Standards and/as Innovation: Protocols, Creativity, and Interactive Systems Development in Ecology

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ABSTRACT

Standards and protocols play important but under-theorized roles in HCI research and design efforts, including those dedicated to the development of new collaborative infrastructures in the sciences. Building on several years of ethnographic fieldwork, this paper examines standardization efforts attached to new forms of design and computational development in American ecology. We explore the role that standards play in large-scale research networks; how standards are enacted and enforced in complex interactive systems like science; how standards struggle and fail (and what happens when they do); and how actors work across the gaps that standards leave to produce more effective forms of practice and design. We also argue for the potentially *creative* role of standards, including contexts in which they function as fulcrums for change and innovation. We conclude with reflections on how HCI researchers might rethink the nature and possibilities of standards and standardization in their own work.

Author Keywords

Standards; standardization; infrastructure; science; ecology; collaboration; ethnography.

ACM Classification Keywords

H.m. [Information systems]: Miscellaneous.

INTRODUCTION

Standards have long been central to human-computer interaction in complex real-world settings. Standards order and constrain the sprawl of worldly activity, producing stable contexts of action and expectation into which new artifacts and systems can enter. Standards support the exchange of knowledge, experience and objects across scale and context, making practices that are simultaneously distributed and collective possible. And by holding parts of complex systems constant while others change, standards establish the possibility of growth from old to new, allowing complex interactive systems to learn, grow, and change over time. In all these ways, standards help to gather, organize, and stabilize the worlds around us, making the environments we study and design for more stable, coherent, and predictable places. To repurpose Woodrow Wilson's old point on democracy, standards help produce a "world made safe for design" [37].

Topically, this paper joins a growing body of HCI research [16,18,21,24,29] that explores the nature and challenge of collaborative work and computational development in the sciences – a site of research and practice that sometimes flies under the name of 'cyberinfrastructure' or 'e-science'. This work represents a large and growing area of HCI insight and opportunity. It also poses an ongoing challenge to HCI researchers to rethink their work both 'outwards' and 'upwards': towards wider and more varied fields of human-computer encounter; and towards scales of technical and social practice larger than discrete artifacts, systems, and users [22,28].

This paper addresses the tensions and ambivalences of standards and infrastructure development at two separate scales and moments of collaborative ecological practice: the traditional PI-led research group, which continues to characterize and define the social and practical organization of much ecological research today; and newer forms of big data and continental-scale research associated with the development of new computational tools and infrastructures (above all with the National Ecological Observatory Network, described more fully below).

Building on scholarship in HCI and the social sciences, and long-term ethnographic fieldwork in ecology, we seek empirically grounded answers to four basic questions. What role do standards play in coordinating collaborative work and new systems development in ecological research today? How are standards enacted, realized and enforced across complex distributed activities? How can standards struggle or fail, and what consequence might this have for the forms of practice and discovery they are meant to support? And how do individuals, groups, and organizations work across the holes and gaps that real-world standards inevitably leave, to produce more effective forms of design and collective action in the world? We conclude with reflections on the potentially *creative* role of standards, and argue for

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new approaches that move standards more to the center of HCI thinking and practice.

BACKGROUND AND LITERATURE REVIEW

In their immediately technical form, standards drive and constrain the design and operation of interactive systems across a wide variety of application areas. In the field of software engineering, for example, standards and protocols can play an important role in managing or overcoming the severe coordination challenges that often attend distributed software development efforts [7,14,15]. Standards pervade spaces ranging from home networking [12,23], to sustainability [8,9,27], to the development of first responder systems [26,31], supporting (or trying to) the forms of interoperability needed to produce coherent, stable, and extensible technical systems at the margins of complex and variable human environments. Standards also establish points of connection between parts of systems actively designed by HCI researchers and those received from wider worlds of computing, including those structured, for better or for worse, at 'lower' or 'deeper' levels of operation [13].

The centrality of technical standards in HCI work is matched by findings in other fields. Work in information policy from both academic and industrial sources has pointed to problems of technical standardization as an issue both poorly understood and badly practiced among technology players in industry, academia, and government [6,36]. And work in science policy and the social studies of science has pinpointed technical standards as key and widely misrecognized features of robust, sustainable, and scalable communities of knowledge [11,17,22].

