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Diversity and Unity of Modularity

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Abstract

Since the publication of Fodor's (1983) *The Modularity of Mind,* there have been quite a few discussions of cognitive modularity among cognitive scientists. Generally, in those discussions, *modularity* means a property of specialized cognitive processes or a domain-specific body of information. In actuality, scholars understand modularity in many different ways. Different characterizations of modularity and modules were proposed and discussed, but they created misunderstanding and confusion. In this article, I classified and analyzed different approaches to modularity and argued for the unity of modularity. Modularity is a multidimensional property consisting of features from several dimensions specifying different aspects of cognition. Among those, there are core features of modularity, and these core features form a cross-dimensional unity. Despite the diverse and liberal characterizations, modularity contributes to cognitive science because of the unity of the core features.

Keywords: Modularity; Cognitive system; Information processing; Information encapsultion; Domain specificity

Do not let your left hand know what your right hand is doing (*Matthew 6:3*)

1. Introduction

Since the publication of Fodor's (1983) *The Modularity of Mind,* discussions of modularity and computational autonomy have been a popular topic among cognitive scientists. Generally, in those discussions, a module refers to an independent unit of information processing, a specific type of cognitive process, or a body of information. In actuality, there seems to be no consensus among cognitive scientists about the use of the terms *modularity* and *module.* For example, Chomsky talked about the language faculty as a module, whereas some neuroscientists call it a specific anatomic organization of the brain module (Hubel & Wiesel, 1979; Mountcastle, 1978; Szentagothai, 1975, 1987). It seems that *modularity* is a blanket term that covers a wide variety of psychological or neurological phenomena. Are there any central claims, or is there only family resemblance among the different uses of the term? If the latter is

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the case, can modularity be used to describe and explain cognitive phenomena? In this article, I argue that modularity is a complex property, but it has its own unity. Despite the diverse and liberal characterizations, modularity contributes to cognitive science because of this unity.

I begin by discussing and classifying different notions of cognitive modularity and their theoretical orientations. Many psychologists define modularity by a group of functional and computational features (Coltheart 1999; Fodor, 1983, 1985; Garfield, 1987, 1994; Marshall, 1984). As a group, these features identify and describe modular processes and their functions in a cognitive system. I discuss how those features are understood and emphasized in different approaches to modularity.

Next, I classify and compare different types of modules and their properties currently studied in different areas of cognitive science. Generally, a cognitive module is a specialized cognitive system that processes only a specific type of information. So far, many modules have been proposed and studied, from large modules such as the language faculty (Chomsky, 1986) and input systems (Fodor, 1983) to very specialized modules such as line detectors (Hubel & Wiesel, 1974) and cheater detectors (Cosmides, 1989). I categorize them and discuss their features.

I conclude my discussions of modularity by asking questions about the use of modularity in psychological theorizing. If modularity is a property with multiple characterizations, is it a predicate of psychology, or is it just a term that refers to features grouped together accidentally? Can modularity be used to describe cognitive phenomena and their regularities? I discuss whether features of modularity form a unified whole that can serve as a useful tool in the study of human cognition.

2. Features and dimensions of modularity

In the ordinary use of the word, a *module* means an independent unit of complex machinery, that is, a separable compartment of a machine or self-contained segment of a spacecraft. In the same context, a cognitive module means an independent unit of a complex cognitive system. In this article, I concentrate on the technical uses of the words *module* and *modularity* by distinguishing different dimensions and features.

In psychology, modularity is a property of a cognitive system. A cognitive system is a physical mechanism that carries out a cognitive function. It processes inputs and generates outputs by following rules of operation. In carrying out its function, it processes information in a specified way. One way to process information is to run computational processes. By running these processes, a cognitive system manipulates formal (i.e., syntactic) features of information. I define a *cognitive system* as a physical structure that carries out a cognitive function by running computation.

When a cognitive system processes information, its computation is sometimes run by specialized processes. It is the features of these specialized processes by which modularity is primarily defined. I briefly summarize the following eight features of modularity frequently discussed in the modularity literatures (Carruthers & Chamberlain, 2000; Coltheart, 1999; Fodor, 1983; Garfield, 1987; Hirschfeld & Gelman, 1994; Marshall, 1984; Marslen-Wilson & Tyler, 1987; Segal, 1996).

1. *Domain specificity* (DS). Each cognitive module has a distinct stimulus domain and processes its stimuli within the boundary of the domain. That is, a cognitive module has

special constraints on the range of information it can access and on the range of distal properties it can process.

2. *Mandatoriness* (M). Cognitive modules process information in an automatic and autonomous way. A cognitive system has limited control of initiating, terminating, or changing the way its modules process information.
3. *Limited central access* (LCA). An external system or process cannot access or intervene in the processes run by a cognitive module. Only the outputs of the module are accessed.
4. *Speed* (S). Cognitive modules process information fast.
5. *Informational encapsulation* (IE). Cognitive modules process information without accessing information available outside their boundaries.
6. *Fixed neural architecture* (NA). Cognitive modules are hardwired in the brain. There are groups of brain cells that are dedicated to certain cognitive functions.
7. *Specific breakdown patterns* (BP). Cognitive modules have specific BPs; they tend to be selectively impaired. Damage to or breakdown of one module does not influence the function of other modules.
8. *Specific ontogeny* (SO). Cognitive modules have specific developmental patterns. It is hypothesized that they display specific patterns of development following endogenously determined processes under the impact of environmental releasers. (I will use the abbreviations to refer to the features listed here.)

It should be noted that there is no single defining property of modularity; several of these features together form a group that refers to a relevant meaning of modularity. For example, when determining modularity of the language faculty, Fodor (1983, pp. 36–37) considered features such as DS, innateness (SO), assembly (BP), hardwiredness (NA), and autonomy (M, IE) more important than others. Modularity, from this perspective, is a bundle of related features combined together.

As previously listed, features of modularity, such as IE and DS, are the properties that define or characterize modularity. When these features characterize a modular cognitive system, they represent different aspects of the system. A modular cognitive system can be characterized entirely from the perspective of computation (the way it processes information). From this perspective, it makes little sense to study BP because this pattern deals with physical structure, not the computation of the system. I call these perspectives or aspects *dimensions.* Dimensions are the aspects of information processing to which modularity is ascribed. Features, on the other hand, are the properties identified in the specific dimensions. I define them in the following way:

Features of modularity: Properties that define or characterize modularity in a specific dimension.

Dimensions of modularity: Aspects of a cognitive system to which modularity is ascribed.

Because modularity can be studied and understood from different dimensions, distinguishing different dimensions is as important as distinguishing different features of modularity. If a cognitive system is a physical structure that carries out a cognitive function, at least five different questions can be asked about the nature and the structure of the cognitive system: How is it physically assembled? What does it do as a cognitive system? How does it process information? What kind of information does it use when it processes information? How does it come to function as a cognitive system? I propose the five dimensions of modularity based on these questions.

1. *Physical structure:* How is a system physically assembled?
2. *Cognitive function:* What does it do as a cognitive system? What kind of inputs does it process? What kind of outputs does it generate?
3. *Computation:* How does it process information?
4. *Information:* What kind of information is employed in carrying out its cognitive function?
5. *Development:* How does it come to function as a cognitive system?

If modularity is a property of a cognitive system, it is ascribed to at least one of the five dimensions listed here. Features of modularity, then, are the properties identified in these dimensions of modularity.

In the matrix of features and dimensions, modularity is defined as a multidimensional property of a cognitive system, consisting of features from different dimensions in which different aspects of cognition are emphasized. There are features that specify how modules process information. They are computational features such as M, LCA, S, and IE. There is a feature that describes the functions modules carry out. It specifies the type of inputs modules process. There are still other features that specify how modules are realized in the human brain. They are physical or structural features such as NA and BPs. There is a feature that specifies the type of information employed in modular cognitive processes. Lastly, there is a feature that tells us how modules come to exist. It is a developmental feature of modularity; SO is this feature. Table 1 summarizes dimensions of these modular features. The discussion of how these basic features and dimensions are developed into theories and approaches is followed.

3. Different approaches

If modularity is a property of a cognitive system—a property that characterizes a cognitive system in its functional, computational, and structural aspects—its features and dimensions should be clearly identified and specified. But, it is also important to see how modularity, with

Table 1
Dimensions and features of modularity

Dimensions	What Do They Specify?	Features
Physical structure	How a cognitive system is physically assembled	Fixed neural architecture, Specific breakdown patterns
Cognitive function	What a cognitive system does	Functional specialization
Computation	The way a cognitive system processes information	Speed, mandatoriness, limited central access, information encapsulation
Information	The type of information employed in carrying out its cognitive function	Domain specificity
Development	How a cognitive system comes to exist	Specific developmental patterns, specific ontogeny

different research interests and emphases, is actually studied in cognitive science. Considering the different theoretical interests, I ask two different types of questions.[1] The first group of questions focus on modularity as a property described and explained in cognitive science. What is modularity? What are the defining features of modularity? How is modularity used in the explanation of cognitive phenomena? Questions in the second group ask about the modularity of actual cognitive processes. Questions such as "which cognitive systems or processes are modular?"; "is language faculty one module or composed of several modules?"; and "is the mind completely modular?" are the questions of the second group. Unlike the questions in the first group, these are the questions of psychological studies requiring careful experiments and observations. In this section, I discuss different approaches to modularity as answers to the first group of questions. In the next section I discuss different types of modules as answers to the second group of questions.

