PAPER

Characterizing Complex Marine Systems and Technology Using Visualized Vocabularies

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ABSTRACT

The next decade will usher in significant changes in ocean observational infrastructure and how students engage with marine sciences content. Faced with the challenge of helping undergraduate students make sense of very complicated marine systems, a computer sciences-based organizational structure (i.e., ontology) has been employed to characterize the Ocean Observatories Initiative (OOI). Five interlinked vocabularies that include terms, descriptions, and images define the overall system from high-level science themes to specialized data products. Given the importance of visual representations in learning, particularly for novices, an associated interactive tool called the "Vocabulary Navigator" has been developed. Created in tandem, the design of the vocabularies and their visualizer is based on principles related to the needs of the target audience such as placing information in a broader context and promoting self-directed discovery. Overall, this effort has resulted in not only innovative online resources for learning about the OOI but also, perhaps more importantly, valuable "lessons learned" and transferable software that could be used by other marine technology endeavors.

Keywords: ocean observing, marine technology, ontology, vocabulary

Background

Advanced marine technologies provide "unparalleled views of the ocean basins, their changing interaction with the atmosphere, the great biological shifts in near-surface waters, and the emerging view of the long-hidden deep ocean basins" (National Science Foundation [NSF] Ocean Sciences Decadal Committee, 2001). Funding agencies such as the NSF have invested significantly in ocean observational infrastructure. The vision statement in a recent report from the Committee on Guidance for NSF on ocean research priorities includes the creation of "innovative educational programs that will engage and inspire the next generation" over the next decade (National Research Council [NRC], 2015).

Beyond engaging and inspiring students, there is a critical need for enhanced workforce development in science, technology, engineering, and mathematics (STEM) fields. This issue has been addressed in numerous national reports (e.g., American Association for the Advancement of Science, 2011; NRC, 1999; NSF Advisory Committee to the Directorate for Education and Human Resources, 1996; Rutherford & Ahlgren, 1991), which led the President's Council of Advisors on Science and Technology (PCAST, 2012) to outline a plan for producing one million additional college graduates with degrees in STEM over the next decade. Key to this goal is diversification of teaching methods beyond traditional lectures, particularly the adoption of effective, evidence-based pedagogy. One such example, discipline-based education research, focuses on students gaining in-depth knowledge of the fundamental concepts, nature, and practices of a discipline, along with understanding its domain-specific representations like graphs, models, and simulations (Kober, 2015; NRC, 2012).

The complex nature of ocean sciences makes its visualized representations particularly challenging for undergraduate students to grasp. In the 2012 report, "Visualizing Oceans of Data—Educational Interface Design," Krumhansl et al. recommend designing representations with the appropriate cognitive load for students. Key guidelines include providing complementary information in multiple formats, eliminating unnecessary distractions, drawing attention to important features and patterns, and enabling users to customize the information they are seeing (Krumhansl et al., 2013).

The future of ocean sciences will continue to rely on increasingly complicated technology and data. The future of ocean sciences education relies on making such content approachable to the next generation of scientists. To do so will require innovation that is grounded in good educational principles, merging effective practices in interface design and cognitive science. Today's ocean observation systems provide exciting testing grounds for cross-disciplinary efforts to provide data, information, and integrated resources for education.

Project Overview

Ever-expanding ocean observation systems (e.g., Global Ocean Observing System, Integrated Ocean Observing System, Ocean Observatories Initiative [OOI]) are being used to monitor societally relevant issues such as climate change and ocean acidification. The evolution of these systems, however, has outpaced the ability of traditional educational materials such as textbooks to adequately represent their complexity. Thus, the need for tools through which nonscientists can explore both ocean science and its latest technologies is becoming more imperative.

Building a bridge between the broad appeal of ocean sciences and the inherent details of marine technologies is a significant undertaking. To address the linkages between marine technology and its scientific drivers, this effort took advantage of an organizational structure widely used in computer science, known as "ontologies." An ontology is a formal description of knowledge encompassing a particular subject area, called a domain (Noy & McGuinness, 2001). The domain described may encompass an entire subject or discipline (e.g., ocean sciences) or a particular facet (e.g., salinity measurements).

In computer science, ontologies are defined more specifically as collections of encoded *terms* and *relationships* used to facilitate communication between computer systems (Antoniou & van Harmelen, 2004). As seen in Figure 1 (top), relationships between terms are mapped using standard symbols (e.g., > or <). For marine scientists, ontologies are often used to describe dense, complex systems and are highly appropriate for organizing information about ocean observing infrastructure and marine technology (Rueda et al., 2009).

For this effort, however, it was important to create software that allows nonscientists to see and explore the elements contained within a marine sciences ontology. Thus, an online visualization tool, known as the "Vocabulary Navigator," was created in conjunction with a specialized ontology describing the OOI. Within the OOI's Vocabulary Navigator, ontological *terms* are viewed as interactive objects, while *relationships* are depicted as labeled arrows between objects (Figure 1, bottom).

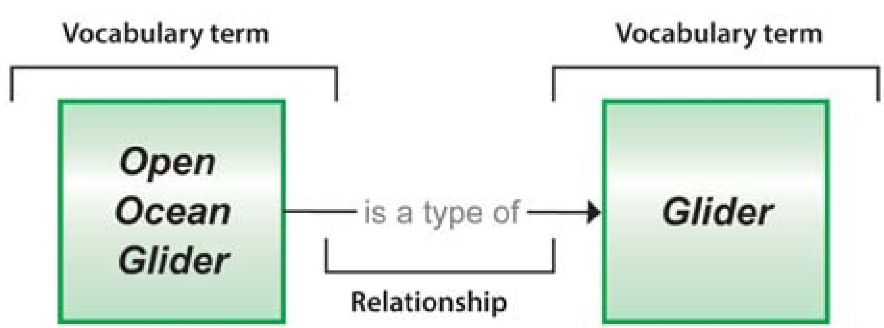
Funded by the NSF, the OOI is an integrated infrastructure of science-driven platforms and sensor systems to measure physical, chemical, geological, and biological properties and processes from the seafloor to the air-sea interface. The OOI consists of seven arrays—one cabled, two coastal, and four global. There are over 800 instruments deployed among these arrays from nearly 75 models of specialized instrumentation that measure or derive over 200 unique data products. After final deployment and commissioning, OOI operations are expected to continue for up to 25 years.

