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Using concept maps to evaluate preservice biology teachers' conceptualization of COVID-19 as a complex phenomenon

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Introduction: The COVID-19 pandemic showed the critical importance of supporting teachers' and students' systems thinking when making sense of complex phenomena. This study sets to explore preservice biology teachers' (PBTs) mental models of COVID-19 as complex phenomenon using concept maps.

Methods: 27 PBTs concept maps of COVID-19 outbreak were collected and taken for analysis. Structural and complexity attributes were identified in participants' concept maps and the relationships between them were tested, providing statistical analyses using exemplary concept maps.

Results: The results suggest that the appearance of many concepts in a map (structural attribute) does not necessarily indicate high level of complexity, but rather the amount of simple structural relationships (complexity attribute). On the other hand, the results indicate that higher structural sophistication (e.g., high number of connections and junctions) could be associated with the complexity level of the map.

Discussion: This study provides a practical method for evaluating the complexity level of PBTs' systems thinking, suggests a possible link between structural and complexity attributes in their concept maps, and demonstrates the need to further support PBTs in developing their systems thinking skills in the context of complex biological phenomena.

KEYWORDS

systems thinking (ST), complexity, concept map (CM), COVID-19, preservice biology teachers

1. Introduction

In the modern world, people are exposed to a variety of phenomena, such as climate change, ozone depletion and rising carbon dioxide levels, which are characterized by a complex web of interactions. More recently, the COVID-19 pandemic, also known as the coronavirus pandemic, is an ongoing global pandemic of coronavirus disease 2019 (COVID-19), which is caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). This pandemic has upended the lives of all people across the globe (see Supplementary material 1 for summary World Health Organization, 2021 information about COVID-19 from the World Health

Organization). COVID-19 vaccines can help end the pandemic, but it's essential that everyone has access to them. It is also important to recognize that there are several scientific and non-scientific opponents for the COVID-19 vaccines who question the effectiveness and usefulness of the vaccination regimes adopted around the world. This requires the public and science students to be more aware of the different views, the scientific and non-scientific evidence that are available to support these views, and the complexity of information that should be considered when making decisions on this matter. This complexity cannot be fully understood and, hence, solved with the disciplinary tools or methodology that are commonly use, in which each variable is isolated and tested separately. Rather, it requires the development of an appropriate approach, which addresses such problems holistically, as an interconnected, complex system (Haley et al., 2021; Puig and Uskola, 2021)–a whole that is more than the sum of its parts (Jacobson and Wilensky, 2006). Uskola and Puig (2023) argued that the pandemic of COVID-19 has highlighted the need to develop a citizenry with skills to analyze complex socioscientific problems, in which systems thinking and futures thinking worked together, allowing students to make decisions and to be active citizens.

Capra and Luisi (2014) Systems View of Life portrays the twenty-first century as having inherited major problems involving the environment, energy, climate change, biosecurity, and financial security. They characterize these as systemic problems in that they are all connected. Capra's deep ecological view requires a "radically new conception of life" and a new understanding of how the world is changing. Capra and Luisi (2014), have asked for shifts in perceptions and ways of thinking understanding social–ecological systems as complex adaptive systems, especially at the level of the Earth System as a whole. This approach emphasized the systemic properties level that emerge from the underlying patterns of organization—suggesting that systems cannot be understood, nor their behavior predicted on the sole basis of information relating to their individual parts.

Understanding and analyzing such complex phenomena requires students to engage in "systems thinking"—a higher order thinking skill associated with the ability to understand how the behavior of complex systems is manifested at different scales (from the microscopic to the global/biospheric) and how patterns emerge from the interactions among system components (Gilissen et al., 2021). Rachmatullah and Wiebe (2021) suggested that given this broad definition of systems thinking, research in science education has identified many different types of thinking processes that fall under the umbrella of systems thinking, such as thinking in levels, causal reasoning, mechanistic reasoning, structure–function-behavior, dynamic thinking, cyclic thinking, and interdisciplinary thinking.

Complex systems are prevalent in many scientific fields, and at all scales—from the micro scale of a single cell (such as a human fertilized egg) to macro complex systems such as cities or ecosystems (Yoon et al., 2017). Systems are a central feature of biological sciences. Such systems are made up of many entities, reflecting the multiple levels of organization, and whose interactions emerge into distinct collective patterns (Verhoeff et al., 2018). Hmelo-Silver et al. (2000) defined the dynamic system as a coherent whole composed of multiple components working cooperatively both on a single level and between levels. Because of the dynamic nature of the connection between the system's different levels of hierarchy, complex systems are difficult to understand, even for experts (Hmelo-Silver and Azevedo, 2006). Recent review studies indicate that there are only few studies on science teachers and systems thinking (York et al., 2019; Bielik et al., 2023). further, little is known about (preservice) teachers' abilities to appreciate complex phenomena—such as the COVID-19 pandemic—as systems. Supplementary material 2 provides detailed description of the COVID-19 pandemic as complex system, using the eight system characteristics of Gilissen et al. (2020).

In biology education, the teaching of complex systems is further emphasized, since many complex biological systems also incorporate a variety of social, political, and cultural elements, which expand the boundaries of the system and add even more layers of complexity (de Sousa et al., 2019). One of the important questions that should be asked, in light of this issue, is: Are biology teachers able to grasp these issues well enough to convey them to their students?

This study addresses the above question by examining the systems thinking of preservice biology teachers (PBTs). Specifically, concept maps were used through which the PBTs were able to externalize their mental models of one of the most pertinent examples of a complex, socio-scientific system—the Coronavirus pandemic. Following this, both qualitative and quantitative analyses of PBTs' concept maps were performed in order to determine which characteristics of systems thinking were reflected in their visual representations. The goal in doing so was that the specific strengths and weaknesses revealed by their concept maps could be used as a basis for scaffolding strategies in future preservice education.

