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# MODULARITY: *AN APPLICATION OF GENERAL SYSTEMS THEORY TO MILITARY FORCE DEVELOPMENT*

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Although researchers in the fields of mathematics, psychology, biology, and social systems theory have long used the concept of modularity, none of these fields offered an explicit causal model of how and why increasingly modular forms are adopted. The authors apply constructs and models developed in the study of organizational modularity to explain the adoption of increasingly modular organizational designs in the U.S. military and offer some implications of this work for force development, future concept development and experimentation, and acquisition.

There is a move underway to increase modularity in the design of our forces, as evidenced in our *National Military Strategy* and in the family of *Joint Operations Concepts* (see Figure 1). Many recent force-structuring efforts, especially by Army Training and Doctrine Command (TRADOC), appear to increase the *disaggregation* of forces into separable modular systems so they can be rapidly reconfigured to respond to a wide variety of mission needs. However, at the same time that many forces are being made more modular, other efforts appear to increase unit consolidation and joint integration (e.g., Pentagon efforts to create *born joint* systems).

So what drives some force developments toward increasing modularity and others toward increasing joint integration? When will forces benefit more from the flexibility of modular systems versus the tight coordination of less flexible configurations? Although researchers in the fields of mathematics,[1] psychology,[2] biology,[3] and social systems[4] have long used the concept of modularity, none of these fields offered an explicit causal model of how and why increasingly modular forms are adopted. Recent work on product and organizational modularity, however, has begun to tackle this question in an effort to

*Defeating adaptive adversaries requires flexible, modular and deployable joint forces with the ability to combine the strengths of individual Services, combatant commands, other government agencies and multinational partners…. Adaptive organizations must be more modular and support rapid reconfiguration of joint capabilities for specific missions. Modular forces build on the core competencies of each Service component while enhancing the strength of joint operations.*

—National Military Strategy, 2004

*The U.S.-led force consists of capabilities-based, expeditionary, networked, modular, adaptive force packages.*

—Major Combat Operations Joint Operating Concept, September 2004

*Future expeditionary joint forces must be modular in design so they can be quickly tailored to meet a wide range of contingencies.*

—Force Application Functional Concept, February 2004

*The command and control structure must be modular and tailorable in order to fit with a variety of organizations across the range of military operations.*

—Functional Concept for Battlespace Awareness, December 2003

**FIGURE 1.**
EVIDENCE OF PUSH FOR INCREASING MODULARITY IN FORCE DEVELOPMENT

understand when modular products or organizations will outperform their more tightly integrated counterparts.[5] This article applies constructs and models developed in the study of organizational modularity to explain the adoption of increasingly modular organizational designs in the U.S. military, and offer some implications of this work for force development, future concept development and experimentation, and acquisition.

## MODULARITY

Modularity can increase exponentially the number of possible task organization configurations achievable from a given set of requirements and capabilities, greatly increasing the flexibility of a military force. Modularity is a general systems concept: it is a continuum describing the *degree to which a system can be separated and recombined*, and it refers to both the tightness of coupling between elements and the degree to which the *rules* of the system enable (or prohibit) the mixing and matching of components' capabilities.[6]

It is possible to view almost all entities—social, biological, technological, or otherwise—as hierarchically nested systems, meaning that at any unit of analysis, the entity is a system of capabilities and each of those capabilities is, in turn, a system of finer capabilities until we reach some point at which the capabilities are *elementary particles*, or science constrains our decomposition.[7] The continuum from large joint and multinational organizational systems (e.g., combatant or coalition commands) to the single individual (e.g., soldier, sailor, airman, or Marine) as a stand-alone module is indeed a wide one.

