K-12 Engineering and the Next Generation Science Standards: a Network Visualization and Analysis (Resource Exchange)

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Abstract
We present an interactive network visualization of the Next Generation Science Standards (NGSS) and its coverage by collections of aligned curriculum. The visualization presents an alternative to the usual presentation of the NGSS as a set of linked tables. Users can view entire grade bands, search for or drill down to the level of individual NGSS standards or curricular items, or display groups of standards across grade bands. NGSS-aligned curriculum collections can be switched on and off to visually explore their NGSS coverage. Viewing the NGSS and associated curriculum this way facilitates navigating the NGSS and can help with assessment of alignments as lacking or anomalous. Modeling the NGSS as a network also allows for the computation of network metrics to provide insight into core characteristics of the network. It also provides for detecting anomalies and unexpected patterns.

Introduction: NGSS as a Network

The Next Generation Science Standards (NGSS) comprises a set of K-12 science and engineering learning outcomes, developed by the National Science Teachers Association (NSTA), the American Association for the Advancement of Science (AAAS), the National Research Council (NRC), and Achieve with the assistance from 26 US states [1]. Released in 2013, the standards have since been adopted by 20 US states as their official K-12 science and engineering learning outcome standard set. An additional four states have based their standards on the NGSS framework [2].

The NGSS are comprised of assessable learning outcomes or *Performance Expectations* (PEs) which are composed of three-dimensional learning elements: *Disciplinary Core Ideas* (DCIs), *Science and Engineering Practices* (SEPs), and *Crosscutting Concepts* (CCs) [3], [4], [5]. The integration of these three dimensions into PEs illustrates the importance —and interdependence— of content knowledge and practices that engage students both in scientific inquiry and engineering practices. SEPs, CCs and DCIs are grouped into broader learning concepts. PEs are grouped into *Topics*. Whereas PEs, DCIs, SEPs and CCs are grade- or grade-band specific, the DCI-, SEP- and CC groups span grade bands. In all, the NGSS comprises 913 individual components and 2,145 (direct) relationships between those components (Table 1).

Table 1. NGSS component types and their counts

NGSS component type	***Count***
Topic	61*
Performance Expectation (PE)	208
Disciplinary Core Idea (DCI)	292
Science and Engineering Practice (SEP)	162
Crosscutting Concept (CC)	122
DCI group	41
SEP group	15
CC group	12
Total number of components	913
Total number of relations between components	2,145
*12 topics repeat in all grade bands	

Almost all existing representations of NGSS content follow a tree-like, hierarchical model. Figure 1, for instance, shows a commonly found representation of two PEs (*1-ESS1-1* and *1-ESS1-2*), their 3D elements and their articulation across grade bands via three DCIs: *PS2.A* (grade 3), *PS2.B* (grade 5) and *ESS1.B* (grade 5) [4].

Figure 1. Common display of NGSS Performance Expectations

1.Space Systems: Patterns and Cycles

Students who demonstrate understanding can:

1-ESS1-1. Use observations of the sun, moon, and stars to describe patterns that can be predicted. [Clarification Statement: Examples of patterns could include that the sun and moon appear to rise in one part of the sky, move across the sky, and set; and stars other than our sun are visible at night but not during the day.] [Assessment Boundary: Assessment of star patterns is limited to stars being seen at night and not during the day.]

1-ESS1-2. Make observations at different times of year to relate the amount of daylight to the time of year. [Clarification Statement: Emphasis is on relative comparisons of the amount of daylight in the winter to the amount in the spring or fall.] [Assessment Boundary: Assessment is limited to relative amounts of daylight, not quantifying the hours or time of daylight.]

