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Function propagation through nested systems

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Abstract: *Concepts of function are central to design but statements about a device's functions can be interpreted in different ways. This raises problems for researchers trying to clarify the foundations of design theory and for those developing design support-tools that can represent and reason about function. By showing how functions relate systems to their sub-systems and super-systems, this article illustrates some limitations of existing function terminology and some problems with existing function statements. To address these issues, a system-relative function terminology is introduced. This is used to demonstrate that systems function not only with respect to their most local super-system, but also with respect to their more global super-systems.*

Keywords: design model; design theory; engineering design; industrial design; philosophy of design

Concepts of function are important for the study and practice of design. For example, it is common to hear statements such as "the function of a motor is to convert electrical energy to rotational energy" or "the function of a corkscrew is to extract corks from bottles". More generally, these statements are of the form "the function of *X* is *Y*", by which it is variously meant that *X* is intended to *Y*, is used to *Y*, has been selected to *Y*, and so on.[1] Such statements are important for developing and analysing the components and products at which they are aimed, whether those objects exist or are only imagined. Function assignments are thus central to design research, to design tool development and to design activities themselves (Winsor & MacCallum, 1994). Despite this key role in design, the word 'function' means different things to different people, and can mean different things to the same person depending on context. So, function is at once intuitive and important, but is also either vague or overloaded (for recent commentaries, see Erden, Komoto, Van Beek, D'Amelio, Echavarria, & Tomiyama, 2008; van der Vegte, Horváth, & Mandorli, 2011; for evidence from design practice, see Eckert, Alink, Ruckpaul, & Albers, 2011).

Ambiguity surrounding function statements leads to difficulties in formally describing or modelling function. This problem has attracted attention in two distinct areas of design research that both seek a clear ontology for design. On the one hand, philosophers of design are concerned by the confusion surrounding function concepts and by the disconnect with other domains of function theory (e.g. Galle, 2009; Houkes & Vermaas, 2010; Kroes 2010a, b). On the other hand, design methodologists note that inconsistency with function hinders efforts to develop technologies (such as CAD systems) that can represent and reason about the function of a device rather than just its geometry (e.g. Umeda & Tomiyama, 1997: p. 43; also see Chakrabarti, Shea, Stone, Cagan, Campbell, Hernandez, & Wood, 2011). With such challenges and opportunities in mind, my aim here is to explore and clarify what function statements involve. This is with a view to contributing to philosophical work in this area, whilst also recognising that such work may in turn contribute to those areas in which the representation of function has practical consequences for design practice.

Efforts to clarify or elaborate the meaning of function has led function theorists to acknowledge that it describes at least two different concepts. These concepts are commonly referred to as *device-centric functions*, focussing on the internal behaviour of the device, and *environment-centric functions*, focussing on the external effects that a device has on the things around it (Chandrasekaran & Josephson, 2000). The device-environment distinction clearly separates one type of function statement from another, and also indicates how different perspectives on the same device may lead to different functions being assigned to it. What is less clear is how a device's functions should be defined when that device (internally) has components within components and when it (externally) affects environments which in turn affect their own environments. This view of devices actually represents the general case, and so it is important to be able to account for it in our definitions and representations of function. Such matters are at the heart of this article, matters which I seek to clarify by exploring and illustrating the system-relativity of functions.

Considering the relationship between functions, components and environments is not new; it is a long-standing feature of the literature on systematic design methods. This can be seen in descriptions of functional decomposition and system composition. In such processes, designers (i) identify an overall function that the system must perform, (ii) decompose that overall function into sub-functions that can be arranged in various function structures, (iii) assign physical components to perform the sub-functions, and (iv) structure those components to compose the overall system (Hubka, 1982; Pahl & Beitz, 1984; Hubka, Andreasen, & Eder, 1988). This process can be represented with a pair of matched hierarchies (see Figure 1): there is an overall function which branches into ever finer-grained sub-functions (the function hierarchy); these sub-functions directly correspond with a set of physical sub-systems which combine into ever larger sub-systems (the physical hierarchy) until a single overall system results (Umeda and Tomiyama, 1997: p. 43; also see Chakrabarti & Bligh, 2001: p. 497). Satisfying each sub-function can be viewed as the means by which the function above it (the ends) is achieved, which in turn, is the means by which the function above *it* is achieved (Dym & Brown, 2012: p. 35; see Pahl and Beitz, 1984: pp. 9-15 for a review of early function-led engineering design approaches, including those by Roth ,1968, Rodenacker ,1970, and Koller ,1973; for a recent philosophical analysis see van Eck, 2011).

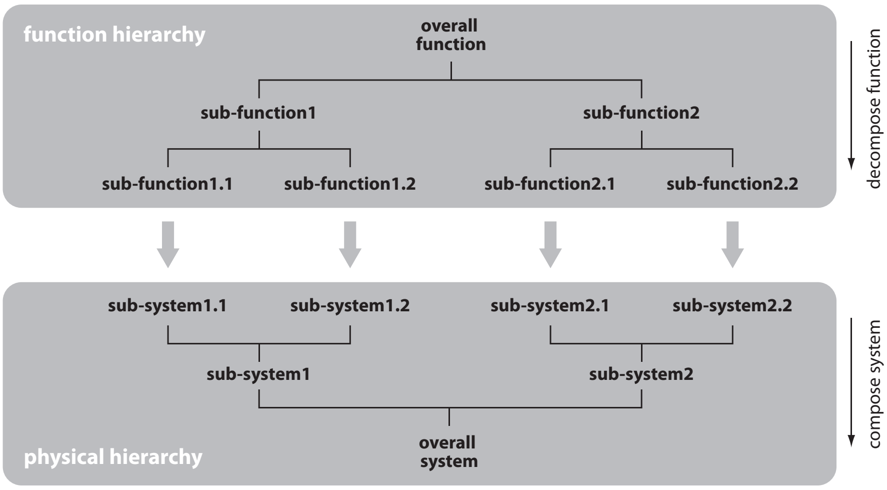


Figure 1. Representation of the processes of functional decomposition and system composition. Adapted from (Umeda & Tomiyama, 1997).

Processes of functional decomposition and of physical composition both involve thinking about the parts that wholes are made up of (and vice versa). Part-whole relations are also the concern of this article, but the objective is different. Rather than prescribing that design should proceed by breaking whole functions into parts and by combining physical parts into wholes, I aim to show instead how the relativity of parts and wholes means that parts have many wholes and therefore many functions. To assist in making this argument, a new function terminology is introduced, one that is system-relative and flexibly applicable across hierarchies of components and hierarchies of environments. However, even with this terminology in place, the relationships between functions and systems can be difficult to comprehend without a visual reference. Many different kinds of function diagrams are already in use (e.g. Pahl & Beitz, 1984; Umeda and Tomiyama, 1997; Chakrabarti & Bligh, 2001; Deng, 2002; Van Wie, Bryant, Bohm, McAdams, & Stone, 2005), including those that associate functions with systems (e.g. see Erens & Verhulst, 1997: p. 175; Kirschman & Fadel, 1998; Szykman, Racz, & Sriram, 1999; Ulrich, 2011: pp. 72-73). Unfortunately, none of these relate functions to multiple levels of a systems hierarchy and so an alternative method of diagramming is used here, a method that has some precedent in the work of Freeman and Newell (1971: p. 624).[2]

This article is structured so as to introduce the necessary concepts, terms and diagrams as the argument progresses. First, I review the distinction between function as the behaviour of a device and function as that device's effect on the environment (section 1). By considering that components also have components and that environments also have environments (i.e. that systems can be 'nested'), I then argue that any given function can be described either in terms of a device's internal behaviour or its external effect (section 2). This observation leads away from the device-environment distinction, and towards a function terminology that explicitly refers to a functioning system's sub-systems and super-systems (section 3). Next I examine the potential to assign a system with functions that relate to each of its many super-systems (i.e. the potential for functions to 'propagate' through layers of nested systems). This is used to resolve an apparent conflict in previously unconnected arguments from different fields (Section 4). Having established that multiple super-systems contribute to the assignment of a system's functions, the determining properties of those super-systems are then considered, including their capacities and the users they contain (section 5). In concluding the article, I review the advantages of a system-relative perspective on function and illustrate three propositions for how function statements should be constructed (section 6).

