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Integrating Research and Education in the NSDL

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Abstract

The National Science Digital Library (NSDL) has the potential to be the premier agent of dissemination for instructional purposes the exciting research results that are supported by the disciplinary directorates of the National Science Foundation (NSF). Integrating research and education has long been an important priority of NSF's mission to support "People, Tools, and Ideas", and translation of scientific results into instructional practice is increasingly used as evidence of NSF's "Broader Impacts" review criterion. Digital libraries provide an ideal environment to support the processes of discovery and inquiry that can make Science come alive for learners at all levels and in formal (K-16) and informal (for the interested and inquiring public) instructional settings. The NSDL can play an essential role in NSF's mission by providing collections and services that directly link scientific results, data and data products, background information on scientific principles and methods, pedagogic strategies, instructional materials, teaching tips, assessments, and human resource development opportunities for students and instructors. Through contributing projects to the NSDL, the DLESE Community Services (DCS) and Microbial Life Educational Resources (MLER) projects, we have experimented with numerous formats to demonstrate ways in which integrating research and education can be achieved in a digital library environment.

The important lessons learned from this body of work include: 1) a centralized metadata repository is not as effective for use by self-defined communities of users as specialized portals designed and built to address targeted community expectations, needs, and standards; 2) placing learning resources in the full context of scientific principles and results, pedagogic practice, teaching activities, assessments, and opportunities for personal development adds value to all these types of resources and to the experience of the users; 3) building thematic collections of resources is useful to a point, but instructors are most interested in having access to instructional resources that they can readily download to adopt or adapt for immediate classroom use; 4) digital libraries can be used to help build and nurture communities of learning, and can also effectively tap these communities for contributions and reviewing of these resources; 5) digital libraries can also be used to effectively create collections of non-digital resources (e.g. links to instrumentation and facilities), to make available the "gray literature" of a field, and to capture the experience and advice of a community which is not readily available through other media; and 6) digital library technology can optimize the use of resources by diverse audiences by facilitating repurposing and enabling bi-lateral links between closely related collections of resources.

This contribution provides a review of the experiments completed by the Microbial Life Educational Resources (MLER) and DLESE Community Services (DCS) projects that were designed to explore a variety of constructs and approaches to delivering digital learning resources to students and instructors that integrate research and education. Each of the following sections provides a summary of the philosophy, goals, development, and lessons learned as a result of these experiments:

- **Introduction:** Responding to goals articulated for the NSDL in Pathways *to Progress (2001)* to provide access to scientific data, and to support integrated science education across the STEM disciplines.
- **Integration of Research and Education**: reflections of many facets of what this means and how it can be achieved; particular emphasis is placed on the ability of digital libraries to support inquiry and discovery.
- **Project Development**: design principles and strategies used in the design and development of MLER and DCS digital library sites.
- **Reflections on Collections**: a broad definition of "collections" including collections of teaching activities, on-line resources that support teaching and learning, access to data, tools and data products, and non-digital resources; all require different representations in a digital library environment.
- **Using Data in the Classroom Portal**: collections of data, data tools, data products, including the use of "DataSheets" which provide educational metadata about potential use of data-rich resources in the classroom.
- **Development of Thematic Collections:** collections of web-based resources to provide a holistic coverage of a topic, including suggested teaching activities.
- **"Primers" on research methods and instrumentation:** the fundamental information about research methods you need to know to attend a lecture or read a journal article that will allow you to be a "critical consumer" of data, results and interpretations.
- **"Profiles" of Microbial Observatory research projects (NSF/BIO-sponsored);** collaborations with PIs of funded research projects where the scientific objectives, methods and results are reported to encourage use in the classroom and to assist these projects in demonstrating "broader impacts".
- **Collections of non-digital learning objects.** A registration service of analytical instruments that are available for use by students and faculty, and used to optimize the use of these instruments and to support teaching and learning in modern research methods.
- **Use of large on-line databases (from NSF/GEO-cyberinfrastructure projects);** on-line tutorials that demonstrate how to access, use and interpret results from large databases; examples include the EarthChem geochemical database and Mineralogical Society of America crystal structure database (as an example of how professional societies can be integrated into the NSDL network).
- **Modules Developed for Underrepresented Groups**: collections of materials designed for specific underrepresented groups to help foster recruitment and retention of students in the STEM disciplines; case studies of interest to Native American students are developed.

- **Aggregation of community-based experience and advice on how to use emerging technologies in instruction:** These collections include a) examples from the "gray literature", e.g. road logs and field guides in the geosciences, and b) advice from "innovators" of new teaching technologies where pooled experience and advice has been collected to help others avoid "reinventing the wheel"; the example is in the use of "GeoPads"—ruggedized computers that can be used in field settings.
- **Development of modules that integrate resources that cover topics from "first principles" to the most advanced modeling programs:** an example of Teaching Phase Equilibria that includes introductory materials typically introduced at the sophomore level all the way through applications of the most advanced thermodynamic modeling programs used in research.
- **Overarching Lessons Learned—**The NSDL has not addressed many of the goals laid out in *Pathways to Progress*, and rapidly changing advances in information technology require realignment of NSDL goals, practices and development.
- **Summary**
- **References**

Introduction

The early vision of the NSDL identified key needs to

> "…provide mechanisms for incorporating primary scientific research data," and "…to enable student-friendly access to scientific data to support learning by direct experience with the methods and processes of inquiry and discovery…" (*Pathways to Progress*, Manduca et al., 2001).

In addition, one of the primary educational goals of the NSDL was to facilitate integrated science education across the STEM disciplines as articulated in *Pathways to Progress* (Manduca et al., 2001):

> "First and foremost, there is the opportunity to develop a SMET education community that is interdisciplinary. There is intrinsic value in recognizing and accentuating the connections among the knowledge bases, skills, and methodologies employed by those disciplinary communities that contribute to the NSDL. The NSDL can make a substantive contribution towards bridging current disciplinary boundaries by effectively integrating concepts, knowledge and methods across the SMET disciplines…..Robust linkages are needed to allow discovery of resources across disciplines and educational communities… A NSDL that effectively integrates concepts, knowledge and methods across the SMET disciplines will be a much greater resource than a collection of discipline-specific libraries."