The performance expectations above were developed using the following elements from the NRC document *A Framework for K-12 Science Education*:

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Planning and Carrying Out Investigations Planning and carrying out investigations to answer questions or test solutions to problems in K–2 builds on prior experiences and progresses to simple investigations, based on fair tests, which provide data to support explanations or design solutions. ▪ Make observations (firsthand or from media) to collect data that can be used to make comparisons. (1-ESS1-2) **Analyzing and Interpreting Data** Analyzing data in K–2 builds on prior experiences and progresses to collecting, recording, and sharing observations. ▪ Use observations (firsthand or from media) to describe patterns in the natural world in order to answer scientific questions. (1-ESS1-1)	**ESS1.A: The Universe and its Stars** ▪ Patterns of the motion of the sun, moon, and stars in the sky can be observed, described, and predicted. (1-ESS1-1) **ESS1.B: Earth and the Solar System** ▪ Seasonal patterns of sunrise and sunset can be observed, described, and predicted. (1-ESS1-2)	**Patterns** ▪ Patterns in the natural world can be observed, used to describe phenomena, and used as evidence. (1-ESS1-1),(1-ESS1-2) --- ***Connections to Nature of Science*** **Scientific Knowledge Assumes an Order and Consistency in Natural Systems** ▪ Science assumes natural events happen today as they happened in the past. (1-ESS1-1) ▪ Many events are repeated. (1-ESS1-1)

Connections to other DCIs in first grade: N/A

Articulation of DCIs across grade-levels: **3.PS2.A** (1-ESS1-1); **5.PS2.B** (1-ESS1-1),(1-ESS1-2) **5-ESS1.B** (1-ESS1-1),(1-ESS1-2)

One can find similar representations in on-line K-12 STEM collections such as TeachEngineering (www.teachengineering.org) and NGSS@NSTA (https://ngss.nsta.org/).

Although this hierarchical breakdown provides 'focus' on single components, it lacks the other core aspect of a good information visualization, namely 'context'; *i.e.*, a sense of how a single or local component relates to its surroundings in the NGSS network [6]. As a 'reader' of the NGSS, one can follow the relationships between components by looking up connecting nodes in tables elsewhere in the NGSS documentation. The problem with this approach, however, is that it is a little like following the colored dots on a marked hiking trail without having an overview map of the trail and its surroundings. You are not really lost —you can find your way, both forward and back, but you do not really know where you are relative to your surroundings. Navigating the NGSS this way, it is very easy to lose one's orientation on where in the standard set one is located or where the various connecting paths may lead.

Alternatively, one can consider the NGSS as a network consisting of 913 nodes and 2,145 connections between nodes. Conceptualized this way, it can be much more easily navigated with each component given both its focus and its context. As a consequence, many questions about the NGSS which are difficult to answer with focus-only representations, become much easier to answer with a network-based, 'focus+context' representation. Moreover, once modeled as a network, we can use standard network properties such as centrality and betweenness to analyze the NGSS's structure.

The notion of educational standard relationships and learning progressions as networks has previously been explored in the *AAAS Atlas of Science*, both in print [7] and in electronic-interactive form [8], [9]. However, not only have web-based network rendering and interactive technologies steadily progressed, but a growing number of curriculum providers have 'aligned' their curricular resources with standards. These developments provide means for better, more flexible visualizations and a way to simultaneously visualize the standard networks and their aligned resources.

Web-based Network Visualization of the NGSS

Figures 2-4 show renderings of the NGSS as a network using the interactive, web-based visualization application available at https://www.teachengineering.org/ngss_visualization. The application lets users select aspects of the NGSS network; *e.g.*, entire grade bands as well as individual standards and their direct and indirect connections, which types of nodes to include, *etc*., after which the associated network is rendered accordingly.

Standards in the network can be displayed using one of two labeling conventions: NGSS identifiers (Figure 2) or ASN (Achievement Standard Network) identifiers (Figure 3) [10]. For reasons unknown to us, NGSS SEPs and CCs lack identifiers. Instead, they are listed as text in NGSS documentation such as in Figure 1. This makes it difficult to not only compute with them, but also to communicate about them. In the ASN however, all PEs, SEPs, DCIs and CCs have their own unique identifiers.

Positioning of the nodes in the network visualization follows either the Fruchterman-Reingold (FR) [11] or the Kamada-Kawai (KK) [12] method. Whereas FR tries to keep adjacent nodes in close proximity, KK positions nodes based on their network distances to other nodes. FR/KK network positioning is accomplished through the *R igraph* package [13]. Actual drawing of the networks in the web browser is done with the *vis.js* library [14]. Figures 2-4 provide some examples of NGSS network rendering.

