Interactive Network Visualization of Educational Standards, Learning Resources and Learning Progressions

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***Abstract*—We present a novel, network- and browser-based visualization of the Next Generation Science Standards (NGSS). The NGSS are meant to guide (USA) K-12 science and engineering learning and are almost always presented using text and tables. Understanding, explaining and navigating the NGSS through tables and text, however, is difficult. In this paper we present a different approach, namely one that capitalizes on the explicit network structure of the NGSS. By rendering the NGSS and its parts as interactive, visual networks, the NGSS becomes much easier to comprehend and navigate. In addition, whereas representing the NGSS with tables and texts hides patterns and anomalies, network visualization makes them prominently stand out.**

Keywords*—*NGSS, networks, visualization, K-12 standards

I. Introduction: K-12 Educational Standard Sets

In the USA, individual states determine what students are expected to learn as part of their K(indergarten) to 12th grade education. Hence, all states periodically –on average every five years or so– (re)formulate their own version of K-12 learning outcomes for fields such as Social Science, English, Physics, Environmental Science, Math, History, *etc*. To glean an impression of the resultant complexity of this 'educational standards landscape,' we invite the reader to browse http://asn.jesandco.org/resources/ASNJurisdiction [1].

This proliferation of standards causes practical problems. For instance, it impedes K-12 teachers from moving to other states, and it makes it quite difficult for curriculum providers to align –and periodically realign– their curriculum to each and every state's standards.

Occasionally, parties other than the states undertake formulating standard sets. Examples of these are AAAS Project 2061 [2], Common Core Math and English [3] and most recently the Next Generation Science Standards [4]. The latter two in particular –Common Core and NGSS– have seen some piecemeal adoption by states. To date, five US states have rejected the Common Core and 12 states have introduced legislation to repeal its standards after initially accepting them. Only 20 states have adopted the NGSS. A few more states have adopted most of the NGSS but have excluded certain parts of it, while others have formulated their own standards but modeled them on the NGSS.

Most standard sets are hierarchically organized. The following are two (arbitrary) examples:

- Arizona:
  - Grade 8 Mathematics:
    - The Number System:
      - Know that numbers that are not rational are called irrational. Understand informally that every number… etc.
      - Use rational approximations of irrational numbers to compare the size of irrational numbers. Locate them approximately on a number line diagram… *etc*.
      - Understand that given any two distinct rational numbers, a < b, there exist a rational number c and an irrational number d such that… *etc*.
- Louisiana:
  - Grade K-5 Science:
    - Definitions of Energy:
      - Make observations to determine the effect of sunlight on Earth's surface.
      - Identify the source of energy that causes an increase in the temperature of an object (*e.g.*, Sun, stove, flame, light bulb).
      - Use evidence to construct an explanation relating the speed of an object to the energy of that object.

The NGSS, however, is somewhat different. It too is largely hierarchical as it is organized in grade-bands and topics; *e.g.*, *Energy* or *Matter and its Interactions*; with each topic having one or more so-called *Performance Expectations* (PE). For example:

- Grade K-2:
  - Topic: Energy
    - Grade K:
      - PE: Make observations to determine the effect of sunlight on Earth's surface.
      - PE: Use tools and materials to design and build a structure that will reduce the warming effect of sunlight on an area.

A PE, in its turn, is an aggregate of more detailed standards: *Science and Engineering Practice*s (SEP), *Disciplinary Core Idea*s (DCIs) and *Crosscutting Concept*s (CCs). These SEPs, DCIs and CCs themselves, however, can be associated with other PEs as well, thereby breaking the purely hierarchical structure of more typical standard sets.

Although the NGSS is not the largest of standard sets, its size –845 elements and 2,100+ connections (Table 1)– its size, and non-hierarchical properties render it sufficiently complex to

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warrant searching for a representation that facilitates improved comprehension, navigation, explanation, searching and communication.

Table 1. NGSS network node and edge counts.

