Complicating the 'logic of design'

Vinod Goel

Department of Architecture, Carnegie-Mellon University, Pittsburgh, PA 15213, USA

A 'logic of design' was outlined by March in 1976. Since then it has gained wide acceptance among designers and recently has been used in several knowledge-based systems of design. This paper makes a suggestion for extending the model by taking into consideration the logical nature of the laws in the argument form. This focus on the logical nature of laws brings out interesting and subtle differences in the inference process which are lost in the current analysis. It also results in some interesting complications. It means that it is no longer adequate to talk of the three phases of design – performance prediction, knowledge acquisition, and design generation – in the simple categories of deduction, induction and abduction, respectively. In particular, it means that performance prediction is not necessarily (or even usually) a deductive inference.

Keywords: design theory, design process, logic of design

In a well known paper, March[1] outlined a logic of design. Design activity was decomposed into (i) the production of artifacts, (ii) the prediction of performance and (iii) the accumulation of knowledge, and these processes identified as abductive, deductive, and inductive reasoning, respectively. This model has gained much currency over the years and has recently been used by a number of researchers[2,3] in their knowledge-based design systems.

March derived his 'Logic of Design' by direct analogy from Peirce's logic of science. Peirce or his editors Hartshorne and Weiss, it is not clear which, is quoted as saying (p.17):

> We naturally conceive of science as having three tasks: (1) the discovery of laws, which is accomplished by induction; (2) the discovery of causes which is accomplished by hypothetic (abductive) inference; and (3) the prediction of effects, which is accomplished by deduction.

This is transposed into the following statement on design (p.18):

> We conceive of rational designing as having three tasks: (1) the creation of a novel composition, which is accomplished by productive [abductive] reasoning; (2) the prediction of performance characteristics, which is accomplished by deduction; and (3) the accumulation of habitual notions and established values, an evolving typology, which is accomplished by induction.

During the course of this discussion, deduction is defined as (p.16) 'the application of a general rule (y is z) to a particular case (x is y) to give a logically determined result (x is z)'. Induction is defined as the 'inference of the rule from the case and the results'. Abduction is defined as the 'inference of a case from a rule and the result'.

Coyne *et al.* advance a similiar model, though with a slightly different vocabulary. Instead of 'rule' they talk of knowledge; instead of 'result' interpretation; and instead of 'case' design description. They call the inference of an 'interpretation' from a 'design description' and 'knowledge' deduction. The inference of 'knowledge' from the 'design descriptions' and 'interpretation' is called induction. The inference of 'design descriptions' from 'inter-

 0142–694X/88/04229–06 $03.00

pretation' and 'knowledge' is called abduction.

The model is based on a classification of the propositions in the argument form into the categories of case/design description, rules/knowledge, and results/interpretation. This is fine as far as it goes. It is here suggested that the next step in developing the model is to realize the importance of the logical nature of the rules/knowledge/laws involved in the argument form. (March uses the term 'rules', Coyne *et al.* prefer the term 'knowledge', we prefer the term 'laws'. In this paper these three terms are used interchangeably.) In this paper we attempt to motivate the existence of three types of laws and argue that they have a different ontological status and/or logical realization. This step has some interesting consequences for the analysis as it currently stands. First it means that performance prediction is not always (or even usually) a deductive inference. Secondly, focusing on the knowledge-base brings out interesting and subtle differences in the inference process as the logical nature of the knowledge changes. This is lost in the current analysis where the focus has been on relatively unimportant, contingent matters, to the exclusion of more substantive inferencing concerns.

The next section briefly defines three types of knowledge that are pertinent to the discussion and argues for different ontological and/or logical status for each one. The subsequent section illustrates the impact of the logical nature of knowledge in the inference process.

TYPES OF LAWS

As noted above, the steps necessary to draw a conclusion from a set of premises depends in part on the laws governing the system. The laws of interest to designers can be divided into two broad categories, natural laws and laws governing complex adaptive systems. Natural laws are of either type universal[4] or statistical[5]. The laws of physics are the classical instances of natural laws. The laws that govern the behaviour of complex adaptive systems might be called quasi-laws[6]. Complex adaptive systems are those to which one can ascribe intrinsic goal-directed behaviour. (The author offers a more substantive discussion of adaptive systems in another paper[7].) The most complex and challenging such systems are individual people and the various organizational frameworks in which they participate. During the course of any design activity, a designer will be required to deal with all three types of laws, though the amount of time he allocates to each type will vary with the design task and discipline. For the present purpose, the relevant point is that there are important qualitative differences in the nature of these laws which result in differences in conceptual machinery needed for inferencing. We try to motivate these differences in the sections below.