These problems only intensify when we expand our definition beyond the technical frame to include *all* forms of standardization that go into distributed collective practices of all sorts. Standardized interfaces establish the baselines and connection points to wider technological systems to which our own design efforts can attach (such that we can build applications around, for example, mobile health or environmental sustainability without navigating the insides of Android or iOS). Standards structure the forms of data we pull from the web into our applications and programs, making large bodies of numeric, textual and visual data tractable and actionable through analysis. Other standards – for example, around privacy or accessibility – make sure that our work gets out into the world in its most general and inclusive form. Standards also structure the way we take the world in: for example, through user studies that sort unruly masses of individuals into more and less stable categories of 'users' (see for example [25]). At the most general level, standards channel and regularize the conduct and behavior of actors of all sorts, making practices and systems of exchange or interaction possible: while we can imagine a market without laws for example, it's harder to imagine one without standards.

Such insights are backed by a growing but still nascent body of HCI research that seeks to restore standards and standards work from a background element of technical development and social practice to an active and sometimes contested feature of collaborative life. Within the broader HCI field, this work has shown up most forcefully in the Computer Supported Cooperative Work (CSCW) literature to date. Classic work from the early years of CSCW on problems of collaboration and joint work identified standards as one among a suite of "coordination mechanisms" by which distributed and technically supported work is accomplished [30]. Separate work by Star and Griesemer [33] and Star and Strauss [35] identify standards as integrally connected to the sorts of "boundary objects" and "articulation work" that support collaboration across complex and heterogeneous landscapes.

Standards make a more direct appearance, however, in an influential line of work on infrastructure beginning from Star and Ruhleder [34] and Bowker [3] and extending up through more recent work in HCI, CSCW, and the social sciences [10,11,16,22,29]. In this definition, infrastructure provides the framework or scaffolding for social and technical activities of all sorts, and exemplifies a number of key features or properties: its embedding in other structures; its frequent transparency (or invisibility) in use; its reach or scope beyond single sites of practice; its connections to conventions and communities of practice; its embodiment in standards; its dependence on an installed base of practices and material; and its tendency to 'reappear' (or return to conscious reflection) upon breakdown [4,34].

Within this list, standards take on special scope and importance, embodying and extending many of the other features in Star and Ruhleder's list. Standards for example perform a special role in linking infrastructure to established communities of practice (think of the frequency with which professional groups issue standardized credentials, guidelines, or professional codes of conduct, for example). Standards account in part for the inertia and stability of the installed base named in Star and Ruhleder's description: once grooved and certified through standards, local departures from global or more general practices can become costly or impossible. And per design discussions above, standards are a key mechanism by which problems and questions at the margins of systems can be made to disappear, helping infrastructure sink into the obscurity it 'seeks'.

More recent work by Lampland and Star [20] has called out this connection more explicitly, devoting additional attention to the nature of standards as an integral aspect or component of infrastructure. In this work, they argue that standards are: 1. nested inside one another; 2. distributed unevenly across the sociotechnical landscape; 3. relative to communities of practice; 4. linked and integrated (to each other and to organizations, nations, and technical systems); and 5. codify or embody ethics or values. The relationship between this list and the earlier infrastructure list is striking, calling out the deep and arguably inseparable connections linking the two concepts: to a large extent, infrastructure works through standards, and vice versa.

While much of the emphasis above is on the stability of infrastructure and the consequences of being excluded from it (as in Star's later discussions of 'infrastructural orphans' [32]), it's also important to note the potentially *dynamic* character of a world structured through standards. Imagine for example the challenge of changing the world one system, practice, or user at a time across a truly non-standardized landscape (a situation echoed in parts of the empirical section that follows). Now imagine the task of changing those practices by switching or flipping a standard that exists. The latter case is hard (maybe impossible, depending on circumstance) but in principle and with the right alignment of forces doable. That's because standards provide a fulcrum or pivot point around which change can unfold, reconciling innovation in parts of systems with 'global' demands for stability and coherence.

In all these ways, standards and protocols maintain the practices and expectations of users and designers against the messy churn of the worlds around them. Standards shape the space available to system developers, ensuring that innovation meets the world in workable fashion. From a traditional design perspective, this is a rich story of artifacts, tools, and the complexities associated with bringing features of the built world around us into better and more sustainable alignment through design. But it's also a story of everything that design touches: practices, organizations, values, and expectations – all of which may be implicated and shaped by the work of standards development. We design to, from, and with standards. If there weren't standards, we'd have to design *everything*, and be a lot smarter than we in fact are.

The sections that follow develop these claims by reference to an ongoing program of work around the development of new computational infrastructures in American ecology. We explore the role that standards play in the large-scale research networks increasingly (yet perhaps erroneously) viewed as the future of ecology and other fields; how standards in complex interactive environments can struggle and fail (and what happens when they do); and how actors work across the gaps that standards leave to produce more effective forms of design and interaction in the world.

