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AFFORDANCES AND COMPUTATION

Gibson’s affordances and Turing’s theory of computation

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Abstract

The concept of affordance is a central component of the ecological psychology of J.J. Gibson. Affordances are properties of the environment taken relative to an observer. Ecological theorists have developed formal models for the analysis of affordances. Models proposed by Shaw and Turvey (1981), Turvey (1992) and Greeno (1994) are described and evaluated and another approach, using Turing’s theory of computation, is outlined. Affordances are characterised as the configurations of Turing machines. It is shown that Turing’s work provides a natural vehicle for exploring Gibson’s ideas.

Gibson's affordances and Turing's theory of computation.

Introduction.

The concept of affordance is a central component of J.J. Gibson's ecological approach to psychology. Early references to the concept are found in Gibson (1966) where he proposed that perception should be understood in terms of perceptual systems rather than channels of sensation. A theory of affordances was developed in Gibson (1977) and in his final book, Gibson (1979). Like many other profound ideas, the concept of affordance is intuitively simple, but its richness makes it hard to pin down precisely. Gibson eschewed formal definition and used examples to illustrate the wide-ranging nature of the idea. Other ecological theorists have developed formal models to provide a basis for further theoretical development. Shaw & McIntyre (1974) examined the nature of the invariance relations linking physical and psychological laws, and formal schemas for affordances were developed by Turvey & Shaw (1979), Shaw & Turvey (1981) and Shaw, Turvey & Mace (1982). A framework for ecological psychology, based on the concept of a "coalition", was set out by Shaw & Turvey (1981). Turvey (1992) offered an alternative formal definition of affordances and Greeno (1994) suggested an analysis based on situation theory. This paper reviews these approaches and argues that an account of affordances based on Turing's theory of computation provides a stronger and simpler formal foundation for ecological psychology.

It has been widely agreed both by its proponents and opponents that Gibson's ecological theory stands in opposition to computational theories of perception, (cf. Gibson, 1979; Ullman, 1980; Fodor & Pylyshyn, 1981; Turvey, Shaw, Reed & Mace, 1981; Carello, Turvey, Kugler & Shaw 1984; Pylyshyn, 1984; Shepard 1984; Reed 1991; Greeno 1994; Thelen & Smith 1994; Kelso, 1995; Port & van Gelder, 1995; Clark, 1997). However, Turing's original theory of computation contains striking formal parallels to the affordance concept that have not previously been considered. They are outlined in this paper. The approach is not Procrustean. It does not attempt to bring affordances within the purview of a traditional computational framework for perceptual theory in the way advocated, for example, by Vera & Simon (1993). Instead, it is based on the idea that the theory of computation, as presented in Turing (1936-7), is a natural vehicle for clarifying and exploring questions that arise within ecological psychology. Turing's theory lends itself to this purpose because it is an ecological theory. It is concerned with entities that are defined at the ecological scale and it demonstrates the reciprocity or mutuality of the agent and its environment. The abstract conception of a computing machine that Turing developed in 1936 treats the fundamental relationship between the agent and the environment in a completely different fashion from later theories based on stored program computers (see discussion in Wells, 1998). This crucial point has not been widely recognized.

The new computational approach is intended to promote analysis of questions about the internal states of perceivers in a way that is consistent with Gibson's ecological approach but goes beyond his primary concern with the informational content of the environment. Many theorists, who are otherwise sympathetic to Gibson's ideas, have found his apparent rejection of the perceptual significance of the internal states of the perceiver untenable. Shepard (1984), for example, argued that perceptual theorists need to consider constraints that have been internalized as a result of selective pressures operating over evolutionary time. He suggested that the metaphor of resonance, which Gibson had derived from Lashley, could be developed to this end. This line of development has had only limited success. Kelso (1995, p.188) suggests that it remains "underelaborated". The approach taken in this paper shows how the internal states of the agent can be incorporated into ecological theory.

Affordances were characterised by Gibson as properties of the environment taken relative to an animal. Gibson emphasised the mutuality or reciprocity of the relations between animals and their environments but his own work was concerned primarily with the analysis of environmental information. Other ecological theorists have stressed the need to provide a complementary account of those properties of animals that enable them to act on affordances. The term "effectivity" has been widely used for this purpose and much of the formal work that has been done has had as a goal the elucidation of the relation between affordances and effectivities. Shaw, Turvey and their colleagues have argued that affordances and effectivities are "duals" of each other and the coalitional framework set out by Shaw & Turvey (1981) treats the concept of duality as fundamental. It is argued here that Turing's computational model provides a clear account of effectivities and affordances and demonstrates the mutuality between them better than does the concept of duality.

Gibson on Affordances.

Gibson (1979, p.22) described psychology as "the study of the perception and behavior of animals and men as a function of what the environment affords." He regarded the hypothesis that information in the ambient optic array specifies affordances to be "the culmination of ecological optics" (Gibson 1979, p.143). Affordances have many characteristics. They can be subsumed within a framework that focuses on the following seven features; affordances are ecological, they are relational, they are facts of the environment and behavior, sets of them constitute niches, they are meanings, they are invariant combinations of variables and they are perceived directly.

Affordance is an ecological concept.

The world, as Gibson observed, can be described at many levels because reality has structure at many levels. He argued that the appropriate level at which to study human, and other animal, behavior was the ecological level. The characterization of the ecological level has been controversial (see discussion in Fodor & Pylyshyn 1981; Turvey, Shaw, Reed & Mace 1981), but it can plausibly be regarded as a level of analysis whose ontology contains the everyday objects and events with which human behavior is concerned. Turvey (1992) suggested that ecological ontology is materialist and dynamicist but is not committed to the reductionism of classical physicalism. Issues about the appropriate ontology for ecological psychology have also been discussed by Kadar & Effken (1994), in a review of Turvey's paper, and by Still & Good (1998) whose concerns include the importance of the social affordances of conspecifics. The ecological level for a species is thus partly determined by the kinds of objects and events that have constituted significant selection pressures for that species. However, although ontology and evolution are both important, the key point about Gibson's ecological approach to perception is that it is concerned with natural, unfettered vision. One corollary of this approach is that one cannot be interested simply in the anatomy and physiology of the eye or in the activity of the brain. "We are told that vision depends on the eye, which is connected to the brain. I shall suggest that natural vision depends on the eyes in the head on a body supported by the ground, the brain being only the central organ of a complete visual system." Gibson (1979, p.1). A further corollary of the approach is a fundamental concern with what the environment offers the unconstrained perceiver. The theory of affordances is central to the ecological approach because it examines the nature of the relationship between the mobile perceiver and the environment.

Affordances are relational.

The ecological nature of affordances implies that they are also relational, i.e. that they are predicated of two or more things taken together. Gibson described affordances as pointing two ways, to the environment and to the observer. He coined the term "affordance" in order to be able to refer to an organism and its environment in a new way. Lombardo (1987) has suggested that affordances exemplify the principle of reciprocity which he takes to be the central insight in Gibson's ecological approach. Lombardo suggests that reciprocity in this sense means distinguishable yet mutually supportive realities. However, the relational or reciprocal nature of affordances creates a tension in Gibson's theorizing because he also claims that affordances are facts of the environment and not dependent on the needs of the observer. Thus, while reciprocity is an important part of the ecological approach, Gibson's view of the nature of animal/environment relations can best be described as *asymmetric inter-dependence*. The relationship is one of inter-dependence because the terms "animal" and "environment" are complementary, but it is asymmetric because the environment is a more important source of perceptual structure than the animal. The asymmetry in Gibson's approach has been a source of controversy particularly with regard to his unwillingness to concede a substantial role for internal representations in perception.

An early presentation of the concept of affordance, Gibson (1966, p.285), was made in the context of the theory of information pickup. The context makes it clear that affordances are part of the information available in the environment. Affordances are defined as "what things furnish, for good or ill." The notion that affordances are relational with both environmental and animal components is not prominent. The emphasis is very much on their environmental character.

Gibson (1977) and Gibson (1979, Ch.8) provide an opportunity to examine the evolution of Gibson's thinking about the relational nature of affordances. Gibson (1977) is a preliminary version of Chapter 8 of Gibson (1979). The two versions of the chapter are structurally very similar but there are revisions and additions which, presumably, reflect changes in Gibson's thinking. One of the notable developments from 1977 to 1979 is an increased emphasis on the relational nature of affordances.

In Gibson (1977, p67) an affordance of an object is defined as "*a specific combination of the properties of its substance and its surfaces taken with reference to an animal*". Although affordances are defined in this passage "with reference to an animal" it is not clear how the reference is to be understood. Gibson does not refer to the properties of animals even though an intuitive and natural way to understand the relational nature of affordances would be in terms of matching properties of objects and individuals. Presumably he wanted to avoid the suggestion that affordances depend on the individual.

The corresponding passage in Gibson (1979, p.127) reads as follows; “The *affordances* of the environment are what it *offers* the animal, what it *provides* or *furnishes,* either for good or ill…It implies the complementarity of the animal and the environment.” An interesting difference between these two passages is the introduction of the term “complementarity” in 1979 to describe the relation between environment and animal. Complementarity is a concept, originally developed in physics, that refers to the existence of superficially inconsistent views of an object or phenomenon such as the wave/particle duality of light. If Gibson had this in mind, the use of the term to describe affordances suggests that he considered the relation between animals and environments to be stronger than simple reciprocity or interdependence. One possibility is that environments and animals are, in a sense, co-defined. Then “animal” would be one particular way of referring to the animal/environment duality and “environment” would be another. As with waves and particles, the choice of term would vary according to the particular aspect of the system under investigation. Some support for this notion can be found in Gibson (1979, p.8) where he says:

> The fact is worth remembering because it is often neglected that the words *animal* and *environment* make an inseparable pair. Each term implies the other. No animal could exist without an environment surrounding it. Equally, although not so obvious, an environment implies an animal (or at least an organism) to be surrounded. This means that the surface of the earth, millions of years ago before life developed on it, was not an environment, properly speaking.

One important final point is Gibson’s absolute rejection of dualism. His claim that affordances point to the environment and to the observer “is wholly inconsistent with dualism in any form, either mind-matter dualism or mind-body dualism. The awareness of the world and of one’s complementary relations to the world are not separable.” Gibson (1979, p.141).

Affordances are facts of the environment and facts of behavior.

Gibson was a realist about the objects of perception. The fact that affordances are relational does not imply that the things that afford behavior depend on the observer. “The observer may or may not perceive or attend to the affordance, according to his needs, but the affordance, being invariant, is always there to be perceived.” Gibson (1979, p.139). Thus affordances are facts of the environment. At the same time, a core part of the ecological approach is the activity of the perceiver. Gibson was frequently at pains to stress that perception is an achievement of the active observer. “The eyes, ears, nose, mouth, and skin can orient, explore, and investigate. When thus active they are neither passive senses nor channels of sensory quality, but ways of paying attention to whatever is constant in the changing stimulation.” Gibson (1966, p.4). The theory of affordances links what objects offer to the possibilities for behavior that exist for a given creature. The theory “implies that to see things is to see how to get about among them and what to do or not do with them.” Gibson (1979, p.223). Moreover, affordances are not neutral. Some are positive and some negative and it is this that “makes locomotion through the medium such a fundamental kind of behavior for animals.” Gibson (1979, p.232). Thus affordances are also facts of behavior.

Sets of affordances constitute niches.