The functional specifications for education and instruction in the NSDL called for

> "…creation of logical links to cross and multi-disciplinary collections" (Manduca et al., 2001).

The ability to access scientific data and tools, and to utilize these resources for interdisciplinary instruction, are important components of integrating research methods and results into STEM education. To be most useful for instruction, these scientific resources must be placed in contexts that are well-aligned with learning goals defined for specific groups of learners, courses, and curricula. The power of the digital library environment is that it allows learners to navigate information networks "vertically" to explore a given topic to the extent of the user's curiosity, interest, and ability. Digital libraries also allow interested learners (students and the inquiring public) to navigate "horizontally" to make interdisciplinary connections between scientific content in related fields. For educators, these navigational capabilities extend to provide linkages between scientific content and pedagogic practice along a continuum of information that includes scientific principles and discoveries, pedagogical strategies, tested and reviewed instructional activities, assessments, and faculty professional development resources to enhance teaching and learning about a given topic.

Perhaps most importantly, digital libraries provide the opportunity to place instructional resources in contexts that are important to users (Lagoze et al., 2006). Instructional resources gain value to the extent they are understood and used by self-defined user communities (e.g. "communities" may be defined by sharing commonalities along many possible dimensions such as targeted audience or grade level, scientific discipline, and geographic setting; Manduca and Mogk, 2001, DLESE Community Plan). By using digital library technologies that emphasize development of specialized portals, thematic collections, domain-specific controlled vocabularies, rich descriptive metadata for precise cataloging, targeted (faceted) search capabilities, and annotation services, instructional resources can readily be placed in contexts that facilitate discovery by diverse communities of users (Fox et al., 2005). In addition, digital libraries can further serve communities of learners by repurposing resources for discovery in multiple contexts, and by establishing related links to enable discovery of complementary resources in sister disciplines or modules (Manduca et al., 2006). For example, an instructional unit on adiabatic processes can be illustrated by the example of how a boiler works in an engineering, chemistry, or physics class or in a thunder cloud or magma chamber in an Earth science class.

Directly linking scientific discoveries with effective pedagogic practice in the NSDL creates a win-win-win situation: the results of scientific investigations get immediate and broad recognition by inclusion in STEM curricula and exposure to the interested public; the NSDL will continue to grow by incorporating exciting new scientific advances and will strengthen its internal networks by linking this new science with existing instructional resources; and learners and instructors will have rapid and direct access to novel scientific discoveries with supporting contextual information that will enable learning through inquiry and discovery.

Integrating Research and Education

There are many dimensions of integrating research and education that can be pursued through the NSDL. A report of the NSF/GEO advisory group convened to address Geoscience Education in the Next Millennium has identified four key components that can be more broadly applied to STEM education (*Bridges: Connecting Research and Education in the Earth System Sciences*; Mogk, 2000):

- Research in Education: focusing on ways to optimize opportunities for students to actively engage science by direct experience, working in laboratory and field settings, asking questions, collecting evidence, making interpretations, and developing "scientific habits of the mind" (AAAS, 1989; NRC, 2007).
- Research and Education: developing mechanisms to translate new scientific discoveries into effective instructional practice, including delivery of real-time (or near real-time) data, tools and interfaces to effectively use scientific databases, brokering collaborations between research and educational programs, and coordinating priorities between the research and educational missions of the NSF.
- Research on Education: using the recent advances from the cognitive and learning sciences on "How People Learn" (e.g., Bransford et al., 2000) to optimize emerging instructional technologies (e.g. visualizations, modeling programs, virtual learning environments). This area of study also encompasses motivations for student learning (Edelson, 2001), diversity issues (what works for different populations of students?), misconceptions and preconceptions brought by students to the classroom, motivations and barriers to learning (e.g. aspects of the affective domain), and an arsenal of assessment tools that are available to demonstrate learning outcomes. This field of scholarship also has a positive feedback on the research enterprise by shedding light on how researchers learn and interpret the world around them in their own investigations (through self-reflection and metacognition).
- Education in Research: instructional practices necessarily impact the research enterprise. Are we adequately preparing the next generation of scientists? The quality of STEM educational experiences is a major contributing factor to the recruitment and retention of students as young scientists (e.g. Seymour and Hewlitt, 1994). This also is a major contributing factor to preparation of the workforce for the 21st century (e.g. Rising Above the Gathering Storm, NAS, 2007), and the public's perception of the value of Science to society.

Integration of research and education has always been a high priority of the National Science Foundation. For the past decade, a particular emphasis has been placed on the value of *inquiry* and *discovery* in STEM education:

> "…infuse the joy of discovery and an awareness of its connections to exploration through directed inquiry and careful observation, and analytic thinking for students at all levels." *NSF in a Changing World* (1995)
>
> "What we urge is an America in which
> *1. All* students have access to supportive, excellent undergraduate education in science, mathematics, engineering and technology.
> *2. All* students learn through direct experience with the methods and processes of inquiry." *Shaping the Future of Undergraduate SMET Education (NSF, 1996)*

(Note: the very existence of the NSDL derives from the recommendations in this report to NSF, pp 47-48, 72).

The NSDL is an ideal environment to address these many aspects of integrating research and education. Digital library technologies are particularly adept at supporting inquiry and discovery by users, and are prime motivators for learning (e.g. Edelson, 2001). The challenge is to aggregate, characterize, organize and make accessible for discovery the spectrum of resources available through the NSDL relating scientific content, data and tools, pedagogic practice, research on learning, and opportunities for students and instructors to support learning and instruction.