2. Theoretical background

2.1. Systems thinking

Systems thinking is widely acknowledged as an important component in science education, the development of which is necessary for helping students make sense of complex phenomena in biological systems (Verhoeff et al., 2018). As mentioned in the Next Generation Science Standards (NGSS Lead States, 2013) and stressed in Nordine and Lee (2021), systems and system models are a critical crosscutting concepts that K-12 science students are required to develop in order to make sense of phenomena. Researchers agree that this higher-order thinking skill provides students with a more coherent understanding of biology by revealing the universal principles that apply to biological systems on different biological levels of organization (Hmelo-Silver et al., 2017; Knippels and Waarlo, 2018; Mambrey et al., 2020). These universal principles, or "system characteristics," are generally divided into three different groups, which Yoon et al. (2018) summarize in their comprehensive review as (a) *structures*, referring to the components, the physical features of the system, (b) *processes*, referring to the dynamic interactions and mechanisms that fuel the evolution of complex systems, and (c) emergent *states*, which describes the systemic patterns and properties that govern how complex systems exist in the world.

While systems thinking is part of many science curricula or standard documents (e.g., KMK, 2005, 2019; NGSS Lead States, 2013), multiple definitions of systems thinking can be found in science education literature. The differences between the various models for assessing systems thinking are largely due to variations in how the precise characteristics of a complex system are defined, based on the specific scientific phenomena addressed in the respective studies.

Several models have been put forth as useful means of representing the various forms and levels of system thinking. One promising approach for portraying systems thinking in a way that reflects the system's multiple interacting components and their states is Structure-Behavior-Function (SBF) thinking (Hmelo-Silver et al., 2007). In SBF terms, the structure portion of an SBF model of a complex system specifies the "what" of the system, meaning the components of the system as well as the connections among them. Behaviors specify the "how" of the complex system, namely the causal processes occurring in it. Functions specify an understanding of the "why" of the system. The SBF model, has been recognized as useful for students' understanding of various biological systems, including human body systems (Hmelo-Silver et al., 2007; Gnidovec et al., 2020), and ecological systems (Jordan et al., 2014; Nesimyan-Agadi and Ben-Zvi Assaraf, 2021). Recently, Momsen et al. (2022) introduced the biology systems-thinking (BST) framework, which describes four levels of systems-thinking skills: (1) describing a system's structure and organization, (2) reasoning about relationships within the system, (3) reasoning about the system as a whole, and (4) analyzing how a system interacts with other systems. Each level of the BST is described using structure–relationship–function (SRF) language, where structures are the components that comprise the system; relationships are the mechanisms that explain how structures are related; taken together, structures and behaviors interact to result in a particular system function.

Hmelo-Silver et al. (2017) modified the SBF model, creating an alternative conceptual framework called Components-Mechanisms-Phenomena (CMP). This framework provides a representation of all the system's attributes, including the structures (components) within the system, the specific processes and interactions (mechanisms) that occur between them, and the macro scale of processes and patterns within a system—the phenomena. The refined conceptual representation was presented by Hmelo-Silver et al. (2017) and was later adopted by Snapir et al. (2017), reflecting the mechanistic reasoning of human body learning. Another form of conceptual representation is the Systems Thinking Hierarchy (STH) model developed by Ben Zvi Assaraf and Orion (2005). This model divides how people think about and understand complex systems according to eight hierarchical characteristics or abilities, which are evinced by students in an ascending order. These eight characteristics are arranged in ascending order of advancement and subdivided into three sequential levels: (A) analyzing the system components (e.g., identifying the components and processes of a system); (B) synthesizing system components (e.g., identifying dynamic relationships within the system, and organizing the system's components, processes, and interactions, within a framework of relationships); and (C) implementation (e.g., thinking temporally, identifying patterns and making generalizations). Each level of systems thinking in this model serves as the prerequisite and the basis for developing the thinking skills on the level above.

Summarizing, three generally agreed-upon central skills of systems thinking are proposed in the literature (e.g., Ben Zvi Assaraf and Orion, 2005; Mehren et al., 2018; Mambrey et al., 2020): (1) "identifying system organization": identifying a complex phenomenon in terms of its organization as a system and be able to describe the relevant components and patterns within it; (2) "analyzing system behavior": examining the system's development and functional processes, as well as both direct and indirect cause-and-effect relations between the identified elements of the system; and (3) "system modeling": modeling the hypothesized prospective target states of the system. This study explores these skills using the CMP conceptual framework. Specifically, Hmelo-Silver et al. (2017) declared that the CMP conceptual framework reflects the mechanistic reasoning of ecosystem learning, in the context of a complex system. Since the aim is to explore students' conceptualization of the underling mechanism of the COVID-19 outbreak, this framework is appropriate for this study allowing identify system thinking learning trajectories.

2.2. Concept maps as a tool for the externalization of mental system models

One of the key principles in planning the teaching of complex systems is representing the conceptual framework explicitly to the students and helping them to represent their mental models explicitly (Knippels and Waarlo, 2018; Eberbach et al., 2021). The external representation of mental models is a useful means of assessing students' understanding of the multilevel structure that characterizes complex, non-linearly organized biological phenomena (Dauer et al., 2013). One way to do this is to use concept maps as a visual means of externalizing and examining students' internal mental models (Kinchin et al., 2000; Hay et al., 2008; Brandstädter et al., 2012). Snapir et al. (2017) emphasize the importance of presenting complex systems within a conceptual framework that addresses, expresses and organizes all of the system's components and the relationships between them. Such conceptual representations can not only help students organize their ideas, but might also make it possible to identify differences in the extent of individuals' system thinking skills, and of the development of these capacities within each learner.

The importance of concept maps as a research tool lies in the possibility of conducting comparisons between multiple maps—either to compare the mental models of different people or to compare the mental models of the same person at different points in time. Comparisons between the maps of multiple students can also help researchers and educators identify and assess recurring patterns in the development of students' systems thinking (Dauer et al., 2013). Concept maps can also be analyzed for their structural attributes. The structural attributes reflect the way the concepts are organized and connected in the map, such as identifying junctions where more than two concepts are connected to another one (Tripto et al., 2017; Nesimyan-Agadi and Ben-Zvi Assaraf, 2021). This is important for complex phenomena in which students may display fragmented understanding (Kinchin et al., 2000). External representations of mental models (like concept maps) are used to evaluate not only conceptual understanding, but also the ability to solve problems in a complex system's content (Johnson-Laird, 2001, 2004).