To capture the complexity of this enormous endeavor for nonscientists, it was necessary to develop specific tools such as the Vocabulary Navigator, part of the OOI Education and Public Engagement (EPE) software infrastructure. Collectively known as the "Ocean Education Portal" (OEP), these tools and their underlying resource database can be accessed online by a computer or mobile device at

FIGURE 1

An example of the relationship between vocabulary terms established by an ontology (top) and visualized by the Vocabulary Navigator (bottom). Ontologies provide formal structure through "mapping" the relationships between terms using mathematical symbols (top). The Vocabulary Navigator converts these coded relationships into arrows and linking terms (bottom).

Vocabulary term	Relationship	Vocabulary term
A:/ooi_platforms	>	A:/mobile_asset
A:/ooi_platforms	>	A:/mooring
A:/open_ocean_glider	<	A:/glider
A:/open_ocean_profiler_mooring	<	A:/wire-following_profiler_mooring
A:/open_ocean_profiler_mooring	>	A:/mid-water_platform



http://education.oceanobservatories.org.

Methodology

This effort has involved the creation of an ontology consisting of five distinct vocabularies, each covering a specific portion of the OOI program (i.e., science, sites, platforms, instruments, and data products; see Table 1). Each vocabulary contains three major elements: (1) *terms* chosen to represent OOI-relevant concepts; (2) a *description* for each term; and (3) links to relevant educational *images* in the OEP database, which were newly created or modified from existing materials to be audience appropriate.

The vocabularies were created in spreadsheets listing terms, their descriptions, and hyperlinks to images in the OEP database. These files were then uploaded into the Marine Metadata Interoperability (MMI) Ontology Registry and Repository, a public database of vocabularies and mappings in marine science domains (http://mmisw.org/orr/). The MMI Web application converts these spreadsheet-based terms and descriptions into a standard ontology format, coded as Extensible Markup Language (XML), which can be read by the Vocabulary Navigator.

After contents of the spreadsheets were uploaded, the MMI application was used to "map" terms within and between the vocabularies. This step provided the organizational structure needed to establish connections displayed by the Vocabulary Navigator including arrows labeled with linking phrases that describe relationships between terms (Figure 1). By combining the vocabulary content and mappings, the Vocabulary Navigator allows users to view and explore interterm relationships or investigate any term's description and image(s).

Design Principles

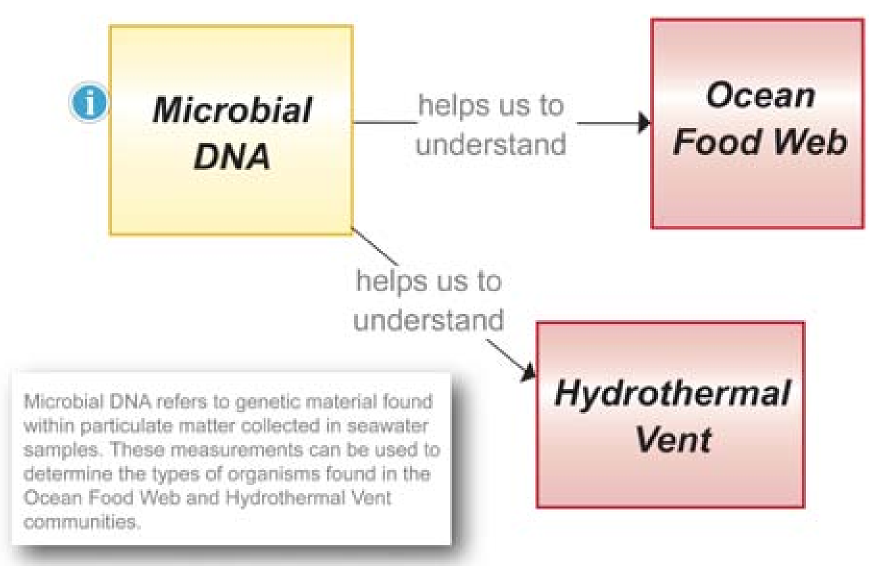
The ontology and Vocabulary Navigator are designed using three key principles to ensure their educational effectiveness, including (1) meeting the needs of the *target audience* of undergraduate students not majoring in science, (2) placing detailed information within a *broader context*, and (3) *promoting exploration* of connected concepts using a visual tool.

Given the target audience of nonscience undergraduates, the ontology's language (i.e., terms and their descriptions) is aimed at the high school level, avoiding or explaining jargon as necessary. Gleaned from OOI documentation (Consortium for Ocean Leadership [COL], 2012, 2011, 2007), the original candidate ontology list totaled 335 terms. These were grouped or split as necessary to achieve a level of complexity suitable for the target audience. Examples of grouping include equivalent instruments that are subsumed within one term (e.g., Conductivity, Temperature, and Depth sensors or "CTDs"). Conversely, much of the content of the "Science" vocabulary is deconstructed from the six overarching "science themes" being addressed by the OOI (COL, 2007). Descriptions are purposefully kept brief (i.e., two to four sentences), using capitalization to emphasize the importance of linked terms (Figure 2).