STANDARDS & INTERACTIVE SYSTEMS IN ECOLOGY

In this section, we report on data from a long-term ethnographic field study around patterns of computational development, governance, and collaboration in American ecology. Since 2010, we have interviewed over 150 ecologists and conducted participant observations across more than a dozen centers of ecological research, including both the individual lab and large-scale research network described in greater detail below. Interviews ran from one to three hours, and several participants were interviewed more than once in the course of the research. Wherever possible, interviews included observation and sometimes direct participation in research work practices. Interviews were transcribed by members of the project team or hired transcriptionists, producing more than 2000 pages of transcript data. These were then coded using grounded theory concepts and the NVivo software application. The code set developed for this paper focused heavily on issues of standards development, practices, training, difficulties, and challenges, and the wider tasks of coordination and interoperability these activities were meant to support.

The empirical accounts that follow focus on practices and problems of standards in two immediate contexts: an individual research program ('the Lab') operating out of a Midwestern university whose primary field work occurs in a remote northern site; and the National Ecological Observatory Network, a continental-scale observatory for ecological work and collaboration that is currently under construction and headquartered in Boulder, Colorado. This structure is designed to pull out similarities and differences in problems of standardization and design in interactive systems development at scales both local and global in nature.

LOCAL STANDARDS

Our first empirical case concerns an ecological research lab ("the Lab") based at a large Midwestern research university. Its fieldwork is primarily located at "Northern Station," a remote and mostly seasonal research site that is part of the larger Long-Term Ecological Research Network (LTER), a grouping of 26 diverse field sites dedicated to building long-term ecological knowledge critical to understanding ecological processes ranging from invasive species and nutrient cycling to food chain dynamics and climate change. While the Lab is invested in routine, long-term monitoring at Northern Station, it runs additional grant funded projects at the site as well. It also works collaboratively with other labs operating onsite, sharing infrastructure, expertise, and occasionally data.

At first glance, the Lab would seem to represent a relatively straightforward case of standardization. The Lab is small (fewer than 10 people in a given field season), its research is mostly restricted to a single field site, the PI has worked at the site for over two decades, and the Lab's responsibilities to coordinate with outside research programs are fairly light. If there is a simple case for standards in collaborative ecological work, this should be it. That standards and standardization are *not* simple in such a setting tells us much about the function and complexity of standards work in complex interactive environments.

At the heart of the Lab's standardization efforts lies its protocol book, a 375+ page manual that contains methods and protocols for each and every action performed by the research team, whether in the field or back in the lab at their home institution. The manual includes sections covering preparations for the field season, starting up and shutting down field operations, sampling methods and equipment usage, laboratory and analysis procedures, data processing and storage, methods for fieldwork in other sites and projects, software and key statistical analysis packages, and a series of short-form descriptions called "wallocols" described in greater detail below. The protocol book is constantly updated (it is currently in its 29th edition) and supports standardization in all things the lab does. A lab manager explained to us that he consults the protocol book "anytime [he's] starting anything new," and cited several instances of using the protocol book to successfully execute unfamiliar tests and procedures. New graduate students and summer research assistants are given relevant entries from the protocol book to read upon joining the lab, more experienced technicians periodically consult it, the protocol book is regularly checked and updated to reflect new equipment and minute changes in practice, and the entire research team reviews and amends the protocols at the end of the active research season. These changes are themselves meticulously documented, so that the entire document ends up containing a history of its own development. If the fictional cartographers of the Borges story, *A Universal History of Iniquity* [2] ('the map that covers the territory'), ever wrote a protocol book, this would be it.

While the protocol book serves as the master reference, its formal prescriptions of action are carried into the world through an intermediate set of documents. As the protocol book has grown into a dense and unwieldy artifact, the lab has created shortened versions of key techniques called "wallocols." These wallocols function as "a reminder note of the major steps" and convey the essentials of a particular protocol boiled down to one page and literally taped to a wall in their lab at the site. These range from reminders of what to pack before heading out for a day of fieldwork to an abbreviated list of critical steps for particular field or lab procedures. One lab manager has gone on to create versions that are shorter still and printed in field notebooks to map out key and notably tricky field operations (e.g. measuring stream discharge rates under varying local terrains). The field notebooks themselves have become standardized over time: twenty years ago they were blank "Rite in the Rain" notebooks, but have since evolved to include pre-printed form-like pages that guide the field worker on what data to record (time, date, weather, temperature, etc.) at a particular site. These intermediate forms and artifacts are important parts of the Lab's efforts to coordinate data collection and interpretation across time and space, and are crucial to the standardizing ambitions of the Lab's research efforts.