Furthermore, we can distinguish between a system capability and the context within which it exists; if the system capability is a solution to a problem, the context is what defines the problem. It might include the physical environment, inputs that eventually become a part of the system, or even a point in time—anything that places demands upon the system.[8] The identity of any element as system capability or context is not fixed; the level of analysis we choose determines this identity. For example, what the Department of Defense (DoD) refers to as a standing joint force headquarters "core element" (SJFHQ-CE) can be perceived as a system within a context of a wider multinational and/or interagency task organization.[9] If we move in the other direction, we can deconstruct the SJFHQ-CE to discover it actually comprises predominantly single-Service-department acquired and trained people, single-Service-procured equipment, and so forth.

Many complex systems adapt or evolve, shifting in the pursuit of better fitness in response to changes in their context or underlying capabilities.[10] Often, however, a system will not achieve an *optimal* fit with its context. First, *inertia* prevents a system from being perfectly responsive to shifts in its context. Biological organisms may be incapable of purposeful change, and evolution through variation, selection, and retention requires many generations to achieve; organizations and other social systems tend to resist change even when the environment provides strong pressure; and before we can change socio-technological systems, we must often first fumble around in search of better solutions. Although systems respond to fit their context, they may do so slowly and clumsily.

Finally, it is also important to recognize that as a system shifts in response to its context, it may also change its context in significant ways. For example, a new non-state actor (such as the terror network Al-Qaeda) might create new potential inputs as a by-product of its adaptation, or it might alter the nature of demands upon the system by creating new competitive dynamics among systems—the system and its context coevolve.[11] Such change in context may be the unintentional result of the system's response to its context or the deliberate result of purposeful behavior.

The primary goal of deliberately increasing modularity is to enable heterogeneous inputs to the system to be translated into a variety of heterogeneous capability configurations. Therefore, whether a system responds to a shift in its context (by becoming more modular) is a function of both the degree to which the elements of the system are separable and the pressure to be able to produce multiple configurations from diverse potential inputs. What will be lost by separating the capabilities? Will the ability to produce multiple configurations increase the system's fitness? We address both questions in turn to develop a model of modularity at the general systems level.

## SEPARABILITY OF COMPONENT CAPABILITIES

The components of almost all systems are ultimately separable, though much may be lost through their separation. We may disassemble products, split apart social institutions, and even cut apart biological organisms. Some of these systems (e.g., computer systems) readily permit recombination of the separated modules and will continue to function in desirable ways, while others (e.g., most biological organisms) do not so readily permit recombination. Systems are said to have a high degree of modularity when their capabilities can be disaggregated and recombined into new configurations, possibly substituting new capabilities into the configuration, with little loss of functionality.[12] The capabilities of such systems are relatively independent of one another; if they are compatible with the overall system architecture, they may be recombined easily with one another.

However, even in systems in which recombination is possible, there may be some combinations of components that work better together than others. The degree to which a system achieves greater functionality through the specificity of its components to one another is referred to as *synergistic specificity*—the combination of components achieves *synergy* through *specificity* (i.e., a uniquely interdependent functionality) to a

