From Function to Structure in Engineering Design[1]

Louis Bucciarelli
Professor of Engineering & Technology Studies, Emeritus, MIT

Introduction

I consider the question raised by Peter Kroes regarding the concepts of function and structure as they relate to engineers designing. In “Engineering Design and the Empirical Turn in the Philosophy of Technology“[2], Kroes describes the challenge facing participants in the design of the new as that of bridging the divide between function and structure, as moving from a statement of functional requirements to the definition of (physical) structure - the latter, in large part, taking the form of design drawings, parts-lists, user manuals, and the like. I quote:

> Insofar as it is a physical object, a technological object can be described in terms of its physical (structural) properties and behavior....The structural mode of description ...is free of any reference to the function of the object. ...Physics has no place for functions, goals, intentions.
>
> With regard to its function, a technological object is described in an intentional (teleological) way...Purely functional descriptions of an object have, from a structural point of view, a black-box character in the sense that they do not specify any physical properties of the object.
>
> “... a fundamental problem. ...engineers are somehow able to bridge the gap between a structural and a functional description of a technological object: A function - which is described in an intentional language - is explained in terms of a structure, which is described in a non-intentional, structural language. How is this possible[3]?

My purpose is to flesh out this picture of the engineering design task, showing how, while definition of the “material structure” of the parts is the final endpoint, the translation from a statement of functional requirements *of the whole* to this final state is made via the positing and manipulation of abstract “formal structures”, theoretical models of the behavior *of the parts* - individually and *joined together* - to meet specified (sub)functions

The notion of “structure”, then, is best understood as of two sorts: There is “material structure” as the definition of the concrete material parts of the object of design - the detailed description of what Polanyi referred to as the “physico-chemical topography” of the artifact (technological object)[4] but there is structure again in a formal sense - as abstract, engineering models and representations of the parts of the design (object- worlds here). It is this latter “formal structure” of the parts and their place in a hierarchy of wholes that participants in design work to define (in full, i.e., all relevant parameters specified), given the stated functional requirements of the parts of the whole.

---

1. Based on a talk given at CEPHAD 2010: The Borderland Between Philosophy and Design Research, a Conference at the Danish Design School, Copenhagen, January, 2010. The author thanks Peter Kroes and Wybo Houkes for their helpful comments on an earlier draft of this paper.
2. *The Empirical Turn in the Philosophy of Technology*, P. Kroes & A. Meijers, (eds.) JAI, 20009.
3. ibid, p. 29.
4. Cited in Kroes (ibid).

An Example - The Resistor

Consider an element used in electronic circuits - that referred to, labeled as, a "resistor". What is its material structure? What is its formal structure?

A 100 kohm, 5% through-hole resistor

Wikimedia Commons.

The picture on the right shows a resistor, one type among many. Its *material structure* is described by means of a list of ingredients - e.g., copper, ceramic, carbon, paint - and the geometry of these materials as defined in the instructions and drawings one would give to the manufacturing department to produce the device. All that is its material structure[5].

$$V = I \cdot R$$

Its *formal structure* is described by its behavior in accord with electrical circuit theory. In a circuit, the voltage drop or difference across the two ends, *V*, is proportional to the current, *I,* passing thru the device. The constant of proportionality, *R*, is the *resistance.* The equation shown at the top is the mathematical representation of the behavior of the resistor. The wiggly line drawing is how it would appear in a circuit diagram as drawn by an engineer (in the US). For a given voltage difference across the device, the bigger the resistance, the smaller the current. One can say that the device "resists" the flow of current. If the voltage is measured in *volts* and the current in *amps*, then the resistance has the units of *ohms*. This description of formal structure makes sense only within the framework of circuit theory, e.g., Kirchoff's laws.

Here, then, is the abstract, formal structure of a resistor. The equation describes its *essence*. A *structural* description of the device omitting this relationship is deficient. Without this picture of formal structure, the device looses its identity. It becomes indistinguishable from a pebble picked up on a beach, a mere trinket.