The scale of these efforts is best understood when mapped against the difficulties that standards are meant to address. As the Lab's Principal Investigator (PI) explains to us,

> Just about everything that we do, either in the field or in the lab can have an impact on the final numbers that we produce. So there is a direct link from each step all the way through to saying, "This is the number. The number is 5 plus or minus 1." We feel that either shows there's an impact of climate change or doesn't. And because each and every step is linked to the other and can have an impact on the final numbers that we generate, we have to be extremely explicit about how to do each step.

Standards protect the integrity of this chain, and provide infrastructure crucial to the integrity and ultimately credibility of the work.

Despite the care and intensity of this work, efforts at formal standardization as represented by the protocol book face challenges grounded in the material, placed-based, and human dimensions of ecological work. Ecology is a messy field and heterogeneity in environments and organisms makes data collection, use, and interpretation challenging. At the same time, while some routine activities performed by the Lab lend themselves to formal and abstract description, others rely on elements of 'feel' or 'touch' that are much harder to codify in this way. One lab member for example offered the following description of difficulties in formalizing protocols for the measure of permafrost:

> Is this a rock or ice? So you stick a metal probe into the ground and the steel probe penetrates it, it's just a big T handle. You stick it down; you put your hands across the top on the T and push it down into the ground until it won't go any further. And then you put your hand down at this little surface and wrap your fingers around the thaw probe, pull it out, and then it's graduated. You measure where your fingers are, "Oh that's 10 centimeters, that's 20 centimeters, and that's 32 centimeters." And that's the depth. So one of the things you can read about in the protocol, it says, "Make sure that you're hitting ice, that you're hitting frozen soil and not a rock because a rock will stop you just like the ice will stop you." And you could read that all day and never know the difference between a rock and the ice. You wouldn't know that in the field unless you actually had a feel for it and someone was there telling you: *Dink!* "Hear that sound?" "Yeah, I haven't heard that before." "Yeah, that's a rock. Now move it a little bit over and do it in the permafrost, that is the ice. Do you see the difference?" "Yes." "Do you feel the difference?" "Yes." "Done."

Other difficulties stem from over reliance on formally expressed protocols, to the neglect of contingencies and mitigating factors necessitating workarounds, improvisation, and discretionary judgment. All manner of occasions arise where a person must make creative decisions that mediate between the protocol in its formal dimensions and the details of a non-compliant reality. Have voles chewed through some wires? Is a thunderstorm on the horizon likely to shorten available field time? Has a bear eaten or disrupted the collection equipment? Even apparently simple processes like measuring the water discharge rate of a stream by sticking a rod in the water and reading a number off an attached box may provoke exceptions:

> Let's say there's a big rock in the middle of the stream and you stick the probe right behind it and it measures zero discharge because all the water's flowing around it, right? And someone did that because that's what the protocol says, just step two steps across the stream every meter. Or if there's vegetation, or if you can tell like, oh wait a minute, you can see there's an eddy here pooling the water so it's actually flowing like, negative discharge or something, which can happen.

Adding an additional layer of complexity, small labs depend on teams of research assistants, graduate students, and post-doctoral workers whose composition can change from season to season, affecting the apprenticeship styles of learning that shape the deployment of protocols in lab and field, and may cause shifts or breaks in practice. Even where teams remain the same, memory or habits can fail, introducing subtle variations in technique that may affect the data, suggesting patterns where none exist and obscuring others that are real. These problems can be traced to minute and usually innocent changes in practice that can produce collective forms of protocol "drift" over the course of time – an example of 'bad' creativity that PIs at Northern Station often worry about and frequently encounter. The Lab PI described one such seasonal example:

> There has to be constant checking, because protocols evolve extremely rapidly and constantly. So, I'll leave at the start of the summer, and I'll come back at the end. They say, "No, this is the way we always done it," and I'm looking and they're doing it completely different. "What do you mean this is the way you've always... ?! I told you how to do this in June, what happened?" [laughs]. So, constant vigil on that is required.

To meet these challenges, standards processes, even highly ambitious and formalized ones like those represented in the Lab's protocol book (or the more computational forms described under NEON below), will frequently return to the trust and judgment of human agents. For this reason, a great deal of the standards action at Northern Station resides in training and apprenticeship: periods of collaboration, teaching, and practice in the field through which procedures are taught and corrected, discretionary skill and judgment is built, and basic understandings of standards and the broader objectives behind them are shared. Operating in this mode, standards take on a clear authoritative or "disciplinary" role vis-à-vis the human and object worlds around them, enforcing fealty and conformance to worlds of established practice and expectation. To stray from this path is to court disaster, and turn data, sometimes literally, into dirt. It is also to leave the community of science (and if you're a field tech or undergraduate research assistant making too many such departures, to earn an early one-way ticket home).

