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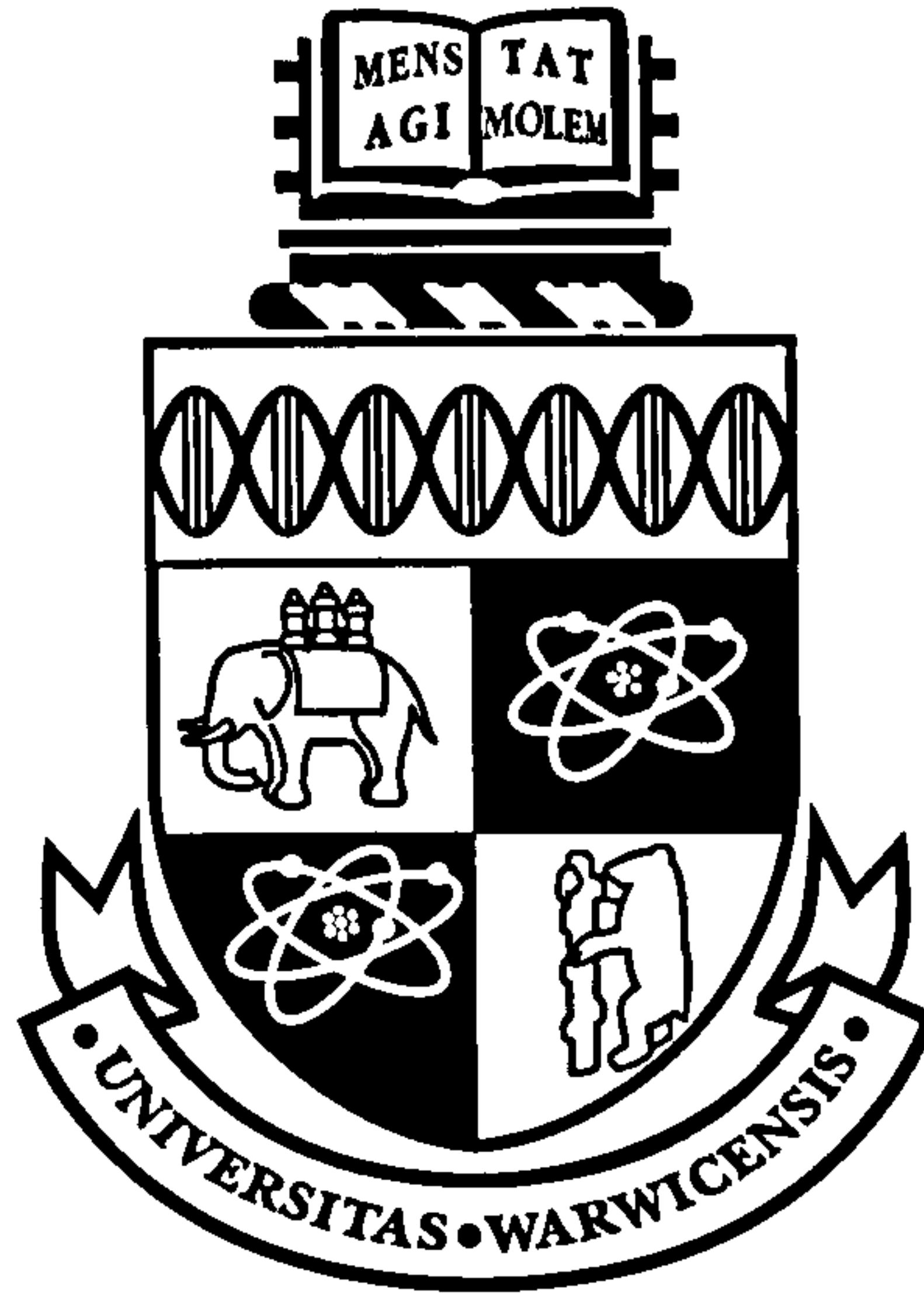
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**From analogy-making to modelling:
the history of analog computing as
a modelling technology**

by

Charles Philip Care

A thesis submitted in partial fulfilment of
the requirements for the degree of

**Doctor of Philosophy
in Computer Science**

**University of Warwick
Department of Computer Science**

September 2008

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This thesis is the result of three years full-time study and has been gratefully supported by a research scholarship awarded by the Department of Computer Science, University of Warwick. The genesis of the theme originated in my undergraduate dissertation on the history of planimeters, but the topic resonates with interests in technology, science, and mathematics, that go back much further.

Among the many who have offered insights, ideas, and encouragement, a few names are salient. Dr Steve Russ, my supervisor, has worked hard to guide my reading and writing. He has fostered in my work a blend of philosophy, history, and computing, which has made the experience all the more enlightening. Similarly, my advisor, Prof. Martin Campbell-Kelly, has always provided excellent advice and support.

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Finally, this thesis would never have reached completion without the support and encouragement of my family and friends. My parents and sister have always supported my studies. However, special thanks are due to my wife Rachel, who has lived alongside this research. She, like no other, has experienced the ups and downs of this project, and her ongoing love and support are deeply treasured.

Charles Care
September 2008

Declaration

This thesis is presented in accordance with the regulations for the degree of Doctor of Philosophy. It has been composed by myself and has not been submitted in any previous application for any degree. The work in this thesis has been undertaken by myself except where otherwise stated.

The review of the history of integrating mechanisms given in Chapter 2 is an extension of my third year undergraduate project on the history of planimeters (Care, 2004).

Much of this work has been presented at various workshops and conferences. In terms of publication, Chapter 2 is an extended version of a published chronology of analog computing (Care, 2007a). Also, Chapter 3 is partly based on a paper discussing the relationship between analog computing and scientific instruments (Care, 2006).

Abstract

Today, modern computers are based on digital technology. However, during the decades after 1940, digital computers were complemented by the separate technology of analog computing. But what was analog computing, what were its merits, and who were its users? This thesis investigates the conceptual and technological history of analog computing.

As a concept, analog computing represents the entwinement of a complex pre-history of meanings, including calculation, modelling, continuity and analogy. These themes are not only landmarks of analog's etymology, but also represent the blend of practices, ways of thinking, and social ties that together comprise an 'analog culture'.

The first half of this thesis identifies how the history of this technology can be understood in terms of the two parallel themes of *calculation* and *modelling*. Structuring the history around these themes demonstrates that technologies associated with modelling have less representation in the historiography. Basing the investigation around modelling applications, the thesis investigates the formation of analog culture.

The second half of this thesis applies the themes of modelling and information generation to understand analog use in context. Through looking at examples of analog use in academic research, oil reservoir modelling, aeronautical design, and meteorology, the thesis explores why certain communities used analog and considers the relationship between analog and digital in these contexts.

This study demonstrates that analog modelling is an example of information generation rather than information processing. Rather than focusing on the categories of analog and digital, it is argued that future historical scholarship in this field should give greater prominence to the more general theme of modelling.

Abbreviations

- AC Alternating Current (electricity)
- ACA Automatic Control Analyzer
- ACE Automatic Computing Engine
- ACM Association for Computing Machinery
- ADI Alternating Direction Implicit (a mathematical method)
- ANT Actor-Network Theory
- ARC Aeronautical Research Council
- BINAC Binary Automatic Computer
- CAT College of Advanced Technology
- CEGB Central Electricity Generating Board
- CNRS Centre National de la Recherche Scientifique
- DC Direct Current (electricity)
- DDA Digital Differential Analyser
- DFT Discrete Fourier Transform
- DSIR Department of Scientific and Industrial Research
- EDSAC Electronic Delay Storage Automatic Calculator
- EDVAC Electronic Discrete Variable Automatic Computer
- EMIAC EMI Analogue Computer
- ENIAC Electronic Numerical Integrator And Computer
- FAU Friends Ambulance Unit
- FRS Fellow of the Royal Society
- GAP/R George A. Philbrick Researches

- GPAC General Purpose Analog Computer
- HCI Human Computer Interaction
- ITC International Training Centre for aerial survey (Delft)
- LIMSI Laboratoire d'Informatique pour la Mécanique et les Sciences de l'Ingénieur
- MADDIDA Magnetic Drum Digital Differential Analyzer
- MIT Massachusetts Institute of Technology
- MoS Ministry of Supply
- MU Machine Unit
- NACA National Advisory Committee for Aeronautics (US)
- NASA National Aeronautics and Space Administration (US)
- NDRC National Defense Research Committee (US)
- NPL National Physical Laboratory
- OED Oxford English Dictionary
- ONERA Office National d'Etudes et de Recherches Aeronautique
- ONR Office of Naval Research (US)
- OR Operational Research
- RAE Royal Aeronautical Establishment (Farnborough)
- Rep-Op Repetitive Operation
- RSSA Royal Scottish Society of Arts
- SBAC Society of British Aircraft Constructors
- SCOT Social Construction Of Technology
- STS Science and Technology Studies
- TNA The National Archives (Kew)
- TRE Telecommunications Research Establishment
- TRIDAC Three-Dimensional Analogue Computer
- UGC University Grants Committee
- UMIST University of Manchester Institute of Science and Technology
- WPNP Weather Prediction by Numerical Process (Richardson, 1922b)
- WWII World War II

Chapter 1

Introduction: Analog computers in the history of computing

Now an almost forgotten technology, analog computers are machines that allow the user to model a complex physical system through interacting with another, analogous, physical system. For example, an economy can be modelled by virtue of an analogy between hydraulic flow and monetary flow,¹ and a physical mass-spring problem can be modelled by the analogous behaviour of a resistor-capacitor circuit. As well as modelling physical systems, analog computers were used to model systems of equations: the classic example is the differential analyser, which mechanised the solution of differential equations.

In an analog computer, quantities are represented using a *continuous* physical medium such as shaft rotation or electrical voltage. Digital computers, on the other hand, use a *discrete* representation of state. Although, this is the technical distinction, data representation is not the only difference between these technologies. For Vannevar Bush, a famous American scientist and inventor of the differential analyser, emphasis was placed on the cognitive support provided by these machines. Bush had a rich vision of blending empirical and analytical investigation, and described the differential analyser as providing a ‘suggestive

¹The economist A. W. (Bill) Phillips demonstrated an analog computer based on this principle at the London School of Economics in 1949. See Leeson (1994) p. 612; Morgan and Boumans (2004); Hally (2005) pp. 185–205.

auxiliary to precise reasoning'.² Rather than placing emphasis on automation, an analog computer mediated knowledge through experimental interaction, providing an environment where the human investigator was actively involved in the computation process.

Studying the history of the analog computer provides an opportunity to explore the context of a superseded technology. Many histories of computing describe a period of analog dominance sandwiched between Charles Babbage's early attempts to construct a digital machine and Howard Aiken's IBM-Harvard computer project (initiated in 1937).³ However, analog computing was certainly not just a 'predecessor' to digital, as this thesis will emphasise. During the 1990s a number of scholars noted that the history of post-World War II analog computing had been under-represented. For instance, in *The Analogue Alternative*, James Small argues that the technology was a 'real alternative' to digital, and he presents the analog and digital computers of the period 1950 to 1980 as competing technologies.⁴

Much of the scholarship re-visiting the analog story emerged from the 'failure studies' approach (the exploration of technological histories that, in hindsight, appear unsuccessful.) This thesis does not see failure as central to the history of analog computing. Although there are significant distinctions between analog and digital hardware, at an application level many of the key features of analog computing, such as the interactive visualisation, now exist within digital com-

²Bush (1936) p. 649.

³See Campbell-Kelly and Aspray (1996) pp. 60–64; Augarten (1985) pp. 84–88.

⁴Small (2001). For the traditional pre-war account see either Bromley (1990) or Campbell-Kelly and Aspray (1996). Recognition of post-war analog begins with the work of Bromley (1983) and Aspray (1993). Further scholarship includes Edwards (1996); Small (2001); Mindell (2002). Interestingly, there is still some controversy about the relative emphasis that historians should place on the two categories. For example, when a recent historical encyclopedia on scientific instruments (Bud and Warner, 1998) devoted approximately equal space to analog and digital computers, reviewer Field (2000) argued that it was 'absurd' to give such prominence to a class of 'disparate devices that set up simulations...[and] ceased to be used in the 1960s.' Clearly Field has a point. However, the key challenge for history is to see past the barriers of these classifications and to situate analog computing within its wider heritage, showing how modern (digital) computing is in many ways the result of a consolidation of these two approaches that in the 1960s were considered separate.

puters.⁵ Thus in the language of failure studies, the history of analog computing provides an example of failure, but not complete failure: the dis-enrollment of an older underlying technology accompanied by a continuity in practice.

Early on in this research project, it became evident that the connections between the words ‘analog’, ‘digital’, ‘computer’, ‘model’, and ‘continuous’, were complex, intriguing and previously not studied in great depth.⁶ The early chapters of this thesis investigate the history of these terms and the classifications they define. However, before this broader history can be investigated, it is necessary to understand the key elements of the analog identity – what made an analog computer (the technology) *analog*, and more importantly, what made analog computing (the culture) *analog*.⁷

As well as exploring the origins of the analog-digital distinction, this thesis is interested in investigating what it meant to be a user of analog computing. It is therefore important to understand the relationship between analog and digital, both in terms of technology and also in terms of practice. To begin this study, two observations of analog computing must be introduced. First, that the term ‘analog computer’ is complex to define, and second, that a major use of analog computing was modelling.

Analog computer – a challenge to define

Throughout its history and historiography, there have been many attempts to define analog computing and each is deficient in capturing the full breadth of contemporary usages and associations. As a further complication, the meaning

⁵We will return to this point later in the thesis. See Chapter 3, pages 82–92, below.

⁶The major studies of analog history are Small (1994, 2001) who investigated the electronic analog computers that replaced the differential analyser; Tympas (1996, 2003) who looked at the history of the network analysers from the perspective of computing labour; and Mindell (2002) who offered interesting perspectives as part of his account of the history of control and cybernetics.

⁷Analog culture is central to the social shaping of analog computing. Chapter 4 will consider how that culture – a network of inventors, users, ideas, rhetoric, machines, and applications – was established, and eventually de-constructed.

of ‘analog’ has also shifted since 1940.⁸ As the following insightful quote from George Philbrick, himself an analog computer pioneer, suggests, the meaning of ‘analog’ is broader than the technology to which it gave its name:

This term Analog, although it is fairly well understood in connotation, needs a note of apology owing to certain current illogical usages. Any mechanism which involves continuous variables is nowadays in danger of being called ‘analog’, of course to distinguish it from ‘digital.’ This even applies to the most familiar transducers, whether they are input or output transducers, which have no computational or simulative purposes whatever. To make matters still more confounded, the common usage for computing structures, whereby only continuous methods are called analog, is wrong, since it is clear that discrete or digital machines may also embody and constitute analogs of prototype phenomena.⁹

This broad usage, coupled with the fact that technical definitions evolve, makes setting the boundaries of the technology’s history a significant challenge. One excellent account of the pre-history of analog computing was given by Bromley (1990), and tells the story of a variety of technologies such as orreries, planimeters, tide predictors, gun directors, differential analysers, and network analysers. Such a chronology, however, carries with it the danger that a diverse range of artefacts become the defining content of analog computing. To combat this, a useful strategy is to ‘follow the actors’ through history and attempt to understand the definitions employed by those who used, developed, and wrote about analog computing.¹⁰

⁸Although modern technical use of ‘analog’ refers to continuity, this was not always so. A look at the primary sources exposes that far from using continuity to make an analog-digital distinction, many contemporary actors used the idea of continuity to contrast between different types of analog. A good example is found in a 1959 textbook by Walter Karplus and Walter Soroka. They draw a distinction between ‘finite-difference networks’ (analogues based on electrical networks of resistors) and ‘continuous field analogs’ (such as an electrolytic tank, or a conductive paper analog). See Karplus and Soroka (1959), p. ix.

⁹Philbrick (1961) p. 1. Philbrick also highlighted the philosophical concern that the first differential of an analog function – and therefore clearly analog – would be considered discontinuous by the mathematician.

