

Exploring the Concept of Valence and the Nature of Science via Generative Artificial Intelligence and General Chemistry Textbooks

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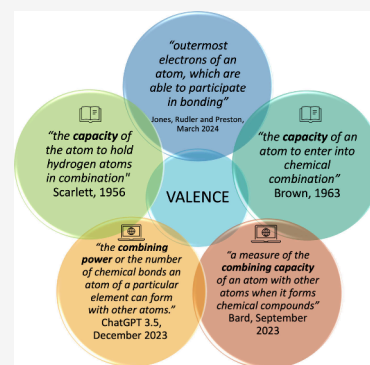


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ABSTRACT: Like science itself, our understanding of chemical concepts and the way we teach them change over time. This paper explores historical and modern perspectives of the concept of valence in the context of collegiate general chemistry and draws comparisons to responses from generative artificial intelligence (genAI) tools such as ChatGPT. A fundamental concept in chemistry, valence in the early and mid-20th century was primarily defined as the “combining capacity” of atoms. Twenty-first century textbooks do not include this historical definition but rather use valence as an adjective to modify other nouns, e.g., valence electron or valence orbital. To explore these different perspectives in other information sources that could be used by students, we used a systematic series of prompts about valence to analyze the responses from ChatGPT, Bard, Liner, and ChatSonic from September and December 2023. Our findings show the historical definition is very common in responses to prompts which use valence or valency as a noun but less common when prompts include valence as an adjective. Regarding this concept, the state-of-the-art genAI tools are more consistent with textbooks from the 1950s than modern collegiate general chemistry textbooks. These findings present an opportunity for chemistry educators to observe and discuss with students the nature of science and how our understanding of chemistry changes. Including implications for educators, we present an example activity that may be deployed in general chemistry classes.



KEYWORDS: Valence, Generative AI, Nature of Science, General Chemistry

INTRODUCTION

Conceptual understanding is a core goal of chemistry education. As educators, we can use various methods and tools to present concepts and assess competencies. Besides instructor curated materials, students can also seek supplemental and alternative resources (e.g., YouTube, Wikipedia, or ChatGPT) which may be easier to access and appear more helpful. In 2023, Lawrie observed “students have transitioned from resources that were 100% text-based printed matter including images to 100% digital resources, often multimodal, dynamic and interactive”.¹ This shift in how chemistry concepts are experienced and learned reflects the nature of the science itself. In this paper, we explore how generative artificial intelligence (genAI) tools, like ChatGPT, can demonstrate the nature of science as it relates to the concept of valence.

The nature of science refers to how scientific knowledge is created: curiosity and scientific inquiry lead to experiments and empirical data, which may be interpreted and synthesized into new models and concepts, thereby increasing our understanding of the topic being explored. A vital component of scientific literacy, understanding the nature of science has been an implicit learning outcome in science classrooms for over

100 years² and, more recently, has been considered important enough to merit explicit inclusion into science curricula.³ The National Science Teachers Association explain that “understanding of the nature of science enhances students’ understandings of science concepts and enables them to make informed decisions about scientifically-based personal and societal issues.”⁴ An appreciation of the nature of science can help students grasp how scientific knowledge changes over time and why scholars do not always agree. The nature of science provides a framework for comprehending how scientific knowledge can be concurrently trustworthy and open to revision.⁵

Historical examples have been used to effectively demonstrate how chemistry concepts have changed over time, providing students an opportunity to learn about the nature of science. Schultz and Gere developed a writing-to-learn

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Table 1. Selected Quotes Regarding the Concept of Valence from 20th Century Textbooks Published in the United States

Book Title	Author(s)	Year	Quote regarding valence
<i>College chemistry: an introductory textbook of general chemistry</i>	Linus Pauling ¹⁴	1950	"some elements have a definite combining power or valence, from Latin <i>valentia</i> for vigor or <i>capacity</i> "
<i>College Chemistry</i>	Scarlett ¹⁵	1956	"the <i>capacity</i> of the atom of an element to hold hydrogen atoms in combination"
<i>General Chemistry</i>	Nebergall and Schmidt ¹⁶	1959	" <i>combining capacity</i> " or valence determines the number of others atoms with which an atom of an element can combine."
<i>General Chemistry</i>	Brown ¹⁷	1963	"the <i>capacity</i> of an atom to enter into chemical combination with other atoms"
<i>General College Chemistry</i>	Keenan ¹⁸	1980	valence is " <i>combining capacity</i> ", also discusses "valence electrons" as "those electrons in the outermost energy levels"

activity which demonstrates the changeability of the nature of science.⁶ In their activity, students read a historical article written by Lewis and compared it to the ideas taught in their class. Making connections to the nature of science and the human component, Aparicio and Elizalde describe the historical story related to the structure of water and use the human dimension to demonstrate basic tenets of the nature of science.⁷