Gibson distinguished the niche an animal occupies from its habitat. The habitat of an animal, he suggested, refers to where it lives, whereas its niche refers to how it lives. The relational treatment of niches and animals suggests an analysis in terms of affordances and Gibson made this explicit when he said that “a niche is a set of affordances” Gibson (1979, p.128). This idea implies that “the environment from an ecological viewpoint…is a complex set of relationships among various affordances" Shaw, Turvey & Mace (1982, p.196). The nature of the links between affordances is tackled in Shaw and Turvey's analysis of ecosystems as coalitions and also has a natural explanation in Turing machine terms.

Affordances are meanings.

An important aspect of the characterization of affordances as ecological is the hypothesis that affordances are meanings. "Perhaps the composition and layout of surfaces *constitute* what they afford. If so, to perceive them is to perceive what they afford. This is a radical hypothesis, because it implies that the "values" and "meanings" of things in the environment can be directly perceived." Gibson (1979, p.127). Gibson also says quite clearly that meanings *qua* affordances are independent of the observer. "An affordance is not bestowed upon an object by a need of an observer and his act of perceiving it. The object offers what it does because it is what it is." Gibson (1979, p.139). His approach requires a distinction between the physical conditions for meaningfulness and the perception of a meaning at a specific place and time. Consider, for example, that British rock climbers in a less secular age deployed the concept of a "thank God" hold. In Gibsonian terms, a thank God hold is an attached object on a cliff face that affords safe, secure, and relatively relaxed grasping. It is the kind of hold that a climber fervently desires at the end of a long, strenuous pitch on exiguous holds when nerves and muscles are complaining. The climber who grasps such a hold in trying circumstances experiences a release of physical and nervous tension, feels exhilaration and a sense of ease, and may utter the words that give the hold its name. However, despite the intimate connection between the hold and the thoughts and feelings of the climber, the physical conditions for a thank God hold obtain whether there is anyone using it or not and it is always there to be perceived and used.

Affordances are invariant combinations of variables.

The notion of invariant structure that underlies the flux of stimulation is a central aspect of Gibson's theorising. It provides the basis for his approach to the fundamental question of how constant perception is possible. For Gibson, constant perception is possible because "certain higher-order variables – stimulus energy, ratios, and proportions, for example – do *not* change. They remain invariant with movements of the observer and with changes in the intensity of stimulation." Gibson (1966, p.3). This view contrasts with the constructivist proposal that the constants of perception are built by internal operations of the perceiver on the changing deliverances of the senses.

Invariant structure is also important in the Gibsonian framework because it explains the conditions that supported the evolution of animal life and encourages an evolutionary approach to perceptual theory. The link between evolutionary processes and affordances is quite explicit. Gibson described how the medium allows breathing and locomotion, and can be filled with illumination, vibrations and odours. "All these offerings of nature, these possibilities or opportunities, these *affordances* as I will call them, are invariant. They have been strikingly constant throughout the whole evolution of animal life." Gibson (1979, pp.18-19).

A further linkage between invariants and affordances in Gibson (1979) emphasizes the significance of mobility. It occurs in Gibson's appraisal of his early theory of how ambient light is structured. One source of variation in the structuring of ambient light is the diurnal rotation of the earth. Another, highly significant, source of variation in optical structure is found in the flow of stimulation that is available to a mobile creature. "The perceiver extracts the invariants of structure from the flux of stimulation while still noticing the flux. For the visual system in particular, he tunes in on the invariant structure of the ambient optic array that underlies the changing perspective structure caused by his movements." Gibson (1979, p.247). The linkage between the detection of invariants and the mobility of the perceiver is a key aspect of the theory of affordances. "The theory of affordances implies that to see things is to see how to get about among them and what to do or not do with them. If this is true, visual perception serves behavior, and behavior is controlled by perception." Gibson (1979, p.223).

One other important aspect of the characterisation of affordances as invariant combinations of variables is that it allows for different orders of affordances. If primary affordances are always found in particular combinations then those combinations can themselves constitute higher order affordances. Gibson may have had this idea in mind when discussing the optical information for perceiving affordances where he says, 'a unique combination of invariants, a *compound* invariant, is just another invariant…it could be argued that when a number of stimuli are completely covariant, when they *always* go together, they constitute a single "stimulus".' Gibson (1979, p.141).

Affordances are perceived directly.

Gibson recognised that, in general, complex affordances have to be learned. However, he claimed that the basic affordances of the environment are perceived directly. Gibson used the idea of direct perception to distinguish the theory of affordances from earlier theories such as that of the Gestalt psychologist Kurt Koffka. Koffka had suggested that the directness and immediacy of the perception of what he called "phenomenal" objects arose from a dynamic relation between the object and the ego. Gibson reports that he found this theory unintelligible and said, Gibson (1979, pp.139-140) that:

> There is an easier way of explaining why the values of things seem to be perceived immediately and directly. It is because the affordances of things for an observer are specified in stimulus information. They *seem* to be perceived directly because they *are* perceived directly.

Coalitions as models for ecosystems.

The formal treatment of coalitions forms part of a wide ranging paper by Shaw & Turvey (1981). That paper is part of an extensive body of work developed by Shaw, Turvey and their co-workers over a period of more than twenty five years. A summary of some of the key aspects of this literature can be found in Turvey & Shaw (1995). Turvey and Shaw reject dualism and argue for an understanding of the relation between an animal and its environment in terms of the concept of duality. The link between perception and action is characterised by the claim that affordances and effectivities are duals. This claim is worked out in detail in Shaw & Turvey (1981). The focus of the coalitional style of inquiry is "the animal-environment system described in full" Shaw & Turvey (1981, p.344), but a coalition is only a partial model of an ecosystem, because "it is not intended to be a dynamic model of natural systems, for these must include…both time-dependent and energy-dependent processes." Shaw & Turvey (1981, p.393). Instead, a coalition "provides a formal description for how many grains of analysis are minimally required and maximally allowed over which variables must be selected (bases), related, ordered, and evaluated" Shaw & Turvey (1981, p.393).

A coalition is a mathematical model of an ecosystem. The model pays particular attention to the issues of mutuality and nesting of contexts. The "fundamental building block" is the concept of a duality relation which is claimed to hold between affordances and effectivities. This is intended to capture the core notion of animal-environment mutuality. Dualities exist in various branches of mathematics. In plane projective geometry, for example, "to each theorem of the subject the statement obtained from it by interchanging the words 'point' and 'line' is also a theorem." Kleene (1971, p.56). Similar relationships can be found in the algebra of sets, in propositional logic and in the predicate calculus. Dualities are typically expressed in terms of syntactic transformations, but they reflect a deeper underlying reality. Care is needed, however, even in those systems where dualities are known to exist, not to overstate the generality of the principle. Kleene (1971, p.123), for example, shows that duality holds only as a subsidiary deduction rule for the propositional calculus.

It is important to note that the existence of a syntactic transform T which is such that $T(\alpha) = \beta$ and $T(\beta) = \alpha$ does not suffice to demonstrate the existence of a genuine duality between α and β. If that were so, we could demonstrate a duality between cats and dogs by defining T as the relative complement (B – *a*) of the pair set B = {cat, dog} for each *a* in B. Under this definition T(cat) = {dog} and T(dog) = {cat}. Clearly this tells us nothing about cats and dogs, but only something about the structure of the set B. If a duality is known to exist then an appropriate syntactic transform can be used to obtain one member from the other, but it is fallacious to infer the converse. It is necessary, therefore, to distinguish syntactic duals from substantive duals. Syntactic duals can be created by stipulative definition but substantive duals depend on the prior existence of deeper relationships although they will also have syntactic expressions. Shaw and Turvey’s analysis is based on syntactic duals derived from stipulative definitions. They say that a duality is specified by “any symmetrical rule…where *T* applies to map *X* onto *Z* and *Z* onto *X*” Shaw & Turvey (1981, p.381). This definition allows the dog/cat example to count as a duality.

The failure to distinguish syntactic from substantive dualities leads Shaw and Turvey into a circular argument in the discussion of schemas for affordances and effectivities that precedes the exposition of the formal structure of a coalition. Drawing on earlier work, Shaw and Turvey propose (X,Z,O | X = Z) = Y as an affordance schema. This is read as “X affords Y for Z on occasion O if and only if there exists a duality relation between X and Z”. They then suggest that if affordances are “truly dual” concepts of effectivities there will be a syntactic relation between the affordance schema and the effectivity schema. This they then define. The syntactic relation transforms (X,Z,O | X = Z) into (Z,X,O | Z = X). Having defined the rule they say “By inspection, we see then that the schema that defines an affordance (X,Z,O|X = Z) is dual with the schema (Z,X,O|Z = X) under application of the rule already stipulated. This resulting schema should correspond to an effectivity." Shaw & Turvey (1981, p.388). Finally, they claim that "The general form of this duality of perception and action, vis à vis affordances and effectivities, is by no means trivial; for *it provides the basis for our original assumption that perception and action must be closely linked*." Shaw & Turvey (1981, p.388, emphasis added). The argument is clearly circular; if there is a substantive duality between affordances and effectivities there will be a syntactic duality. There is (by stipulation) a syntactic duality, therefore there is a substantive duality.

A coalition relates four categories of entities, a set B of bases, a set R of relations, a set O of orders and a set Vof values. Each category of entity, i.e. bases, relations, etc. is said to identify a "grain" of analysis. Thus there is a basis grain, a relation grain, an order grain and a value grain. Grains are related to each other on a dimension of coarseness g(B) > g(R) > g(O) > g(V) where ">" indicates "coarser than". One might think that a fine grain would stand to a coarse grain as a molecular analysis stands to a molar analysis. But that is not what is intended. In a footnote to the formal model (p.389), grains of analysis are explicitly distinguished from scales of analysis which refer to the molecular/molar type of dimension and from levels of analysis which refer to the degree of abstraction of a model. Grains model what Shaw and Turvey call contexts of constraint. The basis grain describes the set of variables over which the model is defined. The relation grain describes the ecological relations that are possible given the basis variables. It allows the theorist to describe ecological relations that are independent of specific animals. The relation of edibility for example, can be described at the relation grain independently of particular animals and particular foods. The order grain provides descriptors for the affordance structure of the environment and for the effectivity structure of an animal. This grain is, therefore, animal specific. Finally, the value grain specifies which affordances are noticed or which effectivities are activated on a given occasion.

Shaw and Turvey stipulate that grains must be characterised as "the disjoint union of dual subsets" Shaw & Turvey (1981, p.389). This allows them to specify syntactic dualities at each grain. The term "disjoint union" has different definitions in different branches of mathematics but Shaw and Turvey intend it to mean that each grain is structured as a set with two non-overlapping members which are themselves sets. Thus the basis grain is a set B = {X,Z}, the relation grain is a set R = {ϕ,ψ}, the order grain is a set O = {A,E} the value grain is a set V = {S,N}, and in each case, the members X and Z, for example, have no elements in common. The disjoint subsets are related by a "duality operation" T which is such that for a given grain G = {α,β}, T(α) = β and T(β) = α. Thus, for the basis grain, T(X) = Z and T(Z) = X, for the relation grain T(ϕ) = ψ and T(ψ) = ϕ and so, *mutatis mutandis,* for the order and value grains. T is defined in terms of set complementation and is clearly a syntactic duality.

