A Navigation Guide to Cyberinfrastructure Tools for Botanical and Lichenological Systematics Research

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ABSTRACT

In this paper we describe a navigation guide to the frontiers of cyberinfrastructure for systematic research of plants and lichens. We define this term as it applies to systematics and provide links to resources that can assist the many stages of botanical and lichenological systematic research projects. This guide specifically addresses the concerns of new graduate students, although it should be useful to established researchers as well as interdisciplinary researchers who have an interest in systematics. Included in this paper are links and descriptions of 131 websites distributed in 15 categories. We encourage additions to the curated electronic form of this guide, http://www.botany.org/students_corner/systematics_resources.php, as a means of developing an up-to-date community-driven resource that will assist beginning and established systematic researchers worldwide.

Key words: cyberinfrastructure; internet resources; lichenological systematics; botanical systematics; student resources

The field of systematics has grown to incorporate a bewildering array of internet-based sources of data, from archived resources that were previously only available in physical form (e.g., rare floras, museum specimens, printed datasets) to newly generated molecular genetic and genomic datasets (Harrison and Kidner, 2011). Coincident with the increased availability of such open-access data has been the advent of cyberinfrastructure tools that not only speed systematic analysis of these data but also promote collaborative and interdisciplinary research. What is perhaps most striking about the development of these resources besides their ever-increasing scope and depth is their accessibility, which has "flattened" the field of systematics to some extent. Resources that were previously only available to students and researchers at large research institutions are now more freely accessible to all. An open question is how best to marshal these resources to enhance the study of biodiversity and raise support for systematic research, especially in light of the ongoing extinction crisis and dwindling institutional support for taxonomic expertise.

Cyberinfrastructure tools and their synergistic effects within the field of systematics have been generated within the US in part as a consequence of multimillion-dollar funding initiatives by the National Science Foundation's (NSF) Cyberinfrastructure Framework for 21st Century Science and Engineering (CIF21) and Software Infrastructure for Sustained Innovation (SI2). In 2003, the NSF charged a Blue Ribbon Panel with exploring challenges, opportunities, and trends in science cyberinfrastructure. This panel prepared a document that describes cyberinfrastructure priorities in science and engineering, but perhaps more importantly defines the term as "infrastructure based upon distributed computer, information, and communication technology... [and] we could say that cyberinfrastructure is required for a knowledge economy" (NSF, 2003). In much the same way that traditional infrastructure such as roads, bridges, and other structural developments allow for an improved flow of goods, people, and services, cyberinfrastructure lays the foundation for the transmission of information across the research community. Cyberinfrastructure can consist of online data storage, data exchanges, and distributed computing facilities that support remote analysis of data.

The opportunities and challenges of new research emerging from this scientific cyberinfrastructure have received considerable attention. For example,

a recent issue of Science titled, "Dealing with data," focused on these issues in depth (Science Staff, 2011). However, there is no navigation guide to the cyberinfrastructure tools for botanical and lichenological systematics researchers in this new era of "Big Data". This deficit is certainly a consequence of the constantly evolving landscape of internet resources, as any guide would be destined to be out of date by the time it was published and could never be fully comprehensive. Other Internet databases for botanical resources (e.g., the Internet Directory of Botany; http://www.botany.net/IDB/ and Botany online; http://www.biologie.uni-hamburg.de/b-online/e00/frame.htm) contain an overwhelming number of links, many of which are no longer active and do not distinguish resources by subdiscipline, such as systematics.

Beginning researchers often confront the online frontier alone and established researchers cannot be certain that they are fully utilizing all available resources. In our experience, locating relevant cyberinfrastructure tools or becoming aware of new ones relies on a substantial element of kismet, even after consulting internet search engines, bibliographic databases, and colleagues. Even the most savvy explorer may have difficulty determining whether some tools are more appropriate than others for a particular task or if they provide high-quality results. Moreover, we have encountered examples of functional redundancy among tools that may represent an unnecessary duplication of effort, which could have been avoided had there been even a partial guide to pre-existing resources.

If one of the goals of cyberinfrastructure is to expedite and improve scientific research, systematists must be able to navigate this wealth of resources more effectively. To date, we have found only one existing guide to web-based systematics tools. This resource is operated and maintained through the Entomological Society of America and its content is specific to entomological research (Shockley, 2009, available at http://www.entsoc.org/resources/Systematics_Resources). Other resources include an annual "Database Issue" published through the journal Nucleic Acids Research that provides a listing and brief description of new or updated molecular databases each year (see Galperin and Fernández-Suárez, 2011). Several other cyberinfrastructure guides have been published in peer-reviewed journals recently with the intent of assisting researchers in using data-sharing tools or other networked technologies; however, the scope of these publications is often narrow in focus (i.e., Huttenhower and Hofmann, 2010).

To address the need for a resource guide to cyberinfrastructure tools in plant and lichen systematics, we have compiled a list of web resources using several criteria. We recognize that there are numerous taxon-specific web resources, but due to the sheer volume of such resources we have opted to exclude taxon-specific tools from this guide. We selected online resources related to plants and lichens that are broad or introductory in scope. We have also included resources that cover general systematics research methods. Finally, we limited our selection of resources to those pertinent to US researchers, due to our familiarity with such resources, but also included some well-known international resources that may have broader appeal. We welcome the contribution of other resources we may have overlooked, especially if they fit the criteria of general utility to the systematics research community. These can be contributed to the online version of this paper hosted by the Botanical Society of America: http://www.botany.org/students_corner/systematics_resources.php. One particular strength of an online version of this guide is that it may be curated continuously as new resources become available and others become obsolete. The categories we have established for our internet resources follow a hypothetical workflow new graduate students might want to pursue as they explore and develop a research project in systematics.