Devices with this formal structure, may exhibit different material structures, e.g., there are carbon composition resistors made of a mixture of carbon powder and a ceramic; carbon film resistors; metal film; and wire wound resistors.[6] For any particular type, the geometry of the material ingredients can be configured to give different values for the resistance, *R*. And there are "variable resistors" where the device provides a means for changing the value of the resistance, *R*.

I must say something about function. I find myself sliding in this direction. For it seems a short step from stating "the voltage drop across a resistor is equal to the product of the current flowing

---

[5] Should we include the "properties" of the resistor in the definition of its material structure? For example, the device shown is a "5% resistor". This means that when you purchase a particular resistor with this stated property value, its actual resistance will, almost certainly, fall between 95 kohms and 105 kohms. (Is this a property of this particular device alone?) There are other properties that may be important in application -e.g., the parameter whose value tells you how the resistance changes with temperature, or its power rating from which one can deduce a value for the maximum, allowable current.

[6] http://en.wikipedia.org/wiki/Resistor

thru the device and the resistance" to the statement "the function (purpose) of the device is to produce a voltage drop when a current flows through it". Indeed, does not this expression of *formal structure* define the *function* of a resistor?

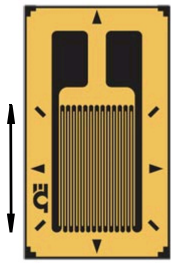
No.

The reason is because a device, categorized by this formal structure, *can fulfill different functions*, can be used for different purposes. The function of a resistor depends on how it is used, on context of use, on a use plan. For example, a resistive element may be used to obtain a specified voltage at a specified point in an electrical circuit. It may be used to obtain a specified current through a particular branch of an electrical circuit. It may be used as a heating element, to produce a specified power.

Note that in this last instance, to fully specify the element's formal structure, we must supplement the defining relationship between current and voltage with a derived equation expressing the power dissipated by the resistive element, namely $P = I^2R$. This is as much a part of the formal structure of a resistor - all resistors dissipate power - as the relationship between current and voltage[7].

A resistor may be used to measure temperature - a *thermistor's* material structure is made such that the resistance, R, of the device varies significantly, measurably with temperature. In this instance, to fully specify the element's formal structure, we must supplement the defining relationship between current and voltage with an empirical expression for how the resistance varies with temperature.

A resistive element may be used to measure small, relative displacements - a *strain gage's* material structure is made such that the resistance between two points changes significantly, measurably, when the distance between the two points change[8]. In this case, to fully specify the element's formal structure, we must supplement the defining relationship between current and voltage with a (more "fundamental" in a sense) relationship which describes how changes in the value of the resistance depend on changes in the cross-sectional area and the length of the resistive material - or accept the manufacturer's characterization, one which directly relates the relative displacement, or strain, to the change in resistance.



www.omega.com

We see then, that in some sense, the definition of the *formal structure* of a part, in this case an electronic device, is more "fundamental" vis a vis whatever particular *function* the device may be used for and whatever particular *material structure* of which it may consist.

---

[7] The power dissipated by a resistor must also be taken into account in choosing a resistor for use in a circuit. From the power rating, you can compute a maximum allowable current through the device.