1. Functions, devices and environments

The central yet problematic position of 'function' in design has led to various attempts to unpick its definitions and to offer guidance as to the different senses in which the term is used (e.g. Vermaas & Dorst, 2006; Galle, 2009, Crilly, 2010). Although function terminology is varied, functions are most often discussed with respect to a relatively small group of common themes. For example, Chandrasekaran and Josephson (2000: p. 170) say that "all meanings [of function] arise from the idea of a machine, system or person *doing* something or having a property that is *intended* or *desired* by someone". Similarly, Vermaas (2009: p. 118) says that different types of functional descriptions "capture the role a device should play in its environment for the agent when the agent is using the device". Saying that function statements describe the role a device *should* play is compatible with many different definitions of function, including those that emphasise the roles that the device was intended to play, is used to play, has been selected for playing, and so on (see recent summaries in Preston, 2009; Houkes & Vermaas, 2010).

Even if functions are defined by normative statements about role playing, there are still different types of function. Two are especially common in the literature: function as the internal actions that a should device should perform, and function as the effects that the device should have on its environment. Using function in one or other of these ways has precedent in the earliest works of design theory (see review in Winsor & MacCallum, 1994: pp. 166-167). More recently, many variants of this conceptual distinction have been proposed, including *function-as-intended-behaviour* and *function-as-abstract-purpose* (Chakrabrati, 1998), *device-centric functions* and *environment-centric functions* (Chandrasekaran & Josephson, 2000), *action functions* and *purpose functions* (Deng, 2002), and *internal functions* and *external functions* (Gzara, Rieu, & Tollenaere, 2003). Such continued attention to distinguishing internal actions from external effects indicates how useful this is for making sense of functions while also explaining much of the diversity of function concepts.

Perhaps the most influential action-effect distinction has been Chandrasekaran and Josephson's (2000) device-centric functions and environment-centric functions, which they introduce in their article on 'Function in device representation':

> "a device is used because someone desired that something desirable happen *outside* the device. Thus, a central meaning of function is *function as* (*desired*) *effect*. However, functions are also often described in terms of the device's properties or behaviour, without any explicit mention of what the device might help achieve in the world outside it. Thus, functions can be described from a *device-centric* or an *environment-centric* viewpoint, or even in a mixture of the two viewpoints." (p. 170)

Although not formally defined, from Chandrasekaran and Josephson's examples it is clear that device-centric functions refer to the device's behaviour, stated "in terms of variables associated with specific structural elements". In contrast, environment-centric functions refer to the device's effect on the environment, stated "entirely in terms of elements external to the device." In connecting device-centric functions with environment-centric functions, Chandrasekaran (2005) explains that the former are the means by which the latter are achieved. Erden et al. (2008) extend this to show how the performance of device-centric functions permits the performance of environment-centric functions which in turn satisfy people's needs.

Chandrasekaran and Josephson's device-environment distinction has proven to be extremely popular in the function literature, presumably because it so neatly relates two common meanings of function (e.g. see discussions in Brown & Blessing, 2005; Erden et al., 2008; Borgo, Carrara, Garbacz, & Vermaas, 2009; Kitamura & Mizoguchi, 2009; Vermaas, 2009; Kroes, 2010b). Especially useful for this article is the example of the pen that Vermaas (2009: p. 115) develops from Brown and Blessing's (2005) work. Employing the device-environment distinction, Vermaas says that a device-centric description is that "the function of the pen is to cause ink to flow out of its ink container and onto the tip" (see Figure 2a). Environment-centric descriptions are that "the pen's function is to cause a piece of paper to have ink on it" (see Figure 2b) or "to communicate information" (see Figure 2c). This example illustrates the similarity between the device-environment distinction, and the distinction that Gero and colleagues draw between the behaviour of a device and its function (Gero, 1990; Rosenman & Gero, 1998; Gero & Kannengiesser, 2004).

2. Nested systems

In the above discussion of the pen, the device is assumed to be located in an environment, and both the device and the environment are assumed to have components. We could thus say that the device is an environment to its components, and that it is also a component of its own environment. Going further, we could say that the device's local environment is contained within another more global environment, and thus that the local environment is a component of the more global environment, and so on. This suggests a set of 'nested' objects, each of which can either be viewed as components, devices or environments depending on the perspective we adopt. Because of this, it is productive to simply reclassify components, devices and environments as 'systems', where a system is defined as a set of interacting elements that work together as a whole (for a review of definitions see Skyttner, 2005, pp. 57-58; Veeke, Ottjes, & Lodewijks, 2008: p. 9). In a systems hierarchy, the systems are nested within each other; each system is a sub-system of the systems that contain it, and a super-system of the systems that it contains (see Simon, 1962; Savageau, 1976: p. 80; Hughes, 1987: p. 54; Kroes, Franssen, van de Poel, & Ottens, 2006).[3] Although systems can be physically nested within each other (e.g. where ink *is located* inside a container), the emphasis in this article is on conceptual nesting (e.g. where the container is seen to be *part of* the pen but the ink is *not part* of the container).

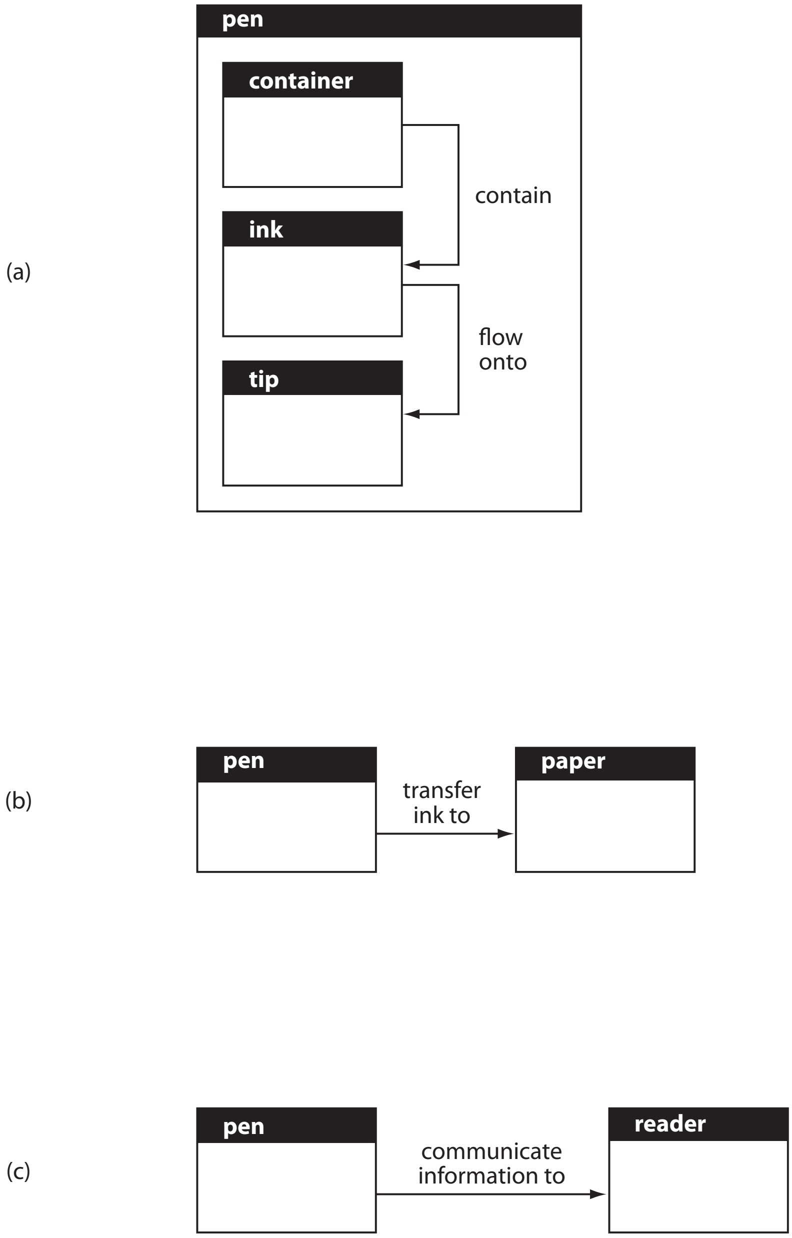


Figure 2. Representations of the three functions that Vermaas (2009) assigns to the pen: (a) the device-centric function of causing ink to flow out of the ink container and onto the tip; (b) the environment-centric function of causing a piece of paper to have ink on it; (c) the environment-centric function of communicating information. The functional role that each system plays with respect to another system is indicated with labelled arrows. The arrangement of the systems within each other is significant (as it indicates sub/super-system relationships), but the relative position of systems at the same level of hierarchy is not significant (the boxes could equally be arranged one-above-the-other or side-to-side).