For this project, we consider the concept of valence, an idea often taught in the first semester of college general chemistry classes. The manner in which valence is explained to college chemistry students has changed significantly over the last 130 years. In the 19th century, Elijah Paddock Harris, a professor of chemistry at Amherst College described valency as "the quantitative value in chemical force of the different atoms...shown, by uniting elementary substances and decomposing compounds, that each kind of atom has, under the same circumstances, a certain quantity of combining power".⁸ The perspective of valence as "combining power" or "combining capacity" is connected to the etymology of the term from the Latin *valentia*, which means vigor or capacity. In 1917, after the subatomic particles had been discovered, the definition of valence began to change, as seen in the writings of Henry Carlton Smith; valence was described as "a property of atoms and represents their combining power relative to hydrogen measured, perhaps, by loss or gain of electrons".⁹ In the writings of American chemists and educators G.N. Lewis^{10,11} and Linus Pauling^{12,13} and in other works from the 20th century, we see connections being made to (presumably valence) electrons. Table 1 includes five quotes related to this concept from select general chemistry textbooks published from 1950 to 1980. The preelectron concept of "combining capacity" endures in textbooks well into the 20th century.

In contrast to these historical texts, modern textbooks from the 21st century use the word valence only as an adjective coupled with a noun, as in "valence electrons", "valence orbitals", "valence shell", and "valence-bond theory".^{19–23} Textbooks now include detailed examples of how valence electrons can be used to sketch Lewis structures, and valence bond theory can be used to explain the equivalent bonds in methane. Textbooks from the 21st century do not include the definition of "combining power", but rather the concept of valence is connected to the "outermost electrons" in an atom.

Similar to modern collegiate general chemistry textbooks, we use the term valence to refer to the outermost or valence electrons of an atom, which are able to participate in bonding. We recognize the term valency, common in British English, as being synonymous with "valence". We define a valence electron as one in the outer shell or orbital of an atom that can participate in chemical bonding with other atoms. The valence shell is the outermost layer of orbitals in an atom (often with highest *n* quantum number, e.g., 2s and 2p for O)

where valence electrons are located. Valence orbitals describe the probable region around the atom where the valence electrons are located. From our research of historical chemistry textbooks and sources, we define "combining power" or "combining capacity" as a numerical quantity ascribed to a particular element on the basis of empirical data regarding how it has been shown to combine chemically with other elements. Over the last 120 years, the concept of valence has progressed from being a fixed value for an element defining its "combining capacity" to a descriptive adjective regarding shells, orbitals, electrons, bond theory, and more.

While examining the shifts of the concept of valence in textbooks, we also explored alternative digital resources that students may use to study and learn chemistry, taking particular interest in generative AI. For the purposes of this project, generative AI (genAI) refers to the recently released large language models, such as ChatGPT, which use statistical analysis of source material to generate probabilistic plain language responses to user prompts or questions. These models are receiving increasing attention, and educators have begun to assess how they might impact chemistry education. West et al. analyzed the ability for ChatGPT to write a lab report and collected data on student awareness of genAI.²⁴ Leon and Vidhani explored the accuracy of ChatGPT in answering chemical questions, observing that it generally struggles with complex concepts and produces carried answers regardless of the prompt.²⁵ In their paper evaluating ChatGPT responses, Fergus et al. conclude this "disruptive technology" could be useful for catalyzing change in assessment practices.²⁶ Watts et al. present a detailed quantitative analysis of how genAI responses compare to student responses in a writing-to-learn assignment.²⁷ In exploring how ChatGPT might be leveraged to promote critical thinking, Guo and Lee identify the need for training of educators to effectively incorporate these tools.²⁸

In this study, we used multiple genAI tools to explore the concept of valence and related terms. We assessed the responses from multiple prompts over two different times and compared those responses to modern and historical perspectives on the concept. For the purposes of our analysis, a historical definition is one that includes "combining power" or "combining capacity", phrases that are not present in any of the 21st century textbooks we reviewed. A modern definition is also one which uses valence in combination with another term, such as valence electron. We acknowledge the concept of valence is very nuanced and these modern and historical definitions of valence are, in fact, not mutually exclusive. Our labels of the various definitions of valence are meant to enable critical comparison of the genAI output and not imply one is more correct than another.

