MODULARITY IN MULTIPLE DISCIPLINES

A commentary on "Towards a general modular systems theory and its application to interfirm product modularity," and exploration of modularity in psychology, biology, American studies, and mathematics.

Melissa A. Schilling

In the article, "Towards a general modular systems theory and its application to interfirm product modularity," I argued that since modularity was a general systems concept, we might be able to develop a general systems theory of modularity. Such a theory, if articulated abstractly enough, could be used to derive more specific models for a wide range of systems. In the paper, I developed a simple causal model for modularity (what factors may drive a system to adopt increasingly or decreasingly modular forms) and then demonstrated its application to inter-firm product modularity.

Since publishing the general systems model, a colleague and I have applied a variation of it to the adoption of modular organizational forms at the industry level (Schilling and Steensma, 2001). However, we are still at only the beginning steps of having a general systems theory of modularity. First, while a causal model is useful and interesting, there are many other models that remain to be built. For instance, a model of the outcomes of the adoption of increasingly modular forms would be valuable, as would be more development of the different ways that a system can manifest modularity. Secondly, before a unified theory can be readily applied to multiple disciplines, it would be helpful if we had a greater understanding of the way that different disciplines use the concept of modularity. By comparing and contrasting the way that modularity is defined and used in other disciplines, we are both more likely to develop a more complete theory, and more likely to employ a language that is readily understood by multiple disciplines.

Towards furthering this objective, I offer here a brief review of how modularity is used in four different disciplines: psychology, biology, American studies, and mathematics. Admittedly, these reviews are greatly constrained by my lack of experience in these disciplines. Perhaps, however, they will provide a useful launching pad for others who are better equipped to bridge multiple disciplines, and who are interested in further developing a general systems theory of modularity. A review of the use of modularity in technology and organizations seems superfluous here, therefore I will focus on the use of modularity in the other disciplines, and relate them back to modularity in technology and organizations in the final section.

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Modularity in Psychology

Probably the most noted work on modularity in psychology is Jerry Fodor's book, The Modularity of Mind (1996/1983). In the book, he proposes a 'modified' modularity theory of cognitive processes. His theory builds on the premise of faculty psychology that there are certain faculties innate in the mind, and mental "organs" that are biologically predisposed to perform certain types of computational processes.[1] Fodor does not argue that the entire mind is modular; rather he proposes that the central cognitive system responsible for complex cognitive activities (such as analogical reasoning) is not modular, but that input systems (which interpret the neural signals from physical stimuli, and are responsible for basic cognitive activities such as language and vision) are likely to be modular (Coltheart, 1999).

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[1] One rather dire implication of this is that there may also be endogenous limits on what the mind can process. This is not the same as Simon's bounded rationality; rather it is an implication that the mind is epistemically bounded such that there may be concepts or theories the mind is incapable of entertaining (Fodor, 1996/1983:120).

Input systems, or "domain specific computational mechanisms" (such as the ability to perceive spoken language) are termed vertical faculties, and according to Fodor they are modular in that they possess a number of characteristics Fodor argues constitute modularity. Fodor's list of features characterizing modules includes the following:

1) Domain specific (modules only respond to inputs of a specific class, and thus a "species of vertical faculty" (Fodor, 1996/1983:37)
2) Innately specified (the structure is inherent and is not formed by a learning process)
3) Not assembled (modules are not put together from a stock of more elementary subprocesses but rather their virtual architecture maps directly onto their neural implementation)
4) Neurologically hardwired (modules are associated with specific, localized, and elaborately structured neural systems rather than fungible neural mechanisms)
5) Autonomous (modules are independent of other modules)

Fodor does not argue that this is formal definition or an all inclusive list of features necessary for modularity. He argues only that cognitive systems characterized by some of the features above are likely to be characterized by them all, and that such systems can be considered modular. He also notes that the characteristics are not an all-or-nothing proposition, but rather each of the characteristics may be manifest in some degree, and that modularity itself is also not a dichotomous construct--something may be more or less modular: "One would thus expect--what anyhow seems to be desirable--that the notion of modularity ought to admit of degrees" (Fodor, 1996/1983:37).

