Supplemental Material

CBE—Life Sciences Education

Kohn *et al.*

Appendix A - Structure-Property and Structure-Function Relationships as Described in Curriculum Reform Documents

<table>
<tr><th>Reference</th><th>Structure-Property</th><th>Structure-Function</th></tr>
<tr><td rowspan="2">AP Chemistry Curriculum Framework (2015)</td><td>Big Idea 2 (p. 19)
Chemical and physical properties of materials can be explained by the structure and the arrangement of atoms, ions, or molecules, and the forces between them.</td><td>Big Idea 2 - Essential Knowledge 2.B.3.e (p.27)
The structure and function of many biological systems depend on the strength and nature of the various Coulombic forces.</td></tr>
<tr><td colspan="2">Big Idea 5 - Essential Knowledge 5.D.3.b (p. 62)
The functionality and properties of molecules depend strongly on the shape of the molecule, which is largely dictated by noncovalent interactions.</td></tr>
<tr><td>AP Biology Curriculum Framework (2015)</td><td>Big Idea 4 (p. 78) - Biological systems interact, and these systems and their interactions possess complex properties
Enduring Understanding 4.A: Interactions within biological systems lead to complex properties
● Essential Knowledge 4.A.1: The subcomponents of biological molecules and their sequence determine the properties of that molecule.
● Essential Knowledge 4.A.4: Organisms exhibit complex properties due to interactions between their constituent parts.</td><td>Big Idea 4

Enduring Understanding A
Essential Knowledge 4.A.2 (p. 82)
The structure and function of subcellular components, and their interactions, provide essential cellular processes.

Enduring Understanding B
Essential Knowledge 4.B.1 (p. 89)
Interaction between molecules affect their structure and function</td></tr>
<tr><td>Tansey, Baird, Cox, Fox, Knight, Sears, & Bell (2013)

American Society for Biochemistry & Molecular Biology</td><td></td><td>Essential Concept - Macromolecular Structure and Function (p. 294-5)
Structure and Function are Related
The function of a protein, nucleic acid, or other macromolecule is defined to a large extent by the specific molecular interactions it takes part in. Those interactions are in turn dictated by the structure of the macromolecule...
Macromolecular Structures are Dynamic
Macromolecular structures are not static. Conformational changes large and small are often critical to function…
Some Macromolecules are Intrinsically Unstructured
Segments of some proteins, and in a few cases entire proteins, are intrinsically unstructured…The lack of structure in solution may facilitate a function in which interactions must occur promiscuously with several other molecules, as documented for some proteins with a signaling function.
Macromolecular Function is Subject to Regulation
A wide variety of possible covalent modifications (e.g. partial proteolytic cleavage, intrachain and/or interchain disulfide formation, glycosylation, and phosphorylation) occur, and play a role in regulation, cellular targeting of the protein, or directly in the protein’s function.</td></tr>
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<table>
<tr><td>Anchoring Concepts Content Map for General Chemistry (2012)</td><td colspan="2">Anchoring Concept - Structure & Function (p. 6)
Chemical compounds have geometric structures that influence their chemical and physical behaviors.
(A) Atoms combine to form new compounds that have new properties based on structural and electronic features.
(E) Three-dimensional structures may give rise to chirality, which can play an important role in observed chemical and physical properties
(F) Reactions of molecules can often be understood in terms of subsets of atoms, called functional groups.
(G) Periodic trends among elements can be used to organize the understanding of structure and function for related chemical compounds.
(H) Many solid state, extended systems exist, and geometric structures play an important role in understanding the properties of these systems.</td></tr>
<tr><td rowspan="2">NRC Framework for K-12 Science Education (2012)</td><td colspan="2">Crosscutting Concept - Structure & Function (p. 84)
The way in which an object or living thing is shaped and its substructure determine many of its properties and functions.</td></tr>
<tr><td>Core Ideas PS1.A: Structure and Properties of Matter (p.104)</td><td>Core Ideas LS1.A: Structure and Function (p.143)</td></tr>
<tr><td>Vision & Change (2011)</td><td>Systems
A systems approach to biological phenomena focuses on emergent properties at all levels of organization, from molecules to ecosystems to social systems...Through these models, researchers seek to relate the dynamic interactions of components at one level of biological organization to the functional properties that emerge at higher organizational levels.</td><td>Core Concept - Structure & Function (p. 12)
Basic units of structure define the function of all living things. Structural complexity, together with the information it provides, is built upon combinations of subunits that drive increasingly diverse and dynamic physiological responses in living organisms. Fundamental structural units and molecular and cellular processes are conserved through evolution and yield the extraordinary diversity of biological systems seen today.</td></tr>
<tr><td>College Board Science Standards (2009)</td><td>Standard C.2 - Matter and Change
The properties of matter and the changes that matter undergoes result from its atomic–molecular level structure. For any chemical or physical change, matter is conserved.
C.2.2 Structure–Property Relationships - Students understand the relationship between molecular-level structure and chemical and physical properties.</td><td>Unifying Concept - Form & Function (p. 4)
[Quotes NSES 1996]</td></tr>
<tr><td>Engineering in K-12 Education: Understanding the Statue and Improving the Prospects (2009)</td><td>Engineering Concept in the category of systems - Emergent Properties (p.125)
Not all systems can be analyzed in terms of causal behaviors or a direct, linear sequence of events. Another framework for understanding systems is focusing on behaviors that emerge from dynamic interactions among system components. These emergent properties can be global, aggregate, or macrolevel behaviors that emerge from local, simple, or micro-level interactions between (or among) individual elements or components of a system.</td><td>Engineering Concept in the category of systems - Structure-Behavior-Function (SBF; p. 122)
SBF, a framework for representing a system, can be used to describe both natural and designed systems. SBF relates the components (structures) in a system to their purpose (function) in the system and the mechanisms that enable them to perform their functions (behavior).</td></tr>
<tr><td>National Science Education Standards (1996)</td><td>Structure and Properties of Matter (p. 178)</td><td>Unifying Concept - Form & Function (p. 119)
Form and function are complementary aspects of objects, organisms,and systems in the natural and designed world. The form or shape of an object or system is frequently related to use, operation, or function. Function frequently relies on form. Understanding of form and function applies to different levels of organization. Students should be able to explain function by referring to form and explain form by referring to function.</td></tr>
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Appendix B. Student responses when prompted to describe function in GC1/GC2