METHODS

Selection of genAI Tools

To assess the comparative performance of various genAI sources, comprehensive research was conducted to identify the most frequently used genAI tools in late 2023. Four distinct tools—ChatGPT, Liner, ChatSonic, and Bard—were chosen for the study. We understand that these tools are changing over time and respond differently to prompts, so we collected data from multiple prompts and over two separate times; the date, version type, input, and complete exact output of each genAI tool were documented each time they were utilized.

Collection and Analysis of Responses

Table 2 shows the two main prompts and the variable terms we used in our investigation. The prompts selected for this

Table 2. Summary of Prompts

General prompt A: "define _____ as it relates to chemistry"	
Variable term	Full prompt
valence	"define valence as it relates to chemistry"
valency	"define valency as it relates to chemistry"
valence electron	"define valence electron as it relates to chemistry"
valence orbital	"define valence orbital as it relates to chemistry"
valence shell	"define valence shell as it relates to chemistry"
General prompt B: "define valence from a _____ perspective"	
Variable term	Full prompt
general chemistry	"define valence from a general chemistry perspective"
biochemistry	"define valence from a biochemistry perspective"
physical chemistry	"define valence from a physical chemistry perspective"
organic chemistry	"define valence from an organic chemistry perspective"
inorganic chemistry	"define valence from an inorganic chemistry perspective"

project were inspired by direct observation and communication with undergraduate general chemistry students, who have anecdotally indicated regular use of genAI tools to help with various tasks, such as lab reports, homework, and preparing for exams. Considering these experiences, we developed prompts that are very simple and straightforward to mirror potential inquiries that a novice general chemistry student might pose about valence. We acknowledge that this approach restricts the output of the genAI tools and that more specific or fully

developed prompts would yield different results. However, this condition was acceptable, as we aimed to replicate potential queries of an average student and approximate how general chemistry students might typically utilize such resources.

Each iteration (September 2023 and December 2023) was completed within a single day, hopefully mitigating the impact of changes in sampled text or version updates across different days. The generated responses were then systematically copied and pasted into a spreadsheet for subsequent analysis. This procedure was replicated three months later to investigate whether there were any alterations in the responses over time. Upon completion of data collection, the responses were thoroughly reviewed and compared. Specific phrases and concepts of interest were identified, and their frequency across each response was documented. This quantitative approach provided insights into the variations and consistencies in the genAI responses, contributing to a comprehensive analysis of the selected genAI sources in relation to the chemistry concepts surrounding valence.

RESULTS

Comparison of Responses to Prompt A

The responses to prompts requesting definitions of valence, valency, valence electron, valence orbital, and valence shell reveal intriguing patterns and distinctions. When focusing on the singular concept of valence, we observe frequent reference to the historical definitions (Table 3). The responses highlight the significance of valence in structural arrangements and bonding, with a recurring theme of combining power. The relationship between valence number and the potential for bond formation is also observed, elevating the intrinsic "combining power" value of valence as a distinct characteristic. Similarly, the investigation into "valency" yields parallel results, with definitions consistently revolving around outermost electrons and their role in shaping structure and bonding. The interchangeable use of terms valence and valency aligns with our perceived synonymy of the two terms.

When comparing the results obtained three months apart, we observe discernible disparities concerning the historical versus modern definitions of valence. Figure 1 illustrates the frequency of the appearance of the historical definitions. Across all the genAI tools sampled, responses to the variable