3.1. General notions of modularity

Many cognitive scientists proposed different features and dimensions of modularity. In some way, these features and dimensions not only characterize cognitive modularity but also provide general perspectives from which modularity is understood and studied. I classify major approaches of modularity that have dominated the field for the past several decades. The first three approaches (design modularity, anatomic modularity, and neuropsychological modularity) focus on physical and functional dimensions of modular cognitive systems. The fourth approach (Chomskian modularity) focuses on the dimension of information. The dimension of computation is the target of the fifth approach (computational modularity). The sixth and the seventh approaches (developmental modularity and Darwinian modularity) focus on the developmental dimension.[2] Before I outline these approaches, I briefly discuss general notions of modularity to contrast them with more elaborate ones.

There are a few basic and general (unelaborated or unarticulated) notions of modularity, the notions that define modularity as a property of independently functioning components of a complex system. Stillings (1987) defined modularity in the following way. He said:

> Complex computational systems are at least weakly decomposable into components. There exists a decomposition of the system such that the computational interactions within components are much more complex than those between components. This constitutes a very general notion of modularity that can be developed in a variety of ways which can be difficult to distinguish both theoretically and empirically. (Stillings, 1987, p. 325)

As a very *general* notion of modularity, Stilling's definition focuses on the density of computational interaction. According to Stillings (1987), a modular computational system has relatively sparse computational interactions with outside systems compared with the intense interactions among its internal components. Almost the same degree of generality can be found in the following definition of a module.

> The usual definition of a module is simply a processing unit with some degree of self-containment (not complete self-containment, because modules must transmit information to other parts of the cognitive organization). This partial or high degree of self-containment is gained by limiting access to the modules and by limiting their output paths to other units. (Maratsos, 1992, p. 19)

According to this definition, modularity means a high degree of self-containment. That is, a cognitive system is modular if its information processing depends more on its internal processes and resources than external ones. Because the high degree of self-containment is achieved by structural (such as a capsule), informational (such as an independent database), or computational (such as an isolated information process) autonomy, we can imagine many different types of modules.

As general characterizations of modularity, Stilling's (1987) and Maratsos's (1992) definitions capture modularity in the broadest possible way. There is no doubt that they serve their specific goals in psychological studies. Compared with other elaborated specifications of modularity, however, they provide too general or too generous characterizations. If we concentrate on those general features of modularity, we might end up with an arbitrary class of processes that do not generate meaningful psychological generalizations. For example, we could claim the modularity of reading (Patterson & Kay, 1982), chess playing (Chi, Hutchinson, & Robin, 1989), even driving (Schwartz & Schwartz, 1984), based on a few general features such as a high level of self-containment (Maratsos, 1992) or dense internal interaction (Stillings, 1987). On the one hand, these diverse skilled activities (reading, chess playing, driving) share some features of modularity; at least they are served by cognitive processes that display a high degree of self-containment and internal interactions. On the other hand, they do not seem to form a genuine group of processes that can be picked up uniquely by modularity. If reading, chess playing, and driving are modular, any well-trained skills are modular too. If well-trained skills are modular, then almost every human activity is modular. It seems that these general definitions are too general.

If we compare these seemingly modular activities with the well-specified and confirmed cases of modularity, such as the modularity of perceptual processes, the limitation of these general definitions becomes clear. Perceptual processes are modular not because they are self-contained in some *general* way but because they are self-contained in a very *specific* way. From the perspective of scientific explanation and generalization, this specific mode of cognition is very important. Reading, chess playing, driving a car, and other trained skills are a too-heterogeneous group to be used in the explanation of cognitive phenomena. They have all sorts of unrelated features and dimensions, making them hard to fit in cognitive generalizations. Modularity should be a well-specified and well-behaved property so that scientists can use it in describing, explaining, and predicting cognitive phenomena. I think it is very important, at least in serious theoretical discussions, to avoid liberal characterizations of modularity unless we want to include reading, playing chess, and driving on a par with well-specified cases of modularity such as auditory processing and visual processing. I discuss this problem further in the last section where I discuss modularity as a property featuring in scientific explanations and generalizations. More elaborated and specific notions of modularity can be found in the following approaches to modularity.

3.2. Anatomical modularity

Modularity can be defined on the basis of brain anatomy (Hubel & Wiesel, 1979; Mountcastle, 1978; Szentagothai, 1975, 1987). According to this view, a module refers to a specific anatomical structure (group of cells) of the brain. It is well known in neuroscience that the basic units of brain functions are not found at the level of a single cell but of a network of cells. That is, brain functioning is a matter of interaction among sets or structures of neurons (Churchland 1986; Churchland & Sejnowski, 1989, p. 43). The best anatomical evidence for the existence of these groups of neurons is the columnar organization of the neocortex. This type of anatomic organization is called the *module of the brain.* Most neuroscientists accept the existence of this neocortical structure as an established fact (Hubel & Wiesel, 1979; Mountcastle, 1978; Szentagothai, 1975, 1987).[3]

3.3. Design modularity

Design modularity elaborates the idea of an independently functioning unit of a complex physical system. In this approach, modularity is understood as a specific design principle (Ellis & Young, 1988; Marr, 1982; Simon, 1962). That is, modularity refers to the way components (physically and functionally independent subsystems) are organized in a system. A system with the modular design has the following features. First, the whole system is assembled from a number of physically separable subassemblies. Second, a single, specialized function is assigned to each subassembly. In this way, each subassembly is physically separable and functionally specialized, and therefore, its ability to function is independent of the ability of other components.

Herbert Simon's analogy captured the essence of design modularity. Simon (1962) compared two watchmakers, Hora and Tempus. Tempus made his watches in such a way that "if he had one partly assembled and had to put it down—to answer the phone say—it immediately fell to pieces and had to be reassembled from the elements." Hora made watches in a modular fashion. His watches are no less complex than Tempus's, but their internal structures are different. Hora designed watches in a special way "so that he could put together subassemblies of about ten elements each. Ten of these subassemblies, again, could be put together into a larger subassembly; and a system of ten of the latter subassemblies constituted the whole watch." Because of the differences in their assembly design, the two kinds of watches have different economic viability. "When Hora had to put down a partly assembled watch to answer the phone, he lost only a small part of his work. …" (Simon, 1962, p. 470). This analogy compares modularity to a certain design principle. A modular system is built by combining a small number of independent subassemblies. The advantage of the modular structure is efficiencies in assembly, repair, and operation. In Simon's analogy, Hora's watches can recover from damage quickly because of their modular design.

The modular design is also discussed in the context of biological evolution where changing a biological trait without affecting other traits is important. Wimsatt and Lewontin (Lewontin, 1978; Wimsatt, 1980, 2001) argued that adaptive change requires traits to be quasi-independent or modular. For a species to evolve it is important for it to allow a trait to be changed without affecting others. Otherwise, it is not possible to move a developmental lineage away from its current organization. The modular construction, therefore, is an important condition of *evolvability* (the capacity of a species to evolve by changing its biological traits). Sterelny (2004, p. 496) summarized the view.

> If the developmental program of an organism is holistic, then development of any given trait will be connected to that of many others. Hence, that trait cannot change without other changes. But as the

> number of changes in an organization goes up, so too does the probability that one of those changes will be disastrous. The more modular the developmental network is, the more contained are the consequences of change. (Sterelny, 2004, p. 496)

Marr (1982) understood modularity in the same context. He proposed a principle of modular design in which a large computation is decomposed into a set of independent components carrying out subsidiary tasks. Marr discussed two important features of the modular design. First, he hypothesized that biological subsystems evolve in such a way that adding extra components does not change the performance of the overall system. Second, he suggested that complex systems can be revised easily or efficiently on the basis of the modular design. Marr believes that, because of these features, the modular design can maintain stability and flexibility when a cognitive system faces changes or revisions. He explains the design principle and its advantage in the following passage.

> This principle is important because if a process is not designed in this way, a small change in one place has consequences in many other places. As a result, the process as a whole is extremely difficult to debug or to improve, whether by a human designer or in the course of natural evolution, because a small change to improve one part has to be accomplished by many simultaneous, compensatory changes elsewhere. (Marr, 1982, p. 102)

3.4. Neuropsychological modularity

Modularity can be defined from the perspective of cognitive neuropsychology (Coltheart, 1985; Shallice, 1988; Tulving, 1983). In cognitive neuropsychology, cases of dissociation have been used to demonstrate the existence of modules, that is, functionally independent systems in the brain (Shallice 1979, 1988; Teuber 1955; Weiskrantz 1968). A typical dissociation occurs when a patient, due to brain damage, is impaired in one cognitive function A, but the other function B is relatively intact. In this case, A and B are functionally and physiologically independent and served by separate modules.

The classic example of dissociation can be found in a pair of cognitive impairments, Broca's aphasia and Wernicke's aphasia. Broca's aphasics can understand spoken language, but their speech is ungrammatical and fragmented. Wernicke's aphasics can speak fluently, but they have hard time understanding spoken language. The two distinct cognitive functions (the generation of grammatical speech and the comprehension of spoken language) are selectively impaired and matched with damages in two different brain regions—Broca's area (left frontal lobe near primary motor cortex) and Wernicke's area (left temporal lobe near primary auditory cortex), respectively. Based on the dissociative pattern, it is hypothesized that the two impaired cognitive functions are served by their own modules. Modularity here means independent cognitive functions with dedicating groups of brain cells. In this context, Coltheart (1985) defined modularity as a system's being isolable after brain damage.

