The Analogue Computer as a Scientific Instrument

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Abstract

The users of analogue computing employed techniques that have important similarities to the ways scientific instruments have been used historically. Analogue computing was for many years an alternative to digital computing, and historians often frame the emergence of analogue computing as a development from various mathematical instruments. These instruments employed analogies to create artefacts that embodied some aspect of theory.

Ever since the phrase 'analogue computing' was first used in the 1940s, a central example of analogue technology has been the planimeter, a nineteenth century scientific instrument for area calculation. The planimeter mechanism developed from that of the single instrument to become a component of much larger and more complex instruments designed by Lord Kelvin in the 1870s, and Vannevar Bush in the 1920s. Later definitions of computing would refer to algorithms and numerical calculation, but for Bush emphasis was placed on the cognitive support provided by the machine. He understood his "differential analyser" to be an instrument that provided a "suggestive auxiliary to precise reasoning" and under the label "instrumental analysis", classified all apparatus that "aid[ed] the mind" of the mathematician. Rather than placing emphasis on automation, an analogue computer provided an environment where the human investigator was far more involved in the computation process.

This paper will argue that the analogue computer can usefully be considered as a scientific instrument. The role of the analogue computer as a scientific instrument will be investigated from the perspective of the users' techniques and applications. The study will particularly focus on the users' approach to the planimeter, the differential analyser and the electronic analogue computer.

When we consider the various artefacts that have historically been associated with analogue computing, we find that they often have characteristics that do not always fit well with definitions of computation we have today. The process of attempting to understand analogue computers, and through this analogue computing, leads us to the topic of this paper: That for the users of analogue computing (who were often research scientists) the computer was a scientific instrument, an artefact of experiment that guided their reasoning. Throughout the development of analogue technology, we can see a user-driven evolution motivated by a desire to model and understand the world. By considering the analogue computer an instrument, we can explore the history of analogue computing within the larger context of scientific instrument development.

The association of both analogue and digital technologies through the common word *computer* can be misleading. As a point of historiography, Nyce (1996) suggested that it is almost impossible to consider analogue computing in its own context due to our understanding of computation and computers being dominated by digital views. There is a significant distinction between the two types of computer and some members of the analogue community have thought that labels like "analogue simulator" would have better captured the use of the technology.[1] In this paper we will summarise the properties of an analogue computer and then focus on its position within the history of certain scientific instruments. With the emergence of the analogue computer it became possible to provide a mechanical or electrical account of the dynamic relationships governed by a set of differential equations; the use of such mechanisations could change the way their users thought about the governing mathematics.

Analogue computers are machines which allow the user to model a mathematically complex physical system through interacting with another, *analogous*, physical system. For example, a model of an economy can be developed by identifying an analogy between fluid flow and monetary flow;[2] or a physical mass-spring problem can be represented with the analogous behaviour of a

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[1] See Atherton (2005).

[2] A. W. Phillips demonstrated an analogue computer based upon this principle at the London School of Economics in 1949.

resistor-capacitor circuit. Another example of an analogue computer is the *differential analyser* which mechanised the solution of differential equations through each component of the equations being modelled by physical analogues that individually embodied that component. This type of analogue computer would later become the electronic analogue computer and be the most commercially successful analogue.

Analogue computers as instruments

One of the best summaries of various types of scientific instrument is the introduction by Van Helden and Hankins (1994). A number of examples of instruments are considered, although as the authors acknowledged, the examples given do not constitute an exhaustive list:

> Scientific instruments... can be models or analogies to nature, as in the case of orreries or ether models; they can be extensions of the senses, such as the telescope and microscope; they can be measuring devices, as in the case of meters, micrometers, or gauges; they can be the means for creating extreme conditions that do not occur naturally on the earth, as in the case of the air pump and the particle accelerator; they can be apparatus for controlling and analyzing phenomena, as in the case of the pendulum or chemical apparatus; and they can be the means of visual or graphic display, as in the case of recording devices.
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> (Van Helden and Hankins, 1994)

As an instrument, the analogue computer can be associated with two of these categories. The first relates to the instrumental status of the artefact created on the computer (hereafter referred to as the *computational artefact*[3]) and the second to the analogue computer itself. Firstly, in many applications of analogue computing, users created computational artefacts that were “models or analogies to nature”. Secondly, just as the air-pump provided a new environment from which to explore phenomena, so the analogue computer provided a new environment through which to think about and construct models of certain physical systems.