Table 3. Examples of responses From genAI tools to General Prompt A

Variable Term	Representative quote from genAI responses
valence or valency	"In chemistry, valence (US spelling) or valency (British spelling) is a measure of the combining capacity of an atom with other atoms when it forms chemical compounds or molecules." ²⁹
	"Valency in chemistry is a term used to describe the combining power or the number of chemical bonds an atom of a particular element can form with other atoms." ³⁰
	"In chemistry, "valency" (sometimes spelled "valence") refers to the combining capacity or the number of chemical bonds that an atom of a particular element can form when it reacts with other atoms." ³¹
valence electron	"In chemistry, a valence electron is an electron that is located in the outermost energy level or shell of an atom." ³¹
	"In chemistry, a valence electron refers to an electron that is located in the outermost energy level or shell of an atom. These electrons are involved in the formation of chemical bonds and determine the reactivity and bonding behavior of an element. The valence electrons are crucial in determining the valency, or combining power, of an atom." ³²
valence orbital	"a valence orbital refers to the specific region or space around an atom where its valence electrons are most likely to be found. It is also known as the outermost electron shell or the highest energy level of an atom." ³³
valence shell	"the valence shell refers to the outermost energy level or electron shell of an atom. It is the shell where valence electrons, which are involved in the formation of chemical bonds, are found. The valence shell determines the chemical properties and reactivity of an atom. The valence shell is also known as the outermost shell or the highest energy level." ³²
	"The valence shell determines the chemical behavior and reactivity of an atom. The number of electrons in the valence shell determines the atom's valence, or combining capacity, and influences its ability to form chemical bonds." ³⁴

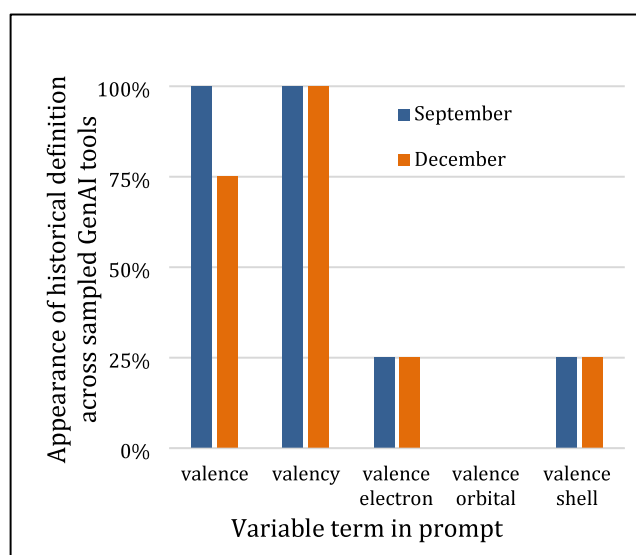


Figure 1. Comparison of appearance frequency of the historical definition (combining power or combining capacity) across the four sampled GenAI tools with respect to the variable term in the prompt. Data are shown from the two collection times: September 2023 (blue) and December 2023 (orange).

terms valence and valency consistently incorporate references to either combining power or combining capacity. When the prompt included “valence” as an adjective in the variable term (e.g., “valence electron,”), the responses become more consistent with our modern understanding. They incorporate modern concepts such as electron configuration and stability, with only one source mentioning combining power. Responses regarding valence orbital are similarly modern and also incorporate concepts like hybridization. In the case of valence shell, the responses encompass bonding, stability, and electron gain or loss, with a subtle mention of combining power in only one source. The responses take the modern perspective relating valence shell to the outermost electron shell in the context of chemical interactions.

One noteworthy exception is observed in the December data from Liner, which does not use the historical definition at all in relation to valence. Interestingly, this response still encapsulates the essence of atoms combining, asserting that “the valence of an element determines the number of other atoms with which an atom of that element can combine, influencing chemical bonding and molecular structure.” In the response from September,³³ we do not see the phrase “combining capacity”, but the phrase was observed in the December response: “The number of valence electrons an atom possesses determines its valence, or combining capacity, and influences the types of bonds it can form.” Additionally, when the more specific and modern

phrases—valence electron, valence orbital, and valence shell—are used as the variable term in the prompt, we see the incorporation of the historical definition much less frequently, with valence orbital notably never directly referencing “combining power” or “combining capacity and the other two only observed in one out of four responses.

Changes in Responses over Time

Table 4 summarizes the word counts for the full genAI responses to Prompt A, where only a single word in the prompt was altered, and the prompt was deployed across multiple genAI sources. Responses connected to the noun terms valence and valency are generally shorter than those for their modern counterparts, where valence is used as an adjective—valence orbital, valence shell, and valence electron. Additionally, a distinct pattern is evident when evaluating results by individual genAI sources. Notably, ChatSonic consistently exhibits a markedly lower word count in its responses compared to any other AI source. Furthermore, a temporal analysis reveals that responses generated by ChatGPT became shorter overall in the December data, suggesting some shift in its generative patterns. Conversely, responses from Bard exhibited a significant increase in word count over the same period. These findings illuminate variations in word counts across different genAI sources and highlight some dynamic shifts in response lengths over time.

