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THE RELATIONSHIP BETWEEN FUNCTION AND AFFORDANCE

David C. Brown
AI in Design Group
CS Dept., WPI
Worcester, MA 01609, USA.
Dcb@cs.wpi.edu

Lucienne Blessing
Engineering Design and Methodology
Dept. of Mechanical Engineering and Transport Systems
Technical University Berlin
D-10623 Berlin, Germany.
Lucienne.Blessing@fgktem.tu-berlin.de

ABSTRACT
The purpose of this paper is to attempt to clarify the concept of affordances, as introduced by Maier and Fadel, to relate affordances to function, to try to reduce confusion about both of these terms by providing a detailed model, and to expose some of the existing research on function to a wider audience. The paper starts by constructing a model of function that relates devices to an environment. We then extend the model to include goals. Next we express the concept of affordances in terms of the model already constructed. The paper concludes by discussing the impact that use of affordances might have on the designer's pattern of reasoning.

Keywords: Affordance, Function, Behavior, Intention, Goal.

1. INTRODUCTION
It is common to propose the use of functions and functional decomposition as a principled way of designing artefacts [Pahl & Beitz 1999] [Hubka & Eder 1996]. Many software systems have been developed to demonstrate the use of functions [Umeda & Tomiyama 1997] [Stone & Wood 2000] [Stone & Chakrabarti 2005].

Maier and Fadel [2001; 2002; 2003] (M&F) have proposed an alternative approach to designing that uses "affordances". Affordances are "the set of interactions between artifact and user in which properties of the artifact are or may be perceived by the user as potential uses" [Maier & Fadel 2003].

The purpose of this paper is to attempt to clarify the concept of affordances, to relate affordances to function, to try to reduce confusion about both of these terms by providing a detailed model, and to expose some of the existing research on function to a wider audience. Note that this paper is *not* intended to be a survey of the work on function or affordances, and the reader is urged to consult the references of the publications cited.

The paper starts by constructing a model of function that relates devices to an environment. We then extend the model to include goals. Next we express the concept of affordances in terms of the model already constructed. The paper concludes by discussing the impact that use of affordances might have on a designer's pattern of reasoning.

2. FUNCTION
In this section we will establish an initial detailed model of function that is based on the work by Chandrasekaran and Josephson [2000] (C&J), and then extend it with additional concepts influenced by Rosenman and Gero [1998] (R&G). The intention is to establish the model of objects and user actions in the world, with its associated terminology and concepts, so that affordances can be described in terms of those concepts. We will focus on a default case of designed artifacts, rather than natural objects, with human users. Note that in this paper we will not include all of the subtleties presented by C&J or M&F, and the reader is urged to study their work for a full account.

2.1 An Initial Model of Function
A designed *device*, D, exists in a w*orld*, W, where the rest of the world (non-D) is referred to as the *environment*, E.

> E.g., a device called a pen exists in an environment that contains, amongst other things, a sheet of paper and a human.

The device can be placed in *many* ways in the environment. If D is placed in some portion of the environment, E_i, at a particular time it will establish *relationships*, R_i, between D and E_i. The set of relationships, $R = \{R_1, R_2, \ldots, R_i, \ldots, R_m\}$ can vary over time, forming a time-varying pattern of relationships. C&J refer to this pattern as the "*mode of deployment*", $M(D, E_i)$.

> E.g., the pen is held by the human at an appropriate angle to the paper with the tip of the pen pointing downwards and the tip touching the paper, so that slight pressure is applied by the tip to the paper.

The relationships are often referred to as "structural" as many of them are stable physical relationships, such as support or connection. Other relationships may occur due to *operations*, O_i, (i.e., actions) carried out by entities in E_i: often a human user. For example, a button on the device may be pressed. Such operations may cause relationships to be appear and disappear over time.

> E.g., The human can vary the position of the pen tip on the paper by moving their hand, while the other relationships are maintained.

The mode of deployment is "intended to capture the notion of how to use the object so that it produces the intended effect" [Chandrasekaran and Josephson 2000]. It is how you have to hold the device or place it when you need it to function. Note that strictly this is the intended effect for the user, not necessarily the designer's intentions, and that different modes of deployment might be used for other effects.

However, to have an "effect" the device needs to behave. When $M(D, E_i)$ is established, some causal interactions between D and E_i are enabled, leading to *behaviors*. Behaviors can be values of state variables, or relationships between them, either at an instant or over time. Behaviors are often described with verbs: e.g., the voltage increased; the beam bent.