Nevertheless, Kinchin (2011, 2014), claimed that "poor" maps are not always indicators of poor performance and "good" maps not always predictors of good performance. There is no one common determination whether a concept map is really good in terms of indicating the presence of a sophisticated understanding. For example, a spoke structure may develop into a chain or a network over a period of time as the student's understanding develops and is more systemized and complex in response to further learning.

Akçay (2017) used concepts maps to identify prospective elementary science teachers' difficulties regarding the connection between photosynthesis and cellular respiration processes in terms of energy and matter cycling. De Sousa et al. (2019) analyzed primary school teachers systems thinking concept maps on the interconnectedness of soil and climate change. The research study indicates that the teachers struggled to use systems thinking to illustrate understanding of the interconnectedness of soil and climate change, for example, how healthy soils can mitigate the impact of climate change. Ben Zvi Assaraf and Orion (2005, 2010) demonstrated how concept maps allow students at the junior high school level, to link processes to the nodes representing the system components to present causal dynamics and cyclic mechanism, within the earth system. Although concept maps enable relational links to be made between relevant concepts, Safayeni et al. (2005) pointed their limitation in to capture "cyclical" relationships representing complex natural and social systems. Therefore, they suggested cyclic concept maps for representing dynamic relations and hybrid maps for representing both the concept map and the cyclic concept map portion of a knowledge representation in an aggregated map.

2.3. Aims and research questions

This is a mixed methods study aiming at identifying PBTs' systems thinking in the context of COVID-19 using concept maps. To do so, concept maps were qualitatively analyzed for their complexity and structural attributes, and statistical analyses between obtained scores was performed.

The following research questions are addressed in this paper:

What are the complexity and structural attributes of PBTs' concept maps about COVID-19?

What are the relationships between the complexity and structural attributes of PBTs' concept maps about COVID-19?

3. Methodology

3.1. Context and participants

This study was carried out at one public university in Germany, that is, in the first phase of teacher education. Preservice teachers in Germany usually study two subjects in a six-semester bachelor's program, followed by a four-semester master's program (concurrent teacher education programs). At the end of their studies, preservice teachers are expected to develop basic professional knowledge and competences needed for their profession (Neumann et al., 2017). These include knowledge and competences regarding complex biological phenomena and systems thinking skills (Fanta et al., 2019).

The sample of this study consists of concept maps produced by PBTs from the fourth (i.e., the last) semester of the Master of Education program. All students enrolled in a course focusing on biology education research, were asked to participate in this study by producing a concept map on the COVID-19 pandemic. The participation in the study was not mandatory for the course; participation was voluntary and anonymous. Researchers and participants had no formal relationships to one another.

3.2. Tools and methods

3.2.1. Concept maps

Twenty seven concept maps were produced and submitted by students in the course after receiving explicit instructions provided both orally by the course teacher and as written text in the task introduction. All produced concept maps included text on most or all of the connecting arrows and were taken for analysis.

3.2.2. Semi-structured interviews

To test whether the aspects of complexity identified in students' concept maps reflect their systems thinking and understanding, semi-structured individual interviews with three additional PBTs were conducted, in which they were asked to reflect about their concept map as a visual representation of COVID-19 outbreak as complex phenomena, provide evidence for that given connection, and add concepts or connections if needed. The aim of the interviews was stimulating students' explicit use of the system characteristics to evaluate how the analysis capture their system thinking reasoning in terms of the components (C) of a particular phenomenon (P) and how they interact to result in a specific mechanism (M) of the phenomenon (COVID-19 outbreak).

Interview questions and protocol were based on Tripto et al. (2016) and revised collaboratively developed by all authors (interview questions provided in Supplementary material 3). The three interviewed students, named students A, B, and C, were females master students in the same program as the rest of the study participants and were selected as a convenience sample. Interviews lasted 20–30 min each. An example of one of the interviewed students' concept map is provided in Figure 1.

3.3. Data collection

The PBTs were asked to anonymously produce a concept map that describes their understanding of the COVID-19 outbreak ("In recent months, we have experienced COVID-19 as a global phenomenon. Please create a concept map that describes your understanding of the various factors influencing the spreading of COVID-19"). To produce and save the concept maps, the PBTs used SageModeler (Bielik et al., 2019), an open access online drawing tool, which allowed them to add as many boxes to the drawing board, to connect between them with arrows, and to label the boxes and arrows. The software allowed the PBTs to create and digitally send a shared link of their final concept map. PBTs were not provided with specific instructions on how to produce a concept map, as they were already familiar with this method from their previous studies. As far as we know, PBTs did not receive any explicit teaching materials concerning COVID-19 in their academic studies at the time of administration of the task. However, it was accepted that they all were exposed and informed of the COVID-19 situation from media and other sources.

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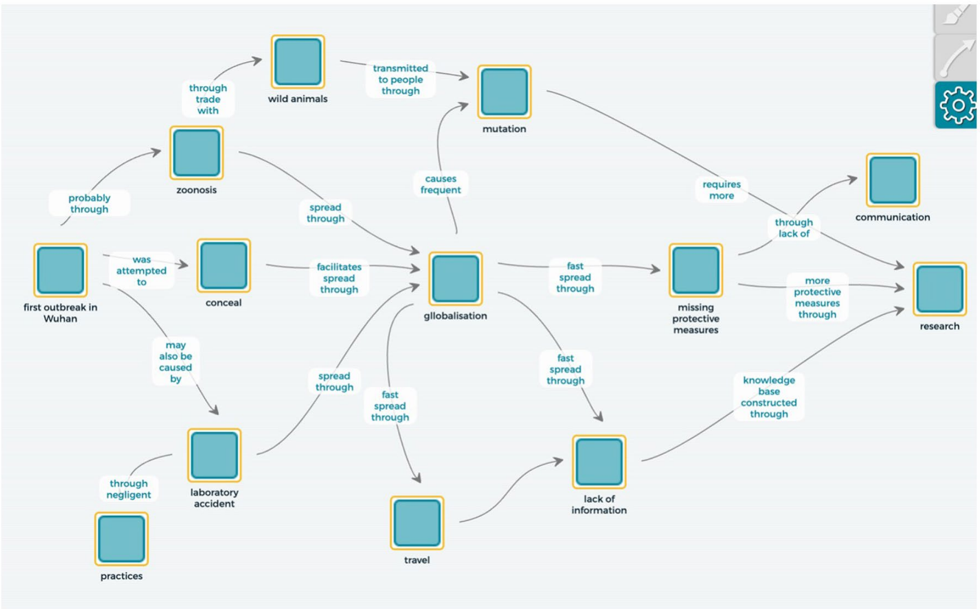

FIGURE 1
Concept map of interview student C.