Figure 2. NGSS K-2 standards as a Kamada-Kawai network (nodes labeled with NGSS identifiers)

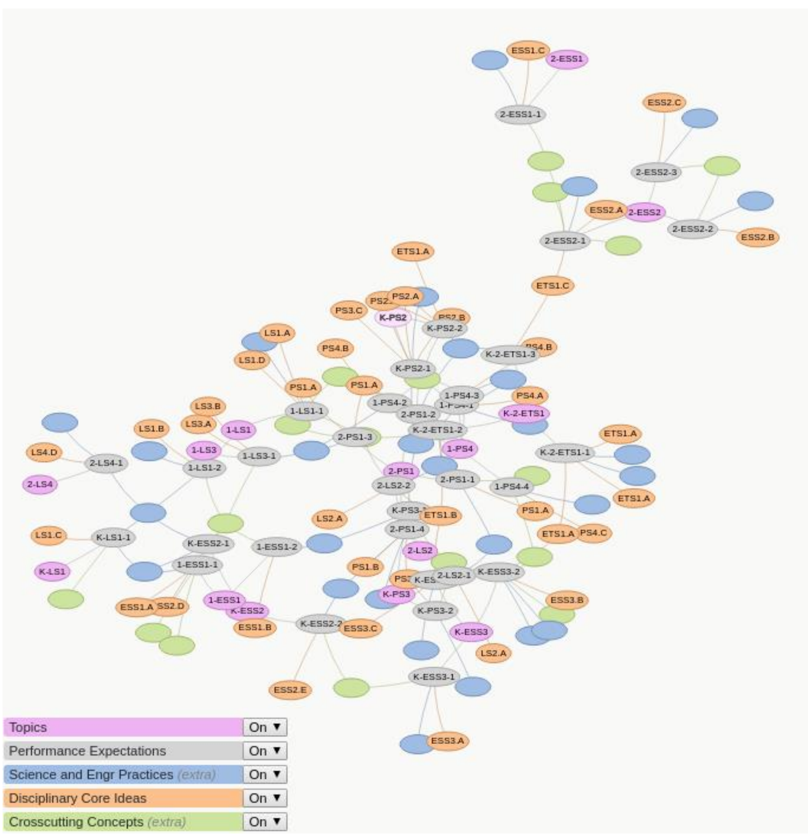


Figure 2 shows the NGSS standards in the K-2 grade band.

Figure 3 shows the NGSS from the perspective of the CC group *Stability and Change*. It includes all CCs from the *Stability and Change* group as well as CCs from other CC groups and all PEs, SEPs and DCIs which are linked. It also shows that the NGSS does not program any *Stability and Change* learning in grades K, 1, 3, 4 and 5. We do not know whether this is intentional or not. Regardless, this does demonstrate one of the advantages of network visualization, namely that anomalies become easy to detect.

Figure 3. NGSS *Stability and Change* CC learning progression (nodes labeled with ASN identifiers)