Along with language-level considerations, the organization of information within vocabularies is designed to aid the audience's comprehension of its context. The Vocabulary Navigator includes arrows and linking phrases between terms, allowing the user to infer broader meaning. A key objective of the ontology, however, is to not overwhelm users with excessive visual objects. Thus, by design, no term has more than 24 direct connections. Implementation of this constraint required adding 27 new higher order terms to the

FIGURE 2

Example output of the Vocabulary Navigator. Terms within the ontology are presented as squares. The arrows' linking phrases and directionality are determined by the ontology. Capitalization within descriptions highlights other terms in the ontology (i.e., *Ocean Food Web* and *Hydrothermal Vent*).



overall ontology (e.g., *Physical*, *Biological*, *Chemical*, and *Geological Oceanography Data Products* were added to the "Data Products" vocabulary). The resulting ontology (i.e., vocabularies in Table 1) has 245 terms, a 27% reduction relative to the original list.

The ontology has flexible starting points and no "dead ends," thereby promoting self-directed exploration. The five vocabularies are distinct from one another yet highly complementary. Definitions include terms from other vocabularies to encourage exploration and have consistent language levels, regardless of how deeply or broadly the user ventures. Overall, this approach is designed to promote open-ended discovery, allowing users to investigate topics at their own pace and to the extent that they wish.

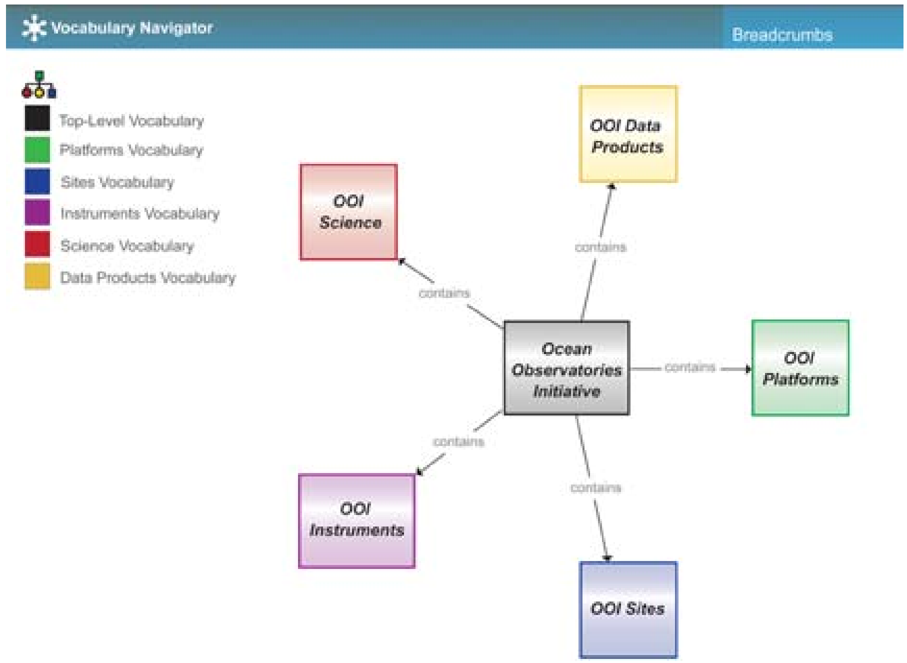
At its top level, the Vocabulary Navigator automatically loads the central "parent" term—*Ocean Observatories Initiative*—with links to the entry points for the five vocabularies (Figure 3). Each of the five vocabularies has a unique color. Thus, if a map contains terms from multiple vocabularies, their sources are easily distinguishable through the color-coded legend. Functionally, deselecting a color in the legend hides all the terms from that particular vocabulary.

If a user has a specific interest, he or she can enter a keyword in a search field, which generates a drop-down list of matching terms. Selecting any of these generates a new map with that term at its center. As shown in Figure 4, hovering over a term and selecting the relevant icon reveal associated descriptions (i.e., "i" button) or captioned images (i.e., camera).

Clicking on any term will create a new map with that term as its center. As a user progresses through the ontology, a list of breadcrumbs is revealed (Figure 4). Hovering over items in the breadcrumb list displays thumbnail images of previously generated maps, which can be revisited. The ability to examine their path through the ontology is another piece of contextual information provided to the user by the Vocabulary Navigator.

FIGURE 3

Top-level vocabulary terms for the OOI. Terms throughout the ontology are color coded to reflect the vocabulary from which they are drawn.



Example Pathway Through Vocabularies

To illustrate the contents of the ontology, this section describes a path

TABLE 1

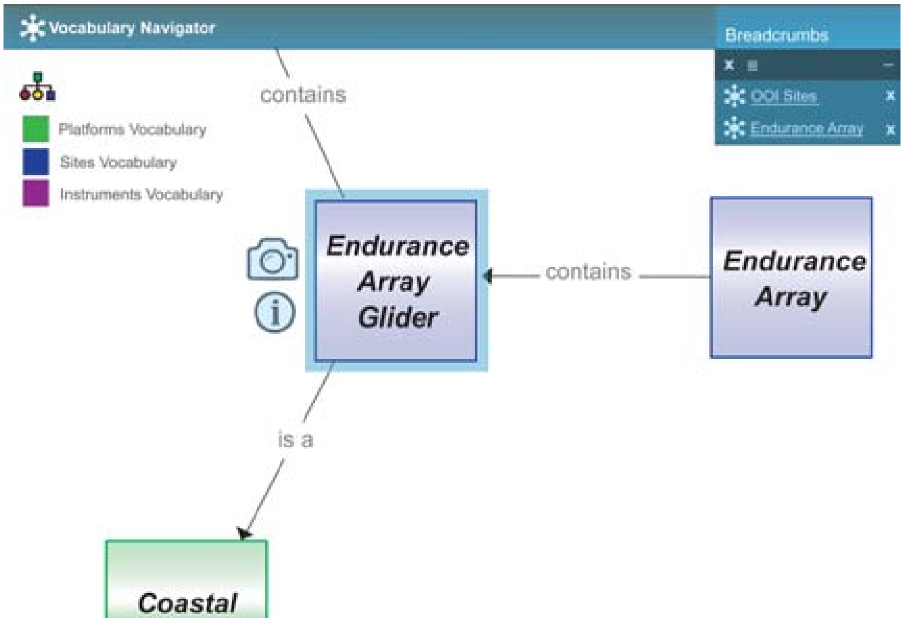
OOI vocabularies, their contents, and example terms.