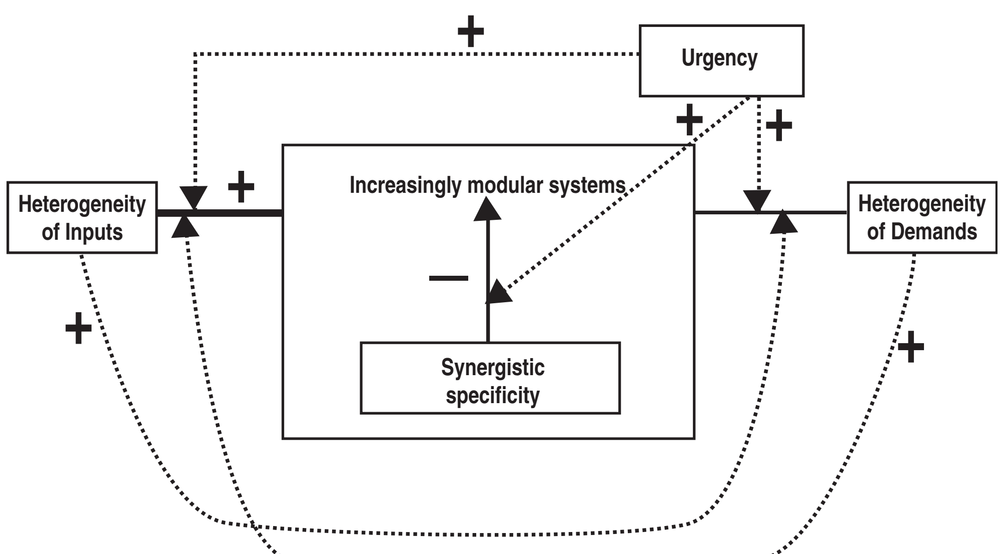


**FIGURE 2.** MODULAR SYSTEMS

particular configuration. Systems with a high degree of synergistic specificity may be able to accomplish things that more modular systems cannot; they do so, however, by forfeiting a degree of *recombinability*. The system capabilities may be so interdependent that any change in one may require extensive compensating changes in others in order that integrated functionality not be lost.[13] High levels of synergistic specificity act as a strong force against the system's shifting to a more modular design. For example, a commander of a Marine Air-Ground Task Force (MAGTF) that habitually trains and fights together, objects to a joint-force air component commander taking away his air element for other missions outside the MAGTF.

The degree to which a system is separable is a continuum. Some systems are relatively inseparable (though very few are perfectly inseparable); whereas other systems may be decomposed easily with no loss of performance. *Separability*, influenced primarily by the degree of synergistic specificity characterizing the system, will be one of the strongest factors influencing whether a system will respond to pressures to become more modular.

### HETEROGENEITY OF INPUTS AND DEMANDS

When will the ability to produce multiple configurations increase the system's fitness? The answer is already revealed in the action of modularity, when there are heterogeneous inputs and heterogeneous demands placed upon the system. The more heterogeneous the inputs used to compose a system, the more possible configurations are attainable through the recombinability enabled by modularity. Furthermore, the more heterogeneous the demands made of the system, the more valued such recombinability becomes.

### INERTIA AND URGENCY

There is one more element we must consider, even at this very general level of abstraction. As mentioned earlier, systems often exhibit *inertia*. They do not respond immediately and vigorously to every external influence. Therefore, it is possible that a system will be more or less modular than the balance of its separability, heterogeneity of inputs and demands would otherwise indicate. The degree to which a system responds to its context is influenced by pressures that create *urgency* to adapt.

## MODULARITY IN FORCE DESIGN

Forces, like other kinds of socio-technical systems, are typically *packages* of Service and coalition capabilities. For example, a multinational army division (MND) might consist of a combined headquarters; a variety of national brigade headquarters; and different sorts of functional battalions, companies, and platoons. Many of these *capabilities* are designed separately by Service/national functional force developers and then, once fielded, are task-organized by the designated MND commander. The functional battalions, in turn, are packages of many other diversified entities based on equipment technologies, sub-professions of knowledge, and socio-cultural attributes that combine to accomplish the MND missions.

Since all forces are characterized by some degree of coupling (whether loose or tight) within and between Service capabilities, and very few Services have units that are completely inseparable and cannot be recombined, almost all existing force elements are to some degree modular. Some military organizational systems are *highly modular* in that they can be decomposed into a number of elements that can be mixed and matched in a variety of task organizations with little loss of functionality. The elements can connect, interact, or exchange resources (such as material or data) in some way, by adhering to standing operating procedures or other common coordination technologies. Unlike a tightly integrated force (such as an M1A1 tank and its crew), where each element is designed to work specifically—and often exclusively—with other particular elements in a *tightly coupled* system, modular-designed units are systems of elements that are more *loosely coupled* (such as an Air Force composite wing that has a diversity of capabilities that can be mixed and matched).