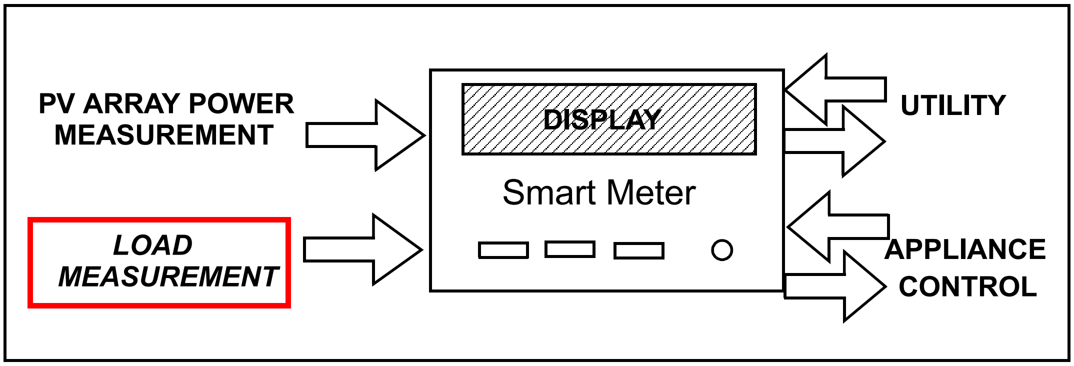
[8] In the figure, the double arrow indicates the active portion of the metal foil gage. The active length of the foil loops is 26 times the length of this arrow. As this length increases, the resistance of the device increases proportionally.

Formal structures of parts, parts together as wholes, are fundamental in the thinking of engineers as they design. Given the prescribed function of a part, parts together as a whole, or the whole in itself, engineers posit formal structures, abstract representations, e.g., "models", that might meet their intended purpose, to function accordingly. These are embellished, fitted out with particular values of essential parameters, e.g., the value of the resistance, *R*, creatively con-joined with other parts, yielding a (tentative) picture of a part of the whole. In the "background" sits an infrastructure of parts of real material structures and means for their assembly, testing, production. But formal structures are foremost in the conjuring up links between functions and material structures.

To justify this claim, I construct a picture of design process in which work with formal structures is foregrounded. I will use a scenario to frame and illustrate my thesis.

A Design Scenario

I will consider an object-world task of an electronics engineer participating in the design of a "smart meter" for a single-family residence. The figure below suggests what the "parts" of this system/product might consist of view from a high level.



I will not say much about the design task in the large but simply assume it has been taken on by a private, say medium size, firm. Nor will I say much about the intended "function" of the system at this high level; my focus will be on the relationship of function to structure at a lower, electronic, object-world level. (Deep down within the box labeled *Load Measurement)*.

It suffices to say that the function of the system could be conceived and/or set in different ways, e.g., defined as providing the home-owner with sufficient information (real time energy/power consumption) enabling he or she to judiciously manage his or her demand in order to lower a monthly electric bill. In this case the utility's role might be minimal (erase the arrow from right to left) and appliance control left up to the home owner (erase both arrows).

A more complex system would include active monitoring and control of appliances. Add the possible active control of loads by the utility at times of peak demand and the system becomes still more complex. The function of the system might then be described quite differently; indeed, one might eliminate the display altogether and leave the home owner out of the picture. (Some will claim that "after all, she doesn't want to be bothered; an ill-informed user is likely to screw up the system, so make it "idiot proof"[9]) The primary function in this case would be to provide a means for the utility to reduce demand at times of peak load via active control of residential consumption. This, in turn, puts the boundary around design further afield - i.e., around a collection of households on the grid.

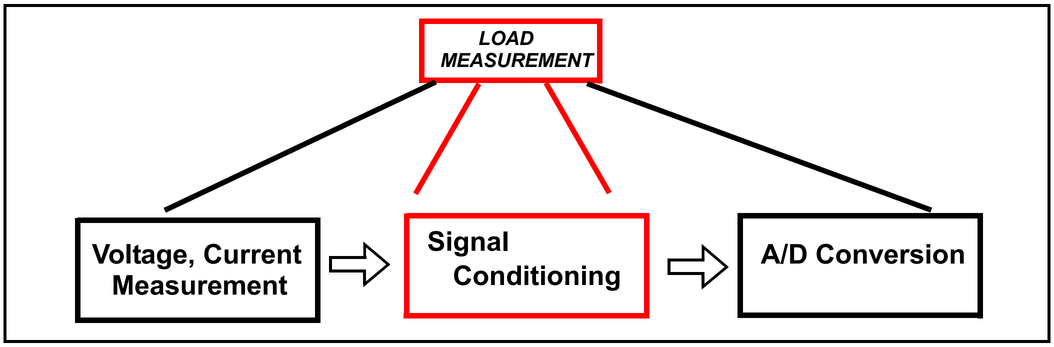
The definition of function of the whole at this high level would require consideration, if not negotiation, of the interests of the different "stakeholders" - the utility, the home owner, appliance makers, product managers, legal staff within the firm. But this social/political/ phase of the design process is not my focus.