Universal laws

Universal laws, also referred to as causal or deterministic laws, have the basic characteristics of the scientific laws of nature – they are true, non-analytic, universal generalizations – but in addition are arguably characterized by nomic necessity and hypothetical force[8,9]. Nomic necessity brings with it an element of must be, of inevitability. A universal law to the effect

All As are Bs

has the symbolic form

$(x)\ (Ax \rightarrow Bx)$

and is interpreted as

All As must be Bs.

(Note the universal quantifier in the symbolic form does not have nomic necessity and hypothetical force. Therefore in some sense it does not capture the strength and certainty of universal laws. But it is sufficient to capture the point that is being made here and in subsequent examples.)

For instance, consider the following statements:

(1) To every action there must be an equal and opposite reaction (Newton's Third Law)

(2) All Americans who watch the Superbowl like football

Statement (1) has a degree of necessity about it not shared by (2) (which though may be equally true). Statement (1) is also not confined by space and time. It applies to unrealized hypothetical possibilities with equal force.

Example:

(3) If X is an action (which it is not) then X must result in an equal and opposite reaction.

(4) If X is an American who watched the Superbowl (which it is not) then X will like football.

The nomic necessity of (1) shows itself as hypothetical force in (3). The accidental generality of (2) is lost in (4). This quality of universal laws allows for prediction by logical derivation[4].

Statistical laws

Statistical laws have only recently (and reluctantly) been accepted as bona fide laws of nature. Most philosophers now grant that they have the nomic necessity and hypothetical force required for predictive power and explanatory status[5,8]. However there is a logical distinction between universal and statistical laws. Hempel[5] points out that in a system governed by statistical laws, the relationship is one of induction rather than deduction. This means that, whereas a universal law is stated thus:

(5) All As are Bs

(5a) $(x)\ (Ax \rightarrow Bx)$

a statistical law is stated thus:

(6) All As are Bs with probability p

(6a) $(x)\ \mathrm{Prob}\ (Ax \rightarrow Bx)=p$

The symbolic form in (6a) is due to Angell[10] and is read as follows: For all x, the probability that x is **A** (where **A** is some reference class) then x is **B** (where **B** is the predicate in question) is p.

Quasi-laws

Quasi-laws[6] are rule-like statements that govern the behaviour of human and other complex adaptive systems. They have explanatory value and counter factual force. They are, however, restricted to a time and place and are loose. The looseness results from the impossibility of knowing all of the operative conditions and sanctions the admission of exceptions. Examples of quasi-laws are:

(7) Producers try to maximize profit

(8) If one person strikes another person, that person will strike him back

One might look at (7) and come across a company that is not trying to maximize profits. Such a violation would be explained by showing that a legitimate, but unarticulated precondition has been violated. The law should (for instance) actually read

(7a) Producers try to maximize profits unless they are philanthropists and think it unconscionable to overcharge for their goods, etc.

Similarly, after examining (8), one might encounter an incidence in which one individual struck another with impunity. This would be rationalized as in (8a).

(8a) If one person strikes another person, that person will punch him back, unless he believes in 'turning the other cheek', or does not wish to provoke further hostilities, or thinks that a law suit is a more appropriate reply, etc.

Such laws are not vacuous, but certainly of a very different nature than universal or statistical laws.

They are represented here by the use of the existential quantifier.

$$\exists\ (x)\ (Ax \rightarrow Bx)$$

This may actually be too strong a formulation. It entails that the specified relationship will hold for at least one entity at the time the assertion is made. This may not be the case. Quasi-laws are time and place sensitive. So all that is required is that the relationship has held at some time and place (which allowed for the inference of the 'law') but there is no accompanying guarantee that it will hold at the time of the application of the 'law'. Obviously predictions cannot follow from logical derivation in such cases. All that can be asserted is that, **A** is likely to be followed by **B** unless there is a 'legitimate' exception.

ROLE OF KNOWLEDGE IN INFERENCE

In this section the inference mechanisms involved in the three aspects of the design process identified by March and Coyne *et al.* are re-examined, but with an eye towards the logical nature of the knowledge or laws involved in the argument form. The symbols '#' and '?' are used to signify deductive and non-deductive inference respectively.

Inference of performance prediction

In the uncomplicated model the inference involved in the prediction of performance is restricted to deduction. The three examples below show three different predictive argument forms. They are stated verbally first, then symbolically. A discussion follows each example. It can be seen that only the first is deductive, the other two are clearly not deductive.

Example A.1. Universal law system

All buildings with characteristics C1, C2, . . . Cn have structural property P.
A is a building of characteristics C1, C2, . . . Cn.