***Military systems can be made increasingly modular by both expanding the range of compatible elements (increasing the range of possible configurations) and uncoupling integrated functions within elements (making the system modular at a finer level).***

Military systems can be made increasingly modular by both expanding the range of compatible elements (increasing the range of possible configurations) and uncoupling integrated functions within elements (making the system modular at a finer level). Should a commander prefer to combine the Service/national-specific element with other Service/national elements, the originating Service might eventually adopt a standard input-output protocol (i.e., a standardized interface) that makes the element compatible with other Service/national elements, thus employing *joint/combined force modularity*. If pressure continues for even greater flexibility, the joint/combined force commander might uncouple many of the functions of the core system, and begin to detach them as modular elements that may then be combined in a greater number of task organizations with both the Service capability and other Service or multinational capabilities. In each of these stages, the task organization has become increasingly modular. For example, a U.S. Army armored brigade combat team can be attached to a U.S. Marine expeditionary force to create a heavier ground maneuver element, or a French light armored division can be attached to a U.S. Corps, as occurred in the 1991 Gulf War.

Service elements are typically developed in a way that employs modularity within the Service, but does not extend the modularity to the joint/combined force commander. For instance, departments design their elements so that particular personnel can be reassigned in a variety of elements, thereby employing *economies of substitution*. Different elements might be included in multiple unit configurations, but the provision of forces themselves do not allow for joint/combined commander discretion over internal configurations.

Modularity within the design of military elements not only enables economies in design, but may also greatly simplify coordination. If born-joint systems must be tightly integrated and optimized for each other, systems development often requires that all Services be involved in such design and fielding and must work in close contact. A modular design, in contrast, can enable the task organization process to be decentralized. A Service that creates a well-defined *joint interface* can allow the Services working on particular elements to operate in whatever departmental configuration they deem most desirable (even if that means that the departments design the configurations with high autonomy) and still be assured that the elements will interact effectively with other Services' elements.

There are a number of advantages and disadvantages to employing increasingly modular designs, and the most-cited advantage is modularity's ability to greatly increase flexibility in the task organization by allowing a variety of possible configurations. Modular organization can give commanders greater discretion over the function and scale of the desired task organization, enabling them to choose building-block capabilities more closely suited to their unique mission needs. In the case of joint or multinational force modularity, such organization also enables commanders to use elements from a variety of different Services or nations, rather than be locked in to a single Service or nation.

By applying the general modular systems framework developed earlier in the article to the specific case of modularity in military elements, we can simultaneously gain a deeper understanding of modularity as a general systems concept and explain why the dominant design of a system should migrate toward or away from increasing modularity.

## SYNERGISTIC SPECIFICITY IN FORCE CAPABILITIES.

Integrated forces can achieve synergistic specificity both in the obvious way, through providing greater functionality by optimizing capable elements to work together, and in not-so-obvious ways, through providing greater confidence that capabilities will work well together and obviating the need for commanders to task-organize them.

Some forces may work better if designers optimize particular sets of other like-Service capabilities. This is often argued to be the case for special operations forces (SOFs), and it might explain the migration from many independent SOF Service elements to jointly integrated SOF packages, even though joint SOF elements are not as easily transferable for conventional force commanders. Furthermore, more recent pressures for compatibility between SOF and conventional forces pressured commanders to consider a greater degree of integration, further encouraging forces to become more homogeneous. At the same time that SOFs are pressured to become less differentiated, there is growing demand to make existing Service SOF-differentiated elements work better together (hence the creation of U.S. Joint Special Operations Command). Through such integration and specificity, the SOF community is yielding much greater capability.

If it is difficult for a commander to choose appropriate elements or to task-organize those elements into the proper effects-based configuration, then a non-modular force structure may offer the commander additional functionality by eliminating selection and task organization responsibilities—he or she would ask for an integrated unit rather than a modular capability. For commanders to choose blocks of capability of a modular system, they must be willing and able to distinguish among the performance, quality, and value attributes of different capabilities, which frequently calls for great understanding of how the capabilities work individually and interactively. For simpler elements or those products where quality and performance are easily measured and the interaction among capabilities is well understood, commanders may have great confidence in their own ability to choose among elements. However, where quality or performance is difficult to assess, they may be more likely to rely on a Service or national expert to choose capabilities.