Whilst distinct physical objects can be usefully considered as systems, systems need not actually exist 'in the world' but can instead just be a way to organise our thoughts about that world (Skyttner, 2005: p. 57). Consequently, we might define a system boundary[4] to be coincident with a physical boundary (such as the perimeter of a room), but that is a choice rather than a requirement; non-physical systems such as codes and institutions can also be considered (but see Vermaas, Kroes, van de Poel, Franssen, & Houkes, 2011: p. 80). A focus on systems, rather than on components, devices and environments, emphasises that the objects we are interested in are defined by their relationship to other objects rather than by some innate characteristics. Considering things in this way prevents us from having to view an entity as being a device at one moment and then as a component or environment at another. At most scales of interest, systems are always sub-systems to their super-systems and are also super-systems to their sub-systems. This only has limits at very small and very large scales where no further sub- or super-systems are perceived or relevant (Ropohl, 1999: §2.2).

Recalling Vermaas's example of the pen, we can observe that the pen is a system that comprises a number of sub-systems, such as the ink container, the ink and the tip. If the pen is (temporarily) treated as the device, then its device-centric function is "to cause ink to flow out of its ink container and onto the tip", a function that is performed entirely by the pen's sub-systems and within the pen's system boundary. To consider the environment-centric functions of the pen we must look beyond the pen's system boundary, to see what opportunities there are for the pen to affect components of its super-system, a super-system which is (temporarily) treated as the 'environment'. For the pen to be used conventionally, this super-system must minimally include the pen itself, a writer to use the pen, and some paper to write on. With these systems in place, the pen can perform its first environment-centric function: "to cause a piece of paper to have ink on it" (see Figure 3).

If the container, ink and tip can be combined to form a pen system, then we can also combine the writer, the pen and the paper to form a writing system, a system which can in turn affect its own super-system. For communication to take place, this new super-system must include a reading system, which could be composed of a reader and a text (the inked paper). We could then consider the function of the writing system with respect to some encompassing system, such as the communication system. If the writing system is now (temporarily) treated as the 'device', then one of its device-centric functions is to transfer ink from pen to paper (pen and paper now being components of our device). This means that what was previously described as an environment-centric function of the pen is now described as a device-centric function of the writing system (for similar arguments see Roozenburg, 1998; Wood, 2009: p 545).

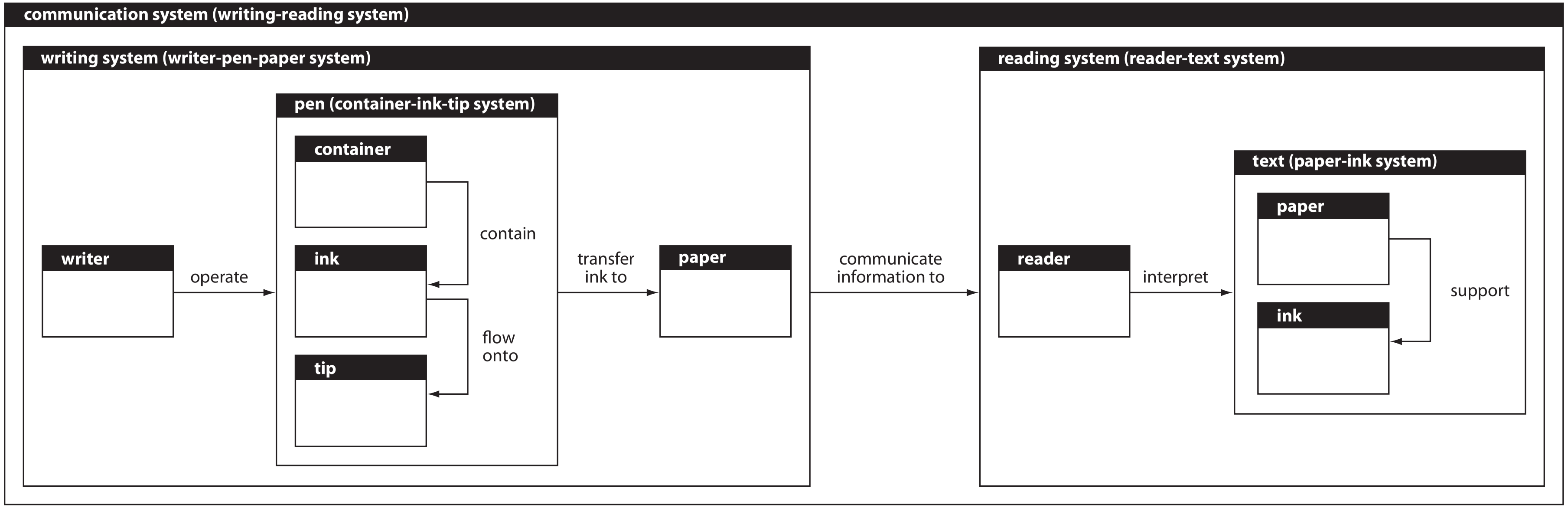


Figure 3. The pen, its sub-sytems, its super-systems and other systems. To be read (for example): "the (environment-centric) function of the *pen* is to 'transfer ink to' the *paper*".

Our progression outwards through the nest of systems can be taken further. If the writing system is now treated as the device, then its environment-centric functions must be specified in terms of the effects it has beyond its system boundary. This leads us to say that the environment-centric function of the writing system is to communicate information to the reading system. Note that the pen's second environment-centric function was "to communicate information", so it is not just that device-centric functions are the means by which environment-centric functions are performed, but also that environment-centric functions are the means by which other (more global) environment-centric functions are performed. This progression reveals that a given function can be described in device- or environment-centric terms; it just depends on what system is said to be performing that function, and what system that function is being considered with respect to.

3. Endogenous and exogenous functions

In discussing the nested systems within which the pen exists, the terms 'device' and 'environment' kept being reintroduced even though we had previously recast all these objects as 'systems'. This was because using the concepts of device-centric and environment-centric functions demanded inclusion of the devices and environments that they refer to. The reintroduction of the device-environment distinction was inconvenient because it again meant that objects which were defined as an environment in one statement had to be redefined as a component or a device in the next. Any representation of functions based on such statements would consequently be limited to the perspective from which the statements originate (e.g. the system of interest being the pen rather than the writing system, or *vice versa*). To avoid this and to permit more flexibility and precision, we should not only define components, devices and environments as systems, but also categorise functions according to how they relate those systems.

A system has both *endogenous* and *exogenous* properties. It has endogenous properties to its sub-systems, and exogenous properties to its super-systems (Skyttner, 2005: p. 67). We can extend this distinction to functions: if a system's function is described in terms of the role that its sub-systems play with respect to it then this is an *endogenous function* of the system; if a system's function is described in terms of the role that it plays in its super-system then this is an *exogenous function* of the system.[5] Although similar, there are differences between this endogenous-exogenous distinction and the traditional device-environment distinction. Recall from section 1 that device-centric functions refer to the device's "specific structural elements". These structural elements can be considered analogous to the sub-systems referred to here, and so device-centric functions are equivalent to endogenous functions. However, environment-centric functions need only refer to "elements external to the device." Although these elements are required to be outside the device they are not required to be components of a specified super-system. Exogenous function statements do require the specification of a super-system, and so environment-centric functions are not equivalent to exogenous functions (for a visual representation of the difference, compare Figures 2b & 2c with Figure 4b & 4c).[6]

Examining the example of the pen showed us how a system's (the pen's) endogenous function (causing ink to flow onto the tip) permits the performance of the system's exogenous function (causing a piece of paper to have ink on it) with respect to its super-system (the writing system). This, in turn, permits the performance of the super-system's (the writing system's) exogenous function (communicating information) with respect to its own super-system (the communication system), and so on. Connecting functions in this way is relatively straightforward. We just proceed out through a pre-defined set of nested super-systems. However, systems are only defined in analysis and there are no rules for deciding how many system boundaries should be interposed between any two nested systems. So, whether the pen is described as having the function of inking the paper or of communicating information is seemingly at the discretion of the analyst. If the super-system of the pen was considered to be the communication system directly (i.e. bypassing any writing system that might be interposed), then an exogenous function of the pen with respect to the communication system would be to communicate information. This is how the pen was previously assigned two environment-centric functions by Vermaas: first it was (implicitly) being considered with respect to a local super-system and then (again implicitly) with respect to a more global super-system (see Figure 4).