> E.g., Contact between the pen tip and the paper allows the ink to flow from the pen onto the surface of the paper. The paper now has ink on it, while the pen contains less ink. In addition, the tip makes a small impression in the paper, and the pen flexes slightly under the pressure.

We can identify particular, interesting patterns of interactions over time, involving the state of D and the state of E_i, and express them as constraints. They are conditions involving behavior that can become true. C&J refer to these as "*behavioral constraints*", B_i.

> E.g., The ink coats the surface of the paper.

Let $B = \{B_1, B_2, \ldots, B_i, \ldots, B_n\}$ be a set of behavioral constraints that can be tested when $M(D, E_i)$ is established. If the constraints B_i are 'satisfied' it can be said that D is playing a *role* in E_i. Note that this is independent of any intention (by user or designer). It can be used in a purely descriptive way.

> E.g., The pen causes a hole in the paper when pressed against it with enough force.

Because there are many possible ways to establish $M(D, E_i)$, and many possible sets of behavioral constraints, a device may play many different roles. However, some roles are desirable: usually those intended by designers, and desired by users.

If a role is *desired* by some *agent* (e.g., a user of the device) then we say that the set of behavioral constraints B provides a *function* for D in E_i.

> E.g., The pen writes on the paper.

In the case where the role desired by the user corresponds with the role intended by the designer, the device is providing the *intended function.* In the case where the role is desired but it is not what was intended by the designer the device is still providing a function. The user often finds this by using analogical reasoning: e.g., the cell phone as a paperweight; the pen as a hole puncher.

Thus devices may have many functions in addition to the one intended. They can be established by using a new set of behavioral constraints, by changing what is desired, or by changing the mode of deployment. In addition, many devices may have the same function, by satisfying B in alternative ways: digital versus analog watches for example.

Many people have pointed out that in natural language one can describe the function of a device without knowing anything about its structure, or even about exactly what behaviors are at the D to E_i interface. Those descriptions tend to be more abstract and closer to the user's desire. C&J refer to these descriptions as *environment-centric* (EC). At the other extreme, the description can be solely in terms of the device: i.e., *device-centric* (DC). Mixtures are also possible.

2.2 An Extended Model

A key ingredient of the definition of function is that a role is "desired". If a role is desired there must be some reason why that's the case. To extend the model developed above, we need to model that reason as well.

Consider an *agent*, with an *intention*, I, to achieve a *goal*, G. Norman [1988, p.46] says that to produce actions, goals must be "transformed into specific statements of what is to be done", called *intentions*, as in "I intend to...", but that intentions are still not specific enough to control actual actions.

For now we assume that the agent is a human: a potential user of a device. The goal is some desired state of the world. It may be one of a set of goals, perhaps subgoals of a more abstract goal. The intention, a description of how to reach that goal, may be concrete, abstract or a mixture.

> E.g., A person has the goal of providing another human with some information. They intend to get some paper, get a pen, write a message, and then give the paper to other person.

Let a plan P consist of a set of operations O_i such that $P = \{O_1, O_2, \ldots, O_i, \ldots, O_p\}$. This plan is a set of executable operations, probably a sequence, which corresponds to all or part of the intention. It should make progress towards achieving the goal: i.e., it either achieves the goal or reduces the complexity of the intention. The agent uses the plan, and the O_i may be physical or mental.

> E.g., The person's initial plan, which carries out the first portion of their intention, is to grip the pen, orient the pen correctly, put the pen tip to the paper, apply pressure, and start to move the pen.

The operations (i.e., plan actions) have conditions, C_i. These conditions may be pre-conditions (i.e., they must be true prior to being able to execute the operation), or may occur during the operation. In either case, the conditions must be true for the operations to complete.

> E.g., The pen must be of small enough diameter to be gripable, rigid enough to resist the pressure applied, light enough to lift and move, and have ink available at the tip.

So, for the agent to execute the plan, and eventually achieve the goal, a pattern of conditions over time must be true. Different goals would require different patterns, as would different ways of achieving the same goal. This pattern of conditions is desired, because achieving the goal is desired.

Let $B = \{B_1, B_2, \ldots, B_i, \ldots, B_q\}$ be a set of behavioral constraints that can be tested when $M(D, E_i)$ is established. As described earlier, if the constraints B_i are 'satisfied' it can be said that D is playing a role in E_i. If the role is desired then the set of behavioral constraints B provides a function for D in E_i.