Vocabulary	Overview of Vocabulary Contents	Example Terms
Science	High-level scientific concepts being investigated.	*Climate*, *Ocean Acidification*, *Seismology*
Sites	Locations where remote sensing equipment are deployed.	*Cabled Array*, *Pioneer Array*, *Station Papa*
Platforms	Types of oceanographic platforms deployed at the sites.	*Moorings*, *Gliders*, *Autonomous Underwater Vehicles*
Instruments	Scientific instrumentation mounted on observing platforms.	*CTD*, *Hydrophone*, *Water Temperature Sensor*
Data Products	Parameters measured or derived by the instruments.	*Salinity*, *Water Temperature*, *Turbidity*

Each vocabulary covers a specific component of the OOI and collectively comprises the ontology developed during this effort.

FIGURE 4

Vocabulary Navigator icons and "breadcrumbs." Each term has a description, accessed by clicking the "i" icon. Terms with attached images also have a camera icon. The user's click path through various terms is revealed as an interactive breadcrumb list (top right).



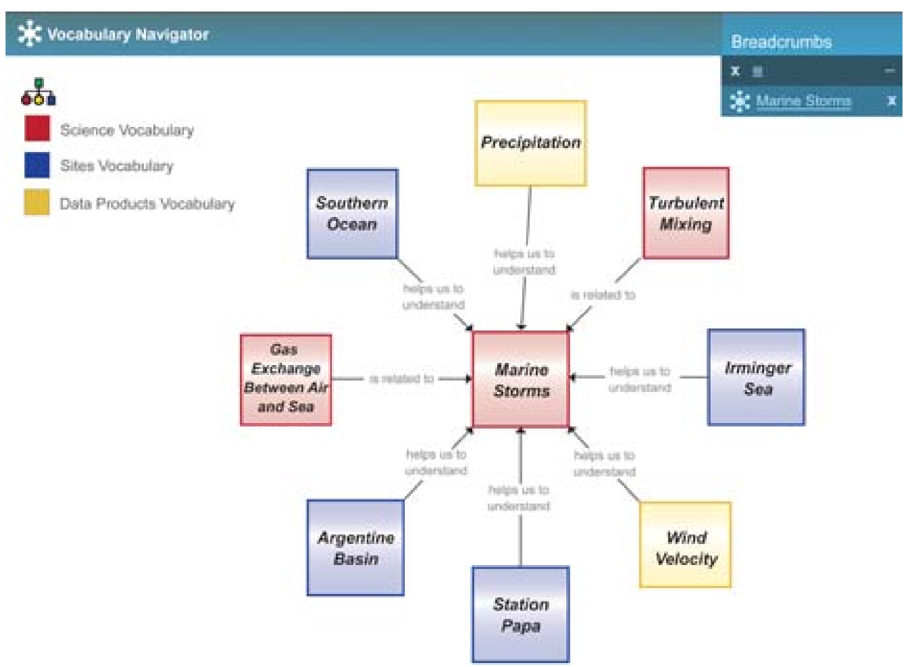
through the five vocabularies (Table 1) as navigated by a student who is interested in storms. The journey begins with the student entering the term *storms* in the search field, which causes *Marine Storms* to appear as a drop-down list option. Selecting this option automatically generates the map shown in Figure 5 whose central concept is found in the "Science" vocabulary.

The "Science" vocabulary describes the natural phenomena being addressed by the OOI at its sites and through its data products. The *Marine Storms'* map legend (top left of Figure 5) shows that its content is pulled from three vocabularies: "Science," "Sites," and "Data Products." As prescribed by the ontology, the linking phrase, "is related to," connects *Marine Storms* with two other terms in the "Science" vocabulary (e.g., *Turbulent Mixing*). On the other hand, terms from the "Sites" (e.g., *Irminger Sea*) and "Data Products" (e.g., *Wind Velocity*) vocabularies have a common linking phrase, "helps us to understand."

As opposed to some of the vocabularies created for this project, which required extensive grouping of terms, the "Science" vocabulary began with a few overarching themes that were too complicated for the target audience of nonscientists. These themes were deconstructed into more specific elements. For example, *Marine Storms* is derived from OOI's theme on ocean-atmosphere exchange, a broad umbrella that also encompasses the ocean's nitrogen and carbon cycles. While creating the "Science" vocabulary, an important design element was judiciously highlighting key linkages rather than displaying all possible interconnections. Given these considerations, the "Science" vocabulary grew from six parent OOI themes to 57 terms.

FIGURE 5

Pathway step focused on the "Science" vocabulary. The central concept, *Marine Storms*, is viewed in the context of other science terms, along with terms from the "Sites" and "Data Products" vocabularies. Overall context shows that data from various OOI sites are being used to understand *Marine Storms*.