But the same processes also build creative and discretionary skills that can in fact rescue and renovate standardized programs when things go wrong or new opportunities arise. Humans can be flexible, contextually aware, and creative, applying discretionary judgment in appropriate and science-saving ways when breakdowns and unexpected situations arise. Skilled field workers with deep knowledge of the science (rather than rote or mechanical understanding of the protocol) can adjust in subtle and consequential ways when the need and opportunity arises – *changes which can then be incorporated into the living body of the standard.* It is this history of change and emergence that accounts for the length and ongoing elaboration of the protocol book (now in its 29th edition), and provides the counterbalance to the purely constraining or 'disciplinary' view above. The story of standards as practiced at Northern Station is not solely about freezing practice, or locking it into variants established in unchanging form at the moment of launch or origination. Rather, standards retain important and necessary dimensions of discretion and creativity (though these capacities may be jealously guarded and differentially distributed). If standards constrain change, they also enable it, and are in fact central to ongoing processes of innovation by which ecological knowledge and technique learns and grows [5]. The protocols of Northern Station are written in solid and well-pressed pencil, but it's not indelible ink.

GLOBAL STANDARDS

Our second empirical case involves the National Ecological Observatory Network (NEON), a $434 million observatory system funded by the U.S. National Science Foundation. NEON plans to gather ecological data across a diverse suite of ecosystems throughout North America for 30 years to better understand and predict continental-scale ecological questions of climate change, land use change, and invasive species. Having successfully navigated its design and planning phases, NEON is now in a five-year construction process that will culminate in full operational status by 2017 (though parts of the observatory are already collecting live data). NEON intends to use existing data from satellites, site-based remote sensing data, and a standardized field collection program to describe ecosystem changes across space and over the next three decades. Data collected at over 100 sites will reflect information about climate, atmosphere, soils, streams, and other water bodies, and a range of organisms. This data will in turn be repackaged into high-level data products, calibrated and curated for open use through the network website.

Within this world, standards take on complex and important roles. Some of the standards issues faced by NEON parallel those experienced by the Lab above, though often magnified and made more complex by the greater collaborative and ecological range of the work in question. Others represent problems specific to scale, or that attach in particular to organizations and research endeavors in their moments of start-up and formation. In either case, through a good part of its planning and current construction phase, a disproportionate amount of the efforts of NEON staff have been dedicated to crafting, building, anticipating, and working around the difficulties that standards pose. This work begins with the efforts of the science team, and proceeds through most or all members of the NEON engineering, computing, education, civil construction, data products, project management and field operations staff.

NEON's standards challenges stem from a single daunting fact: namely, that through most of its history and across many of its disciplinary and methodological sub-communities, ecology has remained radically non-standardized (or rather, has resolved its standards issues at the scale and through mechanisms as outlined in the case of the Lab above). NEON's organizational scale and its ambition to function as a single 'instrument,' collecting and distributing comparable data across the vast array of sites and ecological diversity represented under the network's sampling footprint make this solution untenable. But it also produces sometimes severe and perplexing challenges for those seeking to build effective standards to support NEON's growing program of work.

Some of these challenges attach to the extreme range and heterogeneity that standardized tools and protocols in NEON are required to address. From rivers that freeze for large portions of the year to those that dry up in the summer, scientists in the NEON field program – the side of the organization most closely aligned with the types of activities described earlier at Northern Station – are required to arrive at sets of standards sufficient to preserve the integrity and comparability of data, while remaining workable in the varied sites in which they'll be practiced. Within this range, some things are harder to standardize than others, reflecting differences in sampling methods but also the prior organization of the underlying scientific communities. As one staff scientist described:

> Because of the breadth of those sampling activities, plants, insects, mammals, aquatic environments and so on, you're sourcing information from a variety of different communities. And even within each of those communities, there are no standard methods of practice. One PI and another PI will differ quite strenuously about the right way to do it, and so there is no standard within the community of practice.

While some of these differences connect to personal choice and history (and the desire to have the new network produce data consistent with extant field programs), others stem from legitimate differences in site-specific needs at individual sites and the difficulties of one-size-fits-all protocols in meeting these. Another staff scientist for example described the challenges of insect collection, and how emergent NEON protocols for mosquito sampling were bad at capturing the specific species responsible for carrying dengue fever in NEON's more southerly sites (even though insect-borne diseases were one of the stated targets of the network). Working across such differences, and making the inevitable trade-offs and compromises that result, can involve NEON protocol developers (many of them junior and early-stage researchers) in complicated and sometimes contentious disciplinary negotiations.