We have developed a curated navigation guide for 15 categories of internet resources that will be relevant to beginning plant and lichenological researchers, although established researchers and systematists of other taxa should find the list useful. For each category, we have provided a list of links to individual resources with a brief description of their content and utility. These categories reflect the stages of being a new graduate student; therefore, we start with sections to help the student get the process started, such as consulting (1) **Checklists** and (2) **Visual and other Multimedia**. We follow these introductory resources with categories that can help students gather data already available online, such as (3) **General Plant and Lichen Biodiversity** and (4) **Nomenclatural Resources**. Other resources described below emphasize methods of generating new data in (5) **Collections and Collections Management**, (6) **Fieldwork**

and Permitting, and (7) **Laboratory Protocols**. We continue with suggestions on how and where to get training with (8) **Courses, Workshops, and Guides** and another important part of graduate student life, learning the process of applying for grants under (9) **Funding**. We carry on with suggestions of resources that will help students to analyze their data, such as (10) **Computing**, (11) **Molecular and Phylogenetic Databases**, and (12) **Geographic Information Systems (GIS) and Maps**. After that, we identify resources to assist students with networking and learning about their profession in (13) **Professional Societies**, and (14) **Social Networking.** Finally, we have discussed some relevant resources for obtaining a job in (15) **Employment and Career Development**. Each of these categories has been selected because it represents an important concern for beginning researchers, and we preface each category with an example of typical questions that may occur to new graduate students. Some categories are noticeably absent, such as a section on how to improve teaching skills and where to find teaching materials, as we feel such categories are beyond the scope of this effort.

As a static list of web-links, this guide's lasting value is admittedly ephemeral and as the product of several individual's efforts, it is neither comprehensive nor claims to be authoritative. Moreover, we urge a sense of critical skepticism in using data or services from any internet site as errors can and do occur in their creation. As always, it is good practice to verify the source of the information and, if errors are found, to contact the site administrator with corrections. It is our hope that the electronic form of this guide hosted by the Botanical Society of America, http://www.botany.org/students_corner/systematics_resources.php, will become the basis of a curated, community-driven resource for all botanical and lichenological systematists, as well as a means of welcoming new students into the era of Big Data.

"What taxa might be present at my study site?"

1. Checklists—These lists describe which species are present in a certain locality but can also reveal erroneous records of taxa or the significant absence of others. Checklists for a given region are not static, since species occurrences do change over time. Checklists can also be used to develop hypotheses about ecological interactions and biographical histories of taxa and to refine taxon distribution maps.

Catalogue of Life (CoL):

http://www.catalogueoflife.org/

Catalogue of Life is a partnership linked with several other important projects related to biodiversity (such as GBIF and EOL, described below) and aims to create an integrated checklist of all living organisms. There are 1.3 millions species included already, about 70% of known species. CoL can be used to look up a species' taxonomy and to compile regional checklists.

Checklists of Lichens and Lichenicolous Fungi:

http://www.biologie.uni-hamburg.de/checklists/lichens/portalpages/portalpage_checklists_switch.htm

This website hosts checklists of lichens worldwide. It also includes information about collectors, the general diversity of lichens, and assessments of known species in several countries. The resource is maintained by contributing lichenologists from around the world.

eFloras:

http://efloras.org

eFloras provides a searchable database of regional floras, including checklists, interactive keys, image galleries, and herbarium records. eFloras can be a powerful tool for learning about particular taxa in a given study site or geographic region.

Kew World Checklists of Selected Plant Families (WCSP):

http://apps.kew.org/wcsp/home.do

WCSP contains updated checklists of 173 plant families in different stages of completion. Users can also develop their own checklists using a tool on the site. By selecting the family and genus under study as well as the continent and region of interest, the user may generate a summary or detailed checklist.

Lichenicolous fungi —worldwide checklist:

http://www.lichenicolous.net

A curated checklist of lichenicolous fungi, which are fungi that live exclusively on lichens as host-specific parasites, broad-spectrum pathogens, saprotrophs, or commensals (Lawrey and Diedrich, 2011). It is useful to lichen systematists, since lichen-fungus interactions are diagnostic for certain lichen lineages.

North American Lichen Checklist:

http://www.ndsu.edu/pubweb/~esslinge/chcklst/chcklst7.htm

A curated checklist for the lichen-forming, lichenicolous and allied fungi of continental United States and Canada with 5,355 species currently included (Esslinger, 2012). It is a cumulative project since the original version was first posted online in 1997 with 3,580 species, and it has been updated yearly by Dr. Theodore L. Esslinger at North Dakota State University.

"Where can I find high quality images of my taxa? Are there interactive learning tools available online to help reinforce difficult concepts and classroom material?"

2. Visual and Other Multimedia— Visual and multimedia resources are critical to systematics research by providing rich, descriptive information for the taxa of interest as well as their habitat. Visual and other multimedia resources include databases and interactive galleries with collections of images.

Arkive - Images of Life on Earth:

http://www.arkive.org/

Arkive is a project to centralize a digital image library from organisms across different domains of life, but with an emphasis on creating an image library of endangered species before they become extinct. It has high-quality videos and photographs of algae, plants, fungi (including lichens), and animals in nature and/or as voucher specimens.

Flickr:

http://www.flickr.com/

Flickr is a website (from Yahoo) used to share and manage pictures. It provides a search tool that improves its basic features. Flickr may not always provide scientifically accurate identification for images; however, Flickr does support image sets that are managed through other web resources listed in this guide, such as the Biodiversity Heritage Library and the Encyclopedia of Life. The Flickr format allows commenting on images, which may help researchers to identify unknown specimens.

Inside Wood:

http://insidewood.lib.ncsu.edu/welcome

Inside wood is a project to promote knowledge in wood anatomy. This site is useful for both research and teaching applications, with a search tool and large image database. The website provides an interactive key with over 200 features of wood anatomy that can help one to identify the material under examination.

Karlostachys Plant image gallery:

http://gardenbreizh.org/photos/karlostachys/album-9314.html

This photo album contains more than 50,000 plant images, organized by family and lower taxonomic ranks. Photos have been collected from around the web; users should take care to properly credit the original photographer and verify determinations.