Project Development

Through the DLESE Community Services (DCS) and Microbial Life Educational Resources (MLER) projects we have developed and tested numerous approaches to integration of research and education in a digital library environment. The key principles that have guided the development of these projects have been: 1) identifying and responding to community-based interests and needs (i.e. first asking what is needed, what is expected; engaging colleagues to identify what resources exist; allowing these communities to determine the breadth and scope of coverage, and standards to evaluate and access resources; and to develop the controlled vocabularies and navigation structures that correspond to common practices established for that community); 2) placing digital resources in contexts that are meaningful and useful for instructors and students; and 3) using information technologies to make bilateral links between bodies of information among related disciplines; this includes a spectrum of resources that permit deeper exploration by interested users as well as resources that connect science, teaching strategies and methods, assessments, and professional development opportunities to support instructors and their diversity of instructional needs.

Most of the examples below are drawn from our continuing work in the Earth Sciences and microbial ecology, but the approaches we've used can be extended to STEM education and research in the breadth of programs supported by all disciplinary directorates at NSF. All of this work was done using the information technologies made available through the Content Management System at the Science Education Resource Center (SERC), Carleton College (Fox et al., 2005; http://serc.carleton.edu/serc/cms/index.html). The following sections provide an overview of the collections and services developed in these projects, and the lessons learned about design, development, implementation and usability. The full range of modules can be accessed at:

http://serc.carleton.edu/microbelife/index.html
http://serc.carleton.edu/research_education/index.html

The strategies we used to promote integration of research and education include:

- Development of portals, web-based modules, and thematic collections that provide sufficient context for learners and instructors to be able to understand and explore scientific content and principles, including descriptions of the scientific questions that are addressed, the methods used, the key findings, and their significance to Science and society.
- Identification of topics that showcase exciting new scientific discoveries or that address questions of particular significance to Science and society that a) build on the foundations of "first principles" in the STEM disciplines, and b) are deserving of "fast-track" inclusion in STEM curricula (recognizing the very long lag time between discovery and development of traditional instructional materials such as text and lab books).
- Identification, aggregation and organization of resources by "mining" the NSDL (and related NSF/EHR programs) to provide links to instructional resources related to the topics of interest. These collections of resources have been scaffolded to the extent possible so that interested learners can explore the topic to their own level of interest.
- Engagement of strategic partnerships with other NSDL projects. For example, we have drawn heavily from the pedagogic services afforded through the NSDL-funded Starting Point/Pedagogy in Action project, and have subsequently contributed to their collections of

activities and examples (http://serc.carleton.edu/sp/index.html). We have also collaborated with other NSF/EHR projects such as the CCLI-National Dissemination-sponsored *On the Cutting Edge--Professional Development for Geoscience Faculty* program (http://serc.carleton.edu/NAGTWorkshops/index.html).

Reflections on Collections

In the MLER and DCS projects we have taken a very broad view of what constitutes a digital "collection", and have created collections of five different types of resources:

- Activities; these are resources that can be directly downloaded by instructors for either adoption or adaptation for use in classrooms. These resources will typically include educational metadata developed for users as ActivitySheets which include descriptions of the activities, learning goals, context for use, teaching notes and tips, assessments, links to related resources, and .uploads of all required teaching materials (see Sheets- Models for Community Sharing, developed by SERC, http://serc.carleton.edu/serc/sheets.html).
- Web-based resources; these are resources that provide important or interesting information about a topic, but do not necessarily provide actual activities that could be done in a class. In general, we have developed *thematic collections* that include resources available from the open WWW related to a topic of interest that we have discovered, reviewed, aggregated and cataloged; *"primers"* that provide essential links about a topic and links to collections of resources to enable deeper exploration of the topic; and *"profiles"* of research projects to introduce collections of information covering the relevant scientific questions, methods, and results. In the Earth Sciences, these on-line resources come from credentialed sources such as governmental agencies (e.g. USGS, NOAA, EPA, and NASA) which provide access to rich arrays of information sheets, visualizations, animations and summaries of recent research results. Similarly, information from scientific professional societies and from on-line resources from institutions, research projects, or individual faculty also provide useful resources that support learning (e.g. on-line tutorials, PowerPoint presentations, images and other visualizations). One of our goals in our integrating research and education projects is to encourage educators to explore these web-based resources and then develop new curricular materials to help grow our collections of activities. The ethic of "users as contributors" was one of the central tenets of the DLESE Community Plan (Manduca and Mogk, 2000).
- Data, tools, and data products, combined with tutorials in their use and interpretation of results (see below);
- Reference collections of foundational information that provide background and contexts that to enable deeper exploration of thematic collections; and
- Collections of non-digital resources; these include descriptions of and links to instruments; descriptions of people (profiles of scientists) and places (field study sites); descriptions of, and pointers to, the "gray literature" (which contain important first order observational or procedural information that is commonly edited out of peer-reviewed journals); postings of tips, advice and community-based experience; and links to opportunities for professional development.

In sum, we have attempted to expand the understanding of what a collection is in the digital library environment to include not only catalogues of on-line teaching activities and related web-based instructional resources, but also collections of hard-to-find print resources, collections of hard-earned community-based expertise and advice, and representations of non-digital instructional resources (e.g. analytical equipment).

For the digital resource collections, our selection and review criteria have been extremely important as a first step to inspire confidence among our user base. We generally follow the guidelines of the DLESE Community Review Service (Kastens, 2005), which requires that resources are a) scientifically accurate, b) pedagogically effective and well-documented, c) easy to use, and are d) robust as digital resources (i.e. they work). Discovery and cataloging of resources has been done by a dedicated staff that is knowledgeable about scientific content, pedagogic practice, and digital library technologies. Our attempts to encourage *ad hoc* community contributions to the collections (e.g. via broadcast solicitations of contributions to listservs) have been only minimally successful. Relatively few resources are submitted via on-line "contribute" services, and resources that are submitted in this manner typically do not provide sufficient required or recommended information to create useful metadata records. However, collection building activities related to community-based events (workshops, meetings) where participants have a shared interests and "ownership" of a give topic have been very successful in generating thematic collections (e.g. On the Cutting Edge professional development workshops on Teaching Topic X and similar DCS workshops convened to develop curricular modules). These event-based collection-building efforts have provided templates and web-authoring services to ensure that required metadata and other contextual information are built directly into the on-line resources.