The behavioral constraints are a set of conditions that are established over time. To be "desired" the set must contribute to providing all the conditions C_i such that plan P can be executed. In that case the device D is behaving in such a way that progress is made towards achieving a goal, or even that the goal is achieved: i.e., its role is desired, and hence it is functioning. Note that it is possible for some of the conditions to come from the environment, and some from other devices. Some may be provided by chains of causal interactions that start with the device.

2.3 An Example

D: Pen.

Structural element: tip.
Structural element: ink container.

Structural connection: tip is at the end of the ink container.
Structural connection: tip is connected to the ink container.

State variable: pressure.
State variable: orientation.
State variable: location.

Mode of Deployment: human is gripping pen; pen is tip down; tip is in contact with paper; the tip exerts pressure on the paper.

B: ink flows from the tip; ink coats the paper; the tip is moving.

Goal: to have another human know the information that you want to tell them.
Intention: get paper, get pen, write message, transfer paper to other human.
Plan: grip pen, orient pen, put pen tip to paper, apply pressure, move pen.

Device-centric function: The function of the pen is to cause ink to flow out of its ink container onto the tip.

Mixed function: The function of the pen is to cause ink to flow from the ink container to the tip, and onto some paper.

Environment-centric function: to cause a piece of paper to have ink on it.
Environment-centric function: to write.
Environment-centric function: to communicate information.

3. AFFORDANCES

Norman [1988, p.219] writes that he believes "that affordances result from the mental interpretations of things, based on our past knowledge and experience applied to our perception of the things about us." His view is that "the term affordance refers to the perceived and actual properties of the thing …that determine just how the thing could possibly be used" [Norman, 1988, p.9].

Both Norman [1988] and Carroll [2003] note that this conflicts with the views of Gibsonian psychologists (J. J. Gibson introduced the theory of affordances, as M&F discuss). However, highly influenced by Donald Norman, this newer more cognitive view has become standard in the design of Human Computer Interaction systems [Carroll, 2003] [Dix et al., 1998] [Preece et al., 1994].

In this paper we adopt this cognitive view, allowing affordances to be recognized from experience, to be learned, and to be inferred by analogy. Thus affordances are *context-dependent action or manipulation possibilities from the point of view of a particular actor.* The actor is considered to be the entity, human or otherwise, capable of taking action.

Maier and Fadel [2003] (M&F) consider affordances to be "potential uses" of a device. This means that the human is able to do something using the device. They stress that the device allows the user to behave in such a way that neither could manifest alone. That is, the device 'affords' the possibility of the user's behavior. Their examples include: a typewriter affords typing behavior to a person, and a ball affords throwing behavior to a person. They consider "throwability" to be the name of the affordance in the latter case, and presumably "typeability" in the former.

Hence one could consider the affordances of a device to be the set of all potential human behaviors that the device might allow. This, of course, is a very large set.

4. THE RELATIONSHIP BETWEEN FUNCTION AND AFFORDANCES

In the model of function developed above, "user behaviors" are the operations O_i that form part of the plan, P, which will either achieve the user's goal, G, or reduce the complexity of the intention, I. As both P and I can be considered to be names of more abstract, non-primitive behaviors, we can also include those as user behaviors that a device might allow.

Hence the affordances, A, of a device are the set of all potential human behaviors, O_i, P_i, or I_i, that the device might allow. While the plan and the intention imply the existence of a goal, operations might not. Thus, unlike functions, affordances may or may not be associated with a goal. Also, if a goal is specified, affordances may or may not support it, as not all operations will belong to a plan that leads to it. In fact, as M&F point out, some affordances may be undesirable, clashing with the goal: what they call "negative affordances" [2003].

To refine this further we need to explain what it means for a device to "allow" a user behavior. In our model, the operations O_i are enabled by conditions C_i. These conditions are either provided by the device in question, or by the environment (e.g., by other devices in the environment). If the conditions are provided solely by the environment, then the user does not need the device in question and there is no need to consider its affordances.

The conditions are indicated by the behavioral constraints, in the context of a particular mode of deployment $M(D, E_i)$. Hence a device, in a particular mode of deployment might cause behavioral constraints to be satisfied, thus directly or indirectly providing the conditions that allow some operations (i.e., some user behaviors).

Thus affordances are dependent on what operations the human is capable of executing in general, the set of behavioral constraints being considered, and the mode of deployment chosen. For example, it is easy to imagine modes of deployment where "throwability" is very hard or impossible (e.g., when embedded in peanut butter, or when the ball is too heavy).