Assigning the pen an exogenous function relative to the communication system rather than to the writing system might seem odd because the pen does not communicate information all by itself. An enormous range of other systems would need to act or behave in just the right way for the pen to play a role in communicating, including the writer, the paper, the reader, and so on. However, the pen does not cause a piece of paper to have ink on it all by itself either. A large (but smaller) number of systems must support that role in just the right way in that instance too. As Vermaas (2009: p. 115) says, the functions of the pen are performed only if the writer's operations realise the correct 'mode of deployment', including that the writer is gripping the pen, that the tip is down, is in contact with the paper, is exerting pressure on the paper, and so on. The functioning of the pen might also depend on environmental conditions such as the ambient air pressure (for the ink to

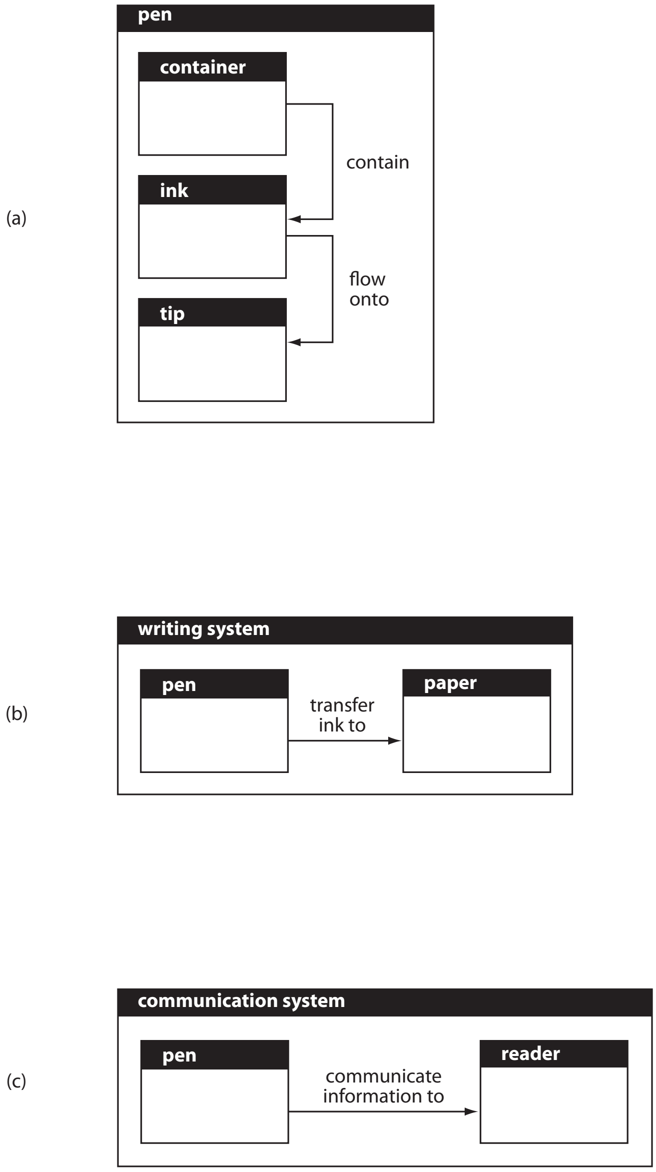


Figure 4. Representations of the three functions that Vermaas (2009) assigns to the pen, now recast as system-relative functions: (a) the endogenous function (with respect to itself) of causing ink to flow out of the ink container and onto the tip (unchanged from Figure 2); (b) the exogenous function (with respect to the writing system) of causing a piece of paper to have ink on it; (c) the exogenous function (with respect to the communication system) of communicating information.

flow) and the presence of a suitable reader (for communication to be achieved). Functions are only ever performed if the circumstances of use support or enable that performance. Those factors that are more general or more consistent are often assumed and left implicit in mode of deployment statements even though they are essential to the functioning of the device. For a function to be performed with respect to a more global super-system just requires a greater number of factors to be ‘in agreement’, but this is a change in degree rather than a change in kind.

4. Function propagation

The discussion above suggests that any given system, *X*, can be described as performing an exogenous function with respect to one of its super-systems, and also as performing all the exogenous functions that its possible super-systems perform so long as those functions all depend on the presence of *X*. This is how functions 'propagate' through a nest of super-systems, yielding multiple function statements for any given system. Functions and systems are both subjective; they are just labels that people assign to things to reflect how they think about them. Function propagation is therefore subjective also; *assigning* a function at one layer in a nest of systems leads to *making assignments* at other layers also. The term propagation is used here because it denotes transmission, progression, dissemination and inheritance, all of which describe ways in which function assignments can be considered to spread.[7]

The multiple functions implied by function propagation are different to how multiple functions are normally discussed. When engineers talk of a multi-function device, they are typically referring to that device's capacity to perform more than one type of function at the same level of hierarchy, or at the same layer in the nest. For example, the body of a car (automobile) has the functions of deflecting the flow of air around the vehicle and of resisting various structural loads (Ulrich & Seering, 1990: also see Chandrasekaran & Josephson, 1997).[8] In contrast, we are here concerned with how systems perform different functions at different levels of abstraction; that is, how they perform different functions with respect to different layers of a set of nested super-systems. The aforementioned functions of the car body are all functions it performs with respect to the car. However, we might also ask what functions the car body performs with respect to the traffic or the city or the state, all of which can be considered super-systems of the car body just like the car itself is.[9] The validity of these additional, more global, functions is considered differently in different branches of the function literature, but these considerations have not previously been connected or contrasted. They are brought together here to show the disagreement that exists and the reconciliation that is possible.

Chandrasekaran and Josephson (2000) offer their own example of functions that potentially propagate. If someone has the need, N_1, to possess some merchandise found in a shop, this need creates another need, N_2, which is to have cash; this need creates another need, N_3, which is to withdraw cash from a bank account. The functional specifications of an ATM ('automated teller machine' or 'cash machine') match N_3 exactly, so using the ATM permits satisfaction of N_3 which permits satisfaction of N_2 which permits satisfaction of N_1 (for a more extended example of a needs hierarchy see Ulrich 2011: pp. 28-30). Chandrasekaran and Josephson suggest that while we feel comfortable thinking that the satisfaction of N_3 is the ATM's function, we don't feel that it is appropriate to say that the function of the ATM is the satisfaction of N_1 (see Figure 5). This is despite the fact that the operation of ATM did contribute to this first need being satisfied. Generalising from this, Chandrasekaran and Josephson conclude that "a device is to be assigned a function at the lowest level of abstraction in the chain of needs it can satisfy" (p. 174).[10] That is, they do not support the notion of function propagation.

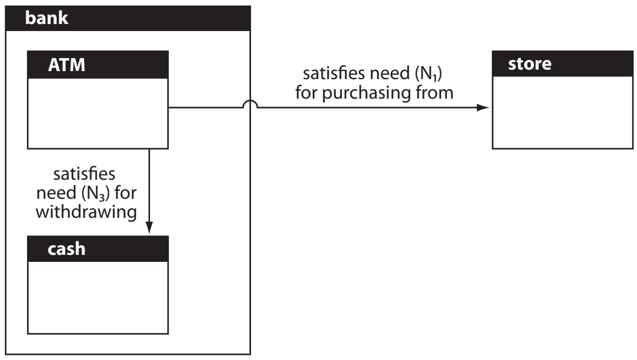


Figure 5. Two possible functions of the ATM. Chandrasekaran and Josephson (2000) argue that the most local function of the ATM (satisfying N_3) is valid but that the more distant one (satisfying N_1) is not.

Chandrasekaran and Josephson's conclusion is much more restrictive than a related argument in philosophical function theory. With reference to biological organisms, Neander (1995) provides an alternative view of how functions propagate through nested systems. As an example, she describes how, in a species of antelope, a given trait might alter the structure of haemoglobin which increases oxygen uptake which permits the antelope to survive at higher altitudes which contributes to gene replication (p. 115). Neander notes that as we move through this list of selected effects, we are describing the functions of ever larger systems: within individual *cells*, the trait alters the structure of the haemoglobin; the *circulatory system* takes up oxygen; the *animal* survives; the *species* replicates genes (p. 117). Neander argues that all of the listed downstream effects that the trait has (in its many super-systems) are all functions of the trait (also see Chakrabarti, 1998; McLaughlin, 2001: p. 55).[11] In considering such arguments, Lewens (2005: pp. 133, 158) similarly concludes that for organisms *and* artefacts there is no basis for assigning only single functions to a given system where we can distinguish different functions of the system at different levels of explanation.[12]

Almost anticipating Chandrasekaran and Josephson, Neander (1995) notes that “It might be suggested that only the lowest level describes the function of the trait in question, the others describing the functions of the super-systems of which that trait is a part” (p. 118). However, by most definitions of function (including that which Neander adopts) these other more global functions are functions of the system in question because they describe roles that the system should perform. Neander’s view clearly differs from that of Chandrasekaran and Josephson, but we can reconcile these views by distinguishing between systems for which there is a dominant analytic perspective, and systems for which multiple perspectives are possible.