A has structural property P.

$$(x)\ (Cx \rightarrow Px)$$
$$Ca$$

$$\#\quad Pa$$

This is the form prediction takes in classical physics. This is the model Peirce was referring to in his comments on prediction in science. It became inaccurate with the discovery of indeterminism in nature. It is also applicable to many design situations, e.g. determining the structural capacity of a beam*. But it is by no means the only or even the predominant model of performance prediction in design. It works in the above example because the universal quantifier (representing a universal law) allows for universal instantiation of an individual.

Example A.2. Statistical law system

Buildings with characteristics C1, C2, . . . Cn have a life-span property P with probability *p*.
A is a building of characteristics C1, C2, . . . Cn.

A will have life-span property P with probability *p*.

$$(x)\mathrm{Prob}\ (Cx \rightarrow Px) = p$$
$$Ca$$

$$?\quad Pa$$

This is the form prediction takes in much of modern science and in some design situations. The reader will

*This is of course only true in principle. In practice complications arise because designers may have insufficient knowledge of the laws governing the system or the internal states of the system, or have insufficient computational power to effect an infallible prediction. But this does not affect the point being made for two reasons. (1) For surprisingly many daily applications – the design of bridges, computers, planes, etc – the laws and the relevant states are known, and there is sufficient computational power to effect a prediction to a desired accuracy. (2) But perhaps more importantly, from a logical point of view, the fact that one is unable to make a precise calculation in practice, has no bearing on the universality of the physical laws governing the behaviour of a system.

note that the major premise does not satisfy the requirements of a universal quantifier and therefore cannot sanction universal instantiation. Thus strictly speaking the conclusion cannot be logically derived from the premises. In fact if the system is truly stochastic there is no mechanism for making an accurate prediction.

It seems that March wishes to treat inferences based on statistical laws as deductive. Thus he writes (p.19) 'Deductive inference is determinate, but the premises may involve probabilistic statements, in which case the conclusion will also be probabilistic, not because of any uncertainties in drawing the inference itself but because of the nature of the premises.' But to do so is to reduce the original problem of performance prediction to the comparatively innocuous problem of calculating the entailments of premises true by virtue of the definition of probability. But by most common sense accounts this is not what the problem of performance prediction is about. For example, if you have a coin that you know will, when flipped, land with heads up with probability 0.5, and you wish to bet on the occurrence of it landing 'heads up' twice in succession, you can use the probability calculus to figure out that the probability of this occurring is 0.25. But while this is useful information, it is not a prediction of the actual outcome. The problem of performance prediction is the problem of predicting the behaviour of the specific artifact being designed, not in the possible class of such objects. To view it in this latter fashion is to reduce it to a much less interesting problem.

Example A.3. Quasi-law system

Buildings with characteristics C1, C2, . . . Cn sometimes have aesthetic property P.
A is a building with characteristics C1, C2, . . . Cn.

A might have aesthetic property P.

$\exists$ (x) (Cx $\rightarrow$ Px)
Ca

? Pa

For many designers – especially those dealing with people – this is the form prediction usually takes. There are no logical grounds for instantiating an individual. There is usually even no guidance in terms of probability expectations. Typical examples of this type of situation are: 'What will be the impact of this shopping mall development on this neighbourhood?' 'How will the building users react to this colour scheme?', etc.

To treat this type of argument form as a deduction, March would presumably wish to force it into the mould of the previous statistical example. While probability theory is one of the great intellectual achievements of the twentieth century, there are two problems with the proposal. First, it would only reduce the inference problem to that of indeterministic system (i.e. provide guidance in terms of probability expectations, but leave the problem of individual instantiation untouched). The second and more fundamental problem is that probability theory makes certain assumptions that are not applicable to complex adaptive systems. The first assumption is that the system whose behaviour is being predicted be comprised of many (billions) of individuals. Furthermore, it is required that each individual behave completely randomly with respect to any other individual. This is what Weaver[11] termed random complexity. But as is well known, while adaptive systems can be very complex, they are anything but random. They exhibit what Weaver called organized complexity. The question as to what type of mechanism can be used to draw inferences in such argument forms is a fascinating one. It is taken up elsewhere[7]. Here the intention is only to demonstrate that it is not deduction.

Inference of design descriptions

This is the inference which March and Coyne *et al.* call abduction. The three examples do fall into this category, but a more interesting generalization might be to notice that each argument proceeds by affirming the consequent (not logically valid) but encounters different situations – depending on the type of knowledge – in instantiating an individual.

Example B.1. Universal law system

All buildings with characteristics C1, C2, . . . Cn have structural property P.
A has structural property P.