Lichens Home Page—Sharnoff Photos:

http://www.sharnoffphotos.com/lichens/lichens_home_index.html

This website offers a photo collection to help users identify more than 1,200 lichens of North America. The website is linked to the most up-to-date North American Lichen Checklist and it was developed by two lichen photographers and several lichenologists. The photographs were taken in the development of the book Lichens of North America (Brodo, Sharnoff, and Sharnoff, 2001).

Morphbank:

http://www.morphbank.net/

Morphbank is a free database containing hundreds of thousands of specimen-based biological images. It allows researchers to deposit taxon images in private or private workspaces and to query other images deposited in the database.

Mushroom Observer:

http://mushroomobserver.org/

Mushroom Observer is a portal dedicated to fungi pictures. It helps people to identify different types of fungi, including lichens, in addition to offering networking opportunities. Users can upload pictures and the community may help identify species based on images. This helps establish a dialog among amateurs and professionals. It also has a search tool to easily find a specific taxon.

Paldat:

http://www.Paldat.org

Paldat is a palynological database of images and other pollen data for plant research. Paldat is maintained by the Society for the Promotion of Palynological Research in Austria.

Pictures of tropical lichens:

http://www.tropicallichens.net/

The largest collection of pictures of tropical lichens online, including a searchable list of thousands of species with photo credits and locality data. Photos are organized by genus and species. It is maintained by several lichenologists around the world and is linked to Index Fungorum and GBIF (both databases are listed below).

Smithsonian Institution Plant Image Collection:

http://botany.si.edu/PlantImages/

A searchable collection of more than 49,000 plant images, including species and their habitats. All images are freely available for non-commercial use, if properly credited.

Texas A&M University Vascular Plant Image Library:

http://repository.tamu.edu/handle/1969.1/97046

A gallery of vascular plant images organized by taxa. The gallery is organized alphabetically, first by family and then by genus.

Ways of Enlichenment:

http://www.waysofenlichenment.net/lichens/gallery.html

This site provides a regularly updated database of lichen images, which is searchable by several criteria.

"Where can I find relevant information about the taxa I am working on?"

3. General Plant and Lichen Biodiversity—In this section, we aim to help people identify information about taxa of interest. Most of these resources include websites that contain digital books, voucher specimens belonging to important collections, links to other sites, and repositories of images, but they may also include phylogenies and identification keys.

3a. Biodiversity reference—Angiosperm Phylogeny

Website: http://www.mobot.org/MOBOT/Research/APweb/welcome.html

A searchable website and tool for up-to-date information on angiosperm phylogenetics, hosted through the Missouri Botanical Garden. This site is organized according to ordinal classification and taxa are searchable on a scrolling left-hand panel. The angiosperm phylogeny website also includes

distribution maps, a regularly updated bibliography, and glossary in addition to the detailed information on taxa.

Biodiversity Heritage Library:

http://www.biodiversitylibrary.org

BHL is a consortium of natural history libraries with the goal of providing thousands of historical biological documents online. A digitized bibliography helps users find old and new literature, which may be otherwise hard to find. One can browse by author, year, subject, titles, and languages, among other search criteria (e.g., search by species name).

Cyberliber: an Electronic Library for Mycology:

http://www.cybertruffle.org.uk/cyberliber/index.htm

Cyberliber is a digital library dedicated primarily to fungi (including lichen literature). There are several books, journals, and catalogues available online as well as a search tool to find literature about the study taxa.

Encyclopedia of Life (EoL):

http://eol.org

The Encyclopedia of Life is a publicly accessible database of natural history information that was initiated in 2007 with the goal of developing "a webpage for every species". With several collaborating institutions, EoL actively pursues this goal with a priority list for certain taxa. The Encyclopedia of Life continues to be updated and is a growing resource for researchers, as well as those with a passing interest in biodiversity. The EoL contains nomenclatural, phylogenetic, and visual and multimedia content for taxa. Much of the content is collected from other web-based biodiversity resources, such as GBIF, LifeDesks, Tropicos, etc.

General MOBOT Resources:

http://www.mobot.org/mobot/research/alldb.shtml

Missouri Botanical Garden's website lists numerous general botanical resources. It hosts several links to regional floras (linked to tropicos.org), and additional databases with valuable information about plants.

Global Biodiversity Information Facility (GBIF):

http://www.gbif.org

GBIF is a freely accessible resource for biodiversity information, including taxa, distribution, and digitization services. Much of the data available on GBIF is shared with and retrieved from other web-based biodiversity resources, including the databases of natural history collections. GBIF currently includes over 400 million records and continues to grow. GBIF communicates with many other biodiversity-related web resources, making it one of the largest biodiversity data tools available online.

Global Plants Initiative (GPI):

http://gpi.myspecies.info/

The Global Plants Initiative (GPI) is an international collaboration with the goal of digitizing and making available plant type specimens, as well as other resources to be used in education. The output of GPI is presented through JSTOR Plant Science.

Google Books

http://books.google.com/

Google books is another service for searching freely available online literature.

JSTOR Plant Science:

http://plants.jstor.org

This site is a digital archive and repository of plant science resources, specializing in historical collections. It contains numerous images and type collections, as well as digitized floras. Priorities of this initiative currently include digitizing type specimens; 2.2 million specimens are expected

to be digitized by 2013. Other resources, such as regional floras, are also available.

Kew Science and Research Resources:

http://www.kew.org/science-research-data/index.htm

The website of the Royal Botanical Gardens, Kew describes their extensive research programs and distributes photographs, videos, collections data, and more.

Lucid Key Database:

http://www.lucidcentral.com/en-us/keys173;/searchforakey.aspx

This online tool allows users to search for interactive keys based on several criteria, including taxon, geographic range, and ecological features.

Missouri Botanical Garden Research Links:

http://www.mobot.org/MOBOT/Research/links.shtml

The pages associated with this site contain many hyperlinks to resources relevant to systematics researchers, under categories such as phylogeny, botany, societies and organizations, and tropical biology.