The semi-structured interviews that were conducted with three additional PBTs took place online and were led in German by one of the authors. Each interview lasted between 20 and 30 min and all interviews were video recorded. Interviews were fully transcribed and translated into English. Authors collaboratively analyzed the interview transcripts.

3.4. Analysis

All 27 maps were translated from German to English and qualitatively analyzed for complexity and structure attributes. The analysis was conducted as a collaborative social interaction over time, with the combined efforts of three of this manuscript's authors, which are researchers in the field of science education. The concept maps were examined repeatedly, with the CMP model serving to guide the reading and the analysis toward the formation of a series of codes. Since every researcher interprets data according to their own subjective perspective, content validation was done until 90% agreement was achieved. Following this, interrater agreement was tested by two researchers independently and Cohen's Kappa ($K = 0.85$) indicates an "almost perfect" (Landis and Koch, 1977) interrater agreement. Cases of disagreement were resolved by discussion until full agreement was reached.

Because of the multidisciplinary nature of the COVID-19 outbreak, almost all concept maps described systems that included both biological concepts (e.g., COVID-19 outbreak, virus mutation, infectious rate, etc.) and social concepts (e.g., lockdown, globalization, travel restrictions, etc.), with the exception of student #17 map which included only biological concepts.

To test students' understanding of social and biological concepts, student in the interview were asked to identify these concepts in their maps. All three students were able to correctly identify and distinguish between social and biological concepts. For example, one student said:

"*The social aspect for me would be, on the one hand, the interaction of organisms in factory farming or also the volume of travel or the density of people in cities, that would be the social aspect for me. How do people deal with each other, as well as lack of information and governments. So social constructs in society. And the biological* [concepts] *would be for me then just something like mutations, infection times, but also intervention in nature and habitats, where it is for me then really about the natural factor.*" (Student B interview).

The analysis did not focus on the disciplinary content since this was not the aim of this study, as it aims to characterize the system language in the maps rather than assessing the sophistication level of students' biological conceptual knowledge.

Based on the statistical analysis that was performed to address the second research question, two exemplary concept maps were chosen for in-depth analysis. The two concept maps represent typical cases that demonstrate the statistical correlations that were found.

3.4.1. Complexity attributes

For complexity attributes, maps were analyzed based on Hmelo-Silver et al. (2017) CMP framework, which provides a representation of all the system's attributes. The analysis was performed by Snapir et al. (2017) for specific CMP and structural attributes was carried out, as described below.

3.4.4.1. Components

Concept maps were analyzed for component attributes that describe COVID-19 as complex systems. As suggested by Ben Zvi Assaraf et al. (2013), biological concepts in each map were analyzed for their organizational level, with three types of biological organizational levels that were classified: only macro level concepts, macro and cellular micro level concepts, and macro level and

TABLE 1 Biological organizational levels analyzed in concept maps in this study.

Level	Description	Example of concepts
1	Maps that include only macro level concepts	Habitats, population, animals, humans
2	Maps that include both macro level and micro cellular level concepts without any micro molecular level concepts	Virus, immune system cells
3	Maps that include at least one micro molecular level concept	mRNA, mutation

TABLE 2 Type of relationships in concept maps.

#	Type	Description	Possible connecting terms	Example of constructs
1	Simple structural relationships	Relationships describing how components are connected or part of other components	"Part of," "connects to," "has"	"Disease has severe symptoms," student #5
2	Simple mechanistic relationships	Relationships describing how components are affecting other components without determining the kind of effect or rate	"Influence," "lead to," "effects"	"COVID-19 influences economy of countries," student #8
3	Sophisticated time-based relationships	Relationships describing the rate and trend of the effect	"Increase," "decrease"	"Mutation can increase COVID-19 outbreak," student #14

molecular micro level concepts (elaboration and examples provided in Table 1). These organizational levels represent the commonly used levels when examining biological phenomena. In their interviews, all three students were able to identify the correct biological organizational level of their biological concepts or to recognize which organizational levels are missing from their concept maps. For example, student C said: "*So the organism level I would definitely be the wild animals and the zoonosis, the molecular then would be the mutations.*"

3.4.1.2. Mechanism

To analyze the concept maps for mechanism attributes, specific processes and interactions between components and the outcomes of these interactions, such as feedback loops, were identified by analyzing the connections between concepts in the maps. Analysis included two categories: type of relationship and organizational level changes.

Type of relationship were coded based on the nature of connections between concepts in maps. Three types were identified, based on Tripto et al. (2017): simple structural relationships, simple mechanistic relationships, and sophisticated time-based relationships (see Table 2 for elaborated description and examples). Percentage of each type of relationships from total number of connections in each map was calculated. In their interviews, all students were asked to identify sophisticated time-based relationships in their maps and were able to correctly do so. For example, student B said: "*High travel increases the density of people in the cities, so to speak. And high travel volume also increases rapid spread. That would be something like that* [sophisticated time-based relationship]."

Organizational level change was defined as a connection between two concepts that are from different biological micro/macro hierarchical levels (e.g., viral RNA attacks human host, student #24). Percentage of organizational level changes was calculated as number of connections with organizational level change out of the total number of connections in the map.

In their interviews, students were able to identify organizational level changes. For example, student B said:

"*Then cellular to organism* [organizational level] *for me would be human infection and mutation. So, what happens at the cellular level and what effects it has on the organism. And then of course cellular to pandemic* [organizational level] *would be then from infection to rapid spread and then to pandemic.*" (Student B interview).

3.4.1.3. Phenomena

For the phenomena attributes, characteristics of the overall behavior or properties of the system that results from certain mechanisms or processes were analyzed. The phenomena present the macro scale of processes and patterns within a system (Tripto et al., 2017). Two categories were coded: number of mechanistic relationships chains and global dynamic concepts included in the maps.