For Fodor, one of the most important features of modularity (though not explicitly on his list) is information encapsulation. Information encapsulation implies that all (or most) of the necessary information or processing needed to perform a computation is within the module. The module does not have to interact with other information within the individual. Information encapsulation enables input systems to do their jobs quickly, by not accessing or using all of the information conceivably available. Fodor notes, "The informational encapsulation of the input systems is, or so I shall argue, the essence of their modularity. It's also the essence of the analogy between the input systems and reflexes; reflexes are informationally encapsulated with bells on" (Fodor, 1996/1983:71).

Notably, Fodor's "not assembled" feature contrasts sharply with the use of modularity in other fields in which modular systems are seen to be hierarchically nested (that is, modules are themselves composed of modules, which in turn are composed of modules, etc.) However, Coltheart (1999) notes that Fodor's commitment to the non-assembled feature appears weak, and other scholars (e.g., Block, 1995) have proposed that Fodor's modules could be decomposed into finer modules. For instance, while Fodor distinguishes between separate modules for spoken and written language, Block might further decompose the spoken language module into modules for phonetic analysis and lexical forms (Coltheart, 1999): "Decomposition stops when all the components are primitive processors--because the operation of a primitive processor cannot be further decomposed into suboperations" (Block, 1995).

Though Fodor's work on modularity may be considered the most extensive, there is other work in psychology on modularity worth noting for its symmetry with modularity in other disciplines. For instance, while Fodor focused on cognitive input systems as modules, Coltheart (1999) proposes that there may be many different kinds of cognitive modules, and distinguishes between, for example, knowledge modules and processing modules. The former is a body of knowledge that is independent of other bodies of knowledge, while the latter is a mental information-processing system independent from other such systems.

With respect to the evolution from integrated systems to modular systems, Hulme and Snowling note, "interaction between systems in probably the norm in development, and it may only be after a very extensive period of development that the relative modularity or autonomy of different systems in the adult is achieved" (1992:906). Their point is that in the child, cognitive processes likely entail extensive interaction and integration, and autonomy of modules is only achieved after the individual's cognitive processes are well developed and the mind has a relatively complete cognitive map of which processes and knowledge are most closely related. This is highly analogous to arguments made by Christensen, Verlinden and Westerman (2001) and Baldwin and Clark (1997) that new technological innovations tend to be introduced in integrated form. It may take extensive effort and experience before the architecture of the technological system is understood well enough to enable definition of design rules that facilitate the modularization of the system.

Also analogous to arguments made about modularity in technological systems, psychologists have emphasized the role of modularity in breaking up complex systems into smaller, more specialized parts: "any large computation should be split up into a collection of small, nearly independent, specialized subprocesses" (Marr, 1982: 325). From my limited perusal of the topic, it would seem that modularity in cognitive systems relates very directly to modularity in biological systems (in particular the evolution of homologous parts), but I found no evidence of any direct connection between studies of modularity in psychology and biology. If such connections are truly lacking, then there are likely to be important synergies ripe for discovery between the two groups of scholars.

Modularity in Biology

As in some of the other disciplines, the term modularity may be used in multiple ways in biology. For example, it may be used to refer to organisms that have an indeterminate structure wherein modules of various complexity (e.g., leaves, twigs) may be assembled without strict limits on their number or placement. Many plants and sessile benthic invertebrates demonstrate this type of modularity (by contrast, many other organisms have a determinate structure that is predefined in embryogenesis) (Andrews, 1998). The term has also been used in a broader sense in biology to refer to the reuse of homologous structures across individuals and species. Even within this latter category, there may be differences in how a module is perceived. For instance, evolutionary biologists may focus on the module as a morphological component (subunit) of a whole organism, while developmental biologists may use the term module to refer to some combination of lower-level components (e.g., genes) that are able to act in a unified way to perform a function (Bolker, 2000). In the former, the module is perceived a basic component, while in the latter the emphasis is on the module as a collective. As Bolker (2000) states:

> "Formulating a definition of modularity that is both comprehensive and practical is a non-trivial task. It is surprisingly hard to define something we easily recognize in the biological world, namely its organization into individualized yet interconnected units across a range of physical and functional scales. Part of the difficulty may be precisely that it is often easy to recognize modularity, and to develop practical, working definitions that are never made explicit. For example, evolutionary biologists and morphologists readily identify the tetrapod forelimb as a discrete structure that is homologous across different taxa, despite its structural, functional and adaptive diversity. Developmental biologists recognize the limb bud as an embryonic region with unique intrinsic patterning and developmental integration that can be physically displaced or induced ectopically, yet retains its fundamental structure and identity...Such local definitions of modularity are restricted to a single context, or at most a single level of the biological hierarchy, precisely because they are based on particular functions or mechanisms within that context. They have great power within a level, but limited ability to bridge different levels."

