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Multiple Visual Representations Of The Periodic System Of Elements: Epistemological And Pedagogic Implications

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Abstract

The periodic system is a rich and complex domain—a deeply interconnected system involving the interplay of a wide variety of chemical concepts at multiple levels. This allows chemists to represent it in a variety of formats. However, this multifaceted and complex nature of the periodic system is rarely presented to students. This paper offers an analysis of the various representations of the periodic system and explores the pedagogical and epistemological implications of utilizing these multiple representations in the classroom. This theoretical argument is the basis for the development of FLiPS: an interactive multimedia hypertext for flexible learning in chemistry.

> *A single map is but one of an indefinitely large number of maps that might be produced for the same situation or from the same data.* — Mark Monmonier (1991)

> *Pictures, tables, graphs can be dangerous things. Revealing one point, they hide assumptions, eliminate possibilities, prevent comparisons—silently, unobviously. Thus, a pattern makes sense of data but also limits what sense it can make.* — Root-Bernstein (1989)

The organization of the periodic table by Mendeleev is undeniably the greatest breakthrough in the history of chemistry. It is a remarkable demonstration of the fact that the chemical elements are not a random clutter of entities but instead display trends and lie together in families. All that we see around us, *everything* (from stars to microbes; from aardvarks to zoologists) is made up of these hundred or so elements. Each chemical element has a unique atomic number and fixed position in the table, and from this we can predict its behavior: how it would react with other elements, what kind of compounds it would form, and what sort of physical properties it would have.

A version of Mendeleev's original periodic table has become a central feature for teaching chemistry—specifically inorganic chemistry (Woodgate, 1995) and most textbooks of inorganic chemistry have chapters arranged according to it. The periodic table is presented as a conceptual tool that not only integrates and organizes the field of chemistry but also helps develop a foundational framework for further learning in the domain.

The Periodic System And Its Representations

At the heart of the periodic table is the Periodic Law—a statement which recognizes an empirical periodic variation of physical and chemical properties of the elements with their atomic numbers. A modern statement of the periodic law is:

> The electronic configurations of the atoms vary periodically with their atomic number. Consequently, all properties of the elements that depend on their atomic structure (electronic configuration) tend also to change with increasing atomic number in a periodic manner. (Sanderson, 1977, p. 761).

It is important to distinguish between the statement of this law and its visual representation. In order to erect a framework upon which the myriad facts of the Periodic Law can be organized, the chemical elements can be arranged in orderly arrays called "periodic tables." Thus a periodic table is a specific visual representation of the Periodic Law. As Sanderson says:

> The Periodic Law is fundamental, but the periodic table is merely an arbitrary attempt to arrange the elements to represent their periodicity most usefully. Any such arrangement can be satisfactory if it organizes the elements in some order of increasing atomic number, showing the separate periods and at the same time grouping elements of greatest similarity together—in other words, placing the corresponding parts of the several periods together. There is wide variety of ways in which this can be done (Sanderson, 1966, p. 789).

The periodic system of elements (the word "system" is used to distinguish it from a specific representation) contains within it an infinitely large number of possible representations. As Rich (1963) says in his book *Periodic Correlations*:

> One of the fascinations of inorganic chemistry is the existence of a wide variety of relationships among the elements and their properties—rela-

> tionships that show an encouraging degree of order, but a tantalizing variability and novelty. These qualities make the "family of elements" an apt metaphor: while members of a family have much in common, each member also has his [sic] own individual personality. The quality of relatedness among elements makes periodic tables possible. But the diversity of their interrelationships bars any one table from a monopoly on the advantages. (p. xx)

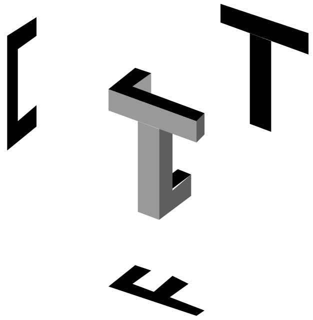
This is the reason why, though a single representation—a modification of the original Mendeleev version—dominates most textbooks, chemists have not stopped trying to create new tables. Over the years, hundreds of versions of the periodic table have been proposed, each attempting to map out the complex relationships among the elements or groups of elements. A large variety of tables have been developed because of the large number of possible relationships between elements (or groups of elements) that can be mapped. It has been cast into three-dimensional forms (spirals, screws, cones and spheres) as well as many two-dimensional types (Mazurs, 1974; van Spronsen, 1979).