In Neander’s example of the antelope species, every sub-system (e.g. animal, circulatory system, cell) exists because it contributes to the continued existence of the species. In biological examples, such evolutionary perspectives dominate, determining the functions of every functional sub-system in the species. Consequently, as we proceed outward through the nest of systems surrounding the antelope’s cells, the functions *do not* proliferate at each stage; each sub-system simply contributes to the survival, adaptation and reproduction of the antelope species. Conversely, in technical examples like Chandrasekaran and Josephson’s ATM, the system in question is not necessarily placed in the context of another system for which a clear analytic perspective dominates. This means that the functions *can proliferate* at each layer of the nest. At their level N_1, the ATM could be assigned the function of satisfying someone’s need to possess merchandise, but could also be assigned the function of satisfying someone’s need to donate money to charity or to lend money to a friend. These are all things that the ATM might usefully do as a component of a larger system like an economy and so picking only one of these roles as the function seems inappropriate (see Figure 6).

If we place the ATM within a system for which a clear analytic perspective dominates, or if we explicitly specify our analytic perspective, then we can assign the ATM functions with respect to multiple super-systems. For example, we can imagine that a private shopping mall might pay for, install and maintain an ATM within the mall. If the functions of the ATM are analysed from the perspective of the mall’s capacity to make money, then it is appropriate (by most definitions of function) to assign the ATM not only the function of satisfying someone’s need to withdraw cash from a bank account, but also of satisfying the mall owner’s need for economic exchange in the stores that comprise the mall (see Figure 7).[13] Although from some other

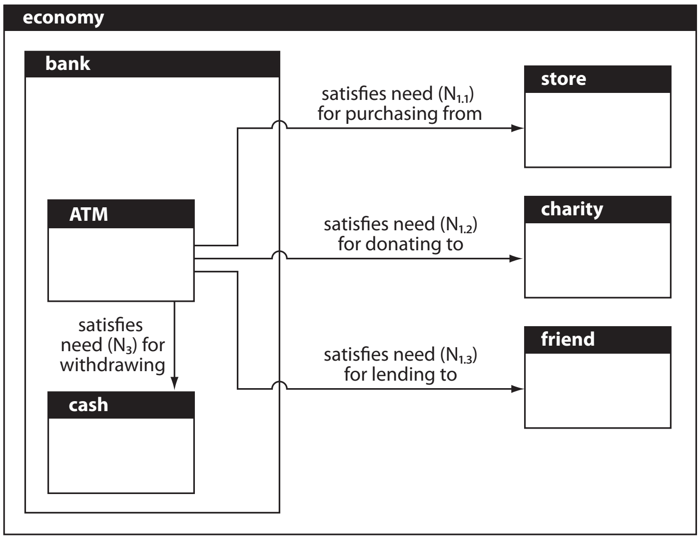


Figure 6. The functions of the ATM proliferate as they become more distant.

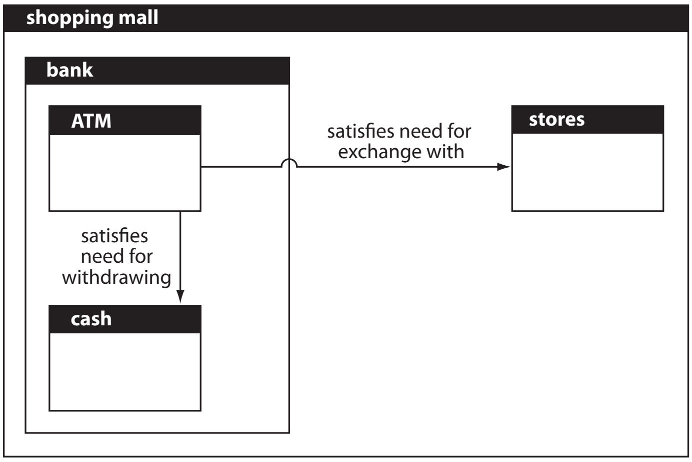


Figure 7. Exogenous functions of the ATM with respect to two different super-systems.

perspectives, permitting the donation or lending of money might be functions, they need not be functions from the perspective of the mall's commercial operations. This implies that when making function statements with respect to systems that do not have a clear role, we should specify the analytic perspective that has been adopted.

Specifying an analytic perspective for any of a system *X*'s super-systems, removes the requirement to only assign functions to *X* with respect to its most local super-system (Chandrasekaran and Josephson's "lowest level of abstraction"). However, it may in any case be impossible to identify some most local super-system if we acknowledge the subjective nature of system boundaries. Chandrasekaran and Josephson's chain of needs from N_1 to N_3 reads as a definite sequence and so the most local super-system of the ATM seems definite also. However, a chain of needs, or a nest of systems, is only defined in the process of analysis. If the granularity of the analysis is relatively coarse then a functioning system's most local super-system will be at a further remove from that system than if the analysis had been finer-grained. Consequently, what constitutes the most local super-system may vary depending on the degree of system granularity that the analyst perceives.

5. Capacities and users

Analytic perspectives, especially those determined by the properties of super-systems, are discussed in the philosophical literature on function. However, these discussions do not account for the multiple super-systems that make up nested systems. Considering a basic statement of the form "the function of *X* is *Y*", two different options are presented: for Cummins (1975: p. 762) and Kitcher (1993: p. 390), *X* functions with respect to a capacity of *Z*, where *Z* is a super-system of *X*;[14] for Searle (1995: p. 19) and Houkes and Vermaas (2009: p. 407), *X* functions with respect to a capacity to fulfil the goals of a user contained by *Z* ('goals' here are similar to the 'needs' discussed above).[15] If these two perspectives were used to construct function statements for the pen discussed earlier, they would be as follows: first, "the function of the pen is to transfer ink to paper with respect to the writing system's capacity to communicate information" (see Figure 8a); and second, "the function of the pen is to transfer ink to paper with respect to a writing-system that contains a writer with the goal of inking paper" (see Figure 8b).

Both of the perspectives outlined above are potentially useful: the first for systems in which no user is explicitly contained by *Z*; the second for systems in which *Z* does explicitly contain a user. By adopting the first perspective, we describe the function of the pen with respect to the writing system; the writing system may contain a writer, but that writer is not referred to because it is the capacity of the writing system that is critical. By adopting the second perspective, we still describe the function of the pen with respect to the writing system; that writing system explicitly contains a writer, and now it is the writer's goals that are definitive.[16] Which of these perspectives is to be preferred depends on the analytic frame adopted. This is because the writer can either be viewed simply as one of many components of the pen's super-system (Figure 8a) or as a user of the pen (Figure 8b).

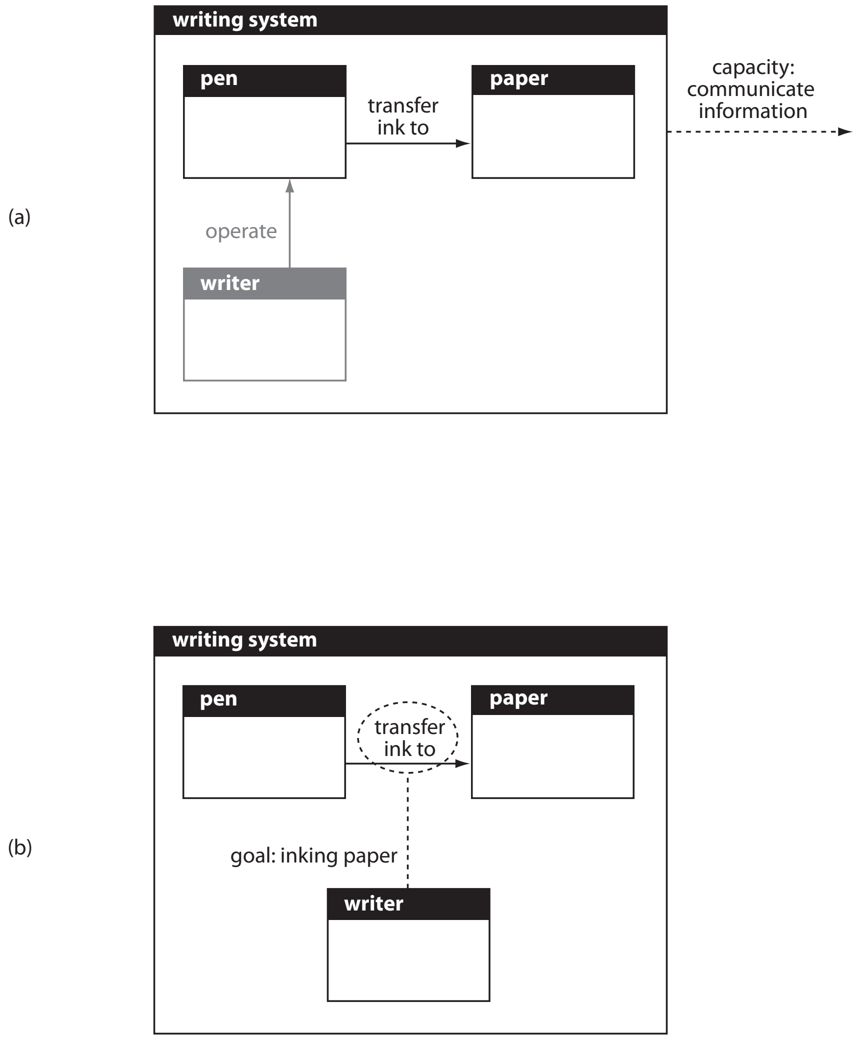


Figure 8. Representations of the exogenous functions of the pen, defined (a) with respect to the capacity (dashed arrow) of the writing system (here the writer is a component and need not be specified), and (b) with respect to the goal (dashed loop) of a writer using the pen (here the writer is the user and must be specified).