Instead of providing definitions, some biology scholars have provided a list of features that should characterize a module (much as Fodor did in The Modularity of Mind). For instance, Raff (1996) provides the following list of characteristics that developmental modules should possess:

1) discrete genetic specification
2) hierarchical organization
3) interactions with other modules
4) a particular physical location within a developing organism
5) the ability to undergo transformations on both developmental and evolutionary time scales

To Raff's mind, developmental modules are "dynamic entities representing localized processes (as in morphogenetic fields) rather than simply incipient structures ... (... such as organ rudiments)" (Raff, 1996, p. 326). Bolker, however, attempts to construct a definitional list of characteristics that is more abstract, and thus more suited to multiple levels of study in biology. She argues that:

1) A module is a biological entity (a structure, a process, or a pathway) characterized by more internal than external integration
2) Modules are biological individuals (Hull, 1980; Roth, 1991) that can be delineated from their surroundings or context, and whose behavior or function reflects the integration of their parts, not simply the arithmetical sum. That is, as a whole, the module can perform tasks that its constituent parts could not perform if dissociated.
3) In addition to their internal integration, modules have external connectivity, yet they can also be delineated from the other entities with which they interact in some way.

Another stream of research on modularity in biology that should be of particular interest to scholars in other disciplines is that of Gunter Wagner. Wagner's work (e.g., Wagner and Altenburg, 1996; Wagner, 1996) explores how natural selection may have resulted in modular organisms, and the roles modularity plays in evolution. Wagner's work suggests that modularity is both the result of evolution, and facilitates evolution--an idea that shares a marked resemblance to work on modularity in technological and organizational domains.

Modularity in American Studies

Though I have frequently suspected that it may be fruitful to conceive of social systems as modular systems (for example, the disintegration of the urban center into more loosely coupled neighborhoods), I found very little use of the modularity construct among studies of population or culture. Fortunately, the one very notable exception, Blair's Modular America (1988), is so rich and extensive that it provides ample fuel for our discussion here. Blair's central premise is that as American's began to replace social structures inherited from Europe (predominantly England and France), they evolved a uniquely American tendency towards modularity, in fields as diverse as education, music, and architecture.

Blair observes that when the word module first emerged in the sixteenth and seventeenth centuries, it meant something very close to model. It implied a small-scale representation or example. By the eighteenth and nineteenth centuries, the word had come to imply a standard measure of fixed ratios and proportions. For example, in architecture, the proportions of a column could be stated in modules (i.e., " a height of fourteen modules equaled seven times the diameter measured at the base" (1988:2)) and thus multiplied to any size while still retaining the desired proportions.

However in America the meaning and usage of the word shifted considerably:

> " Starting with architectural terminology in the 1930s, the new emphasis was on any entity or system designed in terms of modules as subcomponents. As applications broadened after World War II to furniture, hi-fi equipment, computer programs and beyond, modular construction came to refer to any whole made up of self-contained units designed to be equivalent parts of a system, hence, we might say, "systemically equivalent." Modular parts are implicitly interchangeable and/or recombinable in one or another of several senses" (Blair, 1988: 3).