¹⁰‘Following the actors’ is the basic principle behind the Actor Network Theory (ANT) popular in the Science and Technology Studies (STS) community. For a detailed description of ANT, see Latour (2005). Studying the labels and classification of a technology is complex. In his study of the epistemology surrounding scientific tools and instruments, Carroll-Burke (2001) notes that ‘the names the actors use are numerous, fluctuating and contested.’ The strategy

By looking at the textbook literature from the 1950s and 1960s, we can explore what 'analog' really meant for its users. One helpful definition dating from the early 1960s comes from Stanley Fifer, the director of Dian Laboratories, an analog computer manufacturer based in New York. In 1961 Fifer published an extensive four volume work covering every aspect of analog computing, including a historical review of its development.¹¹ Identifying that analog computers exhibited three main characteristics – analogy, continuity, and measurement – he wrote:

It is no simple matter to define the term 'analogue computer,' for, as we shall have occasion to note, it encompasses a wide variety of calculating devices and machines. Among the characteristics which serve to identify analogue computers are (1) the analogue computer itself, (2) the continuity of the solutions furnished by the computer, and (3) the observation and recording of the results by means of measurement.

The word analogue denotes 'a resemblance of relations.' Accordingly, an analogue computer is one which calculates the behaviour of a physical system by virtue of the fact that the computer variables are proportional to the variables of the desired solutions, and the computer configuration becomes, thereby, the analogue of the given system...

Secondly, analogue computers are characterized by the fact that the computer variables are, in general, continuous quantities such as voltages, currents or shaft rotations, rather than discrete states as in a digital computer. This is to be expected, as the physical phenomena of which the computer solutions are the analogues are usually continuous in nature...

Thirdly, the variables, being continuous, are customarily measured rather than counted. Among the instruments employed for this purpose are ammeters, voltmeters, oscillographs, magnetic and optical recorders, plotting boards, and analogue-to-digital converters. (In the latter case, however, the distinction between the analogue concept of measuring and the digital characteristic of counting loses some of its significance.)¹²

Note that, for Fifer, analogy had priority over continuity. An analysis of similar passages within the contemporary textbook literature shows that between

adopted in this thesis is to choose classifications and theoretical distinctions that are faithful to the actor's own terminology and classification.

¹¹Fifer's work has been a major source for historians – both Bromley (1990) and Small (2001) draw heavily on the historical account provided in vol. I.

¹²Fifer (1961) pp. 2-3.

1950 and 1970, it became more common for authors to favour continuity, indicating that analog computing's 'identity' was shifting away from analogy. Although continuity was favoured by the technical communities, others formed their own interpretation of the analog-digital dichotomy. Based on the idea that analog supported more speculative investigation, Douglas Hartree described the distinction in terms of instruments and machines.¹³ Similarly, for the British scientist Donald Mackay, the classification hinged on quantitative versus qualitative:

The distinction between numeral and number is thus the real *raison d'être* of this dichotomy of technique. At a deeper philosophical level it lies roughly parallel with that between the qualitative and the quantitative.¹⁴

So it appears that neither analogy nor continuity offered a 'defining content' for analog computing. Firstly, 'continuity' has been interpreted in a variety of senses, and secondly, 'analog' – the technological label – was also shifting in its meaning. This emphasises that the historian cannot rely on technical issues and must follow the classifications and associations of the original actors. We need to consider four main aspects: technologies that were labelled analog; predecessor technologies which inspired the development of analog computing; technologies used to perform similar tasks to analog computers; and technologies where the approach of its users was empirical and speculative (see Figure 1.1).

Interestingly, the technical labels of 'analog' and 'digital' first emerged in the 1940s to provide a handle on two emerging classes of computer technology. Over the following decades, analog-digital evolved to distinguish two types of computing. Other uses of this dichotomy in describing and classifying signals, transmission, and clocks, developed from there. While classification can guide the

¹³See Chapter 2, page 58 note 91, below.

¹⁴MacKay (1951) pp. 1.4–1.5. In appealing to the distinction between 'numeral' (exemplified in abstract digits) and 'number' (grounded physical quantities), MacKay was speaking from his own perspective as a physicist – namely the tradition extolled in N. R. Campbell's famous textbook *Physics the Elements*. Campbell's idea of numerals and numbers was central to his presentation of physics (Campbell, 1957/1920, p. 269).

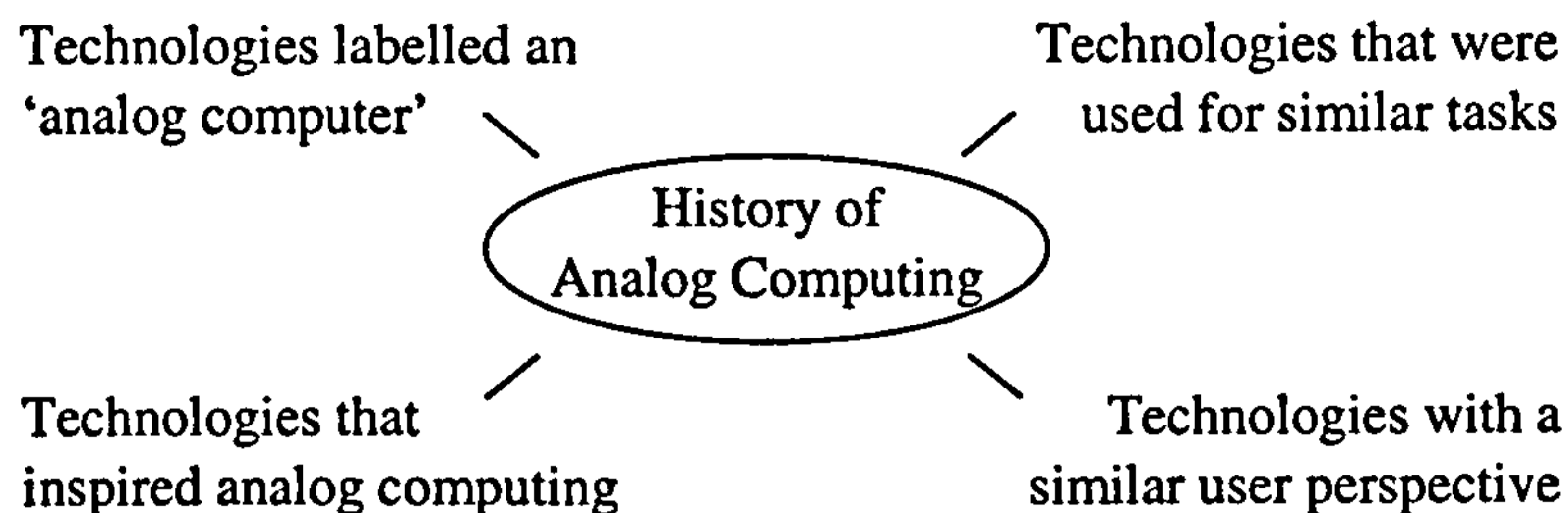


Figure 1.1: Relevant themes to the history of analog computing.

historian, it can also create barriers between the two themes, making it difficult to provide a synthetic account.¹⁵

Because later definitions of analog were absorbed into the historiography of analog computing, there have been disagreements over how the history should be presented. For example, Campbell-Kelly and Aspray (1996) who defined analog computing in terms of ‘analogy’, came under criticism from Small (2001). Small wrote that ‘[they] fail to explain the fundamental differences between analogue and digital computing... the former operates on continuous data and the latter operates on discrete data’. Furthermore, Small argued that referring to analogies and models was ambiguous because ‘both analogue and digital systems were used to build analogues (or models) of physical systems.’¹⁶ This disagreement pivots on whether the history of analog computing should be framed in terms of technical classification (continuity) or type of use (modelling). This thesis argues for a framework based on the perspective of use, thus helping to avoid ‘back-projecting’ modern understandings of the analog-digital classification. As introduced in the next section, a modelling perspective will help present the relationship between

¹⁵Commenting on the history of mathematics, Lax (1989) highlights that a major problem with the so called ‘internalist historians’ is that ‘they describe the development of an idea as it should logically have unfolded rather than as it actually did.’ (p. 533). In relation to the history of scientific instruments see the commentary on the Bennett/Hackman debate by Carroll-Burke (2001). Because analog history is highly dependent on technical texts for its source material, avoiding internalist historiography is a challenge. This highlights the importance of an approach that ‘follows the actors’.

¹⁶Campbell-Kelly and Aspray (1996) p. 60; Small (2001) pp. 6–8. Similarly, in introducing the analog-digital classification, David Clark wrote that: ‘There are two versions of this distinction... Firstly there is a distinction to be made between computation by modelling, and calculating by the formal manipulation of tokens and symbols. Secondly, is the distinction drawn between representing quantities by the measure of some analogous substance or physical state, and representation by number symbols.’ (Clark, 2002, p. 79).

the two classes of machine.

Analog computing as modelling technology

Whilst a diverse collection of technologies are considered part of the history of analog computing, many early analog devices were actually modelling technologies. Orreries, or clockwork models of the solar system, were used to illustrate the orbital dynamics of the planets; tide predictors embodied mathematical models of tidal heights, and were used to assist shipping and trade; and network analysers had their origins in the scale models of electrical power distribution networks. To be properly understood, the history of the analog computer must be situated within the history of modelling technology.¹⁷

When Campbell-Kelly and Aspray (1996) introduced analog computing into their account of computer history, they did so with a context of modelling.¹⁸ In making their text accessible to a general readership, this was a good choice: modelling being far more intuitive than the technical concept of continuous variables. Indeed, while the technical texts (contemporary textbooks, articles, and manuals) define analog in terms of the continuity of variables, analog computing was often described to non-technical audiences in terms of its use. For example, when the *London Illustrated News* ran an article on TRIDAC, a large (analog) aeronautical computer developed during the early 1950s, the machine was introduced within a context of modelling:

TRIDAC differs from other electronic 'brains' in that it provides a model of the system being studied. When making calculations, for instance, of a fighter aircraft chasing a bomber, the motion of the bomber may be reproduced by setting into the computer a pre-arranged

¹⁷It should be noted that whilst a narrative of modelling captures many analog devices, for others such as planimeters and gun directors it does not. The inclusion of these in the history of analog computing is generally a result of their importance as prior-technologies of the differential analyser. Thus, modelling and calculation should be explored together, an approach taken in Chapter 2.

¹⁸See Campbell-Kelly and Aspray (1996) pp. 60–63.

programme, which may include periods of straight flight, slow turns or violent, evasive manoeuvres.¹⁹

Describing analog computing in terms of modelling and simulation emphasised its applications and was therefore common in analog sales literature. For instance, EMI chose to market their commercial analog (the EMIAC II) as the modern successor of scale models (see Figure 1.2). An EMI brochure from the mid-1950s opens with the following passage:

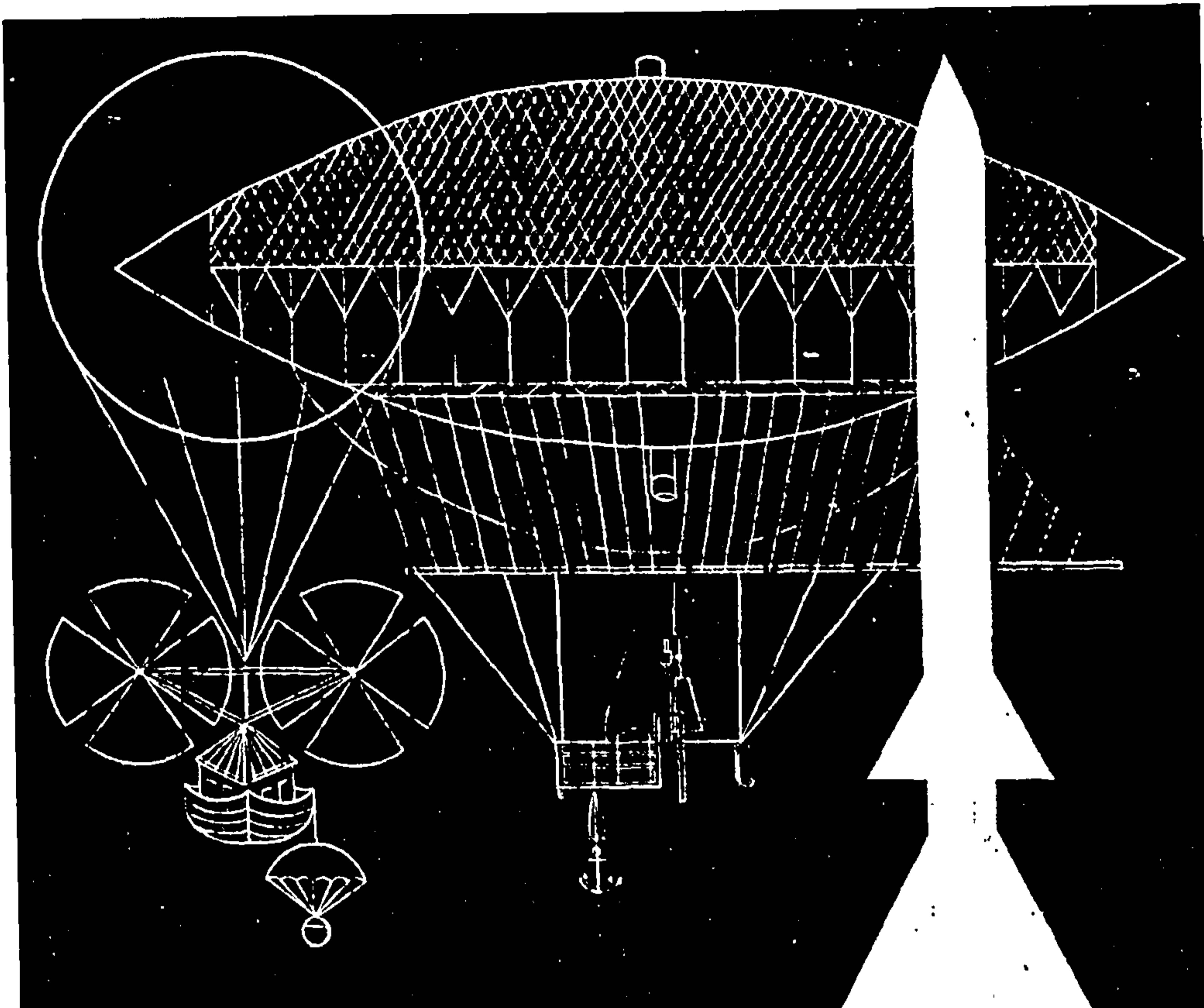
From Leonardo da Vinci to Lord Kelvin, working scale models have been the classic means of examining new designs. Even today they persist in pilot plants and similar trial mechanisms. But their usefulness is limited. Systems grow ever more complex and the laws of Nature do not allow for scaling in the atomic piles, chemical reactors or supersonic aircraft which form the subject of the studies of tomorrow. Today the analogue computer is capable of producing veritable models, truly scaled, of any engineering system which can be represented mathematically, without cost of materials or manufacture, only substituting electrical voltages for the quantities to be measured and networks of resistors and capacitors for the physical structure of the plant or mechanism.²⁰

Research in the history of computing has at various times considered the computer in the context of a broad spectrum of technologies. This leads to certain meta-narratives or 'histories' of the computer. In particular, the 'history' of the computer as an information processor captures the modern computer's wide use in office applications such as document preparation or accounting. This study therefore introduces another 'history' of the computer, a narrative of modelling technology.

Alongside classic information processing tasks such as preparing technical documentation and performing engineering calculations, computers can be used to represent physical systems and natural phenomena. While applications in science and industry commonly use software for modelling, the history of the computer as a modelling technology has not yet received the coverage that might be expected.

¹⁹Anon. (1954) p. 995.

²⁰EMI (Undated).



CONTRASTS IN FLIGHT: NEARLY A CENTURY AND A HALF SEPARATES CAYLEY'S PROPOSED BALLOON, 1816, AND GIFFORD'S AIRSHIP, 1852, FROM THE ROCKETS OF TODAY.

Gaining years of experience in a matter of seconds

Turning a designer's idea into practical reality by the slow process of trial and error once took months and often years of work. The pace of progress today and the complexity of the problems to be overcome call for something faster than scale models, prototypes and lengthy testing; something beyond the limited capabilities of the unaided human brain.

An Analogue Computer often provides the answer. By simulating the problem in the form of an electrical analogue, it can solve in a few hours problems that might take months of calculation. It can speed up processes, compressing into a matter of seconds operations that might take weeks; or slow down disturbances which are too fast for the human mind to grasp. Knowledge is speedily gained rather than laboriously acquired by experience.