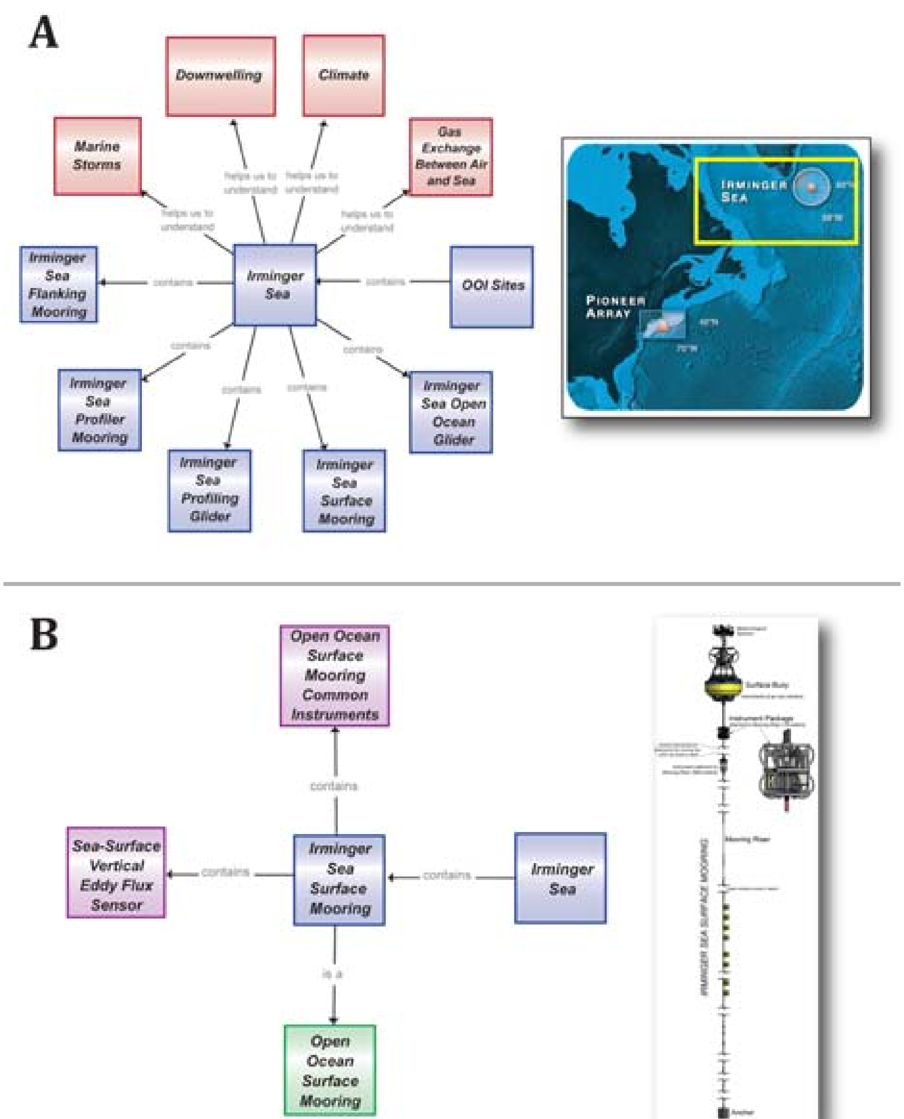


Being unfamiliar with the *Irminger Sea*, the student clicks on this term from the “Sites” vocabulary. The resulting map (Figure 6A) shows how studying this region “helps us to understand” various science topics including *Downwelling*, *Climate*, and air-sea gas exchange.

Within the “Sites” vocabulary, one arrow points toward the center from the parent term *OOI Sites*. Other arrows in this vocabulary point outward to *Irminger Sea* subsites. Subsite terms describe the major infrastructure categories deployed within OOI sites. In the Irminger Sea, for example, there are three types of moorings (i.e., surface, flanking, and profiler) and two types of gliders (i.e., profiling and open ocean).

FIGURE 6

Pathway step focused on the “Sites” vocabulary. The central concepts, *Irminger Sea* (A) and *Irminger Sea Surface Mooring* (B), are examples of an OOI site and subsite, respectively. Image insets show the location of OOI infrastructure within the Irminger Sea (A) and a technical drawing of the surface mooring (B), which has been modified for the target audience of nonscientists.



An important feature of the “Sites” vocabulary is its linked images, which reflect the differences between sites and subsites. For sites, images show the geographic position within the ocean basin. The inset of Figure 6A shows the location of OOI’s Irminger Sea site in the North Atlantic Ocean, off the southern coast of Greenland. For subsites, simplified audience-appropriate technical infrastructure drawings are provided. For example, clicking on the subsite term *Irminger Sea Surface Mooring* allows the student to access an image depicting hardware from the ocean surface to the seafloor, including an instrument package at 15-m depth (see inset of Figure 6B).

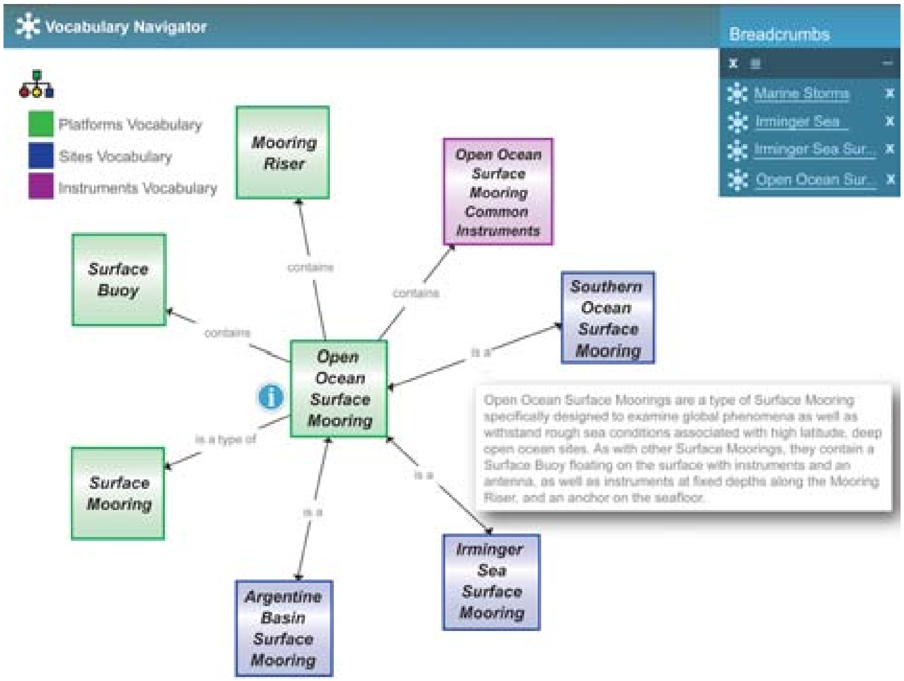
Interested in learning more about technology in general, the student selects the term *Open Ocean Surface Mooring*, which is found in the “Platforms” vocabulary (Figure 7). She immediately sees that this type of mooring is located not only in the Irminger Sea but also in the Southern Ocean and Argentine Basin. The map also references two terms she previously saw in the *Irminger Sea Surface Mooring* image (Figure 6B, inset): *Surface Buoy* and *Mooring Riser*.