Likewise I am not going to say much about the negotiation across object worlds among participants in the design process once the system function of the whole has been fixed - how participants structure the design task, reduce the overall whole into more or less independent parts and set interface conditions; establish a schedule including milestones; allocate resources including personnel. Nor about how they, at various stages in the process meet to articulate their proposals and plans, decide on next steps, make revisions, decide to eliminate some functions, enhance others, then return to their object worlds to work out next steps and meet obligations agreed to.

Object World Function & Structures

It suffices, for the purpose of my object world scenario, to say that the electronics engineer is just one of a team. Other team members might would include an engineer responsible for design of the software, another with experience in the design of power distribution systems, a person from the marketing department, an engineer/ethnographer who has responsibility for the user interface, a manufacturing engineer, even a person from the legal department concerned with privacy issues and whatever contractual agreements the home owner might enter into with the electric utility. Our electronic engineer's responsibility is for designing the load management subsystem (or part). There may be other electronic engineers engaged in the project, for example, another whose responsibility is to work up the means for monitoring and control of all appliances in the residence but I will focus only on the load management bit.

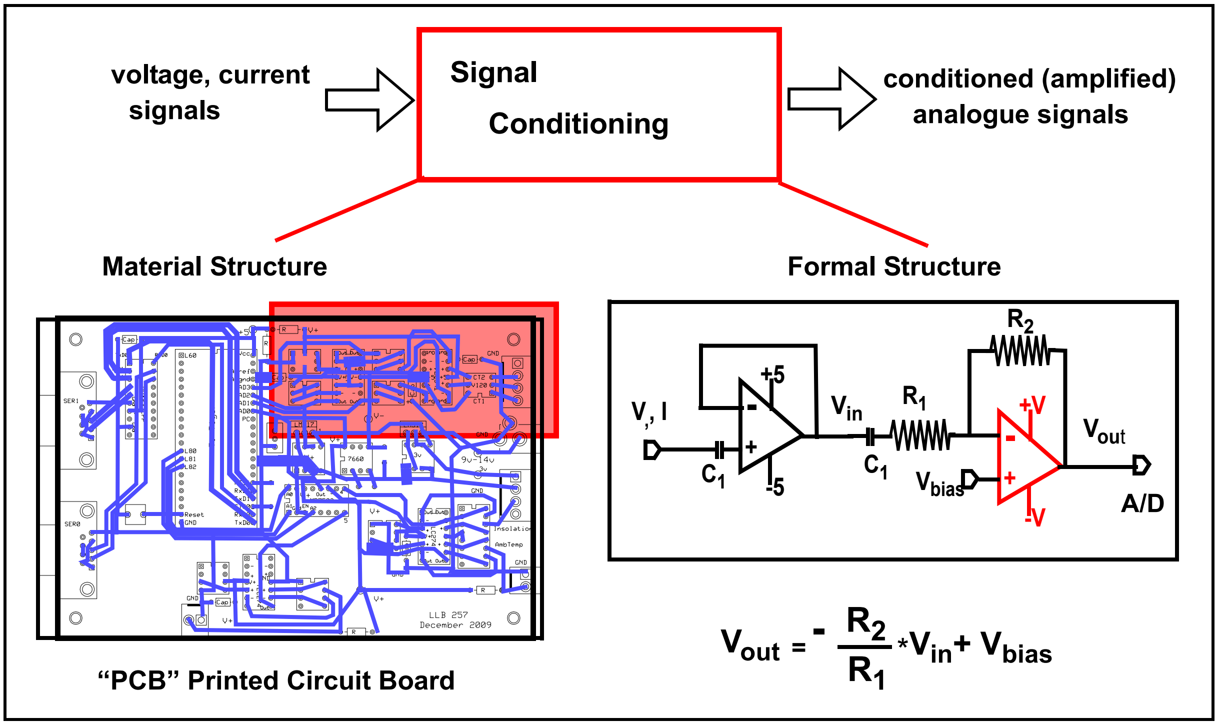
This part, in itself, might be broken down into three parts -. the block on the left with the function to measure the power flowing from the utility lines into (and out of)[10] the home. Output of this part is input to another, the block labeled "Signal Conditioning" where the time varying, voltage signals are amplified, possibly shifted, then passed along to the third part where the analogue sig-



