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A taxonomic renaissance in three acts

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Abstract

Rapid species extinction means that a limited time exists in which to revitalize taxonomy and explore the diversity of species on earth. Three actions have the potential to ignite a taxonomic renaissance: (1) clarify what taxonomy is, emphasizing its theoretical advances and status as a rigorous, independent, fundamental science; (2) give taxonomists a mandate to organize and complete an inventory of earth species and the resources to modernize research and collections infrastructure; and (3) collaborate with information scientists, engineers, and entrepreneurs to inspire the creation of a sustainable future through biomimicry.

Introduction

Taxonomy is in crisis. Species as theory-rich constructs are being replaced by convenient estimates based on averaged genetic distances. Taxonomic principles are rarely found in biology textbooks or classrooms; taxon experts are not replaced in kind. And natural history museums, once world centers of taxonomic discovery, pursue more fashionable areas of biology in search of funding and recognition.

Taxonomy is misunderstood, maligned, and marginalized at a time when its particular kind of knowledge is needed most. Species are going extinct so rapidly that many believe we are on the brink of a sixth mass extinction event (Barnosky *et al.* 2011, Kolbert 2013). At the estimated current rate of extinction, 70% of species may be gone in just three hundred years. Pointing to the lack of hard data skeptics question this conclusion (e.g., Briggs 2017), but every available indicator points to accelerated extinction (Wilson 2015). Estimates are based on the loss of habitat, assessed on the ground and by satellite, and knowledge that many species have narrow distributions, as well as extrapolations made from the limited available data on species decline. While the exact rate of extinction varies by taxon and region and can be debated, that species are disappearing faster than at any time in human history cannot be denied. Nor can the value of creating baseline knowledge about what species exist and where.

Rather than simply returning support to taxonomy to complete an inventory, proposals are floated to find a cheaper, faster, technology-based alternative. Avoiding the deep scholarship required to interpret complex anatomical structures, it is suggested that we rely instead on molecular data. Were our goal to merely tell species apart, this could be a promising path. But considering the knowledge we stand to lose with the extinction of large numbers of species, isn't this aiming rather low? Molecular data appropriately joins comparative morphology, the fossil record, and studies of embryonic development to expand and enrich our insights into patterns of relationships among species (Nelson & Platnick 1981). But no single source of evidence can eclipse the others without sacrificing valuable knowledge.

Using all relevant evidence, and embracing the traditional goals of taxonomy, we can discover the most interesting and useful things about biodiversity. But a relatively complete inventory of species is a now-or-never proposition. Millions of species facing imminent threat of extinction will leave no fossil record and disappear along with all they could have taught us about their role in the biosphere, evolutionary history, and adaptations for survival. Let's face it, the reason that exploring species is exciting has nothing to do with their numbers. If natural selection had only produced millions of identical-looking species, differing only by percentages of genetic similarity, we would soon lose interest in naming or conserving them. Who would care whether one or ten million exist, so long as ecosystems did not collapse? But evolutionary history is far more interesting. Dawkins (1986) described life as statistical improbability on a colossal scale, and so it is. What makes the study of species fascinating is the seemingly inexhaustible diversity in anatomy and natural history. To dumb-down taxonomy to DNA barcodes and cladograms devoid of species' improbable attributes is to miss the most intellectually rewarding aspects of exploring life.

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Well-intentioned efforts to address the pragmatic need to identify species and rapidly produce estimates of phylogenetic relationships, combined with a strong bias toward the latest technologies, have resulted in molecular studies largely displacing so-called descriptive taxonomy. Molecular methods have secured an important and enduring place in the exploration of species, but must be integrated with other comparative studies in order that taxonomy achieve its mission. Imagine that the only evidence that dinosaurs ever existed was in the form of DNA sequences. We would recognize their reptilian roots, and that some are more nearly related to birds than others, but having almost no idea what they looked like they would merit little more than a footnote in the chronicles of evolution. It is the diversity, unexpected anatomical structures, and sheer size of their fossils, of course, that have captivated our imaginations. We owe it to future generations to pass on a good deal more than molecular evidence of the diversity of species soon to be lost.

The clock is ticking. Tens of thousands of species go extinct each year (Wilson 1992) taking with them irreplaceable evidence of their uniqueness and phylogenetic history. We have access to more, and more diverse, species than any generation will have in the future. The opportunity to explore the breadth and origins of biodiversity is fleeting. We owe it to ourselves and posterity to complete an inventory of species as they exist in the early Anthropocene, an inventory that includes detailed descriptions of each species backed up by specimens, observations, and tissues preserved in natural history collections. We cannot permit taxonomy to be limited to a single data source or reduced to a mere identification service. Monographs, the gold standard in taxonomy, have not yet been fully transformed by information science to dynamic, real-time knowledge bases they have the potential to become (Wheeler 2008). We can adapt available cyberinfrastructure to design a taxonomic research platform that adds efficiency without sacrificing the traditional goals or standards of taxonomy.