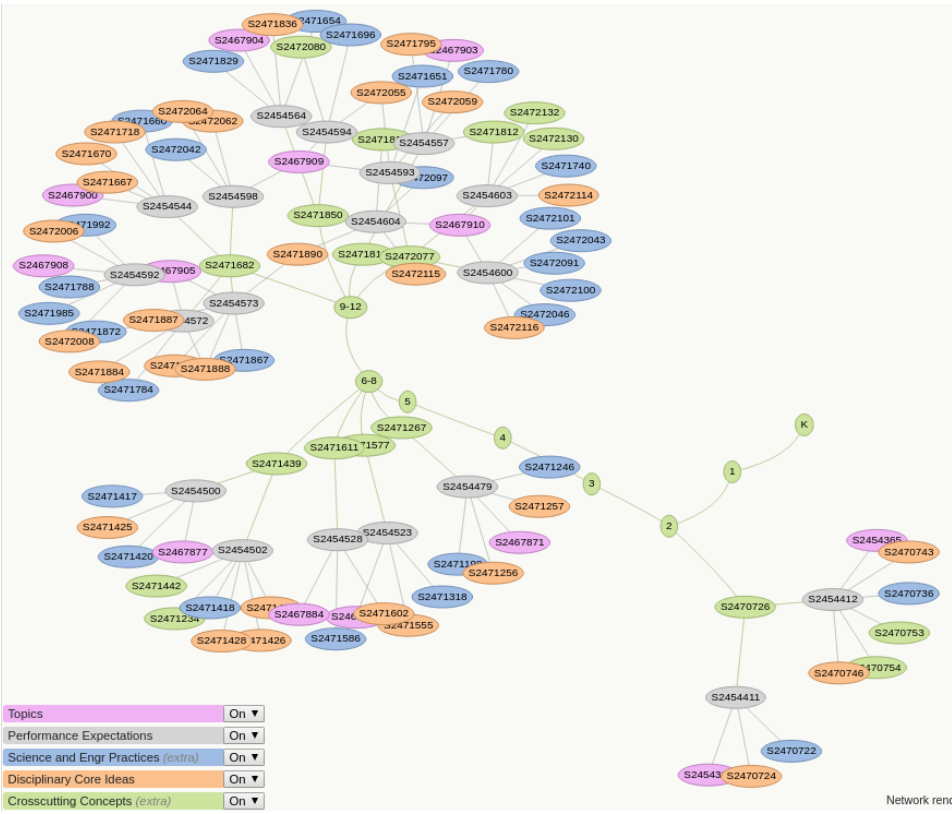


Figure 4 shows a rendering of NGSS standards resorting under the *Engineering Design* topic.

Standard search results as networks

The customary way of displaying NGSS standards; *i.e.*, as linked tables of text, also makes it difficult to obtain an overview of where standards relating to certain topics are located in the NGSS.

For example, a search for ‘magnet’ on the NGSS web site results in a series of results, each of which points to a different table of text. This is certainly useful, but what it once again lacks in the focus+context perspective. Whereas each table provides a focus, it lacks overview (context) of where else in the NGSS magnetism is addressed. As shown in Figure 5, however, a network layout can easily visualize this.