Most (11 of 14) described function as more applicable in B1

Clarice:[Function is] I guess what each thing is supposed to be doing. I don't know.I can't really, relate it back to chem, not that I can think of right now. But like, bio I guess...the function of cellular respiration is to like get CO— or not make CO2, but like, yeah, no, make CO2. And like give off CO2. Like that's the function of that cycle. Whereas I don't know I don't really think about it like that in chem.

Evelyn: Function, I automatically think of biology, like the different organelles and all their different functions that they have inside of a cell...I have a harder time applying function to chemistry… properties reminds me chemistry and then function reminds me of biology.

John: Uh, chemistry— with like the acid— with acid bases is pretty easy and how the— an acid's going to have the hydrogen that you can give up, on a very electronegative atom and how that's structured. I'll just draw HCl I guess...taking in the hydrogen to make up for, the lost electrons would be its property. And then the function would be, um, **just the acidicness**— I don't really know the function here...I guess you don't talk about the function as much because like you're not really talking about like what they're going to end up doing, I guess? As opposed to like bio where you talk about like what the function— like what it actually does.

Lida: In chemistry I would say we do a lot on the structure and properties. **For function, I guess that would be the actual reaction that produces something**. **But I don't know**, in chemistry I think it's harder for me to be like, 'Oh, this reacted with this to produce NaCl.'...I don't think of that as function, like what is this all doing? It's not doing anything...for bio I think it's a lot easier for me to incorporate that. Whereas function in chemistry, I don't know, I think it's easier for me to imagine structure and properties rather than function because I don't think there's a lot of chemicals that we're actually using to do something with.

Louanne: And I think I relate function more to like biology a little, definitely a little bit more than I do in chem. But then like structure and properties, I think I relate more to chem than bio...Function I would say a little bit more into biology, just because biology you're thinking more of how things like work to move on to the next step. Where in chemistry, I don't know— Like **I know we're like mixing chemicals and all that stuff. And I guess you could probably think of that as like a function**, but I would definitely put function more into biology than I would chem.