Even after a network-wide standard is achieved, the difficulties don't go away. If the Lab faced challenges coordinating standards across the turnover of graduate and seasonal workers, NEON faces the daunting task of practicing and enforcing its standards across a still larger and more distributed team of field workers, themselves coming out of specific trainings but required, under the organization of the NEON field teams, to perform field operations that in fact span several disciplinary and methodological traditions. As with the Lab, some of these procedures involve elements of feel or judgment that do not reduce well to formal description. Still others concern matters of skill and routinized action whose appropriate level of description – when is the protocol detail insufficient, and when is it too much? – is a subject of ongoing debate and experiment between members of the science and field operations staff. (One of the more interesting versions of this work involves the process of 'cold-testing' protocols, in which non-domain experts are handed draft protocols and asked to reproduce the procedures described, to wildly different outcomes).

Under such conditions, risks of error and protocol drift become acute: in an ecological variant of the 'broken telephone' game, there is a real and frequently expressed worry that even if the field teams *start* doing things in a standardized way, they may very soon not be. At the same time, risks of mindless or too-literal adherence to the protocol (especially among field workers with little background in the technique or science behind it) may grow, raising the prospect that NEON data will be rendered useless by failing to exercise the discretionary adjustments and accommodations needed to preserve the spirit as sometimes against the letter of the protocol. The geographic distribution of NEON makes these issues all the more acute, as individual technicians and field managers in some of the farther flung domains cannot easily 'drop by' NEON headquarters in Colorado to check such issues.

To counter this, members of the science and field operations team we spoke to described a number of ideas and strategies, some of which indeed pushed the organization further in the direction of standardization. One of these predictably involves training, and in particular a strategy by which field managers routinely travel to Boulder to 'recertify' on core NEON methods operative in their domain. Another involves quality assurance through periodic and randomized tests and spot-checks, checking the local application of NEON protocols as these develop in specific domains over time. Yet another concerns the ultimate authority of staff scientists in Boulder for checking and certifying any domain-specific departures from protocol, and the evolution of the protocol as a whole over time. As one field manager argued,

> The local workaround is exactly what we want to try to avoid. I think it's just going to be not only talking to my fellow people, but I really view the scientists in Boulder as kind of that point of contact for any potential challenges and making sure that they're the holder of the keys that says, "Oh, it's okay to adjust your process because of where you are," versus, "No. You need to do it the same way"… I am a trained scientist. I can figure this stuff out, but it's really not my call, and it shouldn't be my call, and it shouldn't be my technicians' call. It's really the folks in Boulder—the ones that wrote that protocol, came up with that design.

If standards challenges in the NEON field program show up in particularly acute and immediate ways, subtle but no less consequential issues confront other operational groups at NEON. Members of the remote sensing team described to us the difficulties of deriving common and reliable forest cover and vegetation density readings on the basis of satellite and airborne measure, and the practices of calibration dependent on overflying well-characterized sites. Cyberinfrastructure team members spoke about the challenges of standardized file names and structures, and NEON's efforts to leave the one-off spreadsheet world behind. Members of the sensor team talked about the challenges of ensuring reliable and comparable sensors, and their work with manufacturers to ensure equipment would meet the quality assurance and error tolerance standards set by NEON. And project management and systems engineering staff described to us the challenges of making the organization cohere as a whole, holding the various project teams and sub-units to standardized schedules and project interfaces. While few of these match the scale and complexity of standards challenges facing the field team, standards issues are fully absent for none.

The NEON case sketched here extends and amplifies many of the practices and challenges experienced by the Lab above. Like the Lab (but more so), NEON faces challenges of coherence and coordination rooted in the natural variability of the landscapes it covers. It also faces issues owing to the collaborative and distributed character of ecological work, and the multiplicity of human agents involved in carrying it out. Some of its challenges are rooted in the character of the work itself, including forms of skill work and discretionary judgment that fit uneasily within the world of formally codified standards. Others are rooted in the nature and organization of NEON itself, and the work required to make such an entity cohere. Given these challenges, many of NEON's efforts in the standards space are oriented to limiting, constraining, and otherwise managing the sprawl of the human, technical and natural environments they face.

But not all of NEON's efforts and conversations point in this direction. Scientists in our interview set also spoke to us about NEON's need to grow and evolve, and the danger that rigid standards and protocols, narrowly and statically applied, might compromise the network's capacity to respond to new techniques, opportunities, and new scientific and social interests in the phenomena under study. This concern accounts in part for the network's choice to retain mobile and relocatable sites and units that can be shifted and redeployed in strategic and opportunistic ways. It has also prompted internal discussions around the appropriate conditions and procedures under which the standards they are working so hard and painfully to produce might be changed, relaxed, or abandoned.