NGSS node type	*Count*
Topics	61*
Performance Expectation (PE)	208
Disciplinary Core Idea (DCI)	292
Science and Engineering Practice (SEP)	162
Crosscutting Concept (CC)	122
Total number of nodes	845
Total number of edges	2,172
*Several topics repeat in multiple grade bands	

II. Tables are the Norm; but why not a Network?

The common means of presenting NGSS standards is through a series of linked tables. Figures 1 and 2 show some examples.

Fig. 1. NGSS as tables (NSTA, 2022).

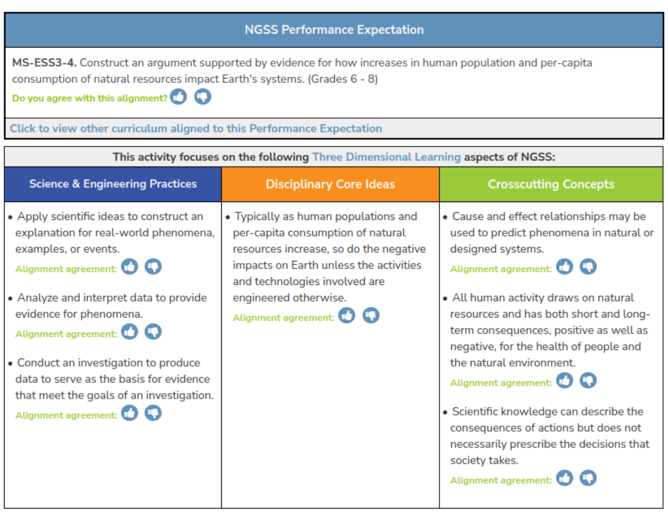

Fig. 2. NGSS as tables (www.teachengineering.org).

These table-based representations properly list standards and first-degree relationships between standards, and provide (hyper) links to related/connected standards.. What they do not provide, however, is a sense of context; *i.e.*, we can link from table to table, but as each table only shows a small, focused part of the NGSS, we quickly lose track of how our focus relates to the NGSS as a whole. As such, NGSS tables serve only one half of the well-known 'focus+context' criterion that stipulates that where possible, information visualizations should provide both focus and a sense of context. One of the best examples of 'focus+context' visualizations is Lamping and Rao's hyperbolic browser for viewing hierarchical data [5].

We offer that the NGSS provides ample opportunities for 'focus+context' visualization if we take advantage of its explicit network structure; *i.e.*, the 2000+ connections between the standards. This network-based approach was previously taken by AAAS Project 2061 in visualizing its educational learning progressions in a series of so-called 'strand maps,' rendered as directed graphs [6]. Initially, these maps were only available on paper, but they were later made available electronically through the (now defunct) NSDL Strand Map Service [7][8]. Although these networks provided 'focus+context' advantages over lists and tables, they were created at a time when web-browser technologies were not yet sufficiently developed to efficiently render complex, real-time networks on commodity hardware. Recent technical advances, however, have been such that we decided to try again, this time with the NGSS.

III. NGSS Network Maps

By using modern JavaScript and Web frameworks, combined with standard network layout methods such as Kamada-Kawai [9] or Fruchtermann-Reingold [10] and a back-end database that stores all network connectivity data, we can efficiently and flexibly render and interact with the complete NGSS network.

Once displayed as a network, certain properties of the NGSS readily reveal themselves. Figure 3, for instance, shows that rather than being a single network, the NGSS consists of four networks; each one associated with a different grade band. Whereas this is trivially clear from even a quick glance at the network rendering, for anyone but an NGSS expert this information is next to impossible to glean from the table representations.

Things become increasingly interesting, when we remap the network from different perspectives, for instance that of topics, SEPs or DCIs. Figure 4, for instance displays the topic *Matter and Its Interactions*. The network shows that whereas *Matter and Its Interactions* is taught in grades 2 and 5-12, it is not taught in grades K, 1, 3 and 4. We see a similar pattern when we generate the network for SEP *Using Mathematical and Computational Thinking* (Figure 5). We can again immediately observe that this SEP is only addressed in grades 5 and higher. Once more, whereas these are obvious to glean from the network renderings, they would be significantly harder to extract from the much more common table representations.