If we imagine that the more global communication system contains some additional agent that gives instructions to the writing system then a similar decision about analytic framing is required. This agent could either be seen as just a component of the communication system, or as a user of the writing system. In turn, another agent in a more global system may use the communication system for some purpose. This demonstrates how we can alternate between viewing systems (such as people) as users of some other system or as components of systems that are used by other users. Just as with function assignments and system boundaries, determining whether a system is a user or a component is at the discretion of the analyst (Franssen & Jespersen, 2009).

Systems, their capacities and their users are often left implicit in function statements, perhaps because they are taken to be obvious. For example, in Figure 3, the assumed endogenous functions of the pen's super-systems are evident in their naming (also see Hilpinen, 1993: p. 161): the endogenous function of the writing system is for the writer to meaningfully transfer ink from the pen onto the page (i.e. the writing system works *by* writing); the endogenous function of the communication system is for the writing system to communicate information to the reading system (i.e the communication system works *by* communicating). The writing and reading systems might alternatively have been conceptualised and thus named as *room1* and *room2*, respectively, and the communication system might have been conceptualised as an *office* (see Figure 9). A room in an office might have many functions, both endogenously and exogenously. It is only in the context of the office's communicative activities that room1 has the endogenous function of the writer transferring ink from the pen onto the page, and also the exogenous function of communicating information. In the context of the office's structural requirements (i.e. to sustain its self-weight or to withstand externally applied loads), the rooms would perform very different endogenous and exogenous functions. This reconceptualising of the systems represented in Figure 3 illustrates how the drawing and naming of system boundaries can involve decisions about functions, whether or not that is explicit.

6. Conclusion

In this article I have attempted to emphasise the relativity of devices and environments, and the relativity of the device- and environment-centric functions that are associated with them. Of course, out of habit or inclination, the objects of our attention can very well be thought of as devices and environments; it is just important to recognise that a device can also be viewed as an environment, and that an environment can also be viewed as a device. Similarly, people can be seen as users of a device or, along with that device, they might simply be seen as components of an encompassing system. Acknowledging this relativity is important when assigning functions to parts of a complicated whole. For example, large design projects may involve many designers, with one designer's device being another designer's component or environment. In such cases, any given function that is identified might be an endogenous function to one designer whilst being an exogenous function to another. Applying a nested systems perspective to functioning systems emphasises this system-relativity, and suggests three revisions to conventional function statements.

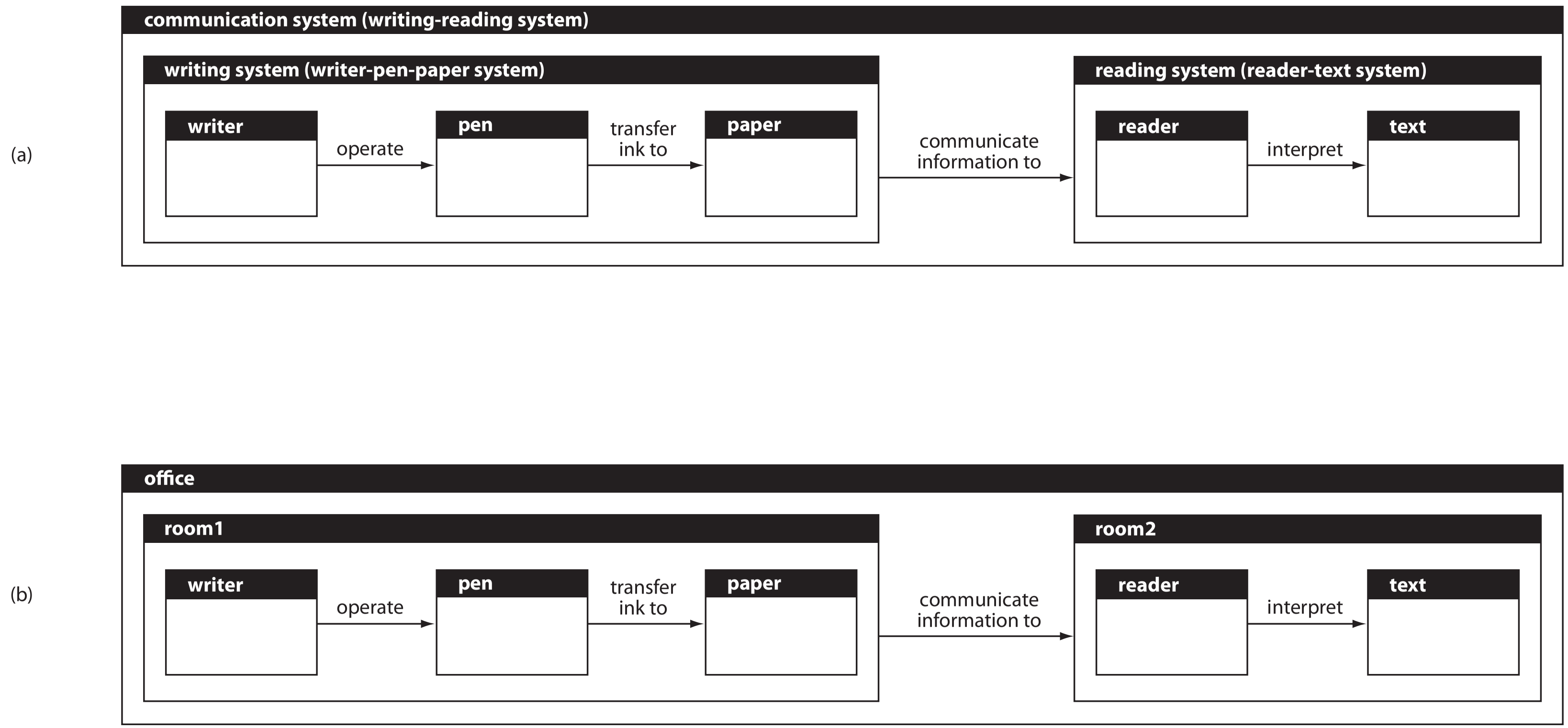


Figure 9. Comparison of (a) the simplified systems from Figure 3 with (b) alternative systems that do not predetermine the functions of their sub-systems.

First, a statement such as "the function of *X* is *Y*" is not explicit about what system the function, *Y*, is performed with respect to. It could be with respect to *X* itself (an endogenous function of *X*) or with respect to *X*'s super-system, *Z* (an exogenous function of *X*). So, function statements are made more complete if they either take the form "the (endogenous) function of *X* is *Y* with respect to *X*" or "the (exogenous) function of *X* is *Y* with respect to *Z*", where *Z* is a super-system of *X* (see Figure 10).

