1 The future of natural history collections

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Introduction

In 2016, the Yale Peabody Museum of Natural History celebrated its 150th anniversary. It was an occasion to look back on an illustrious history of scientific collecting, through the publication of two books (Conniff, 2016; Skelly and Near, 2016), a program of talks, and a temporary exhibit entitled *Treasures of the Peabody Museum: 150 Years of Exploration and Discovery*. In a darkened exhibit hall a handpicked selection of objects was presented, drawn from the nearly 13 million specimens that make up the Peabody's collection: an eclectic physical précis of the museum's holdings that encompassed a rifle belonging to Buffalo Bill; a type specimen of a Tahitian fern collected on the US Exploring Expedition of 1838–42; a pickled tentacle of a giant squid captured in Newfoundland in 1873; the first microscope ever used at Yale, from 1735; and a dog-drool collector belonging to Ivan Pavlov.

Natural history museums and their collections are often thought of in terms of the past, which is not surprising. We are probably the only type of scientific research facility that can claim the ability to time travel, albeit in a patchy and far from perfect way. Our business is intimately connected with the past, both recent and deep time, and much of what humans know about the natural world of a hundred, a hundred thousand, or a hundred million years ago arises directly or indirectly from the specimens held in our collections. When your child states with certainty that *Tyrannosaurus rex* lived in the Cretaceous period they are, knowingly or unknowingly, drawing on the results of research done using museum collections.

There is, however, a considerable difference between studying the past and belonging in the past. A cursory glance at the cavalcade of sepia-toned images, polished brass instruments, and handwritten jar labels in the Peabody's anniversary exhibition might give the impression that the Museum's glory days are behind it. Nothing could be further from the truth. Closer inspection of the exhibition revealed specimens that were collected only a few years ago, research performed with cutting-edge technology, and collection-based science projects that address some of the most pressing issues facing us today; fundamental questions about the future of the planet and our species.

Natural history collections face four main challenges: acquiring material, preserving that material, making it available for use, and making the case that the first three activities are worthy of support. These challenges are eternal ones, which have faced museums since their inception and are likely to persist for as long as museums exist. But natural history collections have undergone a quiet revolution in the last thirty years, which has the potential to create an exciting future in which collections play an even greater role in society.

To say that natural history collections are facing a dynamic future that is both exciting and alarming may surprise many people. But in some ways, that future is already here, and the extent of the surprise being expressed is one of the challenges we face in responding to it.

The challenge of collecting

In 1921, a caravan of heavily loaded Dodge automobiles passed through the Great Wall of China at Kalgan and headed west, into the deserts of Mongolia. Led by Roy Chapman Andrews (frequently cited as the inspiration for George Lucas's Indiana Jones, despite repeated denials from Lucas), the American Museum of Natural History's (AMNH) Central Asiatic Expeditions have shaped the public perception of natural history collecting. Between 1921 and 1928, Andrews and his colleagues shipped thousands of paleontological, zoological, and botanical specimens back to New York. The tales and images of weather-beaten explorers, gun-toting bandits, camel trains, and dinosaur bones being hacked from the rocks of the Gobi Desert in books and periodicals made Andrews very much the media star of his time (Gallenkamp, 2001).

But the expeditions were also a product of their time, as was Andrews. Frequently forgotten amid the triumphalism of their finds was the underpinning purpose of the trip: to find evidence of early humans that would support the theory of American Museum of Natural History (AMNH) President Henry Fairfield Osborn that Central Asia was the cradle of human evolution. In Osborn's worldview, people of color occupied the far-flung edges of the planet, having been displaced by the more "advanced Nordics" situated in Eurasia. Absurd though this idea may seem today, in the 1920s such racially based theories were not considered outside the scientific mainstream. They reflected prevailing attitudes of the time, which could also be seen in the conduct of the expedition. Neither Osborn nor Andrews showed much respect for their Chinese hosts, who they variously described as corrupt, callous, effeminate, self-indulgent, and lazy. Team photographs show the expedition personnel to be almost entirely white and male. The few Mongolians present are relegated to the role of cooks, camel drivers, and porters (Regal, 2002).