To understand coalitions it is necessary to consider the structure of each grain of analysis in greater detail. The basis grain B = {X,Z} is derived from a set U which is defined by Shaw and Turvey as a set of ordered pairs of descriptors for "the 'polar' concepts of all dimensions of significant variation in nature" Shaw & Turvey (1981, p.390). U = {(b_1,b_1'), (b_2,b_2'), …}, each b_i is a variable and b_i' is its dual covariate variable.[1] Shaw and Turvey suggest that a b_i might be a dimension of thermal variation and its dual, b_i', a covariate dimension of radiant variation. Thus b_i would, presumably, be a number representing heat and b_i' a number representing light. B = {X,Z} is derived from U. X and Z are defined as ordered tuples, but it is not clear whether X and Z are intended to be finite or infinite. In one place (p.390) the definitions are bounded by a number *k* such that X = (b_1, b_2, …, b_k) and Z = (b_1', b_2', …, b_k') elsewhere (p.392) they are unbounded X = (b_1, b_2, …) and Z = (b_1', b_2', …).[2] For present expository purposes this is not a crucial point. The simplest coalition need have only two variables, one in X and one in Y and is clearly finite. Consider the activity of grasping a ball. To a first approximation, a person can grasp a ball if their hand-span is compatible with the diameter of the ball. In the analysis of this case X contains just a single environmental variable, the diameter of the ball, and the corresponding single animal variable in Z is the hand-span of the agent. It is assumed that the diameter of the ball and the hand-span of the agent are measured in some appropriate set of units, but in the illustration of the formal model given here the variable names alone are used. Because there is just one variable in X and one in Z, X and Z are treated as singleton sets rather than ordered tuples. Thus X = {ball-diameter}, Z = {hand-span} and B = {ball-diameter, hand-span}.[3] For the sake of brevity “b” stands for ball-diameter and “h” for hand-span. Thus X = {b}, Z = {h} and B = {b,h}.

The relation grain R is intended to model the ecological relations that are possible given the particular basis grain chosen. R is defined as the Cartesian product B x B. Thus, in the example, R is the set of ordered pairs {<b,b>, <b,h>, <h,b>, <h,h>}. By stipulation, R is also characterised as the set {ϕ,ψ} such that ϕ = {<b,b>, <b,h>}and ψ = {<h,b>, <h,h>}. The set ϕ is said to correspond to the environment and the set ψ to the animal but the nature of the correspondence is unspecified. On inspection it is clear that each pair in ϕ has “b” as its first member and always includes “b” whereas each pair in ψ has “h” as its first member and always includes “h”. Thus there are more references to the environmental variable “b” in ϕ and more to the animal variable “h” in ψ. Beyond that, the interpretation of the members of R is opaque because the ordering is not interpreted. One can imagine that an ordered pair like <b,h> might be used to indicate, say, an information flow from environment to animal and a pair like <h,b> for a flow in the other direction but Shaw and Turvey do not suggest these or any other interpretations. Without an interpretation of the elements of R it is impossible to tell what ecological relations Shaw and Turvey intend to model with the relation grain. In the context of the example one might hope to be able to specify ecological relations like grasping, catching, throwing, rolling and bouncing, but the formal model provides no clues as to how this might be done. Given this lack of specificity, the fact that a transform T can be defined such that $T(\phi) = \psi$ and vice versa, provides nothing more than a syntactic duality, even though Shaw and Turvey suggest that it demonstrates a fundamental duality between environments and animals.

From the point of view of the analysis of affordances, the order grain is the most important because it provides formal descriptors for affordance and effectivity structures. The order grain is based on a set O which is defined as the Cartesian product R x R. Thus the members of O are ordered pairs of ordered pairs. Continuing with the example of grasping, O = {<<b,b>,<b,b>>, <<b,b>,<b,h>>, <<b,b>,<h,b>>, <<b,b>,<h,h>>, <<b,h>,<b,b>>, <<b,h>,<b,h>>, <<b,h>,<h,b>>, <<b,h>,<h,h>>, <<h,b>,<b,b>>, <<h,b>,<b,h>>, <<h,b>,<h,b>>, <<h,b>,<h,h>>, <<h,h>,<b,b>>, <<h,h>,<b,h>>, <<h,h>,<h,b>>, <<h,h>,<h,h>>}. Like B and R, O is divided into halves by stipulative definition such that O = {A,E}with A = {<<b,b>,<b,b>>,…, <<b,h>,<h,h>>} and E = {<<h,b>,<b,b>>,…, <<h,h>,<h,h>>}. The sets A and E are intended to provide descriptors for affordances and effectivities respectively. Inspection of A and E shows that the members of A all have a member of ϕ as their first element (<b,b>, for example, is the first element of <<b,b>,<b,h>>) and the members of E all have a member of ψ as their first element. However, like the elements of R, the elements of O, including eight different affordance schemas, are uninterpreted. This leaves important and difficult questions open. Should one always expect to find eight types of affordance regardless of the domain over which the variables in the ecosystem ranged? Could there, for example, be eight types of ball grasping affordance? When one considers the different types of ball game and the different types of grip it seems plausible, but it is not obvious that it would always be possible to populate the full range of schemas. If it were not possible for an arbitrary domain, restrictions would have to be specified indicating which types were compatible with the domain. That would further complicate the analysis.

Shaw and Turvey define a transformation T such that T(A) = E and T(E) = A. They argue that T demonstrates the duality of affordances and effectivities. The definition of T is more complex than the relative complement operation used to define the transforms for the sets B and R but like them it is open to the criticism that it is a purely syntactic duality. T has two stages; in the first stage a structure <<a,b>, <c,d>> is mapped to <<c,d>, <a,b>> and in the second stage <<c,d>, <a,b>> is mapped to <<c’,d’>, <a’,b’>>. Thus the first stage takes an ordered pair of the form <A,E> and turns it into a pair of the form <E,A> and the second stage takes each lowest level element and transforms it according to the transformation defined for the basis grain. Using the current example and combining the two stages, T(<<b,b>,<b,h>>) = <<h,b>,<h,h>>. If one catalogues all the transforms on O as Shaw and Turvey do in their Table 11.2, (Shaw & Turvey, 1981, p.395) they fall into three classes. There are mappings from affordances to effectivities and vice versa which Shaw and Turvey call “Other-Duals”, mappings from affordances to affordances and effectivities to effectivities, which Shaw and Turvey call “Order-Reflexive Duals” and identity mappings which Shaw and Turvey call “Self-Duals”. Other-Duals are said to reflect the fundamental linkage between perception and action, Order-Reflexive Duals are said to specify complementary affordance or effectivity properties and Self-Reflexive Duals are said to specify repetitive cycles of perceiving or acting, Shaw & Turvey (1981, p.394).

The three-fold classification of Other-Duals, Order-Reflexive Duals and Self-Duals arises from the specific form of T and prompts two questions. Why does T have two stages and why are the stages as they are? There is no discussion of either of these questions but they are important because other transforms can easily be defined. Suppose, for example, that a transform T' is used which is just the first stage of Shaw and Turvey's transform T. In that case, the duality T': A -> E and E -> A still exists but its character is changed. Under T' there are no Order-Reflexive Duals or Self-Duals. Every transformation yields an Other-Dual. This shows that the categories "Other-Dual", "Order-Reflexive Dual" and "Self-Dual" are artefacts of the definition of T which is given no independent justification. Without it, T has no more claim to represent truths about the nature of affordances and effectivities than does any other syntactic duality that can be defined for the order grain.

The finest grain of analysis in a coalition is V, the value grain. This is not defined as O x O, which one might expect given the preceding definitions of O and R, but as O x {+,-}.[4] The value grain is intended to distinguish those affordances and effectivities that are selected and activated on a given occasion from those that are not. The formal definition of V inherits the lack of specificity of its predecessors and is similarly difficult to interpret.

Without interpretations of the orderings found at the different grains, coalitions do not provide the precision that one looks for in a mathematical model. Nor does they fulfil Shaw and Turvey's stated aim of demonstrating how the potential regress of explanatory levels can be blocked. They suggest that a regress to coarser grains than B is blocked because the addition of new dual variables to B simply increases the number of elements without adding a new level. At the value grain they argue that no new subsets of V are produced by the addition of variables to B. These points do not make the case. At the level of the basis grain, it is precisely the choice of variables that is important for explanatory closure. The fact that the basis grain is closed under duality is a consequence of the stipulation that each variable in X has a covariate in Z. It does not ensure that the set of variables chosen for X and Z will suffice to explain the phenomena under study. Thus the definition of B and the exclusion of coarser grains is irrelevant to explanatory closure. At the value grain it is argued that any "attempt to fabricate arbitrary partitions under V, aside from those dual partitions specified by {+,-}, will fail to be closed under a duality operation." Shaw & Turvey (1981, p.392). It does not follow that V is the finest grain possible in the analysis of an ecosystem. An indefinitely large number of further grains can be defined, starting with the Cartesian product V x V, because the hierarchy of Cartesian products is endless. To block the regress it would be necessary to show that neither V x V nor any finer grain could have any explanatory value. Shaw and Turvey's analysis does not achieve this. Indeed, when one considers that the grain V x V would consist of relations between selected and unselected affordances and effectivities, it is apparent that it might provide structures relevant to the explanation of behavioural sequences.

In conclusion, the formal structure developed by Shaw & Turvey (1981) does not do justice to the issues raised by the philosophical analysis in the earlier part of the paper. The coalition does not prevent the possibility of an explanatory regress and it does not demonstrate either that there are substantive dualities at the different grains described or that the concept of a duality is the most appropriate way of modelling the reciprocity of relations between animals and their environments.

Turvey's analysis of affordances and prospective control.

Turvey (1992) discussed the concept of affordance and its theoretical development in the context of the prospective control of animal activity. Prospective control is concerned with future actions such as the attainment of goals. Turvey suggested that affordances for actions are fundamental and that understanding them provides the foundation on which other types of affordances might be based. It is not obvious how Turvey's work on prospective control should be related to coalitions. Both build on the analysis of mutual compatibility undertaken by Turvey & Shaw (1979) and Turvey retains the idea that the relationship between an animal and its environment can be described as a duality, but his formal analysis is different from that of Shaw & Turvey (1981) and is treated here as a distinct line of theoretical development.

Turvey set out to establish that possibilities for action constitute an ontological rather than an epistemological category. His analysis supports the direct realism which is characteristic of ecological psychology. Turvey began his paper by offering a picture of ecological ontology as materialist and dynamicist but not reductionist, thus allowing for real things to exist at a variety of physical scales. He then characterised properties from the ecological standpoint. He distinguished formal properties from substantive properties, the latter being the main object of his exegesis. Substantive properties, he says, are to be distinguished from attributes. Attributes are epistemological entities whereas properties are ontological entities. Properties may be *intrinsic*, that is inherent to individual things, or they may be *mutual*, that is properties of pairs or n-tuples of individuals. Solubility is an example Turvey gave of a mutual substantive property. Intrinsic and mutual substantive properties are equally real.

Turvey characterised affordances as substantive properties rather than as attributes. This establishes their ecological reality and makes them independent of the epistemological or perceptual state of the agent in a way which makes the analysis consistent with Gibson's claim that affordances exist independently of the observer. Turvey also discussed the status of possibility. This was done in terms of a brief discussion of laws and how they are to be identified at the ecological scale. A much fuller discussion of ecological laws and the important question of whether laws must be exceptionless can be found in Turvey et al. (1981). Turvey defined a law as "an invariant relation between or among substantial properties of things." Turvey (1992, p.177). He then argued that laws prescribe what can happen but not what must necessarily happen at a particular time. Actual occurrences depend on circumstances as well as on laws. Turvey then identified real possibility with lawfulness rather than with lawfulness plus circumstances. This allows for exceptions and shows, if his arguments are sound, that although an affordance may or may not be actualised on a given occasion, it is nonetheless a real possibility that embodies an ecological law and not one that is dependent on the current conceptualisation of an agent. Thus the fact that an agent eats an apple rather than using it as a missile leaves open the real possibility that apples afford throwing as well as nourishment.