A is a building of characteristics C1, C2, . . . Cn.

(x) (Cx $\rightarrow$ Px)
Pa

? Ca

This form is the least problematic of the three. The universal instantiation is valid. The only problem is in affirming the consequent.

Example B.2. Statistical law system

Buildings with characteristics C1, C2, . . . Cn have life-span property P with probability *p*.
A has a life span property P with probability *p*.

A is a building of characteristics C1, C2, . . . Cn.

(x) Prob (Cx $\rightarrow$ Px) = p
Pa

? Ca

This second form is a little more problematic. In addition to the affirmation of the consequent there is the problem of individual instantiation as in A.2.

Example B.3. Quasi-law system

Buildings with characteristics C1, C2, . . . Cn sometimes have aesthetic property P.
A has aesthetic property P.

A is a building of characteristics C1, C2, . . . Cn.
$(x)\ (Cx \rightarrow Px)$
Pa

? Ca

This form is the most difficult. In addition to the affirmation of the consequent, the problem of individual instantiation appears in its most extreme form (as in A.3.)

Inference of knowledge

The inference of knowledge differs from the above argument forms in that the laws themselves are being inferred. The premises are provided by observations of object characteristics and performance. There is in each case an unstated assumption (made explicit between the brackets < > in the symbolic representation) which constitutes the major premises of the arguments. The nature of this assumption determines the nature of the knowledge that will be inferred (i.e. universal, statistical, or quasi). The observations provide evidence for the assumption. The amount and type of evidence required to substantiate the assumption depends on whether it is universal, statistical, or quasi. Apart from this the inference proceeds by affirming the consequent.

Example C.1. Universal law system

A, B, C, . . . are buildings with characteristics C1, C2, . . . Cn.
A, B, C, . . . have structural property P.

All buildings with characteristics C1, C2, . . . Cn have structural property P.
$< (x)\ (Cx \rightarrow Px) \rightarrow (\ (Ca \rightarrow Pa)\&(Cb \rightarrow Pb)\ \&(Cc \rightarrow Pc)\ .\ .\ .\ ) >$
$Ca\ \&\ Pa$
$Cb\ \&\ Pb$
$Cc\ \&\ Pc$

? $(x)\ (Cx \rightarrow Px)$

Example C.2. Statistical law system

A, B, C, . . . are buildings with characteristics C1, C2, . . . Cn.
A, B, C, . . . have a life-span property P with probability p.

Buildings with characteristics C1, C2, . . . Cn will have a life-span property P with probability p.
$< (x)\ (Prob(Cx \rightarrow Px)=p) \rightarrow ((Prob(Ca \rightarrow Pa)=p)\ \&(Prob(Cb \rightarrow Pb)=p)\ .\ .\ .\ )>$
$Ca\ \&\ Prob(Pa)=p$
$Cb\ \&\ Prob(Pb)=p$

? $(x)\ Prob(Cx \rightarrow Px)=p$

Example C.3. Quasi-law system

A, B, C, . . . are buildings with characteristics C1, C2, . . . Cn.
A & C (but not B, D, . . .) have aesthetic property P.

Some buildings with characteristics C1, C2, . . . Cn have aesthetic property P.
$< \exists(x)\ (Cx \rightarrow Px) \rightarrow ((Ca \rightarrow Pa)\ V\ (Cb \rightarrow Pb)\ V\ (Cc \rightarrow Pc)\ .\ .\ .\ )>$
$Ca\ \&\ Pa$
$Cc\ \&\ Pc$

? $\exists(x)\ (Cx \rightarrow Px)$

CONCLUSIONS

In this paper we have suggested a way of extending the 'logic of design' model as originally outlined by March. We have proposed an extension based upon the recognition of different ontological and/or logical status of laws that participate in argument forms of interest to designers. In making this distinction we are attempting to capture what we feel is a real and interesting feature of the world. This of course also complicates the model in so far as it is no longer sufficient to divide the three phases of design activity into the simplistic categories of deduction, induction and abduction. It also means that the claim that prediction of performance is a deductive inference is not true in any interesting sense. It depends on the logical nature of the laws governing the system. Furthermore, while the inference of design descriptions and knowledge are inductive processes, there are internal differences in the inferencing problems encountered. These differences are directly related to the logical nature of the knowledge involved in the inference (not to the contingent matters of 'case' 'rule' and 'result'). It is important to explicate these subtle differences because they are the issues that knowledge-based reasoning systems will have to deal with.

ACKNOWLEDGEMENT

This work was conducted while the author was supported by an Andrew Mellon Scholarship.

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