Lessons learned:

a) *A trained staff is required to discover, aggregate and catalog resources (or at least oversee these activities) for digital library collection building; this level of professional services is necessary to create high quality metadata to ensure successful searching/browsing by users.*
b) *Growth of the NSDL cannot be effectively done by accessioning individual resources. A much more effective growth strategy is to develop and accession comprehensive thematic collections that have been developed by community interest groups. These groups can readily define the scope of the collections, develop controlled vocabularies, articulate needs and expectations, and set standards for selection and review. In this regard, the NSDL could do more to support collection development by communities of scholars.*
c) *Resources that are currently available through the "open" WWW typically do not provide the information required for full metadata records (e.g. information as basic as authorship, permissions, intended audience, etc. are commonly not built into most instructional materials posted on the WWW). The NSDL must provide more leadership and guidance for creators of web-based instructional resources to make sure that essential information is built into on-line resources to better inform users about the intended use of the resource , and to facilitate metadata development by catalogers and for automated metadata generation.*
d) *A single portal with general search capabilities is not very effective. The metadata can never be comprehensive enough to promote effective searching for users with specific interests, and development of a single set of metadata standards is ultimately too costly to develop and implement. As an alternative, portals, modules and websites that speak directly to the needs, interests, and applications of self-defined community groups are better positioned to address the scope and breadth of collections, selection and review criteria, and development of vocabularies and metadata that enhance discovery for these groups.*

The *Using Data in the Classroom* Portal
http://serc.carleton.edu/usingdata/index.html
http://serc.carleton.edu/usingdata/about_datasheets.html
One of the early products of the NSDL was the *Using Data in the Classroom* workshop, report (Manduca and Mogk, 2002), and portal which provided recommendations for data managers regarding instructional access and use of data and tools, and advice for instructors on the successful design and implementation of data-rich instructional activities. This site contains collections of data sources and tools, instructional activities and worked examples, and pedagogic resources from all STEM disciplines. An important advance was the development of DataSheets which characterize essential information (metadata) on educational use and relevance of the datasets for uninitiated users . The DataSheets were developed according to criteria established by the DLESE Data Access Working Group. Educators have provided advice to providers of scientific data, and have indicated they want students to be able to:

- Find and access relevant data
- Evaluate quality of data
- Use appropriate tools and interfaces to manipulate and render data
- Combine multiple and diverse data
- Subset data, select resolution of data
- Generate visualizations, representations,
- Contribute data, and view in context of larger data sets

Lessons learned:

a) *It is neither effective nor fair for providers of scientific data to simply provide access to databases for instructional use without providing ancillary tools and tutorials for accessing, manipulating, representing and interpreting data and data products. "Raw data streams are often unintelligible to the uninitiated, specific data products are often difficult to find, linking data to software for viewing, processing, and/or interpreting the results is often difficult, and data products are often much larger and/or more comprehensive than can be effectively used in a classroom environment" (Manduca and Mogk, 2002).*
b) *Educational interfaces are needed to help users find and access data; evaluate the quality of data; use appropriate tools and interfaces to manipulate and render data to answer questions; combine multiple and diverse datasets to solve a central problem; generate visualizations and representations that communicate interpretations and conclusions; contribute student data to larger datasets; and view individual student data in the context of larger datasets. (ibid).*

Development of Thematic Collections

http://serc.carleton.edu/microbelife/extreme/index.html
http://serc.carleton.edu/microbelife/marine/index.html
http://serc.carleton.edu/research_education/cretaceous/index.html
http://serc.carleton.edu/research_education/yellowstone/index.html
http://serc.carleton.edu/research_education/katrina/index.html
http://serc.carleton.edu/research_education/paleontology/index.html

The MLER project has created thematic collections focused on a) life in extreme environments and b) life in marine environments. Over 800 resources have been cataloged for discovery according to topics related to the biosphere (e.g. ecology, diversity, evolution, etc.), resource type, audience, and type of microbial environment. All the resources have been cataloged using a variety of controlled vocabularies available through the Content Management System at SERC, and two important features have been built into these collections: 1) all the resources are placed in appropriate contexts (e.g. sub-collections) to better support learning rather than relying on a single large metadata repository for discovery, and 2) a curious user can readily navigate among numerous topics in the module to readily discover the interconnections among the different topics within the collections—this is in accord with pedagogic approaches to "Earth system science thinking" (see Starting Point module on Using an Earth System Approach, http://serc.carleton.edu/introgeo/earthsystem/index.html).

Similar thematic collections were developed for the DCS project, focusing on topics that have interest and utility in introductory Earth science courses. Topical modules include: All Things Cretaceous, Exploring the Yellowstone Geoecosystem, Teaching with Hurricane Katrina, and Advances in Paleontology—New Ways to Study Ancient Life. All have developed thematic collections of resources built upon Key Topics that utilize community-vetted controlled vocabularies. In addition, we have developed self-guided discovery pathways through these collections, a series of focused investigations of "Compelling Research Questions" (e.g. What is the nature of the K/T boundary, and how is it related to the extinction of the dinosaurs? Is Yellowstone volcanism caused by a deep-seated mantle plume?), and we also provide links to instructional activities such as role playing or jigsaw activities (also accessible through the NSDL-funded Starting Point portal and/or the CCLI-National Dissemination *On the Cutting Edge* collection of instructional activities for introductory courses).