Natalie: Function is what something does specifically, so just what it does.What a certain molecule does or what a certain reaction does I guess, would be its function...I think that probably the thing we talked about least in chemistry is function. **Now that we're talking about reactions we're talking a little bit more about function, I would say**...I think biology has a lot more to do with function though than chemistry does. We talked a lot more about how these different things work in different living systems then you really do in chemistry. I think you're more focused on structure and properties there.

Priyah: [In GC1/GC2] I can see the structure and properties part but the function I kind of don't see, if that makes sense. I get how atoms interact and how that affects the property like if it's— like for metals, like if it's malleable or like hard or that. But then I don't know how that would relate to its function I guess...I think the structure, well like structure and function are more like biology and then the structure and properties are more chemistry I think...**for like metals conducting electricity and stuff. So that would be their function and— or would that be property?** I feel like these are kind of related— well they're all related but these kind of blur together. But they conduct electricity and that relates back to its structure with the electrons and how they can move freely and— **I guess the function would be how you could use the metals like wires** and stuff I guess.

Ruth: In chemistry, [function] makes me think of— (pause) not much. Maybe I think of like **compounds as drugs**, or something like that. Biology, I think of proteins functioning and I think of organelles and— But mainly proteins, I think a lot of proteins...it's weird for me with function for chemistry...I think the part where structure can change the properties was emphasized more [in GC1/GC2]. I didn't feel like there was much talk about function.

Serina:[In GC1/GC2] for structure I think of like drawing out the Lewis structure and drawing out reactions and what happens. Properties, knowing if like the properties of like a metal and a nonmetal and knowing those differences. I can't really think of function so much in chemistry, but definitely structure and properties...but I feel like I'm better able to relate these three words in biology than chemistry...I'm able to know in biology like how things do function versus in chemistry?

Shelly: For biology [function] would be like what they do and then for chemistry I would more of relate it to what— how they react with each other and what each part of the thing does I guess. Hard time putting it into words...for chemistry I would think structure and properties a little more...we haven't really talked about the functionality of it, just like what it does and like the, scientific reasons behind it. But we haven't really talked about like— aside from just the little bit of **pH and buffers in the human body, like that's where we're getting into a little more functionality,** but otherwise it's more of just like, the structure and how that relates to the properties with it.

Simon: When I think about function, yeah I guess I just think about how— It's job. Whatever it is, whether it's a molecule, **whether or not it will hydrolyze another molecule or whether or not it'll form a complex or whether or not this electronegative atom will interact with this non-electronegative atom**...I think if you define [function] as what happens, it's not going to really work for chemistry...[In GC1/GC2] For me, it should be properties to structure.

Three students expressed no difficulty applying function to chemistry

Aaron: So based on the structure and based on the properties, I see function as the combining of this and then you can determine what the function is or you can predict what the function is going to be. I think function is simply what comes of it. After you've determined the properties and analyzed the structure of something, function is what would naturally come of that, I guess. If that makes sense. If we're given a reaction and then I draw a Lewis diagram, then **I can see the function as a reduction— as a redox reaction versus acid-based reaction**. I look more at the properties in chemistry than I do anything else because I personally think that that's a bigger reason of why something is, which would be the function...**I think of the function as the answer**, I guess, as what I'm trying to get to.

Daniel: In biology we talk about how the structure determines the function by like, 'Oh, if an amino acid is polar then it can cross the lipid bilayer.' Maybe it's the other way around, but something like that maybe. And I guess in chemistry we talk about it as maybe polar and nonpolar structures, **how they interact** with other polar and nonpolar structures, stuff like that.

Joseph:[In GC1/GC2] A function, let's see. I have ideas. I just don't know how to word them, you know?...So properties like what kind of bonds are being formed between two atoms. So I don't know. Just anything, any different atom, what kind of bonds are being formed, and that will determine the kind of strength they'll need to overcome the bonds. That's actually a property, like the strength needed to overcome a bond, then the different structures. [00:57:01] So the different atoms combined to form different structures, then that structure will have a certain function.

Appendix C. Overlap between structure and properties

Joseph describing...

- **shape as structure:** The shape of whatever we're talking about...When I think of structure, I automatically think of structure determines function.
- **shape as properties:** Let's see. Like what kind of characteristics everything has. Just size, I feel like is a big property. Size, shape, stuff like that.