Recent Literature on Lichens:

http://nhm2.uio.no/botanisk/lav/RLL/RLL.HTM

This website is updated often; therefore, it is a valuable tool for finding current publications pertaining to lichens.

Tree of Life:

http://tolweb.org/tree/

The Tree of Life Web Project (ToL) is a collaborative effort of researchers to provide information about the biodiversity. Contributors must apply for authorship on taxon pages and supply a description of the morphology and evolutionary history (phylogeny) for each taxon.

Tropicos:

http://www.tropicos.org

Tropicos is a database and information network maintained by the Missouri Botanical Garden. Tropicos contains specimen, nomenclature, distribution, and other reference data for plant specimens from around the world, specimen data are mostly gathered from their holdings.

3b. Biodiversity tools—

Discover Life:

http://www.discoverlife.org

Discover Life is an initiative for educators and researchers that provides interactive tools for learning about biodiversity. Classroom activities and more complex student research projects are presented on the site. It includes online tools for developing labels, field guides, and maps as well as storage for images of taxa and locality information. Locality data for accessions can be uploaded and linked to a particular accession to generate maps and labels quickly.

Internet Directory for Botany (IDB):

http://www.botany.net/IDB/botany.html

The IDB is an extensive catalog of botany-related websites, organized alphabetically. Numerous gardens, guides, checklists, organizations, and other databases and references are included; the list is searchable.

iPlant Collaborative:

http://www.iplantcollaborative.org/

The iPlant Collaborative has developed a suite of cyberinfrastructure tools for plant biologists. The site promotes collaboration, learning, and research in plant science. Educational and research resources developed by the iPlant team cover evolutionary development, genomics, and phylogenetics. Researchers can use information resources such as cloud computing and storage on the iPlant Atmosphere service. iPlant also offers community-networking tools.

Symbiota:

http://symbiota.org

Symbiota provides software tools for sharing biodiversity data. Symbiota packages facilitate the development of electronic floras and faunas, keys, and other resources for improved collaboration on biodiversity research projects.

"How do I correctly use taxon names and know which one is valid?"

4. Nomenclatural Resources—Nomenclature is the practice of establishing the correct name for a taxon and is a key component of systematic research. Knowing a little bit of Latin can help, but understanding the International Code of Nomenclature (ICN) and using the correct taxonomic reference databases is essential. It is important to note here that taxonomy and its attendant nomenclature do change over time, for reasons that may be subjective (e.g., opinion of the researcher) or objective (e.g., changes in ICN rules). Consequently many databases do not reflect the current consensus regarding the accepted name of a given taxon but may list bibliographic information about possible synonyms. Moreover, nomenclatural databases may have errors in them. You should always verify names with reference to the most recent taxonomic literature in addition to scrutinizing the original publication documents. As always, it is good practice to contact the online nomenclatural database administrators with corrections if errors are found.

AlgaeBase:

http://www.algaebase.org

This database includes nomenclatural resources in algae, including taxa that are part of the lichen symbiosis.

Global Names Initiative (GNI):

http://www.globalnames.org

This website helps you to find information about biological groups across all domains of life through a search system that leads the user to other web resources. Under the find names service, the system detects scientific names in documents, URLs, or any type of free text. This service is very useful for finding names in encrypted or image-based PDFs.

Index Fungorum and Species Fungorum:

http://www.indexfungorum.org/

http://www.speciesfungorum.org/

Index Fungorum and Species Fungorum are nomenclatural databases for fungi (including lichens) with over 380,000 names.

Integrated Taxonomic Information System (ITIS):

http://www.itis.gov/index.html

ITIS is a federally funded taxonomic data clearinghouse for organisms, predominantly those found in North America, and aims to provide up-to-date authoritative information. Data are collated from US, Canadian, and Mexican partner agencies and are provided to larger global clearinghouses, such as GBIF. It also provides the user with a list of experts for given taxa and links to where one can find information about individual species.

International Code of Nomenclature for algae, fungi, and plants online (ICN):

http://www.iapt-taxon.org/nomen/main.php

The ICN establishes rules for nomenclature and is the most authoritative resource for understanding the nomenclatural system for plants and lichens.

International Plant Names Index (IPNI):

http://www.ipni.org

The International Plant Names Index (IPNI) is a searchable database containing information on plant nomenclature, authorities, and author publications. IPNI is an excellent resource for looking up plant names and authors. Nomenclatural data come from the *Index Kewensis* database, supported by the Kew Botanical Gardens.

MycoBank:

http://www.mycobank.org/

MycoBank is a database created with the purpose of serving the scientific community through documentation of new mycological nomenclature (names and combinations, including lichen) and other data, such as descriptions and illustrations.

PhyloCode:

http://www.ohio.edu/phylocode/

The PhyloCode is a formal set of rules governing phylogenetic nomenclature. It is designed to name the parts of the tree of life by explicit reference to phylogeny. The draft is available online and is open for suggestions and comments.

The Plant List:

http://www.theplantlist.org/

This site contains a working list of all known plant species. It provides an accepted name for most species along with links to all synonyms.

Plantminer:

http://www.plantminer.com/

This web-based application searches for names and synonyms of plant species. Users can submit a taxonomic query and a list will be returned via email from the Tropicos and Plant List databases.

Universal Biological Indexer and Organizer (Ubio):

http://www.ubio.org

Ubio is designed to integrate biological name data *and* classification data. The Name Server tool is described as a biological "name thesaurus". It also contains introductory information on classification and species concepts.

"Where can I find scientific vouchers for study? How do I handle specimens appropriately?"

5. Collections and Collections Management— Herbaria are located all over the world and are rich sources of material for plant and lichenological systematics research. Contacting these institutions and examining loans of specimens is a component of many systematics research projects. These specimens, all of which are irreplaceable and unique samples of the natural world, require archival storage conditions and careful handling procedures, and all beginning researchers should be aware of these practices. The following are links to a searchable index of international herbaria, as well as links to organizations that serve herbarium curators and provide best practices for collections-based research, including preparation of specimens for both physical and digital preservation.