We have also developed modules on Topics of Interest, Case Studies and Special Collections in the MLER project on special interest topics such as: Mono Lake (life in an alkaline environment and implications for water supply of Los Angeles), Rio Tinto (acid mine drainage), Looking for Thermal Viruses in Yellowstone National Park, and many more. These resources are also linked to Resources for K-12 Teachers and Students, and include Teaching Activities such as Are Viruses Alive: Sample Socratic Questions, and Teaching with Data: Bioinformatics. Guided discovery exercises place MLER resources in instructional contexts in formal instructional activities known as "Webquests" which include articulation of the question, definition of tasks, process to address the question, resources, evaluation and notes to instructors.

Lessons learned: Feedback from focused user groups indicated that compared with searching across the open WWW (e.g. Google searches) the aggregation, organization, and vetting of high-quality resources was appreciated and valued by instructors. However, they were somewhat at a loss regarding how they would use these resources in a classroom setting. Consequently, we felt compelled to provide some model examples of activities to demonstrate possible instructional uses of the thematic collections. In most cases, we used the teaching method modules available through the Starting Point/Pedagogy in Action projects to efficiently develop teaching activities that utilized the thematic collections. We also developed related activities using the protocols designed for WebQuests (http://serc.carleton.edu/microbelife/k12/webquestinfo.html). Even though digital library development should not be confused with course and curriculum development, it may be necessary to create or recruit at least some example teaching activities to demonstrate the utility of digital library collections and services.

“Primers” on Research Methods and Instrumentation

http://serc.carleton.edu/microbelife/research_methods/index.html
http://serc.carleton.edu/research_education/geochemsheets/index.html

The intent of these modules is to help students and novices to be “critical consumers” of scientific data, results and interpretations. The goal is to help learners be able to attend a departmental seminar or read an article in a science journal and have a fundamental understanding of where the data come from, what methods were used (from sampling to data acquisition to data interpretation), to understand the applications and the limitations of the methods, to be able to critically evaluate interpretations of the results, and to be able to ask the next question. In the MLER project we developed these types of primers on: Environmental Sampling, Biogeochemical Methods, Genomics, Microscopy, and there is an example of an integrated research project that employs most of the above methods (Geobiology and the Emergence of Terraced Architecture during Carbonate Mineralization, Mammoth Hot Springs, Yellowstone National Park). We have also produced tutorials on Geochemical Instrumentation and Analysis which include descriptions of the following instruments and techniques: X-ray diffraction (single crystal and powder), SEM, EMPA, WDS, EDS, BSE, CL (SEM and optical), EBSD, XRF, INAA, TIMS, MC-ICPMS, SIMS, Gas Source Mass Spectroscopy, X-ray Computed Tomography (CT), ToF-SIMS, Mossbauer spectroscopy, and related pages on generation of characteristic X-rays, Bragg's Law, and Electron-Beam Interactions. These modules provide related links to the NSDL-supported Analytical Sciences Digital Library and Reciprocal Net projects. This collection of “primers” can be viewed as a type of reference collection that provides the fundamental information required for first-order understanding of these research methods. Each primer then leads to thematic collections of on-line and print resources to enable further exploration of the topic by interested users and instructional activities for instructors that can be used directly in the classroom or laboratory.

Lessons learned: There is a tremendous gap in understanding about the products and methods of scientific research produced by practicing scientists and students/novices encountering this information for the first time. The NSDL can serve an important function in the training of future scientists (and to enhance the understanding of Science by the inquiring public) by providing services that condense, explain and put in context the methodologies used to advance scientific knowledge. Reference collections of this type could be developed across all STEM disciplines as a point of entry to explore related thematic collections developed for deeper understanding. The NSDL could do more to help identify and establish bi-lateral linkages between similar projects to fulfill the vision of a truly interdisciplinary digital library.

"Profiles" of Current Research Programs

http://serc.carleton.edu/microbelife/microbservatories/index.html
http://serc.carleton.edu/research_education/paleontology/index.html

In the MLER project we have worked directly with the principal investigators of research projects funded by the NSF Microbial Observatory program (in consultation the Program Officer, NSF/BIO). We use the NSDL digital library environment as a key mechanism to help researchers more fully realize the broader impacts of their research, according to NSF Review Criterion 2. In each of the modules we present an overview of the research projects, define the scientific goals of the project, introduce the key personnel, demonstrate methodologies used in the field and lab, present the key scientific outcomes, provide links for further exploration on the topic, and if available, link to related instructional activities. These sites have been immensely popular with the principal investigators as the outcomes of their investigations receive global exposure for use in classrooms. Teachers, students, and the interested public have expressed a keen interest in understanding the questions, motivations, and outcomes of these cutting edge research projects. Molecular Observatory projects that have been profiled include: McMurdo Dry Valleys (Antarctica), Novel Viruses from Yellowstone National Park, the "Red Layer" in Yellowstone National Park (also the site of a NSF supported REU program), the North Inlet Salt Marsh Estuary (Georgetown, SC), Marine Sponges MO (Conch Reef, Key Largo, FL), Nevada Hot Springs, Oligotrophic Ocean (Sargasso Sea, Bermuda), Monterey Bay National Marine Sanctuary, Sapelo Island Salt Marsh (Georgia), Contaminated Aquifer (South Glens Falls, NY). We have done similar profiles of researchers and their research projects in the DCS module Paleontology—New Ways to Study Ancient Life. Thematic collections of instructional resources have been developed to include research methods, scientific outcomes, instructional activities if available, and related links for future exploration.