The Central Asiatic Expeditions reflected a belief that American knowledge exceeded that of the Chinese and Mongolians, and that this justified taking possession of specimens and data from their territories (Rainger, 1991, p. 104). The great natural history collections of the world were born in the heyday of Western colonialism when the right of their scientists to collect specimens from around the world was unquestioned. Today we work in a world that is very different, and our assumptions about our role and that of others are, we hope, also very different from those that underpinned the building of the museum collections in which many of us work. For natural history museums, one of the key elements of this is the Convention on Biological Diversity (CBD), which was launched at the 1992 Earth Summit in Rio de Janeiro and has been in force since 1993. The principles behind the CBD were that biodiversity should be conserved for the benefit of humanity, that the benefits should be derived from sustainable usage, and that those benefits should be shared fairly and equitably (United Nations, 1992).

Traditionally, natural history museums saw their role as supplying the science on which our understanding of biodiversity was based, but there were cases where more directly commercial benefits could accrue. For example, alkaloids extracted from specimens of poison dart frogs collected in Ecuador by the AMNH form the basis of a number of promising analgesic drugs under commercial investigation (Angerer, 2011). But the implementation of the 2010 Nagoya Protocol to the Committee on Biological Diversity (CBD), which sets out the legal framework for access and benefit sharing of genetic resources came as an unpleasant surprise to many museums. With the implementation of the protocol in 2014, biological collections of the sort that museums have been making for decades are regarded as valuable resources and treated accordingly (Neumann et al., 2014).

This has implications not just for collecting, but also for routine operations such as processing of specimens, sampling, or loans of specimens from one museum to another. All these operations require Prior Informed Consent (PIC) for the procedure from the country of origin beforehand and Mutually Agreed Terms (MAT) for how any resulting benefits will be handled. The country of origin for the material is entitled to place limitations on the purposes for which specimens are used, and to specify conditions that ensure a reciprocity of benefits. Those benefits can be monetary or non-monetary, which means that arguing that the results of museum-based research are rarely commercialized makes no difference—in principle, any benefits obtained from the possession or study of the genetic material in the specimens, be they commercial, scientific, educational, or promotional—should be shared with the country of origin (Neumann et al., 2014).

To some extent, museums are already addressing these issues, and have been for some time. Modern collecting expeditions are usually partnerships between the host country and the museum, encompassing multiple stakeholders, and with an emphasis on training staff, and building collection capacity in the host country. They are governed by a raft of documentation, including collaborative agreements, collecting permits, export permits, and import permits. In most cases, the collecting agreement will also specify the disposition of any specimens collected, limiting the number and type of specimens that can be exported, and for certain categories of rare material, such as vertebrate fossils, it is not unusual for the overseas institution to retain none of the material; instead, permission is granted to make casts of the fossils, with the originals and molds returning to the host country.

Nonetheless, it is likely that Nagoya will bring more challenges, as host countries seek both to capitalize on their biodiversity and build local capacity. As museums, we should embrace this; greater stakeholder engagement, transfer of skills, and the creation of new collaborating partners are all good things for our long-term future. But it also raises the question of whether, as local capacity grows, Western institutions can continue to grow their collections globally. The countries in question are often the regions of greatest biodiversity—not only are they the places where everyone wants to collect, but they are also the areas in which collecting efforts should be concentrated, as they are often regions where the potential for biodiversity loss is most sizable. Previously, museums in the Western world took a rather asymmetric view of the collaborations necessary to achieve this.

One example of this is the concept of the "parataxonomist," attributed to the ecologist Daniel Janzen (1991) and embraced with enthusiasm by the taxonomic community during the 1990s. The parataxonomist was a local worker who had been given basic training in species identification. The idea was that this individual would carry out the initial bulk sorting of specimens, but as soon as something interesting emerged, an expert (usually not local, and often from an overseas institution) would be called in to describe it. The work of the parataxonomist thus saves the more valuable time of the taxonomist. It was a well-intentioned idea, which sought to cope with the very real resource challenges associated with describing massive numbers of species in a finite period, but it is questionable whether it could be described as truly collaborative.