Astronomers before Copernicus believed the sun circled the earth, but this does not detract from respect for modern astronomy. There was a time in taxonomy when ideas about species and their relationships were largely speculative, but the theoretical revolution sparked by Hennig changed all that (Williams, Schmitt & Wheeler 2016). Taxonomic theories today stand toe to toe with the most rigorous science, and far above any other form of historical scholarship.

Astronomers were not content to limit knowledge of the unique properties of neighboring planets to what they could see with earth-based telescopes. Instead, they deployed satellites and rovers to image planetary surfaces in detail. Similarly, taxonomists should not accept a single data source as the extent of our knowledge of species. We can and must continue to collect and preserve museum specimens, make careful comparative observations, and compile detailed descriptions of species. But we cannot discover and describe millions of species with a declining workforce and antiquated research infrastructure. Taxonomists know exactly what ought to be done and how to do it. We need to meet the needs of taxonomists to do taxonomy.

A great deal has been written about the decline of taxonomy, loss of expertise, and the "taxonomic impediment"—our inability to identify species, particularly at species-rich sites in the tropics. From the Encyclopedia of Life to National Science Foundation grants to digitize museum specimens, dozens of well-intentioned initiatives and projects have had the stated aim of addressing the decline in taxonomy, but little has improved. The rate of species description has remained more or less constant for decades, between 15,000 and 20,000 species per year, even though large numbers of new species sit undescribed in herbaria and museums (Bebber *et al* 2010); few doctoral dissertations include a taxonomic monograph; and few taxa are revised more than a few times each century. In general, these failed projects shared one thing in common: they focused on the needs of users of taxonomic information rather than those of taxonomists themselves. If we are serious about addressing the biodiversity crisis, preserving evidence of phylogenetic history, adopting evidence-based conservation goals, and adapting to our rapidly changing world, then it is time to meet the needs of taxonomy. Even if your primary concern is the services taxonomy provides to other life scientists, you can do no better than meeting the needs of taxonomists themselves. The best taxonomy results in the most reliable information.

Supporting pure, curiosity-driven species exploration will result in countless discoveries and enable many other goals. A comprehensive species inventory would enable ecologists to drill down to species-species interactions in any ecosystem; support measurable conservation goals; reveal the fascinating story of phylogeny; and advance our search for more efficient, less wasteful designs, materials, and industrial processes.

Actions to Meet Taxonomy's Three Greatest Needs

So, what three actions could we take to spark a renaissance in taxonomy? I suggest that the following actions have the potential to lay the foundations for a reversal of the decades-long decline of taxonomy. One action addresses widespread misconceptions about what taxonomy is, and where the best taxonomic information and knowledge comes from. Another puts a fine point on the immediate opportunity to complete an inventory of species before extinction has decimated earth's biota. And the third makes a strong connection between taxonomic knowledge and society's urgent need to conceive sustainable ways to meet human needs and adapt to changing environments. These represent a return to the traditional goals of taxonomy, but with a twist. Taxonomists were ahead of their time when Linnaeus set out to inventory all species, when billions of specimens were assembled in internationally distributed museums, and when they sought to make classifications natural, reflecting phylogenetic relationships and explaining similarities and differences among species. But taxonomy's time has arrived. Advances in taxonomic theory, information science, digital technologies, travel, and communication mean that these planetary-scale ambitions are finally within reach. We should not judge taxonomy based on the limitations it faced in the past, but by the possibilities in its future. Benefits will flow from a renaissance in taxonomy in the form of advances in agriculture, medicine, natural resources, and new generations of truly sustainable designs, materials, and processes. And in pushing the boundaries of our understanding of ourselves and our world by revealing the origins of biodiversity, of which *Homo sapiens* is one among millions of species.

Act I—Image Makeover

Taxonomy has an image problem. Many biologists, poorly educated in taxonomic theory and the philosophy of science, see non-experimental approaches as suspect. Taxonomy is frequently derided as "stamp collecting" and "merely descriptive." The latter is an odd derision given the respect afforded mapping of the surface of Mars, the human genome project, and any number of other merely descriptive projects. That aside, the best taxonomy today is replete with explicitly testable hypotheses.