3.5. Chomskian modularity

Modularity can be understood as a special property of an organized body of innate knowledge. In this approach, a module means an innate and domain-specific body of information

(Carey & Spelke, 1994; Chomsky, 1965, 1968, 1980; Hirschfeld & Gelman, 1994, p. 10; Segal, 1996, pp. 142–143). For example, knowledge of language (linguistic competence) is a module in this sense (Chomsky, 1965); linguistic competence is based on innate, domain-specific knowledge of human language. Language is not the only area where this type of modularity is studied. It is reported that young children have well-organized, domain-specific knowledge bases (Carey & Spelke, 1994; Gopnik & Meltzoff, 1997). Young children use these minitheories when they solve domain-specific problems in physics, psychology, and mathematics. The modularity of a domain-specific body of information is not limited to the human mind; it can be found in an artificial system. A math coprocessor, a hardwired component of a digital computer, displays such modularity. The processor is not a hardware structure or a special function of a computer. It is a body of information (program) that carries out a special function (mathematical processing). This type of modularity is called Chomskian modularity and has been the focus of many psychological and philosophical discussions (Fodor, 1983, pp. 3–10; Harnish, 1998; Higginbotham, 1987; Samuels, Stich, & Tremoulet, 1999; Segal, 1996, pp. 142–143).[4]

3.6. Computational modularity

Modularity can be specified in the dimension of computation. According to Fodor (1983), a major theorist of computational modularity, the mind is understood as a computational system that processes information by formally manipulating signals that represent things in the external world. If the human mind is a big computational system, there are special purpose subsystems that process information in a specific way. These subsystems process information fast without using the resources or information outside their boundaries (Fodor, 1983). Computational modularity refers to this specific mode of information processing (Fodor 1983; Forster 1976, 1979, 1990; Marslen-Wilson & Tyler, 1987).

IE is the most important feature of computational modularity (Fodor, 1983, p. 71; 1985, p. 3; 2000, p. 63). A computational system is informationally encapsulated if it does not access and use relevant information available somewhere outside the system. Because of the constraint on the information access and use, an encapsulated system is blind to available information. Its information processing, therefore, is very much like a reflex (Fodor, 1983, p. 71). A reflex is an instant bodily reaction to a specific type of input. As such, it is automatic (Fodor, 1983, p. 64) and bullheaded (Fodor, 1983, p. 70); it is an uncontrolled and fast reaction to an input. Fodor compared modular information processing with an eyeblink. An eyeblink is an automatic and bullheaded response because "you don't have to decide whether you should close your eye when someone jabs a finger at it." Like an eyeblink, a modular system processes information quickly and automatically without considering important information available outside the system.[5] Fodor summed up his view in the following way:

> Imagine a computational system with a proprietary (e.g., Chomskian) database. Imagine that this device operates to map its characteristic inputs onto its characteristic outputs (in effect, to compute a function from the one to the other) and that, in the course of doing so, its informational resources are restricted to what its proprietary database contains. That is, the system is "encapsulated" with respect

> to information that is *not* in its database. … That's what I mean by a module. In my view, it's informational encapsulation, however achieved, that's at the heart of modularity. (Fodor, 2000, p. 63)

3.7. Developmental modularity

Most studies of modularity focus on fully developed modules without considering their change and development over time. I call this approach the *synchronic* approach. In synchronic approach, researchers study a module in its endpoint of cognitive development, or they ignore the development altogether. Marr's (1982) discussion of modular visual processes focuses on the fully developed visual competence of an adult. He does not discuss how human infants visually recognize an object and how the visual perception with its modular features changes over time. Fodor's (1983) input systems (i.e., groups of basic perceptual processes) are also fully developed modules.[6]

Synchronic approach is not the only way to study modularity. Modularity can be studied by focusing on a group of developmental features of a cognitive system. I call this approach the *diachronic* approach. According to diachronic approach, a module develops along a specific and predetermined path, and this specific development pattern is the defining feature, or at least an important feature, of modularity. Typically, a cognitive module goes through quick, early, and domain-specific development. The language faculty matures fast in the early years without seriously affecting the development of other cognitive capacities. There are two competing views explaining this special development pattern. According to the first view, modular development is viewed as environmental fine-tuning or parameter setting. If a module is regarded as an innate component of mind and fully specified from the beginning of life, the subsequent development of the module is to simply set some of its optional variables (Changeux, 1985; Chomsky, 1981; Piatelli-Palmarini, 1989). I call this view the *parameter-setting theory* of development. The role of the environment, in this view, is to trigger the organism to select one parameter over others.

The second view sees development as a complex interaction between mind (a module) and its environment. If a module is given as an initial bias or disposition, the environment plays an active role in the subsequent development of the module. At the starting point of development, the initial inclination constrains the organism to attend more to a specific group of inputs and to process them in a specific way. To mature, this domain-specific disposition needs a considerably active environmental interaction beyond simple triggering. I call this the *interaction theory of development.* In this view, modularity is the endpoint of active interaction between the mind and its environment (Karmiloff-Smith, 1992). Karmiloff-Smith (1992) called this process modularization.[7]

3.8. Darwinian modularity

There are two different ways to understand the development of a modular cognitive system. Ontogenic development takes place during the lifetime of an organism or a system, and this is the development that I discussed in the previous section. Phylogenic development is the development that takes place over several generations in the evolution of a species. In biology, phylogenic development is characterized as the process of evolution by natural selection. Mod-

Table 2
Approaches of modularity

Different Approaches of Modularity	Major Theorists	Central Features of Modularity
Anatomic modularity	(Hubel & Wiesel, 1979; Mountcastle, 1978; Szentagothai, 1975, 1987)	Specific brain anatomy
Design modularity	(Simon, 1962; Lewontin, 1978; Wimsatt, 1980; Marr, 1982; Ellis & Young, 1988)	Design principle
Neuropsychological modularity	(Tulving, 1983; Coltheart, 1985; Shallice, 1988)	Functional independence that can be revealed in the study of damaged brain
Chomskian modularity	(Chomsky, 1965, 1980; Carey & Spelke, 1994; Gopnik & Meltzoff, 1997)	Innate and domain-specific body of knowledge
Computational modularity	(Fodor, 1983; Marslen-Wilson & Tyler, 1987; Forster, 1976, 1990; Garfield, 1987, 1994)	The way a computational system processes information: speed, information encapsulation, etc.
Developmental modularity	(Chomsky, 1981; Karmiloff-Smith, 1992)	Developmental pattern
Darwinian modularity	(Barkow et al., 1993; Cosmides & Tooby, 1994; Pinker, 1997; Plotkin, 1997)	A biological solution to information processing problems that our ancestors had in their environment

ularity, seen from phylogenic development, is a cognitive property created and developed by the process of evolution. If this process is driven by natural selection, modularity should contribute to or, at least, not hinder the overall reproductive success of the species. This interpretation of modularity is called *Darwinian modularity.* Darwinian modularity sees the development of modularity as phylogenic changes and characterizes modularity as a property of an innate and domain-specific cognitive mechanism that comes to exist by natural selection (Cosmides & Tooby, 1994).

Darwinian modularity is a popular approach among evolutionary psychologists. According to evolutionary psychology, the human mind has two distinct features (Barkow, Cosmides, & Tooby, 1992; Pinker 1997; Samuels, 2000; Samuels et al., 1999). First, it consists of special-purpose systems with specialized functions and specific domains of applications. Second, these systems, sometimes called modules or mental organs, have been shaped by natural selection to solve problems that were important in the environment where our ancestors evolved. In short, the evolutionary approach sees modularity as a biological solution to information processing problems that our ancestors faced in their environment.[8]

4. Different types of modules

In previous sections, I discussed the concept of modularity and its defining features (i.e., what is modularity? what are the defining features of modularity?). In actual psychological research, a different group of questions (i.e., which cognitive systems are modular? how and why are they modular?) seem to have more significance. These are the questions about the modularity of specific cognitive functions and their computational processes.

Many psychologists pointed out the modularity of the language faculty. Human linguistic capacity is domain specific. It has little to do with general reasoning capacity; IQ does not match linguistic skills (Smith & Tsimpli, 1991, 1995). Also the human language faculty works on a limited type of stimulation (speech sounds or written sentences), and it has its own domain-specific information processing rules (Chomsky, 1981). Language processing is mandatory. Almost instantly we understand human speech and we cannot help hearing those sound streams as meaningful messages (Fodor, 1983, pp. 52–53; Marslen-Wilson & Tyler, 1981, p. 327).[9] Data from cognitive neuropsychology suggest that damage to a certain area of the brain produces language-specific impairment (Goodglass & Kaplan, 1972).[10] Like a detachable stereo in a car, the human language system appears to be *functionally independent* of other cognitive capacities.

I chose language as an example because its modularity is well studied and widely discussed (Chomsky, 1981; Fodor, 1983; Garfield, 1987). This does not mean that modularity is restricted to language processes. Modularity of other cognitive processes is reported and studied. For example, the modularity of perception is evidenced by a few well-known facts.[11] Perceptual processes are fast (Fodor, 1983, pp. 62–63). Perceptual processes do not seem to be influenced by one's beliefs. They are informationally encapsulated; as Müller–Lyre illusion demonstrates, knowing that the arrows are the same in length does not help *see* them as equal in length (Fodor, 1983, p. 66).[12] Also, perceptual processes work on limited classes of stimuli; they are modality specific.