Turvey argued that to understand how affordances embody laws it is necessary to consider real possibility in dispositional terms. He suggested that dispositional properties are fundamental to affordances and that they have three key characteristics; dispositions precede activity, they come in pairs whose members complement each other, and they are always actualised in suitable circumstances.

In the light of his analysis of properties, laws, possibility and dispositions Turvey offered a tri-partite characterisation of affordances. They are real possibilities, they are dispositions and they are complemented by effectivities. Thus, “An affordance is a particular kind of disposition, one whose complement is a dispositional property of an organism.” Turvey (1992, p.179). Turvey provided a more formal characterisation of affordances that makes his commitments precise. This was done in terms of what he called a “joining” or “juxtaposition” function. The juxtaposition function is analogous to the formal dualities of Shaw & Turvey (1981) but is quite different in detail. Consider an entity X with dispositional property p and an entity Z with dispositional property q. $W_{pq} = j(X_p, Z_q)$ is the unit formed by X and Z being conjoined in an appropriate way such that a third property r is made manifest. r is a mutal or relational property of the second order unit W_{pq}. Turvey gave the example of a prism that refracts light. Refractibility is a dispositional property of light, refraction is a dispositional property of a prism, and when a prism and light are brought together in appropriate circumstances, as in Newton’s famous demonstration of the spectrum of visible wavelengths for example, they yield "a light-bending-in-prism system" Turvey (1992, p.179). What is not clear from Turvey's example is whether the manifest property *r* should in this case be identified with the bending of the light or with the manifestation of the rainbow hues of the spectrum. It might, in fact, be better to think of *r* as a member of a set *R* of properties, because there is no reason in principle why the juxtaposition of the entities *X* and *Z* should lead to only one manifest property. Turvey applied the ideas of a system W_{pq} formed by juxtaposition and a new property *r* to define both affordances and effectivities. If *X* is an entity with property *p*, *Z* is an entity with property *q*, and W_{pq} is the juxtaposition of *X* and *Z*, then *p* is an affordance of *X* and *q* is an effectivity of *Z*, if and only if there is a third property *r* such that three conditions hold;

C1. $W_{pq} = j(X_p, Z_q)$ possesses *r*

C2. $W_{pq} = j(X_p, Z_q)$ possesses neither *p* nor *q*

C3. Neither *Z* nor *X* possesses *r*

This definition ties affordances and effectivities together. It stipulates that affordances and effectivities exist if and only if there is a transformation of the properties *p* and *q* of *X* and *Z* to the property *r* of W_{pq}. This formal definition cannot be right because it is too restrictive. C2 rules out many of Gibson's examples of affordances. Turvey's paper gives only one example of C2. "The disposition *p* of salt to be soluble rests with the fact that it is a lattice of electrically charged ions bound by an electrical attraction between opposite charges…The salt-dissolved-in-water system lacks the attraction between ions; it does not possess *p*." Turvey (1992, p.181). C2 works in this instance but there are many others where it does not. Consider the affordance of grasping again. "To be graspable, an object must have opposite surfaces separated by a distance less than the span of the hand." Gibson (1979, p.133). Using Turvey's formalism, a person who perceives the affordance of grasping is *X*. The property *p* of *X* is their hand-span, which is *k* units measured in some appropriate scale. *Z* is the object that affords grasping, and *q* is the property that *Z* has opposite surfaces less than *k* units apart. W_{pq} is the hand-grasping-object system. C2 requires that *Z* affords grasping and *X* effects grasping if and only if W_{pq}, the actualised hand-grasping-object system, possesses neither *p* nor *q*. This cannot be correct. A hand-span is not changed by the act of grasping, nor, in general, is the distance between opposite surfaces of an object changed when it is grasped. A similar objection can be made with respect to many other affordances. Cups do not lose the properties that afford drinking when we use them for that purpose, nor do agents lose the properties that afford social life when they interact with each other. It is so obvious that C2 is too strong that one might wonder why it was included. C1 and C3 seem sufficient to bind affordances and effectivities together.

Greeno’s analysis of affordances.

Greeno (1994) discussed affordances in a paper which draws on situation theory, (Barwise & Perry, 1983; Barwise, 1989; Devlin, 1991). Greeno makes the fundamental point that “In any interaction involving an agent with some other system, conditions that enable that interaction include some properties of the agent along with some properties of the other system.” Greeno (1994, p.338). He characterises affordances as the relevant properties of the environment in agent-environment interactions and uses the term “ability” to describe the contribution of the agent. Greeno’s emphasis on the study of conditions that enable interactions between animals and their environments shows that his analysis tackles some of the issues that Shaw & Turvey (1981) were engaging with when they described grains of analysis as contexts of constraint.

Greeno suggests, citing the work of Warren & Whang (1987), that the most productive empirical work on affordances has treated them as graded properties. A graded property, in Greeno’s terms, is one that admits of degrees of presence. Loudness is an example. A sound can vary continuously from a scarcely perceptible whisper to a painful roar. Greeno also suggests that the use of different formal systems can promote the development of theoretical perspectives and proposes that situation theory provides a natural way to treat affordances. Linking ecological psychology and situation theory is a promising strategy. It seems particularly apposite in the context of Gibson’s proposal that affordances provide a new theory of meaning, because situation semantics is committed to a form of realism that fits well with Gibson’s thinking. Barwise (1989, p.51) says that situation semantics is committed to the claim that “meaning does not reside in the head or in some mysterious realm but in the interaction of real, living things and their actual environment.”

Greeno’s specific proposal is that affordances and abilities can be characterised as conditional constraints as these are understood in situation theory. This proposal is less convincing than the general case for thinking about ecological psychology in situation theoretic terms as an analysis of the core terms shows. A football match is a situation and so is a marriage. We speak of facing threatening situations, such as becoming unemployed or falling ill, or experiencing a change in our situation as a result of winning a lottery or receiving an inheritance. What counts as a situation for an individual depends on their scheme of individuation that is on how they understand the world. Roughly speaking, a situation is a structured part of the world that an agent treats as an entity and that has particular relations to behavior. Individual situations belong to one or another situation type. Two football matches belong to the same type even though the players may be different, the results may be different and the locations and times of play are different. Situations belong to the same type by virtue of sharing aspects of structure such as a set of rules, a causal sequence or common perceptual elements. A situation type is a class of situations with one or more specific relational properties. Some types are systematically related to other types. In Association Football, the type of situation called a “win” is systematically related to the types of situations describing the number of goals scored by each side. Side A wins a match against side B if and only if it scores more goals than side B. The dependencies that exist between situation types are called constraints, and it is constraints that make situations meaningful. The constraints that determine what counts as winning a football match are conventional, but there can also be natural, causal constraints between situation types. A common example is enshrined in the saying "There's no smoke without fire." The saying implies the existence of the constraint that all situations of the type where smoke is present are also situations of the type where fire is present.

Many, perhaps most, constraints do not hold absolutely but are conditional upon background circumstances. Barwise (1989) gives an example involving his daughter Claire. When she was very small Claire rubbed her eyes when she was sleepy but not otherwise. As a result Barwise and his wife came to believe that all the situations in which Claire rubbed her eyes meant that she was sleepy. They believed that there was a systematic relation or constraint between the type of situation described by "Claire rubs her eyes" and the type described by "Claire is sleepy" such as to justify the inference "If Claire rubs her eyes, she is sleepy". Thus they believed that Claire's rubbing her eyes *meant* that she was sleepy. In due course, however, it became obvious that Claire was also rubbing her eyes at times when she was not sleepy and the Barwises concluded that she was suffering from an allergy. This meant that "If Claire rubs her eyes, she is sleepy" no longer held without exception but only in cases where the allergen was not present. Thus the constraint was conditional on the absence of the allergen.

A conditional constraint, therefore, is one that holds relative to certain background conditions, which may be positive or negative, and Greeno's analysis identifies affordances and abilities as those background conditions under which constraints do, in fact, hold. The attraction of this idea is that it gives a clear sense of the relational nature of affordances and Greeno discusses a number of examples including using a doorway to enter a room and changing the direction of a car by moving the steering wheel. One might also consider Gibson’s characterisation of a surface of support. “If a terrestrial surface is nearly horizontal (instead of slanted), nearly flat (instead of convex or concave), and sufficiently extended (relative to the size of the animal) and if its substance is rigid (relative to the weight of the animal), then the surface *affords support*.” Gibson (1979, p.127). In situation theoretic terms, a constraint exists between situations involving horizontal, flat, extended, rigid surfaces and situations involving the support of animals when appropriate background conditions link the extension and rigidity of the surface to the size and weight of the animal.

The principal problem with Greeno’s idea is that it runs counter to two of Gibson’s ideas, that affordances are meanings and that some of them are directly perceptible. Consider again the case of baby Claire Barwise. It seems natural and in keeping with Gibson’s intentions to suppose that it was Claire’s rubbing her eyes that afforded the inference that she was sleepy. This identifies the affordance with the constraint rather than with the conditions under which it holds and is compatible both with the affordance being a meaning and with it being directly perceptible. That is not what Greeno’s proposal suggests. Greeno’s proposal suggests that the affordance should be thought of as the absence of the allergen since that was the condition under which the constraint held. But the absence of the allergen is neither directly perceptible nor a meaning. It is certainly true that if conditions fail then affordances fail, but conditionality is probably better used as an explanation for the misperception of affordances than as a characterisation of them.

It seems, therefore, that it would be better to think of affordances as constraints linking situation types rather than as the conditions under which constraints hold. Even then, it is not clear that the analysis works quite as required because the concept of a constraint is broader than the concept of an affordance. Constraints are relations between situation types and these can be of many kinds whereas affordances are quite specifically relations between an animal and its environment. Thus affordances would have to be specified as particular classes of constraints, namely those involving agents. Greeno was right to draw attention to situation theory as a source of ideas for the formal development of Gibson's principal ecological concepts but the specific analysis he proposes needs to be reconsidered.

Turing machine theory.

The key feature of an affordance is that it is something "that refers to both the environment and the animal…It implies the complementarity of the animal and the environment." Gibson (1979, p.127). This feature must be captured in an adequate formal treatment of affordances. Shaw, Turvey and Greeno treat the term "affordance" as having a purely environmental reference and use the terms "effectivity" and "ability" to refer to the animal's contribution to action. The environmental and animal components have then to be bound together in a way that demonstrates their complementarity. Shaw and Turvey (1981) use dualities for this purpose, Turvey (1992) uses the juxtaposition function and Greeno (1994) proposes that both affordances and abilities are conditional constraints on successful performance of an action.

The treatment of affordances in purely environmental terms rests on Gibson's emphasis on the physical reality of affordances and their independence from the observer's perception. However, he also wrote passages in which the distinction between the environment and the animal is much less clear. In a classic example, Gibson (1979, p.129, he says:

> But, actually, an affordance is neither an objective property nor a subjective property; or it is both if you like. An affordance cuts across the dichotomy of subjective-objective and helps us to understand its inadequacy. It is equally a fact of the environment and a fact of behavior. It is both physical and psychical, yet neither. An affordance points both ways, to the environment and to the observer.