In the twenty-first century, the only way this massive species description effort will work sustainably is with at least some of the leadership coming from the countries that actually "own" the biodiversity. As many of them are struggling to lift their people out of the trap of poverty, this will be a big hurdle to overcome. More recent efforts to address the biodiversity crisis, such as the "call to arms" by Wheeler et al. (2012), have placed a strong emphasis on providing resources to develop collections and in-country expertise in areas of high biodiversity; this is at least as important as developing expertise and building collections in the developed world. It was telling that of the thirty-nine authors and twenty-five institutions represented in the Wheeler et al. paper, thirty-four authors and twenty-one of the institutions were US based, and only one author was from a country with an emerging economy (in this case, Brazil), even though most of the world's undescribed biodiversity resides outside the United States and Europe. There is a considerable (and perhaps understandable) resentment in many parts of the world toward the mining of biodiversity by "first world" institutions, and any large-scale program of species description needs to address this imbalance.

The process of collecting itself is receiving increasing scrutiny. The emergence of social media and the ability of scientists to share their work with the public have resulted in valuable exposure for museums' biodiversity conservation activities, while raising uncomfortable questions concerning long-established work practices. One example of this was the first-ever collection of a male specimen of the moustached kingfisher (*Actenoides bougainvillea*), an endemic species from the Solomon Islands, by a team from the American Museum of Natural History. The discovery, in October 2015, was announced on the expedition blog by the ornithologist who captured the kingfisher (Filardi, 2015a). When it emerged that the animal had been euthanized there was a storm of protest, communicated via comments on the Audubon Society article that reported the discovery (Silber, 2015), a subsequent article by the collector explaining the basis of the decision to collect the bird (Filardi, 2015b), and negative coverage in mainstream media (for a typical example, see Klausner, 2015).

This is not a new issue, especially in ornithology (see Remsen, 1995; Donegan, 2000; Winker et al., 2010), but it has been given new urgency by the increasing use of technology in collecting. If a biologist can take digital images, sound recordings, deoxyribonucleic acid (DNA), and other tissue samples sufficient to produce a species description (see, for example, Sangster and Rozendaal, 2004; Athreya, 2006), is it still necessary to kill the individual in order to obtain a voucher specimen? Many members of the public would say "no," as do some academics. In 2014, a paper in *Science* by Minteer et al. (2014) argued that given the precipitous decline in abundance for many species, it was unethical for museums to kill additional members of these species when nonlethal alternatives exist. There are, of course, strong counterarguments in favor of physical vouchers. Any species whose long-term viability can be significantly affected by the removal of one or two individuals is already effectively extinct: without aggressive human intervention (through, for example, capture and captive breeding), natural mortality will far exceed this. The process of capturing, anesthetizing, and sampling a small animal will significantly compromise its fitness, increasing mortality rates. Finally, a blood sample and a photograph can provide only a very limited amount of information about a species—a fraction of what could be obtained from a full body voucher specimen. It is not possible to re-examine the type specimen to validate the original description, and any new questions not answered by the type description will require the collection of another specimen, compromising the fitness of yet another individual.

The Minteer paper triggered an immediate response from the taxonomic community (Rocha et al., 2014), and the resulting debate was extensively reported in the media, supplying a valuable opportunity to expose the public and opinion formers to the underlying issues in a way that was not possible in the specific case of the kingfisher. But it does raise the question of whether, as we seek to engage a wider range of stakeholders in the work of the museum, we need to modify our long-held work practices to address the concerns of the public. We can no longer rely on distance, be it physical or intellectual, to protect us from criticism.