Still, there are other modular systems that are neither linguistic nor perceptual, such as the cheater detector module for social contract and social exchange (Cosmides, 1989) and the theory of mind module for understanding and predicting human behavior with underlying mental states (Baron-Cohen 1994; Leslie 1994). It is exciting to see several different modules carving the human mind into autonomous cognitive components. In what follows, I dol not discuss these modules one by one. Instead, I classify and explain different types of cognitive modules and their features discovered in actual psychological studies.

4.1. Big box modules and small box modules

Boxology or box talk of cognitive systems is derived from box and arrow diagrams that cognitive scientists use in their presentations of information processing (Shallice, 1984, p. 243). In those diagrams, boxes represent cognitive systems and arrows represent informational flow or informational link among different systems. Usually, the sizes of boxes are determined by the complexity of intermediate processes and the existence of subsystems and databases (Arbib, 1987; Maratsos, 1992; Meyering, 1994).

Following this general guideline, I define small box modules as highly specialized, reflex-like systems. These systems have very limited or eccentric domains of operation but do not have huge databases. I call them *micromodules* or small box modules. For example, systems for phonetic analysis (Samuel, 1981), line orientation (Hubel & Wiesel, 1974), and 2.5 sketches (Marr, 1982) are small box modules.[13] Compared with these small box modules, big box modules have complex structure. Big box modules, such as the language module and the visual perception module, are defined as systems that have huge databases and several subsystems. Big box systems do not detect specific physical features of the world in a reflex-like manner. Instead they specialize in complex inferences that require many interlevel or intermediate processes.

The modularity of small box systems looks easy to demonstrate. Because they are small systems doing very simple things, such as line detecting, their information processing is already constrained computationally and physically. The same is not true of big box systems. Because they employ several interlevel processes and databases, it is very likely that their computation uses external resources and information. Because of these intermediate processes and databases, the modularity of big box systems looks hard to achieve and maintain. Surprisingly, even with these complexities, the modularity of big box systems is sometimes reported. Consider the language system. It is a big box system, including several subsystems (phonological, lexical, syntactic, and semantic processing) with their intermediate processes. When the language system processes speech sounds, it is easy to imagine the cooperation of a language subsystem (speech recognition system) with an auditory subsystem because they both deal with sound. We can hypothesize that both speech and nonspeech sounds are processed by a single system. After the primary auditory process is completed by this hybrid (language–auditory) system, the result is fed into the language system for further analysis. If this hypothesis is true, is the language faculty at the level of speech recognition modular? When Liberman and colleagues (Liberman, 1982; Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967; Liberman & Mattingly, 1989) found independent processes for speech sounds and nonspeech sounds, the discovery was surprising and the result strongly suggests the modularity of the language system at the level of speech recognition (phonetic analysis). Speech sounds and nonspeech sounds are all auditory signals, but they are processed *separately* from the beginning.

Can lexical processing display the same type of modularity? Consider the sentence, “I will meet you at the bank.” The ambiguity of the sentence is derived from the ambiguity of the word *bank.* Because *bank* has two different meanings (a financial institution and the side of a river or lake), the meaning of the sentence is not uniquely determined. One way to resolve the ambiguity is to consider background (contextual) information. If the sentence is uttered in the middle of the conversation about a local park near the river, then the word *bank* means the side of that river. Is this what the language system (the lexical processing unit) does when it determines the meaning of an ambiguous word? If it resolves the ambiguity in this way, it is not encapsulated (i.e., not modular) because it uses nonlexical information (contextual information and general knowledge about the human life and physical environment) available outside its own knowledge base. Swinney (1979) reported, from his cross-modal lexical-priming data, that when an ambiguous word (*bugs*) is presented in a biasing context (pest control), the lexical decisions for both a related word (*ant*) and an unrelated word (*spy*) were significantly faster than a neutral word (*sew*). That is, when *bugs* was presented, even the inappropriate meaning of an ambiguous word (*spy*) was primed. After several hundred milliseconds later, however, only the contextually related word (*ant*) was facilitated. It appears that modularity at the level of lexical processing is demonstrated in this cross-modal priming experiment. Context had an effect on the resolution of ambiguity, but the effect came *after* the modular activation of all the possible meanings of the word (Seidenberg, Tanenhaus, Leiman, & Bienkowski, 1982; Swinney, 1979; Tanenhaus, Leiman, & Seidenberg, 1979).

Can modularity be demonstrated for syntactic processing, where the grammatical structure of sentences is determined? Some psychologists hypothesize that syntactic processing precedes and works independently of either semantic or pragmatic processes (Garrett, Bever, & Fodor, 1966). Others believe that syntactic processing is interactive; information from all different levels (phonological, lexical, syntactic, semantic, and possibly pragmatic) interacts and mutually constrains processes at the other levels (Tyler & Marslen-Wilson, 1977). Psychologists are still debating over the nature of syntactic processing, but if we consider the speed with which the human language faculty determines the syntactic categories of words and phrases it receives and processes in a conversation, syntactic processing appears to be interactive. To assign appropriate syntactic structure to incoming sentences and to generate meaningful messages *quickly,* the language system, as soon as lexical processing is completed, seems to use not only syntactic information but also semantic and pragmatic information. For example, if it sees *but* or *however,* it anticipates semantically contrasting words or phrases. If it sees any indexical indicators such as *here* or *this,* it looks for relevant reference points near the speaker. So, this big box system (the language system) does not look completely modular. It seems that when the language faculty assigns syntactic categories to words and phrases it uses all sorts of nonsyntactic information (Hanna & Tanenhaus, 2004; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995).

This seemingly interactive nature of sentence processing, however, does not necessarily deny the modularity of the language module. First, we need to determine whether the contextual information (semantic or pragmatic information) is accessed and used at the output level of syntactic processing or at the level of parsing (at the level where the language module assigns syntactic categories to words and phrases). The modularity of the syntactic process will be unaffected if the contextual information is used after the syntactic process generates its outputs. Without specifying the locus of contextual influences, we cannot decide the modularity of syntactic processing. Second, even if syntactic processing is proved to be nonmodular, this does not necessarily imply nonmodularity of the whole language system. It only indicates that modularity is reserved for the cognitive processes at or before syntactic processing. In this case, the language module is not as big as it was initially believed to be. The area of language system now covers only a small portion of language processing. Obviously, more research and analysis are needed to draw the exact boundary of the language module.

4.2. Peripheral modules and central modules

According to Fodor (1983), input systems that process perceptual and linguistic information and output systems that generate behavioral outputs are the best examples of modules. These are peripheral modules located close to the input or output terminals of the mind. Simply put, peripheral modules are specialized and well-tuned input and output systems. Because prime examples of Fodorian modules are peripheral modules, the central modules were not studied and discussed much in the subsequent discussions of modularity. One interpretation of Fodorian modularity is that any such nonperipheral systems tend to function as belief fixation systems or decision-making systems that are paradigmatically nonmodular.[14]

Peripheral modules are better studied and discussed, but this does not mean that all modules are peripheral. Consider Darwinian modularity proposed by Cosmides and Tooby. Cosmides and Tooby (Cosmides & Tooby, 1992; Tooby & Cosmides, 1995) believed that along with peripheral modules, central modules do exist. There can be specialized modular systems "for grammar induction, for face recognition, for dead reckoning, for construing objects and for recognizing emotions from the face" (Tooby & Cosmides, 1995, p. xiv). They also claim that "there are mechanisms to detect animacy, eye direction, and cheating … theory of mind module … a variety of social inference modules … and a multitude of other elegant machines" (Tooby & Cosmides, 1995, p. xiv). It seems that, for every specialized cognitive function, there exists a module. Cosmides and Tooby (Cosmides & Tooby, 1992; Tooby & Cosmides, 1995) hypothesized that the mind is largely or entirely composed of modules, and some of those modules are central. This view is called the massive modularity hypothesis (Samuels, 2000; Samuels et al., 1999; Sperber, 1994; Tooby & Cosmides, 1995).[15] Because this hypothesis is proposed by evolutionary psychologists and modularity is understood in the context of evolution, those (central) modules are called Darwinian modules (Samuels, 2000, pp. 20–21). According to Darwinian modularity, modules are cognitive systems that are designed by natural selection to solve adaptive problems of our hunter-gatherer ancestors.

Massive modularity, with its Darwinian hypotheses, creates a big change in the study of the mind and modularity. The change here is not just the expansion from one possible set of modules to another set of modules. Nor is it merely a change from a modularity-poor mind to one that is modularity-rich. It is the complete change of how we understand and study the mind. According to the massive modularity hypothesis, the mind has a specific path of evolution, the path to specialization and modularity. Regarding the function and the structure of the mind, evolution prefers many specialized systems to a small number of general systems. For this reason, the mind is regarded as the system of massively modular structure.