Aaron describing…

- **shape and size as structure:** When I think of structure, the immediate thing I think of is a shape of some object, really basic. That's what I would think of. Then I would think of, how big size-wise. I guess that's the same thing as shape.
- **types of bonds as properties:** Like electronegativity, effective nuclear charge, if something is polar and nonpolar...If one molecule has bonded this way and another molecule has bonded this way, then those would have different properties maybe, or those are different. Those are the properties. This is covalently bonded; this is ionically bonded.

Clarice describing…

- **shape as structure:** Like a Lewis structure. Like— or like what shape like if it's going to— like tetrahedron or a trigonal planar. It makes me think of that...When I think of bio I think of like, 'Oh, DNA structure is double helix'

Shelly describing…

- **shape as properties:** Like what, the characteristics that come with different things. Like their reaction abilities, their physical properties too, like their shape and, in macroscopic like colors and everything and how that— all of that kind of stuff and solid or liquid or gas, that kind of thing.

Ruth describing…

- **types of bonds and interactions as structure:** I think of the types of bonds that are occurring, the different elements— or I guess molecules that are being bonded to each other. I think of the arrangement of the molecules and— Yeah. I think that's probably what I think of...I think of something very similar in about biology, but I also think of, I guess— (pause) There was like, for proteins specifically there were different levels of the structure. So there was the just, the sequence of nucleotides and then there was how those form like, alpha helices and beta pleated sheets, and then how those interact. Then like, the final structure of the protein, how everything is folded in on itself.

John describing…

- **shape and polarity as structure:** Like the shape or polarity of a substance or, uh— (three knocks) uh, I cannot think of what it is— element or atom or something… [In biology] I would say the structure's like the same— just how something's composed.
- **size and polarity as properties:** Uh, if it's polar or nonpolar— size— big, small— hydrophobic, hydrophilic.

Appendix D. Additional quotes describing connections between GC1/GC2 and B1

Lida:...you don't understand the function unless you understand the first two [structure and properties]...my [high school] biology class we just learned the functions of everything...I was like, 'Okay, great, that's what that does. But why? You didn't explain why it does that.'...most bio classes, especially in high school, I'm sure all the bio classes will just teach you the function of things, they won't teach you the structure or the properties. So you can just memorize functions, but then you don't actually understand how they work unless you learn in chemistry the structure and the properties in order to take it over to bio…

Natalie:...I mean I feel like the structural knowledge and the properties came a little bit more from chemistry. And then applying that in biology, I see more of the functional aspects of things and how they relate to the function but I think that it seems pretty equal, equally coming from the two in the classes. Yeah, I would say it's a little bit more evenly distributed between the two, my overall understanding of them...I've definitely heard the phrase, 'structure determines function' a lot more in biology than I've heard in chemistry but I think that it would hard to relate structure to properties and things like that without having learned chemistry.

Ruth:I think [the courses] worked together because I took what I learned in chemistry from structure determining properties, and was really able to apply that when I was thinking of structure going from properties and then that really changing the function, in biology...I think it was helpful because realizing that if you change the structure, no matter how small that change may be, maybe you're just swapping this element for another element, it can completely change the whole entire property of that compound. I think that realizing that made it helpful to not just go like, 'Oh, it doesn't seem like much has changed when I write it,' but it may have changed a lot.

Simon:Say, if I'm in biology and [the instructor] asks me to think about how this protein is structured, like what amino acids make it up, the first thing I think about is how that would relate if I were to try and do this in chemistry. Because it's just easier for me to, you know, draw out the Lewis structure of the amino acid and see how it interacts...[In GC1/GC2] Like when you have water, it's easy for you to say that this water molecule will hydrogen bond with this water molecule and, you know that's the end of it...thinking about that in terms of biology, I can see why it would do that and I can see how that could be important to how water functions in the body. So it just— I guess it helps me understand the bigger picture of what these things really mean.

Appendix E. Additional quotes describing the relative necessity of considering properties

Clarice:...now that like you've kind of gone through both [courses], I can see like how they intermix. You can kind of skip the properties in bio. You kind of go from structure to function. So you— it's not like focusing on each one every time...you're supposed to have that understanding so they can kind of skip a step. Whereas in chem, it kind of like builds it up. It kind of gave me the initial understanding...