DISCUSSION

As the above analysis makes clear, problems of standards and standardization constitute central and ubiquitous elements in programs of computational development and collaborative work in the sciences. These came to the fore with particular clarity in the context of NEON, both because standards there are still being established, and because the effort to connect ecological work and infrastructure across previously unconnected sites and practices raises deep challenges of coordination to which standards are a natural, if by no means simple, response. But standards and protocols were no less present or challenging in the context of our lab-level study, despite the much smaller scale of sites and personnel involved. While we saw how the Lab manages unevenness and variability in the natural, material, and human environments around it through elaborate exercises in standardization built around the protocol book, we also saw how hard and necessarily incomplete such efforts were, and the constant work needed to update, maintain, and work around the problems and gaps that standards, as practiced in this domain, inevitably leave.

These cases demonstrate the range of forms that standards may take. While the examples foreground immediate problems of artifact, practice and environment, the worlds of standardization encountered in our work were more varied and complicated than that, and included many instances where scientific efforts met standards processes and problems in other domains. Members of the environmental safety and permitting team at NEON, for example, described the challenges of navigating the legal and institutional procedures emanating from a maze of municipal, county, state, and federal institutions, each with their own requirements and procedures. Standards questions also arose around the evaluation and long-term career trajectories of NEON employees, many of whom operate in modes and roles relatively new to ecology, and that sit uneasily within the standardized metrics of performance and reward (publication, research productivity, teaching, etc.) that have typically structured the field.

Our cases also point to just how hard standards work is, whether measured by time devoted to activities, incidents of breakdown, or the sheer frustration that standards and their failure can occasion. Despite the Lab's best efforts, the practices of seasonal and even veteran field workers can drift over the course of one or several summers. This is exacerbated when new or inexperienced field workers miss key contextual clues that necessitate flexible and appropriate tweaks to standard practices. Scientists, engineers, and systems developers at NEON face the same problems of consistency and coordination in radically expanded form, exacerbated by organizational scale and the ecological diversity their procedures are required to cover.

Finally, our cases point to the varied ways such effects play out across the range of activities, practices and entities that go into the production and maintenance of a collaborative research program (and other complex distributed practices). Some practices and entities reduce to standards more easily than others. Some build on past histories of standardization, or occur in forms that lend themselves to clear and uncontested descriptions that *can* be effectively captured, codified, and reproduced. Others don't codify so neatly, and are marked by forms of contingency and emergence that resist easy simplification: 'square' or irregular pegs in the 'round' holes that systems of standardization inevitably require and produce. Some things are 'hard' to standardize, and others are 'easy' (which often simply means that the work has happened in the past, or that entities left outside of the standard lack the power or position to contest it). Any complex interactive system (science, for example!) is likely to contain a mix of such elements, leading to complex internal dynamics and accommodations. Such differences can become a source of frustration and misunderstanding, including in the development of new computational systems designed to bridge and coordinate such heterogeneity.

So: standards are everywhere and come in many varieties, some of them surprising. They're also hard, and hard *differentially*, affecting different parts of complex interactive systems in different ways. These difficulties may increase with scale, as practices move towards higher levels of aggregation. They also grow with heterogeneity, as systems seek to bring increasingly diverse worlds – people, artifacts, and environments – into alignment.

But standards are also intimately connected to much of what HCI researchers seek to accomplish in the world. Whether it's new forms of environmental monitoring and awareness [8,9,27], new infrastructures for crisis management and response [31], or new collaborative infrastructures in the sciences [16,17,22], standards are at the heart of what we do. A great deal of HCI work relies on standards produced elsewhere [13], whether those constraining the tools and objects we build with, those shaping practices of use amongst our target populations, or those sustaining the conditions of action and knowability in our target domains (try to imagine the field of sustainable HCI, for example, without the standards of environmental measure and accounting it depends on). At the same time, HCI researchers may be important *producers* of standards, establishing protocols for action and design with long-standing weight, durability, and 'stickiness' across the systems and fields we engage.

For all of these reasons, building more thoughtful and productive relationships with standards constitutes an HCI research and design priority of the highest order. The following rules of thumb are some practical starting points:

Build from extant standards: We have seen how efforts at new infrastructure development in the sciences must account for the uneven landscape of inherited standards, formal and informal, and how such initiatives may struggle when such standards are sidelined. But this principle holds true across many (perhaps all!) spheres of HCI engagement. New and perhaps especially integrative design efforts must negotiate with what may be very old standards that structure work and interaction in the settings they cover and in part construct. Viewed positively, extant standards provide crucial shortcuts to action, bounding and limiting the design space in frequently useful ways: we design further by standing on the shoulders of standards. More problematically, contradictory, divergent or unaccounted for standards may undermine or torpedo our best efforts, producing frictions, breakdowns, or simple non-adoptions that limit the scope and impact of HCI work.