Evolutionary psychology is not the only way to study central modularity. Consider psychological processes that support mathematical calculation (elementary arithmetic). These processes are believed to be nonmodular. They are not innate; they are learned and culturally transmitted. They are not mandatory; it is not the case that whenever you see numbers you cannot keep yourself from adding or multiplying them. They are not autonomous; they use short-term stores that are used in language processing (Hitch, 1978). It is assembled from other basic capacities (Young & O'Shea, 1981). In cognitive neuropsychology, this calculating capacity is shown to have strong modular features. Warrington (1982) reported that some patients with damaged brains suffer from specific disorders of calculation. In this case, all other cognitive and language processes, including patients' knowledge of numbers were normal, but the ability to solve overlearned arithmetic problems such as 3 + 4 or 12 – 5 was impaired. Here the capacity of elementary arithmetic is shown to have a modular BP. Dehaene and Cohen (1995) hypothesized that mental representations of arithmetic properties are generated by a specific brain region (right inferior parietal cortex). According to them, a dedicated brain structure serves the specific arithmetic function.

Certainly, the capacity of elementary arithmetic and representations of arithmetic properties do not belong to any peripheral system; they do not deal with environmental inputs or behavioral outputs. With these nonperipheral features, they still display strong neuropsychological modularity. Based on neuropsychological features (selective BP and dedicated neural structure), many cases of central (nonperipheral) modularity have been reported and studied (Coltheart, 1985, p. 4; Plaut, 1995, p. 292; Tulving, 1983, p. 66).

4.3. Deep modules and surface modules

Modules can be divided into two distinct subtypes: deep modules and surface modules. A module is deep if it is part of the basic structure of the mind. A module is superficial if it comes from other nonstructural sources, such as conflicts in representational schemes, conflicts in control procedures, and general inefficiency of cognitive processing. By the structure of the mind I mean the mind's basic set of resources for information processing. They are usually hardwired with dedicated circuits in the brain. Roughly the idea is that some cells in the brain are dedicated to serve specific cognitive functions and the states and processes generated by these cognitive functions are structural, that is, deep. If modularity is a property of these states and processes, then it is deep modularity.[16]

There are, at least, three different types of deep modules depending on how we understand the basic structure of mind (Samuels et al., 1999; Segal, 1996). First, innate data structure (a body of information) can be included in the basic structure of mind. For example, innate knowledge of language, according to Chomsky (1965), is such a basic data structure. Thus, we have Chomskian modules as one type of deep module. Second, the basic structure of the mind can be understood as psychological mechanisms. For example, Fodor's input systems are the basic structure of the mind in this sense. Third, the basic structure could be the combination of data structure and psychological mechanism. The hypothesized "theory of mind" module is the third type of deep module (Baron-Cohen, 1994; Leslie, 1994). It is an innate, domain-specific body of information used by a dedicated psychological mechanism to understand and predict the behavior of conspecifics.

Surface modularity comes from entirely different sources. It may come from conflicts at the level of software (Bever, 1992; Harnish, 1998), such as incompatible representation schemes, unreadable data structures, conflicting control procedures, or conflicting principles of memory management. According to Harnish's (1998) digital computer analogy, programming (postnatal experience) imposes surface modularity on the system. For example, in a digital computer, if the word processing is done by WordPerfect but the central processor is Lotus 1–2–3, then they will not exchange information even on the same hardware without a translator. This problem of information exchange due to software conflict produces modular features such as IE. Two surface modules, a module for WordPerfect and a module for Lotus 1–2–3, will explain this conflict. The problem of information exchange due to software conflict illustrates that nonstructural features of mind (learning, training, and general experience) can generate modularity. By enforcing different representational formats or control procedures, these nonstructural conditions create modular processes seemingly isolated from other cognitive processes in the mind.

Another example of surface modularity can be found in multilingual speakers. Multilingual speakers do not speak their languages in exactly the same way (Groisjean, 1989). Depending on sociolinguistic environment, they tend to specialize in the different languages they use. For example, an English–German–French multilingual speaker speaks English for everyday conversation, German for science, and French for music and arts. Also, for bilingual speakers, specific patterns of lexical access are reported. The way they access the lexical items (mentally represented words and phrases) of L1 (naturally acquired language, mother language) is different from the way they access lexical items of L2 (the second language; Chen & Leung, 1989; Kroll, 1993; Kroll & Stewart, 1994). These differential access patterns produce modular translation processes; the translation process from L1 to L2 is different from the L2 to L1 translation process (Kroll & Sholl, 1992; Kroll & Stewart, 1994). It is hypothesized that different control procedures or memory principles are responsible for this type of differential processing pattern. Based on the data, it could be argued that each language constitutes its own surface module in the multilingual mind.

Surface modularity could be generated by inefficiency of information processing. Consider specific language impairment (SLI) and Williams syndrome at the opposite extremes of human language capacity. On the one hand, SLI children can perform many nonlinguistic tasks that require general intelligence (such as reasoning, memory, and calculation), but their linguistic ability, their speech in particular, is impaired. Many grammatical errors are found in their speech (Pinker 1994, pp. 48–50). On the other hand, children with Williams syndrome have very sophisticated linguistic capacity. They can speak with fluency, using all sorts of well-developed vocabularies. Unfortunately, most of their nonverbal cognition is impaired; their average IQ is 50 and their spatiovisual skills (except for face recognition) are severely impaired (Karmiloff-Smith, 1992, pp. 168–169). This pattern of disorders seems to demonstrate that there is an impairment that affects language capacity, only and there is another impairment that affects nonlinguistic capacities only.

There are two possible explanations for this selective impairment pattern. First, this pattern can be regarded as a structural independence of language faculty from other cognitive capacities (Pinker, 1994). According to this hypothesis, two deep modules are involved in this pair of cognitive impairments, each responsible for SLI and Williams syndrome. Second, the impairments, SLI in particular, can be explained by general cognitive problems such as inefficient or insufficient information processing. Several studies of SLI report that children with SLI have a problem in processing rapid temporal sequences of auditory and visual stimuli (Tallal, 1988;

Table 3
Types of modules

Types of Module	Features	Modules
Big modules	Modules with interlevel processes and subsystems	Language module (Fodor, 1983)
Small modules	Reflex-like systems with highly specialized functions	Line detector (Hubel & Wiesel, 1974)
Peripheral modules	Modules that process environmental inputs or behavioral outputs	Input systems and output systems (Fodor, 1983)
Central modules	Modules that do not process environmental inputs and behavioral outputs	Cheater detector module (Cosmides, 1989; Cosmides & Tooby, 1994)
Deep modules	Modules that reflect basic structure of mind	Language module (Fodor,1983)
Surface modules	Modules that reflect learning/training, or general cognitive conditions	Language production module of SLI (Tallal et al., 1995)

Note. SLI = specific language impairment.

Tallal, Stark, & Mellits, 1985; Tallal et al., 1995). These studies hypothesize that SLI is not a specifically linguistic deficit but a general cognitive problem of processing rapid sequential materials. If SLI is a general processing problem, we do not need to propose a separate module for language processing. Instead, SLI can be explained at a surface level as a by-product of a general cognitive deficit.

5. Challenges and problems

I have discussed different approaches to modularity and surveyed different types of modules. Modularity is studied from many different perspectives, and modules are proposed from different theoretical interests and orientations. On the one hand, cognitive modularity plays an important role in psychological theorizing. Modularity is used to explain perceptual input processes (Fodor, 1983), language (Chomsky, 1972), social contract (Cosmides, 1989), and theory of mind (Baron-Cohen, 1994, 1995; Botterill & Carruthers, 1999; Currie & Sterelny, 2000; Leslie, 1994). Modularity is also involved in many other psychological researches (Bloom, 1970; Chomsky, 1972, 1986, 1988; Deutsch, 1975, 1983; Forster, 1976, 1990; Gelman, 1990; Karmiloff-Smith, 1979; Liberman et al., 1967; Marr, 1976; Rock, 1984; Spelke, 1991; Ullman, 1979). It seems that almost every cognitive process is researched and explained from the perspective of cognitive modularity.

On the other hand, there are a few challenges to the idea of modularity as a basic cognitive property and the existence, size, and distribution of cognitive modules. In a recent article, Hauser, Chomsky, and Fitch (2002) distinguished between the faculty of language in the broad sense (FLB) and the faculty of language in the narrow sense (FLN) and analyzed the modular character of FLN. According to them, FLB includes a sensorimotor system, a conceptual–intentional system, and the computational mechanisms for recursion (the process where a finite set of elements creates an infinite range of expressions). It seems that their FLB corresponds to the big box language module, but they quickly narrow down the uniquely human component of the faculty of language to FLN, which includes recursion only. Often, the faculty of language is regarded as a big box module consisting of all the language-related processes. According to this analysis, however, the human language faculty is not a big box system; it is a small system with very specific operations.

This is not the only problem of the modularity of the language faculty Hauser and his colleagues (Hauser et al., 2002) discuss. According to one hypothesis they developed, recursion was originally a domain-specific process, designed for a particular function (navigation), but it was recruited by human species (in the process of evolution) to solve other problems such as representation and manipulation of numbers and linguistic entities (words and sentences). It seems that some of our mental faculties evolved from very specialized and domain-specific cognitive processes to solve more general problems necessary for our survival. If this hypothesis is true, FLN (recursion) does not seem to be completely modular because it was developed by demodularizing its original domain (navigation). The process of generality and flexibility created the language faculty. Is the language faculty still modular? I believe that the development or the evolution of FLN is not necessarily the movement away from modularity because, in principle, modularity can be developed in any specialized domains of inputs. Compared with the original domain of recursion (navigation), FLN (as newly developed recursion) is a relatively general process, but its application in a group of selective cognitive domains makes it a very exclusive process.