There are no obvious limits to the problems which can benefit from the application of analogue computer studies. Already they have been applied successfully to fields as diverse as car suspension systems, chemical plant designs, guided missiles, nuclear reactors, aircraft flight and tidal flow.

EMIAC II—AN INFINITE RANGE OF ANALOGUE COMPUTERS

EMIAC II is a general purpose analogue computer which has been carefully engineered so that it can be supplied as a small unit and extended to solve more complex problems as they arise.

We do not anticipate that you will be prompted to place an immediate order for an EMIAC II analogue computer, but we do hope that you will give us the opportunity to demonstrate how this modern 'tool' solves your specific problems efficiently and economically. Many leading companies, including Sir W. G. Armstrong-Whitworth Aircraft Ltd., De Havilland Propellers Ltd., Hawker Siddeley Nuclear Power Co. Ltd. and the Australian Government Aircraft Factory, have taken advantage of this opportunity and subsequently placed orders for EMIAC II installations.

Why not write or telephone for full details of EMIAC II? We also manufacture the outstanding range of EMIDEC digital computers.



E.M.I. ELECTRONICS LTD.

COMPUTING DIVISION • HAYES • MIDDLESEX • TELEPHONE: SOUTHALL 2622

Figure 1.2: An advert for the EMIAC, from *The Times*. Source: EMI (1959a).

This has also been noticed by Michael Mahoney with reference to software. Commenting on the conference now published as *History of computing: Software issues* (Hashagen et al., 2002), he wrote:

A recent conference... attempted to map out the history of software, considering it as science, engineering, labour process, reliable artefact and industry... The focus lay on software and its production as general phenomena. What the conference missed was software as model, software as experience, software as medium of thought and action, software as environment within which people work and live. It did not consider the question of how we have put the world into computers.²¹

Before we can begin to think about how software is used to represent or model the world, it is necessary to have a clear understanding of how these tasks were performed in the pre-software period. Returning to scholarship on the history of analog computing, David Mindell's *Between Human and Machine* suggests that alternative narratives of the computer have been overlooked. Instead of taking the view that analog technology was primitive and digital progressive, Mindell recognised that the transition from analog to digital was 'neither instant, obvious, nor complete'.²² This highlights how themes other than information processing have contributed to the development of the computer.²³

To understand the history of computer modelling requires an investigation of analog computing. This thesis argues that there were communities within British research establishments, industry, and academia, which all required technology to support a common activity that we shall call modelling. Just as a demand for office technologies such as the typewriter, calculating machine and tabulator emerged during the late nineteenth century; the need to create visual and interactive models of physical phenomena created a similar demand for modelling technology. Initially, modelling was supported by special purpose direct physical

²¹Mahoney (2005) pp. 107–108.

²²Mindell (2002) p. 10.

²³For Mindell, pre-war feedback culture was central to the history of computing and the foundation of cybernetics. See Mindell (2002) ch. 6, and also the review articles by Owens (2003) and Haigh (2003).

models such as scale models, then as mechanical or electrical analogs, and finally as software packages installed on digital computers. This thesis contributes to the history of computer-based modelling technology. It is about users representing their experience of the world in a machine, and using these representations to understand or make predictions about natural phenomena.

The thesis: an overview

Building on previous investigations into the history of analog computing, this work aims to develop connections with wider work on modelling. The thesis falls into two parts: Chapters 2–4 investigate the development of the overarching themes of theory and identity, and Chapters 5–8 explore the second theme of analog application and practice. This mix allows us to combine both the theory-driven approaches of history of science scholarship with more social-driven approaches common in the history of technology. This is important for two reasons. First, it allows us to explore the linkages between concepts and communities – vital for understanding the evolution of analog culture. Second, it encourages the use of classification that is grounded in context and not back-projected.

By combining the theoretical study with the technological story, it becomes possible to see the dynamic relationship between the two: theory shaping practice, and practice shaping theory. Exploring the themes of theory and identity exposes the prominence of modelling as an application of analog computers. By bringing modelling to the forefront, we see analog computing in the light of its merits, and begin to understand how digital computing evolved to replace analog applications. However, the theory behind a technology never evolves in a vacuum and here enters the second theme of practice. Through exploring specific user contexts, we see what analog computing meant for the people ‘on the ground’. These were the actors who made decisions about the technology, and so shaped the classifications and associated assumptions. Of course, practice does not develop

in isolation either: the people who drove the analog story forward were themselves shaped by its theory.

Within the theme of understanding theory, this thesis contributes to our understanding of the relationship between analog and digital, and the history of these technological labels. In terms of understanding practice, this thesis contributes to our knowledge about how the discipline of analog computing evolved.

Part I: Modelling, calculation & analogy: the themes of analog computing

Chapters 2–4 address the main themes surrounding analog computing, and hinge on the difficulty of using technical jargon and classifications in historical scholarship. Recent historiography of computing has been informed by the frameworks provided by sociologists of technology, approaches that emphasise the social shaping of technology.²⁴ While previous scholarship has shown such technological shaping to be key, this thesis confirms that the same is true of the technology's labels, keywords and classifications – an observation noted by Bowker and Star (1999) in their history of classification. In identifying a history of 'analog identity', we draw on the importance of labels such as analog and digital, concepts such as continuity and analogy, and 'use-themes' such as modelling and calculation.

Chapter 2 – chronological themes in the history of analog computing

As we explore the history of analog computing, we will see that much of the conceptual framework provided in the secondary literature conflates what are really two separate themes of analog computing: calculation and modelling. Chapter 2 reviews the history of analog computing technology and gives an overview of the variety of analog computers in history, exposing continuity and analogy as dual

²⁴There are three major approaches to considering the sociology of technology: the Social Construction of Technology (SCOT) movement, Actor-Network Theory (ANT), and Hughes' systems theory approach. See Bijker and Law (1992) for the discussion of these different approaches. Much history of technology draws heavily on the SCOT tradition. This thesis also draws from that literature, but also employs some of the ideas developed within ANT.

meanings of 'analog'.

In attempting to construct a chronology of analog computing consistent with the two themes of continuity and analogy, Chapter 2 concludes that the history is best represented with separate time-lines. Through a multi-strand chronology, a perspective of modelling technology is shown to be particularly applicable to understanding the history of direct analog computers, and that a dichotomy of 'equation-solving' versus 'modelling' is emergent from the sources.

Chapter 3 – analog computing as modelling technology

Building on these multiple perspectives of use, Chapter 3 develops the idea of 'the computer as a modelling machine'. It establishes philosophical and historical motivations for investigating the computer as a modelling technology and discusses conceptual issues surrounding the history. With analog computing the relationships between problem, machine and user were dynamic and less prescribed than typical data processing, equation solving, or calculating.

Chapter 4 – this history of electrical analogy

Tracing the formation of the culture of electrical analogy during the 1920s, Chapter 4 returns to the role of labelling and classification in the formation (and subsequent destruction) of analog culture. As discussed above, the definition of analog computing is complex, and was in flux during the 1940s. Particularly interesting is the blending between analogy and continuity that enrolled previously disparate technologies into computing. Initially, this enrollment was good for analog technology. Within the technological frame of computing,²⁵ analog was associated with digital, both technologies being 'computers'. However, later in the history, this association turned sour. Analog became the 'poor relation' of computing and was redefined to become non-computational.

²⁵In Chapter 4, Bijker's conception of a 'technological frame' is used to describe the combination of technology, theory, and practice, that defined analog culture at a specific time. See Chapter 4, page 109, below.

Part II: Analog computing in use: a selection of contexts

While Chapters 2–4 discuss the overarching themes and the formation of analog culture, the discourse of analog identity is strongly situated in technological contexts. The rest of this thesis therefore investigates a number of those contexts.²⁶

Each chapter narrates a particular story based on original research. Chapter 5 explores the use of analog machines in British higher education; Chapter 6 discusses analog modelling of oil reservoirs at BP; Chapter 7 discusses aeronautical use; and Chapter 8 considers an analog model used for meteorological modelling.

These studies reinforce the idea of studying theory and practice. On the pathway to digital domination, digital actually developed to encompass some of the practices and culture of analog. Following the idea of partial failure, each chapter highlights that the relative merits of analog and digital were not obvious. Although analog technology was replaced, its technical culture continued to grow and evolve.

Chapter 5 – analog computing in British higher education

Chapter 5 undertakes an investigation into the activities of British Universities and their use of analog computing. As well as providing a history of analog activity at a number of key institutions, the issue of funding is also discussed. The chapter undertakes a more quantitative analysis of its use by looking at the research theses published by British Universities during the period. This analysis demonstrates the wide application of activities that can be described as *normal computing* – the day-to-day application of stabilised technology rather than the innovation of new technology.²⁷

²⁶Bijker and Law (1992) emphasise the importance of ‘thick description’ in describing the history of technology. Detailed case studies are necessary to understand the ‘social, economic, and technical complexity of a technology’ (p. 5).

²⁷This use of ‘normal’ follows Walter Vincenti’s analysis of engineering practice in which he distinguishes between normal and radical design. For Vincenti, radical design is innovation where anything is subject to change; normal design involves innovation within certain stabilised boundaries. This mirrors Bijker’s theory of technological innovation, radical corresponding to non-stabilised technologies (he cites pre-1880 bicycle technology as an example) and normal

Supporting the argument for multiple perspectives of use, this chapter describes how the various applications of analog (calculation, modelling, and control) follow different historical trajectories. Secondly, it explores the consequences of classification in the funding of analog computing. Through looking at the funding of these machines in the wider policy making climate, we see how this initiated the dis-enrollment of analog users.

Chapter 6 – analog computing and oil reservoir modelling

Chapter 6 takes the idea of normal application further and explores why in 1961 the research division of BP, a world class petroleum company, would choose to install an analog computer. This story discusses the use of electrolytic tanks and resistance networks for aquifer modelling.

BP's analog computer is an example of ordinary computing application. It was a normal device and so not on the radar of mainstream computing commentary. Because BP procured both an analog and a digital computer at the same time we conclude that analog-digital superiority was not of immediate concern, and that instead of alternatives, these two classes of computer were complements. This study confirms that historians of computing must look at normal usage in order to fully understand the technology's contemporary use.

Chapter 7 – analog computing in aeronautical engineering

Before an engineer can rely on a technology to assist with design work, it has to become 'trustworthy'. Considering the claim that analog was intuitive to use and well-regarded amongst engineers, Chapter 7 examines their use in aeronautical design. The persistence of analog computing is explored in terms of its reliability and trustworthiness, and how engineers belonged to the 'analog generation'.

design to the innovation of technologies within a well-established 'technological frame'. See Vincenti (1990) pp. 8-12; Bijker (1992) p. 159.

Chapter 8 – physical analogs and experimental culture in meteorology

The history of meteorology is intimately related to the history of the computer, weather forecasting being one of the first applications of the (digital) American ENIAC. Today, meteorology has evolved into a computational science, a discipline underpinned by computer modelling.²⁸

In the history of computing literature, meteorology is always presented as an area dominated by digital. However, Chapter 8 shows that experimental and inexact techniques existed alongside the numerical/computational parts of this science. In fact, we find that physical analog models were in use, but were not called computers. While there were no analog-digital tensions, the dichotomy of numerical versus physical was of concern. Hence the idea of technologies being enrolled in and out of computing culture is key, emphasising the importance of the mutual shaping of theory and practice.

Analog computing and the application of modelling – new contributions to the history of ‘direct’ analogs

The four case studies described in Chapters 5–8 differ from previous research in the history of analog computing. Much of the existing literature relates to the technologies that developed from the tradition of calculating machines. For instance, James Small’s work focuses exclusively on the so-called ‘general purpose’ analog computers. Because we are thinking about the analog identity in terms of modelling, new importance is given to ‘direct’ analog computers.

While ‘indirect’ analogs modelled a mathematical system such as a set of differential equations (and could therefore be used to solve equations), ‘direct’

²⁸William Aspray wrote that ‘the computer almost transformed meteorology’ (Aspray, 1990b, p. 152), and when Frederik Nebeker wrote a history of meteorology, he presented the stored program digital computer as a unifier of three previously separate meteorological traditions (Nebeker, 1995, p. 2). Following Nebeker, Dahan Dalmedico (2001) wrote that the unification of the three themes ‘hinged mainly on the new availability of fast computing machines’ (p. 397). In contrast, Agar (1997) suggests that this view is a return to success-oriented history, effectively downplaying the role of non-digital computing.

analog computing did not rely on mathematical formulation.²⁹ Instead, direct analogs modelled a physical system based in one medium with another physical system.³⁰ In terms of multiple perspectives of use, direct analogs persisted even after many of the calculating uses of analog were being replaced by digital computing. These technologies, typically resistance networks or electrolytic tanks, were used for modelling heat flow and other complex physical phenomena. Following multiple perspectives of use encourages us to take a broader look at what was understood as analog computing. Situating analog computing within the wider history of modelling technologies, this study includes technologies such as the electrolytic tank, electrical models, and even wind tunnels.

²⁹It should be highlighted at the outset that while the direct-indirect distinction has proved useful, it is possible that in different applications, the same machine might be interpreted as both indirect and direct. The MIT network analyser is a good example: this machine began as a generic tool for modelling power networks (a computation based on 'direct' analogy) and was later interpreted as a tool for solving systems of differential equations (a computation based on an 'indirect' mathematical representation). This problem derives from a variance in use.

This is mirrored in other classification problems in the history of science. For example, in an edited collection on the history of experiment, two perspectives on the classification of instruments were suggested. The first (Hackman, 1990) suggested a conceptual framework of 'active' and 'inactive' instruments, while the second (Bennett, 1990) refutes the active/inactive classification, pointing out that a single artefact could be considered as both active and inactive by different perspectives of use. Carroll-Burke (2001) explores these approaches – which he describes as 'theoretical' and 'historicist' respectively (p. 596).

³⁰See Bromley (1990) p. 157 and Small (2001) pp. 30–31.

Part I

**Modelling, calculation & analogy:
the themes of analog computing**

Chapter 2

A multiple-strand chronology of analog computing[†]

It was in the early 1940s that the foundations of the digital computer were being laid. A mechanical computer was developed by Howard Aiken at Harvard University;¹ John Vincent Atanasoff invented an automatic electrical calculator at Iowa State College; and in Pennsylvania, researchers at the Moore School assembled the electronic ENIAC.² Scientific culture was thirsty for mechanised mathematics, and it was from this inventive soup that, inspired by a need to contrast the old with the new, the technical labels of ‘analog’ and ‘digital’ first emerged.

The first use of the word ‘analog’ to describe a class of computer is attributed to Atanasoff, who, although a pioneer of digital, had previously used analog methods (before they were so-called) for solving partial differential equations.³ With a new classification scheme at hand, practitioners very quickly began to apply the labels ‘analog’ and ‘digital’ to a whole range of problem solving technologies,

[†]This chapter is an expanded form of a previously published article (Care, 2007a) and the discussion of planimeters is partly based on the research detailed in my undergraduate dissertation (Care, 2004).

¹Developed during wartime USA, the Harvard Mark I became operational in 1944 and was based on electro-mechanical components. The future for both analog and digital computers would be found in the speed and flexibility of electronic components.

²Other important early work was that of the German Konrad Zuse, and the British code breaking effort of WWII. However, in terms of future influence on computing technology, much of the significant innovation was American.

³Atanasoff developed the Laplaciometer, a special purpose computing device used for solving Laplace’s equations (a partial differential equation problem) during the 1930s (Murphy and Atanasoff, 1949). We will return to the origins of the analog-digital classification later in the chapter.

enrolling them into a computing culture. Some of these technologies were already associated through the literature on calculating machines,⁴ while others were seen as completely disparate technologies.