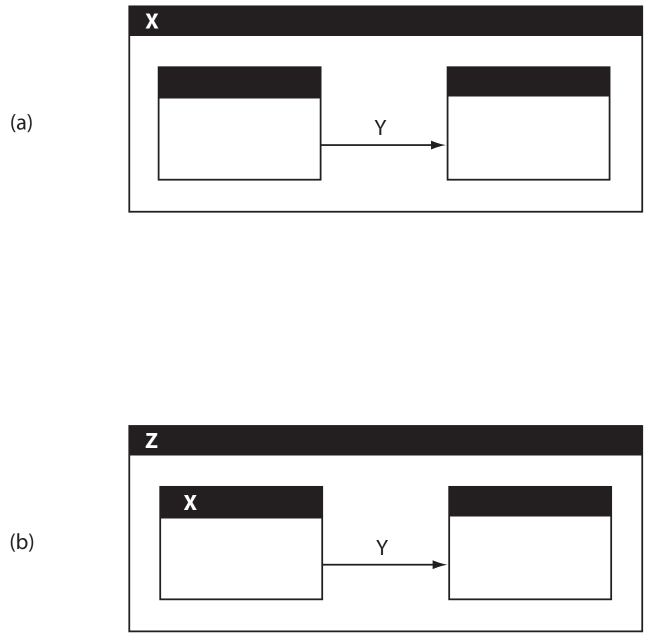


Figure 10. General representations of (a) an endogenous function of *X*, and (b) an exogenous function of *X*. Relating this abstraction to the earlier example of the pen, *X* might be the pen itself, with *Y* being the flow of ink and *Z* being the writing system. In (a), the flow of ink is from one pen component to another; in (b), it is from the pen onto the page.

Second, a statement such as "the (exogenous) function of *X* is *Y* with respect to *Z*" is only one of a family of similar statements that can be made depending on which of *X*'s many possible super-systems has been selected for analysis. It is more complete to say "the (exogenous) functions of *X* are Y_1 with respect to Z_1, Y_2 with respect to Z_2, … and Y_n with respect to Z_n." Here, Z_n represents a super-system of *X* at the *n*th (integer) layer out from *X* in the nest, and Y_n represents the associated role that *X* plays at that layer (see Figure 11).

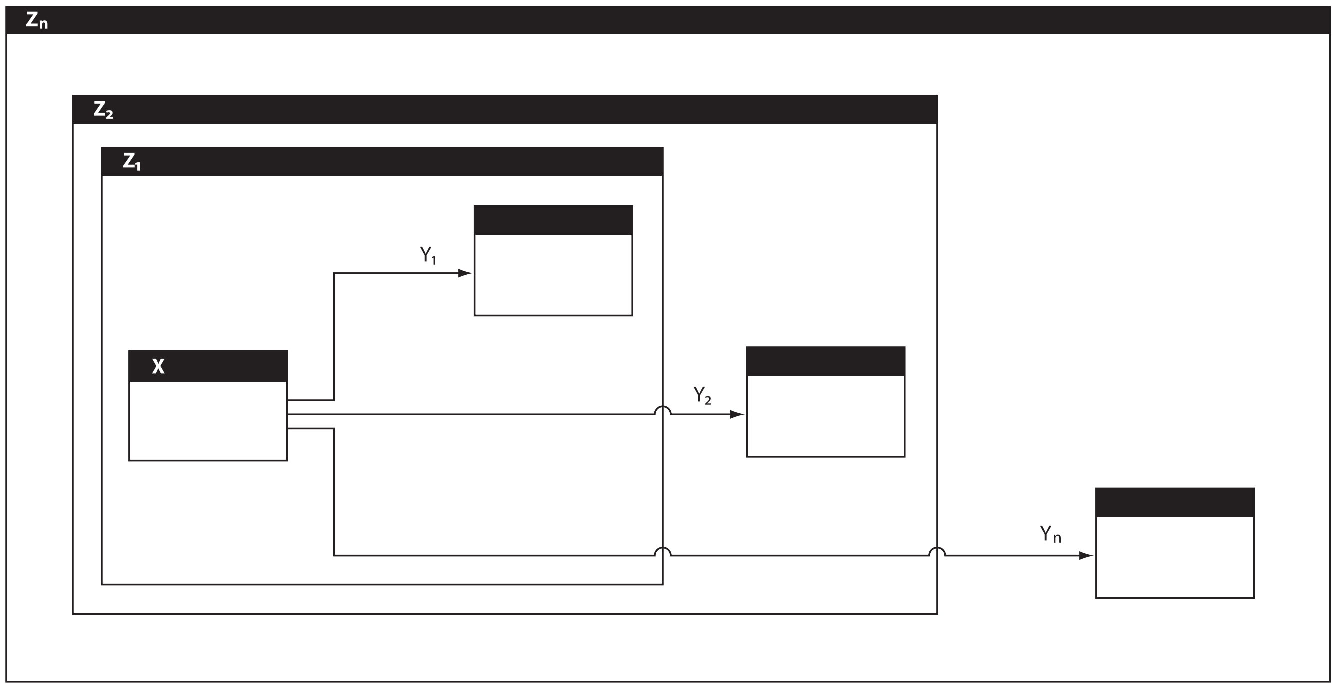
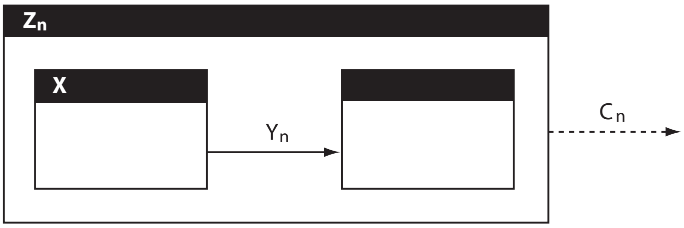


Figure 11. A general representation of (exogenous) function propagation, where *X* is the functioning system, Z_1 to Z_n are the super-systems of *X*, and Y_1 to Y_n are the functions performed with respect to those super-systems.

Third, a statement such as "an (exogenous) function of X is Y_n with respect to Z_n" leaves implicit those properties of Z_n that define Y_n as a functional role. This could either be a capacity of Z_n, or the goals of a user encompassed by Z_n. Exogenous function statements are more explicit if they take the form: "an (exogenous) function of X is Y_n, (i) with respect to a capacity, C_n, of Z_n, or (ii) with respect to a user, U_n, in Z_n who has goals, G_n, served by Y_n" (see Figures 12a and 12b respectively).

(a)



(b)

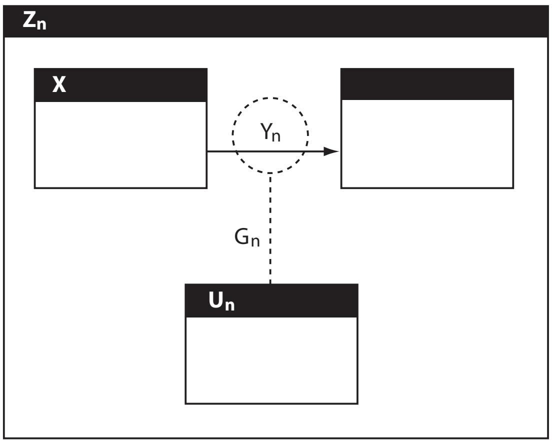


Figure 12. General representations of the (exogenous) function of *X*: (a) an exogenous function defined with respect to a capacity, C_n (marked with a dashed arrow) of *X*'s super-system Z_n, and (b) an exogenous function defined with respect a user, U_n, in Z_n who has goals, G_n (marked with a dashed arrow), served by Y_n.

The above function statements collectively draw out what is often left implicit even in formal representations of function. However, this article only offers an introduction to what might be achieved by examining functions in the context of nested systems. There is much more to consider, especially with respect to how different systems are related. For example, here attention has been restricted to examples where a system, X, affects some other system that is physically outside X. When considering the design of systems that also contain environments of significance (e.g. buildings, vessels, containers), the mapping between the physical world and a representation of nested systems might be less direct. What is more, not all systems nest in the relatively neat way discussed here. Instead, it might be that a system is contained by two or more encompassing super-systems which overlap rather than nest within each other. Those roles or effects that are considered non-functional with respect to one set of super-systems might still be considered functional with respect to another. A complex of nested and overlapping systems can thus be envisaged, where functional and non-functional effects propagate through multiple nests. Attending to such matters would move beyond the linear thinking presented here, and towards some of the richer systems concepts like circularity, stability and multifinality (e.g. see von Bertalanffy, 1968; Checkland, 1981). In doing so, further progress could be made in supporting the intuitive use of function concepts whilst also tackling those issues that pose problems for formal representation.

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Notes

[1] A device can play many roles, not all of which are necessarily functions. For example, the motor does not just convert electrical energy to rotational energy; it also generates heat and noise. Consequently, there is debate over how to define what subset of all the roles that a device plays are its functional roles. Depending on the perspective taken, it is variously argued that a device's functions are restricted to the roles that it was intended to play (e.g. by a designer), is used to play (e.g. by someone able to operate it), has been selected for playing (e.g. market forces), and so on. Although there are some classic examples that distinguish one definition from another, in many cases a device is intended to play some role and is also used to play that role, has been selected for doing so, and so on.