A mechanistic relationships chain was identified as a sequence of three or more concepts connected by simple or sophisticated mechanistic relationships. For example, map of student #9 included the following chain: governments fight COVID-19 influences economy of countries. Total number of mechanistic relationships chains in each map was calculated.

To test this in the interviews, students were asked to identify mechanistic relationship chains in their maps. They were all able to correctly point out the chains in their maps. For example, student A said:

"*Yes, I think above all below left* [pointing at a series of variables in map]*: COVID, bat, patient zero, Wuhan, epidemic, globalization and pandemic, and maybe also individual countries. This is in any case a very long chain of events, at least that's how I thought of it and that's how I also started when constructing to show the temporal course* [of events]." (Student A interview).

Maps were also analyzed for including at least one global dynamic concept, such as immigration, trading between countries, moving of COVID-19 variants etc.

In their interviews, all students were able to identify these types of concepts, as student C said:

"*I have also written globalization here in the middle* [pointing at the concept on map] … *More contact with people, which comes about because of globalization, leads to more mutations, which is why more research must take place worldwide, which means also globally, because* *you have to gather the world's knowledge or global knowledge about this virus in order to draw conclusions from it."* (Student C interview).

3.4.2. Structural attributes

For the structural attributes, indicators were identified, which emphasize the structural aspects of the concept map as a lens for understanding students' mental model complexity. As analyzed by Snapir et al. (2017), structural indicators included the number of concepts, number of connections, and ratio between connections and concepts in each map. The higher the ratio between concepts and connections, the more structurally complex the map, since there are more concepts that are connected to each other. In addition, number of junctions was calculated. Junction was defined as a concept in the map that had more than two arrows going in or out of it. The more junctions, the more structurally complex the map.

The analysis process of the concept maps included the following steps: first, each concept was identified as biological or social. Each biological concept was coded as global or non-global. Each biological concept was than coded for its biological organizational level (macro, micro-cellular, or micro-molecular, see Table 1). Next, each connection between concepts was given a number and coded for type of connection, and whether it represents an organizational level change. Each map was than coded for the number of mechanistic connection chains, and all structural indicators were calculated.

To address research question two (i.e., relationships between the complexity and structural attributes), the data were *z*-standardized and the Spearman correlation coefficient was calculated. As there are 45 separate correlational analyses (Table 3), $p = 0.001$ (i.e., $p = 0.05/45$) was set as the criterion for significance to control the familywise error rate ("Bonferroni correction"; Field, 2013).

4. Results

4.1. Complexity and structural attributes of preservice biology teachers' concept maps

To address the first research question, what are the complexity and structural attributes of PBTs' concept maps about COVID-19, all 27 concept maps were analyzed and scored for complexity and structural attributes. Table 4 provides the descriptive statistics for complexity attributes. Full data obtained from all 27 maps is provided in Supplementary material 4. From the component perspective, in the organizational level attribute, about half of the maps included only macro level biological concepts (13 out of the 27 maps), while only 7 maps included also micro level concepts and 7 maps included also included molecular level concepts. From the mechanisms perspective, about 20% of the connections in the maps demonstrated organizational level changes, and most of the relationships in the maps were of the simple mechanistic type. From the phenomena perspective, maps included an average of about 5 mechanistic relationships chains.

Table 5 provides the descriptive statistics for the structural attributes. Maps included a wide range of number of concepts, connections and ratio between them, and an average of about 4.5 junctions in each map.

4.2. Relationships between complexity and structural attributes

To address the second research question, what are the relationships between PBTs' complexity and structural attributes as portrayed in their COVID-19 concept maps, correlational statistical analysis was performed (Table 3)—with a corrected criterion for significance of $p = 0.001$ as described above.

Concerning the relationship between complexity and structure indicators, the number of concepts was significantly positively correlated with the percentage of simple structural relationships ($r = 0.63$; $p < 0.001$). This means that the more concepts a concept map included, the higher was the amount of simple structural relationships in the map—and vice versa—but not the amount of more sophisticated relationships (i.e., simple mechanistic and sophisticated time-based relationships).

The number of mechanistic relationships chains was significantly positively correlated with all three other structural attributes besides concepts (connections: $r = 0.64$; $p < 0.001$; ratio between connections/concept: $r = 0.69$; $p < 0.001$; junctions: $r = 0.76$; $p < 0.001$). Hence, there is a positive association between these three structural attributes and the amount of mechanistic relationships chains in the concept maps.

4.3. Examples of concept maps

Two concept maps were chosen to further examine the correlations that were found between the structural and complexity attributes. Descriptive analysis of the maps is provided below.

The map produced by student #8 (Figure 2), demonstrates relatively low scores of structural and complexity attributes. From the structural perspective, the concept of COVID-19 is placed in the center of the map and most other concepts are connected to it. The map includes below average number of concepts and connections and below average ratio between connections and concepts (11 concepts, 10 connections, ratio of 0.91), and two junctions ("COVID-19" and "governments").

From complexity perspective, the component attribute includes only macro level components (e.g., "governments," "WHO," "Superspreader"). In the mechanism attributes, most of the connections (90%) are of the simple mechanistic type (e.g., "COVID-19 influences economy of countries") with no connection of the sophisticated time-based type, and with a relatively average percentage of the connections demonstrating organizational level change (20%, e.g., "patient zero unconscious spreading worldwide"). From the phenomena attributes perspective, this map has only four chains of mechanistic connections and it includes several global level concepts, such as "spreading worldwide" and "interconnected world globalization."

The map produced by student #24 (Figure 3), demonstrates relatively high structural and complexity attributes. From the structural perspective, this map demonstrated high level of interconnectedness among concepts. The map includes above average number of connections and very high ratio between connections and concepts (14 concepts, 23 connections, ratio of 1.64), and seven junctions (e.g., "outbreak of COVID-19," "risk of infection," "viral RNA" etc.). From complexity perspective, this map describes connections between both biological and social concepts, e.g., "risk of

TABLE 3 Results of correlational analysis (Pearson *r*) between all attributes (*z* standardized) considered in this study.