This chapter presents a chronology of analog computing in which a distinction is drawn between two major strands of analog computer: one concerned with uses for calculation, another concerned with modelling. These two strands roughly correspond to the classification established by practitioners, that of indirect and direct, as discussed earlier. While the importance of both calculating and modelling is evident from secondary literature, the principal difference between this chronology and previous accounts is the claim that it was not until the concept of an 'analog computer' emerged that these two thematic strands became unified.⁵

Two meanings of analog: the tension between analogy and continuity

In English, the word 'analog' (or analogue) has traditionally been used to convey likeness, similarity or correspondence. Like *analogy*, it derives from the Greek for equalities of ratio or proportion.⁶ During the twentieth century, the word developed a second technical meaning now commonly employed to describe electromagnetic waveforms. Rather than a discrete or digital signal, an analog wave-

⁴The survey of calculating machines by Vannevar Bush in his Gibbs lecture (Bush, 1936) and Irven Travis' Moore School lecture (Travis, 1946) indicate how the early technology was perceived. Travis also produced an extensive bibliography (Travis, 1938) which nicely preserves his perspective on the scope of relevant technology. In this work, Travis makes no reference to network analysers or other physical models.

⁵As Akera (2007) writes: 'Before World War II, computing was not yet a unified field; it was a loose agglomeration of local practices sustained through various institutional niches for commercial accounting, scientific computing, and engineering analysis.' (p. 25).

⁶The similarity is understood to be structural, concerning correspondences of form rather than content. See 'analogue, *n.*, and *a.*', *The Oxford English Dictionary*. 2nd ed. 1989. *OED Online*. Oxford University Press. Accessed 1st September 2006. <http://dictionary.oed.com/cgi/entry/50007887>; 'analogon', *The Oxford English Dictionary*. 2nd ed. 1989. *OED Online*. Oxford University Press. Accessed 1st September 2006. <http://dictionary.oed.com/cgi/entry/50007883>; and 'analogy', *The Oxford English Dictionary*. 2nd ed. 1989. *OED Online*. Oxford University Press. Accessed 1st September 2006. <http://dictionary.oed.com/cgi/entry/50007888>.

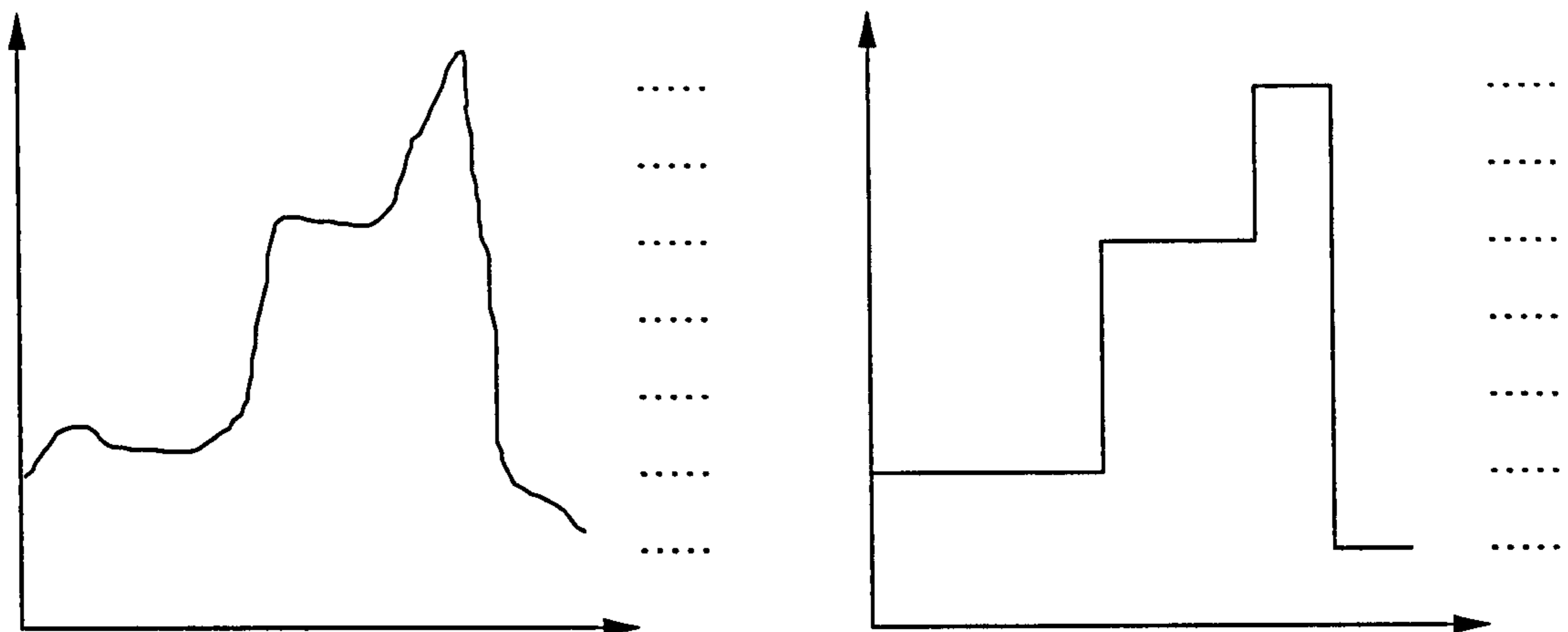


Figure 2.1: An example of an analog and digital signal varying over time. The signal on the left varies over a continuous range to the granularity imposed by physical properties. The signal on the right has been digitalised over a range of seven discrete values. Alongside analogy, continuity is a second meaning of analog. Note that this example only demonstrates digitalisation of the signal's magnitude (or range), waveforms can also be discrete or continuous with respect to time.

form is a continuous function (see Figure 2.1). It is from this second meaning that the technical labels 'analog television' and 'analog radio' are derived, and as a result of this technical use, 'analog' now refers to continuity in general. Popular usage of the analog-digital dichotomy is found in the classification of clocks. Furthermore, recent advances in digital audio have resulted in digital acting as a key word for sound reproduction: analog representing the crackly, out-moded, and less desirable technologies of vinyl records and tape cassettes.⁷

Analog computing can be understood in terms of both meanings: firstly, analog computers rely on the construction of a suitable analogy (or correspondence) between two physical systems; secondly, analog computers use an internal representation that is continuous.⁸ That analog computing can be interpreted through these two different meanings is not simply a convenient coincidence. Certain ana-

⁷Many examples of shifting contexts and the 'overloading' of technical labels exist. One example is 'personal stereo', the technical term for two-channel audio – stereo – becoming synonymous with a product. Similarly the musical term for soft dynamics (*piano*) has become a label for the instrument that was intended to be known as the *piano-forte* – named in light of its ability to play the full dynamical range. Ten years ago, 'broadband' was a telecommunications term, today it refers to high speed Internet access. The migration of technical jargon into cultural key words is observed whenever technology and society meet.

⁸Singh (1999) commented on analogy being the 'true meaning' of analog. It is certainly the original meaning.

log computers were originally referred to as 'analog machines' and the association with continuity arose through the comparison of these machines with their competitor technology, the digital computer.

Shaped by usage, 'analog' evolved to become synonymous with continuity, establishing a term that was subsequently exported to other technical cultures such as signal processing and control engineering, and in turn became a technical label in the consumer culture of audio and video technologies.⁹ Indeed, this is the most significant cultural legacy of analog computing. Had the technology not been compared with digital machines, common language would have not received the key word 'analog'. Essentially, analog computing is the *raison d'être* of the analog-digital classification common in modern technical rhetoric. If analog computing had not been so-called, we would probably be replacing our out-moded 'continuous' radios and televisions in favour of new 'discrete' versions.¹⁰

Towards a chronology of analog computing

In setting out a chronology for analog computing we will see that the conflation of the two meanings of analog, while obvious in the technology's contemporary context, has led to confusion within the historiography.¹¹ Although the blending of analogy and continuity was central to the development of analog computing, an analysis that can temporarily disassociate them will offer clarity on the pre-history of analog computing.

Historians of technology well understand the complexity of technological evolution and will not be surprised that the story of analog is not a linear progression

⁹In this evolution we see that the idea of 'analog' was at each stage exported into new technological domains, a process akin to that described by Actor-Network Theorist as 'translation'. See Latour (2005) pp. 9, 6, & 78.

¹⁰The OED's etymological notes claim that waveforms and signals were not described as 'digital' until the 1960s – long after the 'digital computer' became common. See 'analogue, *n.*, and *a.*', *The Oxford English Dictionary*. Draft additions, September 2001. *OED Online*. Oxford University Press. Accessed 1st September 2006. <http://dictionary.oed.com/cgi/entry/50007887>.

¹¹See the debate over the identity of analog computing in James Small's critique of Campbell-Kelly and Aspray (1996) as described in Chapter 1, page 7, above.

of development, but rather the consequence of an unfolding relationship between continuous calculating devices (the ‘equation solvers’), and the technologies developed for modelling. To capture this, the following chronology is structured into three thematic time-lines. The first describes the invention of *continuous* calculating aids – analog devices well known to the history of computing.¹² The second time-line focuses on the perspective of modelling and analogy-making technologies such as models of power networks or alternatives to wind tunnel modelling. Finally, the third time-line takes up the story from the point when the two perspectives became unified by the common theme of ‘computing’. Beginning around 1940, this third theme traces how the analog computer was enrolled into the domain of computing technology, paving the way for the eventual migration of analog/digital rhetoric into other disciplines such as communications and control engineering.¹³

As already noted, the division into separate time-lines is an attempt to organise the variety of devices that we now call ‘analog’ while remaining faithful to the distinctions emergent from the contemporary source material (an attempt to ‘follow the actors’). Labels relating to calculation include ‘continuous calculator’ (promoting technical features), ‘indirect’ (highlighting the role of mathematical representation), and ‘equation solvers’ (identifying a type of use). The corresponding labels relating to modelling are ‘electrical analogy’, ‘direct’, and ‘simulators’. By using the more generic terms of calculation and modelling, we can maintain an application-oriented approach that does not focus solely on the technical details. Hence the remainder of this chapter should not be read as a chronology of machines, but rather as an account of evolving *use* of technology.

¹²These technologies can be grouped together under the banner of ‘continuous calculating machine’, a label that appeared in the late Victorian period. Elsewhere, such devices have been classed as ‘mathematical instruments’ (Croarken, 1990, p. 9), or as ‘analog computing devices’ (Bromley, 1990, p. 159).

¹³Control systems will not be considered in detail in this thesis and interested readers are directed to the work of Mindell (2002) or Bennett (1979). However, some of the technologies mentioned as we pass through this chronology relate to the developing association between control and analog (particularly the gun directors and other embedded computation).

First thematic time-line – Mechanising the calculus: the story of continuous computing technology

The computer as we know it today, a programmable and digital machine, emerged during the middle of the twentieth century. However, throughout history, computing tasks have been supported by a variety of technologies, and the so-called ‘computer revolution’ owes much to the legacy of the various calculating aids developed in the preceding centuries. The history of early calculating devices ranges from practical astronomical tools such as the astrolabe, through to more abstract calculation devices such as Napier’s bones and the slide rule. Using material culture to embody aspects of theory, these mechanisations encoded particular mathematical operations, equations, or behaviours, into physical artefacts. These inventions became known as calculating machines and at this stage there was no explicit distinction between discrete and continuous representations of quantity.

A mechanism to perform basic addition was first proposed in the seventeenth century. However, producing a mechanisation of higher mathematical operations such as differentiation and integration remained unsolved until the early 1800s when mechanical integrators emerged. As it turned out, mechanical embodiments of the calculus were far more straightforward to engineer for those technologies that were later labelled ‘analog’, hence it was during this period that the continuous-discrete dichotomy first became an issue.¹⁴ Following the analytical scheme of this chapter, a more complete history of calculating machines could include an extra time-line that focused on non-continuous calculating devices such as mechanical stepped-drum calculators, key-driven Comptometers, and other

¹⁴On early mechanical calculating devices see Aspray (1990c) pp. 40–45; Williams (2002); Swartzlander (2002); Henrici (1911); Horsburgh (1914). The major strength of the technologies that later became known as analog computing was always elegant handling of the calculus. Thus, the major users of this class of machine were engineers and scientists interested in solving differential equations. Although the most common component was the mechanical integrator, mechanical analogies were developed for a whole variety of mathematical functions (Svoboda, 1948).

late-Victorian calculating aids. However, this chapter focuses on continuous calculating machines, and in particular, the mechanical integrator and its technical predecessor, the planimeter.

1814–1850: Towards the mechanical integrator: the invention and development of the planimeter

Like many other technologies in the history of computing, the mechanical integrator was adapted from another device. This device was the planimeter, a mechanically simple but conceptually complex instrument that was used to evaluate area.¹⁵ Beginning with the invention of the planimeter in 1814, the development of mechanical integrators inspired a number of related ideas, leading to the emergence in the late nineteenth century of the ‘continuous calculating machine’ classification.

The history of science is scattered with examples of parallel invention, and something in the technical and social climate of the early nineteenth century inspired a whole generation of area calculating instruments (or planimeters) to be invented. Before 1814, there were practically no instruments available to evaluate the area of land on a map or the area under a curve; by 1900, production lines were manufacturing them by the thousand.¹⁶ It is interesting to consider why there was such a high demand for the manufacture of planimeters. One reason was the calculation of land area for taxation and land registry purposes. It is no coincidence that many of the early inventors were themselves land surveyors:

¹⁵Croarken (1990) identified that within the context of computer history, the planimeter was ‘the most significant mathematical instrument of the 19th century’ (p. 9). The elegance of the planimeter caught the eye of many Victorian thinkers, and a variety of ‘treatises’ were published on its theory. One such commentator wrote that: ‘The polar planimeter is remarkable for the ingenious way in which certain laws of the higher mathematics are applied to an extremely simple mechanical device. The simplicity of its construction and the facility with which it is used, taken in conjunction with the accuracy of its work, envelop it in a mystery which but a few of its users attempt to fathom...’ (Gray, 1909, Preface).

¹⁶The most popular planimeter to be manufactured was the Amsler polar planimeter, invented in 1854 and selling over 12,000 copies before the early 1890s. By the time of his death, Amsler’s factory had produced over 50,000 polar planimeters. Numerous other instrument makers had entered the market of developing polar planimeters and the instrument was nearly as widespread as the slide-rule. See Henrici (1894) p. 513; Kidwell (1998) p. 468.

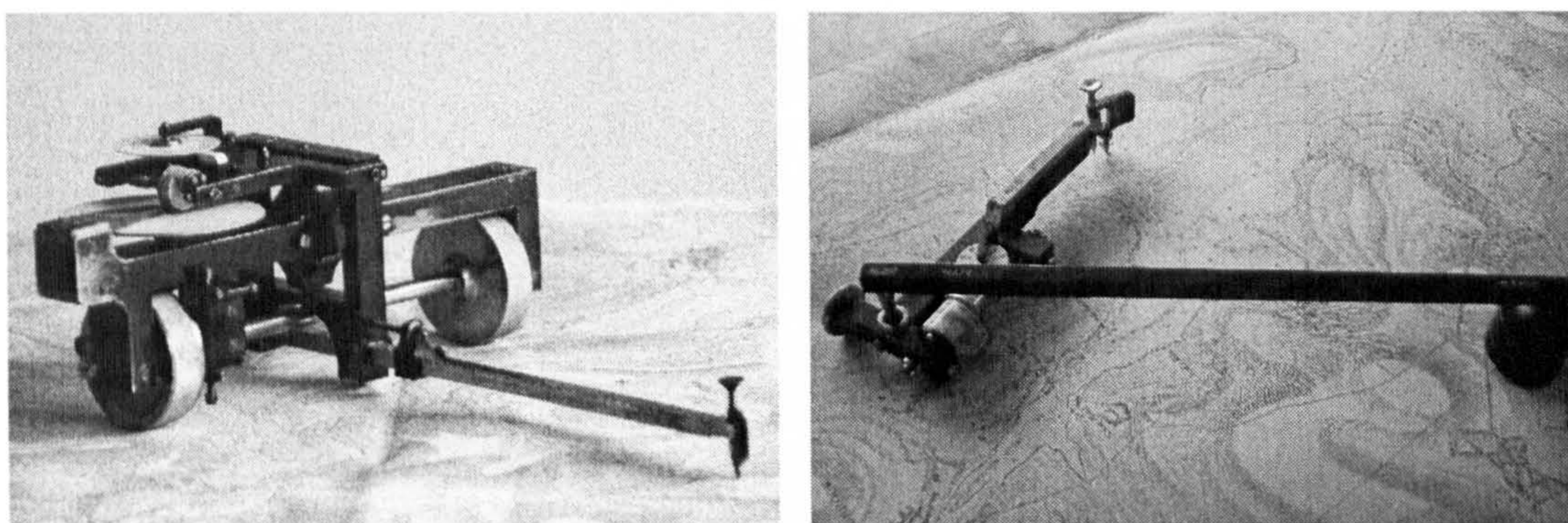


Figure 2.2: A rolling disc polar planimeter (left) and a compensating polar planimeter (right).

during the 1850s, one writer estimated that in Europe alone, there were over six billion land areas requiring annual evaluation.¹⁷ Another major application during the industrial revolution was calculating the area of steam engine indicator diagrams.