Comparison of Responses to Prompt B

We further explored the term valence in relation to different subdivisions of chemistry typically encountered by students: general, biochemistry, organic, inorganic, and physical. The ChatGPT responses shed light on the variation of perspectives on this term (Table 5) and generally show consistent use of the historical definition.

Every response to Prompt B collected in September incorporates a version of the historical definition. For example, in general chemistry, the responses encompass combining capacity and highlight the fundamental role of valence in understanding chemical interactions. In relation to organic chemistry, ChatGPT provides a very brief definition, again referencing the combination of capacity and framing valence in the context of carbon interactions. The definition of valence in relation to inorganic chemistry closely resembles that of general chemistry but shifts the perspective to “complex ions” and “coordination compounds.” Lacking the phrase “combining capacity” or “combining power”, both responses related to biochemistry and physical chemistry in September seem to deviate from the trend. However, upon careful scrutiny, these responses still implicitly reference the ability to form bonds with other atoms, indicating a connection to the historical definition centered around combining.

Table 4. Summary of Word Counts for genAI Responses to Prompt A

Prompt	ChatGPT		Liner		ChatSonic		Bard	
	Sept ³¹	Dec ³⁰	Sept ³²	Dec ³⁵	Sept ³³	Dec ³⁶	Sept ²⁹	Dec ³⁴
“define valence as it relates to chemistry”	165	142	101	326	98	98	244	298
“define valency as it relates to chemistry”	108	191	164	166	98	100	220	316
“define valence electron as it relates to chemistry”	175	109	293	234	106	99	206	356
define valence orbital as it relates to chemistry	355	201	303	321	102	97	239	368
define valence shell as it relates to chemistry	209	157	301	180	95	96	243	398
Average Count	202	160	232	245	100	98	230	347

Table S. Selections from ChatGPT Responses to Prompts Related to Different Divisions of Chemistry

Prompt	Response from September 2023 ³¹	Response from December 2023 ³⁰
"define valence from a general perspective"	"In general chemistry, "valence" refers to the combining capacity or the number of chemical bonds that an atom of a particular element can form when it participates in the formation of compounds."	"In general chemistry, valence refers to the combining capacity of an element."
"define valence from a biochemistry perspective"	"In biochemistry, "valence" is not typically used as a central concept in the same way it is in general or inorganic chemistry... Valence is a fundamental concept that helps explain how elements interact with each other to create molecules and compounds."	"in biochemistry, valence refers to the combining capacity of an atom"
"define valence from an organic chemistry perspective"	"In organic chemistry, "valence" refers to the combining capacity or the number of covalent bonds that an atom of a particular element can form when it participates in organic compounds."	"In organic chemistry, valence refers to the number of covalent bonds that an atom of a particular element typically forms when it participates in organic compounds."
"define valence from an inorganic chemistry perspective"	"In inorganic chemistry, "valence" refers to the combining capacity or the number of chemical bonds that an atom of a particular element can form in the context of chemical compounds"	"In inorganic chemistry, valence refers to the combining capacity of an element, specifically in the context of its ability to form chemical bonds."
"define valence from a physical chemistry perspective"	"In physical chemistry, "valence" refers to the number of chemical bonds that an atom of a particular element can form with other atoms"	"In physical chemistry, valence encompasses various theoretical and experimental concepts related to the electronic structure and bonding of atoms and molecules."

The December data consistently includes the explicit phrase "combining capacity" (or general idea) but also highlights the link between oxidation state and valence and provides concrete examples rooted in periodic trends. The responses related to physical chemistry emphasize the "number of chemical bonds" an atom can form. The responses also imply the complicated nature of this term and its connections to both theoretical and experimental concepts. Notably, the physical chemistry response in December does not mention the historical definition, aligning more closely with a modern definition; these observations suggest differences in the genAI algorithm or text being sampled over the two collection periods.