If modularity of the whole language system is in controversy, is modularity of its subsystems better defended? Consider Broca's aphasia. As I have discussed, Broca's aphasia is characterized as a well-specified and isolated set of output problems (ungrammatical and fragmented speech). This interesting case of neuropsychological modularity is challenged by several studies (Swinney, Zurif, & Nicol 1989; Swinney, Zurif, Rosenberg, & Nicol, 1985; Zurif, 1990). They reported that Broca's aphasia does not occur as a result of the breakdown of the language production system. Rather, it is derived from a general (i.e., nonmodular) cognitive deficit. According to Zurif (1990), labored and ungrammatical speech is caused by the failure to process rapid-input sequences. He argued that the modular dissociation pattern of Broca's aphasia is only a by-product of this general cognitive problem, and therefore, Broca's aphasia can be understood better by focusing on this general problem. If hypotheses such as Zurif's are true, we need to separate two different types of modularity: modularity as an *original* property of innate, domain-specific, cognitive structures and modularity as a *derivative* property or a surface feature of general cognitive conditions. As Zurif's hypothesis indicates, some behavioral or neural dissociations do not necessitate original modularity. If modularity is derivative, it is restricted to features of surface or emergent patterns. As such, derivative modularity does not have its own power to generate any significant differences in information processing. The idea of a module as an independent cognitive mechanism is challenged by the cases of derivative modularity.

To generalize the issue of derivative modularity, imagine a generalist cognitive system that can be used flexibly in many different cognitive areas. A simple model of this generalist system is a connectionist network (Churchland, 1990; Quinlan, 1991; Rumelhart, 1989; Rumelhart & McClelland, 1986). A connectionist network consists of units and connections among them. When input units receive input signals, they are activated following their activation functions and send out their outputs to other units via the connections with varying weights. As the signals spread out to the system, they create a certain pattern of activation. Cognition, in this context, is the result of the overall pattern of interaction created by units and their connections. Because basic cognitive processes in this connectionist network are interactive, that is, nonmodular, either modularity does not exist, or if it exists, it exists only as a surface feature of underlying nonmodular processes, that is, as a by-product of the complex interaction among units. It should be noted that not all connectionist networks have generalist structure; some connectionist systems have specialized subnetworks. For example, Jacobs, Jordan, and Barto (1991) proposed a modular architecture in their connectionist network. But, even in those modular networks, modularity is a derivative property ascribed to the overall activation pattern of the underlying interactive processing among the units. Generally, modularity need not be original in connectionist networks; we do not need to hypothesize the existence of innate, domain-specific, hardwired structures to study and explain cognitive modularity. Obviously, in the context of connectionist information processing, the scope of modularity is narrowed and restricted to derivative features of networks.

Whether cognitive processes are modular in an original way (as in deep, innate, and domain-specific systems) or in a derivative way (as in a connectionist network), modularity is still regarded as an important property of a cognitive system, something worthwhile to investigate and explain. I believe that the most serious challenge to modularity comes from the complexity of modularity. As I listed in previous sections, there are so many features, so many dimensions, and so many modules proposed and discussed. But there seems to be no theoretical unity in the use and application of modularity in cognitive science. In many studies of modular cognitive processes, modularity is loosely defined and liberally specified by a bundle of features from different dimensions. Because of the liberal uses and applications, modularity could be anything (as in massive modularity hypothesis) or almost nothing (as in surface modularity or modularity in a connectionist network). For this reason, I ask whether modularity plays a meaningful role as a property of psychology.[17] My hypothesis is that there is a hidden unity among the features of modularity. Despite the diverse and liberal characterizations, modularity achieves the unity and because of the unity it can contribute to cognitive science.

6. Cross-dimensional unity

Features of modularity form a natural cluster, formed by close computational, functional, and physical constraints of modularity. It should be noted that these features are not clustered in a strict entailment relation. It is not the case that IE *logically* entails speed (S) or mandatoriness (M). Rather it is the function, computation, and physical structure of a cognitive system that combine those features together. For example, in a cognitive system, encapsulated information processes are fast and automatic because these features are associated due to certain computational, functional, and structural constraints. If we find one feature of modularity in a cognitive system, we naturally expect other features of modularity to show up in the same system because, more than likely, those features work together when the system carries out specific cognitive functions.

More specifically, there is a possible companionship among those features. Features of modularity such as IE, S, M, NA, and BP form a natural companionship.[18] A cognitive system processes information fast because it is encapsulated (Fodor, 1983, pp. 69–70), that is, it does not use all the available and relevant information. Mandatory processes and encapsulated processes share one important property together. They are like reflexes; once they start processing information, we cannot control them (Fodor, 1983, pp. 63, 71). NA is the "natural concomitant" of informational encapsulation (Fodor, 1983, p. 99), and BP gets along with IE naturally. In addition to these connections, DS, LCA, and specific ontogeny (SO) are related to IE. LCA, M, and IE display the similar limitedness of information processing and computational autonomy. DS and SO represent functional and developmental specialization, respectively, and relate to IE via a limited style of information processing and development.

Fig. 1 captures the relation among the features of modularity. As I emphasized, this is not a logical or conceptual relation but a factual association among the features related in a principled way in a modular cognitive system. Most important, features of modularity form a cluster around IE, the unifying core of modularity.[19] IE is the central feature of cognitive modularity because it characterizes the main character of modularity (modular information processing) and provides a reason why a certain group of features work together.[20] Without IE, features of

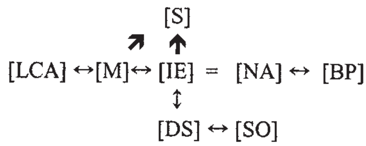

Fig. 1. Relations among the Features of Modularity. (= being correlated, ↔ losely related, → being produced by).

modularity, individually or as a group, create a broad and heterogeneous group of processes that do not serve serious scientific goals. Suppose that speed is the unifying center of modularity. In this case, modular cognitive processes have a cluster of features because of the speed. The speed of those processes might explain why modular processes are automatic and mandatory. But speed alone cannot explain some other features of modularity such as DS, NA, and IE. There are so many fast cognitive processes; some are domain general and some are neurally nonspecific. Also fast processes are not necessarily encapsulated or free from central control. If speed is the central feature of modularity, why is speed, in the context of modularity, associated with these nonmodular features?

Neither mandatoriness nor DS makes any better chance. If mandatoriness or DS is the key feature of modularity, we need to take reading or chess playing as modular processes. Reading seems to be modular because it is mandatory (due to the Stroop effect) and is not affected by other cognitive processes (Patterson & Kay, 1982; Rolins & Hendricks, 1980). Chess playing seems to be modular because it is based on domain-specific spatial memory and fast processes (Chase & Ericsson, 1982; Chi et al., 1989). If reading or chess playing is modular, then any well-trained and specialized activities can be modular too. Most of those activities are domain specific, mandatory, and fast. Often, they even display LCA and specific developmental patterns. Once initiated, we cannot access or intervene in the processes run by those skilled activities. Also some artistic and athletic skills are learned quickly in early ages with a specific developmental schedule; people cannot learn these skills once they pass the appropriate developmental stage. If this is true, there no longer exist well-specified groups of processes uniquely picked up by modularity. Because there are so many skilled activities that are mandatory, centrally inaccessible (or uncontrollable), domain specific, or developed early, we do not expect these skilled activities to form a well-specified group. It seems that almost every human behavior is modular in this sense. Because of the broad and heterogeneous group they create, these features do not serve any serious scientific goals.

Other features of modularity (NA, BP, and SO) generate the same problem. As I discussed, either they cannot explain cognitive modularity without IE, or they create a heterogeneous group of processes that do not serve any serious scientific goals. NA and BP are the neuropsychological features of modularity. These features focus on a specific structure in the brain, and as such, they are closely related to the limited pattern of information processing (i.e., IE). But they do not explain why a specific physical structure is associated with cognitive modularity. In Simon's analogy (Simon, 1962), Hora's watches realize this (modular) physical structure, but are those watches "cognitively" modular?

Considering the nature of modular information processing and its cluster of features, IE is the most important and unifying feature of cognitive modularity. If IE is the unifying core of modularity, can modularity be defined and specified by this single feature? Are other features and dimensions still necessary? To answer these questions, we need a further analysis of IE. IE, basically, is an information processing constraint—the constraint on the "location" of information that a cognitive module can access and use when it processes information. If a cognitive system accesses and uses information outside the system, its information processing crosses the boundary of the system, and therefore, the system is not encapsulated (i.e., not modular). This limitation on information processing is understood better if we compare a module with a reflex. As I explained early, a reflex is an instant bodily reaction to a specific type of input, and a module processes information fast. But the similarity between the two does not lie in their capacity but in their incapacity, the incapacity of not utilizing available information that lies outside the system. The limitation on information access and use generated by the incapacity is the essence of IE. Fodor explained this essential feature of modularity in the following passage: "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, 1983, p. 71).

IE, however, should not be interpreted negatively. First, as a constraint, IE is not an accidental or random limitation; it is a principled limitation derived from the cognitive structure. According to Fodor, IE belongs to the rigid and permanent structure of the mind. Fodor said, "[A] module is … an informationally encapsulated computational system—an inference making mechanism whose access to background information is constrained by *general features of cognitive architecture, hence relatively rigid and relatively permanently constrained*" (Fodor, 1985, p. 3; italics added).