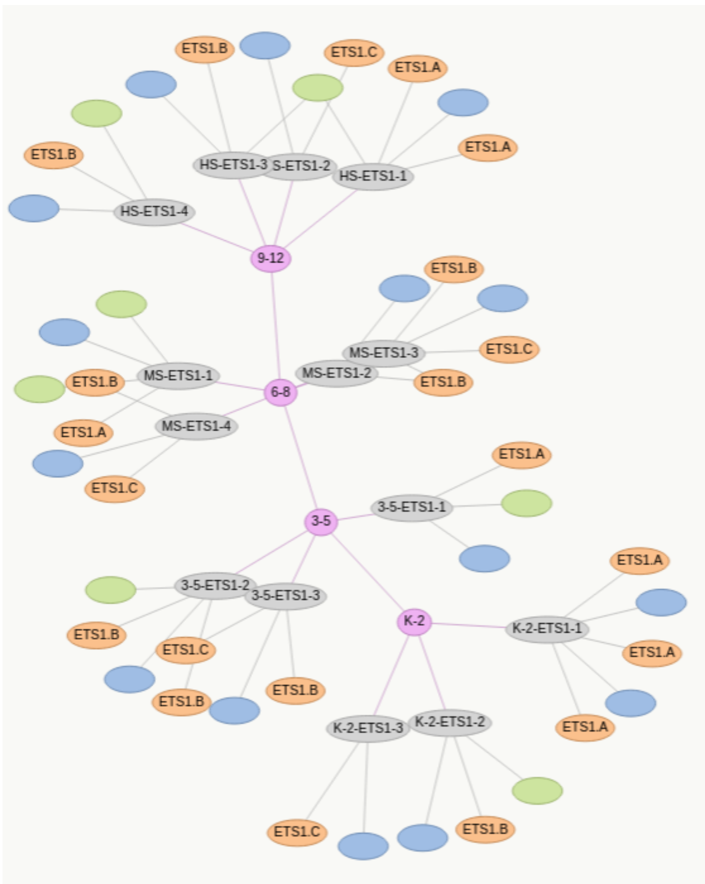
Adding Curricular Resources

One of the advantages of conceptualizing the NGSS as a network is that nonNGSS nodes which maintain relationships with NGSS standards can be added. Figure 6 shows an example of this. Specifically, it shows how three K-12 curriculum collections —*TeachEngineering* (circles), *ScienceBuddies* (squares) and *OutdoorSchools* (triangles)— have aligned their curriculum with NGSS topic *2-LS-2 (Ecosystems: Interactions, Energy, and Dynamics)*. The reader will notice that whereas TeachEngineering and ScienceBuddies align their resources with PEs, OutdoorSchools aligned its curriculum to the *LS2.A* DCI. This represents an important difference since PEs are aggregates of one or more SEPs, DCIs and CCs. Hence, alignment with a PE implies alignment with its 3D learning elements. The reverse, however, might not be the case.

Spotting Anomalies

Although we can, of course, programmatically validate any and all connections between nodes, we cannot always and easily determine *a priori* which anomalies to check for. However, since networks have explicit visual representations and since we, humans, are reasonably good at visually recognizing pattern deviations, displaying the relationships between nodes visually can be an efficient way of diagnosing the alignment data for anomalies. Previously, we saw how the lack of learning outcomes in specific grades manifests itself in an NGSS network graphic (Figure 3). Another example is displayed in Figure 7. It shows resources which are aligned with both a PE and with that PEs DCI. What to make of this? Is this double alignment a mistake made by the cataloger, or did the cataloger try to express that the resources align with the PEs DCI only, and not with the PEs SEPs and CC? Or could the anomaly perhaps represent a computing or data entry error made by those generating these networks? Regardless, however, this type of anomaly is easy to spot once the relationships are visualized in network form.

Figure 4. NGSS *Engineering Design*.



'Underalignment' Through Lack of SEP and CC NGSS Identifiers?

Some anomalies, however, cannot be visualized and/or detected this way. Previously, we mentioned the lack of NGSS SEP and CC identifiers. This lack of identifiers implies that unless their resource aligns with one or more PEs covering those CCs and SEPs, resource providers will have some difficulty aligning their resources with CCs or SEPs, having to use the full text of the standards or ASN identifiers. We therefore hypothesize that the NGSS is currently 'underaligned;' *i.e.*, that significant amounts of good and valid alignments with SEPs and CCs are missing, simply because these SEPs and CCs have no identifiers to align with.

Standard Coverage by Different Collections

Since the network metaphor is space efficient, relatively large amounts of information can be displayed in a relatively small area. Adding interactivity to the displays —a feature the NGSS documentation lacks— furthermore facilitates focusing on an individual node while retaining that node's context. The network in Figure 8, for instance, focuses on grade 6-8 PE *MS-ETS1-2 (Evaluate competing design solutions using a systematic process to determine how well they meet the criteria and constraints of the problem)*. Its immediate network surroundings show all associated nodes and connections, while textual representations of the nodes —standards and the K-12 resources of two curriculum collections aligned with the standard of focus— are listed on the right. Clicking on the textual representation of a standard or a resource highlights it in the network and *vice versa*.

The ability to simultaneously display standard networks and the resources aligned with the standards in those networks also allows for the exploration of standard 'coverage' by different resource collections. Figure 9, for instance, shows coverage by the *TeachEngineering*, *ScienceBuddies* and *OutdoorSchools* collections of the *Stability and Change* group of CCs across all grade bands. (We note the significant number of TeachEngineering resources which have been aligned with SEPs. As per the previous observation, this was facilitated through TeachEngineering's use of ASN standard identifiers).

Coverage checking can be useful in several situations. One is that of conducting a gap analysis; *i.e.*, an investigation by the representatives of a resource collection of where it is lacking coverage. Another is when curriculum users want to explore whether a collection comprehensively covers their area or areas of interest. Figure 9, for instance, shows that none of the three resource collections covers the *Stability and Change* standards in grade 2.

Figure 5. NGSS Coverage of *magnetism*.