Mark Monmonier in his charming and witty book, *How to lie with maps*, begins his book by stating, "Not only is it easy to lie with maps, it is essential" (Monmonier, 1991, p. 1). He continues, "To portray meaningful relationships for a complex, three-dimensional world on a flat sheet of paper or a video screen, a map must distort reality.... There is no escape from the cartographic paradox: to present a useful and truthful picture, an accurate map must tell lies." He offers a single caveat to alert us to our naiveté towards maps: "*A single map is but one of an indefinitely large number of maps that might be produced for the same situation or from the same data.*" (p. 2; italics in original). The main focus should be on whether a given map is appropriate for the task at hand.

A similar argument can be made for the visual representations of the periodic system. Representations of the periodic system are not pictures in the standard sense of the word—for these visual images of the elements are not iconic representations of something that is in the world, but rather a mapping of a series of complex relationships between elements, their atomic structure and chemical and physical properties. In this sense, it is a map—not a photograph[1]. Monmonier's caveat about maps holds true in the case of the Periodic System of elements as well and, in this context, one can paraphrase his statement as follows: *Any given visual representation of the periodic table of elements is but one of an indefinitely large number of table that might be produced. The issue then becomes which representations are useful for what tasks.*

Another metaphor for understanding these different representations is by way of thinking of each table as being a two (or sometimes three) dimensional "shadow" of a multi-dimensional object. Just as a human head can cast different shadows depending on the direction of light—one can imagine the periodic system as being an n-dimensional construct in conceptual space. Each periodic table we create can be regarded as a "shadow" of this multi-dimensional object depending on the "angle" from which we shine the light. This angle (so to speak) is determined by the specific aspect of the relationships among the elements that we wish to emphasize. Just as we need more than a single shadow to get a better understanding of the contours and shape of a head (Figure 1), we need multiple representations of the relationships between elements in order to get a better understanding of their complexity.

Figure 1
CFT TRIPLET



A CFT triplet (inspired by Hofstadter, 1979). Fully understanding the structure of the complex 3-D object at the center of image above requires integrating the three very different shadows cast on the three walls.

Though the periodic table indicates patterns and similarities across elements and groups of elements (and that is its greatest strength) it is important to remember that each element is, in some fundamental way, different from all the others. As Sanderson says, "no amount of organization or correlation will ever alter the fact that each chemical element is an individual and unique" (Sanderson, 1977). For instance, hydrogen differs from every other element in its properties leading to continuing controversy about where it should be placed in the any given periodic table representation. In the standard table it is often placed twice since it shares properties with both the alkali elements (such as sodium and potassium) and the halogens (fluorine, chlorine and the like). As for the question, where does hydrogen really belong, the answer seems to be: at both places. Some representations solve this problem by giving hydrogen its own unique position separated from the other groups/families. Similar problems can also be found with other elements as well.

It seems that there is merit to the thought that the periodic system of elements is a rich, complex and ill-structured domain—dependent on the interplay of a multitude of concepts and allowing for multiple representational formats. The important conclusion here is that the periodic system helps us see and appreciate some very significant patterns across the elements—patterns that helped us conceptualize the periodic system in the first place. However, seeing these patterns or similarities across groups and within families does not mean that everything is homogeneous within that group or family. The theme of "the same yet not the same" repeats itself throughout the periodic system—and also at different levels of analysis.