These last two examples exemplify another advantage of networks over tables, namely that whereas tables present only that what 'is,' network visualizations implicitly reveal what 'is not.'

IV. Standard Alignments Too

Another advantage of using networks for visualizing the NGSS or parts of it is that we can extend them with other types of items such as learning resources. All we need to do in those cases is to add those other itemss as nodes and their connections with the standards as edges, recompute the network layout and re-render the network.

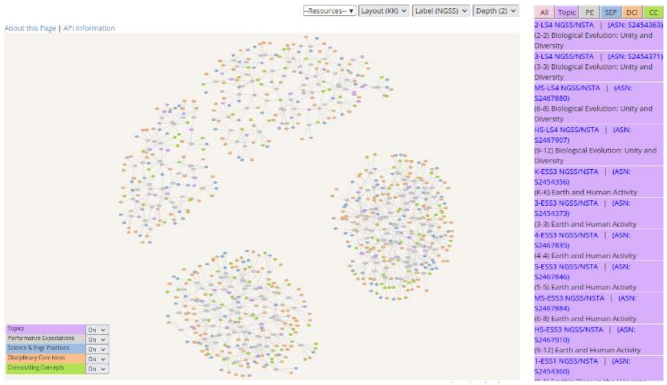

Fig. 3. NGSS complete network. The NGSS visualization is interactive and publicly accessible at https://www.teachengineering.org/ngss_explorer.

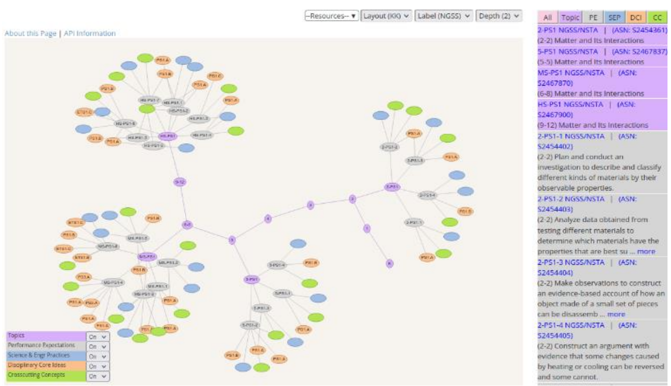

Fig. 4. NGSS topic: *Matter and Its Interactions* (NGSS SEPs and CCs do not have identifiers; hence, the lack of labels on SEP and CC nodes).

Figure 6, for instance, shows the *Engineering Design* (topic) network extended by the 29 aligned learning resources available from the (on-line) South Metro-Salem STEM Partnership resource collection [13]. The resources (triangles) have been absorbed into the network as additional nodes. Their connections show with which PEs they align.

(Note: we care to point out that the concept of standard-alignment –do learning resources support the teaching and/or learning of the skills and knowledge represented by a standard– is not unproblematic. Much has been written about how 'alignment' can be defined and measured *vs.* how teachers might interpret it in practice; *e.g.*, [11] and [12]. In this paper we have chosen to not question the validity of NGSS alignments as found in Web-based resources.)

Once we include learning resources into the network, we also start to observe that whereas the people that formulated the NGSS separated K-12 Science learning into discrete grade bands, some curriculum providers choose not to abide by this administrative discretization of learning.