[2] Freeman and Newell offer a simple figure of one system nested within another. Considering the example of a *knife* with components of *handle* and *blade*, they suggest that the functional requirement of the handle to be held becomes a functional requirement of the knife once it is constructed from its components. They represent this with nested boxes and arrows in a manner similar to that adopted here. However, they do not consider multiple levels of nesting (e.g. see figure 3 of this article). Pahl and Beitz (1984: p. 16) present a generic representation of systems-within-systems that implies multiple levels of nesting are possible. However, they do not discuss bypassing any particular level of nesting (see sections 3 through 5 of this article). The diagrams used in this article also exhibit some structural similarities to UML's class and component diagrams (see Fowler, 2004: Ch 3, Ch 14).

[3] An emphasis on functions being performed with respect to a system calls to mind Cummins' (1975) argument that functions are an artefact's or organism's present capacity to perform a specific role within the context of a specific system. Preston (1998) refers to these types of functions as 'system functions', distinguishing them from those 'proper functions' that a type of artefact (or a species of organism) has been selected to perform. Note that although the definitions do not require it, many functions are both proper functions and system functions.

[4] Systems are defined by *system boundaries*, imaginary lines that divide things within the system from those that are outside. These boundaries can be difficult to draw, but are often chosen to maximise the ratio of within-boundary interactions to across-boundary interactions (Savageau, 1976: p. 80; Simon, 1962: pp. 473-477). If looked at in enough detail, most candidate systems are very complex, with too many interactions to reasonably consider when defining their boundaries. However, it is common to reduce this complexity by attending to a number of issues, including spatial simplifications (e.g. proximity and compartmentalisation) and temporal simplifications (e.g. order of magnitude of time constants that characterise dynamic response) (Savageau, 1976: pp. 81-82).

[5] In the various disciplines in which the terms are commonly used (e.g. biology, botany, medicine, economics), *endogenous* means 'originating from within a system' whilst *exogenous* means 'originating from outside a system'. In contrast, exogenous functions are here described in terms of outward (rather than inward) effects. Despite this, the use of the term exogenous is consistent with use elsewhere because it is the subjective assignment of functions that is being emphasised (not their performance). The assignment of the exogenous

functions depends on effects or properties that originate outside the functioning system (see section 5).

[6] Differences can also be identified between the endogenous-exogenous distinction and the internal-external distinction proposed by Gzara, Rieu and Tollenaere (2003: p. 248): "an external function express[es] an action provided by the product to the environment. It describes what the product does to satisfy a user need" and "an internal function describe[es] the behavior of product components in terms of how they contribute to realization of external functions." The requirement for external functions to satisfy a user need is more constraining than the definition of exogenous functions (see section 5 for a discussion of users).

[7] This article focuses on the propagation of exogenous functions, but endogenous functions propagate too. Although statements about a system's endogenous function make no explicit reference to a super-system, the existence of that super system is implicit in such statements. To say that the pen's "causing ink to flow onto the tip" is an endogenous function of the pen assumes that ink flowing onto the tip contributes to the fulfilment of one of the pen's exogenous functions, such as "causing a piece of paper to have ink on it" (with respect to the writing system). If none of the pen's exogenous functions involved inking then the transportation of ink to tip would not be an endogenous function of the pen. Instead, it would just be one of many internal behaviours that the pen exhibits, including unwanted effects such as the oxidation of components. We could just as well say that "causing ink to flow onto the tip" is an endogenous function of the more global writing system because this behaviour contributes to the fulfilment of the writing system's capacity to "communicate information". If the system boundary that defines the pen is not recognised, then the ink container, the ink and the tip are sub-systems of the writing system directly and can thus perform the endogenous functions of that system.

[8] Different functions at the same layer in the nest need not be performed simultaneously however. For example, an electrical fuse may have the function of conducting electricity during normal operation, but have the function of breaking the circuit under overload conditions (Otto & Wood, 2001: 155-156).

[9] Fransssen and Jespersen (2009) offer the example of a taxi which is used for transportation (by the passenger), but is used to earn money (by the taxi operator). This is in contrast to the *mutually exclusive* multiple roles that are often referred to in the function literature, for example, chairs being used either as seats or as stepladders (Preston, 1998).

[10] The terminology is potentially confusing here due to the lack of consistency across different authors. Accounting for functions at different layers in a nest of systems could be distinguished according to the "layer of nesting" (as here), "level of abstraction" (Chandrasekaran & Josephson, 2000) or "level of explanation" (Lewens, 2005).

[11] Chakrabarti (1998) says that a teleological function can be "viewed at several levels of abstraction, depending on where the system boundary for the context to a solution is drawn." McLaughlin (2001) also recognises the propagation of effects in nested systems, saying "An artefact can […] have a nested set of functions: If the function of the switch is to turn on the motor that opens the garage door, it also has the function of opening the door" (p. 55). If the switch here is the device in question, then it has an effect on another system, the motor, which

has an effect on another system, the door. With this in mind, McLaughlin (2001) distinguishes between immediate and ultimate functions. He gives the example of electric fences that deliver small electric shocks to livestock in order to keep them away from the fence and therefore contained in the field. We are at best disinterested in the immediate function of delivering shocks – and may actually be opposed to it – whilst being interested in and motivated by the ultimate function of containment: the former is the means by which the latter is achieved (McLaughlin, 2001: pp. 55-56). Of course, there is no need to stop there, because we are not ultimately interested in containment. Instead, we are interested in the effects that containment permits. We might (just as with shocks), actually be opposed to containment, but it's necessary so that we can, for example, conveniently access cattle, so that we can milk them, so that we can drink milk, and so on.

[12] Lewens says that "there is no basis in biology itself for arguing, say, that the function of the heart is to pump blood but not to bring nutrients to cells. The heart pumps blood, which in turn brings nutrients to the cells. Both are effects of the heart which contribute to the fitness of the organism which bears it." (Lewens, 2005: p. 133; for the analogy with artefacts, see p. 158). In engineering, functional analysis is not just performed for the purpose of assigning functions to devices that do not yet exist, but also for diagnosing the malfunction of systems that already do exist. For functions to propagate outwards through a set of nested systems does not mean that malfunctions propagate inwards. Just because a system, *X*, has the function to perform its super-system's function does not mean that a malfunctioning super-system implies the malfunctioning of *X*. It is more informative in this case to only assign malfunction to the super-system. Systems may share the functions of their super-systems but they do not share their malfunctions. Therefore, it is only when a system is successfully functioning at a local layer in the nest, but not at a more distant one, that we should give priority to that description of a system's function that is most local (see Neander, 1995: p. 137).

[13] The ATM is one of many 'actors' (including shoppers, retailers, banks, etc.) that make that exchange possible. This is analogous to the way in which the pen is one of many actors (including writer, air pressure, gravity, etc.) that makes the inking of the page possible.

[14] Cummins (1975: p. 762): "It is appropriate to say that the heart functions as a pump against the background of an analysis of the circulatory system's capacity to transport food, oxygen, wastes, and so on, which appeals to the fact that the heart is capable of pumping. Since this is the usual background, it goes without saying, and this accounts for the fact that 'The heart functions as a pump' sounds right, and 'The heart functions as a noise-maker' sounds wrong, in some context-free sense. This effect is strengthened by the absence of any actual application of the analytical strategy which makes use of the fact that the heart makes noise." Kitcher (1993: p. 390): "The constituents of a machine have functions because the machine, as a whole, is explicitly intended to do something".

[15] Searle (1995: p. 19): "Whenever the function of *X* is to *Y*, *X* and *Y* are parts of a *system* where the system is in part defined by *purposes, goals, and values generally*. This is why there are functions of policemen and professors but no function of human as such – unless we think of human as part of some larger system where their function is, e.g., to serve God." Houkes and Vermaas (2009: p. 407): "An agent *a* justifiably ascribes the physicochemical capacity to ϕ as a

function to an item *x*, relative to a use plan *up* for *x* and relative to an account *A*, if [amongst other conditions…:] *a* believes that *x* has the capacity to ϕ; *a* believes that *up* leads to its goals due to, in part, *x*'s capacity to ϕ […]".

[16] Note that whilst the writer is assigned the function of operating the pen with respect to the writing system, the same physical entity (e.g. a person) may perform many other functions with respect to other systems. This can alternatively be phrased as considering different capacities of the same system rather than different systems. For example, in considering assembly line production, Cummins (1975) notes that "Production is broken down into a number of distinct tasks. Each point on the line is responsible for a certain task, and it is the function of the workers/machines at that point to complete that task. … If the line produces several products, i.e., if it has several capacities, then, although a certain capacity *c* of a worker is irrelevant to one capacity of the line, exercise of *c* by that worker may be his function with respect to another capacity of the line as a whole" (p. 760).

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