Blair defines a modular system as “one that gives more importance to parts than to wholes. Parts are conceived as equivalent and hence, in one or more senses, interchangeable and/or cumulative and/or recombinable” (pg. 125). Blair describes the emergence of modular structures in education, industry, architecture, music, literature, sports, law, and religion. The first four will be briefly overviewed here for illustrative purposes:

The college curriculum. Blair notes that in the late 1800s, American universities began to replace the European fixed curriculum with the more modular elective system, partially in response to declining enrollments. In the new curricula, a "course" no longer referred to a course of study as it did in England, but rather to a class, and classes were interchangeable. Credits emerged as a standard unit and gave students the freedom to piece together their own educational path. The college curriculum had been broken into a set of systemically equivalent parts, allowing for substitutability and a rationalization of assembly processes. A nearly identical process was taking place in manufacturing, and the symmetry of these processes is captured in a quote from Laurence Veysey (1965:312): "Assembly-line methods of registration arrived at Harvard in the autumn of 1891, and efficient orange perforated registration cards were introduced in 1896. At most universities, courses were now rationalized into a numerical system of units for credit; the catalogue began to resemble the inventory of a well-stocked and neatly labeled general store."

Industrial assembly by the "American System of Manufactures." The move to a manufacturing system in which standardized parts could be substituted into an assembled product was prompted in large part by a demand for guns that outstripped supply. Early production of muskets in both Europe and America was performed by craftsmen, who laboriously produced an entire gun from start to finish. If the gun was damaged, a gunsmith would have to fit another unique component to the gun. Production was slow, and difficult to expand due to a lack of gunsmiths in America. Around the turn of the nineteenth century, a new approach was developed (termed the "uniformity system" by Eli Whitney, one of its proponents) which would come to be known as the American System of Manufactures. The approach would employ specialized machines (rather than specialized craftsmen) so that unskilled laborers could produce uniform components that could be assembled into a functional weapon. Originally, it was much more expensive and difficult to produce parts which were so precisely manufactured as to be interchangeable. Without military loyalty to interchangeability and government backing of the development costs, the system might have died out quickly. Throughout the nineteenth century the production method spread from guns, to a wide range of assembled products including farm machinery, bicycles, and automobiles.

Skyscraper architecture. Traditional European conceptions of architecture demanded that buildings be conceived of as wholes, with due attention paid to the building's proportions and stylistic coherence. All aspects of the building's size and style had to be carefully coordinated. In America, however, the combination of the advent of structural steel and the liberation from European norms enabled the rise of a new type of building: the skyscraper. By European standards, the American skyscraper was a vulgar and aesthetically distasteful piece of work. Its proportions were determined by practicality rather than beauty. Skyscrapers were modular constructions in that once the basic building blocks (floors) were established, they could be piled up to almost any height. Blair terms this *additive open-endedness*, and demonstrates its close relationship to modularity in literature and music.

Blues and jazz. As described by Blair, blues music is composed of stanzas that may flow in any order, and are held together only by their emotional congruity. The traditional blues singer may interchange, add, or delete stanzas to suit the mood. Jazz music is similar, though because it is typically played by an ensemble, it requires somewhat more architecture in order to ensure that even when playing emergent improvisational sets, the individual musicians are able to follow each other appropriately. To accomplish this, jazz music has basic structural units that provide underlying rules:

> "Every jazz improvisation is based on a theme. Usually it is...a standard song in 32-bar form--the "AABA" form of our popular tunes, in which the 8-bar main theme (A) is first presented, then repeated, then followed by a new 8-bar idea--the so-called bridge (B)--and in conclusion the first 8 bars are sounded once more" (Berendt, 1983: pg 148).

By utilizing these standardized structural units, jazz musicians can abandon the overarching hierarchical form of traditional European music while still retaining a sense of where they are in relation to each other. As noted by Blair, "All members of a jazz group know that the composition will take place in 32-bar segments, though they may not be aware in advance of how many such units will be played or what embellishments of timbre and chordal elaboration may emerge as the sequence moves on. These modular building blocks of musical time are...essential to the very existence of jazz" (pg. 76)

In his concluding chapter, Blair does not commit to a firm view of what causes Americans to pursue more modular structures in the diverse domains in which it has appeared, but he does suggest that it may in some way be related to the American ideology of liberal individualism, and a preference for anti-hierarchical organization.