Registry of Biological Repositories:

http://www.biorepositories.org/

Biorepositories is a database of natural history collections accession information. Biorepositories works with numerous institutions and will also be linking with other large collections databases in the near future, including Index Herbariorum (below).

Consortium of North American Bryophyte Herbaria (CNABH):

http://bryophyteportal.org/portal/index.php

CNABH is a distributed network dedicated to integrating herbaria that carry bryophytes. It offers tools to locate voucher specimens as well as their images, plus checklists curated by experts in the subject.

Consortium of North American Lichen Herbaria (CNALH):

http://lichenportal.org/portal/index.php

CNALH is similarly to CNABH but integrates lichen research tools. Both were initially created by the American Bryological and Lichenological Society, but currently are maintained by separate entities.

Index Herbariorum (IH):

http://sciweb.nybg.org/science2/IndexHerbariorum.asp

Index Herbariorum is a searchable database of all herbaria in the world. IH merged with biorepositories.org in 2012 and can also be accessed through their website.

Integrated Digitized Biocollections (iDigBio):

https://www.idigbio.org/

iDigBio is an online resource for promoting the digitization of biological collections. This site facilitates digitization and makes digitized specimens available to the public.

International Society for Biocuration (ISB):

http://www.biocurator.org

Like SPNHC (below), ISB is a leading international organization for biocuration and provides support of and advocacy for biocuration.

Kew Herbarium Catalogue:

http://apps.kew.org/herbcat/navigator.do

Similar to Index Herbariorum (above), the KHC provides a searchable listing of international herbaria.

Society for the Preservation of Natural History Collections (SPNHC):

http://www.spnhc.org/

SPNHC is an international organization that promotes the curation, preservation, and innovation of natural history collections and provides resources for researchers interested in such collections.

"I need to collect specimens, how do I do this legally?"

6. Fieldwork and Permitting—As a graduate student, you might need to collect your own material, which means you may need a permit to do so legally. We acknowledge that different parks, states, and countries have different permitting processes; therefore, we encourage the user of this guide to look for specific laws that apply to the relevant jurisdiction. We have some suggestions to help start the process. Outside the US, the best recommendation is to contact a colleague at a local accredited institution rather than trying to start the permit process on your own.

Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES):

http://www.cites.org/

CITES is an international organization that governs the import and export of endangered species across international borders. CITES also helps facilitate communication of researchers who may be importing or exporting listed species which require a CITES permit. National agencies charged with permitting can be found at http://www.cites.org/cms/index.php/lang-en/component/cp/.

Lichen collection and identification at the Farlow Herbarium, Harvard University:

http://www.huh.harvard.edu/collections/lichens/index.html

This website hosts guides to several subjects in general and North American lichenology. It provides a vast list of literature about different topics when working with lichens in the US, but also gives tips on important characters of different morphotypes in lichens. Under the "How to collect lichens?" link, the site offers detailed advice on how to collect lichens appropriately based on text developed by Philip F. May. The information available in the website contributes good quality material and analysis in depth.

Missouri Botanical Garden Field Techniques:

http://www.mobot.org/MOBOT/molib/fieldtechbook/welcome.shtml

This website describes standard techniques used by MOBOT botanists in the field. Techniques are categorized and can be browsed with detailed descriptions for each.

United States Fish and Wildlife Service (FWS):

http://www.fws.gov/ and http://www.fws.gov/permits/

The USFWS provides permits for research activities in localities under USFWS jurisdiction. If you are uncertain whether your research requires permits, visit the link above or contact a FWS representative.

United States National Park Service (NPS):

https://science.nature.nps.gov/research/ac/ResearchIndex

The USNPS grants permits for collecting wildlife materials from locations within the US National Park system.

"Where can I find information about protocols for a new or unfamiliar laboratory technique? Are there tools available online to help me troubleshoot my methods and protocols?"

7. Laboratory Protocols—Developing new lab protocols or troubleshooting existing protocols can often take more time than first expected. Searching for the right reference can be difficult; however, there are some helpful resources available to resolve your problems. Two texts highly recommended for laboratory basics and troubleshooting are Barker (2005) and Hillis, Moritz, and Mable (1996).

Lab Protocol:

http://www.labprotocol.com/index.php

Lab Protocol provides information for researchers to look up protocols available from different institutions and to store their own methodologies for easy access. This resource has protocols in several areas of biology.

Promega, Inc.:

http://www.promega.com/resources/

Promega is a well-known distributor of molecular laboratory products and services. Although most support offered online through Promega is specific to products they offer, they also offer many protocols, tools, and other resources free of charge.

Protocol Online—Your lab's reference book:

http://www.protocol-online.org/

Protocol online offers a variety of protocols related to biology in several subcategories. It also provides creative ideas for activities for teaching biology.

"I need intensive or specialized training not available at my university" "Where can I find lectures and other learning material online?"

8. Courses, Workshops, and Guides—Courses and workshops are an important part of graduate student training, but sometimes your university doesn't offer everything you need. In this section, we include a list of courses in systematics-related fields that are offered annually by institutions with open registration to graduate students and professionals. We also present a short list of guides for different programming and scripting languages. Each guide is written with a specific emphasis on biological applications or programming languages that are often used by those in biological disciplines.

8a. Computing languages for research—

Codecademy:

http://www.codecademy.com/

Codecademy is a free training service available to anyone that offers computer code teaching exercises for basic and advanced programming applications. Guided teaching modules allow users to familiarize themselves with basic scripting tools for writing their own applications and developing websites.

iTunes Podcasts on iTunes U:

http://www.apple.com/education/itunes-u/

iTunes U provides lecture and classroom content for download. Material available through iTunes U is available through any device that can run iTunes software. Lectures can be recorded, uploaded, and stored on iTunes and made available to students or the general public. Photos and other multimedia documents can be stored along with individualized notes that can be synchronized with the lecture. This is a free resource, and several universities and colleges are already making lectures publicly available through this venue.