---

9. Bucciarelli, L. "Is Idiot Proof Safe Enough", *Ethics And Risk Management In Engineering,* (ed. A. Flores), University Press of America, Lanham, MD, 1989, pp. 201-209

nals are sampled and converted into digital (time varying) levels. Further steps in this sequence shifts attention to the design of software for the manipulation of the digital data to produce a measure of power in a form for display and information exchange with the utility.



$$V_{out} = -\frac{R_2}{R_1} * V_{in} + V_{bias}$$

The *function* of the signal conditioning (“black box”) takes analogue measures of the main feeder line currents and voltages as input and produces, as output, amplified values of these measures. The *material structure* that meets this functional requirement is shown at the left. It occupies a well defined region of a printed circuit board. The *formal structure*, which defines the elements of the material structure and the circuit topology, is shown at the right. It includes two operational amplifiers, (fulfilling two different functions), several capacitors, as well as our old friend, the resistor. The resistors act, in this instance con-joined with the op-amp on the right, to produce the desired ratio of the output voltage to the input voltage, to amplify the signal as desired, as in the use plan. That is their function in this context. The equation below right (together with the circuit diagram) defines the formal structure of the signal conditioning part.

The positing and elaboration of this formal structure by the electronics engineer requires she know about its parts - know about the formal (and material) structure of resistors, capacitors, operational amplifiers - *and* how these devices (ideally) behave in accord with established principles of electronics, e.g., Ohm’s law $V = IR$; Kirchoff’s laws, and the like. This knowledge (and know how) enables her to draw a picture of a whole that will fulfill the specified signal condition-

---

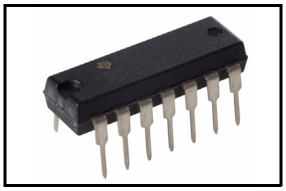
[10] I’ve thrown a photovoltaic system onto the roof to make the design task still more complex. The home owner can reap a substantial benefit selling energy back to the utility if, as in France, the sell-back rate is significantly greater than the buy rate. But again, I am not going to enlarge and enrich my narrative to include deliberations about, nor the technical definition of, this feature of the system.

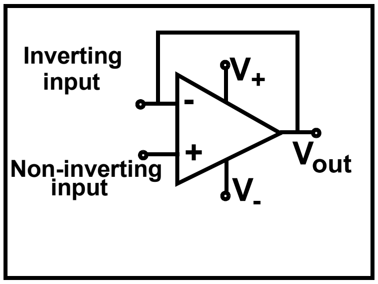
ing function in terms of the parts appropriately joined. It enables too the derivation of the equation shown.

The operational amplifier

I want to take this analysis down to a next level, to consider both the material and formal structure of the operational amplifier (‘op-amp”) repeating what we did for the resistor. (We could do the same for the capacitor but will not). What must the engineer know about the op-amp in order to construct, design an effective signal conditioning whole from these parts?

The picture on the right shows an op-amp, one type among many. Its *material structure* is described by means of a list of ingredients - e.g., metals, ceramic, silicon- the geometry of these materials, and I would include the description of the methods used to manufacture the bits, assemble them into a whole. All that is its material structure.