Modularity in Math

The use of the term "modular" in mathematics is thought to have originated with the theory of congruent numbers by Carl Friedrich Gauss (1977-1955). His congruence theory was published in 1801 in his *Disquisitiones Arithmeticae*, and a translation may be found in Smith's (1959/1929) A Source Book in Mathematics. In the first section, "Concerning congruence of numbers in general", Gauss begins:

> "If a number *a* divides the difference of the numbers *b* and *c*, *b* and *c* are said to be *congruent with respect to a*; but if not, *incongruent*. We call *a* the *modulus*" (Smith, 1959/1929:107).

What this means is that if from any starting number, say 3, one can get to another number, say 21, by the addition of a series of a third number (the modulus), say 6, then the first number and the second number are said to be congruent with respect to the modulus. In this example, 3 and 21 are congruent modulus 6 (3 + 6 + 6 + 6 = 21). To the non-mathematician this seems a strange observation, but it enables several interesting techniques. One of the simpler techniques, termed "casting out nines," was once employed by children as a game and is now often taught in grade schools as a method of checking arithmetic.

Casting out nines can be used for addition, subtraction, multiplication and division (Loy, 1999). It enables the reduction of numbers into their much simpler casting-out-nines equivalents. To obtain the casting-out-nines equivalents, the digits of the number are added up, omitting the nines, or any pair of digits that add to nine. If the resulting number has more than one digit, the process is repeated until a single-digit number is reached. The function is then performed on these much smaller numbers, and the casting-out-nines equivalent answer should be the same as the casting-out-nines equivalent of the original answer. This technique is much easier to explain with an example:

	Casting-out-nines equivalent
1645	7 (1 + 6 = 7, the 4 and 5 can be omitted because they add to 9)
+ 2378	2 (2 and 7 are omitted, 3 + 8 = 11, 1 + 1 = 2)
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4023	9 (4 + 2 + 3 = 9)

Much of modern number theory arose from Gauss’s original work on congruent numbers. Gauss’s use of the *modulus* can be related to Blair’s additive open-endedness; for any given starting number and any given modulus (which may be considered a standardized module), there is an infinite quantity of congruent numbers that may be obtained. The casting out nines example also demonstrates that the modulus nine may be used to break complex problems down into simpler problems, much as modularity may be used to break complex technological systems into simpler components. The analogies are a bit rough here, and the use of number theory and the term 'modular' have evolved into areas in which it becomes even more difficult to identify symmetries with the way modularity is used in other fields. However, a more experienced mathematician might be able to identify more relationships between modularity in math and modularity in other disciplines than I have done.[2]

PERVASIVE THEMES

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[2] I am deeply indebted to Barry Mazur and Paul Garret for this explanation of modularity in math, however all mistakes remain my own.

Comparing the use of modularity by discipline reveals several themes that extend across two or more disciplines (see Table 1). One theme that showed up in psychology and biology but nowhere else in the current study is *innately specified*. Innately specified (as used here) implies that the purpose or structure of the module is predetermined by some biological mandate. It may be possible to construe a type of innate specification for modules in other types of systems, but as I did not stumble upon it in my review, I leave that to the reader.

Domain specificity, that modules respond only to inputs of a specific class (or perform functions only of a specific class) is a theme that clearly spans psychology and biology, and it can be argued that it also spans technological and organizational systems. Domain specificity would be seen in the latter disciplines as specialization of function.

Hierarchically nested is a theme that recurs in every discipline. Though originally disavowed by Fodor, other psychologists have embraced it, and it is readily apparent in the use of modularity in biology (e.g., each module of an organism can be decomposed into finer modules), social processes and artifacts (e.g., we can think of a skyscraper in terms of blocks of floors, a single floor, elements of a floor, etc.), mathematics (e.g., the modulus 6 may be further divided into the moduli 1, 2 and 3), and technological and organizational systems (e.g., an organization may be composed of divisions, which are composed of teams, which are composed of individuals).

Greater internal than external integration is a theme that showed up in every discipline but mathematics. Often referred to as autonomy, this theme acknowledged that there may be interaction or integration between modules, but the greater interaction and integration occurs within the module. This theme is very closely related to *information encapsulation*, which shows up explicitly in both the psychology and technology research.