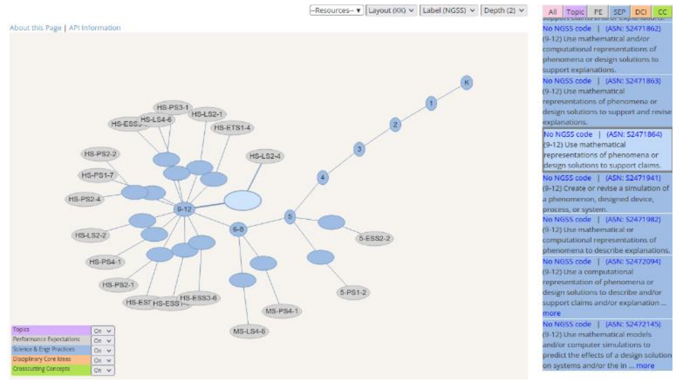

Fig. 5. NGSS SEP: *Using Mathematical and Computational Thinking*. No such thinking until grade 5.

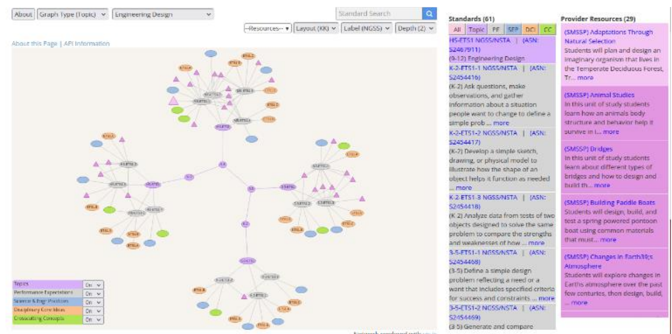

Fig. 6. NGSS *Engineering Design* (topic) network, extended with aligned learning resources by *South Metro-Salem STEM Partnership*.

Instead, they feel free to align their resources across grade bands. An example of this is displayed in Figure 7. Here we see how a cataloger aligned a resource with Middle School (grade 6-8) as well as grades 4 and 5 standards, thereby connecting the otherwise separate Middle School and Grade 3-5 NGSS standard networks.

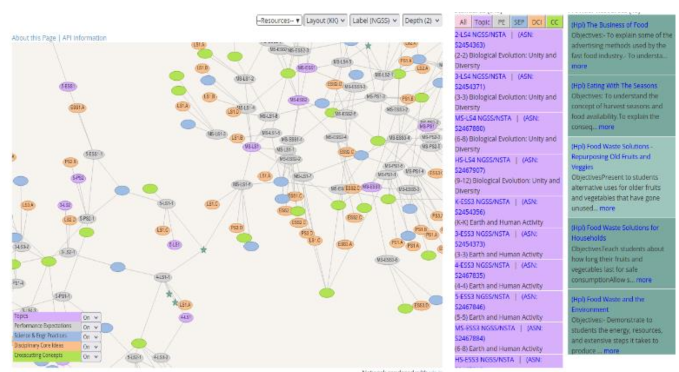

Fig. 7. Although the NGSS's designers discretized learning into grade bands, some curriculum providers bridge grade band boundaries by aligning their resources across them.

V. Detecting Anomalies

Another advantage of educational standard network rendering is that anomalies; *i.e.*, unexpected patterns of connectivity visually stand out, indicating that something is different or perhaps not quite right. Figures 8 and 9 provide some examples of this. Figure 8 shows how a small set of learning resources has been aligned with both a DCI and its PE. This is strange since alignment with a PE implies alignment with all its DCIs.

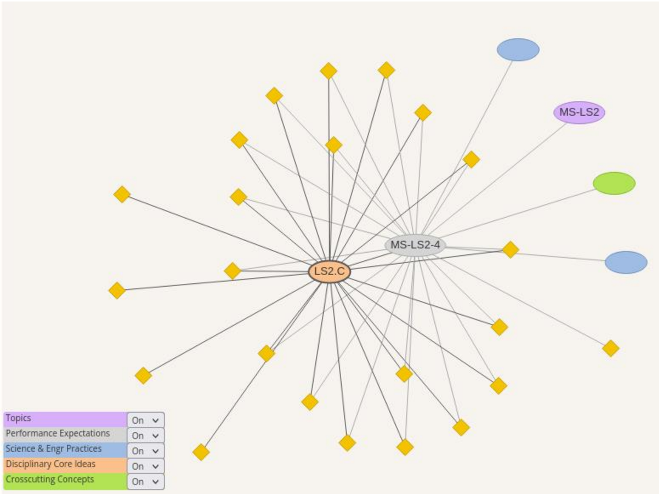

Fig. 8. Anomaly (likely incorrect): learning resources are aligned with both the PE and its DCI.