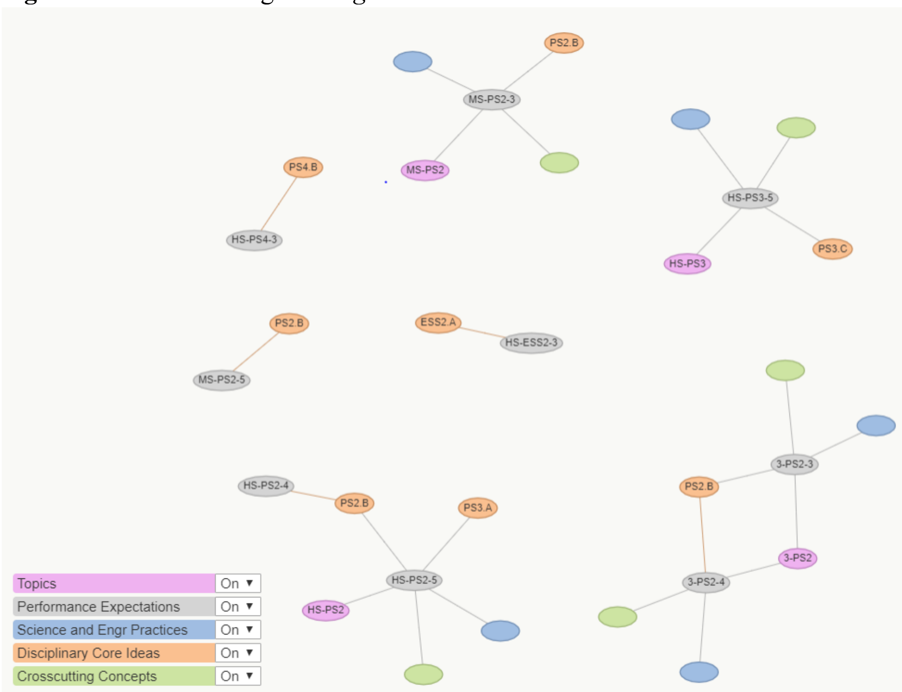


Figure 6. Alignment of NGSS topic *2-LS2 (Ecosystems: Interactions, Energy, and Dynamics)* and three K-12 curriculum collections.

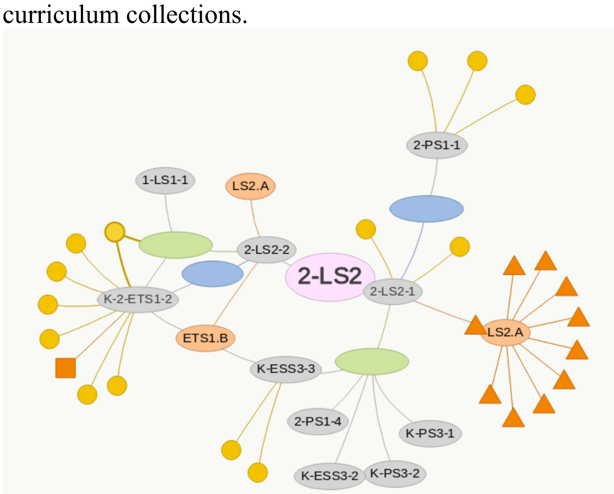


Figure 7. Anomalous alignments of curricular resources with both a PE and its DCI