Hermann, Gonnella, Oppikofer: the various inventors of the planimeter

A planimeter mechanism was first invented by a Bavarian land surveyor, Johann Martin Hermann in 1814. Hermann's planimeter consisted of a cone and wheel mechanism mounted on a track.

The actual instrument constructed by Hermann disappeared during the mid-nineteenth century, but an original diagram of one elevation of the planimeter still exists (see Figure 2.3).¹⁸ In the diagram, the cone is shown side-on, and rotates in proportion to the left-right displacement of the pointer shaft. As the tracing pointer moves in and out of the drawing, the cone moves along a track. This pulls the wheel over a wedge causing the wheel to move up and down the cone. The cone and wheel form a variable gear, with the speed of the wheel's rotation dependent on both the rotational speed of the cone and the displacement of the

¹⁷Bauenfeind [1855] as cited by Henrici (1894) p. 505. Interestingly, the invention of the planimeter roughly coincides with major reform in German land law. The *Gemeinheitsteilungsordnung* (decree for the division of communities) of 1821 and the subsequent need to survey land areas must have increased the demand for such a calculating aid (Weber, 1966, pp. 28–29).

¹⁸A larger copy of this image is included in Appendix A.

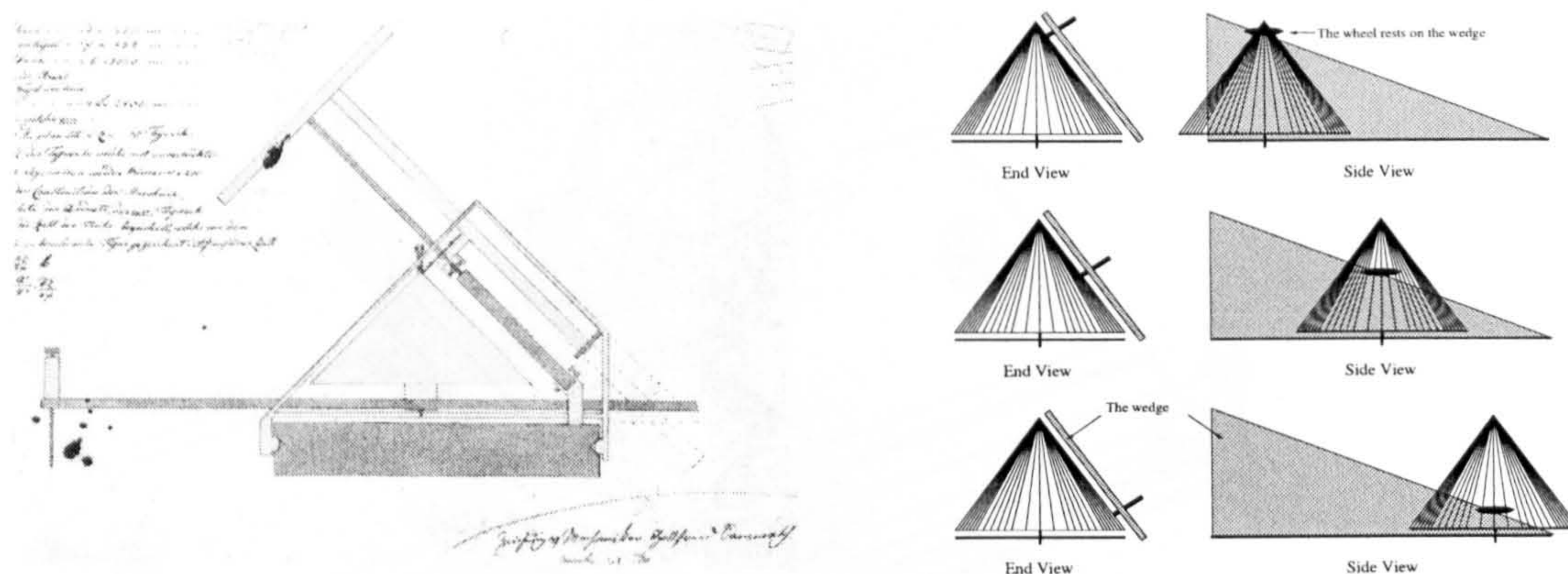


Figure 2.3: An original drawing of the Hermann planimeter (left). Alongside is an illustration of how the ‘wedge’ (shown in blue) was used to guide the wheel up and down the edge of the cone (right). Original drawing: courtesy of Joachim Fischer. Illustration: Charles Care, 2004.

wheel along the track. This enabled the device to function as an area calculator or integrator.

The work of Hermann only became widely known in 1855 when Bauenfeind published a review of planimeter designs. Meanwhile, the idea had also been invented by the Italian mathematician Tito Gonnella (1794–1867). Gonnella, a professor at the University of Florence, developed a planimeter based around a similar cone and wheel mechanism in 1824. Later, his design evolved to employ a wheel and disk, a copy of which was presented to the court of the Grand Duke of Tuscany.¹⁹ Gonnella was the first to publish an account of a planimeter.

A further invention of the planimeter is attributed to the Swiss inventor Johannes Oppikofer in 1827. Oppikofer’s design was manufactured in France by Ernst around 1836 and became a well known mechanism.²⁰ As this planimeter also employed a cone in the variable gear, it is unclear to what extent Oppikofer’s design was an original contribution.²¹

¹⁹The instrument belonging to the Grand Duke was exhibited at the Great Exhibition of 1851 at Crystal Palace. See Royal Commission (1851) vol. III, p. 1295, item 70; Royal Commission (1852) pp. 303–304; Henrici (1894) pp. 505–506.

²⁰Bromley (1990) p. 167; Fischer (1995) p. 123; de Morin (1913) pp. 56–59.

²¹Although it is unlikely that his instrument was copied from Hermann, there is evidence to show that it may have been inspired by Gonnella’s design – Gonnella had sent his designs to a Swiss instrument maker shortly before Oppikofer’s invention appeared. In 1894 Henrici wrote that ‘[h]ow much he had heard of Gonnella’s invention or of Hermann’s cannot now be decided’ (Henrici, 1894, p. 506).

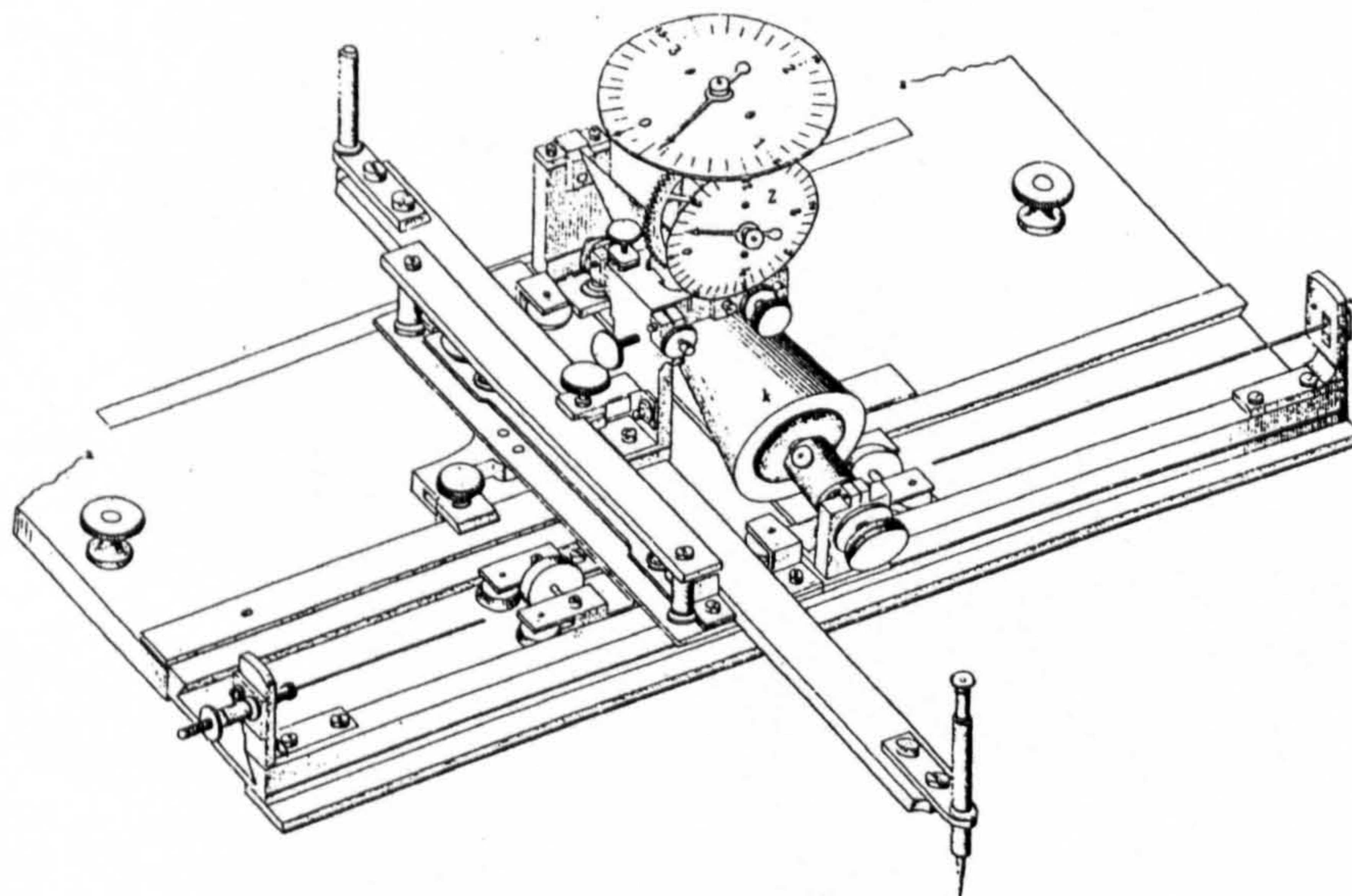


Figure 2.4: Copy of a line drawing of an Oppikofer planimeter (courtesy the Science Museum, London.)

The principal design of the mechanical integrator used in later calculating machines was based around a wheel and disk variable gear. Although the idea of using this mechanism within a planimeter was attributed to the work of Gonnella, the first wheel and disk planimeter to be widely manufactured was designed by the Swiss engineer Kaspar Wetli. Wetli's planimeter was manufactured by Georg Christoph Starke in Vienna and is the archetypal wheel and disk planimeter. Like Gonnella's, it was also exhibited at the Great Exhibition of 1851 where it was shown to trace areas with high accuracy. The instrument worked by moving a disk underneath a stationary integrating wheel, creating the variable gear necessary for mechanical integration. The disk moved on a carriage such that motion of the tracing pointer in one direction caused the carriage to move (changing the gear ratio between the wheel and the disk) and motion in a perpendicular direction caused the disk to spin.²²

Other scientists and instrument makers subsequently developed planimeters. Some of these were also independent innovations such as the 'platometer' devised

²²Royal Commission (1851) vol. III, p. 1272, item 84; Royal Commission (1852) p. 303–304, col. 2.

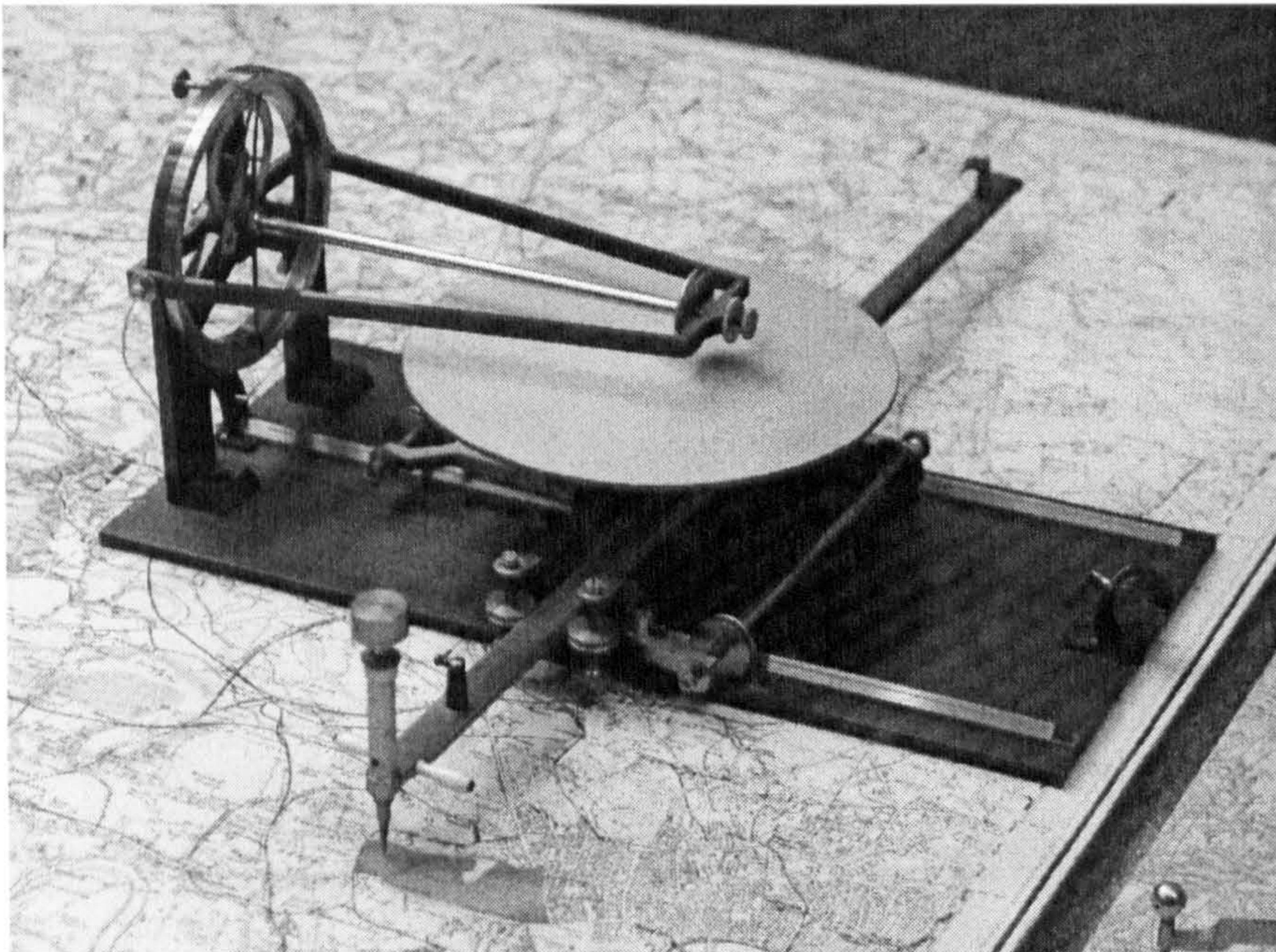


Figure 2.5: A Wetli-Starke planimeter in the Science Museum, London (Photo: Mike Lloyd and Ashley Ward).

around 1850 by the Scottish engineer John Sang which was also exhibited at the Great Exhibition.²³ Another major innovation in planimeter design came with Amsler's polar planimeter. These devices, although important in the history of planimeters, were not developed into mechanical integrator components used in analog computers. As interconnected mechanical integrators, the planimeter mechanisms could solve much richer problems. In the 1870s, a disk and sphere integrator would be employed in Kelvin's harmonic analyser, and in the early twentieth century, the wheel and disk integrator would receive fame as the core computing unit of Vannevar Bush's differential analyser.