DISCUSSION

General chemistry students in the 21st century can encounter chemical concepts in multiple ways beyond the classroom. In this project, we aimed to understand how students might encounter the concept of valence by using generative AI tools. We also aimed to compare those genAI responses to various historical and modern perspectives of valence. Our results show a clear trend to define valence as "combining capacity" or "combining power", which we describe as a historical perspective. Definitions more closely match our modern perspective when we use valence as an adjective, modifying the terms shell, orbital, etc. Generally, the historical definition was less prevalent as the variable terms became more specific, with only a few prompts returning any mention of it. Results where the variable term was "valence orbital" and "valence shell" were broader and less delineated than our perception of the terms, but they did encompass more details and separation than responses to prompts for the single terms valence or valency. The responses sometimes used terms in a circular fashion (i.e., using valence to define valence electrons), but this was not necessarily something we were immune to in developing our own definitions of the terms. From these results, we recognize the importance of prompt specificity when asking genAI for definitions to obtain the most accurate and current relevant results. Future work may explore genAI responses to more specified or detailed prompts.

Considering the different perspectives of the subdivisions of chemistry, we see a similar adherence to the historical definition. It is possible that the frequency of the historical definition in these responses was a product of the simple prompt itself, as we have observed that when valence was treated as a noun, the historical definition is frequently observed. There was also an interesting result in the responses to Prompt B; the responses often included concepts that were specifically applied to the relevant division. For example, responses to the prompt "define valence in relation to inorganic chemistry" include the concepts of complex ions and coordination compounds, which are common topics of inorganic chemistry. Even throughout the divisions, we found varying levels of cohesion and refinement toward a more ideal definition that aligned with our own modern definitions; the responses related to physical chemistry in December provided the most comprehensive and holistic definition from any prompt. For these prompts, there was surprisingly little change in the responses over time.

Despite many of the definitions growing larger in word count, there was not a significant change in meaning and depth. Usually, the responses were scientifically accurate, albeit sometimes presented in a confusing manner. We also observed some major errors, e.g. "each p orbital can hold up to six

Table 6. Think-Pair-Share about Valence and the Nature of Science

Part 1: TPS regarding the nature of science	Instructor prompt: "Think about the following statement: <i>Science is a collection of facts that has always been known.</i> Do you agree or disagree with this statement? Consider this on your own for 1–2 minutes then discuss with your partner."
Part 2: TPS regarding valence	Instructor prompt: "We've been learning about valence electrons and electron configurations in the last week. How would you define the term valence? Consider this on your own for 1–2 minutes then discuss with your partner."
Part 3: TPS with genAI	Instructor prompt: "With your partner, use a generative AI tool (ChatGPT, Gemini, etc.) to explore the term valence. What do you observe about the responses you received? Write some direct quotes below and discuss."
Part 4: Discussion	Instructor led class discussion about how valence has been defined both by students and using genAI. Draw connections to how this relates to the nature of science.

electrons",³² and occasional anthropomorphisms, e.g. "atoms typically strive to achieve a stable electron configuration"³¹ in the responses. While the interval between the trials was not a conventionally large amount of time, we know that generative AI is rapidly changing. This is indicated through the changes and additions in the responses, even though they are sometimes not in the direction we were expecting. In fact, the responses to one of the prompts that had no mention of combining power in September included the historical definition three months later.

Considering the modern definitions outlined in our introduction, the genAI tool with the closest alignment to our modern definition was Bard, now known as Gemini.³⁷ This genAI tool provided sources for some of its key information, which could potentially assist students in assessing the accuracy of the responses they receive. For all the other tools, the responses were presented without citation, and we are unable to determine the sources being used; the prevalence of the historical definition suggests that the genAI tools were sampling from sources much older than modern textbooks. Consequently, we observe that the historical definition is particularly "sticky", in that it is not easily forgotten despite the decades that have passed since it was used in General Chemistry textbooks.