5. DISCUSSION

In what we have developed so far, the assumption has been that the human "user" of the device has the goal, the desire to achieve it, and hence the intention. Another possible analysis is from the designer's point of view.

In this case the designer imagines a particular use for the device they are designing. That is, they envision a potential user, with a specific goal, and a certain intention, and use that to drive the design process. Assuming that the design is good, the device should be perfect for a particular mode of deployment, thus satisfying all the behavioral constraints that will provide the pattern of conditions that lead to plan execution and eventually to goal satisfaction. The envisioned desired set of satisfied behavioral constraints form the basis of the "intended function" of the device.

A common issue in the discussion of function is whether there is a distinction between Device-Device versus Device-User functions. In the latter case the device provides a function because the device can lead to satisfaction of some desired goal. In the case where a device provides a function to another device—something that we take for granted when complex devices have components—in order for the role to be a function it needs to be desired. But how can devices have desires or intentions?

One solution is to assume that when in a particular mode of deployment, where the rest of the device forms all or part of its environment, a component causes a set of satisfied behavioral constraints. That set is needed for some or all of the surrounding components to work in order to provide the complete device's intended function. In that sense they are "desired". In effect, the components inherit the designer's intention. Another possibility is to consider the intentions of the user to be propagated through the device to its components. This allows for both the intended function of the device and unintended functions.

This form of argument circumvents the need for two kinds of function. M&F distinguish between Artifact-Artifact and Artifact-User affordances, but agree that a single view of affordances can be made [2003]. In the context of our model, devices can provide conditions C_i that allow action, regardless of whether the action is performed by a human or another device. Thus the distinction between the two types of affordances does appear to be unnecessary, just as it does for function.

6. DESIGNING WITH AFFORDANCES VERSUS WITH FUNCTIONS

In this section we will attempt a simple analysis of some of the consequences of designing using affordances as opposed to functions. We will consider what reasoning can be done given what is known.

M&F tend to give examples where the device is already known (e.g., typewriter, ball, ladder, and gear pair). So, very crudely, it is tempting to summarize the main difference in reasoning as:

- Affordance-based reasoning = given a device predict possible user actions;
- Function-based reasoning = given a function predict possible devices.

But, when designing, the device is *not* known to start with, therefore it appears initially that affordance-based reasoning is not appropriate for designing in general, but can only be used under certain conditions.

Suppose that the abstract environment-centric function is given as the main requirement for the design. With the function known, designing requires searching for a known device with the given function, or generating a new device, perhaps by using function decomposition.

But if only the abstract function is known, then, without generating the device first, how can the designer predict possible user actions that are afforded? The closer to a description of the device one gets the easier it should be to discover the affordances. This is because precise behavioral constraints are needed to determine precise conditions that allow user actions.

Note that M&F write: "A crucial difference between functions and affordances are that functions are form independent whereas affordances are form dependent" [2003]. This suggests that form is needed before affordances can be determined, hence determining affordances will be very hard without at least some partial form in mind.

However, producing a conceptual design first should allow some affordances to be determined, assuming that a conceptual design can be associated with a 'conceptual mode of deployment' and that this suggests what relationships might be established that could lead to behaviors.

Unless these function-to-affordance or conceptual-design-to-affordance mappings are already known and indexed, this kind of reasoning might involve mentally placing the abstract or incomplete design in different environments to search for different modes of deployment. A lot of prior knowledge from experience will be needed to prune this search for affordances.

The approach proposed by M&F [2003] relies on a "generic affordance structure template" that can help to guide the designer and prune the search during his or her consideration of affordances. However, note that negative affordances are an open set, as it requires consideration of all possible situations.

Unfortunately, this analysis is still not complete, as we need to understand what it means to be "given a function". Is it a device-centric or environment-centric description? Is the goal included? A complete discussion of this is not appropriate here, but note that C&J do address this partially, and Umeda & Tomiyama [1997] present the views of other researchers.

A 'complete' description of a function of a device would be given by the set

{D, M, R, B, C, O, P, I, G}

that includes the mode of deployment, the relationships, the behavioral constraints, the conditions, the operations, the plan, the intention, the goal, and, if only a DC description is provided, maybe even internal aspects of the device itself.

As M&F make a point of discussing the role of detecting negative affordances in determining the quality of a design, it is worth discussing what might go wrong. Clearly, the ideal case is where the effects that the designer intended are what the user desires, and is what the device actually delivers. Other situations are where:

a) Desired = actual (but not intended);
b) Desired = intended (but not actual);
c) Actual = intended (but not desired).