Rolling her cursor over the “i” icon of the central term reveals the definition of the *Open Ocean Surface Mooring*. It states that it is “a type of Surface Mooring specifically designed to examine global phenomena as well as withstand rough sea conditions associated with high latitude, deep, open ocean sites.”

The “Platforms” vocabulary describes the types of infrastructure deployed at various OOI subsites. All terms are parsed under three higher order categories: *Mooring*, *Mobile Asset*, or *Benthic Node*. Unlike the other vocabularies whose contents are directly derived from OOI lists, “Platforms”

FIGURE 7

Pathway step focused on the "Platforms" vocabulary. The central concept, *Open Ocean Surface Mooring*, is seen to contain other platform-related terms (e.g., *Mooring Riser*) and is also present at other OOI sites (e.g., Argentine Basin). The definition for *Open Ocean Surface Mooring* explains that this infrastructure is specifically designed to withstand rough ocean conditions.



The "Instruments" vocabulary describes sensors deployed by the OOI on its platforms. To achieve a level of detail appropriate for the target audience, instruments with the same general functionality are subsumed in a group. For example, OOI documents differentiate five CTD types based on their associated platform. The non-scientist undergraduates for whom the ontology is designed, however, need only one term for CTD. Such grouping within the "Instruments" vocabulary reduced OOI's original list by about 40%.

Interested in waves caused by ocean storms, the student clicks on the *Surface Wave Sensor*, which is contained within the higher order term, *Physical Oceanography Instruments* (Figure 9). She immediately sees that these sensors are also used at other OOI sites (i.e., Pioneer and Endurance).

was specifically created to provide critical linkages between sites, subsites, and the instruments deployed in these areas.

Eager to learn more about the types of equipment that could survive severe marine storms, the student clicks on the term from the "Instruments" vocabulary, *Open Ocean Surface Mooring Common Instruments.* To better focus on the instruments, she uses the Vocabulary Navigator's color-code functionality to hide all terms from other vocabularies (Figure 8). At a glance, the student can see the instruments contained in all open ocean surface moorings, including a meteorological package, biogeochemical sensors, and physical oceanography equipment. Most instruments are accompanied by photographs taken in the laboratory, during deployment, or *in situ*.

FIGURE 8

Pathway step focused on the "Instruments" vocabulary. With terms from the "Platforms" and "Sites" vocabularies hidden from view, the user can focus on the 13 common instruments contained on OOI's open-ocean surface moorings.

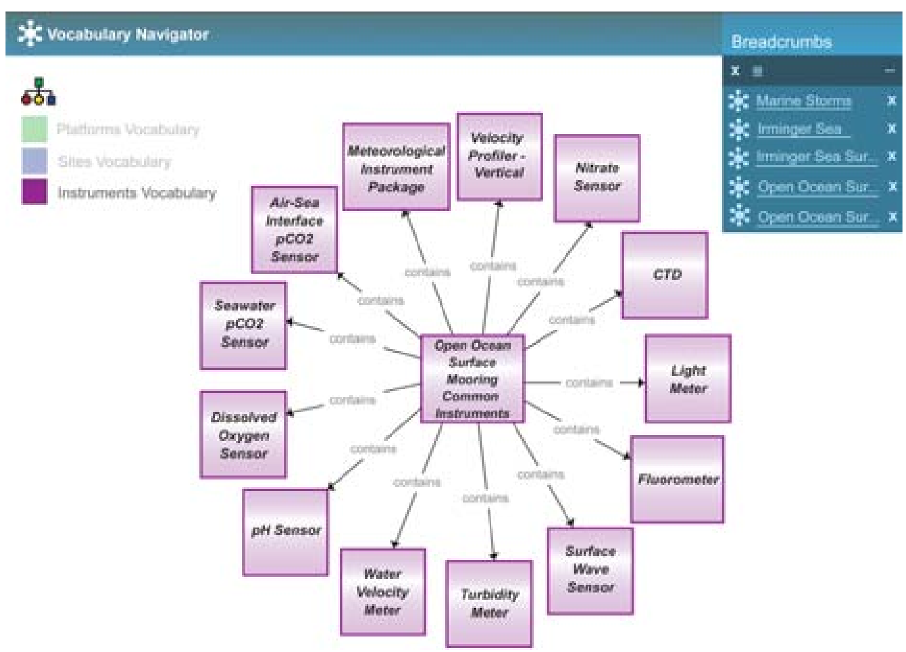


FIGURE 9

Final pathway step. The central concept, *Surface Wave Sensor*, has a direct connection to a term from "Data Products" vocabulary, *Wave Properties*. In addition to seeing the relationship between this instrument and its data, the user can see that these physical oceanography sensors are also deployed in the Endurance and Pioneer arrays. The thumbnail map adjacent to the breadcrumb list can be used to view and revisit previous steps.