Second, IE should not be interpreted as the limitations or incapacities of simple switches or blind automatisms. Cognitive modules are not detectors or switches whose functions are described and explained by physical or biological terms, that is, noncognitive terms. Nor are they computational automatisms running meaningless operations. They are inference-performing systems with full cognitive power. Fodor emphasizes this aspect of modules in the following passage:

> Input analyzers [i.e., cognitive modules] are thus inference-performing systems within the usual limitations of that metaphor. Specifically, the inferences at issue have as their "premises" transduced representations of proximal stimulus configurations, and as their "conclusions" representations of the character and distribution of distal objects. … Input analyzers [i.e., cognitive modules], with their … relatively rigid domain specificity and automaticity of functioning, are the aboriginal prototypes of inference-making psychological systems. (Fodor, 1983, pp. 42–43)

Because a module is not a blind and automatic mechanism, it serves a specific function and performs meaningful operations. IE, from this perspective, is the meaningful incapacity of a module, not a property of random and disabled processes. Therefore, it is important to know this specific type of incapacity when we ascribe IE to a cognitive system. One good way to know about this incapacity is to study principled computational limitations

Consider the Müller-Lyer illusion, a popular example of visual illusion. It creates a visual misjudgment where a line segment can look longer or shorter than it is due to the shape of the wings at the end of the line segment. Unfortunately, this illusion cannot be corrected even if we are informed of the actual length of the two line segments; regardless of the available information, the line segments *look* longer or shorter than they are. According to Fodor (1983, pp. 42–43), the persistence of the illusion is generated by the encapsulated nature of visual processing. That is, visual processing is blind to some available information. Specifically, it is blind not because it does not access the available information (i.e., the belief that the line segments are equal in length), but because it does not access the available information even if the information is relevant and critical to its *function.* If the function of the visual system is to provide truthful judgments about the visual qualities of the world, the available information that the line segments have equal length should be accessed and used. But it is not. To understand the relation between the function of the visual system and its IE, compare the limitation of visual information processing in the Müller-Lyer illusion with the limitation that the visual system has with available olfactory information. Because olfactory information is not relevant to the function of the visual system, not using olfactory information does not affect the IE of visual processing. The visual system does not deal with olfactory information, not because of its IE but because of its DS. DS is the constraint about the *width* of information access; it concerns how wide or narrow information is accessed and used by a module. From a wide variety of information, a cognitive module works on only a limited type of information. On the contrary, IE is concerned about the *depth* of information access and use; how deeply information is accessed and used in a given domain is the main focus of IE. Because a cognitive module does not access most of the relevant information required by its cognitive function, its *depth* of information access is quite limited. For example, a cognitive module does not access relevant information generated and processed by high cognitive states such as beliefs and goals. A module is, to borrow Pylyshyn's term (Pylyshyn, 1984, 1989), cognitively "impenetrable" and unaffected by outside influences due to their limited depth in information processing.[21] To be "truly" encapsulated and to be "really" modular, therefore, a cognitive system should display limited depth (not just limited width) in information access and use.

To measure the depth of information access and use, that is, to determine how much information should be accessed and used by a cognitive system, it is critical to specify the function of the system. In our example of Müller-Lyer illusion, visual processing is encapsulated from available information critical to its function (i.e., what it is supposed to do to provide truthful information about the visual properties of the world). Not accessing and using available olfactory information does not count as the encapsulation of visual processing because olfactory information is simply irrelevant to the function of the visual system. But not accessing available visual information reduces the depth and thereby encapsulates visual processing. To generalize, without knowing the function of a system, we cannot set the relevant depth of information processing, and without the relevant depth, we cannot distinguish genuine IE (a principled limit on the use of available information critical to the function) from other types of limitations such as accidental nonaccess to specific pieces of information or domain-specific constraints on information access. Therefore, the functional specification is necessary in identifying the IE of a cognitive system. It is clear, from my analysis, that IE is closely related to the functional dimension of modularity.

There is another dimension of modularity that IE naturally associates with. One way to achieve IE in a cognitive system is to isolate specialized functions in physically separate structures. If cognitive functions are hardwired in separate structures, IE for those cognitive functions will be achieved. A hardwired system does not access information in other systems because it facilitates only a certain type of information processing. Fodor explained this idea of encapsulation in the following way:

> Hardwired connections indicate privileged paths of information access; the effect of hardwiring is thus to facilitate the flow of information from one neural structure to another. But of course what counts as relative *facilitation* when viewed one way counts as relative *encapsulation* when viewed the other way. If you facilitate the flow of information from A to B by hardwiring a connection between them, then you provide B with a kind of access to A that it doesn't have to locations C, D, E… (Fodor, 1983, p. 98)

To understand IE in a hardwired structure, consider the skills that are learned and practiced every day. Schwartz and Schwartz (1984) reported the IE of driving a car. They (Schwartz & Schwartz, 1984, p. 40) said, "Certainly much of the information that might be relevant to driving decisions and that one might have been entertained during learning no longer implies on us as we drive, even though it might be helpful if it did." Imagine how this skill is hardwired in a system. By learning and training, driving activities create a separate system (a dedicated group of brain cells) serving a very specific function. Due to specialization and facilitation, those brain cells can process information independently of other cognitive processes without considering available and relevant information. This is how hardwiring of a cognitive function generates IE. Whether driving a car can be actually hardwired remains to be seen, but as Schwartz and Schwartz report, it displays IE, and there is a good chance that the encapsulation is generated by dedicated brain cells. In this way, IE is related to NA with dedicated cells. Referring to this relation, Fodor said that "intimate association of modular systems with neural hardwiring is pretty much what you would expect given the assumption that the key to modularity is informational encapsulation" (1983, p. 98).

If IE is closely related to the function and structural specialization of a system, we need to give up the idea that modularity is defined in a single dimension of cognition. IE (computational dimension) is the essential feature of modularity, but as I analyzed, it comes with its accompanying dimensions (functional dimension and physical dimension). Functional dimension specifies that IE is not a property of meaningless automatisms, but a special mode of information processing with limited depth in carrying out a cognitive function. Physical dimension explains limited information processing (IE) in a specialized physical structure; a cognitive function can be hardwired in a dedicated physical structure. Therefore, modularity, by nature, is a multidimensional property; it consists of features from several dimensions specifying different aspects of cognition. We cannot define modularity in a single dimension as we did with "mass" or "energy," where relatively simple characterization is possible.

If modularity is unavoidably multidimensional, how can we understand and use the term *modularity,* given that most scientific terms are defined in a single dimension? Is there any scientific term defined in this way (by several different dimensions) and still playing its theoretical role? There is a scientific term defined with features from the different aspects of the natural world. Consider *gene,* the term that refers to an entity in biology. According to Mendelian genetics, a gene is characterized as a biological mechanism that carries a biological trait (a gross biological characteristic such as eye color) and is responsible for a specific pattern of hybridization. Dobzhansky said,

> Mendelian genetics is concerned with gene differences; the operation employed to discover a gene is hybridization: parents differing in some trait are crossed and the distribution of the trait in hybrid progeny is observed. (Dobzhansky, 1970, pp. 221–222)

In this approach, a gene is defined cross-dimensionally. The aspect of external expression (phenotype), the aspect of function (the role that a gene plays in hybridization), and the aspect of physical implementation (how it is physically realized) are combined to characterize a gene. That is, a gene is defined in such a way that a certain biological mechanism with a specific function is associated with the gross biological trait (such as smallness of peas). The gene achieves its cross-dimensional unity by combining its phenotypical, functional, and structural features. With this unity, it plays a unique theoretical role in biology, describing and explaining biological regularities. In a similar fashion, modularity combines features from different dimensions and generates its own cross-dimensional unity. As I analyzed, IE (from computational dimension), functional specialization (from functional dimension), and neural specificity (from physical dimension) are combined to characterize cognitive modularity. A cognitive module, in this cross-dimensional unity, is a cognitive system where a certain physical structure with a specified cognitive function is served by a specific information processing mode (IE). Fig. 2 compares a Mendelian gene with a cognitive module in their cross-dimensional unity. If *gene* is a scientific term (despite the fact the gene is defined by many features from different dimensions of biological systems), then there is no reason not to give the same status to *module,* given that it achieves its own cross-dimensional unity and plays an important role in cognitive science.

To conclude, modularity is not one of those simple properties that can be defined by a single essential feature. It is a cross-dimensional unity with many features combined together. Despite the diversity and liberal applications, modularity can serve as a psychological kind because features of modularity form a cross-dimensional unity representing different aspects of modular information processing. The unity among diverse features is the essence of modularity. Future studies of modularity, therefore, should focus on this multidimensional character and deeper unity of modularity.

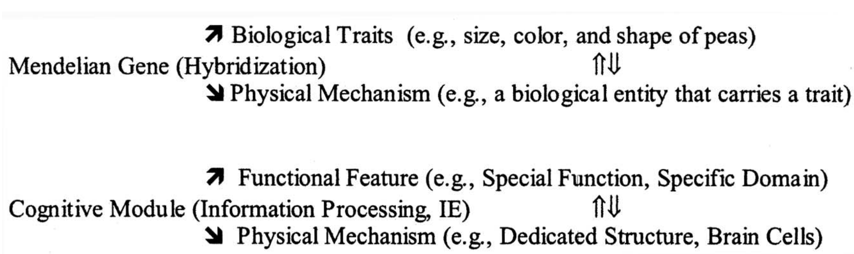

Fig. 2. Cross Dimension Unity—Gene and Module.