What could it mean that a resource has been aligned with both a PE (MS-LS2-4) and its DCI (LS2.C)? We do not know the answer to this but we offer that this likely represents a data entry error or a misunderstanding of NGSS alignment by the learning resource's cataloger. Figure 9 illustrates another unusual situation; *i.e.*, alignment of learning resources with a DCI only. This is unusual as the vast majority of publicly available alignments are with PEs. However, whereas the previous example most likely represents a case of erroneous cataloging, this case is likely the result of careful alignment by a cataloger who decided that although the DCI is 'covered' by the resource, the other parts of the PE are not. Hence, the resource was aligned with the DCI, but not with the DCI's PE.

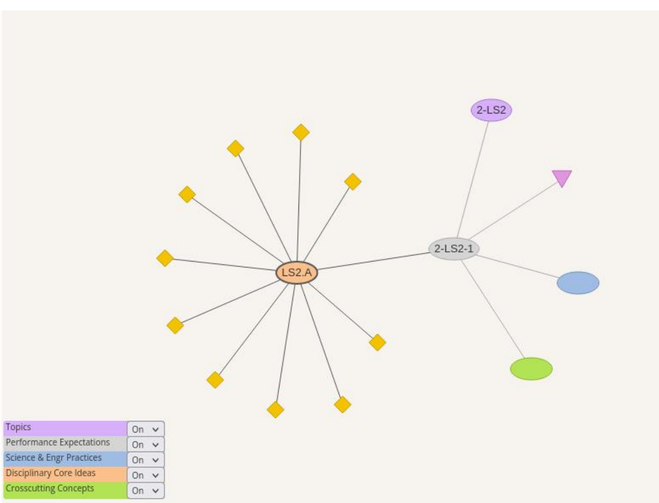

Fig. 9. Anomaly (but likely correct): learning resources are aligned with a DCI, but not with the DCI's PE.

Regardless of these examples, we offer that whereas the anomalies might be difficult to detect in tables and lists, they almost self-identify in network renderings.

VI. BEYOND NGSS AND PROJECT 2061: CURRICULUM PROGRESSIONS

Working in an academic setting, it occurred to us that the network rendering techniques discussed here might also be used to visualize course progressions in academic programs. After all, trying to glean or remember sometimes complex course progressions from tables with long lists of prerequisite courses, or to coordinate prerequisites between different programs in the same college using multiple lists and tables, can be daunting. Yet, when we instead render these progressions as interactive networks, that same complexity all but disappears. The rendering in Figure 10 provides a good example. It models three undergraduate programs in our University's College of Business: 1. the Business 'Core' program (courses that students from all programs must take), 2. the Accounting (ACTG) program and 3. the Business Information Systems (BIS) program. BIS and ACTG students take both the Core program and the additional courses in their respective disciplines. Although this network covers three programs, it takes very little effort to distinguish the different programs and to find which Core courses are prerequisite courses for either of the other programs. Similarly, for folks on the college's curricular committee, it immediately becomes clear (apologies to colorblind readers) that any changes associated with course *BA 370* –a Core course– must be cleared with faculty in both the Accounting and the Business Information Systems programs.

Not surprising, some of the benefits of network visualizations of educational standards mentioned earlier apply here as well. To name just one, the ease of recognizing anomalies as in the 'closed' loop patterns in Figure 10. Why, for instance is *BA 275* (center right) a prereq for *BA 357* if it is a prereq for *BA 270* and *BA 270* is a prereq for *BA 357*? We see a similar situation with *BA 272*, *BA 371* and *BA 372* (lower right), and *BA 211*, *BA 213* and *ACTG 317*. There might, of course, be perfectly good reasons for having these prerequisite patterns, but at least a network visualization makes them stand out so they become harder to miss.