²³See Royal Commission (1851), vol. I, p. 448. John was the younger brother of Edward Sang, a mathematician who with his daughters compiled extensive logarithmic tables by hand. The Sangs were members of the Berean Christian sect and well educated. John studied at the University of Edinburgh and participated in a number of engineering projects in his home town of Kirkcaldy, Fife. See Sang (1852); RSSA (1852); Craik (2003).

1850–1876: Maxwell, Thomson and Kelvin: The emergence of the integrator as a computing component

It was at the Great Exhibition of the works of all nations held at Crystal Palace, London in 1851, that the natural philosopher James Clerk Maxwell first came across a planimeter mechanism which, as he later recorded, 'greatly excited my admiration.'²⁴ This impetus came from Sang's platometer which employed a cone and wheel mechanism designed to measure areas on maps and other engineering drawings.²⁵

Enchanted by the mechanical principle underpinning the instrument, Maxwell began to think of further improvements. He found the limitations imposed by friction to be particularly frustrating and set about developing a planimeter that employed pure rolling rather than a combination of rolling and slipping. Instead of following the prior art, and constructing a variable gear based on the slipping and sliding of an integrating wheel, Maxwell's instrument used a sphere rolling over a hemisphere. Like Sang, he published his work with the Royal Scottish Society of Arts (RSSA), who offered him a grant of ten pounds 'to defray the expenses' of construction.²⁶

Maxwell's design was a complex mechanism and despite the offer of a grant, he did not pursue the development of an actual instrument. This was partly because his father warned him that the cost of such a mechanism would far exceed his budget.²⁷ It is also evident that Maxwell had no real drive to construct a working instrument and was more interested in the theoretical challenge of using pure rolling to eliminating slip.²⁸ Although a working example of Maxwell's design

²⁴Maxwell (1855a) p. 277.

²⁵It is claimed that apart from Gonella's instrument, Sang was unaware of other planimeters at the Great Exhibition. The exhibitions were arranged by nation, not by class of device, so it is difficult to judge which instruments Maxwell discovered there. By 1855 Maxwell was aware of Gonnella's work in Italy and made reference to it in his paper. See RSSA (1852); and Maxwell (1855b).

²⁶Maxwell (1855d).

²⁷Maxwell (1855e); Campbell and Garnett (1882) pp. 114–5. Planimeters were more of a recreational interest for Maxwell. He conceived of the design of a theoretically elegant 'platometer' while away from Cambridge caring for his sick father (Maxwell, 1855c).

²⁸When James Thomson simplified the design and introduced some slipping, although the

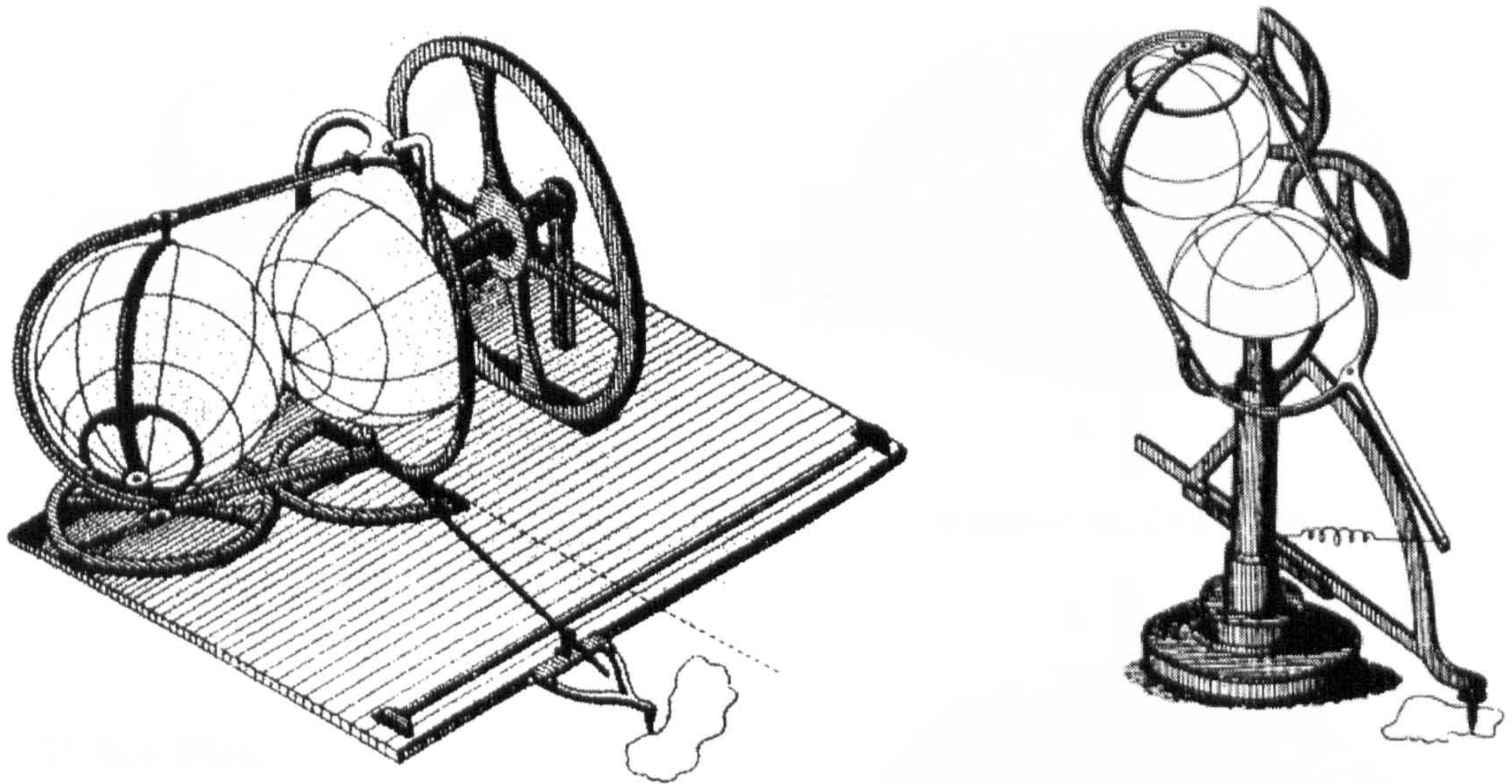


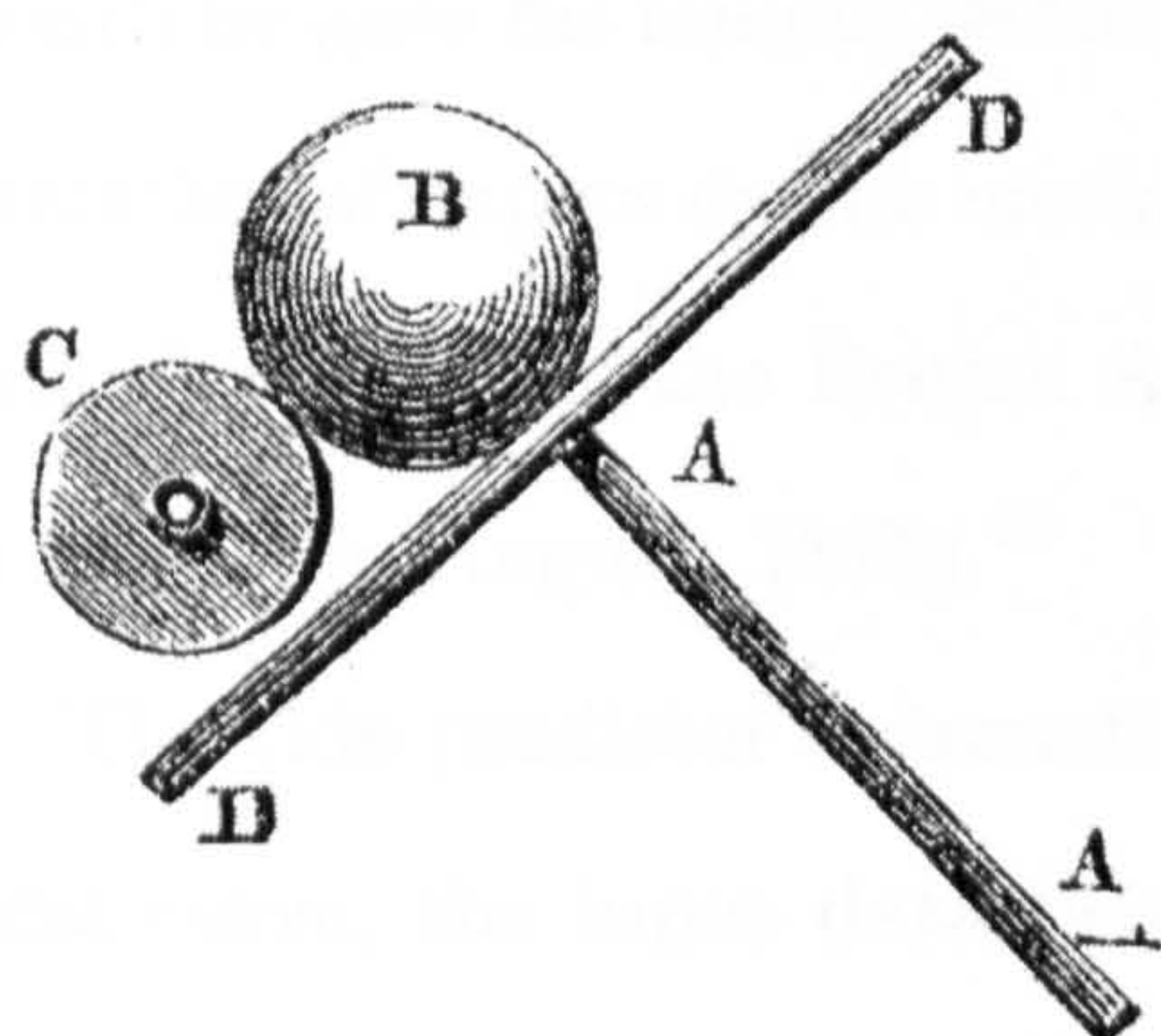
Figure 2.6: Maxwell proposed two planimeter designs based around his pure-rolling sphere-on-hemisphere mechanism. One (left) corresponded to integration over a Cartesian coordinates system and the other (right) to polar coordinates. Source: Maxwell (1855b).

was never constructed, the idea inspired James Thomson, a Scottish engineer, to consider a more practical and simpler version with a perfectly acceptable accuracy. Thomson referred to his instrument as an *integrator*.

James Thomson's invention is an important chronological landmark, marking the beginning of integrator-based analog computers.²⁹ The use of this word marks the end of a story about planimeters, an instrument, and the beginning of the mechanical integrator, a component. While the progression from instrument to component is quite obvious in hindsight, this effectively involved a re-invention of the artefact's purpose. To understand the significance of the integrator required not just inventiveness, but also the application-drive for mechanised mathematics. Well over a decade passed before Thomson's younger brother, the eminent Lord

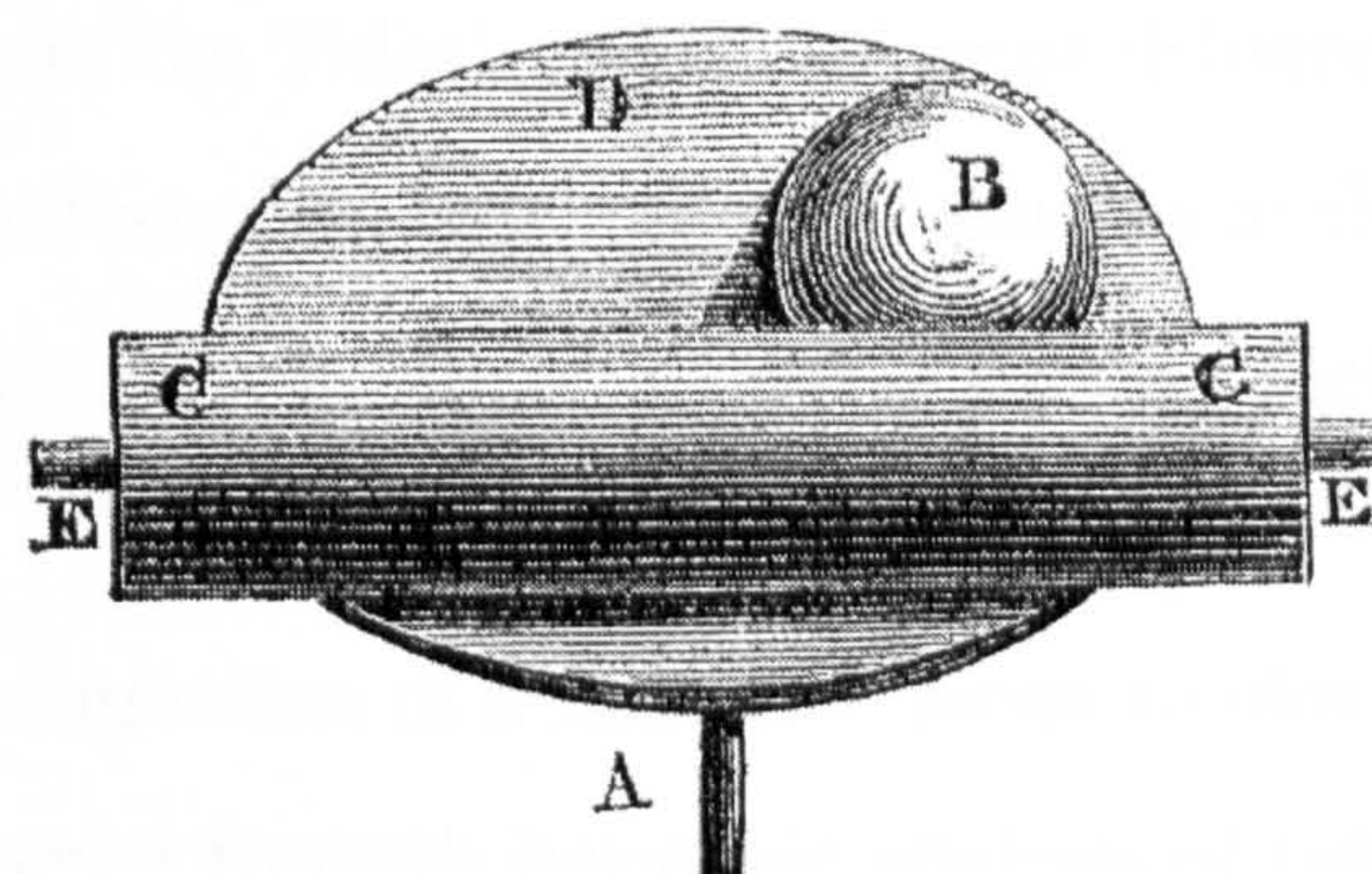
accuracy was acceptable, Maxwell wrote to him and suggested various strategies to return to rolling. See Thomson (1876a); Maxwell (1879).

²⁹Earlier it was identified that integrators, first mechanical and then later electronic, were an important enabling technology. According to the *Oxford English Dictionary*, the 1876 publication of Thomson's invention is the first occurrence of the word 'integrator' in English. The dictionary defines integrator as: 'One who or that which integrates', with the earliest known usage being due to James Thomson. See 'integrator', *The Oxford English Dictionary*. 2nd ed. 1989. *OED Online*. Oxford University Press. Accessed 1st November 2006. <http://dictionary.oed.com/cgi/entry/50118577>.