Every calculation on an analogue computer can be considered an experiment with the computing mechanism, 'playing through' a sequence of actions analogous to a physical experiment. Through considering a computation to be the result of an ongoing interaction, we see that analogue computing encouraged a far deeper relationship between human and machine. Rather than supporting a fully automated model of problem solving, the human operator was guided towards the solution of the equation or system of equations that they were interested in. The analogue provided a modelling environment where the symbols of an equation became dynamic and visually meaningful. Each operator had its analogue, integrals corresponded to mechanical or electrical integrators and the 'equals sign' to a cyclic connection.[4]

An early association between analogue computing and instruments is captured in Hartree's writings on calculating machines[5] where instead of the terms 'analogue' and 'digital', he uses 'calculating instrument' and 'calculating machine' respectively. This language reflects Hartree's own extensive use of early analogue technology. In the 1930s he constructed his own differential analyser out of Meccano and commissioned a full-scale version to be constructed at Manchester.

Previous publications have attempted to relate digital computing to instrumentation and instrument science and discussions in this field usually revolve around the nature and status of a software

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[3] Essentially, this term is referring to what we might describe as the software element of an analogue computer although words such as 'software' and 'program' can be misleading in this context. In particular, the use of the word artefact includes the more tacit aspects of the model created on a computer; the computational artefact is more than a specified set-up but also embodies aspects of the user's scientific knowledge and empirical expectations; representing computational relationships that can be experienced and reasoned about.

[4] See Mindell (2002) page 161, Owens (1996) and Small (2001).

[5] See Hartree (1946, 1947, 1949).

artefact. In particular Beynon et al. (2001) focus on understanding an instrument in terms of the maintenance of an autonomous relationship between two aspects of state. This is helpful, since it can be applied to various physical scientific instruments as well as computational artefacts where an instrument is thought of as maintaining a dependency between a sensually observable aspect of state and a sensually unobservable aspect of state. For example, the thermometer maintains a dependency between the intangible observable of temperature and the tangible observable of length and through this relationship the temperature's state becomes measurable. In their paper, Beynon et al. refer to a particular type of computer-based modelling[6] that has features that resonate with analogue computing.[7] In the analogue computer connections are made between the various components to represent a construal of a phenomena.

A number of philosophers of science[8] have considered the relationship between analogue computers and models used in science; analogue computers being positioned on the intersection of models and instruments. Morgan and Boumans (2004) explore the Phillips machine and its role as a model of an economy although the Phillips machine has a specific application whereas other analogue computers provided a more general purpose approach to modelling and calculating. Instruments are generic objects and can be applied to a number of situations, whereas models are illustrations, embodiments or investigations of one particular theory. The analogue computer is an instrument that provides a generic environment through which analogue models can be constructed; for example, oil reservoir computers provided a way of generically modelling a number of oil fields. Each setup creates a new computational artefact or model of an oil field, but the computer itself provides the scope for many such setups.

The planimeter as an exemplar of analogue computing

During the 1950s and 1960s, most analogue computing textbooks began by introducing the historical context of the technology they covered. Such sources are extremely useful with helping us understand how the computing community of the period perceived its own context. In these historical chapters, the planimeter (a nineteenth century philosophical instrument[9] for calculating areas) is often given prominence as a defining example of analogue computing and further associates the technology with the history of instruments.[10] The planimeter mechanism or mechanical integrator provided a mechanical analogue of the integral and so became the underpinning technology of machines like the mechanical differential analyser.

The planimeter was first invented in 1814 and subsequently re-invented several times throughout the first half of the nineteenth century.[11] The reason for these numerous and isolated developments in planimeter technology is that there was a great need for reliable instruments to calculate area.[12] Many of the early inventors were involved with surveying and the planimeter provided a solution to their numerous practical area calculation problems. However, the real significance of the planimeter to the history of science and technology is that around the 1850s, people started to realise that the mechanism actually offered a automated means of evaluating an integral.

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[6] Named “Empirical Modelling”. See `http://www.dcs.warwick.ac.uk/modelling/`.

[7] Characteristics such as the ability to make real-time changes to a computational artefact, support for constructing analogies and the role of experiment are all correspondences between analogue computing and Empirical Modelling.

[8] See Hesse (1963) and Morgan and Morrison (1999).

[9] At the Great Exhibition of 1851, five planimeters were exhibited in class X (philosophical instruments).

[10] See for example Fifer (1961) and Jenness (1965).

[11] For a fuller account of the history see Henrici (1894), Fischer (1995, 2002) or Care (2004).

[12] Maxwell (1855) wrote that “The measurement of the area of a plane figure is an operation so frequently occurring in practice that any method by which it may be easily and quickly performed is deserving of attention.”