Natalie: It would be helpful to know its properties obviously, and I think that you couldn't get really a holistic view of its function without knowing its properties but I think you could still kind of analyze how the structure affects the function without always knowing the properties.

Shelly: [In GC1/GC2] ...the structure determines what properties it has and then the properties, you can use those to determine what the function would kind of would be...Because I could see structure going to function right away without needing to think about the properties but, I guess it all depends on what you're talking about at the time…[In B1] the more you get into more talking about cells and replication and all that, you think of structure-function. And properties are more like when you're thinking about the biological molecules...for like ribosomes or whatever, they have a part where mRNA combine and then they have the tRNA binding sites and then they just— I wouldn't really know any exact properties for that. We just talk about the function of it. It allows tRNAs to come in and bind to the codons and it's just the function of it. I don't really know any exact properties of it.

Appendix F. Students describing linear relationship S → P → F

Clarice: ...like when you think about structure, you think like it gives it its properties. So then its properties eventually give it its function. They kind of lead up to one another…I feel like one leads to the other and you kind of have the basis of structure to understand like where the properties come from and then, understand like the properties to get where like the function comes from.

Daniel*: Like first you have the structure, which determines properties I guess. And I guess properties and the function kind of work hand in hand together, the structure determines both of that I think...Well, I guess the properties do affect the function of whatever we're talking about, the molecule or atom or whatever, but the structure's really what determines what properties and function it does have...the structure determines what properties it does have, and those properties allow it to carry out the function.
**chosen representation: S→ P & F*

Evelyn: I'd say if something has a specific structure, that gives it specific properties, which then gives it a specific job or function.

John*: The structure kind of determines the properties and the properties determine the function...depending on how you look at it in both properties and structure can be kind of flipped, which one you look in which way— because something— some properties could lead to a different structure.
**chosen representation: (chemistry) S→ P; (biology) S/P → F*

Lida: You can't tell the function without the properties. You can't tell the properties without the structure. So if you don't know the structure of a molecule then you don't know the properties of a molecule, and in order to know the function, then you need to know what the properties are.

Louanne: I think function is more like what it does, and property is more like what causes it to do that, and then structure is more like what makes it able to cause it to do that...So, yeah whenever I think of function, I just think of it actually doing something. And properties is more just like why.

Natalie: I'd say structure is the basic thing...I don't know how I would order properties and function. Because structure definitely determines the function of something but I think it also kind of determines the properties it has. So I don't know if you could really say something's— I mean I guess you could say something's properties determine its function, so maybe that would just be in the order that it's given there, I guess if I had to order the three.

Ruth: I think [the courses] worked together because I took what I learned in chemistry from structure determining properties, and was really able to apply that when I was thinking of structure going from properties and then that really changing the function, in biology.

Shelly*: So because the structure determines what properties it has and then the properties, you can use those to determine what the function would kind of would be...I could see structure going to function right away without needing to think about the properties but, I guess it all depends on what you're talking about at the time, kind of thing.
**chosen representation: S→ P & F*

Appendix G. Students describing alternative relationships

Aaron: So based on the structure and based on the properties, I see function as the combining of this and then you can determine what the function is or you can predict what the function is going to be. I think function is simply what comes of it. After you've determined the properties and analyzed the structure of something, function is what would naturally come of that...I feel as though the structure is a property of something...I think both classes do a pretty good job of not only saying that the structure determines function or that property determines something's function, but just examples and utilizing that. I think it gives an even better understanding of that phrases 'structure determines function' and 'properties determine function.'

John*: Oh, like amino acid change and how an ar— amino acid chains and how like the R group, depending on if that's polar or nonpolar, is going to affect the shape of that protein. And then that protein leading to— the different shape in the protein either leading to like the proper function or if there's like something wrong, where a polar end is supposed to be non-polar. That's going to change how something functions and whether something's able to like bind to it or not.
**An example of his assertion that properties can determine structure. For the SPF relationship description, see Appendix F*

Joseph: When I think of structure, I automatically think of structure determines function...I feel like the different properties will determine what kind of structure is formed, and then depending on what structure it is will determine what kind of function it has...I feel like everything that we learn goes back to structure determines function, everything that we learn...A function is how it will work. For instance last semester we were given something called RAS which works at the checkpoint to not let things go through. So when the structure was altered, then the function was different, whereas it could have functioned properly and allowed damaged cells to go through and cause uncontrollable replication, so stuff like that...I use more so structure and function, but I know properties plays a role as well. We've definitely covered that for sure. (pause) I just can't determine— I don't know what kind of properties it has.