Case a) occurs when the intended function of the device is not being used, but where it is still providing a function. For example, when a screwdriver is used to open a can of paint, or, as mentioned in 2.1, when a cell phone is used as a paperweight. In case b), there's either a problem with the design, a problem with the construction of the device itself, or a problem with constraints that changed over time, e.g. wear. The third case is when the user doesn't want what the device provides, even though it was the intended function—this might suggest incorrect requirements, for example.

7. CONCLUSION

In this paper we constructed a model of function that relates devices to an environment by considering a mode of deployment for the device, plus a set of behavioral constraints that reflect the set of conditions over time that cause the device to play some role. We then extended the model to include plans that assist with satisfying goals. The intention to achieve a goal leads to the device's role being desired, and hence it delivers a function. Next we expressed the concept of affordances in terms of the model already constructed. Affordances are possible actions. Finally we discussed the impact that use of affordances has on the designer's pattern of reasoning.

We see a role for affordances in the design process in addition to functional reasoning. Functional reasoning as proposed in particular in the German literature, assumes that the behavior intended by the designer is the actual behavior of the device, which is considered to be the behavior desired by the user. As a consequence, the focus of reasoning is narrowed down to the functions the device should have, rather than could have. Other potential positive functions, as well as negative functions, might not be identified during the design process, but only during the use phase, due to unexpected modes of employment, user intentions, or constraints.

Several methods have been developed to analyse failures that could occur: i.e., deviations between intended and actual effects of the product. These methods include Failure Tree Analysis (FTA), Failure Mode and Effect Analysis (FMEA), simulation, prototyping, and testing (see [Pahl & Beitz 1999] and [Hubka & Eder 1996] for a description). Of interest here, are those methods that can be used early in the design process, such as FTA and FMEA, that are based on 'mental simulation'. FTA starts with the intended functions (e.g., the valve opens at pressure p), and negates these (e.g., the valve opens too early, too late or not at all). For each negated function, trees of possible reasons for these potential failures are developed and suitable measures proposed. FMEA starts with possible failures of the individual parts or assemblies (e.g., a shaft can break) and then searches for causes and effects, before developing measures for the failures that have the highest risk. In both cases, the behaviour is simulated, mentally or with special software, to find out about potential failures. These approaches are device-centric. The starting point is a given intended behavior (function) and the proposed components, respectively.

Different modes of deployment (e.g., due to untrained users), and different user intentions that do not (or no longer) match the device's intended functions are not considered. User intentions, the device and conditions might match to produce completely different effects, such as the previous example of opening a paint pot with a screwdriver that fits the gap between lid and pot. In many cases, this will work. However, the screwdriver, which was not intended to be used as a lever, might not withstand the applied loads, so negative effects may be caused: it could bend or break, perhaps hurting the user or damaging other objects.

Many liability cases are based on the serious negative effects of incorrect, unforeseen use of devices (e.g., the lady who stood on the door of her microwave to reach for something). Cases exist in which the manual provided no warning (e.g., don't stand on the microwave door), while at the same time the device in its environment did allow the behavior (e.g., the microwave was built into the lowest kitchen cupboard). In many such cases, the designer was probably not aware of the potential uses of the concept nor of their consequences.

In our view, reasoning about affordances could play an important role in design, but it implies a different mindset, not dissimilar to Popper's falsification concept. Designers need to be encouraged to think about other possible behaviors and environments, rather than only focus on securing the intended functionality. The affordance approach requires a broader, more environment-centric view that could help identify potential failures or negative effects which the other methods have difficulty identifying. In our view, considering affordances is a perspective that complements the functional view. This design approach will never provide the designer with *all* potential user actions, but it helps change one's viewpoint to a more reflective, critical one.

This paper is just an initial evaluation of the relationship between function and affordances. Other approaches might be to use other models, such as those proposed by Pahl and Beitz [1999] or Hubka and Eder [1996].

The description of a function of a device can be given by the set {D, M, R, B, C, O, P, I, G}, but not every member of the set might be given. It's clear that a lot of additional work can be done to infer what effect on reasoning each partial specification might have.

Our conclusion is that while affordances, as "possible actions", are an important consideration while designing, it isn't always easy to reason out what they are, as the search space is large. Using function helps to focus the search, as it is backward reasoning. However, once a design or a conceptual design is developed, affordances clearly have a role to play in investigating undesirable possible actions, perhaps leading to designs that are safer and easier to use.

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