Its *formal structure* is defined by the abstract, circuit diagram at the left and two statements, two “golden rules” [11]

I. The output attempts to do whatever is necessary to make the voltage difference between the inputs zero.

II. The inputs draw no current.

These two rules describing the behavior of the device provide sufficient means to derive the equation shown bottom right in the figure on the previous page.

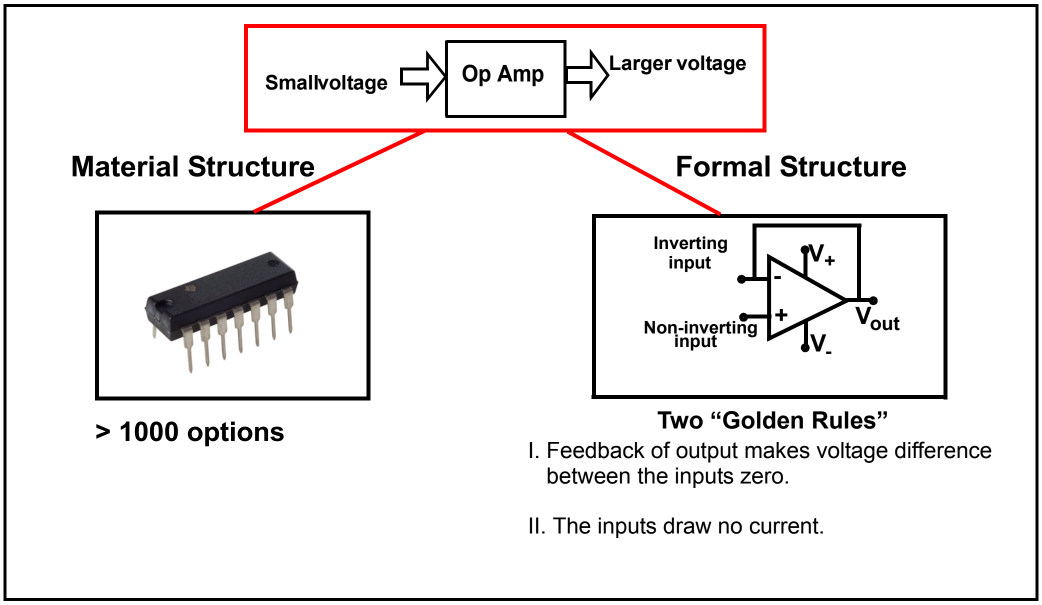
Here, then, is the abstract, formal structure of an op-amp. The rules and the diagram together describe its *essence*. A *structural* description of the device omitting these rules and the diagram is deficient. Without this picture of formal structure, the device looses its identity. It becomes indistinguishable from a pebble picked up on a beach, a mere trinket with legs.

Devices with this formal structure, may exhibit different material structures. As in the case of the resistor, an op-amp can do different things, function differently according to the designer’s purpose. In this scenario, the op-amp on the left in the circuit diagram, figure, page 6, is a “buffer”. It does not amplify. It is there to insure that the act of signal conditioning does not adversely affect the measurement of the line currents and voltages. The op-amp on the right does amplify.

---

[11] Horowitz & Hill: Horowitz, Paul and Hill, Winfred,The Art of Electronics, Cambridge University Press, 1980

The figure below pulls together the material and formal structure of an operational amplifier. The box at the top shows just one possible function of the device - to amplify the output of the sensors that measure the house current and voltage, analogue signals.



I. Feedback of output makes voltage difference between the inputs zero.

II. The inputs draw no current.

With this knowledge and schooled in circuit theory, the engineer can devise, design, a circuit that will behave as she intends. The signal conditioning circuit shown in the figure, page 6 is one such candidate. She still must "size" the elements of this formal structue, picking values for the resistances, for the capacitors, and decide what particular op-amp (among 1000 in the catalogue or on the shelf down in the lab) will best fulfill her purpose. .