This suggests that the term "affordance" was intended to make reference to the animal and to the environment in a way which is not quite caught by either Greeno's or Turvey's analysis. The challenge, then, is to find a way to characterize affordances which can do justice to Gibson's complex intuitions in a clear and productive fashion. The proposal advanced here is that a treatment of affordances and effectivities in terms of the theory of Turing machines captures the essence of these concepts in a profound and illuminating way.

Turing's analysis of computation.

Alan Turing was a British mathematician who developed the concept of the abstract computing machine that now bears his name. In a famous paper, Turing (1936-7), he analysed the processes involved in the calculation of a number using pencil and paper. His investigation was intended to include all numbers that could be calculated using a finitely specified rule. Thus it included mundane numbers like those that result from adding up the prices of items in an invoice and more exotic numbers like π, whose full representation involves an infinite number of digits. Turing's analysis was an ecological one for at least the following two reasons. First, its fundamental objects, people who calculate and the numerals they write on paper, are defined at the ecological scale, Gibson (1979, p.9). Second, the analysis formalized the operations of a relational system consisting of an agent who reads and writes symbols using the structured environment of paper ruled into squares. The system as a whole carries out numerical computations. The analysis was not concerned with purely mental arithmetic, although it makes reference to the internal states of the person calculating. The paper and pencil are essential parts of the system and cannot be dispensed with.

Turing's paper was concerned with foundational issues in mathematical logic which go beyond the scope of the present paper. However, his investigation explored the fundamental notion of a definite method in mathematics and this aspect of his work is directly relevant here. It is clear that a definite method must be finitely specifiable. To this

Turing added the insight that it was in the nature of a definite method that it could be applied mechanically. Informally, this might mean no more than the fact that an over-learned method can be applied without thought. But Turing took the idea a step further and argued that if a method really was definite, then a machine could, at least in principle, be designed to carry it out. He therefore considered what processes a human, working with pencil and paper, might possibly use in calculating a number according to a finitely specified rule with a view to building a machine to perform such calculations. The outcome of Turing's analysis was a class of abstract machines, now called Turing machines. Every Turing machine has components modelling the agent and components modelling the external environment. These components can be used to model affordances and effectivities in the following way.

An affordance *A* is defined as an ordered pair (*q*,*a*) in which *q* is an animal referential term and *a* is an environment referential term. *A* represents a situation in which an animal in functional state *q* perceives an entity *a*. In Turing machine theory pairs of this kind are called "configurations".[5] An effectivity *E* is defined as an ordered triple (*b*,*p*,*k*) in which *b* is an environment referential term, *p* is an animal referential term, and *k* refers to both because it represents a movement of the animal relative to the environment. *E* represents a situation in which the animal carries out behavior *b*, changes its functional state to *p* and moves in direction *k*. In Turing machine theory, triples of this kind are called "actions". Configurations and actions are combined in "instructions". A Turing machine instruction has the form $(A,E) = ((q,a),(b,p,k))$. (A,E) represents a situation in which an animal perceives the affordance *A* and effects the behaviors in *E*. It is helpful to think of instructions as the arguments and values of a function ϕ that maps affordances onto effectivities. A set of instructions constitutes the "machine table" for a Turing machine. It specifies all the configurations and associated actions which define the machine. When configurations and actions are used as models of affordances and effectivities the machine table specifies a set of affordances and their associated effectivities. Thus, in Gibson’s terms, a machine table specifies a niche. The complementarity between animal and environment is captured in the way that the set of instructions relating affordances to effectivities specifies the way that the animal behaves. Turing machines have both structure and dynamics and are thus capable of providing models of the animal, the environment and behavior.

In the brief description above, there are animal referential and environment referential terms. These need further explanation. An affordance is defined as an ordered pair (q,a). q is a member of a finite set Q which enumerates the functional states of an animal. In Turing’s original work, the members of Q were formal analogs of the “states of mind” of a human computer but the restriction to states of mind is not an essential part of the definition. Q is a finite set of functional states of an animal, which may include functional states other than states of mind. It was an important part of the definition of the Turing machine that the state set was finite, and this is carried over into the current context. However, Turing’s work was entirely non-committal about how the functional states might be instantiated in any particular case. The formal scheme simply specifies the relations among states and between states and their inputs and outputs. It was important in Turing’s theory that a machine could, in principle, be built to realise the abstractly defined set of functional states but no constraints were imposed on their realisation. There is, in particular, no requirement that the functional states are, or contain, symbolic representations of the external environment of the kind proposed by conventional computational theories of mind. The other term a in (q, a) is a member of a finite set S of types of entity in the environment. In Turing’s original work, S was a set of symbol types, including letters, digits and punctuation marks. This is because Turing was specifically concerned with the computation of numbers. There is no reason why other types of entity cannot also be modelled by the formal scheme.

The core features of the formal specification of an affordance as a configuration (*q*, *a*) of a Turing machine are that the sets Q and S from which *q* and *a* are drawn are finite sets, that Q is a set of functional states of an animal and that S is a set of entities in the environment of the animal. The particular interpretations that the sets Q and S were given in Turing's original work reflect his specific focus on numerical computation rather than an intrinsic limitation of the model. It is, however, an intrinsic part of the model that the sets Q and S are finite. This means that the set of affordances, which is a binary relation on Q x S, is also finite.[6] Similar points can be made about effectivities.

The formal scheme for an effectivity *E* = (*b*,*p*,*k*) contains three terms. *p* ε Q and *b* ε S are members of the same sets as the components of affordances just discussed. *k* represents a movement of the animal in its environment. In Turing's original work, the environment was a one-dimensional paper tape divided into squares. As a result, only three distinct types of movement were possible, movements left, movements right and no movements. The highly restricted nature of the original Turing machine environment was a consequence of Turing's particular interest in numerical computation and is not an intrinsic feature of the formalism. It is possible in principle to extend the set M of movements to include elements like "sit", stand", "grasp" and so forth. In practice, of course, as the history of attempts to build mobile robots shows, it is difficult to realise a formal scheme containing such movements. The key restriction on M is like those on Q and S, namely that the set M has a finite number of elements.

An example Turing machine.

This section fleshes out the introduction above with a detailed description of a machine which Turing used to illustrate his theory. Consider the activity of writing out the sequence of numbers 0,1,2,… Without the punctuation it is equivalent to a single number with digits 012… We can therefore talk equivalently about a sequence of numbers or a sequence of digits. The base of the number sequence is also irrelevant to the formal nature of the task. Turing used a unary form of representation where 1 is represented by 1, 2 by 11, 3 by 111 etc. The symbol 0 is used to represent the number zero and as punctuation. Thus the sequence 0, 01, 011, … is equivalent in unary representation to the sequence 0, 1, 2, … Although the sequence is infinite the task of writing it out is real and Turing’s abstract specification was for a machine that might, in principle, be built.

To make the situation concrete, imagine an unfortunate life prisoner who has been sentenced to the task of writing out on a paper tape (a portion of) the infinite sequence of digits produced by Turing’s machine. The hapless prisoner is locked in a cell seated at a table with the start of the tape in front of him and the unmarked tape heaped on the floor to the right. He writes 0 on the first square, 0 on the second, 1 on the third and so on. As he works, he moves the tape from right to left to bring fresh unmarked squares into place under his pencil, and the portion of tape he has written on grows steadily on the floor to the left of the table. The pencil he uses is modelled in the Turing machine by the abstract process of printing a symbol. The requirement for an indefinite quantity of paper is met by requiring the tape to be unbounded in the sense that more can be added when needed. The unboundedness of the tape is a general feature of Turing machines.

The internal states of the prisoner are modelled as a finite set of functional states. The model does not include his unhappiness, boredom, resentment or any of the other things he might well be feeling. It is concerned solely with the functional states needed for him to carry out the task at hand. The issue of finiteness of memory is important. At the start of the task, the prisoner will be able to remember where he has got to, and will be able to count out the digits of the current number from memory. But as the numbers increase in size, there will come a point at which he will no longer be able to do this because the numbers will be bigger than his memory can cope with. However, there is a way to manage the task which shifts the burden of representation from the prisoner to the environment. The representation of each number is one digit longer than its predecessor. The next number in the sequence can, therefore, be written out by copying the previous number and writing an additional 1 at the end. If each digit is marked off as it is copied, the load on the memory of the prisoner is constant. He trades load on his memory for book keeping using the tape.

The task of writing out the sequence 0010110111… can be performed by a Turing machine with four internal states. The precise details given here are slightly different from the way that Turing defined the machine but the way it works is essentially the same. A machine table for the machine HP, which simulates the hapless prisoner, is shown in Table 1.

TABLE 1 ABOUT HERE

HP is thought of as a black box equipped with perceptual and motor systems. Its perceptual systems allow it to scan a single square of the tape at a given time and to recognize that it is blank or that it contains one of the symbols indicated in Table 1. This square is called the "scanned" square. HP's motor systems allow it to erase the symbol on the scanned square, to print a symbol and to move one square to the left or right so as to change the scanned square. The environment external to HP consists of a one-dimensional tape divided into squares as discussed above. Time for HP is divided into a series of discrete moments, t_0, t_1, …, t_n which are such that exactly one instruction is carried out in each moment. The key notion is succession rather than duration; t_k follows t_j if and only if $k > j$. This does not rule out the possibility of incorporating a more realistic treatment of time into an extended formal model.

HP is started in functional state q1 scanning the leftmost square of the blank tape. The time is t_0. At this point HP is simulating the hapless prisoner at the start of his sentence. In Table 2, the first twenty eight steps in the infinite sequence of HP's operations are shown.

TABLE 2 ABOUT HERE

Every step of the machine's operations involves both its current functional state and its environment. At each step the environment, i.e. the tape, is perceived to read the symbol on the scanned square and is acted upon by printing and moving.[7] There is no notion of internal processing independently of the environment. Second, information is stored by acting on the environment not by modifying the functional states of the machine. Nevertheless there is a clear need for different functional states to manage the fact that a given input requires different actions at different times. The # symbol, for example, is part of four affordances each with a different effectivity.