Lessons learned:

a) *There are rich opportunities to broker collaborations between research and educational programs at NSF through the NSDL. The DCS/MLER projects have developed modules for researchers to help them address NSF's Broader Impacts review criterion, Tips on Partnering, Tips on Assessment, and Tips on Dissemination to help develop seamless connections between scientific discoveries and effective instructional practices (http://serc.carleton.edu/research_education/researchers.html).*
b) *The NSDL could provide an array of services to develop profiles of every funded research project funded through the disciplinary directorates including resource collections, teaching activities, data and data products, and "primers" on methods and results.*
c) *There is also the opportunity to "mine" existing instructional resources related to these research projects from existing NSDL collections to make these available for discovery in the context of active research programs. Principal investigators of scientific research projects should have the opportunity (and be encouraged) to contribute to the NSDL as evidence of their commitment to NSF's Criterion 2 "Broader Impacts" requirements.*

Collections of Non-Digital Resources

http://serc.carleton.edu/NAGTWorkshops/petrology/instruments.html

We have developed a "match-making" service in an Analytical Instrument Registry (100+ geochemical instruments registered and a new collection of geophysical equipment has just started) to help optimize NSF's investment in instrumentation infrastructure. This service helps a) lab managers build their user base, b) researchers, instructors and students gain access to analytical equipment to support their scholarly work, and c) to build research capacity by increasing the use of existing analytical equipment to support excellence in science and the training of future scientists. All registered instruments provide information about the type of instrument, model, typical applications, sampling and sample preparation, standards, terms of use, and contact information.

Lessons learned: The concept of what constitutes a collection in a digital library can be expanded to include non-digital resources by creating metadata records with links to the physical facilities to help make connections between facilities and potential users.

Use of On-Line Databases in the NSDL

http://serc.carleton.edu/research_education/cyberinfrastructure/index.html
http://serc.carleton.edu/research_education/crystallography/index.html
http://serc.carleton.edu/research_education/healthrisk/index.html

NSF has invested heavily in the development of the cyberinfrastructure needed to create and distribute large scientific databases for use in research and education. EarthChem (http://www.earthchem.org/earthchemWeb/index.jsp) is a major cyberinfrastructure project supported by the Directorate for Geosciences that seeks to develop a global database of **all** whole-rock geochemical analyses (elemental and isotopic, from all published sources), including additional data such as rock type, geospatial referencing, and age data. EarthChem has demonstrated tremendous potential for how geochemical research is done by providing new ways to aggregate, correlate, compare and represent geochemical data to explore relationships among many dimensions. However, in the initial development of this project there were also tremendous barriers to novice users (including students) to accessing the data, culling and parsing the data, and producing data representations. We made the case that the largest potential user base is not the geochemical research community, but rather, undergraduate geology majors (all of whom must study igneous and metamorphic geochemistry at some point in their degree programs; Mogk, 2004). In response, we developed a number of tutorials, worked examples and problem sets that demonstrate the use of EarthChem. The Teaching with the EarthChem Geochemical Database modules have nine example exercises and activities that range in sophistication from step-by-step instructions on how to find, download, render and represent geochemical data to applications that require much deeper levels of applications of geochemical principles. As an example, the Compositional Diversity in Volcanic Suites exercise compares and contrasts the whole rock chemistry of rocks from Mt. Mazama and Yellowstone to demonstrate differences in composition and magmatic processes that produced these two calderas. These tutorials direct students to look critically at the geochemical data and to think as a geochemist to answer questions and to "rediscover" for themselves the fundamental principles of geochemistry.

Another module on Teaching Mineralogy with Crystal Structure Databases and Visualization Software utilizes the Mineralogical Society of America Crystal Structure Database (http://minsocam.org/MSA/Crystal_Database.html), thus making scientific resources from a professional society available via the NSDL network. Exercises are developed based on articles in the peer-reviewed literature. One example is the use of Crystal Structures as Geobarometers in which students examine the crystal structures of clinopyroxenes to determine pressure-sensitive crystallographic parameters.

An example of using on-line databases for lower division classes was developed in a module on Environmental Health Risk Inventory in which students locate and use internet based health-related tools and databases (e.g. EPA's Toxic Waste Inventory). This site includes step-by-step instructions for using the online tools and databases, an example environmental health risk inventory, and teaching activities. This module demonstrates how students can do an environmental risk assessment of their hometowns. The MLER project also has an instructional unit with step-by-step instructions on how to use the National Center for Biotechnology Information database for instruction in genomics.

Lessons learned:

a) *The delivery of data and data products through the NSDL can be enhanced by providing sufficient documentation that demonstrates how to access and appropriately use data, tools, and data products.*
b) *Collections of derivative instructional activities can be aggregated or developed to demonstrate increasingly sophisticated applications, and the cognitive strategies of "master scientists" can be articulated as examples of how these data are used to address significant scientific questions.*
c) *The NSDL can engage the larger scientific community by developing interfaces to datasets maintained by professional societies, research facilities, and individual research projects.*
d) *Collections of instructional activities can be developed by addressing the scientific questions and engaging data analysis and interpretation to emulate the actual research done as reported in the peer-reviewed scientific literature. All peer-reviewed journal articles have the potential to be the foundation of data-rich instructional activities.*

Modules Developed for Underrepresented Groups

http://serc.carleton.edu/research_education/nativelands/index.html

We developed a module on Impacts of Resource Development on Native American Lands to see if these modules could be used to help recruit more geoscience majors from underrepresented groups by using a series of case studies by demonstrating the relevance of the underlying science to the students' personal and societal lives. Another learning goal was to engage general students with topical issues that have important policy, ethical and human health implications. The modules include thematic collections developed on: Uranium Mining on the Navajo Reservation; Gold Mining and the Fort Belknap Reservation, Coal Bed Methane and the Crow Reservation; Water Resources and the Nez Perce Reservation; Gold Mining and the Pine Ridge Reservation; and Resources of the Pribilof Islands. A special collection of resources was developed on Tips for Teaching Indigenous People. Most of these modules were developed as part of a Master's thesis on research on learning in a web-mediated environment (Klauk, 2007), and two were authored as independent study projects by non-geology major undergraduate students. We have developed Role Play and Jigsaw activities to accompany these modules, based on pedagogic resources from the Starting Point/Pedagogy in Action projects.