We would like to end this particular argument with a wonderful example of how the patterns of the periodic table can mislead and how each element is unique in its properties. This is taken from the charming and evocative autobiographical history *The periodic table* by Primo Levi (1984), chemist, author and humanist. He tells the story of an explosion he caused while working at the University of Turin. He needed some sodium to dry an organic solvent, but used potassium instead, another alkali metal, positioned right under sodium in the standard periodic table and very similar in its properties, but obviously, "not the same." Having described the explosion, he writes:

> I thought of another moral... and I believe that every militant chemist can confirm it: that one must distrust the almost-the-same (sodium is almost the same as potassium, but with sodium nothing would have happened), the practically identical, the approximate, the or-even, all surrogates, and all patchwork. The differences can be small, but they can lead to radically different consequences, like a railroad's switch points; the chemist's trade consists in good part in being aware of these differences, knowing them close up, and foreseeing their effects. And not only the chemist's trade.

Using A Single Representation: The Problems

Most textbooks falter in their attempt to depict the complexities of the periodic system.[2] They tend to take the contemporary Mendeleev form, the *long form* as it is popularly known, and use *just* that as a tool to explain chemical and physical periodicities of the elements (Figure 2). It has been pointed out that the long form suffers from a number of weaknesses. As Campbell (1989) says in a paper titled "Let us make the table periodic":

> Most chemistry classrooms display a wall chart labeled "Periodic Table of the Elements." What does a student see? Well, there is a set of rectangular boxes arranged in rows and columns, each box containing some alphabetical symbols and numerals that are difficult (even impossible) to read. Nor is any of the symbols periodic. Not even the format is truly periodic, no matter how one views it (p. 739).

In this form certain groups have to be placed outside the main table and "this segregation does not facilitate learning, and the sense of unity and harmony of the periodic system is lost." Even more serious in the long run is the lack of great usefulness of the symbols and numbers. Elements are difficult to locate, and the atomic numbers and weights say little about chemistry. Yet a major emphasis in chemistry, and perhaps the most difficult to grasp, is the interpretation of observations of atomic behavior. But neither the atomic weight nor number, as such, has much to do with chemical properties and reactivity. It is very easy for students to see the periodic table as being just a chart for inserting elements based on a single criteria—increasing atomic number. There are no apparent reasons for using rows and columns. The properties of individual elements can be better understood only if one considers a variety of factors such as electronic configuration, atomic radius, valence, and electronegativity. In fact even issues such as the nomenclature of elements and the manner in which elements have been used both by humans and nature can help us get a better understanding of their properties. However, these issues are rarely addressed.

In most textbooks, the periodic table is introduced early on even before going on to the properties of the elements. Even when the elements are introduced, they are not regarded as possessing unique properties but rather as being part of an intermediate structure—either a group or period of the periodic table—and it is the membership of the group that determines or defines their properties. This strategy of course does not do justice to the manner in which chemists actually developed these representations. The periodic table was constructed by attempting to group elements according to similarities in their properties not vice versa. Of course, once constructed, the periodic system could be (and was) used to predict the properties of then unknown elements. (Prior to the development of the periodic system, it was not even clear what elements were unknown.)

It is easy to understand the reason for why textbooks follow such a strategy. Introducing the periodic system early is supposed to give students an advance organizer, a framework within which to study the chemistry of the elements. However, lacking a basic understanding of the properties of the elements, such an *a-priori* organizational structure makes little sense to students. Worse yet, it may give them the impression that this is the *only* organizational structure possible. This top-down focus, where a single periodic table defines the place and properties of each element, as opposed to emphasizing the unique properties of the elements themselves, not only impedes students' understanding but also hinders their learning of more advanced topics.

It is not surprising that a review of the educational research into chemistry learning reveals that students do not seem to have an overall conceptual framework within which to place the myriad facts and numbers that they are faced with (Krajcik, 1991). Since they are not given the chance to fully develop an understanding of the complexities of the periodic system, students find chemistry to be just a series of random, disjointed facts. They seem to be "algorithm-dependent," and less flexible when it came to applying the rules they had learned. Also, they erroneously believe that numerical accuracy is very important for success in chemistry. Chemistry faculty, on the other hand, regarded chemistry as being more abstract and feel that it requires a "special way of thinking" (Carter & Brickhouse, 1989).