Although we do not know when the planimeter was first considered an integrator, by the 1870s such an association was commonplace.[13] It is the developments by Wetli in 1949 that provide the first real indication of awareness of the mechanism's significance. Wetli's initial contribution was to augment the standard wheel and cone mechanism with a second cone[14] and he soon after replaced both cones with a wheel. Since these developments relate to the calculation of both positive and negative areas, which is only required if areas bound by functions are being calculated; the only suitable account for Wetli's designs is that he was using, or planning to use, the planimeter as an integrator. In 1876, Lord Kelvin realised that complex problems involving differential equations could be solved through inter-connecting several of his brother's (James Thomson) integrators.

> During many years previously it had appeared to me that the [harmonic analysis] ought to be accomplished by some simple mechanical means; but it was not until recently that I succeeded in devising an instrument approaching sufficiently to simplicity to promise practically useful results. Having arrived at this stage, I described my proposed machine a few days ago to my brother Professor James Thomson, and he described to me in return a kind of mechanical integrator which had occurred to him many years ago, but of which he had never published any description. I instantly saw that it gave me a much simpler means of attaining my special object than anything I had been able to think of previously.
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> (Thomson, 1876b)

This insight was the basic concept behind the differential analyser and was only possible because the planimeter was identified as a mechanical integrator. Kelvin was unable to realise his invention and Vannevar Bush became the first to construct a fully working implementation of this principle in the 1930s.[15]

Techniques and applications

From the perspective of the users of analogue computers, rich correspondences could be made between experience of a model and experiences with the natural world. By supporting experimental interaction with an analogous system, the computer provided an accessible environment through which to explore another system. Prior to constructing a model on an analogue computer, it is necessary to identify an aspect of theory which offers a suitable analogy[16] The model is the union of the analogy, together with the experiments or interactions supported by the computer.

Individual experiment with the analogue was central to the technology's effectiveness. In their study of the Phillips economic computer[17], Morgan and Boumans (2004) identify that while mathematical theory can be used to calculate solutions, the analogue computer can assist with “gaining knowledge of the economy through the mind's eye”. The openness of the modelling medium employed allowed for exploration and embellishment of aspects previously not considered. Also, provision for experimentation was aided by having the various active elements of the underlying model available for inspection.

Once a user is satisfied that the analogue's properties correspond with his or her experience of the world, their experiences of the referent and the analogue start to merge. Thus the instrument becomes a single aspect of theory, supporting the underlying assumptions that were implicit in the identification of the analogue. This process is explained by Ihde (2004) with reference to a thermometer: after continued experience with a thermometer, the associations between length of

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[13] Thomson (1876a) used the term “integrator” and this is the *Oxford English Dictionary*'s first record of usage.

[14] This design is described by Henrici (1894) but it appears unlikely from other evidence that such a design was ever manufactured. A diagram of the design is given in Care (2004).

[15] See Bromley (1990).

[16] In the case of the differential analyser and electronic analogue computer, this theory is the identification of a system of differential equations.

[17] Usually named the “Phillips Machine” or the “MONIAC”.

mercury and temperature grow stronger. Ihde argues that the developing “embodyment relation” allows an observer in a warm room to experience something of the outside cold from the “immediacy of [the user's] reading” of the thermometer.

In an address to the American Mathematical Society, Vannevar Bush (1936) presented the differential analyser as an instrument that provided a “suggestive auxiliary to precise reasoning”. His belief was that there was significant cognitive support for mathematical work and fully expected *instrumental analysis* to become a driving force in mathematics. With hindsight we can see that such a revolution would be confined to applied mathematics. In his autobiography, he recalled how the differential analyser had an educational dimension, allowing the calculus to be communicated in “mechanical terms”. Here, both the referent and analogy were so well accepted that the set-up began to communicate knowledge about the relationship between them, the differential equation. For his draftsman, the differential analyser provided a physical insight into dynamic problems without need for mathematical formulation.

> As an example of how easy it is to teach fundamental calculus, when I built the first differential analyzer... I had a mechanic who had in fact been hired as a draftsman and as an inexperienced one at that... I never consciously taught this man any part of the subject of differential equations; but in building that machine, managing it, he learned what differential equations were himself. He got to the point that when some professor was using the machine and got stuck – things went off-scale or something of the sort – he could discuss the problem with the user and very often find out what was wrong. It was very interesting to discuss this subject with him because he had learned the calculus in mechanical terms – a strange approach and yet he understood it. That is, he did not understand it in any formal sense, but he understood the fundamentals; he had it under his skin.
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> (Bush, 1970)

Through exploring the analogue computer as a scientific instrument, we are able to consider the analogue computer within the contextual setting of its use during the early twentieth century. We have identified a number of correspondences between scientific instruments and analogue computers based on the approach of users to the technology. Of these, the principle correspondence is that both of the two technologies were used to model particular scenarios or aspects of the world. As instruments, the analogue computer was used not just as an embodiment of theory but rather an instrument that mediated knowledge through experimental interaction, a form of usage which has disappeared from today's computing culture.

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