The processing of the machine follows the outline suggested for the hapless prisoner. The sequence 001011011101111…is treated as a sequence of overlapping segments. Each segment is bounded by zeroes which are separated by 0, 1, 2, … ones. Thus the first three segments are 00, 010, 0110. All the zeroes except the first are printed by state q2. The first is printed by state q1 in an action that is unique because the configuration (q1, #) that causes it happens once only at time t_0. The need for this unique action can be appreciated by considering what would happen if the machine were started in state q2 rather than state q1 at time t_0. It would print a 0 on the first square and then try to move left which would not be possible because the machine at t_0 is on the leftmost square of the tape.[8] State q1 starts the machine at time t_0 with an action that simulates the writing of the first of an endless sequence of digits by the hapless prisoner. At time t_1 HP prints the second 0 on the tape. This is both the closing 0 of the first segment 00 and the opening 0 of the second segment 010. Having printed a 0 HP moves leftwards exploring the segment just completed to detect any 1s it contains. If a 1 is found a transition is made to functional state q3 which copies the 1 to the next segment. If a 1 is not found the transition is to q4 which adds an extra 1 to the new segment. At time t_2 there are no 1s on the tape because the first segment is 00 so a transition is made to functional state q4 whose effectivities move HP to the right until a blank square is encountered at t_4. The affordance (q4, #) is associated with the effectivity (1, q2, R) which causes a 1 to be printed on the blank square, moves HP one square right and makes a transition to functional state q2 to begin a new segment. The current segment is now 010 which contains a 1. This is perceived by the affordance (q2, 1) at t_6. The effectivity (X, q3, R) replaces the 1 with an X to prevent its being counted an infinite number of times and makes a transition to functional state q3. The affordances involving q3 have the single function of copying 1s to the new segment. This is achieved by moving HP rightwards until a blank square is found on which a 1 can be printed. This happens at t_8 and a transition is made to functional state q1. The affordance (q1, 0) at t_9 leads immediately to a transition to q2. It is not immediately obvious why the transition is made indirectly from q3 via q1 to q2 rather than directly from q3 to q2. The reason for this does not become clear until t_{27}. At t_{26}, HP has just copied a second 1 to the new segment. If a transition were made to q2 at this point it would misinterpret the 1 scanned at t_{27} and treat it as one to be copied rather than as part of the new segment. So state q1 is used to reposition HP at the 0 separating the two current segments. This illustrates a fundamental point about Turing machines such as HP. A given functional state can have only one set of actions defined for each symbol it can recognize. If this were not so, if for example two different sets of actions were defined for a given input symbol, a decision would have to be made about which of these was to be carried out. This would not be a simple operation in Turing's terms and it is not clear how the decision process would be mechanized.[9] From t_9 to t_{11} q2 continues to check the segment 0X0 for further 1s. No more are found so a transition is made to q4 to append the final 1 to the segment under construction. The effectivities associated with q4 also tidy up the tape as HP moves rightward by changing any Xs back to 1s. The segment is completed at t_{15} and a transition is made to q2 to begin a fresh cycle at t_{16}.

One important aspect of the structure of HP that is not clearly visible either in the machine table or in the trace of HP's processing in Table 2 is the way the functional states are related to each other by patterns of transition. This information is contained in the machine table but it is much more clearly visible in a state transition diagram. A state transition diagram for HP is shown in Figure 1.

FIGURE 1 ABOUT HERE

To summarize, HP is a deterministic Turing machine with four functional states q1, q2, q3, q4 which prints the infinite sequence 0010110111… HP is a formal model of the hapless prisoner endlessly writing out numbers in his prison cell. It is clear from the analysis that even a simple system like HP with just four functional states and an alphabet of four symbols can give rise to complex, structured behavior. That behavior is determined by the interactions between the machine and its environment as specified by its affordances and effectivities.

Configurations and Affordances

HP has fifteen affordances, i.e. its fifteen configurations. The parallels between affordances and configurations are both striking and informative but they have not previously been widely discussed because ideas derived from Turing machines have typically been used in cognitive science exclusively to characterise functional organisation inside the head of the perceiver. In such cases, the tape is treated as a model of memory and the finite state control as a model of executive processes. In fact, however, the Turing machine was developed as a model of the relation between a person and the external environment and not as a model of the mind divorced from the environment. When used to support a relational approach, as it is in this paper, the Turing machine model serves as a critique of computational cognitive science and supports the philosophical foundations of ecological psychology.

Configurations model ecological concepts.

The configurations of Turing machines are models of ecological entities because the concepts of internal state and symbol formalize aspects of the ontology of everyday life that are found at the scale of human behavioral ecology. The states and symbols of HP are models of the functional states of the hapless prisoner and his activities with paper and pencil. Configurations are also ecological models because they are concerned with the reciprocal nature of states and symbols and because they are concerned with the perceptions and actions of a control system which is unfettered with respect to its (admittedly limited) environment.

Configurations are relational.

Affordances point two ways, to the agent and to the environment. So do the configurations of Turing machines. Each configuration of HP refers to one of its internal states and to the contents of a square of its tape. Moreover, the formalisation of affordances as configurations also respects the relation of asymmetric inter-dependence between agents and environments. Interdependence is asymmetric because Gibson saw the environment as prior to animals and as the source of perceptual information for animals. The tape is the source of perceptual information for a Turing machine. There is information of a kind in internal states but a Turing machine depends on its tape for the information with which it computes. That is true even for a machine like HP which is started on a blank tape. Turing machines are provably more powerful than other classes of abstract machines precisely because they are systematically connected to an unbounded environment that is accessed at each step of their operations. Gibson's argument for the priority of the environment, which was based on evolutionary considerations, does not have an exact counterpart in Turing machine theory. It is worth noting, however, that if the environment were changed, by specifying a two-dimensional tape for example, the structure of internal states would also have to change.

The relational nature of affordances also emphasizes the mutuality of animal and environment. This point is strongly illustrated in the configurations of Turing machines. HP has the configurations that it has in order to be able to process a tape which is organised in the way that it is, and the sequence of symbols on the tape has the characteristics that it does because the internal states of HP are organised as they are.

One point where the analysis of affordances as configurations differs from Gibson is in making specific reference to properties of the agent. Although Gibson made explicit references to properties of substances and surfaces in the definition of affordances he referred to these as being taken "with reference to an animal" Gibson (1977, p.67) rather than with references to *properties* of an animal. This was done in order to avoid making affordances depend on the subjective experience of the agent. Gibson was quite explicit about this; "…affordances are properties of things *taken with reference to an observer* but not properties of the *experiences of the observer*. They are not subjective values; they are not feelings of pleasure or pain added to neutral perceptions." Gibson (1979, p.137). The difficulty with this is that it makes it hard to understand what reference to an animal can mean particularly when it is acknowledged that affordances are related "to the motives and needs of an observer" Gibson (1979, p.143). The analysis of affordances as configurations helps to clarify this difficult area. Configurations include both properties of the environment and properties of the agent, but the properties of the agent do not make configurations into subjective phenomena, nor do they necessarily make reference to the experiences of the observer. Configurations preserve the objectivity of affordances because the set S from which the s_j are drawn is a set of environmental entities. Configurations are also independent of the subjective experiences of the observer because internal states are functionally defined. It might happen that the instantiation of an internal state was such as to generate a subjective experience but such experience is not constitutive of the internal state components of configurations.

Configurations are facts of the environment and facts of behavior.

The treatment of affordances as configurations makes it very clear how they can "cut across the dichotomy of subjective-objective" Gibson (1979, p.129). Consider, for example, the configuration (q2, #) of HP. It is a fact of the environment because it occurs at particular times and places and with respect to particular squares on the tape. Table 2 shows that it occurs at times t_1, t_5 and t_{16} and, like every other configuration except (q1, #), infinitely often thereafter. It is also linked to behavior because it is associated with the effectivity (0, q2, L). Similar remarks can be made about each of the other configurations of HP. It is also clear that the internal state components of configurations function in a way that is consistent with what Gibson wrote about perceptual systems. Internal states, considered as parts of the functional apparatus of Turing machines, are active ways of paying attention to what is going on in the environment. This is particularly clear when we consider that different configurations become salient as a Turing machine moves around its tape in the course of a computation. Locomotion through the medium is a fundamental activity for animals. Locomotion across its tape is a fundamental activity for a Turing machine. Configurations show that systematic behavior depends on structure that exists both in the environment and in the agent. Behavior is derived from both of these sources of structure, but to say this is not to say that there is anything like an explicit model of the environment inside the black box of the Turing machine. There isn't. It isn't needed because the environment provides sufficient information. The structure in the black box is there to ensure that the appropriate behavior is carried out at the right places in the environment. Indeed one can think about what attunement to the environment might mean in ecological theory by considering the ways in which configurations mesh structure in the environment with structure in the agent to produce behavior. The Turing machine approach to configurations suggests, therefore, a slightly different thesis than Gibson's. It suggests not that affordances are facts of the environment and facts of behavior, but that they are facts of the environment and of the agent that are determinately linked to behavior via effectivities. The configurations of Turing machines are causally associated with their behavior but are conceptually distinct from the behavior that they cause.

A final issue concerns the nature of the links between affordances and behavior. HP shows that the links can be complex. A Turing machine configuration has two components, an action has three. Configurations are defined in terms of pairs of internal states and symbols. Since HP has four states and four symbols, sixteen configurations could be defined of which fifteen are actually used. By the same logic there are thirty-two definable actions for HP (4 states x 4 symbols x 2 movements). No more than fifteen of these could actually be used because a configuration cannot have more than one action associated with it. In fact, HP uses only ten distinct actions. This means that different configurations share the same actions. This theoretical fact leads to an empirical question. Would the general expectation be that animals have fewer effectivities than affordances? It is plausible to think so. Many things, for instance, afford eating but eating is a single type of activity. Similar considerations apply to other activities like throwing and grasping.

Sets of configurations constitute niches.

When affordances are treated as the configurations of Turing machines, Gibson's idea that sets of affordances constitute niches comes into sharp focus. There are three main components to the niche concept; it specifies the way of life of an animal, i.e. how it lives rather than where it lives, it suggests that sets of affordances have a certain unity or coherence and it suggests that different animals that share aspects of their ways of life have affordances in common. The set of configurations of a Turing machine certainly specifies how it functions rather than where it functions. The tape is where it functions and this is the formal equivalent of the habitat of an animal. But it seems insufficient to call the set of configurations of a Turing machine a niche, because that leaves out of account the fact that the course of a Turing machine computation depends not just on its configurations but also on how the tape, i.e. the environment, is organised at the start of a computation. HP starts on a blank tape but many other Turing machines, in particular all members of the important class of universal machines, depend on structure on the tape at the start of a computation. The treatment of affordances as configurations suggests that the concept of a niche is actually richer than Gibson proposes; it consists of sets of affordances plus a specification of the structure of the environment. A niche, in other words, is a habitat plus a set of affordances.

The idea that sets of affordances have a certain unity or coherence is also true of sets of configurations. HP has the set of configurations that it does and not another set, because the set that it has is needed to perform the task. The point is not that the task could not be handled by another set of configurations but that the members of the particular set defined for HP go together. They jointly define the control structure of the machine. This suggests a strong claim about the coherence of a set of affordances, namely that a set of affordances is constitutive of the ecological specification of an animal.

The idea that different animals may have sets of affordances in common is also one that can be illuminated within the Turing machine framework. HP does not demonstrate the point because it is a very simple machine, but more complex Turing machines are often built using identical sub-machines to carry out common tasks. Turing designed his celebrated universal machine in just this way. This idea can be used in two ways; it shows how Turing machines may have replicated structure if they carry out the same sub-task at different times or with respect to different aspects of their environments and it shows how different Turing machines may have structure in common if they have sub-tasks in common

Configurations are meanings.

The treatment of affordances as the configurations of Turing machines leads to a re-interpretation of Gibson's claim that affordances are meanings. In the light of Gibson's characterisation of affordances as properties of the environment taken relative to the observer, the thesis that affordances are meanings makes them external to and independent of the observer. The treatment of affordances as configurations brings the states of the observer into the definition. This implies that meanings are not entirely external to the observer. However, bringing external states in, in this way, does not make meanings a property of the experiences of the observer. The environmental term in a configuration is both real and external to the observer. It is not, therefore, a subjective experience.

Treating affordances as configurations also helps one to understand the subtle, layered nature of meaning. Three ideas can be distinguished. The meanings of configurations are contextual, configurations are meaningful at more than one level and their meanings are intrinsically linked to the activities of a machine. Consider HP again. The meanings of its configurations are contextual because they can only be understood properly in relation to each other and to the symbol structures on the tape. The configuration (q4, #), for example, illustrates the importance of context. (q4, #) means that HP has reached the end of the printed portion of the tape and that a 1 has to be printed to complete the current number in the sequence. This depends on (q4, #) occurring only after any 1s encountered by HP in state q2 have been copied by the activities of HP in state q3. It also depends on there being no gaps in the printed sequence.