Multiple Visual Representations: Pedagogy And Epistemology

This special way of thinking (and one that we have been arguing for in this paper) entails a view of the elements and their relationships with each other that is multi-dimensional, context-sensitive and flexible. Furthermore, we feel that it is important that students be aware of the fundamental ill-structured and complex nature of the domain itself. It seems that a better understanding of the variability and complexity of the periodic system (i.e. the multifaceted, the dynamic, and the highly interactive/interconnected nature of the periodic system) will allow students to overcome some of the difficulties mentioned above.

Using a single representation implies that there is just one version of reality—Truth with a capital "T" as it were, something that Mendeleev had discovered. Confronting students with multiple representations would demonstrate that what Mendeleev had done was "invent" one particular representation which is just one among many possible versions. What had been *discovered* was the Periodic Law, and Mendeleev's table, and those created by others who followed him, were "snapshots" of the various ramifications of this law. It is imperative for students to realize that the periodic system is not a table but rather a system—a system with fluid relationships between elements, groups and periods. A system that can change depending on one's perspective and need, a complex, open-ended system that people have changed in the past and continue to do so.

Mazurs (1974) documents around 450 different tables and a search of the literature reveals that there are even more. A couple of significant issues arise from an initial analysis of these different representations. First, each table emphasizes some unique aspects of the relationships between elements. In some cases it may be shell-sub-shell structure, in others the manner in which electronic orbitals get filled while in others it may be the distribution of chemical properties.

Second, none of these tables are purely of one kind—for instance there is no such thing as a pure electronic configuration table or a pure chemical table (even though they may be labeled as such). One can use chemical tables to determine electronic structure and vice versa. Similarly shell and sub-shell tables can be used as a chemical table if the elements are color coded. However, doing so makes it difficult to see chemical patterns across groups and periods (Mazurs, 1974).

The fact that different tables overlap in their focus is not surprising given the complex nature of the relationships between elements and their properties. For instance, chemical properties are not independent of electronic structure and hence an electronic table can be used as a chemical table—though it may not be ideal for that task.

This interdependence brings about a third issue, the relationships among these tables to one another. For instance, the helical tables can be flattened in specific ways to generate spiral and lemniscate tables. Further, some of the spiral tables if cut and opened-out can be used to generate certain long forms of the periodic table. For instance, Janet's spiral form can be cut and opened out to generate the standard long form. However, some tables stand out from the others and are very unique in the manner in which they represent relationships. For instance, Treptow's atomic table, with its emphasis on electronic configuration up the level of electron spin provides a very different perspective on the periodic system.

In spite of the hundreds of tables proposed, the potential for a new representation still exists. Atkins (1995) says, "There may well turn out to be a deeper portrayal of the kingdom than any that has been discovered yet, ... An entirely different foundation for the portrayal may well be devised, or layers of portrayal, which will enrich our understanding beyond our current imagination."

Cognitive Flexibility Theory Hypertexts: A Possible Solution

However, just knowing that these multiple representations exist is not enough. The educational goal for teaching such a complex domain then becomes helping students develop into flexible thinkers and problem solvers. Krems (1995) identifies three important mechanisms that are important for flexible problem solving:

(a) multiple representations of data. A flexible problem solver is able to consider several alternative interpretations of a given situation. In the case of the periodic system, this would mean being able to think about the periodic system in various ways (i.e. using various representations).

(b) modifying representations: A flexible problem solver chooses an appropriate representation for the task and current situation and is able to make changes to them as and when required. In our case, it would mean being able to generate new representations or integrate two or more representations if required.

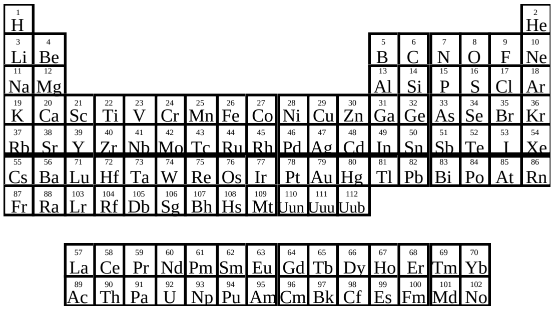
(c) modification of strategies. A flexible problem solver can change strategies to reflect changes in resources and task demands. In our case, it would mean choosing appropriate representations for the task at hand and be able to change from one representation to another when the problem changes.