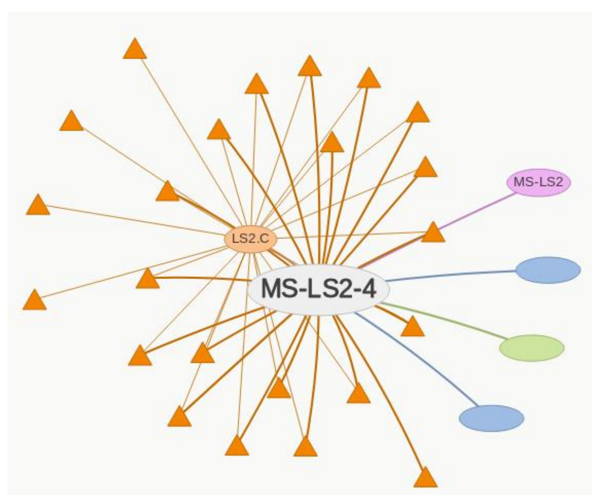
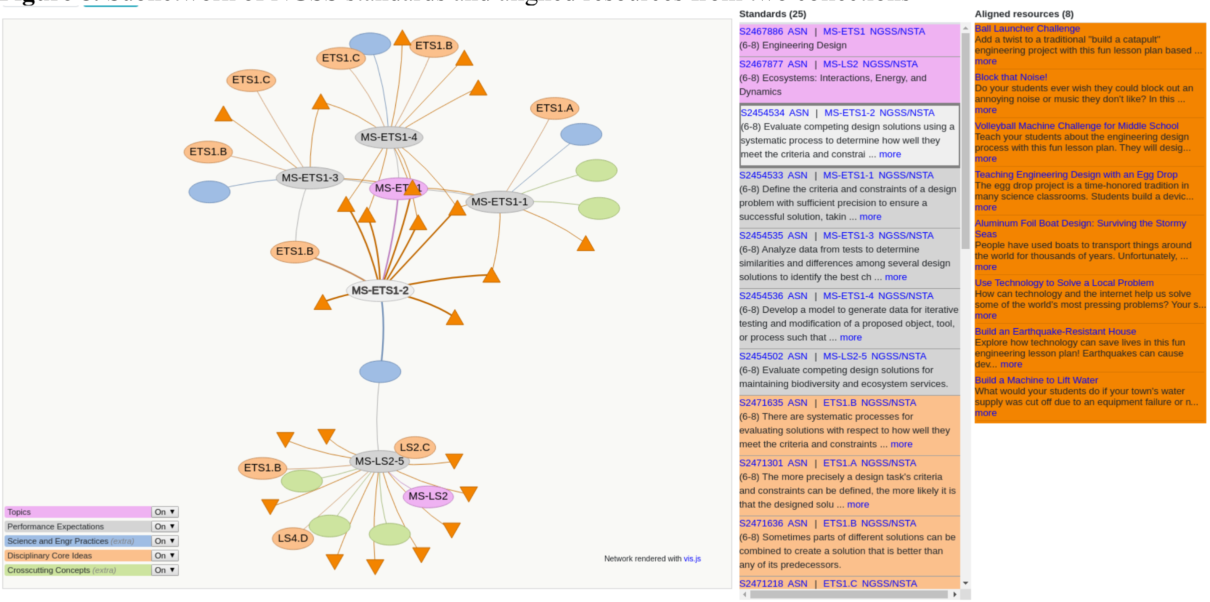


Figure 8. Subnetwork of NGSS standards and aligned resources from two collections



Coverage of NGSS Engineering Design

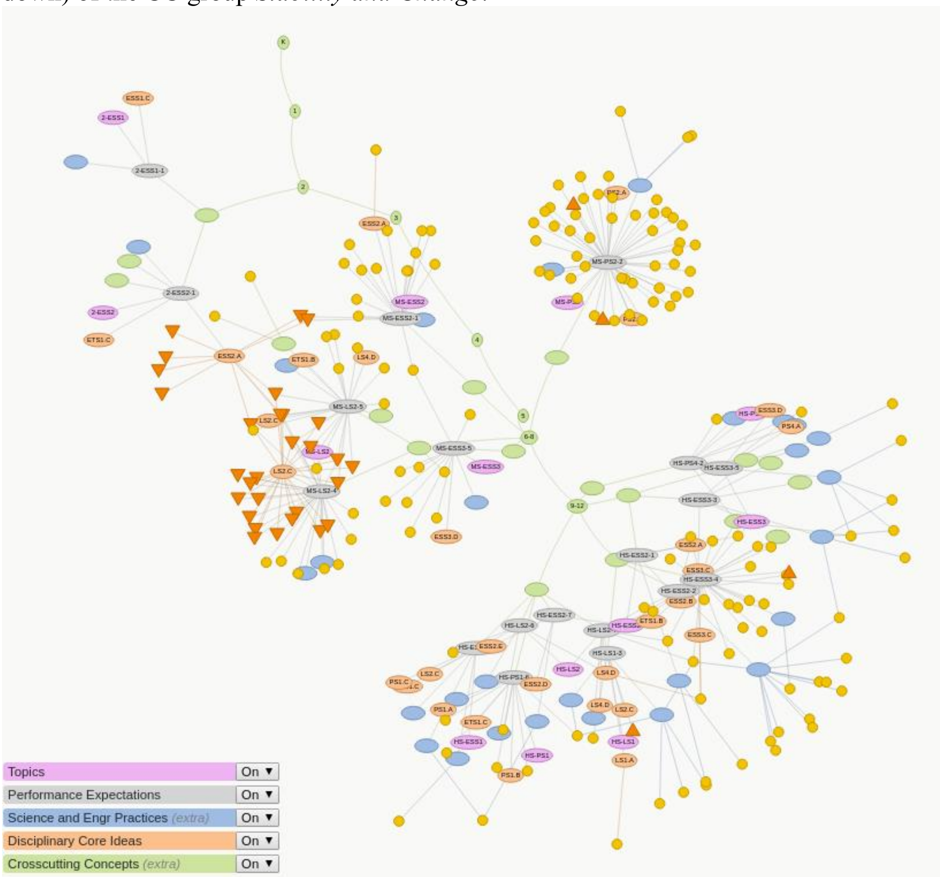
The NGSS explicitly incorporates K-12 engineering learning; 14 (6.7%) of its 208 PEs reside under the topic *Engineering Design*. The topic is represented in all four of the default grade bands (Figure 4). Table 2 lists the average degree centrality; *i.e.*, the number of direct links a network node has, for nine collections, each of which offers 10 or more *Engineering Design* resources. The alignment data were extracted from curriculum collections aggregated by *OERCommons* [15], supplemented with data manually collected for collections not covered by *OERCommons*.

