiple omes such as genome, proteome, transcriptome, epigenome, and microbiome

*Non-ionizing radiation:* Any type of electromagnetic radiation that does not carry enough energy per quantum (photon energy) to ionize atoms or molecules—that is, to completely remove an electron from an atom or molecule. Radiation of lower wavelength than ultraviolet light.

*OGC:* Open Geospatial Consortium, an open standards development organization focused on standards that support integration of geographic information of all kinds.

*Omics:* Omics aims at the collective characterization and quantification of pools of biological molecules that translate into the structure, function, and dynamics of an organism or organisms. Bioinformatics is an important element in the omics disciplines.

*Radiofrequency (RF) radiation:* radiation of frequencies ranging from static magnetic fields, through extremely low frequencies (ELF) to higher radio frequencies (RF) and extremely high frequencies up to the wavelength band of infrared light.

*Unified Modeling Language (UML):* a general-purpose, developmental, modeling language in the field of software engineering that is intended to provide a standard way to visualize the design of a system.