		2	3	4	5	6	7	8	9	10	11
1. Macro–micro level	*r*	−0.10	0.07	0.01	0.46	0.19	−0.19	0.14	0.02	−0.16	−0.13
	p	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
2. Simple structural relationships	*r*		−0.39	−0.45	−0.05	0.13	0.01	**0.63**	0.57	0.17	0.25
	p		n.s.	n.s.	n.s.	n.s.	n.s.	**<0.001**	n.s.	n.s.	n.s.
3. Simple mechanistic relationship	*r*			**−0.65**	0.30	0.13	0.01	−0.23	−0.18	0.00	−0.02
	p			**<0.001**	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
4. Sophisticated time-based relationship	*r*				−0.25	−0.24	−0.01	−0.30	−0.30	−0.14	−0.19
	p				n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
5. Organizational level change	*r*					−0.02	−0.29	−0.15	−0.09	−0.02	−0.12
	p					n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
6. Mechanistic relationships chain (#)	*r*						0.16	0.41	**0.64**	**0.69**	**0.76**
	p						n.s.	n.s.	**<0.001**	**<0.001**	**<0.001**
7. Global dynamic concepts (yes/no)	*r*							0.20	0.21	0.10	0.23
	p							n.s.	n.s.	n.s.	n.s.
8. Concepts	*r*								**0.85**	0.17	0.41
	p								**<0.001**	n.s.	n.s.
9. Connections	*r*									**0.65**	**0.77**
	p									**<0.001**	**<0.001**
10. Connections/concepts	*r*										**0.87**
	p										**<0.001**
11. Junctions											

Highlighted in gray: correlations between complexity and structure indicators. Statistically significant correlations are highlighted in bold ($p < 0.001$); $N = 27$.

TABLE 4 Descriptive statistics for complexity attributes.

	Range	Mean	*SD*
Components			
Organizational level[1]	1–3	1.78	0.85
Mechanisms			
Simple structural relationships (% of relationships in maps)	0–77.27	27.50	22.10
Simple mechanistic relationships (% of relationships in maps)	0–100	53.24	25.94
sophisticated time-based relationships (% of relationships in maps)	0–100	19.26	26.76
Organizational level change (% of maps)	0–57.14	19.26	18.74
Phenomena			
Mechanistic relationships chains (#)	0–10	4.56	2.46
Global dynamic concepts (no/yes)	0 or 1	0.67	0.48

[1]Organizational levels includes 1 (only macro level concepts), 2 (macro and micro cellular level concepts), and 3 (including micro molecular level concepts).

infection" connects with the social concept "protective measures" and the biological concepts of "viral RNA" and "number of infections." The component attributes include macro level components (e.g., "aerosol"), and one micro molecular level component, "viral RNA." In the mechanism attributes, the map includes connection of all types, with 43.5% of them of the structure type (e.g., "mouth-nose covering is protective measures"), 30.4% of them are of simple mechanistic type (e.g., "risk of infection affects number of infections"), and 26.1% of them are of the sophisticated time-based type (e.g., "aerosols decreased by mouth-nose covering"). From the phenomena attributes perspective, this map has eight chains of mechanistic connections, however it does not include any global level concepts.

5. Discussion

This study explores PBTs' concept maps that externalize their mental models of one of the most pertinent examples of a complex,

TABLE 5 Descriptive statistics for structural attributes.

	Range	Mean	*SD*
Concepts (#)	8–30	14.37	4.84
Connections (#)	8–33	16.70	6.74
Ratio connections/concepts	0.89–1.81	1.15	0.24
Junctions (#)	0–14	4.56	3.07

socio-scientific system—the COVID-19 pandemic. The maps created by the students expressed the CMP complexity attributes, encouraging learners to explore the parts or components of the system (C) and to generate or recall plausible mechanisms (M) that result in the emergence of the observed phenomenon (P) (Hmelo-Silver et al., 2017). The concept maps as a conceptual cognitive modeling tool was used to help students construct explanatory models in terms of CMP, allowing students to create, note, and link representations with the nodes representing the system components and links representing mechanisms.

The first research question focused on what are the complexity and structural attributes of PBTs' concept maps about COVID-19. Using the CMP framework, It was found that most maps did not fully address the mechanistic chain of events describing how the COVID-19 outbreak spread out, as evident from the relatively low number of sophisticated time-based relationships and the low number of mechanistic relationships chains. Also, it was found only few incidents of cross-level reasoning, as evident from the low percentage of maps with organizational level change in the relationships. These findings indicate that PBTs did not have a sophisticated perception of COVID-19 as a complex phenomenon at the time of the activity. This could be explained by the fact that the concept maps were collected in the first months of the COVID-19 outbreak, when not enough information was known about the pandemic and the disease. Another possible explanation is that the task itself did not provide appropriate guidance or supports for the students to produce a sophisticated concept map of the phenomenon.

The second research question focused on what are the relationships between the complexity and structural attributes of teachers' concept maps about COVID-19. The results suggest that the appearance of many concepts does not necessarily indicate high level of complexity, as indicated by the positive correlation between the percentage of simple structural relationships (complexity attribute) to the number of concepts in the map (structural attribute). On the other hand, the results indicate that higher structural sophistication (i.e., high number of connections and junctions, and higher ratio between connections and concepts) could be associated with the complexity level of the map, as evident by the positive correlation between these structural attributes to the number of mechanistic relationships chains (complexity attribute). These findings support the assumption that concept maps are external representation of learners' mental models and that the organizational structure of the map reflects the way learners reorganize the concepts in their mental models (Kinchin et al., 2000; Hay et al., 2008). Understanding how students' systems thinking advances is essential in order to develop and facilitate a pedagogical scaffolding that allows students to engage in counterintuitive modes of thought and overcome the variety of cognitive barriers that can prevent them from fully understanding the system's complexity (Snapir et al., 2017).

This study emphasizes the potential of concept maps as a tool to identify understanding of complex systems. Concept maps are a powerful instrument for knowledge integration *and* externalization, helping students advance to higher levels of systems thinking, while also allowing researchers access to their externalized mental system models (Nesbit and Adesope, 2006; Dauer et al., 2013; Schwendimann and Linn, 2016; Hmelo-Silver et al., 2017).