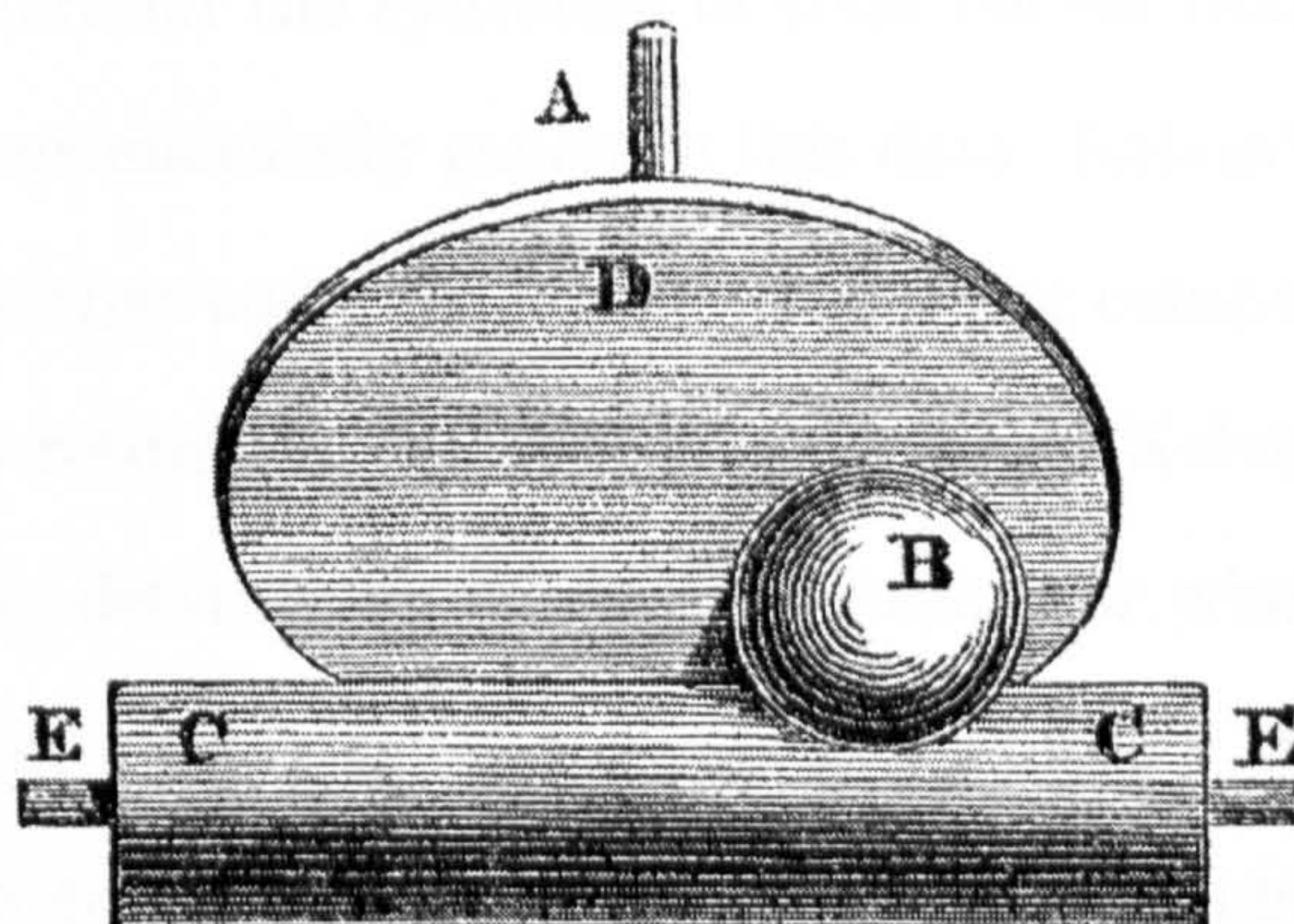


SIDE ELEVATION.

D, the Disk.
 A, the Axle of the Disk.
 C, the Cylinder.
 EE, the Axle or the Journals of
 the Cylinder.
 B, the Ball.



FRONT ELEVATION.



PLAN.

Figure 2.7: The Thomson ‘Integrator’ employed a wheel and sphere mechanism, a blend of the ideas behind the Wetli wheel-and-disk mechanism but with some of the enhancements of pure rolling that Maxwell claimed to be so important. Source: Thomson (1876a).

Kelvin (Sir William Thomson), would provide the necessary motivation, securing a place in history for the disk-ball-cylinder integrator.

Kelvin was a true polymath. A blend of engineer, physicist, and mathematician, his professional life was characterised by a continual flow of innovative research in numerous fields. He researched electricity and magnetism, but also made practical contributions to the world of shipping: inventing a tide predictor, an automatic sounder, and contributing to the design of lighthouse lights. In the early 1880s, he also developed an early gyro-compass.³⁰ During the early 1870s, Kelvin was actively working on tide predicting, and in January 1875 he exhibited a tide predictor and tide gauge to the Edinburgh Royal Society.³¹ The following

³⁰Thompson (1910) vol. II, pp. v, vi, 730, & 745.

³¹Between 1867 and 1876 Kelvin was a member of the tidal committee of the British Association for the Advancement of Science, who with funding from the Royal Society and the Indian

month he gave his famous lecture entitled 'The Tides', and that August delivered a number of papers on the mathematical theory and techniques of analysis at the annual meeting of the British Association for the Advancement of Science (held in Bristol in August, 1875).³²

The tide predictor automated the summation of a harmonic series to plot a tidal curve; the input data being extracted through harmonic analysis of tidal observations. Having successfully mechanised the synthesis of tidal curves from the harmonic base data, he desired to automatically generate this data. Kelvin's engineering brain yearned for a machine that could extract the harmonic components of an arbitrary function. On his return from the Bristol meeting, Kelvin discussed the problem with his brother, determined to find a solution for what he thought 'ought to be accomplished by some simple mechanical means.'³³ He outlined his ideas to Thomson, who in return mentioned the disk-ball-cylinder integrator. In a flash of inspiration Kelvin saw how the mechanical integrator could offer 'a much simpler means of attaining my special object than anything I had been able to think of previously.'³⁴

From this revelation, Kelvin moved with rapid speed and within days, four influential papers were prepared to be given before the Royal Society of London.³⁵ The first was written by Thomson and described his integrator in detail, the remainder were by Kelvin and discussed its application. These papers, published in early 1876, testified to the significance of the mechanical integrator: broadcasting to the world of science that it was now possible to integrate products, solve second order differential equations, and with a particular set-up, solve differential equations of an arbitrary order.³⁶ Kelvin's final paper concluded with a powerful

Government, investigated the mathematics of tides.

³²Thompson (1910), pp. 1247-1254; British Association (1876) pp. 23 & 253; Thomson (1875) p. 388.

³³Thomson (1876b) p. 266.

³⁴Thomson (1876b) p. 266.

³⁵These papers were communicated to the Royal Society by Kelvin. A few years later (in 1878) James would, like his brother and father before him, be elected to FRS.

³⁶Thomson (1876a); Thomson (1876c); Thomson (1876d).

remark about the invention's significance:

Thus we have a complete mechanical integration of the problem of finding the free motions of any number of mutually influencing particles, not restricted by any of the approximate suppositions which the analytical treatment of the lunar and planetary theories requires.³⁷

It was not long before this insight was engineered into the harmonic analyser, a machine that 'substitute[d] brass for brain in the great mechanical labour of calculating the elementary constituents of whole tidal rise and fall'.³⁸ The harmonic analyser was used to derive the composite harmonics of tidal data, and also to solve equations for the Meteorological Office.³⁹ As a technology, it ushered in a new genre of calculating instrument: the continuous calculating machine.⁴⁰

1870–1900: The age of the continuous calculating machine

The latter half of the nineteenth century was a period of intense innovation for those developing calculating aids, and it was in this period that 'discrete' calculating devices became common. Two inventions of particular significance to the history of discrete calculators were the variable toothed gear by Frank S. Baldwin (and its European equivalent invented by Willgodt Odhner), and Dorr

³⁷Thomson (1876d) p. 275. Note that this was only a theoretical result. To employ the integrators in this way would require torque amplification.

³⁸Thomson (1882) p. 280.

³⁹After its exhibition, Kelvin's model analyser was transferred to the Meteorological Office where it was 'brought immediately into practical work.' After preliminary trials, a 'favourable report' was submitted to the Meteorological Council and the council agreed purchase a full-size machine constructed. The new machine, delivered in December 1879, was first put to use in the 'determination of temperature constants.' The results were compared to those measured from photographic thermograms, and others determined through numerical calculations. Previous work had used a polar planimeter to determine a mean value of these plots, the harmonic analyser allowed for more sophisticated processing. The test was successful: '...the accordance is so very close as to prove that the machine may safely be trusted to effect reductions which could only otherwise be accomplished by the far more laborious process of measurement and calculation.' (Scott and Curtis, 1886, p. 386); Thomson (1878).

⁴⁰Special purpose analog machines that could extract harmonics continued to be adapted and reworked well into the following century. Examples of mechanical harmonic analysers were developed by Hele-Shaw in the late nineteenth century. For instance Fisher (1957) described how R. Pepinsky, working at Pennsylvania State College had, in 1952, developed 'a very large computer capable of performing directly two-dimensional Fourier syntheses and analyses' (p. 1.5). Also, it was through the development of a harmonic analyser in the 1930s that Mauchly, one of the major pioneers of the ENIAC, would begin his career in computing.

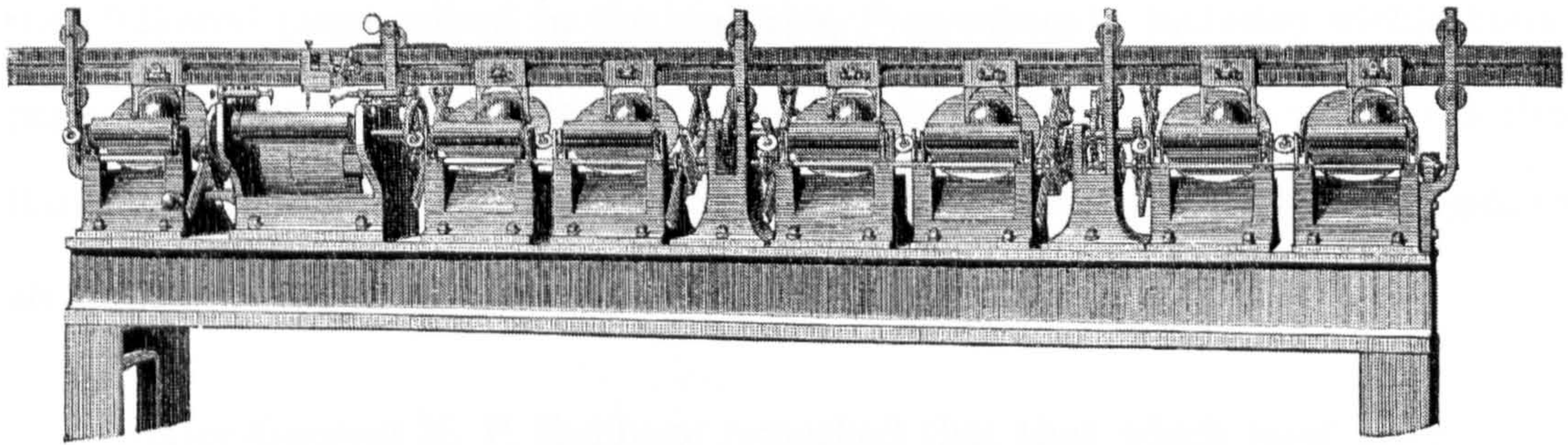


Figure 2.8: Line drawing of the Kelvin harmonic analyser. Source: Scott and Curtis (1886).

E. Felt's key-driven mechanism (developed in the 1880s). These technologies paved the way for commercial products such as the Brunsviga calculator and the Comptometer.⁴¹

In the context of this rapidly developing calculating technology, new machines inspired the creation of classifications, as well as debate over the 'proper' approach to designing such mechanisms. The phrase 'continuous calculating machine', a forerunner of 'analog(ue) computer', was coined by those making technical distinctions.⁴² It was used within the British scientific circle to refer to devices like the planimeter and the harmonic analyser which represented data as a *continuous* physical quantity.

1876: H. S. Hele-Shaw and H. P. Babbage: an early analog-digital debate

Working in London at the Royal School of Mines⁴³ Professor Hele-Shaw had advanced the design of integrator mechanisms and understood the distinction between such devices and the numerical calculating machines available for basic arithmetical tasks. At a meeting of the Physical Society in April 1885, Hele-Shaw presented a paper reviewing the various classes of mechanical integrator. While this paper is an interesting source for understanding the various technologies available for mechanising integration, of particular interest is the discussion

⁴¹Aspray (1990c) pp. 51–54.

⁴²At this time 'analog(ue)' would have referred solely to analogy.

⁴³Now part of Imperial College, London.

that followed (transcribed in the society's *Proceedings*). Included within these pages are comments from Henry Prevost Babbage, the youngest son of Charles Babbage.⁴⁴ Directed towards Hele-Shaw, this is perhaps the earliest example of an analog-digital debate.⁴⁵

Major-General H. P. Babbage remarked that that which most interested him was the contrast between arithmetical calculating machines and these integrators. In the first there was absolute accuracy of result, and the same with all operators; and there were mechanical means for correcting, to a certain extent, slackness of the machinery. Friction too had to be avoided. In the other instruments nearly all this was reversed, and it would seem that with the multiplication of reliable calculating machines, all except the simplest planimeters would become obsolete.

...

[Professor Shaw] was obliged to express his disagreement with the opinion of General Babbage, that all integrators except the simplest planimeters would become obsolete and give place to arithmetical calculating machines. Continuous and discontinuous calculating machines, as they had respectively been called, had entirely different kinds of operation to perform, and there was a wide field for employment of both. All efforts to employ a mere combination of trains of wheelwork for such operations as were required in continuous integrators had hitherto entirely failed, and the Author did not see how it was possible to deal in this way with the continuously varying quantities which came in to the problem. No doubt the mechanical difficulties were great, but that they were not insuperable was probed by the daily use of the disk, globe and cylinder of Professor James Thomson in connection with tidal calculations and meteorological work, and, indeed this of itself was sufficient refutation of General Babbage's view.⁴⁶

⁴⁴Henry spent most his career with the East India Company's Bengal Army. He returned to England in 1874 and, in retirement, continued to promote his father's work on calculating engines, publishing an account of them in 1889. During the 1880s he also assembled some remaining fragments of the difference engine and gifted them to several learned institutions including Cambridge, University College London, and Harvard University. Henry's obituary in *The Times* refers to publications in subjects including occulting lights and calculating machines, topics that had been of great interest to his father. See Anon. (1918a); Anon. (1918b); Babbage (1915) p. 10-11; Hyman (2002) p. 90. The 'fragment' of calculating wheels given to Harvard would later provide an interesting link between Babbage and Howard Aiken's Harvard Mark I, an early electro-mechanical computer constructed in the 1940s. He died in January 1918, aged 93. See Swade (2004); Cohen (1988).

⁴⁵Of course, this is really a continuous-discontinuous debate. The exchange focuses solely on continuity and could not be any broader until the first and second thematic time-line were blended together and enrolled into analog discourse.

⁴⁶Shaw (1885) pp. 163-164.

Was Henry Babbage correct to criticise Hele-Shaw's view of continuous calculators? In many ways, he should be respected for his commitment to digital, because in the long term his view ran true. However, since a reliable digital computer was not to be invented until the 1940s, Hele-Shaw's position would remain dominant for many years. While the potential benefits of digital could be seen by visionaries, many advances in technology, coupled with a significant research budget, would be needed to realise the digital vision.

The concerns, articulated by Babbage, of the consistent and reliable accuracy available with digital computing would be at the centre of arguments for the digital approach well into the 1960s. Similarly, Hele-Shaw's position, that both technologies had their place (each being suited to different purposes), would be a common response of analog proponents throughout the following century.

1880–1920: The integrator becomes an embedded component initiating associations between control and calculation

While Kelvin's innovation had enrolled planimeter mechanisms into the technological genre of calculating machines, integrators also had to be re-invented as an embedded component. As well as being used in calculating devices, mechanical integrators would become embedded in real-time calculation systems, initiating the class of technology known today as control systems. However, in the 1800s there was no general purpose culture and it was not obvious that the technology of a calculating machine could become part of a control mechanism. Essentially, each new application of integrators needed to be discovered. One good example of this is the Blythswood indicator, a simple device based on a cone mechanical integrator, used to determine the speed of a ship's propeller (or its speed relative to a second propeller.)

1884: Determining the engine speed of a Royal Navy warship: The Blythswood Speed Indicator, an example of an embedded integrator

In a paper communicated to the Physical Society of London, engineers Sir Archibald Campbell and W. T. Goolden described a device developed for measuring the angular velocity of a propeller shaft. The text records how on a visit to the Dockyards of the Royal Navy in 1883 they had been drawn to the ‘very urgent need’ for an engine speed indicator that did not rely on gravity.⁴⁷ To offer increased speed and manoeuvrability, ships were being built with two engines driving separate propellers. This led to the difficulty that two separate engineering systems had to be coordinated, a challenge when they were located in separate engine rooms. The idea behind the Blythswood indicator was to automatically measure the speed of the propellers, and to communicate the data back to a central location from where both engine rooms could be managed.