Lessons Learned: These thematic collections proved to be engaging and of high interest for students in an Environmental Geology class. A variety of learning activities can be developed to supplement thematic collections to address different learning goals. Klauk (2007) demonstrated that content mastery using the thematic collections developed for the Uranium Mining on the Navajo Nation module was best facilitated by using a 'jigsaw' approach, whereas affective aspects of learning such as motivating students to learn and establishing personal connections to the situation presented in the case study was best accomplished through role playing activities.

Community-Based Aggregation of Experience and Advice

http://serc.carleton.edu/research_education/mtroadlogs/index.html
http://serc.carleton.edu/research_education/geopad/index.html

The digital library environment has proved to be a particularly useful medium for capturing communal knowledge, wisdom and experience that is not otherwise made available through peer-reviewed literature. This type of information may be well understood by current practitioners as part of the cultural heritage of a discipline, but novices (students, colleagues engaging a new course of study, etc.) typically have an extremely difficult time learning the hidden intricacies of accepted practices. We have experimented with ways to aggregate and disseminate information from legacy ("gray" literature) sources that are not widely circulated in print media. For example, a large part of fundamental geologic knowledge about field occurrences is found in regional road logs and field guides. These limited distribution publications contain essential information that is the foundation for future research and educational activities, but are extremely hard to find. We developed the Montana-Yellowstone Geologic field Guide Database to provide users (field camps, students looking for a new study area) who are newcomers to a field area with information about rock units, major structures, landforms, the field trip route, and other specific information such as land use permissions (if available), and links to related resources. The database of 54 road logs can be searched according to geologic topic, geographic location, and geologic province. This collection of field guides and road logs directs users to physical places of particular geologic interest.

We have also used the digital library environment to capture the aggregate experience and best advice from the community of innovators of new instructional technologies. Early innovators typically work independently while encountering the same types of difficulties and typically "reinvent the wheel". An example of an emerging instructional technology is the use of "GeoPads"—ruggedized computers that can be used directly in the field to record or import data. The advantage of using this technology is that multiple layers of digitized data can be accessed directly in the field (using geographic information system technologies); field notes and annotated digital images and sketches can be produced by students in the field; all control points on a map can be geospatially referenced using an internal GPS receiver; and data reduction software, and reporting functions are built into the system. This technology will be the professional standard for field geologists in the near future, but there are significant barriers to getting this technology set up and we know very little about how to effectively use these instruments in research or teaching. To address these issues, we convened a small working group of the developers of this technology to create a website that captures their best advice. This site provides practical advice on selecting software and hardware, accessing and formatting data, and designing and implementing instructional activities. In addition, "best instructional practices" in using GeoPads are described, including learning goals, expected outcomes, and assessment strategies. GeoPads also have tremendous value in related fields such as ecology, archeology, and any other discipline that requires field work and spatial representations.

Lessons Learned: One of the initial expectations of educational digital libraries was that they would serve as the "intellectual commons" for scholarly communities (Manduca and Mogk, 2000). Serving in this role, the NSDL can provide a medium to help articulate and organize *bodies of information that are widely used by targeted communities but are otherwise undocumented or poorly disseminated. In addition, the NSDL can facilitate the development and implementation of new technologies in STEM education by identifying the innovators and early adopters to aggregate their experience to help move these technologies into regular instructional use.*

Development of Integrated Resources Collections That Cover Topics From "First Principles" to the Most Advanced Modeling Programs

http://serc.carleton.edu/research_education/equilibria/index.html

We were originally interested in developing tutorials on the use of research-level thermodynamic programs (MELTS, ThermoCalc, PERPLEX, TWQ) for use in upper division undergraduate and graduate courses. However, we soon discovered that a thorough treatment of the principles of heterogeneous phase equilibria was required. So, we developed a comprehensive, scaffolded, website that begins with the "first principles" of heterogeneous phase equilibria, beginning with the Gibbs' Phase Rule, and progressing step-wise to multi-component systems, activity models, and finally thermodynamic modeling programs. We utilized teaching activities already available through the On the Cutting Edge Teaching Petrology collections, placing these resources into a complete framework of instruction about heterogeneous phase equilibria. These tutorials were authored by an invited team of experts in the field, all of whom were pre-assigned chapters to write for the module. Using the web-authoring services of the content management system at SERC, we were able to develop the majority of the module like an old-time "barn-raising" in modular fashion during a one weekend writing workshop. Subsequently, authors were able to remotely revise text, add images and figures, format the webpages, and review the entire module. This is an example of a "vertical" collection in which the first couple of modules could be used in a sophomore-level Mineralogy class, the intermediate exercises could be used in junior-level Petrology classes, and the more sophisticated modeling exercises can be used in upper division undergraduate or graduate courses. These online resources can readily be used by students as tutorials to prepare for regular class coverage of the topics, or as a reference base that is referential to material covered in previous courses.

Lessons learned:

a) *Collections of resources can be readily developed by communities of scholars that have a shared interest and investment in a specific topic. Such communities will be well-situated to identify the needs, expectations, scope and breadth, vocabularies, and standards for selection and review for resources on a given topic. The NSDL can provide web-authoring and digital library services (i.e. cataloging, metadata) to help these communities of scholars develop coherent and comprehensive collections of resources.*

b) *The NSDL will continue to grow more efficiently and effectively by harvesting such collections* in toto *rather than by soliciting individual contributions. Face-to-face writing workshops for targeted topics, and more general workshops on teaching (topics, methods; e.g. On the Cutting Edge) have proven very successful ways to involve the community in developing collections of on-line resources.*

Overarching Lessons Learned

The following observations are made from the perspective of one of the co-authors of *Pathways to Progress* (Manduca, McMartin and Mogk, 2001), co-chair of the initial NSDL Community, Education and Pedagogy committee, co-PI of the original Core Integration Services grant, and co-PI of the MLER collections project.