***Even in choosing among given Service or national capabilities, commanders may vary in their degree of knowledge and motivation.***

Even in choosing among given Service or national capabilities, commanders may vary in their degree of knowledge and motivation. For example, although the average commander might request non-modular, single-Service or national units (using reputation and limited socio-technical information to assess overall system quality), more sophisticated commanders would select more modularized elements of capability individually from multiple Services or nations to task-organize a system that more closely matches their mission performance requirements.

Where element capability quality is difficult to assess or uncertain, commanders may choose packaged or pre-integrated units that are believed to provide an acceptable quality across elements, but lack a visibly high granularity of capability functionality.

The development of *standardized interfaces* (e.g., blue force tracking, “identification friend or foe,” linking technologies) can enable greater modularity in forces while preserving their functionality or ease of task organization. Standardized interfaces facilitate the mixing and matching of force elements to ensure that they will work well together. Without such standardized interfaces, Services might be able to provide elements that could be mixed and matched with other Services’ elements by developing specialized interfaces that coordinate the capabilities among particular elements; however, the costs of developing such specialized interfaces are high, and the choice among configurations would be confined to those options predetermined by the Services that had produced the interfaces.

## HETEROGENEITY OF INPUTS AND DEMANDS

The inputs into a force development system include both the technological options available to achieve particular functions and the resources and capabilities of the Services/nations involved in the development process. Heterogeneity in these inputs will increase the value obtained through modular force configurations.

When there are diverse technological options available to be incorporated into a task organization, modular force designs will be more attractive to both commanders and developers. For example, such a diversity of options might compel force developers and acquisition professionals to seek more flexible solutions because being tied to a single commercial source is less attractive. First, the number of available product configurations achievable through modularity is a direct function of the number of available technological capabilities from which the Services may choose. A wider range of modular capabilities quickly multiplies a developer's product configuration options, greatly increasing the gains from modularity. Second, commitment to a single, integrated product system imposes an opportunity cost equivalent to the next best option available. When many different options are available, this opportunity cost is likely to be higher because the next best solution is likely to be better than a situation when there are few options available. Third, when there is great diversity in available technologies, the developer faces more ambiguity about the best option; when there is little diversity in the technological options, developers sacrifice less by being committed to a single vendor, and they face less uncertainty about their technology choice.

***When there are diverse technological options available to be incorporated into a task organization, modular force designs will be more attractive to both commanders and developers.***

Diversity in the available technological options also makes modularity more attractive to the defense industry. It is usually difficult and costly for an industry to support multiple technologies.[14] Very often, defense industries must choose one or two technology designs, gambling on those they believe to be best matches for (1) their capabilities and/or (2) Service requirements. As with Service force developers, a large number of diverse options can increase industry's ambiguity about which technology to support. Furthermore, if the various technologies are incompatible (and products based on the technologies are, therefore, only offered as integrated systems), the industry might face a win-or-lose scenario by it either becoming a Service sole supplier of an entire product system, or it does no business at all with the Service.

Under conditions of technical modularity, the defense industry does not face such a win-or-lose scenario. Modularity enables compatibility between disparate technologies, lowering the risk to a company that is gambling on a particular technology. Multiple technologies can coexist more peacefully. The company does not have to compete for a Service's business for an entire system; it can compete for a particular capability, focusing on a technology in which it excels, allowing other vendors to supply other technologies. This is a key advantage to defense procurement policy—focusing on technological modularity rather than on proprietary acquisitions.

U.S. armed forces and potential coalition militaries have individual sets of core capabilities that distinguish them from others. Forces often are made up of capabilities that draw from different underlying technologies, deployment and employment requirements, or other required skill sets. Because Services have different capabilities, a given Service may have a set of capabilities that put it at a performance or cost advantage in producing some force elements, while putting it at a disadvantage in producing others. Diversity in the technological options available and differentiation in military capabilities will reinforce each other. The more differentiated military capabilities are, the more likely Services/nations will be to produce disparate force module options; likewise, the more options available to Services/nations, the more likely they will be to specialize in different things.