The idea that configurations are meaningful at more than one level can also be illustrated using (q4, #). Each time it occurs it means that another number in the sequence has been completed. Thus on its first occurrence it means that 1 has been completed, on its second occurrence that 2 has been completed and so forth.

The idea that meanings are intrinsically linked to the activities of the machine is illustrated by every configuration. Even here there are some subtleties of interpretation. Different configurations can be associated with the same action. (q3, #) and (q1,1) both trigger the action (1,q1,L). In this case the meanings are different. However, in other cases, different actions arguably have the same larger scale meaning. The configurations (q3, 0), (q3, 1) and (q3, X) have different actions associated with them. But each of those actions moves HP one square to the right as part of a sequence of behavior that seeks the first available blank square in order to print a 1 on it. Their meanings, at this higher level, are the same even though their micro-meanings are different.

Configurations are invariant combinations of variables.

In one simple sense, this point is obviously true. Each configuration of a Turing machine is an invariant combination of variables, one internal state and one symbol. (q1, #), for example, is the invariant combination of the internal state q1 and the symbol #. However, there are more important parallels than this between configurations and invariants. First there is the notion that invariant structure in the environment is the source of information for the perceiver. This idea is true for Turing machines. Symbol tokens are the source of information for a Turing machine. This is true even for machines like HP which start on a blank tape. The first configuration (q1, #) registers the environmental information that the currently scanned square is blank. The interaction of squares and symbols demonstrates a fundamental reliance on invariant structure. The basic property required of the symbol alphabet of a Turing machine is the invariant property “type identity”. Type identity is the requirement that a token of a given symbol, 0 for example, must be identifiable as a token of that symbol and must be distinguishable from the tokens of any other symbol. This does not mean that symbol tokens must share all their properties. The Turing machine treatment of affordances provides an opportunity to examine the use of invariant structure in the service of behavior.

The formal structure of Turing machines may also serve to illuminate the link between evolutionary processes and affordances that Gibson discussed in various places. His point was that some environmental invariants had remained constant during millions of years of evolutionary history and had determined the life and behavior of animals. The permanent structure of the environment, in other words, had causal agency in the determination of the basic behavioral repertoire of a species. A natural question to ask once one recognizes this point is how the permanent structure of the environment is related to the organic structures that define animals and support their perception and behavior. Gibson's own work was not focused on this question although he recognized its importance. The clarity and simplicity of Turing machines can help us to understand what issues are salient even though Turing machines are designed artefacts rather than products of evolution. This is not the place for a lengthy discussion, but a number of points may usefully be mentioned. First, some internal structuring in machines and organisms is a pre-requisite for successful action. A Turing machine without internal states cannot do anything and an animal without internal states cannot do anything either. Second, there is a theoretical trade off between structure in the organism and structure in the environment. Any Turing machine computation can be carried out by a machine with only two internal states provided that the symbol alphabet is made large enough. This was proved by Claude Shannon and is discussed by Minsky (1967). Conversely, it can also be shown that any computation can be carried out using a two symbol alphabet provided the set of internal states is large enough. These results show that one cannot decide, *a priori*, whether a particular behavior results from structure in the environment or structure in the organism. Every behavior will depend on both types of structure and the balance between them is a matter for empirical determination. The fact that there may be sufficient structure in the environment for unambiguous normal perception does not, therefore, preclude the need for and use of internal structure to support perception and produce behavior. The Turing machine model suggests that structure in the organism complements structure in the environment. Behavior results from the co-ordination of perception and the possibilities for action that the environment affords at a given time and place. This is true for people as well as artificial machines.

Configurations are perceived directly.

The activity of a Turing machine as it scans and moves around its tape provides a promising formal model of direct perception. First it is noteworthy that Turing's terminology makes reference to visual perception. The control of a Turing machine scans its tape and recognizes symbols printed on squares. This recognition is "direct" in Gibson's sense of the word even though the object of perception is a symbol. There is no mediation via a picture of any kind. The current internal state does not construct a representation of the symbol on the scanned square nor infer its existence, it simply recognizes it. Second, the process of symbol recognition is part of a process of getting around the environment constituted by the tape. HP's movements back and forth are controlled jointly by its internal states and by the symbols on its tape. In this sense its activities can serve as a model of the process of information pickup. The theory of direct perception does not preclude an active role for the organism. Indeed, it is essential. "Gibson makes it clear in his current theory that one can only have direct perception if the environmental and organismic components of perceptual theory are compatible. Presumably they will be compatible only if one develops each component of the theory with an eye to the other." Mace (1977, pp.46-7).

The status of internal states in abstract machine theory.

The concept of an internal state stems from Turing's original analysis of computation but the need for an internal state variable in abstract machine theory was challenged by

Robert Shaw and James Todd in their response to Ullman (1980). Shaw and Todd questioned Ullman's fundamental assumption that perception requires internal cognitive states. They framed the issues in terms of two questions about machine theory. First, is the state variable a necessary term in all abstract machine descriptions or can it be replaced with some other term filling the same formal role? Second, if the state variable is used, need it be given the standard cognitivist interpretation as an internal representation which causally mediates perceptual effects or can it be treated as something other than a reified internal state? If it can be shown that the abstract machine theoretic approach to perception need not involve internal states, then, *a fortiori*, the computational approach need not involve them either. If that is so, then Gibson cannot be criticised by computationalists such as Ullman for leaving internal states out of his theory of perception. Shaw and Todd argue that the state variable can be dispensed with in abstract machine theory and claim, in consequence, that Ullman's critique of Gibson collapses. If their argument is sound it also undermines the argument developed in this paper.

The foundation on which Shaw and Todd based their argument is the "classes of histories" approach to abstract machines, (cf. Minsky 1967, pp.14-16). The starting point is an animal or machine *A* with a history of interaction with an environment *E*. *H(t)* denotes this history up to time *t* and includes all the effects of *A*'s relationship with *E* including inputs and outputs. Assuming that the states of affairs in which *A* has participated up to time *t* constrain its response to the next input *S*, the response can be described in terms of a function *F* which is such that $R(t+1) = F(H(t), S(t))$. Shaw and Todd note that this formulation makes no reference to internal states of the machine *A* but is based purely on the current input *S(t)* and the history *H(t)* of *A*'s interaction with *E*. Why then do machine theorists typically make use of the notation *Q(t)* to describe a machine's internal state at time *t*? Shaw and Todd argue that it is purely a convenience which allows the theorist to avoid having to consider the entire, cumbersome, history of transactions that may reach back to the remote past. "The variable *Q(t)* has no meaning of its own, except what is derived from the history term *H(t).*" Shaw & Todd (1980, p.401). They further argue that even if the theorist adopts *Q(t)* as a convenience there is no need to reify it as an internal state. Quoting Minsky (1967), they suggest that *Q(t)* can equally well be described as an external state. From this Shaw & Todd (1980, p.401) conclude:

> The fundamental insight suggested by Minsky's observation is that the variables *Q(t)* and *H(t)* have at least two possible semantic interpretations. Whereas the cognitive interpretation describes them as "internal states" the behavioral interpretation describes them as "external states". This implies that the two views are complementary and, therefore, there must exist commensurate formal characterizations under which the two views possess the same explanatory power.

Since *Q(t)* stands for the internal states of a Turing machine such as HP, it is clear that Shaw and Todd's view represents a challenge to the construal of affordances in this paper. In his response Ullman suggested that the classes of histories approach was descriptively correct but was unsatisfactory as a psychological theory.

There are stronger reasons than Ullman gave for rejecting the approach favoured by Shaw and Todd. While it is true that the term *H(t)* refers to the entire history of transactions of a machine with its environment, a particular history refers to what has happened inside the machine whose history it is, as well as to the inputs the machine has received and the outputs it has produced. Minsky makes this clear when he discusses what would happen if we were to "disconnect" a machine from its environment and give it an input. The machine would respond with an output from the set that it can produce and the question is which one. "Just which signal r_j occurs at $t + 1$ would depend, of course, both on which signal s_i is chosen at time t and on the state of affairs inside M at time t." Minsky (1967, p.15). Minsky then goes on to say that if one assumes that the state of affairs inside *M* is determined by the history of *M* then the response produced at a given moment can indeed be understood as a function of the history of the machine and the current input. Thus Shaw and Todd are wrong to say that the state variable *Q* has no independent meaning apart from the history *H*. It refers independently to the state of affairs inside *M*. That state of affairs can be treated implicitly and wrapped up in a description of the machine's transactions with its environment but it does not disappear.

Shaw and Todd's argument misses the point of the classes of histories approach to the definition of internal states. The point of abstract machine theory is to study machines that can be made from a finite set of parts. There are many good reasons for wanting to do this, not least the fact that every constructible machine, natural or artificial, must in fact be made from a finite set of parts. Turing's starting point was the idea that a mechanical model of a human computer could have only a finite number of machine configurations. The classes of histories approach to internal states uses this finitude to good advantage. For any given machine, one can imagine an infinite variety of possible histories. Some of them will be indefinitely long and events from the far distant past may contribute to determining the response of the machine in the present. If every separate event in an indefinitely lengthy history left an independent trace the machine would need an indefinitely large memory capacity to remember them all. A machine made from a given set of *n* parts could not, therefore, possibly store a complete record of the events of an arbitrarily long history. This means that the machine could not, in its behaviour distinguish between all possible histories. Minsky discusses at some length the notion of an equivalence class of histories as a set whose members are indistinguishable from each other but distinct from the members of any other equivalence class. The equivalence class concept, he says, "brings us to the key postulate of the theory of finite automata. We assume that *the machine can distinguish, by its present and* *future behavior, between only some finite number of classes of possible histories. These classes will be called the 'internal states' of the machine*." Minsky (1967, p.16). The concept of an internal state inescapably refers to the finite set of parts out of which a machine is built, but is completely agnostic about the precise details of their implementation. From the standpoint of ecological psychology this is pivotal for two reasons. First, the inescapability clause shows that behavior cannot properly be understood without reference to internal states. But equally importantly, the fundamental agnosticism about implementation shows that there is no a priori reason for supposing that internal states must be arranged as internal representations in the fashion insisted on by computationalists like Ullman. It is the characterisation of internal states that is important not the question of whether they are needed or not and it is this point that Shaw and Todd could more profitably have made the cornerstone of their critique of Ullman. Moreover, although in his later works Gibson says things that look like an outright denial of the need for internal states, reading him this way makes his position both within and between books inconsistent. If he is read as denying only the thesis that internal states must be arranged as structured representations that constitute the basis for perception of the world, then the way is open for an account that builds, for example, on the notion of resonance or some other notion, such as that developed in this paper, that is compatible with an account of perception as direct. One might here notice, as Minsky observes (cf. Minsky 1967, p.17), that although the internal state of a machine at time *t* depends on the whole history of the machine, the dependencies with respect to the past and the present can be separated. Thus one can acknowledge with Gibson that the perceptual systems of an organism depend on the remote past and were evolved with respect to it, without having to concede that perception now depends on memories. The notion of an internal state does not have to be understood in term of memory traces although it is acknowledged that the history of an organism's interaction with an environment has had an impact on its structure. This understanding of internal states also helps with the analysis of how affordances can both be learned and directly perceived. The learning of an affordance increases the set of distinguishable internal states of the learner in a way that enriches the learner's behavioral repertoire. This may, but need not, include a memory of the learning episodes.

Universal machines.