Udacity:

http://www.udacity.com/

Udacity provides free teaching modules for the public in basic and advanced computer programming applications. Udacity's teaching modules are guided and application-based. All lessons can be completed within the web browser of choice.

8b. In-person resources—

Bodega Phylogenetics:

http://bodegaphylo.wikispot.org/

Bodega Phylogenetics hosts an annual Applied Phylogenetics Workshop each summer at the Bodega Marine Lab in Northern California. The Bodega Phylogenetics team also maintains and actively updates their Wiki page, where visitors can download tutorials and participate in discussions.

Evolution and Genomics (Evomics):

http://evomics.org/

Evomics offers workshops and training in molecular evolutionary biology and genomics. Tutorials and other resources are available through their website and several workshops are hosted internationally throughout the year.

Molecular Evolution:

http://www.molecularevolution.org/

This organization offers US and European workshops and as well as online training modules for topics in molecular evolution, comparative genomics and phylogenetics.

National Evolutionary Synthesis Center (NESCent):

https://academy.nescent.org/wiki/Main_Page

NESCent is a non-profit organization that supports interdisciplinary research in evolutionary biology. The organization sponsors annual training courses and small group workshops and offers fellowships for students.

Organization for Tropical Studies (OTS):

http://www.ots.ac.cr/

OTS is a non-profit organization created in a partnership between universities from the US, Australia, and Latin American countries to promote training in tropical field biology. It offers field courses in Costa Rica year-round to undergraduate and graduate students on topics ranging from tropical plant systematics to conservation biology.

Eagle Hill Institute and Foundation:

http://www.eaglehill.us/programs/nhs/nhs-calendar.shtml

This institute and foundation is a nonprofit organization dedicated to education, especially in the natural history sciences. It offers field courses on lichens and plants, among other organisms, every year between May and September on its campus in Maine, the site of the former Humboldt Field Research Institute.

"How will I fund my research?"

9. Funding—Securing funds for research is a requirement for anyone who wishes to pursue research professionally, and graduate school is an excellent place to begin grant writing. Often, professional societies (see later category) offer small research and travel grants to graduate students specifically. Private businesses as well as non-profit organizations such as philanthropic foundations as well as local and federal government agencies sponsor larger awards, which may include grants for research or more inclusive research fellowships. Below are links to groups besides professional societies that provide funding opportunities for graduate research in the sciences.

American Philosophical Society (APS):

http://www.amphilsoc.org/grants

APS has provided grants in support of basic research since 1933. There are several grant and fellowships opportunities available to students and early career scientists.

Fulbright:

http://us.fulbrightonline.org/

The Fulbright student program has been active since 1946 and provides competitive research awards to students internationally, although this link is for students who are US citizens. Research awards include funding for residency in the country of study.

Garden Club of America (GCA):

http://www2.gcamerica.org/outreach-scholarships.cfm

The GCA offers grant-based awards for several categories of plant-related research.

National Geographic:

http://www.nationalgeographic.com/explorers/grants-programs/

National Geographic has annual openings for grants in many subjects relevant to systematists, including a program for scientists under the age of 25. Their site has a search tool under the section "grants A-Z," which can help narrow down the options.

National Science Foundation (NSF):

http://www.nsf.gov/funding/

Opportunities for students include graduate research fellowships and doctoral dissertation improvement grants (DDIG). NSF also provides links to other funding sources for scientific research in broad categories.

"Is there a software program that can do X, Y, or Z with my data already? Or do I have to write it myself?"
"I have a lot of intensive computational analyses to do, but not enough machines or time..."

10. Computing—Computing resources for systematics research have been categorized here as cloud computing resources and software resources. Cloud computing may occur on one or many remote processors; it is also termed *distributed computing*. We suggest that users new to cloud computing always prepare a short input file as a test to make sure that data can be uploaded to, analyzed by, and retrieved from the cloud-based software service successfully. Conducting similar tests using local installations of the distributed software can also help new users use cloud resources most effectively. We also recommend that users explore a scripting language to familiarize themselves with common notation and file formats. A thorough introduction to computing for phylogenetic biologists is described in Haddock and Dunn (2011).

10a. Cloud computing—Cloud computing allows users to both store data and conduct computational tasks remotely. Remote storage and computing can be valuable for backing up data and also accomplishing tasks that often exceed the processing power or time available to researchers at their home institution. Many cloud resources are available for modest fees or are free.

Amazon Web Services:

http://www.aws.amazon.com

AWS offers for-cost storage and distributed computing services for a variety of tasks. Many users have developed computing pipelines for analyzing genomic datasets through AWS.

Cyber Infrastructure for Phylogenetic Research (CIPRes):

http://www.phylo.org/index.php/portal/

CIPRes Science Gateway is a user-friendly portal for performing computationally intensive phylogenetic analyses. It is a free service, but the user needs to create an account. An individual account is allowed to consume up to 30,000 CPU hours of computing time, or 50,000 for users affiliated with US institutions. Once a data file has been uploaded, that file can be analyzed using any of the tools available on CIPRes. CIPRes also provides detailed instructions for file formatting and file testing.

University of Oslo Bioportal:

http://www.bioportal.uio.no/

The Bioportal is another free and user-friendly portal for conducting phylogenetic analyses but

supports a wider range of software programs, including those specifically for population genetics analyses. It hosts more than 40 programs and allows users to download these programs to their local computers as well.

10b. Software and Tools—There are numerous phylogenetic software programs available for download, some of which are free and open-source and others that are proprietary and/or must be purchased. An important point to remember is that not all programs are subject to rigorous beta testing and that their performance cannot be guaranteed. Popular programs typically have community-based message boards, such as wikis, that may list important bugs or other limitations not otherwise described in the user-manual. Many of the programs do not have a GUI component and must be run from the command line, thus one of the first steps to using them is to become familiar with this type of operating environment. We also suggest using a stand-alone text-editing program, such as TextWrangler, in which to create and modify command files. Hall (2011) and Lemey, Salemi, and Vandamme (2009) also present guidance on creating phylogenetic trees through some practical software exercises and explain the theory behind the methods used.