Work creatively across scale: We have seen how much of the value (and challenge!) of standards arises at the transit points between 'bigger' and 'smaller' (or simply *different*) systems. Standards are often most needed and most formalized when moving to larger or more distributed levels of aggregation. This is true of the challenges faced by NEON in moving ecology from its history of small and locally controlled field operations towards its vision of robust interoperability at a global scale. But it's also true of demands placed on standards as HCI design efforts move towards higher levels of aggregation: the move to global, distributed (as opposed to in-house) software development efforts; the movement from experimental to production-grade systems in environmental monitoring and sustainable HCI; the incorporation of a growing range of regional and national organizations in crisis response settings; etc. In Ribes [28] terms, standards constitute crucial "scalar devices," building bridges between design and action at a local level, and possibilities of growth, extension, and interoperability at higher or wider levels of operation. This makes them integral to the ambitions of scale and impact that inform much of HCI research and design.

Accommodate contingency, change, and growth: Finally, we have seen how the actors in our study responded to the simultaneous threat and opportunity of change around the standards that guide their work. This speaks to a potentially *dynamic* character of standards, and the need to balance a too-assiduous fealty to them with opportunities for change and growth emerging in the environment. While periods of stasis are crucial to anchoring or coordinating role of standards, so too are moments and opportunities for change.

This too holds true across other fields of HCI practice and engagement. If we build from standards, we also build *to* them. Reflective consideration of the numerous tweaks, breakdowns, and departures from standards (including in the systems we build) may support a more thoughtful, creative, and resilient engagement with standards over time.

In sum, we should learn to engage proactively with standards, working *with* rather than *against* the 'grain' of the world that standards, in part, supply. This may involve new forms of listening to fields we encounter, seeking new insights into the forces that structure value and action in the worlds we engage – a form of accommodation and humility that may sit uneasily with more heroic notions of design. But we may also need to find *creative* and *improvisational* potentials in and around the settled worlds of standards around us. An outside example of this may be found in the significantly different relationship between standards and innovation to be found in the interactive system of jazz. As described in Paul Berliner's masterful *Thinking In Jazz: The Infinite Art of Improvisation* [1], standards have long played a special role in this world. Standard tunes passed down through generations provide historical continuity, connecting early masters to present practitioners. They establish the basis of 'interoperability,' such that previously unacquainted practitioners (who may share no other background or referent) can 'spontaneously' interact. They also fix the rules and gradations of practice that constitute key markers of belonging and hierarchy in the field: to be a good jazz musician is above all to play the standards well. They are also, however, *the field's key site of novelty and invention*. Some of these emerge as elements of voice and style: for example, where new jazz stylists turn to standards to demonstrate the novelty and value of a 'new sound.' Some emerge from breakdowns not entirely dissimilar to those described in ecology: arranging to available instruments when star performers depart or fall ill, or the novel trains of action that can be set in motion by a single wrong note (as in Klemp et. al.'s [19] analysis of the consequences of a wrong note during a Thelonious Monk recording of "In Walked Bud.") Such thoughtful and sometimes contingent appropriation of standards has anchored forms of improvisation grounding and renewing jazz from generation to generation, preserving its continuity and liveness as a musical form. HCI and other fields of information science could learn much from this example.

CONCLUSION

Our findings hold important lessons for HCI research around new tool and system development in the sciences, whether we're talking about the maintenance and operation of existing systems or the design of new field-specific tools, middleware, or infrastructures. These findings are timely and salient in light of the significant transformations in scale, practice and value currently being attempted across ecology and other fields of science – transformations in which HCI research has had an important role to play.

But our findings also hold implications for wider bodies of HCI knowledge and practice. Standards shape and constrain the worlds of design and practice that HCI researchers inherit and engage. They organize practice, producing forms of stability, routinization, and predictability around which subsequent design can build. They guide local action and expectation towards systemic or collective demands, allowing for the exchange of objects, labor, and knowledge through which larger interactive systems may be constituted. These features become additionally important as HCI scholarship enters into increasingly complex relations with wider and more varied fields of practice. When they're on our side, standards are our friends, adding force and strength to our efforts to make the world flow in the directions we seek, and supporting whatever broader goals – sustainability, innovation, justice, participation – we might assign to our work. When they're against us, no amount of smart and creative design is likely to prevail.

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