With a full structural definition in hand - both formal and material - testing, integration, negotiation, revision, iteration can proceed. She may travel to the top and down again. So it goes[12].

"Explanations come to an end somewhere"[13]

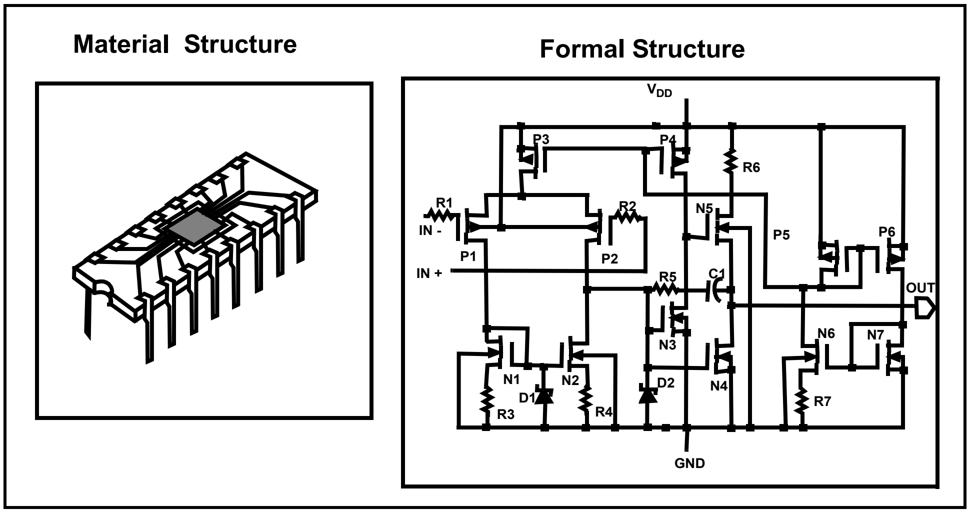
While our electronics engineer may very well stop here at this level of detail and understanding, the reader might wonder about this business of "golden rules" and so simple a representation of the material form of an operational amplifier. One might wonder where these golden rules come from, how one can get away with so "superficial" a model of an op-amp's behavior. We can, of course, go deeper.

---

[12] My giving scant attention to the full scope of the design process should not lead the reader to conclude that object-world work is the most important part of designing. While necessary, it is never sufficient.

[13] Wittgenstein, *Philosophical Investigations*, Paragraph I.

The next figure shows what’s “inside” or lower down - both in terms of material structure and formal structure.



Material Structure

Formal Structure

On the left we see some (very few) of the details of the material structure, indicating how connections between the chip in the middle and the legs of the device are made. Little definition of the material structure of the chip itself is made evident.

The circuit diagram on the right shows the formal structure. A fuller description of this formal structure requires a definition of the behavior of its parts - p-type and n-type transistors, zener diodes, as well as resistors and capacitors.

Ordinarily our electronics engineer need not go this far.If something fails to behave in accord with the golden rules, or the particular device she has in hand melts down or fails in other ways, then she might be driven to look inside, or at least do a closer reading of the op-amp’s “spec sheet”. Engineering education in electronics includes learning about the function and structure of transistors et al. She would be expected to be able to “read” this more detailed formal representation and know something about its material embodiment at this deeper level. But ordinarily, if her design of this part functions as planned, she need not go this far

It’s like there is both an *abstraction barrier* and a *material barrier* in place at this level of design. I borrow the term “barrier” from computer science where the term refers to the setting of boundaries around blocks of code sitting within another, encompassing piece of code, in order to ease the design (and use) of the complex, encompassing system. An *implementer*, implements the code. *Clients,* with many different application needs, functional aspirations, make use of the block without knowing all the details.The idea is that with the separation of what others, responsible for their bits of code, need to know about the implemeter’s code, the design of the complex system eases. The parts others must know is the abstraction. What goes on within, behind the *abstraction barrier* is wholly of the impelmenter’s doing. Clients need not know the details hidden away or be aware of the code’s complexity or cleverness. The abstraction barrier protects the implementation from damage. And the implementation can be changed by its author at will (as long as the interface remains the same).