From our study of historical chemistry texts, we see how over time, the meaning of the term valence has slowly changed in the landscape of general chemistry education. In modern General Chemistry textbooks, the idea of "combining power" is not included, but rather, valence is used as an adjective to describe those electrons involved in forming compounds. Pauling seemed to foresee this transition, when he wrote in 1947 in one of his first General Chemistry textbooks about the shifts in meaning of this term.³⁸

"The effort to obtain a clear understanding of the nature of valence and of chemical combination in general, has led in recent years to the disassociation of the concept of valence into several new concepts...of ionic valence, oxidation number, covalence, coordination number, corresponding to different modes of interaction of the atoms. Some chemists have felt that the word valence might well be allowed to drop into disuse in favor of these more precise terms in practice, however, valence continues to be used as a general expression of the combining powers of the elements, or as a synonym for one or another of the more precise terms."
Pauling 1947, *General Chemistry*, Chapter 8, p.120

In this quote, Pauling's affinity for the "combining power" definition is clear, but he also recognized the evolution of the term and the introduction of more specific ideas.

Implications for Educators

As this paper demonstrates, a historical definition of valence is nearly omnipresent in the responses from modern genAI tools. What other terms and concepts might these tools describe using language not found in our current textbooks? And how

will our students be able to interpret modern vs historical concepts? With how rapidly new versions of these genAI tools are being released, we imagine there will be further variation in the results and perhaps a shift to a more modern perspective on the term. However, in their current state, these tools could, without a question, be a source of profound confusion for students. College and secondary school educators need to be aware that genAI tools can generate responses that are not representative of content in modern general chemistry textbooks and appear inconsistent with our modern understanding of chemistry.

In addition, we encourage educators to consider and include in their class sessions frank conversation about the ethical and moral concerns associated with generative AI tools.^{39–42} Most students comprehend that plagiarism is unacceptable and we would be remiss in using genAI tools in our classes without acknowledging that the information in the responses is almost never cited properly.⁴³ Students also need to understand that genAI tools can create believable but completely imaginary citations.⁴⁴ Furthermore, the errors and confusing ideas we observed in the responses to our prompts compel us to communicate to students a healthy skepticism about these tools. As educators and scientists, we can and should communicate clearly that these tools are not sentient,^{45–47} have no capacity for truth,⁴⁸ and are merely complex statistical algorithms^{49–51} dressed up in plain language "clothing".

Considering the concept of valence, the juxtaposition of the historical definition and our modern understanding within the responses of modern genAI tools implies the development of a chemical concept over time. The findings of this study provide an opportunity to discuss the nature of science with our students. Table 6 describes a multipart in-class activity regarding these topics that utilizes think-pair-share (TPS), a recognized pedagogy for active learning in chemistry.^{52–55} This activity should be deployed near and after when general chemistry students have learned about modern atomic theory, electron configurations, and valence electrons.

Using three scaffolded think-pair-share exercises (Parts 1–3) and the results discussed in this paper, a general chemistry instructor can guide a class discussion (Part 4) regarding how the term valence has been interpreted differently over time and how these differences connect to the malleable nature of science itself. Refining the prompt used in Part 3 may yield interesting responses and create new learning opportunities for students. The discussion in Part 4 may explore how and why the concept of "combining capacity" is no longer included in our collegiate general chemistry textbooks and how, as Pauling predicted, other more descriptive terms are preferred. Instructors may use activities like this to support learning interdisciplinary concepts from the *Next Generation Science Standards*,⁵⁶ such as Scientific Knowledge is Open to Revision in Light of New Evidence.⁵⁷ This think-pair-share activity could also be adapted to explore the historical development of

other concepts in chemistry and make connections to the nature of science.

CONCLUSIONS

This paper presents historical and modern perspectives on the term valence and describes a systematic review of responses from modern generative AI tools in the context of collegiate general chemistry. We observe a prevalence of the historical definitions of “combining capacity” or “combining power” in the responses from genAI tools as well as in textbooks from the early to mid-20th century which tend to use valence as a noun. Modern textbooks use valence as an adjective to modify other nouns related to electron structure such as electron or valence orbital. The shift in meaning and usage of this term is an example of the nature of science itself in that our understanding of chemistry and the manner we teach it is open to revision. Combining historical and modern perspectives with genAI tools, thoughtful in-class activities can model how chemistry has changed over time and create innovative opportunities for student learning.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at <https://pubs.acs.org/doi/10.1021/acs.jchemed.4c00271>.

genAI prompts used and full responses collected on two separate dates (PDF, XLSX)

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Author Contributions

R.M.J.: conceptualization, methodology, investigation, writing—original draft, writing—review and editing, visualization, E.R.: methodology, investigation, analysis, writing—original draft, writing—review and editing, C.P.: investigation, analysis, writing—original draft

Notes

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