Some help in this regard comes from Cognitive Flexibility Theory-CFT (Feltovich, Spiro & Coulson, 1993; Mishra, Spiro & Feltovich, 1996). CFT argues that in ill-structured domains, flexible cognitive representations (as opposed to rigid knowledge structures) enhance the transfer of knowledge to contexts different from those that had been involved originally in the teaching of the material. CFT lends itself prescriptively to the design of complex, multidimensional, and nonlinear environments (Spiro & Jehng, 1990)—specifically computer-based hypertexts—for enabling students to learn complex domains and also to apply this knowledge in new contexts. Our previous description of the chemistry of the periodic system (with its rich and complex relationships at multiple levels) combined with the inadequate nature of students understanding of these issues, make a CFT-hypertext particularly appropriate for instruction in this domain.

Such a computer program must then present both the multiple representations of the periodic system as well as hypertextually linked commentaries that would highlight significant "themes" related to these representations. These themes would work at various levels: at the levels of the elements, groups and tables. This would enable us to look at the particular properties of individual elements while at same time, seeing its relationship to the macroscopic level of the different periodic representations.

The first step in developing a CFT hypertext for the periodic system would be to short-list a finite set of representations taking care to choose ones that would cover significant themes and concepts. A short list of these tables is discussed below[3].

Figure 2
STANDARD LONG FORM

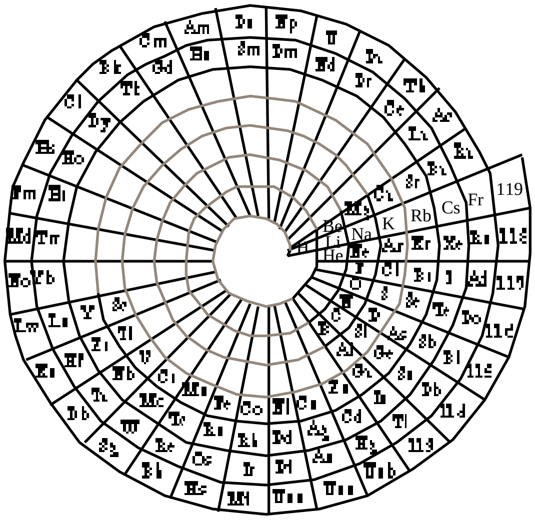


1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Uun	111 Uuu	112 Uub						

57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb
89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No

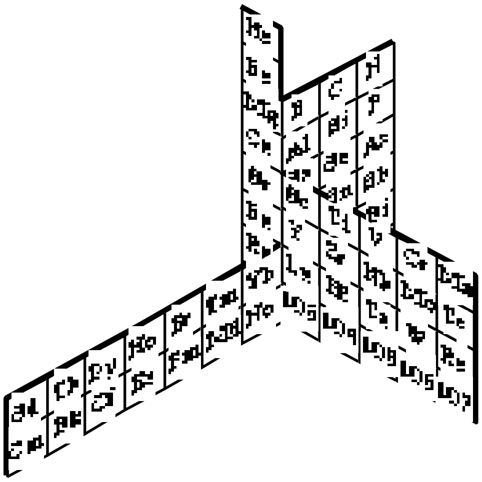
The most popular form of the table. It does a good job of combining the electronic configuration table and a chemical table. However, in this manner it does not do full justice to either.