Near decomposability (as termed by Simon, 1962) shows up in all of the disciplines, but is manifest in a matter of degrees. For instance, in psychology and biology it may refer merely to the ability to delineate one module from another (recognizing the boundaries of the module). In several of the social artifacts, mathematics, and technological or organizational systems, however, it refers to the ability to actually separate components from one another. In several of the disciplines this decomposability also enables the complexity of a system (or process) to be reduced. This is aptly captured in the quote from Marr (1982:325) about psychological processes where he notes that, "any large computation should be split up into a collection of small, nearly independent, specialized subprocesses" (Marr, 1982: 325). Reducing complexity is also the express purpose of casting out nines in mathematics.

Substitutability and *recombinability* are closely related constructs. The former refers to the ability to substitute one component for another as in Blair’s “systemic equivalence” while the latter may refer both to the indeterminate form of the system and the indeterminate use of the component. In college curricula, for example, each course is designed with a credit system that ensures a uniform number of contact hours, and approximately uniform educational content, yielding substitability. By virtue of their substitutability, each student may create their own curricula (recombinability of the curriculum as a system) and each course may be said to be recombinable with a variety of students’ curricula (recombinability of the component within multiple systems). Both substitutability and recombinability are immediately recognizable in Blair’s social processes and artifacts, and are also well captured in Garud and Kumaraswamy's (1995) discussion of economies of substitution in technological systems.

Blair’s systemic equivalence also demonstrates the relationship between substitutability and the *module as a homologue*. Blair’s systemic equivalence refers to the ability for multiple modules to perform approximately the same function within a system, while in biology a module as a homologue refers to different modules sharing approximately the same form or function in different organisms. The extreme of the module as homologue is found in mathematics, where (in the simplest case) the modules refer to the reuse of a particular number and thus each module is exactly alike.

In all but mathematics, there was an emphasis that *modules may be different in kind*. In Fodor's discussion of modular cognitive system, each module performs a unique task. In biology, even modules that are considered homologous may be somewhat different in form and function (e.g., a whale's fin versus a human's hand). In Blair's book, he points out that while jazz music may be composed of structural units that conform to the same underlying rules, those components vary significantly. Similarly in studies of technology and organization, modular systems may be composed of modules that are very similar (as in shelving units that may be piled one atop the other) or very different (as in a stereo system where each component performs unique functions) or any combination in between.

The last theme is not a characteristic given for modules or modular systems, but rather is a proposition about how a system's modularity may change over time. In both psychology research and in technology research it has been argued that *a system may migrate from greater integration to greater modularity*, and intriguingly, approximately the same reasoning is given in both disciplines. In psychology, Hulme and Snowling (1992) argue that only after the cognitive architecture of an individual is well developed and experienced with the variety of computations it will perform can the cognitive process become more modular. In essence, once the brain understands the computational processes well, it is able to parse them out and dedicate particular modules to them. A very similar argument has been made in technological research where it is often argued that technological innovations are often introduced in integrated form, and only after the system is very well understood can the architecture of that system be designed so as to make the system modular.[3]

I have not included every feature of modularity, or argument about modularity, made in each of the disciplines in this section; I have only tried to tease out those themes that recur in at least two distinct disciplines. I have also not attempted to cover every discipline in which modularity may play a role, nor can I claim to have done full justice to the use of the term in the disciplines covered here. However, given those limitations, the preceding still offers us the following conclusion: While there are some marked differences between the ways that modularity is defined or used by the different disciplines, there are also many significant similarities. Exploring both the similarities and differences should enable us to further develop a more complete understanding of modularity.

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[3] In a related vein, Blair noted that it was initially much more expensive to develop machinery and manufacturing processes that would enable modular production of guns.

Table 1: The use of modularity by discipline

Concept	**Psychology**	**Biology**	**American Studies**	**Mathematics**	**Technology and Organizations**
Domain specific	X	X			X
Innately specified	X	X			
Hierarchically nested	X	X	X	X	X
More internal integration than external integration (localized processes and autonomy)	X	X	X	?	X
Informationally encapsulated	X		?		X
Near decomposability (segmentability, delineation between modules, or breaking down complexity)	X	X	X	X	X
Substitutability	X	?	X	?	X
Recombinability		X	X		X
Expandability		X	X	X	X
Module as homologue		X	X	X	X
Modules may be different in kind	X	X	X		X
Evolution from greater integration to greater modularity	X				X

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