Another question is whether we should be putting resources into field collection. It is widely recognized in the museum community that thousands of new species are already sitting, undescribed, in museum collections (Bebber et al., 2010). Because of the steady erosion of curatorial support, the "shelf life" of these species (the time between collection and description) is getting longer, and continued field collection is only increasing the size of the backlog. Also increasing is the space required to store the collections and the energy costs of conserving them. Technology may offer a way to "mine" existing collections for new species (see below), but that will still require the significant investment of resources. It could be argued that a more sustainable and cost-effective approach would be to pump resources into the training of staff and building of collections in areas of high biodiversity while focusing the efforts of the first world museums on curation and care of their existing collections.

The challenge of preserving

The question of whether museums can continue to grow their collections hinges on sustainability. Given our responsibility of stewardship, is it ethical to continue collecting new material when we cannot properly care for the material we already have?

The preservation challenges facing natural history collections in the twenty-first century are, at least in part, a result of the collections community's significant improvement in the standards of collections care. Past practices, particularly during the middle of the twentieth century, when many collections were undergoing rapid growth, amounted to nothing more than benign neglect. Physical care and curation of collections were prioritized according to curatorial research interests, environmental controls were largely absent, and pest management involved the application of large quantities of toxic chemicals whose adverse effects were not limited to pest species.

In the last four decades, however, we have seen a revolution in our understanding of how to care for natural history materials. This change is rooted in conservation science and stresses a layered approach to the preservation of specimens, which starts with control of variables within the building environment, including light, temperature, and relative humidity; encompasses specialized sealed cabinetry that excludes gaseous and particulate pollutants; and, finally, applies archival standard materials to enclose and support specimens within the cabinets (Rose and Hawks, 1995). Specialized environments, such as low-oxygen enclosures, are used to deal with specific problem materials (Collins, 1995), while application of pesticides has largely been replaced by integrated pest management systems that emphasize preventive measures, mitigation strategies, and the use of barriers to separate pests from specimens (Strang et al., forthcoming).

Because of these changes, many natural history collections are in better shape now than in previous decades and more likely to survive into the future, which is not to say, however, that the problem of preservation has been solved. These new practices come at a cost that not all institutions can meet. Even when the direct costs are met, the improvements in preservation have rarely led to an expansion of staffing; as a result, preservation now competes with curation for staff resources. Institutions are required to balance improvements in the physical housing of specimens with basic collections activities such as identification of specimens, cataloging, and taxonomic description. This balancing act raises fundamental questions pertaining to the role of museums as it relates to collections. Is it our primary responsibility to preserve collections, or to study them, and to what extent do these two activities feed off one another?

Another effect of improved collection care has been dramatically increased energy costs. Per square foot, the Yale Peabody Museum's Class of 1954 Environmental Science Center, which houses the collections of six of the museum's divisions, is one of the most expensive of the university's buildings to run, and is less energy efficient than the original 1926 Peabody building (Bratasz et al., 2016). This is because of the energy cost of maintaining temperature and relative humidity in the relatively narrow range specified by community standards for collection environments. Yet it is debatable whether the high costs of running modern collection storage facilities are justified. The building envelope, combined with the well-sealed collection cabinetry, is capable of buffering most of the environmental fluctuations that could lead to collection damage, while the rapid cycling between high and low relative humidity (RH) necessary to keep the average within the limits set may actually prove more damaging to objects in the long term than a slow, seasonal progression from high RH to low and back again.

These issues are pressing enough when they are addressed by relatively affluent institutions like Yale, but they become urgent as we look to encourage and support the building and maintenance of collections in the emerging economies that are the home of much of the world's undescribed biodiversity. In these countries, tight environmental controls and elaborate engineering solutions are neither feasible nor sustainable. There is a real need for more research on achievable standards and the use of passive controls. These topics comprise the subject of ongoing research and discussion within the International Council of Museums collections community (ICOM-CC, 2014), but what is clear is that if museums are to take a leading role in tackling the environmental challenges facing the planet, they may need to start close to home (AAM, 2013).