Figure 3
JANET'S SPIRAL



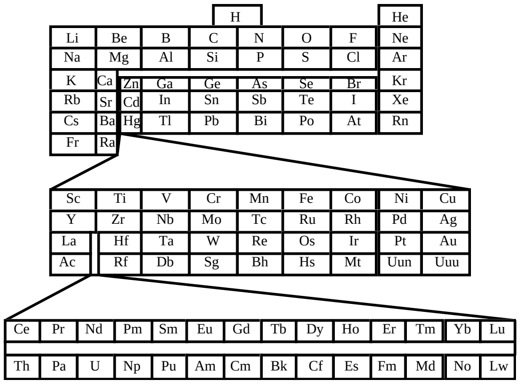
A very good continuous table though it may be difficult to read in some versions. However, it gets its significance from the fact that it can be dissected in various ways. It can be seen as the top view of a three-dimensional helical form. It can also be "cut" to generate the chemical and standard tables as well as "unwound" to generate the valence chain or graphical tables.

Figure 4
GIGUERE'S SPACE MODEL



This is a very interesting table in that it gives a very unique perspective to the manner in which sub-shells and shells get filled with electrons. However, being a space model (i.e. a 3-D table) it is difficult to represent and use in 2-dimensions.

Figure 5
SANDERSON'S SEPARATED FORM



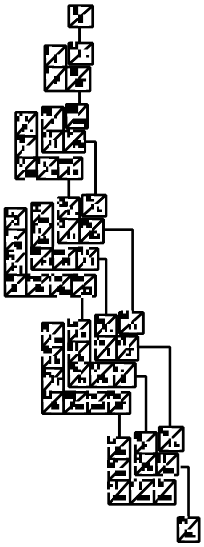
				H				He
Li	Be		B	C	N	O	F	Ne
Na	Mg		Al	Si	P	S	Cl	Ar
K	Ca	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra							

Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu
Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag
La	Hf	Ta	W	Re	Os	Ir	Pt	Au
Ac	Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu

Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lw

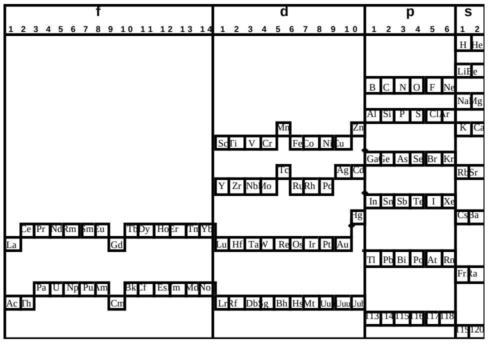
This is an excellent chemical table. Though the arrangement of elements breaks many of the rules of electronic configuration this arrangement is best suited for the understanding of patterns in chemical and physical properties of the elements.

Figure 6
TREPTOW'S ATOMIC TABLE



Elements are arranged in squares with square denoting a period. This is a very unique way of looking at electronic configuration by pairing elements (within a square) that have electrons with opposing spins. Not necessarily a good table for understanding the chemical properties of elements.

Figure 7
MAZURS'ELECTRONIC CONFIGURATION TABLE



The best table for understanding the electronic configuration of elements. This is the only table that considers the exceptional cases of electronic configuration. This fact makes it complement Sanderson's separated form very well. The frame of this table can be used very well to draw continuous graphs of the physical properties of the elements.

FLiPS: A multimedia hypertext for the periodic system

These multiple representations are the basis of the design of FLiPS (Flexible Learning in the Periodic System), a prototype multi-media, multiple representational software package based on educational theory and the properties of the periodic system. The design of FLiPS (Figure 8) is driven by both the nature of the domain and the learning outcomes that we would like to achieve.