Notes

1. Marshall (1984, p. 212) suggested that good theories of modularity should answer at least two questions of modularity. First, which aspects of human cognition are likely to be (in some sense) modular? Second, what constellation of features is likely to pick out the correct modules?
2. Sometimes, different approaches overlap in their characterizations of modularity. For example, both design modularity and neuropsychological modularity focus on the physical and functional structure of a modular cognitive system.
3. Edelman (1982, p. 28) said, "The greatest achievement in thinking about the cortex, the greatest revolution is that the cortex is not just a continuously horizontally disposed sheet, but is vertically organized as stacks of slabs or columns."
4. Segal (1996, p. 142) called it "intentional modularity," and Higginbotham (1987) called it "modules of understanding."
5. There are noncomputational features in Fodor's list, but Fodorian modularity is basically computational. Fodor lists more computational features than noncomputational features in his list. More important, Fodor picks informational encapsulation as the most important feature of modularity (Fodor, 1983, p. 37; 2000, p. 63).
6. In addition to this, Fodor is skeptical about the significance of cognitive development. Fodor said he is "inclined to doubt that there is such a thing as cognitive development in the sense that developmental cognitive psychologists have in mind" (Fodor, 1985, p. 35).
7. According to Karmiloff-Smith (1992) modularization should be understood against a background of children's ongoing cognitive development to more manipulable, flexible, and explicit knowledge. In spite of this general tendency, Karmiloff-Smith does not see modularization as a permanent solution to the problem of getting flexible and explicit knowledge. Modularization constitutes only an intermediate stage where children learn to build domain-specific knowledge or skills. It is interesting to see that, in her discussion of modularity, modularity or modularization is covered, but modules (fully specified innate structures of the mind) are not discussed.
8. This approach should not be confused with Chomskian modularity. There are two different features that separate the two approaches. First, Darwinian modularity focuses on innate and domain-specific cognitive *mechanisms* (Cosmides & Tooby, 1994, p. 94, Tooby & Cosmides, 1995, p. xiii). A Darwinian mechanism can use an innate body of knowledge, but the primary target of this approach is cognitive mechanisms. Second, the Darwinian approach focuses on *how* the modules come into existence. Modules came to exist because they enhanced fitness in the environment of our ancestors.
9. Fodor (1983, pp. 52–53) said, "You can't help hearing an utterance of a sentence (in a language you know) as an utterance of a sentence, and you can't help seeing a visual array as consisting of objects distributed in three-dimensional space." Also Marslen-Wilson and Tyler said,

   > Even when subjects are asked to focus their attention on the acoustic-phonetic properties of the input, they do not seem to be able to avoid identifying the words

involved. … This implies that the kind of processing operations observable in spoken-word recognition are mediated by automatic processes which are obligatorily applied. … (1981, p. 327)

10. A well-known example is Broca's aphasia. It has been believed that if Broca's area is selectively damaged, grammatical language production is impaired. This area involves, at least, the front area of the primary motor zone for the muscles serving speech, that is, muscles for lips, tongue, jaw, vocal cords, and diaphragm. Broca's patients produce labored, ungrammatical speech with poor articulation (Goodglass & Kaplan, 1972).
11. According to Fodor (1983, 1985), most of these perceptual processes are fast, automatic, and innately specified. Also, most basic perceptual processes are modality specific. But, there are some cross-modal effects, such as the McGurk effect (McGurk & McDonald, 1976). Fodor (1983, p. 132) argued that this cross-modal effect is specific to language; the McGurk effect shows cross-modal integration within the boundary of a language module. About McGurk effect: McGurk and McDonald showed that processes of phonetic analysis were activated by either acoustic or visual stimuli. For example, the visual input for articulatory movements of lips say [gaga] is dubbed over by auditory input [baba]. Subjects are asked to report what they hear. They report that they hear [dada]. That is, seeing the shape of lips can interact with phoneme identification process.
12. Churchland (1988) had a different view. He disagreed with Fodor; perceptual processes are *not* informationally encapsulated. They are influenced by information available in the belief system. See the exchange between Fodor (1984, 1988) and Churchland (1988).
13. Fodor mentioned such systems as phonetic feature detectors, color perception systems, shape analyzers, and three-dimensional spatial relation analyzers as "highly specialized computational mechanisms" (Fodor, 1983, pp. 47, 132–133).
14. Fodor (2000) was skeptical about the possibility of central modularity. Consider the theory of mind module proposed by psychologists (Baron-Cohen, 1994, 1995; Leslie, 1994). As we can observe from many cases of autism, this specialized cognitive system is domain specific, selectively impaired, and develops in early years. Specifically, it grows with specific pace and stages. When young children learn to understand others' mental states, they first learn about intentions, then desires and beliefs (Wellman, 1991). Because the theory of mind module does not process environmental input or generate behavioral output, it is a central module. The problem here is that this central module is not completely encapsulated. Knowledge of others' mental states depends on a variety of nonsocial and nonmental factors.
15. "Our cognitive architecture resembles a confederation of hundreds or thousands of functionally dedicated computers (often called modules) designed to solve adaptive problems endemic to our hunter-gatherer ancestors. Each of these devices has its own agenda and imposes its own exotic organization on different fragments of the world. There are specialized systems for grammar induction, for face recognition, for dead reckoning, for construing objects, and for recognizing emotions from the face. There

are mechanisms to detect animacy, eye direction, and cheating. There is a 'theory of mind' module … a variety of social inference modules … and a multitude of other elegant machines" (Tooby & Cosmides, 1995, p. xiv).

16. According to Pylyshyn (1984, 1989), the basic structure of mind is not affected by current cognitive states. For example, some of my mental states and processes are related to or dependent on what I believe, desire, or remember. Consider my belief that the morning star is the evening star. I used to believe that the morning star is different from the evening star. I look up an astronomy book and find out that they are the same star. Because of my current cognitive state (my knowledge that the two are the same), my belief has changed (now I believe that the morning star is the evening star). But some of my cognitive states and processes are not related to or dependent on my current cognitive states. My perception of two Müller-Lyre arrows is not affected by my belief that they are equal in length; however hard I try, I still see them differently. The first group (cognitively penetrable group) of states and processes does not come from the basic structure of the mind, but the second (impenetrable) group of states and processes comes from the structure of mind. If modularity belongs to the second group, it is deep.
17. A *psychological property* is a property that is used in (a) the categorization and the classification of psychological states and processes, (b) the description of psychological phenomena, and (c) the generalization of psychological regularities.
18. Fodor (1983) related informational encapsulation to speed, shallow output, mandatoriness, and neural specificity in the following way:

    (a) informational encapsulation and speed:

    I put the issue of informational encapsulation in terms of constraints on the data available for hypothesis confirmation because doing so will help us later, when we come to compare input systems with central cognitive processes. Suffice it to say, for the moment, this formulation suggests another possible reason why input systems are so fast. (Fodor, 1983, p. 69)

    To the extent that input systems are informationally encapsulated, of all the information that might *in principle* bear on a problem of perceptual analysis only a portion (perhaps only quite a small and stereotyped portion) is actually admitted for consideration. This is to say that speed is purchased for input systems by permitting them to ignore lots of the facts. (Fodor, 1983, p. 70)

    (b) Informational encapsulation and shallow output:

    The more constrained the information that the outputs of perceptual systems are assumed to encode, the shallower their outputs, the more plausible it is that the computations that effect the encoding are encapsulated. (Fodor, 1983, p. 87).

    (c) Informational encapsulation and mandatoriness:

    It may well be that processes of input analysis are fast *because* they are mandatory. Because these processes are automatic, you save computation (hence time) that would otherwise have to be devoted to deciding whether, and how, they ought to be performed. Compare: eyeblink is a fast response *because* it is a reflex—i.e., because you don't have to *decide* whether to blink your eye when someone jabs a finger at it. Automatic responses are, in a certain sense, deeply unintelligent; of the whole range of computational (and, eventually, behavioral) options available to the organism, only a stereotyped subset is brought into play. (Fodor, 1983, p. 64)

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, 1983, p. 71).

(d) Informational encapsulation and neural specificity:

Neural architecture, I'm suggesting, is the natural concomitant of informational encapsulation (Fodor, 1983, p. 99).

19. Hence the importance of IE in Fodorian modularity. Fodor says that IE is an essential feature of modularity (Fodor, 1983, p. 71; 1985, p. 3; 2000, p. 63).
20. Cognitive modularity without IE is a controversial issue. Some are skeptical about maintaining the requirement of IE of modularity (Appelbaum, 1998) and recommend a loose sense of modularity (Botterill & Carruthers, 1999). But others, such as Fodor (2000), argue against dropping the IE requirement of modularity.
21. A positive side of this limitation is that cognitive modules do not have frame problem due to their limited depth of information processing. Fodor said,
To the extent that the information accessible to a device is architecturally constrained to a proprietary database, it won't have a frame problem and it won't have a relevance problem (assuming that these are different); not, at least, if the database is small enough to permit approximations to exhaustive searches. Frame problems and relevance problems are about how deeply, in the course of cognitive processing, a mind should examine its background of epistemic commitments. A modular problem-solving mechanism doesn't have to worry about that sort of things because, in point of architecture, only what's in its database can be in the frame. (Fodor, 2000, pp. 63–64)

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