When considering future challenges, it is also important for museums to embrace the reality of a changing climate. For many areas, this may involve new risks or changes in the frequency of risk. More frequent storms, a higher probability of wind damage, or flooding from rain or coastal storm surge needs to be factored into planning. This will require not only robust plans for business continuity, emergency response, and salvage in collections, but also the use of objective measures of risk assessment in planning new collection storage, or renovating of existing facilities. Given the limited resources available, a risk assessment will play a key role in ensuring that appropriate funds are directing toward mitigating potential risks to a collection in the light of a changing environment (AAM, 2015).

The challenge of access

Preservation of collections is only one part of the totality of museum operations; providing access to collections is another. It is a much-quoted, but nevertheless, core maxim of collection care that collections not used are useless collections.

The dramatic expansion of the World Wide Web over the last twenty years has fundamentally changed how the public accesses information and other material. To their credit, museums have been quick to recognize and respond to this change. Within the natural history collections community, this has resulted in the formulation of national and international strategies to digitize specimens and data from collections and to create tools and infrastructure to make these available to users (NIBA, 2010). The potential, in terms of both increased access and availability of novel forms of use, is enormous (Beaman and Cellinese, 2012).

However, this should not blind us to the enormous task that faces the natural history collections community in terms of converting our analog resources to digital ones. The funding made available from public bodies thus far falls well short of what will be required for mass mobilization of collections data. Novel approaches, such as the Notes from Nature project (Hill et al., 2012), which engages members of the public in a crowdsourced effort to transcribe field notes from museum collections, reveal the imagination and creativity needed to overcome some of the shortfalls in funding, but ultimately mass digitization will require fundamental realignments of museum resources to put digital assets and infrastructure, and the capture of data to populate this, on an equal footing with other core programmatic areas. At the level of collections, it will also require adjustment of workflows to incorporate digitization as a routine activity and changes in staff training and recruitment to support this effort (Wheeler et al., 2012).

Some museums have already embraced these changes; others have been slower to do so. Given finite resources, there are understandable concerns that museums might be tempted to follow the model of libraries, where the growth in digitized books and journals has enabled them to move physical volumes to cheaper, but much-less-accessible high-density storage. This is not a model that natural history collections can adopt: digital access to specimens complements physical access, but does not replace the ability to examine the specimen directly; not all information from the specimen can be captured or transmitted digitally.

Unfortunately, specimens do not have to be moved off-site to become inaccessible. The inevitable competition for resources between physical and digital curation may have the same effect, by diverting funds away from preservation and provision of physical access. There *are* ways in which increased digital accessibility could be leveraged to address shortfalls in other areas. For example, interactive online interfaces for specimen databases would enable specialists to curate collections remotely, providing identifications and flagging potential new species or other interesting material for examination or loan. But as with all the potential benefits of digitization, this will require institutions to invest in the underpinning infrastructure and technical support required.

One of the oft-cited benefits of digitization is the increased accessibility of collections. By making specimens and data available online, we are broadening the public's access to the collections that we hold in trust for them. But in doing so we negate our traditional role as gatekeepers for the collections, deciding who accesses them and how. Previously, these decisions could be justified based on the limited resources available to support physical access, but with digital assets, there is no good resource-based reason why, having made the assets available online, you would need to restrict their accessibility. This is certainly more in keeping with the increasingly connected, participatory world in which we live, but it raises some interesting dilemmas.

Some of these are already becoming apparent. The data and tools already exist to enable specimen localities to be mapped and displayed online, including those of rare and potentially valuable resources such as fossils or endangered plant species. Concerned about the prospect of illegal collecting, many in the museum community believe that locality data online should automatically be redacted, either to an arbitrary level such as the county where a specimen was found or by deliberate "fuzzing" of coordinate data. Anyone with a "legitimate" reason to access the complete data would be able to request these from the museum, thus returning the institution to its prior role as gatekeeper. This would also have the coincidental but desirable effect of preserving a potential revenue stream from companies carrying out environmental impact surveys for construction projects, which also need access to locality data. But it raises ethical issues about whether museums who have received public funds to make their data available online are then justified in restricting access to those data (Norris and Butts, 2014). Similar arguments could be made for restricting access to high-resolution specimen images or scan data (to control potential commercialization of public assets), or field notes and correspondence (because of privacy concerns).