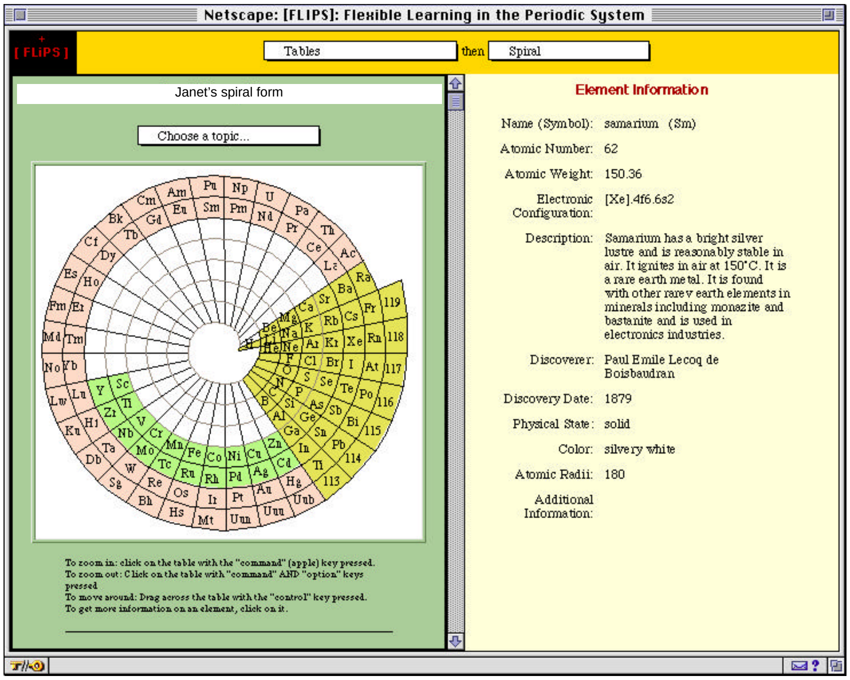
Figure 8
FLiPS LOGO

The FLiPS logo can be read the same even when rotated by 180 degrees; visually suggesting the multiple ways in which the periodic system can be "read."

The software is currently in development. The final program will be a dynamic web site that will allow users to view and interact with different representations of the periodic system. This is made possible with a complex hardware and software configuration including a dedicated web server, that communicates with a database to dynamically generate web pages. The representations are created using proprietary shockwave technology to provide interactive images (i.e. they contain "hot spots" as well as the ability to be magnified and reduced at will).

Below are two screen shots depicting the current status of the program. Figure 9 is multi-frame window with one of the tables (Janet's spiral) selected for further investigation (shown in the left frame). The right frame shows the results of a database search when any of the elements in the tables is clicked upon. What is not obvious from the screenshot is that one could choose from a pull-down menu just above the table to choose a variety of "themes" describing the table selected, which would then appear in the right frame. One can either explore the themes for a given representation or explore the manner in which a given theme is manifested in different representations.

Figure 9
SCREEN SHOT FROM FLIPS (1)



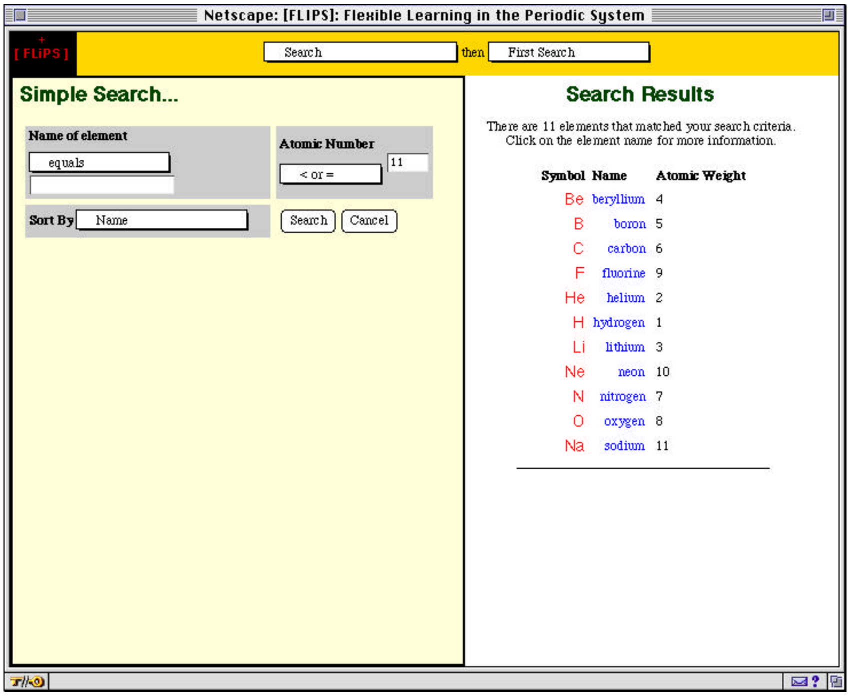
To zoom in: click on the table with the "command" (apple) key pressed.
To zoom out: Click on the table with "command" AND "option" keys pressed
To move around: Drag across the table with the "control" key pressed.
To get more information on an element, click on it.