It is imperative that a prejudice against non-experimental, observational science be confronted. Sadly, taxonomists have been complicit in tarnishing its image. Since the 1940s, taxonomists have repeatedly invited a confusion of their goals with those of more modern and better funded fields (Wheeler 2008). Taxonomists must courageously clarify the goals of their science and unapologetically promote taxonomy done for its own sake. Its incomparable benefits to other sciences and society must be touted, too, but as byproducts of its core mission.

This confusion about the aims of taxonomy is nowhere more evident than in the distinction between studies of species and speciation. The former is the domain of taxonomy and concerned with *patterns* of similarities and differences among species. The latter is the business of population biology whose objects of interest are the *processes* of speciation. The two are complementary, but entirely different sciences. Taxonomists compare fully-formed species while population biologists study species-in-the-making. Taxonomists must distill attributes that are shared by all individuals in a species or all species in a taxon, autapomorphies and synapomorphies in the jargon of Hennig (1966). In contrast, population biologists study mutations and their frequencies within and among diverging populations. As Kierkegaard said of human events, history must be lived forward, but can only be understood by looking back. It is the same with species. Processes of species formation must be studied as they happen, but we can only interpret the history of species (phylogeny) by looking back. Each of these sciences demands its own epistemology, theories and methods.

It is challenging to share the intellectual breadth of taxonomy when the species identifications it provides are so vitally important. Taking nothing away from the importance of such pragmatic concerns, it may help to describe fundamental taxonomy in space age terms. Taxonomists are on a mission to discover, name, and classify every kind of living thing on, under, and above the surface of an entire planet. Were that not enough, their mission includes determining what makes each of millions of species unique and how they are related due to a common ancestry spanning billions of years. This mission is so audacious, it is comparable only to cosmology.

The parallels are striking. Cosmologists must first inventory the universe to discover what kinds of things exist, from stars and planets to black holes and dark matter. Then reconstruct the sequence of events that explains the universe as we see it, from the Big Bang to the present. What cosmologists dare attempt for the universe, taxonomists do for life on earth. We need to support and welcome wave after wave of discoveries by taxonomists in the same spirit in which we hail those of astronomers and cosmologists. One sobering difference between the two is that the universe will remain largely unchanged and available for study for thousands of years to come. The diversity of life on earth will be significantly diminished within a few centuries.

Recent anthropological discoveries have filled important gaps in our understanding of the emergence of modern humans, but anthropologists are only fleshing out the last of many chapters of our story. Unique human characteristics are not as unique as you may suppose. Our impressive brains, for example, are just somewhat larger and differently wired versions of those shared by other primates. And our bipedal gate is one of many modifications of the four-legged condition inherited by reptiles, mammals, and birds. To fully understand what makes us human is to explore the entire history of life, tracing our attributes to ancestors near and distant.

It is time to reassert the importance of taxonomy done for its own sake, coupled with an accounting of the incredible practical benefits that flow from taxonomic knowledge. In *Consilience*, E. O. Wilson pointed out that historians of science have learned that asking the right question is more important than finding the right answer. As he put it, ask a trivial question and get a trivial answer; ask the right question and be led to great discoveries. When it comes to biodiversity, the right questions are those being asked by taxonomists: What species exist? What makes them unique? How are they related? And so forth. Pursuing these questions will lead us to great and unexpected discoveries about our past and inspire us to make a better tomorrow. Taxonomy rarely gets the credit, but its work to date has already contributed to fantastic advances, from the rise of agriculture, to the discovery of antibiotics, and the idea of evolution (without the pattern of similarities and differences among species documented by taxonomists, Darwin's theory would have had nothing to explain, Nelson & Platnick 1981).

Act II—Planetary Species Inventory

Taxonomists need a mandate to organize and implement a NASA-scale mission to complete an inventory of earth species. With tens of thousands of species extinctions each year, there is no time to waste. The current generation of taxon experts has access to more, and more diverse, species than any that will follow. We alone have the opportunity to create baseline knowledge of what biodiversity is like at the opening of the Anthropocene. Enabling such a mission requires the modernization of taxonomy's collections and research infrastructure, and the education of a new generation of taxonomists.

Molecular data will play important parts in an inventory, but the lead role will rightly belong to comparative morphology and details of natural history. Molecular data can identify divergent populations for closer scrutiny, associate disparate life stages, contribute to cladistic analyses, and ease the burden of routine identifications. But let's face it, the reason that species exploration is so enticing is the promise of discovering the unexpected. The story of evolution is worth telling precisely because it includes millions of unforeseeable novelties. The existence of early flowering plants could not have predicted orchids, sundews or giant redwoods. People flock to zoos to see elephant trunks and giraffe necks, not to marvel over species separated by a few percentages of genetic similarity.