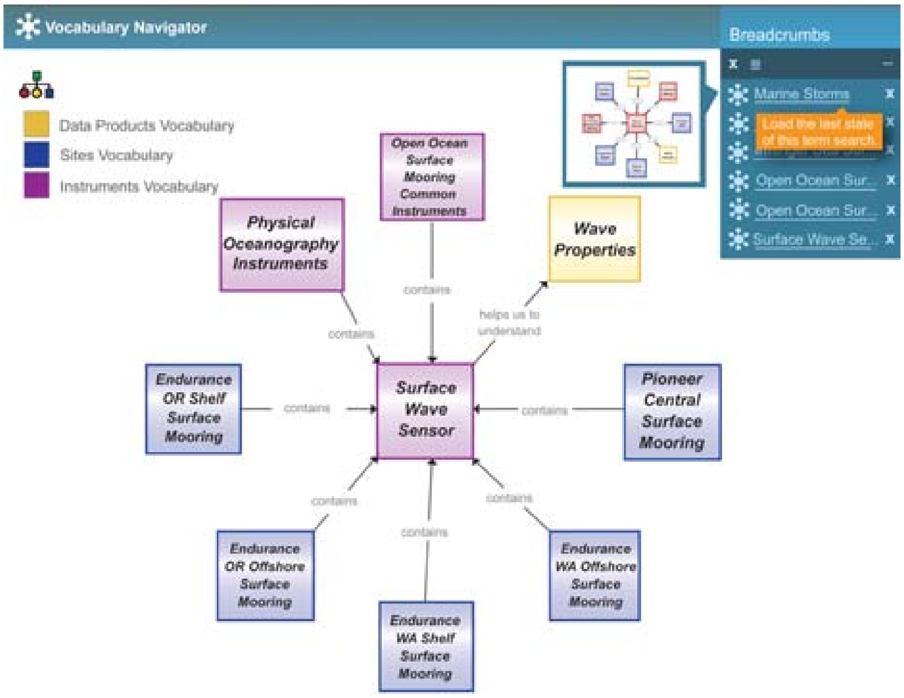


Figure 9 includes a term from the "Data Products" vocabulary, *Wave Properties*. This vocabulary describes parameters measured or derived by instruments in the OOI. The list of data products was greatly reduced (84%) from the OOI Data Product Catalog (COL, 2012), which has 201 items intended for use by scientists and system engineers.

Having begun with a keyword search of "storms," the student's journey through five vocabularies is captured by the Vocabulary Navigator's breadcrumbs (Figure 9, top right). This list provides thumbnail images of earlier maps, in case she'd like to revisit previous terms or she could continue exploring new terms in the ontology to learn more about the OOI.

Potential Educational Applications

By virtue of its design and implementation, the Vocabulary Navigator is an open-ended and inquiry-based tool that can flexibly meet the needs of undergraduate students in many scenarios. The "Example Pathway" above demonstrates how an individual student could use it to understand the continuum from scientific objective to in-water collection sites, technologies, and data. Below are some additional examples of potential activities or assignments for which the Vocabulary Navigator could be used as a point of student engagement and investigation:

- Search on keywords to decide and/or define key questions for science projects.
- Within groups, investigate one particular facet of the OOI (e.g., science, instruments, data), and then merge this information with others to identify key interconnections.
- Research the technology being used to monitor noteworthy ocean events (e.g., Axial Seamount eruption).
- Use field-based images to get a sense of the processes used and career types employed to conduct authentic oceanographic research.
- Explore the OOI as a model for students to design their own ocean observation experiments.
- Based on Vocabulary Navigator map outputs, add new concepts related to, but beyond the scope of, the OOI.

In addition, the maps and linked graphics can serve as background information for student reports, presentations, and so forth.

Lessons Learned

This effort straddles two disciplines, computer and ocean sciences, to create a tool for nonscientists. This nontraditional approach provides several "lessons learned," which may be applicable to and beneficial for other large ocean observing infrastructure and marine technology projects.

Context Is Key

Describing a multifaceted, complicated system requires describing not only *what* but also *why*. In the case of the OOI ontology, the former are vocabularies for "Sites," "Platforms," and "Instruments," while the latter are the "Science" and "Data Product" vocabularies. Mapping relationships within and between these vocabularies adds value well beyond the individual terms and definitions. Moreover, exploring intervocabulary connections helps students gain in-depth knowledge of the nature of ocean sciences, tracing the path from high-level scientific objectives through instrumentation to data products (Kober, 2015; NRC, 2012).

Emphasize the Strongest (i.e., Rather Than All) Connections

Ontologies are powerful tools for formalizing terms and their relationships. Typically, they are used to catalog large groups of information to be read by computers rather than humans. In those cases, there is no need to worry about the end user's "cognitive load," and no value is lost in making all possible connections. The ontology created for this effort's target audience of undergraduate students, however, required judicious decision making for each vocabulary and mapping. For example, the term *climate* could be connected to dozens of terms in each vocabulary, but doing so would overwhelm, rather than inform, the end user. Thus, during the ontology development, decisions were made based on a discrete set of core design principles, which focused on drawing attention to important contextual features and promoting individual exploration (i.e., after Krumhansl et al., 2013). By prioritizing and including only the most relevant connections, the Vocabulary Navigator allows nonscientists to quickly grasp any term's broader context and follow their own meaningful pathway through the ontology.

Tap Into the Strengths of Ontologies While Compensating for Their Limitations

The inherent power of ontologies is in providing a formal structure that can limit complexity and organize information. Terms and vocabularies must adhere to a rigid format, and their relationships are limited to five options, which are operationally defined by symbols (>, <, =, ~, ≈). By default, computers translate these symbols to standard phrases (Table 2). For example, MMI employs Simple Knowledge Organization System (SKOS) methodology, which draws connectivity between two terms (i.e., object and subject) based on a predicate (i.e., interpretation of the relationship between the two). While creating the ontology for this effort, however, it was clear that the default phrases used by SKOS would not be suitable for the target audience. While adhering to relationships defined by SKOS, time was spent on customizing the text of linking phrases to better describe the relationships being displayed by the Vocabulary Navigator (Table 2). As a result, the ontology's strength in logically defining relationships between terms and vocabularies is retained while its output is tailored to meet the needs of nonscientists. The resulting vocabularies and mappings, including customized linking phrases, are derived from a single XML document that was created specifically for this project and could readily be adapted by others. Furthermore, the OOI ontology is available on MMI and readable without the aforementioned XML document.