***Diversity in the technological options available and differentiation in military capabilities will reinforce each other.***

Furthermore, when technological options and differentiation increase, they can spark a mutually-reinforcing process that propels force design even further down a modularity trajectory. First, the more different the sets of skills are among Services/nations and their subcomponents, the more attractive modularity becomes, because it enables disparate capabilities to be combined. Second, the use of modular force designs enables Services/nations to further specialize, encouraging them to pursue unique learning curves and increasing their differentiation from other Services/nations and potential adversaries. Thus differentiation leads to increasing modularity, and increasing modularity leads to even greater differentiation (see Figure 3).

Mission heterogeneity (i.e., "full spectrum operations") is an important factor that influences whether force design will migrate toward increasing or decreasing modularity. When most joint commands desire roughly the same types of capabilities, and their requirements for each individual capability are comparable, a Service is able to produce a force structure that is close to optimal for the majority of commands.

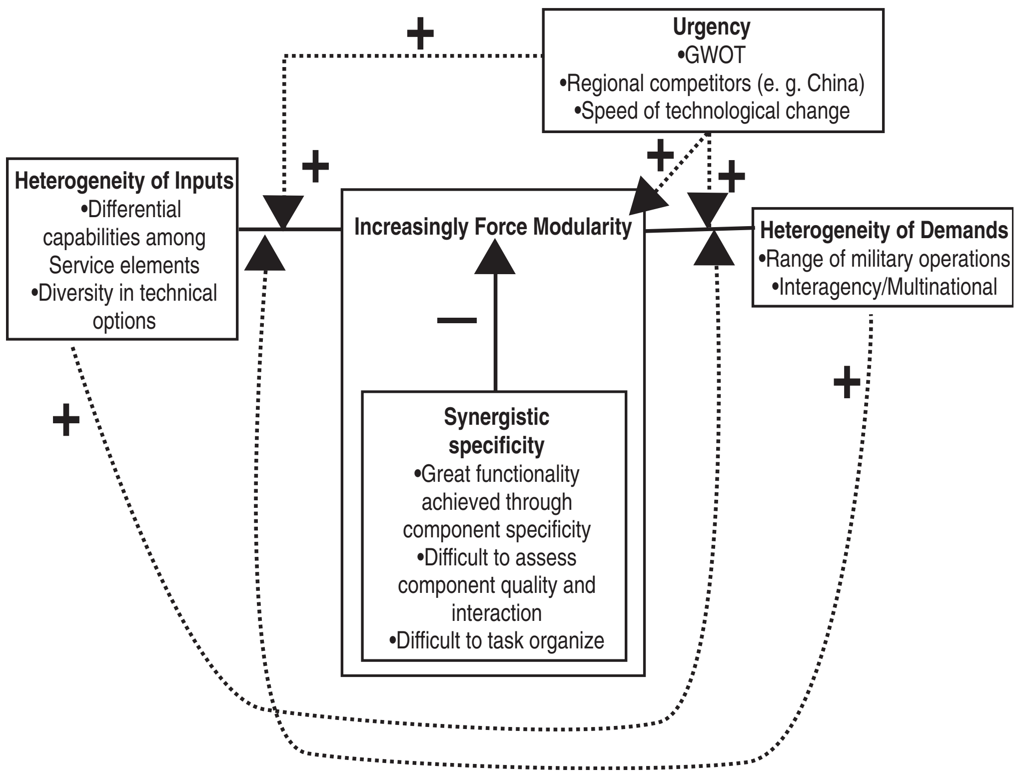


**FIGURE 3.** FACTORS INFLUENCING THE MITIGATION TOWARD (OR AWAY FROM) INCREASING FORCE MODULARITY

Through integrating force design, the Service may be able to create performance or cost advantages that outweigh the sacrifices regional commanders will make in not being able to choose uniquely capable subcomponents.