E. O. Wilson's *Half-Earth* proposal is a brilliant combination of science and common sense. By his estimates, setting aside fifty percent of the globe's surface area could result in saving as many as 80% of the world's species. But, which of a nearly infinite number of combinations of locations would best achieve this goal? Left to a random assembly of places, or limited to places that are easily set aside based on social and economic conditions, his plan is unlikely to yield the best possible outcome. The only way to assure a plan with high chances of success is to begin with knowledge of what species exist and where. Only taxonomy can produce the kind of inventory we need.

A few years ago, I organized a workshop that concluded it would be possible to inventory ten million species in fifty years or less (Wheeler *et al.* 2012a). This would be rapid enough to inform many decisions in the Half-Earth initiative and to preserve specimens and knowledge of millions of species as a hedge against ignorance. The cost would be significant in absolute dollars, but trivial compared to what we stand to lose.

Such an inventory must, of course, be an international effort with rolling decadal goals like those of the astronomy community. No other big science project has as many guaranteed returns on investment. A successful inventory presumes a number of key investments, including but not limited to the following:

- Educating a new generation of taxon experts;
- Enlisting an army of trained citizen scientists;
- Modernizing taxonomic research infrastructure, primarily in the form of a cyberinfrastructure platform, with digital instrumentation and specially designed software to support revisionary and monographic studies. This should include a comprehensive digital library of "e-types" (digital images of type specimens) and a network of remotely operable microscopes to connect taxon experts with specimens around the world (Wheeler *et al.* 2012b). And some simple changes, such as mandating the registration of all nomenclatural acts and making all species descriptions open access. At its core, this modernization should focus on bringing monography into the 21st century, making e-monographs sources of up to the minute information;
- Support for museums to rediscover their leadership role growing and developing collections and supporting their use in taxonomic research;
- A knowledge base that includes search strategies for species attributes with the potential to inspire sustainable, biomimetic solutions for humankind;
- Attention to making taxonomic knowledge as accessible, understandable, and useful as possible to all user communities;
- First and foremost, attention to what taxonomists need to do curiosity-driven taxonomy and produce accurate descriptions of species and phylogenetic classifications;
- A recognition that excellence in taxonomy requires that its hypotheses about characters, species, and phylogeny be repeatedly subjected to critical testing and improvement. An initial planetary-scale inventory is a one-time venture that must be followed by continuing programs of taxonomic research in order to deliver all its benefits to science and society.

Act III—Intersection of Taxonomy with Information Science, Engineering and Entrepreneurism

Taxonomists need to partner with information scientists, engineers, inventors, and entrepreneurs to add a valuable new dimension to their work. Our environment is changing more rapidly than we are adapting. If we are to conserve a significant portion of the natural world and maintain a high quality of human life, then we have no choice but to conceive a new generation of materials, designs, processes, and products that reduce exploitation of non-renewable resources, pollution and waste, and the degradation and conversion of wilderness. Given enough time, we could count on serendipity, as we always have, but time is the one thing we lack. The shortest and most certain path to a sustainable future is through biomimicry—drawing inspiration from observations of nature for new designs, materials, processes, and products (Benyus 1997).

The reason is simple. For billions of years, natural selection has successfully rewarded good "ideas" with survival, and weeded out bad ones. The story of species is one of fierce competition to adapt to life on a constantly changing planet. There are few, if any, problems faced by humans that have not been solved by nature, often many times over. While headlines regularly report exciting biomimetic inventions (see Benyus 1997 for examples), they are arrived at more often by luck than design. Someone must be in a position to connect the dots, to be aware of a model in nature and recognize its potential to address a problem. We can do better.

With taxonomy leading, we can open access to millions and millions of biomimetic models. Working with information scientists, we can invent search strategies to not only find a solution in nature, but to identify *the* best one. Phylogenetic classifications already point to closely related species as likely sources for similar, possibly better, versions of a desirable property found in one species. We need similarly efficient search strategies for instances of evolutionary convergence. When a solution evolves independently in unrelated species, it is likely to be particularly good one.

Taxonomists need to nurture a symbiotic relationship with the emerging field of biomimicry. Taxonomic descriptions, databases, classifications, and collections can help transform biomimicry from a cottage industry to an evidence-driven enterprise capable of reforming economies and industries. In return, biomimicry can help communicate the amazing attributes of species and what is possible with taxonomic knowledge.

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