5.1. Cross-level reasoning

A pertinent outcome of this study was that the students' concept maps showed very little evidence of cross-level reasoning. Biological phenomena manifest themselves at various levels of organization (Gilissen et al., 2021). As noted by Verhoeff et al. (2008), in order to understand biological phenomena, students need to connect concepts and processes across a single level of organization (horizontal coherence) and concepts and processes on different levels (vertical coherence). By asking the students to portray COVID-19 as a complex system, the PBTs were expected to represent different levels of biological organizational levels and acknowledge the various interconnections between them. It is possible that the students' emphasis on the social aspects of the pandemic limited this element in their concept maps by creating an over-representation of macro level system components. Indeed, fewer than one third of the maps included cellular level concepts (e.g., virus) or molecular level concepts (e.g., mRNA) that are essential for cross-level reasoning.

Cross-level reasoning is challenging to both preservice and in-service teachers (Gilissen et al., 2020). In this regard, various researchers have adopted the "yo-yo" learning and teaching strategy to assist teachers to explicitly engage in cross-level reasoning (see, for instance Knippels et al., 2005; Verhoeff et al., 2008; Jördens et al., 2016; Knippels and Waarlo, 2018). Moving up and down the levels of organization is the underlying principle of yo-yo learning, and this technique has been valuable for structuring learning sequences and guiding teaching processes. This emphasizes the role of explicit guidance in developing systems thinking. As Mor and Zion (2019) noted, without explicit teaching that emphasizes the connection between micro and macro levels in the system's hierarchy, students have difficulty seeing the interactions that make complex system patterns like homeostasis possible.

In this study, the task did not explicitly prompted students to use cross-level reasoning in their concept maps. One strategy that could be implemented in future tasks is to prompt students to use explicit mechanisms that involve cross-level reasoning in their explanations. This was recently presented by Gilissen et al. (2021), who asked secondary school students to formulate a hypothesis to explain why Tibetan people are naturally more capable than Dutch people of climbing Mount Everest. The aim was to prompt students to reason between the different levels of biological organization (Mount Everest on the ecosystem level, Tibetan people on the population, respiratory system on organism levels, and genes on the cellular level).

Furthermore, from methodological perspective, although concept maps were already proven to be fruitful in the context of systems thinking and they are known for their capability to foster conceptual system interrelations, It is suggested that presenting cross-level reasoning using concept maps may be challenging for PBTs. It is therefore suggested that future research should combine zooming with concept-mapping (Schneeweiß and Gropengießer, 2022). In this approach, vertical arrows indicate vertical

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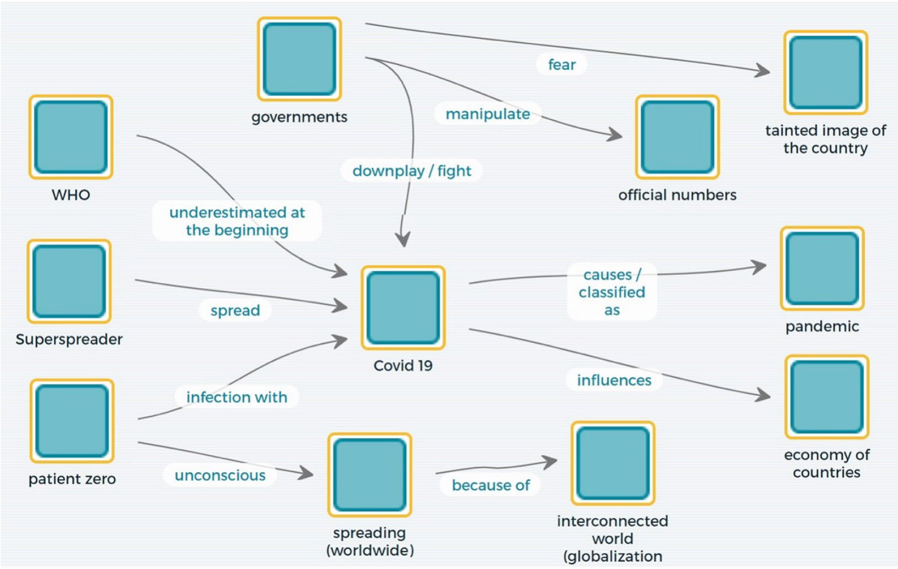

FIGURE 2
Concept map of student #8.

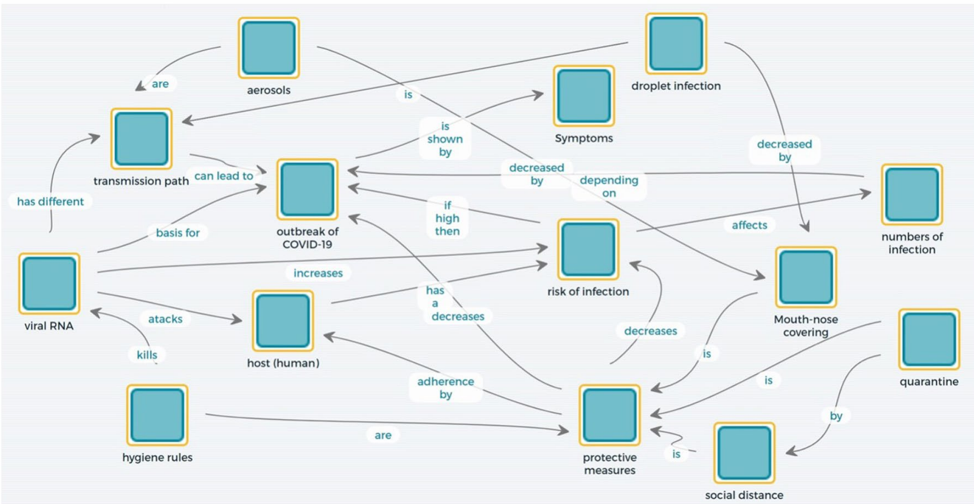

FIGURE 3
Concept map of student #24.

interrelation; horizontal arrows indicate horizontal interrelation, enabling the student present a sophisticated model of cross-level reasoning. The zoom map fosters students' causal explanations across levels of organization through the inherent demand to consider the respective levels. Therefore, the zoom map may help students structure and interrelate fragmented knowledge and achieve integrated knowledge.