Alignment Transformation EnviRonment (ALTER):

http://sing.ei.uvigo.es/ALTER/

ALTER is a tool that interconverts file formats. Different software programs often use separate file formats (e.g., .nex vs. .phy), and you will inevitably need to perform file conversions between them.

BioPerl:

http://www.bioperl.org/wiki/Main_Page

The wiki available through BioPerl offers resources for training biologists in the use of Perl scripts for data analysis. Script templates for common tasks are available for download and the community at BioPerl is able to answer questions for users who encounter problems with datasets or Perl scripts.

Biopython Tutorial and Cookbook:

http://biopython.org/DIST/docs/tutorial/Tutorial.html

This online tutorial of Python is relevant for computation of biological datasets. A library of Python scripts for phylogenetic analyses (DendroPy) is available through http://packages.python.org/DendroPy/.

BLAST: Basic Local Alignment Search Tool (BLAST):

http://blast.ncbi.nlm.nih.gov/Blast.cgi

BLAST finds regions of similarity between DNA or protein sequences. It compares user-uploaded sequences and/or sequences already in the NCBI database (see above) and provides information about the potential identity of query sequence data based on matches in the system.

The Felsenstein Phylogeny Program Pages at the University of Washington:

http://evolution.genetics.washington.edu/phylip/software.html

This is a curated and frequently updated descriptive list of software programs for systematics research, with an emphasis on phylogenetic and population genetic analysis software packages. The user can search for software by name, method, computer system, etc.

R:

http://www.r-project.org/

R is a computing language with broad applications for statistical research. We recommend the APE package in R, which supports comparative phylogenetic functions.

Text Wrangler:

http://www.barebones.com/products/TextWrangler/

Text Wrangler is a dedicated text editing program appropriate for manipulating datasets and command files. It offers greater editing capabilities than standard word-processing programs (e.g., MS Word). For example, it has more "search and replace" options and interconverts UNIX, PC, and Macintosh line-break formats. It is free, but only available for Macintosh OS. We recommend

Notepad++ (http://notepad-plus-plus.org/) as an alternative to Text Wrangler on the P.C.

TreeTapper:

http://www.treetapper.org

This site is similar to the Felsenstein Phylogeny Program site (above) in that it is curated by a single individual. However, it includes a more detailed search engine and discussion of analytical problems that may not yet be addressed by available programs.

Wikipedia: List of phylogenetics software

http://en.wikipedia.org/wiki/List_of_phylogenetics_software

This list is frequently updated by the broader phylogenetics community. For each program entry, there is a short description, a citation, and link to the web address for each program.

"Has someone else collected a dataset I could incorporate into my own research? Where can I archive and store my data, besides my lab notebooks, my hard drives, and my publications?"

11. Molecular and Phylogenetic Databases— Many open access databases exist for storing and sharing biological data, and archiving one's data in these locations is often a prerequisite for publication. In all cases listed here, accessing and downloading data are free.

Barcode of Life Database (BOLD):

http://www.barcodinglife.org

BOLD is a resource meant to promote and support the development of DNA barcodes for living organisms. BOLD serves as an international repository of DNA barcode data and a resource for information on barcodes.

Dryad:

http://datadryad.org/

This is a data repository governed by a consortium of peer-reviewed journals. Since most journals have limited printed space, Dryad offers an opportunity to the authors to deposit additional information and make it available online for further investigation and discussion.

National Center for Biotechnology Information, including GenBank:

http://www.ncbi.nlm.nih.gov/

The Center, funded by the US federal government, maintains GenBank, which is the centralized database for biological sequence data, in addition to other molecular genetic databases. GenBank is part of a consortium of international sequence databases, including the DNA Databank of Japan (DDBJ) and European Molecular Biology Laboratory (EMBL), and cross-lists their entries as well. Currently there are more than 100 million sequence records in GenBank, each of which is publicly searchable. NCBI also maintains a number of online analysis tools, such as BLAST, that can facilitate systematics research.

TREEBASE:

http://treebase.org/treebase-web/home.html

TREEBASE allows researchers to submit and store "phylogenetic trees and the data used to generate them" used in support of published research.

"Where can I find maps to use in presentations, publications, and analyses? GIS software is expensive and challenging to use, so are there any tools that make this easier?"

12. Geographic Information Systems (GIS) and Maps—Visualizing and analyzing distributional data of taxa are often critical components of systematics research projects. Below are links to map resources and other data, as well as software for geographic analysis of biological data.

12a. GIS Data—

CCAFS GCM Data Portal:

http://www.ccafs-climate.org/

The CCAFS GCM Data Portal provides global climate modeling GIS data for use in GIS applications. These data are freely available for non-commercial uses.

Federal Geographic Data Committee (FGDC):

http://www.fgdc.gov/

FGDC is a multi-agency host of geographic data, which provides maps and other resources as well as grants and training opportunities for researchers. FGDC is hosted by the USGS.

Natural Earth:

http://www.naturalearthdata.com/

Natural Earth is a host of open access, public domain map, and GIS data. These high-quality resources are freely accessible. There is also a discussion forum for users.

WorldClim Global Climate Data:

http://www.worldclim.org/

WorldClim is a freely accessible data repository for GIS climate and ecological data.

12b. GIS tools—

DIVA GIS:

http://www.diva-gis.org/

DIVA-GIS is a free GIS software package designed specifically for use with biological data.

Earth Explorer:

http://earthexplorer.usgs.gov/

Earth Explorer is a tool maintained by the US Geological Survey (USGS) that hosts searchable map and GIS data.

ESRI, Inc.:

www.esri.com/

ESRI, Inc. produces ArcGIS, which is an industry-standard geographical information software package. ESRI also provides GIS information and resources for users and hosts data, some of which are available for free through their website.