The discussion thus far has been focused on the example Turing machine HP. HP is a mono-functional or special purpose Turing machine. It carries out only one task, the production of the sequence 0010110111… A countable infinity of special purpose Turing machines can be defined each of which carries out a specific computation. Turing wanted to know what, if any, limits there were to mechanical computation. To this end he designed what he called a "universal" machine. In one sense the universal machine was a Turing machine like any other. It was defined in terms of a finite set of internal states and a finite set of symbols and its control structure could be specified in a machine table. In another sense the universal machine was different from other Turing machines. It was not started on a blank tape like HP but on a tape containing a string of symbols representing the machine table of a Turing machine known as the target machine. The universal machine was able to interpret and act upon this string of symbols and thus to produce the output that the target machine would have produced even though its own control structure was different. The machine was universal in the sense that it could interpret the machine table of any of the countable infinity of definable Turing machines. It was, therefore, the abstract ancestor of the programmable computers that we have today.

The universal machine concept provides a way of extending the formal treatment of affordances begun in this paper. It provides resources for thinking about Gibson's analysis of depiction in Part Four of *The Ecological Approach to Visual Perception* and also for understanding the significance of the other forms of display that humans have developed. The universal machine concept, properly understood, also provides further evidence for the basic Gibsonian proposition that the information for perception is to be found primarily in the environment. An adequate discussion of these issues would probably double the size of an already lengthy paper and will have to be tackled elsewhere. Readers who are interested in the topic of universal machines can find an accessible introduction in Minsky (1967). Turing's own universal machine, which can be found in his 1936 paper, is a wonderful construction and repays careful study but Turing makes no concessions to his readers and his notation is not easy to grasp at first sight.

Conclusions.

Turing's theory of computation provides a suitable formal model for studying Gibson's theory of affordances. There are striking and previously unrecognized parallels between the two theories and a grounding in each theory enriches one's understanding of the other. Turing's theory also provides a clear formalisation of the concept of effectivity which many theorists believe is needed to supplement Gibson's account of affordances. At the start of *The Ecological Approach* Gibson suggested that what psychology needs "is the kind of thinking that is beginning to be attempted in what is loosely called systems theory." Gibson (1979, p.2). Systems theory had its origins in, among others, the work of Wiener on cybernetics and Shannon and Weaver on information theory. Both cybernetics and information theory draw on ideas which were originally formalized by Turing. At the end of *The Ecological Approach* Gibson also said of the terminology and concepts of invariants, "These terms and concepts are subject to revision as the ecological approach to perception becomes clear. May they never shackle thought as the old terms and concepts have!" Gibson (1979, p.311). Formal treatments of affordances and effectivities will be valuable only to the extent that they help to develop rather than shackle the ecological approach. It is to be hoped that the community of ecological psychologists will come to see Turing’s analysis of computation as a fruitful aid to the development of their theories.

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Footnotes.

1. Shaw and Turvey vary their choice of notation. Sometimes they use (x,y) to denote an ordered pair, at other times they use <x,y>.

2. The definitions of X and Z are in conflict with the stipulation that X and Z are to be subsets of B. X and Z, as ordered tuples, are elements of B, not subsets.

3. Strictly speaking, given the definition B = {X, Z}, B should be defined as {{ball-diameter}, {hand-span}}. However, it is clearer and seems more in keeping with Shaw and Turvey's intentions to define B as the union of X and Z.

4. Shaw and Turvey say (p.391) that V = A x E x {+,-} but this cannot be correct given other things they say about V.

5. The notation (a,b) for an ordered pair is more commonly used in the theory of computation than the notation <a,b>.

6. Strictly speaking, affordance types.

7. When the machine reads and prints the same symbol, as in step t_2 for example, there is no formal distinction made between leaving the symbol unchanged and erasing and re-printing it.

8. If a Turing machine encounters circumstances for which it does not have any actions defined, it stops.

9. The control mechanism of HP is a deterministic finite automaton (DFA). It is possible to define non-deterministic finite automata (NFA) in which state changes are only partially determined by the current state and input symbol. Non-determinism of this kind does not increase the computational power of the automaton since for any NFA it is always possible to construct a DFA to compute the same function.

Table 1. The machine table for the four state, four symbol Turing machine HP.

	#	0	1	X
q1	0,q2,R	0,q2,L	1,q1,L	
q2	0,q2,L	0,q4,R	X,q3,R	X,q2,L
q3	1,q1,L	0,q3,R	1,q3,R	X,q3,R
q4	1,q2,R	0,q4,R	1,q4,R	1,q4,R

Note. The first row of Table 1 shows the symbols that can appear on HP’s tape. These are the environmental components of the affordances of HP. The # symbol is used to indicate a blank square. Thus, HP can recognise when a square is blank or when it has a 0,1 or X on it. The symbol X is used for bookkeeping purposes. It enables the machine to count the 1s it has to copy. The first column of Table 1 shows the different functional states that HP can be in. These are the animal components of the affordances of HP. They are labelled q1 to q4. The use of the letter *q* is a convention that stems from Turing’s own work. The entries in the body of the table indicate the actions that HP carries out. They are the effectivities of HP. If, for example, HP is in state q1 reading a blank square, then the affordance (q1,#) is actualised. The corresponding effectivity is (0,q2,R). This means that HP prints a 0 on the blank square, moves right one square and makes a transition to functional state q2. The movement and the change of functional state lead to the actualization of a new affordance (q2,#). This leads to the behaviour indicated by the effectivity (0,q2,L) and so forth.

Table 2. A trace of the first twenty eight steps of the computation performed by HP.

Time	Tape	Configuration	Action
t_0	(#)# # # # # # # # #	q1,#	0,q2,R
t_1	0(#)# # # # # # # #	q2,#	0,q2,L
t_2	(0)0 # # # # # # # #	q2,0	0,q4,R
t_3	0(0)# # # # # # # #	q4,0	0,q4,R
t_4	0 0(#)# # # # # # #	q4,#	1,q2,R
t_5	0 0 1(#)# # # # # #	q2,#	0,q2,L
t_6	0 0(1)0 # # # # # #	q2,1	X,q3,R
t_7	0 0 X(0)# # # # # #	q3,X	X,q3,R
t_8	0 0 X 0(#)# # # # #	q3,#	1,q1,L
t_9	0 0 X(0)1 # # # # #	q1,0	0,q2,L
t_{10}	0 0(X)0 1 # # # # #	q2,X	X,q2,L
t_{11}	0(0)X 0 1 # # # # #	q2,0	0,q4,R
t_{12}	0 0(X)0 1 # # # # #	q4,X	1,q4,R
t_{13}	0 0 1(0)1 # # # # #	q4,0	0,q4,R
t_{14}	0 0 1 0(1)# # # # #	q4,1	1,q4,R
t_{15}	0 0 1 0 1(#)# # # #	q4,#	1,q2,R
t_{16}	0 0 1 0 1 1(#)# # #	q2,#	0,q2,L
t_{17}	0 0 1 0 1(1)0 # # #	q2,1	X,q3,R
t_{18}	0 0 1 0 1 X(0)# # #	q3,0	0,q3,R
t_{19}	0 0 1 0 1 X 0(#)# #	q3,#	1,q1,L
t_{20}	0 0 1 0 1 X(0)1 # #	q1,0	0,q2,L
t_{21}	0 0 1 0 1(X)0 1 # #	q2,X	X,q2,L

t_{22}	`0 0 1 0(1)X 0 1 # #`	q2,1	X,q3,R
t_{23}	`0 0 1 0 X(X)0 1 # #`	q3,X	X,q3,R
t_{24}	`0 0 1 0 X X(0)1 # #`	q3,0	0,q3,R
t_{25}	`0 0 1 0 X X 0(1)# #`	q3,1	1,q3,R
t_{26}	`0 0 1 0 X X 0 1(#)#`	q3,#	1,q1,L
t_{27}	`0 0 1 0 X X 0(1)1 #`	q1,1	1,q1,L

Note. The first column of Table 2 shows the time, the second shows the state of the first ten squares of the tape. Each symbol represents the contents of a single square, and the parentheses round one of the symbols represent the square currently scanned by HP. The third column shows the successive configurations (affordances) of HP and the fourth the successive actions (effectivities) that are taken. The state of the tape at time t_{n+1} shows the modifications made at time t_n. Twenty eight steps are needed to demonstrate all of the machine's instructions.

Figure 1. The state transition diagram for HP.

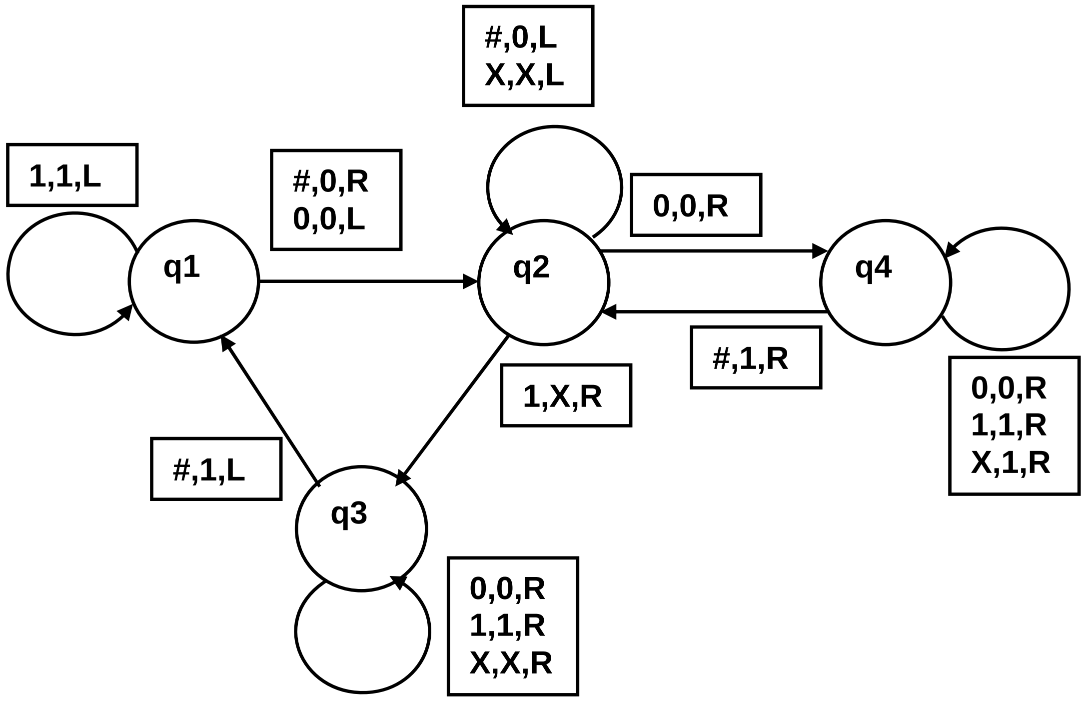

Figure . The circles in the state diagram represent the distinct functional states of HP and the arrows between circles represent the transitions between states. A transition is made from the state at the tail of an arrow to the state at its head. An arrow that returns to the state from which it came indicates a transition from a state to itself or, equivalently, no change of state. The text boxes labelling the transition arrows have one, two or three rows of symbols in them. Each row represents a particular transition. The first character is the input symbol, the second the output symbol and the third the direction in which HP moves relative to the tape. The state diagram shows the pattern of relations between functional states. States q2 and q4, for example, are immediately accessible from each other, whereas state q4 is only indirectly accessible from states q1 and q3.