1) A centralized metadata repository is not as effective for use by self-defined communities of users as specialized portals designed and built to address targeted community expectations, needs, and standards. Current user patterns do not indicate that users go to a central portal and then auger in through many layers and linkages to find what they need. Almost all of our users come into our webpages via searches via the open WWW, and they find our sites based on the metadata about each site that we expose to facilitate search and discovery. We receive less than 1% of the referrals to our site from the NSDL portal. Nor has the development of the "Pathways" projects in the past couple of years improved this situation. We developed the MLER project prior to the advent of the Pathways, but to date have not had these resources harvested by the Biological Sciences Pathway. The issue revolves around similar, but not identical, metadata structures, and the cross-walks needed to access the MLER resources have not been developed. Similarly, the MLER and DCS projects contain content that could be of interest to other Pathway projects (e.g. Materials Science) or other digital library projects (e.g. ReciprocalNet, Analytical Sciences). We have built direct links from our site to these other projects, but through the NSDL infrastructure there is no centralized function that helps direct users in one domain to find collections of related resources in other domains. So, in a "Google" world, one has to ask "What is the value of a centralized metadata repository"? And, the original vision of "The NSDL mak(ing) a substantive contribution towards bridging current disciplinary boundaries by effectively integrating concepts, knowledge and methods across the SMET disciplines" (Pathways to Progress, 2001) is far from realized. Integration and repurposing of related resources from the numerous contributing projects is still a long way off. There are a lot of great digital library projects that have been developed; it's not at all clear that these projects have come together synergistically into a unified NSDL.

2) Learning resources must be placed in the full context of scientific principles and results, pedagogic practice, teaching activities, assessments, and opportunities for personal development. A huge benefit of digital library technology is found in the ability to allow users to search and browse according to their own interests and abilities. The ability to navigate "vertically" to discover richer material within a topic, and "horizontally" between related topics (either from "sister" disciplines, or linking Science with pedagogy) adds value to the resources themselves and to the experience of the users.

3) Building thematic collections of resources is useful to a point, but instructors are most interested in having access to instructional resources that they can readily download to adopt or adapt for immediate classroom use. Instructional digital libraries can provide a tremendous service by linking scientific principles, methods and content knowledge with recommended pedagogic strategies, teaching activities, and assessments. Reviewing services are also highly valued by educators. Consequently, instructional digital libraries should be developed in close association with curricular development projects (e.g. NSF-CCLI). One area where the

NSDL could be more proactive is in support of curriculum development projects by providing technical guidelines and assistance to help make the products of these projects "digital library-ready", i.e. including the full complement of information needed to rapidly (and automatically?) create required metadata records.

4) Digital libraries can be used to help build and nurture communities of learning, and can also effectively tap these communities for contributions and reviewing of these resources. We have successfully experimented with community-building of digital resource collections (i.e. the 'barn-raising' model) in a number of topical areas. This model can be expanded by the NSDL in general to proactively seek out groups who have yet to participate in the NSDL, or who are underrepresented in the current collections, to help them build thematic collections to meet their immediate interests. These efforts can gain value by drawing from, and contributing to, existing collections from related disciplines. This is in accord with the early vision of the NSDL as a "federated" network, with the common goal of supporting excellence in STEM education and adhering to a set of technical standards for interoperability, but with enough autonomy to enable each community to grow its own collections and services as dictated by community standards, practice and expectations.

5) Digital library technology can optimize the use of resources by diverse audiences by facilitating repurposing and enabling bi-lateral links between closely related collections of resources. Once a user enters one of our digital collections, we attempt to keep their interest by either a) embedding direct links to related information, or by b) providing explicit "Related Links" to direct users to other sites or modules where information that will likely be of interest (e.g., Fox et al., 2005). These hard-wired related links have paid great dividends to us in terms of developing a loyal user base, and also for the users who are exposed to new information that should or could be of interest. This is another area where the NSDL could be more effective: helping PIs establish these bi-lateral links among the many NSDL projects. The NSDL Annual Meeting has been partially effective in providing a forum to introduce PIs and their projects to each other via poster sessions, discussion sessions, and oral presentations. The central portal is less effective in this regard. As an example, to learn something about thermodynamics it is not very effective to start at the main portal, and then explore resources in chemistry, back out and dive in again in physics, and then engineering, and then Earth science….whereas treatment of thermodynamic properties could easily be explored side by side with examples from each of these disciplines using bilateral links.

6) Digital libraries can also be used to effectively create collections of non-digital resources (e.g. links to instrumentation and facilities), to make available the "gray literature" of a field, and to capture the experience and advice of a community that is not readily available through other media. The concept of digital resources can be expanded to include instruments, literature, people, and ideas (not formally represented in print or web media) by creating appropriate metadata that makes these "learning objects" discoverable through a digital library environment.

Summary

The NSDL is well-positioned to facilitate integration of research and education in support of NSF's overall mission. The unique navigational capabilities provided by the digital library environment allows connections to be made directly between scientific content and pedagogic practice, placing research outcomes and instructional materials in close proximity for use by instructors and learners. Digital libraries provide a great environment to promote learning through inquiry and discovery, and can readily transcend disciplinary boundaries by facilitating repurposing and establishment of bi-lateral links between related bodies of knowledge. The most important aspect of digital library collections and services is to place learning resources in contexts that are useful to targeted communities of users. In this regard, a variety of approaches to creation of thematic collections can be used to address the interests, needs and expectations of different learning communities. The concept of a collection in a digital library should be expanded to include instructional activities, web-based resources, data, tools, data products, research methods, non-digital learning resources, community experience (hard-to-find print materials and otherwise undocumented "common wisdom"), and information about people, places and things. The NSDL can play an essential role in support of NSF's mission by providing dissemination services to help researchers funded by the disciplinary directorates to address the broader impacts of their work, and at the same time, infuse exciting new scientific methods and results into STEM education at all levels and for all audiences.

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