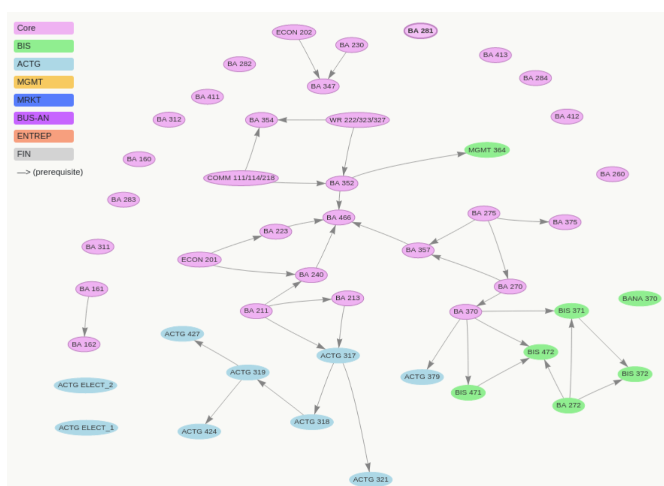

Fig. 10. Network rendering of academic course progressions.

VII. IMPLEMENTATION

We offer some notes on the architecture of the NGSS Explorer tool discussed here:

1. All data about nodes and their connectivity are stored in a (central) NoSQL document database as JSON structures.
2. At initialization a web-browser initiates an HTTP request to a back-end server. The server extracts the complete(!) network information from the database and returns it to the web-browser where it is cached in a JavaScript data structure for the duration of the session.
3. When a user requests a specific network, browser-based JavaScript extracts the requested network from the master network data structure, builds a Graph Modeling Language (GLM) [14] representation of that network and sends it to the server along with a request for node layout coordinates and a parameter indicating which node layout mechanism to use.
4. The server computes the network layout using R igraph [15] and replies with layout coordinates.
5. The web-browser renders the network using the vis.js JavaScript library [16] .
6. All interaction with a displayed network; *e.g.*, zooming and panning, is rendered by vis.js.
7. All subsequent requests for network rendering, start at step 3.

All other, non-network operations; *e.g.*, listing selections of standards and learning resources, *etc.* are handled by standard HTML/CSS/JavaScript methods. Text-based standard searches are conducted through Azure Search.

VIII. DISCUSSION

In this paper we presented interactive, on-the-fly browser-based network visualization as an alternative for presenting the complex structure of the Next Generation Science Standards; a set of four disconnected, grade-specific networks comprising 845 nodes and 2,100+ connections. We offer that such visualization supports interactive exploration and comprehension of the NGSS's structure and intuitive insight into how NGSS learning is distributed among grade bands and topics. We also showed how the networks can be naturally extended with aligned learning resources and how NGSS network visualization facilitates the recognition of patterns and the detection of anomalies.

We are very aware that for some of the claims we have made in this paper, especially with regards to the improvements in comprehension and the efficiency of finding certain types of information, we have not provided any empirical evidence. For the next phase of our work, we therefore are planning some small experiments by means of which we can assess the veracity of at least some of these claims. We could, for instance invite curriculum committee members from various colleges at our institution to answer questions about course progressions and compare response adequacy and response times under either the 'tables' or 'network' condition. We could likewise ask K-12 teachers to explain the rationale and structure of the NGSS to both their students and their students' parents and measure comprehension and ease of communication using tables *vs*. networks. We could also ask curriculum providers –or for that matter K-12 teachers– if they can discover anomalies in resource alignments and measure the efficiency of these discoveries. We obviously have some strong expectations about the results of such experiments, but we should, of course, let reality decide. We might, after all, be quite wrong about all of this.

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