5.2. Mechanistic reasoning

Understanding biological phenomena entails an understanding of the causal relationships across different levels of organization that result in the emergent phenomenon (Knippels and Waarlo, 2018; Asshoff et al., 2020). According to Krist et al. (2019), thinking across levels is an essential heuristic in mechanistic reasoning, which allows students to explain and make predictions about phenomena, directs their intellectual work and implicitly guides mechanistic reasoning. In this study most of the students expressed simple mechanistic relationships, describing how components are affecting other components without determining the kind of effect or its rate. In dynamic systems, two events may be connected, but separated from one another in space and time. Thus, recognizing dynamism also means identifying the interaction between events and predicting the consequences of changes (Hmelo-Silver et al., 2000). In this study, only some of the maps presented sophisticated time-based relationships, describing the rate and trend of the effect. This was reflected in the structure of the concept maps: Very few of which presented a chain of mechanistic relationships, identified as a sequence of three or more concepts connected by simple or sophisticated mechanistic relationships.

Hmelo-Silver et al. (2000) argued that when engaging with complex systems, novices tend to focus on readily observable and stable structures, rather than acknowledging invisible elements, dynamic processes, and exhibit mechanisms and outcomes as experts do. Studies have shown that difficulties with complex systems extend beyond secondary school students to preservice teachers and practicing teachers as well (Yoon et al., 2017, 2018). Akçay (2017), for example, examined advanced education students who intended to pursue science teaching. He found that they had difficulties with micro–macro relations and cross-level reasoning, and with understanding energy flow and matter cycles. Similarly, Haskel-Ittah et al. (2020) have explored undergraduate students' mechanistic reasoning regarding phenotypic plasticity, where genes and environment interact to produce different phenotypes. When trying to explain the mechanisms involved in complex phenomena, first-year students tend to refer to the direct effect of the environment, while third-year students refer more to sensing-responding mechanisms that involve indirect relationships. A possible explanation for this is that students may need more domain-specific knowledge in order to be able to utilize more sophisticated mechanistic reasoning. Since this study did not include a content related intervention about COVID-19 as complex systems, additional studies are required that focus on students' ability to perceive the biological mechanism related to COVID-19 outbreak.

5.3. Social and biological aspects of COVID-19

Almost all of the students' concept maps included both social and biological concepts. This result highlights the multidisciplinary nature of the COVID-19 pandemic, and its profound effect on all aspects of society, including psychological, social, and neuroscientific effects (Holmes et al., 2020). The multidisciplinary nature of complex systems like the COVID-19 pandemic requires educators to expand and adapt models of complexity beyond the biological. Mehren et al. (2018) have developed a competence model for systems thinking in the context of socio-ecological systems. Their competence model consists of four dimensions, namely system organization, system behavior, system-adequate intention to act, and system-adequate action. Reiss (2020) pointed to the potential opportunities for promoting cross-curricula and interdisciplinary approaches in school STEM lessons when addressing wider societal issues like COVID-19. However, engaging with complex socio-scientific issues, such as COVID-19, requires specific knowledge and skills, such as the understanding and competence to comprehend and follow arguments embedded in a complex social and political context. Furthermore, these must be combined with scientific content knowledge, knowledge about the nature of science, and higher-order thinking (Sadler, 2009). Uskola and Puig (2023) employed concept maps as a research tool to analyze dimensions related to systems thinking (System structure) and futures thinking developed by a group of pre-service elementary teachers. They demonstrated how different activities designed were effective in relation to scientific reasoning about the origin of pandemics and possible ways to prevent them as socioscientific problems.

5.4. Limitations, recommendations, and conclusions

This study has several limitations. First, this study included only a small sample of concept maps that may not represent the broader population of PBTs. In addition, the concept maps were produced in the first few months following the COVID-19 outbreak, when not enough understanding of the phenomena was established. Also, the task was performed remotely (because of the COVID-19 restrictions), which may have influenced students' engagement in the task. It is suggested that future studies will include an intervention that explicitly prompts students to use system language and guidance about COVID-19 as complex phenomenon. Another follow-up study can compare these results to PBTs' concept maps about COVID-19 several years after the outbreak of the pandemic, when much more is known and understood about the pandemic outbreak. This may reveal possible increase in sophistication of PBTs' understanding of COVID-19 as a complex phenomenon as the knowledge about it developed.

From a pedagogical perspective, these findings suggests that in order to support teachers' and students' level of systems thinking, they should be explicitly directed to increase the complexity of their concept maps by enhancing the plethora of network connections between the concepts in their maps. This can be achieved by directing them to consider adding a range of sophisticated causal relationships chains to demonstrate the complexity of their understanding of the target phenomenon. In addition, teachers can support their students' systems thinking by reflecting on their produced concept maps and directing their attention to include biological and social aspects, address different organizational levels, and provide sophisticated mechanistic relationship rather than simple structural connections.

Altogether, this study provides a detailed analysis of PBTs' understanding of COVID-19 as a complex phenomenon, adding to the research fields' understanding of the relationships between complexity and structural attributes of concept maps as representations of students' mental models. These findings further support the argument that the number of concepts in produced maps does not necessarily reflect students' systems thinking or the sophistication level of their mental models. However, higher number of connections and junctions in concept maps can indicate a higher sophistication level of students' mental models. These findings contribute to the understanding of systems thinking and complexity, as reflected in students' mental model concept maps, by pointing out to the possible connection between higher structural sophistication of maps to its complexity level. These findings contribute to the understanding of students' and teachers' systems thinking as well as to possible scaffolds and practices that can be used to further support their systems thinking skills. Youth need an opportunity to engage with the science and practice of infectious disease epidemiology in classroom environments. Kafai et al. (2022) scoping review of interventions in K-12 education showed, that learning and teaching about infectious diseases in science education is not yet embrace the full spectrum of practices that provide K-12 students to collaboratively investigate growing levels of complexity around infectious disease as a complex system that included variability and randomness.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study.

Author contributions

TB, JJ, and OB contributed to the conception and design of the study. JJ and DK performed the data collection. TB, MK, and JJ organized the database. JJ and MK performed the statistical analysis. TB and OB wrote the first draft of the manuscript. TB, MK, and OB wrote sections of the manuscript. All authors contributed to manuscript revision, read and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at:https://www.frontiersin.org/articles/10.3389/feduc.2023.1107000/full#supplementary-material

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