So it is in the design of the signal conditioning part of the whole. The electronic's engineer need not, should not, dig deeper, below the abstraction barriers (material and formal) without good reason. This is the end of the line. Explanations come to an end somewhere.

Observations

Several observations are in order concerning - the knowledge community with whom we are concerned; reflections on engineering education; and the notion of "cookbook engineering".

Function And Structures Within Object-worlds

In my explanation of formal and material structures and their relationship to function of a part, whole, or system, I presume a language/knowledge community schooled in a particular paradigm and at home in an object-world - in this case electronics. All members of this community will know the *essence* of a resistor, the formal, abstract structure I have described. A member may *not* be aware of all the ways a resistor might be put to use *nor* all possible material embodiments - just as a speaker of English who knows the *essence* of an adjective may not know all words classified as such (*material embodiments*) nor all the ways an adjective can be put to rhetorical or poetic purpose (*function*). I bracket my argument with this constraint in order to ward off "outside the box" questions about resistors functioning as trinkets, earrings, or cork screws.

Values, Functions and Structures - with an eye toward engineering education.

It is formal structure, the abstract representation of objects, artifacts, "laws" and methods - of parts and wholes - that commands the high ground in engineering education. Within any paradigmatic, engineering science - and throughout the curriculum in fact - the focus is almost wholly on the abstract concepts, principles and methods of the domain and their elaboration via application to exemplary exercises. This is why engineering education (and some say engineering itself) can be claimed to be "value free". Focusing solely on formal, abstract structures avoids any need to speak of values. Evaluative judgements about a device, e.g., this a "good" resistor., are irrelevant if we confine our talk in this way. Only when we speak of the 'function' of technical artefacts do such statements have meaning[14].

A description of function of a part, e.g.,a resistor, requires more than a knowledge of its essence and this necessarily brings into focus a context of use. But this context of use can be defined narrowly or broadly. In engineering education, the context of an exemplary exercise is drawn close-in, so narrowly that function seems to collapse, or dissolve, into the underlying, formal structure. The result: engineering education is seen as value free.[15]

Cookbook Engineering

I have described how there comes a point, a level, in object-world design work when further understanding of formal and material structures (of the parts of the part) is not necessary. Explanation comes to an end. One need only follow the (golden) rules, search the catalogue, order and

---

[14] See MacIntyre, Alasdair, After Virtue, Third Edition, Univ. of Notre Dame Press, 2007, pp. 57-58

[15] See Bucciarelli, L., "Roots", a section in Designing Engineers, MIT Press, 1994, p. 98 ff.

assembles the parts, try and revise, cut and paste. Designing, in this way, may appear to be "cookbook engineering". Engineering design does have this quality in part, but only in part, for there are many options to pursue at any level - different embellishment of a model, different component choices, different ways to join the parts into the whole required at the next level up[16]. Throw in the negotiation across object worlds, about which I have said nothing, and we move a long way from any recipe-driven process.

But there is nothing wrong with the "cookbook" part of the process[17]. Indeed, one of the complaints made by seasoned members of a firm is that some new hires don't know how to make use of the resources, the infrastructure, at their disposal. The neophyte has the urge to figure everything out on his or her own. Perhaps this is another consequence of the placing so much emphasis on formal structures, the engineering sciences, and not enough on design itself in engineering education.

16.See Vincenti,W.G., "The Scope for Social Impact in Engineering Outcomes: A Diagrammatic Aid to Analysis", *Social Studies of Science* (SAGE, London, Newbury Park and New Delhi), Vol. 21 (1991), 761-67, for a brief synopsis of the nature and degrees of constraint in designing.

17. Joe Pitt provides a strong defense of this form of engineering knowledge and work in "What Engineers Know", *Techn-Research in Philosophy and Technology*, Spring 2001, vol. 5, n. 3.