Priyah: [In GC1/GC2] I can see the structure and properties part but the function I kind of don't see, if that makes sense…[In B1] I think [properties] are important and I think we might have learned about it but I just never paid attention but, I think we might just skip it..…I think maybe they [properties and function] blur in biology and that's why I haven't noticed specifically, like all the property of this one molecule leads to the function. I think that they do blur together in both [courses]…

Serina: I know that the structure determines the function so they're— like these are all related. And the function of something has different properties...the structure has properties and the structure has a function so, I just, those three words are very closely related and we revisit that idea a lot...I would say like structure and properties, like those are kind of very closely related and then like the last would be function...Oh yes, so like I would put structure and then properties like, at like the— I don't know they're very closely related, like so I would say they're the same and that these two things determine the function of something

Simon: Well I know that structure determines function and I know that the properties will determine its structure, at least to some degree...If you have a sequence of amino acids and you know that this one has an oxygen attached to a hydrogen, you know it's capable of hydrogen bonding with something else that also has a hydrogen attached to a highly electronegative atom. So you know that it'll fold in that way so they're connected. So you can determine what sort of structure they're going to have…[In bio] Structure determines function which determines properties...the structure of tRNA, if you look at that, you can see that it has a structure with a binding site. And this binding site will allow something to attach to it like an amino acid. And because it can attach it's capable of moving that amino acid. But because we look at the structure of DNA and it doesn't have any binding sites, it doesn't have active sites, it doesn't have allosteric sites, we know that there's nothing it really does. It just sits there...And (pause) when we look at how structure determines its function, after we know what function it has, we can sort of tell what (pause) what it's going to do, like what properties it'll have, whether or not it can move—...Hydrophilic molecules can't pass through the lipid bilayer because they can't be dissolved because it's just so non-polar. So they have to be brought in by something like a protein...So if we know what the structure is, if we know what the function is we can sort of tell whether or not it needs to be diffused into the cell which will have a different result than it being able to just pass through.
**chosen representation S → F → P (bio); P → S (chem)*

Appendix H. Additional quotes describing the relationship in use

Aaron:Then in chemistry, every single time before I attempt a problem— like I said, a lot of times you draw a Lewis diagram. You could just write out a molecule itself and determine the properties of that molecule and ask if it can hydrogen bond or is it polar or whatever. And then it will help determine— even then, if you know it's covalent, you can say 'that's strongly bonded together.' So you can even keep going and going and going and then you'll get a better, a more confident or viable answer. That would be the function. The answer is the function.

Evelyn:I think it's more of a universal thought process. Like I feel like this applies to everything, almost everything at least. Like understanding the basic structure, like that's the foundation of it. And then from there that determines its properties and function. I feel like that works for many things in both courses. It's not just one unit.

Joseph:Yeah when we're given a question [in B1], [structure determines function] is one of the concepts I actually kind of understand in biology. So I feel like no matter what kind of question we're given, I always try and see how I can relate it back to that, because that can give me a better understanding, or guide me in the right direction. So I try and relate it back to that.

Lida:...if I'm presented with a function, like this is what this does. If I'm not given any background. Based off of what I've learned about structure and properties, depending on what the function is, sometimes you can work backwards and give a very educated guess, I guess. You can't just know, but you can give a fairly educated guess as to what the actual structure and properties would be, why that function's happening.

Ruth:So, if you can look at something's function, you can relate it back to its properties or structure, and you can also do the other way around. You look at something's structure, and you can maybe think of what its function might be.

Shelly*:I don't think I do it explicitly, but I feel it's definitely the progression of thought. Because you do, you have to think— like when you're given a problem you have to think, 'Well okay, I have to draw this out.' And then 'Okay, I'm looking at this Lewis structure' and then 'Well now I have to determine how this does this.' So it's not like— I don't think I think like, 'Okay structure to like properties function,' like that's the progression of thought in general, just done in progressive ways of with you doing the material itself.

**Quote also included in article Table 6*