Element Information

Name (Symbol):	samarium (Sm)
Atomic Number:	62
Atomic Weight:	150.36
Electronic Configuration:	[Xe].4f6.6s2
Description:	Samarium has a bright silver lustre and is reasonably stable in air. It ignites in air at 150°C. It is a rare earth metal. It is found with other rarev earth elements in minerals including monazite and bastanite and is used in electronics industries.
Discoverer:	Paul Emile Lecoq de Boisbaudran
Discovery Date:	1879
Physical State:	solid
Color:	silvery white
Atomic Radii:	180
Additional Information:	

Screen shot from FLiPS showing the results of clicking on an element in the Janet's spiral form.

Figure 10
SCREEN SHOT FROM FLIPS (2)



Name of element equals

Atomic Number < or = 11

Sort By Name

Search Results

There are 11 elements that matched your search criteria. Click on the element name for more information.

Symbol	Name	Atomic Weight
Be	beryllium	4
B	boron	5
C	carbon	6
F	fluorine	9
He	helium	2
H	hydrogen	1
Li	lithium	3
Ne	neon	10
N	nitrogen	7
O	oxygen	8
Na	sodium	11

Screen shot from FLiPS showing the results of a simple search of the elements database.

Users will have the ability to search for elements using one or more (Boolean searches) from 30 unique descriptors ranging from atomic number to date of discovery. Figure 10 is a screen shot of a simple search procedure on the periodic system element database.

FLiPS will allow students to see the periodic system as being a fluid and dynamic set of relationships that can be understood in multiple ways. Actually working with a variety of visual representations of the periodic system allows students to "see" relationships that previously seemed intangible and vague when just discussed verbally or using just a single representation. The final aim of this project involves studying the manner in which a group of students interact with the software and the nature of knowledge acquisition that accrues. The goal is to develop rich and complex narrative profiles of these individuals, their backgrounds, beliefs, and processes of working and learning in this complex hypertext environment (Mishra & Nguyen, submitted). Understanding learners'lived through experiences as they interact with this software is an extremely important first step for getting a better understanding of issues of learning such complex concepts using hypertexts.

Conclusion

We would like to end this paper with a final quote from Hoffman's excellent collection of essays on the nature and culture of chemistry (Hoffman, 1995). This statement by a sensitive, reflective practitioner in the field of chemistry succinctly captures a point of view that we have been trying to develop in this paper (and in our research).

> I think chemistry is interesting to its toiling practitioners, and to people who use it (or abuse it) without being chemists, because its activities parallel deep avenues in our psyche—which I prefer to see not as a branching tree of neurons, shaped by genetics and experience (and chance), but as a completely interconnected multidimensional volume. In which a given fact (a molecule, a line from a poem) has a history, a context, to be sure. But come to life only if we think of the molecule (or the poem) as suspended—yes, tensely—in a space that is defined by different themes or oppositions.
>
> In an imperfect metaphor, think of the themes as light of different wavelengths. Or think of them as coordinate axes, not very linear, in a multidimensional space. I turn on the light of identity, of the same-and-not-the-same... The different ways in which any molecule is examined, where it falls not on one by on many polarity scales, make the molecule inherently *interesting.*

The challenge for educators is somehow to convey this "multidimensional" character, in all its richness and complexity, to our students and, possibly, to expose them to these "inherently interesting" ideas. We feel that our approach of using multiple visual representations within a hypertext has much to offer towards achieving this goal.

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Footnotes

[1] Photographs and diagrams are also loaded with hidden conventions and mapping relationships (Gombrich, 1960; Arnheim, 1969). However, for our purposes it may be easier to leave these issues aside for the moment.

[2] Rich, 1963; Tyree & Knox, 1961 are notable exceptions.

[3] Most of these representations have been taken from Mazurs, 1974.