MapWindow GIS:

http://www.mapwindow.org/

MapWindow is a free GIS package for visualizing and manipulating geographic data.

National Geographic Map Maker Interactive (MMI):

http://education.nationalgeographic.com/education/mapping/interactive-map/?ar_a=1

As the name implies, MMI is an interactive, web-based map-making tool that uses a user-friendly Flash interface to explore maps of interest. Map images can be manipulated using the interactive web tool and downloaded to your computer.

"Are there organizations I can join that support my research, or offer assistance through networking and collaboration, funding, or other resources?"

13. Professional Societies—Below are several professional societies, besides the Botanical Society of America (http://www.botany.org), that are relevant to plant and lichen systematics researchers. Some publish journals, offer discounted student membership rates, and sponsor student research grants. Professional societies can be an excellent way to meet potential collaborators and network with other researchers in your field of interest. Due to the sheer number of international professional societies, we have opted to only include societies that are based in the North America; however, we have also included a few organizations that have an international scope but are based outside of North America.

American Bryological and Lichenological Society (ABLS):

http://www.abls.org/

American Fern Society (AFS):

http://amerfernsoc.org/

American Society of Naturalists (ASN):

http://www.asnamnat.org/

American Society of Plant Biologists (ASPB):

http://my.aspb.org/

American Society of Plant Taxonomists (ASPT):

http://www.aspt.net/

Canadian Botanical Association/ L'Association Botanique du Canada (CBA/ ABC):

http://www.cba-abc.ca/cbahome.htm

International Association for Lichenology (IAL):

http://www.lichenology.org/

International Association of Plant Taxonomists (IAPT):

http://www.iapt-taxon.org/index_layer.php

Phycological Society of America:

http://www.psaalgae.org

The Mycological Society of America (MSA):

http://www.msafungi.org/

Society for Systematic Biology (SSB):

http://www.systbiol.org

Society for the Study of Evolution (SSE):

http://www.evolutionsociety.org/

How can I find potential collaborators online or join a community of like-minded researchers?

14. Social Networking—Electronic social networking applications are becoming more widely used by researchers to share ideas and collaborate on projects. News and events can be disseminated, discussed, and tracked for a variety of purposes; we encourage readers to investigate the networking potential that these resources offer.

Academia.edu:

http://academia.edu/

This site caters to students and researchers in academia, providing opportunities to "follow" the research of colleagues or other researchers whose work one might have an interest in. It allows users to post manuscripts and can link users based on their discipline and academic interests.

Facebook:

http://www.facebook.com

Professional organizations, researchers, and funding institutions are networking and updating news and providing research announcements with tools available through traditional social networking sites, such as Facebook.

Figshare:

http://figshare.com/

This website allows users to make an account where they can store and share data in a searchable format. All data uploaded to FigShare is protected by a Creative commons license and, Figshare offers up to 1GB of storage for free.

Google Plus:

https://plus.google.com/

Google+ is a social networking site like Facebook that allows for networking and following groups, which Google calls "circles".

LinkedIn:

http://www.linkedin.com/

LinkedIn is another social networking tool, which specifically focuses on networking for business and academic professionals.

My-Plant:

https://my-plant.org/

My-Plant is a social network hosted through the iPlant Collaborative (listed above). My-Plant organizes participants by their taxonomic specialty using a tree-based phylogenetic approach. Researchers and collaborators can "join" a particular clade of interest and discuss research, news, and interact through the services available at My-Plant.org.

Pinterest:

http://pinterest.com/

The site is a content sharing service that allows members to "pin" images, videos and other objects to their user page.

ResearchGate:

http://www.researchgate.net/

ResearchGate is a social networking website dedicated to professional scientists. The goal of Research Gate is to improve networking and collaboration among researchers.

Twitter:

https://twitter.com/

Similar to the networking possibilities available through Facebook, Twitter has also become a useful tool for interacting with potential collaborators, as well as following news and information from institutions, researchers, and professional societies.

"What am I going to do after graduation? How can I get the job I want?"

15. Employment and Career Development— In this section, we focus on resources available to help guide students through graduate school to their future career. Three texts (Feibelman, 2011; Peters, 1997; and Vick and Furlong, 2008) are recommended, which contain helpful tips for meeting and understanding career and professional development goals.

The American Society of Plant Taxonomists job listings:

http://www.aspt.net/publications/newsletter/jobs.php

Similar to the BSA jobs website (below), the ASPT regularly updates position announcements for plant taxonomy-related careers.

Association for Women in Science (AWIS):

www.awis.org

This association provides career resources, advocacy, and professional development opportunities to women in science.

The Botanical Society of America job listings:

http://jobs.botany.org/

The BSA website maintains an up-to-date listing of jobs available for post-doctoral research, fellowships, and botany-related careers.

The Chronicle of Higher Education:

http://www.chronicle.com

This journal is a leading publication about news and issues in academic research, teaching, and administration. It also maintains an extensive section on academic careers and academic job postings.

EvolDir:

http://evol.mcmaster.ca/evoldir.html

EvolDir is a regularly updated news and bulletin website for evolutionary biology. The website maintained postings for jobs, which include positions in academia, graduate student positions, and post docs.

Science Careers:

http://sciencecareers.sciencemag.org/

This site, hosted by Science Magazine, contains a wealth of career resources, articles, and job postings.

The Society for American Chicanos and Native American Scientists (SACNAS):

www.sacnas.org

This society provides career resources, advocacy and professional development opportunities to American Chicanos and Native Americans in science.

DISCUSSION

This guide is not intended to promote or advocate the use of any particular text, tool, protocol, or database over another, but rather to serve as a clearinghouse for and introduction to the wide variety of tools available to graduate students and early career researchers beginning their studies in plant or lichen systematics. Further, the authors hope that this guide might encourage researchers in other related fields to develop their own cyberinfrastructure navigation guides for students and others entering or exploring new frontiers. We welcome additions to this online version of this guide: http://www.botany.org/students_corner/systematics_resources.php.

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