Questions of access extend beyond digitization to challenge some of the fundamental assumptions that we make regarding our stewardship of collections. As collection professionals, we tend to assume that the collections exist for the purpose for which they were created: as research and education resources underpinning the missions of our institutions. As we look to broaden access to collections and to make the public more aware of their contents, we will inevitably be challenged to look at the material in new ways (Balachandran and McHugh, forthcoming). There are areas of natural history, notably anthropology and ethnology, where this has long been the case, and the involvement of the wider community, including in areas such as questions pertaining to access and ownership, in some cases carries the force of law (Fine-Dare, 2002). Museums now frequently accommodate access to, and interaction with, certain artifacts for purposes of worship.

But all specimens, regardless of discipline, are to some extent items of material culture. People may place different values on them than we do; in the case of collecting, as has already been discussed, they may question our long-established collecting practices, based on their view of the natural world. They may wish to use our data as evidence of past malpractice on the part of a museum, such as illegal collecting. They may want to download specimen images and data to support theories that we regard as scientifically untenable, such as creationism or intelligent design. If our aim is genuine and is to increase accessibility, how comfortable are we with accommodating usage with which we are unfamiliar, or with which we disagree?

Perhaps the ultimate expression of this is the question of whether we should be holding some of this material at all. If, as discussed earlier, we accept that our collections were obtained under circumstances and reflecting attitudes that we now reject, what responsibility do we have to make them accessible through loan or repatriation? How do we weigh the "global museum" model of increased accessibility against challenges to access for those in the country of origin? These issues have already challenged many museums, including Yale Peabody (Donadio, 2014), and it is almost inevitable that more cases will arise as the natural history collections community looks to support and build collections capacity worldwide.

The challenge of image

The developed world is already facing the economic and demographic reality of an aging population. Put simply, people are living longer and require more health care, and more expensive treatments, to maintain life in their final years. This presents public funders with a considerable challenge (International Monetary Fund, 2010). The cost of public health care and benefits continues to rise, putting increased pressure on discretionary funding, including funds for museum collections. If these funds are to be secured for the future, we need to do a better job of arguing for our indispensability. Surveys undertaken by organizations in the museum field have shown that natural history museums are both liked by the public and trusted as a source of information (Lake Snell Perry and Associates, 2001; Griffiths and King, 2008). Unfortunately, being liked is not the same as needed, just as interest by the public is not the same as being in the public interest. A variety of factors including declining public engagement with nature (Balmford et al., 2009), and a shifting focus in undergraduate and graduate education from organismal biology to more lab-based molecular and theoretical approaches (Gropp, 2003; Tewksbury et al., 2014) are eroding some of the traditional support for collections even though their fundamental importance endures.

Natural history collections are widely recognized as part of the national and international research infrastructure for science and humanities (Interagency Working Group on Scientific Collections [IWGSC], 2009; Johnson et al., 2011; Hanken, 2013). Recent advances in digitization and networking of collections, as described above, as well as network biocollections, lend weight to the argument that collections comprise a macroscale research facility (Baker, 2011; Johnson et al., 2011), analogous to other scientific infrastructures such as large telescopes, particle accelerators, or supercomputing clusters, which can be used to support research across a wide range of disciplines. Paradoxically, at least in the United States, most of the operating costs of these national systems are borne by private and public non-governmental entities, which in many cases struggle with affordability (Gropp, 2003; Menninger, 2007; Mares, 2009).

Advocates for collections-based research cite benefits across a wide range of areas of public interest, including human health, education, agriculture, land management, conservation, and national security (Suarez and Tsutsui, 2004; Winker, 2004; Wandler et al., 2007; IWGSC, 2009; Mares, 2009; Johnson et al., 2010; Cook et al., 2014). Evidence for these benefits is almost invariably provided in the form of exemplar projects, such as the frequently cited contribution of museum data to elucidating the source of the 1993 Sin Nombre virus outbreak (Yates et al., 2002). There is a critical need to develop quantitative metrics that complement and reinforce this evidence.