Alternatively, when commanders for particular mission solutions have very different needs, it is more difficult for a single integrated Service or joint solution to closely match their idiosyncratic requirements. Consider the differences in regional combatant commands and the types of operations underway or expected (e.g., major combat operations followed by or simultaneous with small unit actions, natural disaster relief efforts, supporting homeland security, etc.). Combatant commanders naturally have heterogeneous preferences for the type of capability they wish to have and for how and in what battlespace the capabilities will be deployed and employed. Until recently, regional Service capabilities were highly fragmented in terms of design according to regional needs (e.g., a U.S. infantry division in Korea was very different from the one stationed in Europe). The end result was a high-quality system of forces that had unique capabilities.

With the advent of larger global requirements and a relatively steady total force capability, any force will need to be redesigned to be capable of redeployment to another region; hence, there is more pressure to standardize capabilities to globalize force management. A future return to regional focus with decreasing heterogeneity of demands and inputs will have reinforcing effects upon each other; hence, force design would return to more nonstandard capabilities.

## URGENCY IN MILITARY CONTEXT

Speed of technological change and competitive intensity are among the primary factors that create urgency in the context of force development and systems acquisition. Such factors increase the likelihood of the system's responding to pressures to become more modular. Alternatively, when there is low urgency in the context, or when a region (or group of regions) is so powerful that it experiences less urgency, the system may be pushed (or retained) at a point on a trajectory that seems a poor fit with the balance of the demands of its context and the synergistic specificity of the system. For example, Services might wish to prevent the adoption of modular force designs because modularity would decrease their common use or structural design control.

One of the major factors increasing the pressure to migrate toward modular force solutions is the speed of technological change. Where technology advances rapidly, commanders and Services require flexibility to respond to the rapidly changing inputs and demands. High-speed technological change can increase the rate at which new and heterogeneous inputs proliferate and, by rapidly expanding the scope of possibilities for commanders, nurture the rapid evolution of differing demands. Because the force design must be able to adapt quickly to fulfill changing demands (or to incorporate changing inputs), a modular solution becomes very attractive. For commanders, modularity reduces switching costs and enables them to upgrade a particular capability without replacing the entire system.

Modularity also can impact the price Services pay for technology. In an industrial base characterized by product design modularity, defense contractors might benefit by increased specialization. Consider first the opposite scenario. A firm that produces all the capabilities of a system faces greater fixed and variable costs: it must have the equipment required to produce a variety of capabilities, not all of which will be based on the same manufacturing technologies; it might have to employ more people to ensure a wider range of available skills; it will likely have higher inventory costs because it must hold a wider range of raw materials and end products; and it might face greater setup costs to vary production.

Furthermore, technological modularity can increase competition among capability providers, because it lowers both Service switching costs and entry barriers by enabling competitors who only produce one or a few capabilities (but not the entire system) to compete for defense contracts. This can result in greater pressure on firm profit margins and lower costs for Services.

Modular technical systems offer an attractive quality. By encapsulating proprietary technology within a capability that conforms to an open standards-based architecture, Services can reap the advantages of *jointness* (and perhaps *multinational-ness* with international standards) with a wide range of complementary capabilities, while still retaining the force generating potential of their Service-unique capability. Networkcentric capability can increase the pressure in favor of modular systems so that capabilities can be more easily *networked*.

## CONCLUSION

In conclusion, the model of force modularity has immediate implications for force management and defense acquisition policy. The ability to predict and explain a military force system's migration toward increasing or decreasing modularity should prove very valuable to force developers.

There is much left to be done before we can have great faith in the model's ability to explain the integration and disaggregation of different kinds of systems. Such issues as how to aggregate force readiness reporting and how to create inter-module *swift trust*[15] are key challenges. However, if future concept development and experimentation refines and validates the model, we will have a powerful tool for understanding the nature of force modularity. Even if the model fails under future scrutiny, but in the process spurs the development of better models that can achieve such a task, it will have served a useful purpose.

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