Conclusions

The landscapes of oceanography, computer, and learning sciences are evolving rapidly. Strategic planning

TABLE 2

Examples of the five relationship options within vocabularies defined by the ontology including the default and customized linking phrases.

Term A (Example)	Term B (Example)	Symbol	Default Linking Phrase	Customized Linking Phrase
Platform type (*Coastal Glider*)	Platform group (*Glider*)	A < B	*has broader match*	*is a type of*
Platform type (*Coastal Glider*)	Platform instance (*Pioneer Array Glider*)	A = B	*has exact match*	*is a*
Instrument (*Dissolved Oxygen Sensor*)	Data product (*Dissolved Oxygen Concentration*)	A ~ B	*has related match*	*helps us to understand*
Science theme (*Plate-Scale, Ocean Geodynamics*)	Science keyword (*Oceanic Tectonic Plates*)	A > B	*has narrower match*	*contains*
Science keyword (*Oceanic Tectonic Plates*)	Science keyword (*Seismology*)	A ≈ B	*has close match*	*is related to*

Default phrases from the ontology (e.g., "has broader match") are replaced by customized phrases (e.g., "is a type of") to provide added meaning for the target audience (e.g., "*Coastal Glider* is a type of *Glider*").

efforts to define key actions over the next decade have documented the need for improved undergraduate education in STEM. In parallel, advances in technology have opened up an exciting new world of discovery for marine professionals. However, a high degree of complexity, coupled with discipline-specific jargon, presents a significant hurdle for engaging novices who are interested in marine infrastructure and its scientific objectives.

With effective practices for undergraduate STEM learners in mind, this effort has taken advantage of computer-aided organization of information to represent one complicated marine system. Although the ontology created during this effort focuses on the OOI, it is accessible from a community-maintained repository of marine ontologies (i.e., MMI). In addition, the Vocabulary Navigator software has been designed for potential use by other projects. As the OOI becomes increasingly important to society, it is anticipated that the Vocabulary Navigator will be a key tool in achieving the long-term goal of improving marine technology education for the next generation of scientists.

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References

American Association for the Advancement of Science. 2011. Vision and Change in Undergraduate Biology Education: A View for the 21st Century. Available from http://visionandchange.org.

Antoniou, G., & van Harmelen, F. 2004. A Semantic Web Primer. Cambridge, MA: MIT Press. 272 pp.

Consortium for Ocean Leadership. 2007. Ocean Observatories Initiative Scientific Objectives and Network Design: A Closer Look. Available from http://oceanleadership.org/files/Science_Prospectus_2007-10-10_lowres_0.pdf. Accessed March 1, 2015.

Consortium for Ocean Leadership. 2011. Ocean Observatories Initiative Final Network Design. Available from http://oceanobservatories.org/wp-content/uploads/1101-00000_FND_OOI_ver_2-09.pdf. Accessed March 1, 2015.

Consortium for Ocean Leadership. 2012. Ocean Observatories Initiative Technical Data Package. Available from http://tdp.oceanobservatories.org. Accessed March 1, 2015.

Kober, N. 2015. Reaching Students: What Research Says About Effective Instruction in Undergraduate Science and Engineering. Board on Science Education, Division of Behavioral and Social Sciences and Education. Washington, DC: The National Academies Press.

Krumhansl, R., Peach, C., Foster, J., Busey, A., Baker, I., & DeLisi, J. 2013. Visualizing Oceans of Data: Educational Interface Design. Waltham, MA: Educational Development Center, Inc. 76 pp.

Noy, N., & McGuinness, D. 2001. Ontology Development 101: A Guide to Creating Your First Ontology. Stanford Knowledge Systems Laboratory Technical Report KSL-01-05 and Stanford Medical Informatics Technical Report SMI-2001-0880. Stanford, CA: Stanford University. 25 pp.

National Research Council. 1999. Transforming Undergraduate Education in Science, Mathematics, Engineering, and Technology. Committee on Undergraduate Science Education, National Research Council. Washington, DC: The National Academies Press. 126 pp.

National Research Council. 2012. Discipline-Based Education Research: Understanding and Improving Learning in Undergraduate Science and Engineering. Committee on the Status, Contributions and Future Directions of Discipline-Based Education Research. Board on Science Education, Division of Behavioral and Social Sciences and Education. Washington, DC: The National Academies Press. 263 pp.

National Research Council. 2015. Sea Change: 2015-2025 Decadal Survey of Ocean Sciences. Washington, DC: The National Academies Press. 120 pp.

National Science Foundation Advisory Committee to the Directorate for Education and Human Resources. 1996. Shaping the Future: New Expectations for Undergraduate Education in Science, Mathematics, Engineering, and Technology. Available from http://www.nsf.gov/publications/pub_summ.jsp?ods_key=nsf96139. Accessed December 11, 2014.

National Science Foundation Ocean Sciences Decadal Committee. 2001. Ocean Sciences at the New Millennium. Arlington, VA: National Science Foundation. 152 pp.

President's Council of Advisors on Science and Technology (PCAST). 2012. Engage to Excel: Producing One Million Additional College Graduates with Degrees in Science, Technology, Engineering and Mathematics. Washington, DC. Executive Office of the President, President's Council of Advisors on Science and Technology.

Rueda, C., Bermudez, L., & Fredericks, J. 2009. The MMI Ontology Registry and Repository: a portal for marine metadata interoperability. In: Oceans 2009, MTS/IEEE Biloxi-Marine Technology for Our Future: Global and Local Challenges, 1-6. New York: IEEE.

Rutherford, J., & Ahlgren, A. 1991. Science for All Americans. New York: Oxford University Press. 271 pp.