Beyond this, there is a pressing need to change the wider public perception of natural history collections from something that is nice to something that is essential. One of the strengths and weaknesses of natural history collections is the accessibility of the research they support. Many large research facilities are expensive to run, but in the absence of easily understandable research, they are obliged to work hard to improve their ability to explain long-term societal benefits. By contrast, when natural history museums speak to the public about collections, they tend to focus on novelty or quirkiness. This undoubtedly catches the public's attention, but does it do so in a helpful way? Arguably, we should have more gravitas.

As public funding declines, museums will be competing in a shrinking pool of discretionary funds with highly valued programs such as defense, public health, and education. The potential for museums to compete directly with these for funding is negligible. Instead, we need to show how the building, preserving, and using of natural history collections helps contribute to these programs. Museums need to develop value-based arguments for what they do, moving away from catchy anecdotes towards quantitative measurements of impact in science, education, and public health. We also need to talk less about the past and more about the future. As discussed earlier, the fact that we work with the past does not mean that we belong in the past. The pervasive use of the adjective "dusty" in press articles relating to even the most technologically advanced collections-based research is perhaps an inevitable consequence of our own obsession with history.

A vision of the future

The preceding and only partial list of challenges may have given the impression of a grim future for natural history collections in the twenty-first century and beyond. Quite the contrary. While the challenges are real, the opportunities for the museums holding these collections are considerable.

First, it is difficult to overemphasize how transformative the effect of large-scale digitization of collections could be. Natural history collections are, in principle, a massive, distributed facility that can support research in a multitude of fields. In the past, the scope of that research has been limited by the extent to which researchers could visit collections or obtain material on loan. As more and more data become available online, this will change profoundly. Researchers will be able to combine digitized collections data from large numbers of museums to produce massive, aggregated data sets that can be mined using big data techniques to reveal patterns in the natural world that might otherwise be missed (Mayer-Schönberger and Cukier, 2013). These could include modeling changing patterns in disease vectors or using digitized data on species distribution to target areas of high biodiversity for conservation activities. Such activities are already taking place; they will only become easier as more data become available.

The same technologies will increase the efficiency of our own curation efforts. Just as we can map biodiversity hot spots from museum data, we will be able to use these data to predict areas of high biodiversity and compare these models against museum records to help focus collecting activity. By developing interactive technologies to interface with digitized collections, we will have the potential to leverage specialist expertise to identify and curate material in our collections, even if the specialist and the collection are on opposite sides of the planet. By scanning specimens and making scan data available online, researchers will be able to download and print specimens for use without having to travel to the collections in person, a critical issue for museums in emerging economies where travel funds may be limited.

Digital networking will improve our ability to collaborate internationally. Rather than moving people and material between field sites in areas of high biodiversity and museums in the first world, we will be able to shift our focus to building capacity locally, using networking technologies to support training and to access the specimens and data collected. We will combine conservation science with work on building sustainability to develop energy-efficient systems and methods of passive climate control that not only make existing developed-world facilities more energy efficient, but that can be applied to preserving collections in emerging economies where funding for complex engineering solutions is not available. By finally recognizing that collecting without curation jeopardizes our mission of collections accessibility, we may be able to refocus resources on mining our existing collections for undescribed biodiversity.

These activities will be far more visible to the public, as the collections themselves become more accessible. The same networking technologies that support professional collaboration will allow a degree of public participation in crowdsourced projects that has not been seen before. With this exposure, there will undoubtedly be uncomfortable conversations: about our collection practices, past and present, the moral authority under which we hold and display certain categories of material, and the extent to which we share or withhold information. The conversations may be uncomfortable, but they should not be unwelcome either. Just as collections have come a long way from the days of Andrews and Osborn, we should expect them to continue to evolve for the remainder of this century and beyond.

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