Table 2. Degree centrality of nine resource collections covering NGSS topic *Engineering Design*.

Provider	Average Degree Centrality	Standard Deviation	Resource Count
TryEngineering	13.018	4.063	57
Generation Genius	10.000	0.000	5
Allen Distinguished Educators	9.857	8.236	7
South Metro-Salem STEM Partnership	7.034	3.232	29
Lane County STEM Hub	6.333	2.357	6
Concord Consortium	6.000	3.486	13
Science Buddies	5.700	4.196	20
TeachEngineering	4.838	3.145	579
Healthy Planet USA	4.667	0.471	6

Both explicit and implicit alignments are included in the counts; *i.e.*, if a resource declares an alignment with a PE, all of the PEs 3D components are counted. We care to point out that some well-known K-12 engineering collections; *e.g., Engineering is Elementary* [16] and *Project Lead the Way* [17] are not represented here as their data could not be procured at this time. We also care to state that all alignments were taken 'as is' from the metadata as exposed by the various resource providers; *i.e.*, we make no claim as to the validity of these alignments.

Figure 9. Coverage by TeachEngineering (circles), ScienceBuddies (triangles-up) and OutdoorSchools (triangles-down) of the CC group *Stability and Change*.



The differences in average degree centrality between resource collections are an indication that different resource providers approach the NGSS alignment task differently. For instance, *TryEngineering*, *Generation Genius* and *Allen Distinguished Educators* tend to align each of their resources with more than one PE. Since each PE typically covers one DCI, one SEP and one CC, aligning with multiple PEs quickly raises the average centrality. Collections such as *TeachEngineering* and *ScienceBuddies*, on the other hand, tend to align each resource with fewer PEs and also align with single DCIs, SEPs or CCs. This can be seen in Figures 8 and 9 as well.

Conclusion

The NGSS is a complicated set of interrelated standards. PEs are comprised of SEPs, DCIs and CCs and are themselves arranged in topics and grade bands. DCIs, SEPs and CCs, in their turn, are organized in categories and topics that apply across grade bands, but often not across all grades.
To better facilitate navigating this complex set of relationships, we modeled the NGSS as a network. We then collected K-12 STEM collections' alignment data and integrated those into the network. Adding an interactive visualization interface allows for flexibly navigating the entire NGSS and explore both its internal relations and the alignment relations that collections have with it. We hope and expect that by presenting the NGSS this way, rather than in its traditional form of linked tables of text, the NGSS becomes easier to navigate and explore for all. At this time, however, this expectation is merely an hypothesis, the veracity of which must be empirically tested by experiment.

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