The speed indicator employed a cone and wheel in the same way as the planimeters had done previously: the cone was rotated at a steady speed and the wheel shaft at engine speed, forcing the wheel to travel along the surface of the cone until the mechanical constraints imposed by the integrator were satisfied. The speed of the engine was read by measuring the displacement of this wheel (integrating a velocity results in a displacement). The inventors then used a series of electrical contacts to sense the location of the wheel and drive a repeater instrument at a remote location. With the cone being rotated by clockwork, the instrument could be used to determine the speed of one propeller shaft. Alternatively, if the cone was rotated by a second propeller shaft, the instrument would calculate the relative speed. The Blythswood indicator is an excellent example of embedded analog computing for control systems.

⁴⁷Campbell and Goolden (1884) p. 147.

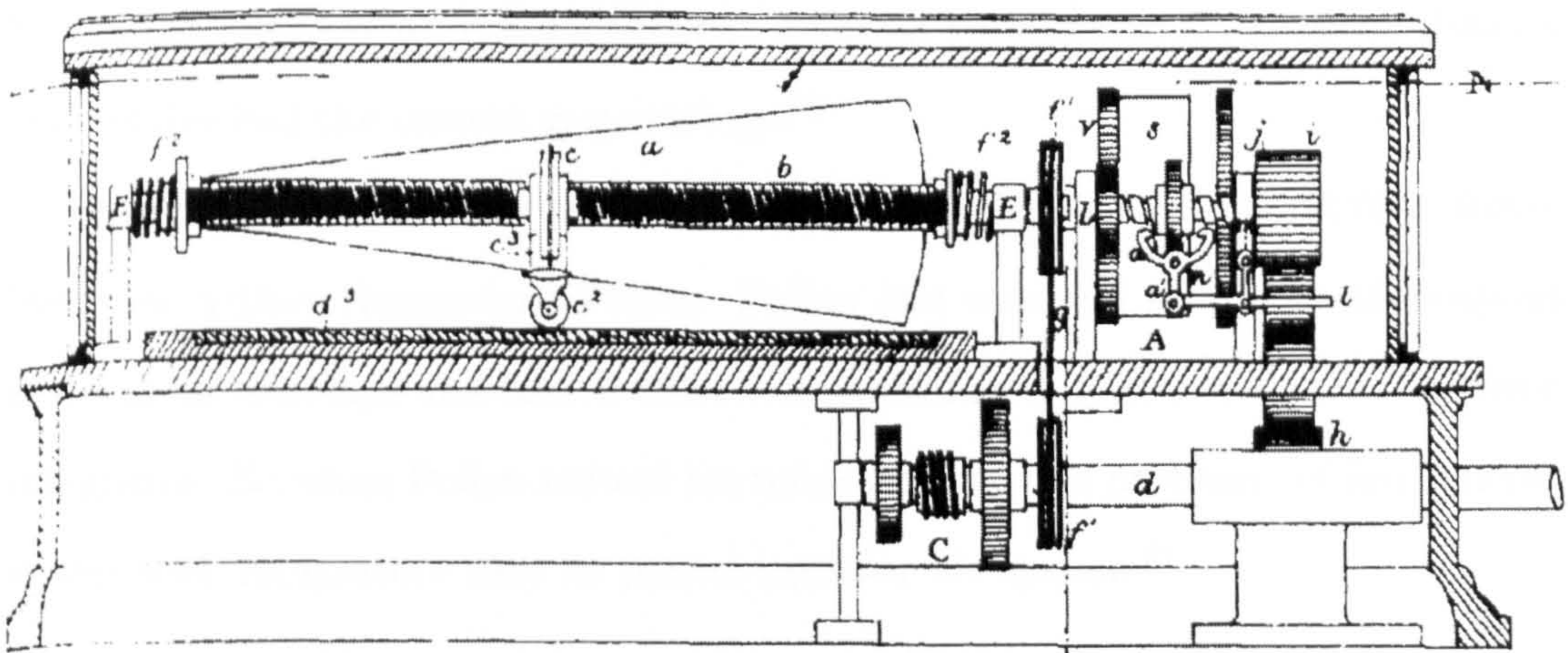


Figure 2.9: Side elevation of the 'Blythswood Speed Indicator', the cone is clearly visible, the wheel (viewed here sideways-on) is halfway along its shaft. Source: Campbell and Goolden (1884).

1911: Integrators in fire control: Arthur Hungerford Pollen and the Royal Navy

Calculations relating to ballistics problems such as the trajectories of shells constitute one of the most established uses of applied mathematics. However, during the early twentieth century advances in gunnery meant that ordinance ranges came to be measured in miles rather than yards. Warships now had to engage in battle at greater distances; over such distances, variables such as the relative speed and heading of the target ship, the ship's pitch and roll, and wind speed became important factors. Dominance in battle was no longer simply a matter of possessing the best guns and fastest ships, a warship also needed advanced computing methods.⁴⁸

In terms of computation, there were two main approaches to solving the complexity: either users were supplied with pre-calculated data, or mechanical computers were installed to provide 'on the fly' calculation. With pre-calculation, the important parameters (such as air speed, direction or speed of target) were tabulated.⁴⁹ The alternative was to build a real-time system whose mechanism re-

⁴⁸A few decades later, advances in aviation would move the battle ground into the skies, requiring even faster modelling of three-dimensional dynamics.

⁴⁹Pre-calculation could be analog or digital (both the continuous differential analyser and the discrete hand driven calculators were used in the preparation of ballistic firing tables).

flected the actual relationships between different variables in the problem domain and established the correct gun settings.⁵⁰

One of the earliest fire control systems was designed for the British Royal Navy by Arthur Hungerford Pollen. Pollen had invented a number of weapons systems for warships and had in 1904 been introduced by Kelvin to the Thomson integrator. So when Pollen turned his mind towards the problems of fire control, it was with integrators that he pieced together his system.⁵¹

1915: Technology transfer: Elmer Sperry, Hannibal Ford and fire control in the US Navy

For various reasons, fire control would find a more natural home on American warships. The principal inventor of the analog computers used for fire control in the US was Hannibal Ford who, in 1903, had graduated from Cornell with a degree in mechanical engineering. His first employer was the J. G. White Company, where he developed mechanisms to control the speed of trains on the New York subway. In 1909 Ford began working for Elmer Sperry, assisting with the development of a naval gyroscope. When Sperry formed the Sperry Gyroscope Company the following year, Ford became both its first employee and chief engineer. Within Sperry, he enjoyed working closely with the US Navy developing early fire control technology, and this eventually resulted in the establishment of his own venture, the Ford Instrument Company, in 1915.⁵²

⁵⁰Computation on the fly needed to operate at high speed, an application that digital technology could not begin to address until after World War II. It was much easier and faster if calculations could be embedded into an artefact. This is not a new concept, for example, a simple instrument recently uncovered from the wreck of the *Mary Rose* used a stepped rule to encode the size of shot and amount of gun powder required for a variety of guns (Johnston, 2005). Gunnery resolvers were also used in anti-aircraft defence, see Bromley (1990) pp. 198–159.

⁵¹See Pollen and Isherwood (1911a,b); and Mindell (2002) pp. 38–39. Pollen found it difficult to sell his idea to the Royal Navy, which had very conservative views towards automation. This conservatism would not be sustainable. May 1916 saw the World War I sea battle of Jutland, a now famous defeat for the Royal Navy, which were unable to compete against the German long range gunnery. Their defeat was partly due to a lack of gunnery computing devices, and Mindell notes how the one ship that was fitted with the Pollen system out-performed the rest of the fleet. See Mindell (2002) pp. 19–21.

⁵²Mindell (2002) pp. 24–25.

While working at Sperry, Ford had been given access to the designs of the Pollen system and so it is perhaps unsurprising that his integrator was also derived from the Thomson integrator (see Figure 2.10). Drawing from his expertise on speed controllers, he made significant modifications to improve the torque output of the integrator, principally by adding an extra sphere and compressing the mechanism with heavy springs (see Figure 2.10).⁵³

1920–1946: The ‘heyday’ of analog computing?

During the inter-war years, application of mechanical analog computers flourished and became an important part of the warfare technologies employed in WWII. As a consequence, historians have christened this pre-1946 period a ‘heyday’ of analog computing.⁵⁴ During this period there was simply no digital competition, thus analog computing *was* computing. This would remain the case until the emergence of electronic digital computers in World War II research programmes. In terms of the technology’s use, David Mindell described the WWII period as ‘analog’s finest hour’.⁵⁵

1931 Vannevar Bush and the differential analyser

Although Kelvin had conceived of how mechanical integrators could be connected together to solve differential equations, a full realisation of the idea would not emerge until the differential analyser was developed in the 1930s. The solution of higher order differential equations required the output of one integrator to drive the input of another (integrating the result of a previous integration). Even more problematic was that automatically solving an equation required a feedback loop

⁵³Ford (1919/1916a); Clymer (1993) pp. 24–25; and Mindell (2002) pp. 37–39.

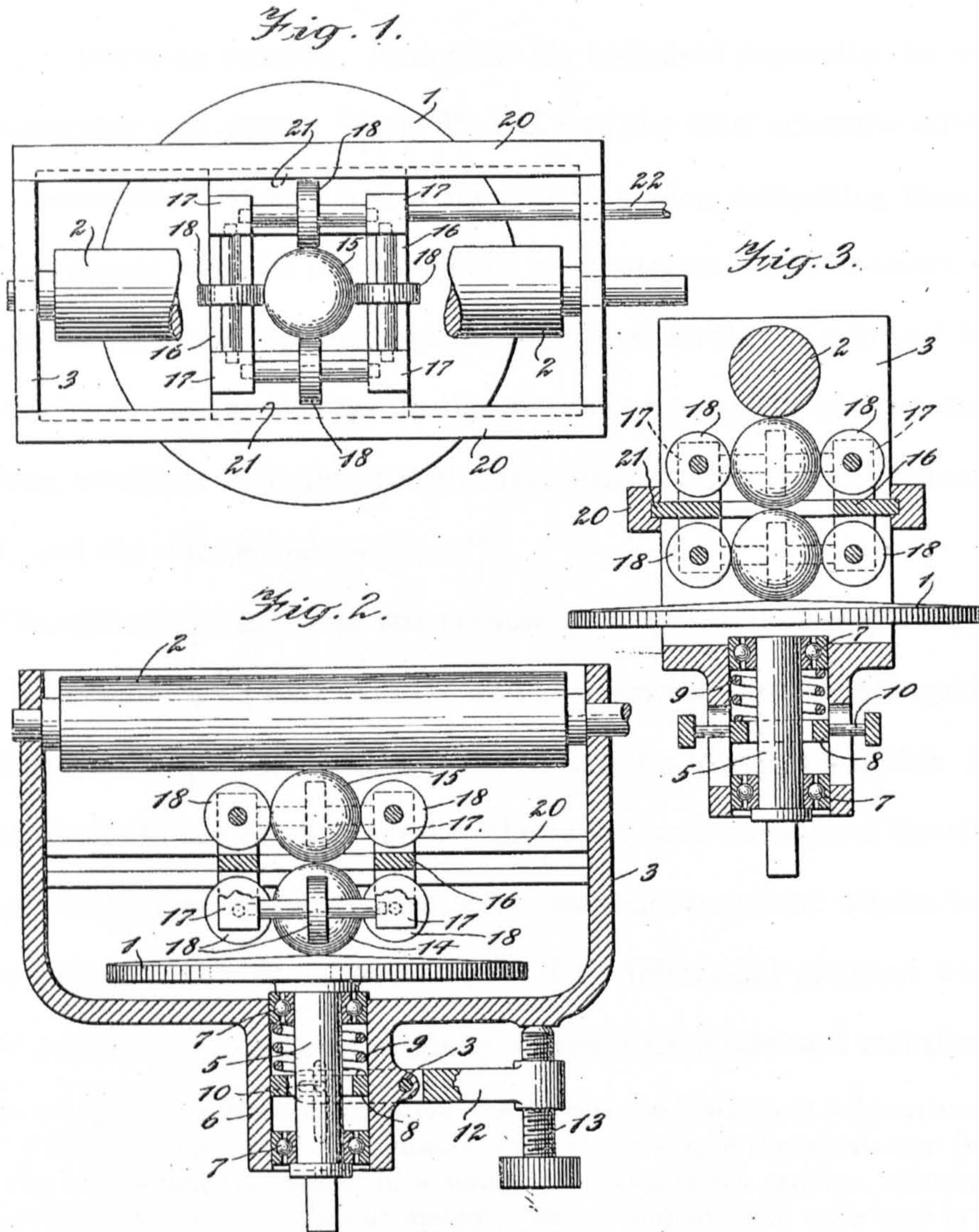
⁵⁴As exemplified by Campbell-Kelly and Aspray (1996), this was based on the observation that many archetypal analog computers (e.g. the differential analyser) dominated in this period. Small (2001) countered this idea because it contributed to the historical devaluation of post-war analog computers. However, labelling this period a ‘heyday’ does not have to imply that there was no successful post-war story.

⁵⁵Mindell (2002) p. 231.

H. C. FORD.
MECHANICAL MOVEMENT.
APPLICATION FILED MAR. 13, 1916.

1,317,915.

Patented Oct. 7, 1919.



Inventor
Hannibal C. Ford
By his Attorneys
Rosenbaum, Stockmayer & Ross

Figure 2.10: Images from Hannibal Ford's patent for an integrator; the disk and cylinder inherited from the Thomson integrator are clearly visible. Source: Ford (1919/1916a). Ford's integrator employed a spring to compress the disk on to a double-sphere mechanism, delivering maximum torque, an invention for which Ford was granted a second patent (Ford, 1919/1916b).

and Kelvin lacked the required torque amplifier.⁵⁶ The torque amplifier used in the differential analyser was developed by Niemann at the Bethlehem Steel Corporation.⁵⁷

Vannevar Bush (1870–1974) is well known for his contribution to twentieth century American science. Alongside his technical ingenuity, he was a superb administrator and during World War II was the chief scientific advisor to President Roosevelt.⁵⁸ Bush's involvement with analog computing began during his masters degree when he developed the profile tracer, an instrument which, when pushed along, would record changes in ground level.⁵⁹ He joined MIT in 1919, and initiated a research program that developed a variety of integrator-based calculating machines including the Product Integraph developed between 1925 and 1927, and the differential analyser.⁶⁰

The differential analyser was completed between 1930 and 1931. It consisted of a large table with long shafts running down the centre. Alongside were eight mechanical integrators and a number of input and output tables. By using the different shafts to connect together the inputs and outputs of the different functional components, it was possible to construct a system whose behaviour was governed by a differential equation.⁶¹ The differential analyser was an exceedingly popular instrument and many copies were made and installed in research

⁵⁶In modelling a differential equation, the mechanical integrators were an analog of the integral ($\int f(x)dx$), and a feedback connection was the analog of the equals sign (=).

⁵⁷The torque amplifier works in a similar way to a ship's capstan, allowing a small load to control a heavier load. Various means of torque amplification were used in the differential analysers and in later years the Niemann amplifier was replaced by electrical and optical servomechanisms. Bromley (1983) p. 180; Fifer (1961) vol. III p. 665–669; and Mindell (2002) pp. 158–159.

⁵⁸There are many correspondences between Bush and Kelvin. Both were successful technologists, who not only advanced their field, but also became known for their successful management of large projects. Kelvin was directly involved in the successful laying of an Atlantic telegraph cable in 1865. See Smith (2004).

⁵⁹The principal component of the profile tracer was a mechanical integrator much like Wetli's planimeter. See page 29, above.

⁶⁰Campbell-Kelly and Aspray (1996) pp. 53–54; Small (2001) p. 41; Mindell (2002) pp. 153–161; Wildes and Lindgren (1985) pp. 82–95.

⁶¹An accessible introduction to the differential analyser (with diagrams) is given by Bromley (1990). A number of differential analysers were constructed out of Meccano (See Chapter 5, page 124) and had reasonable accuracy.

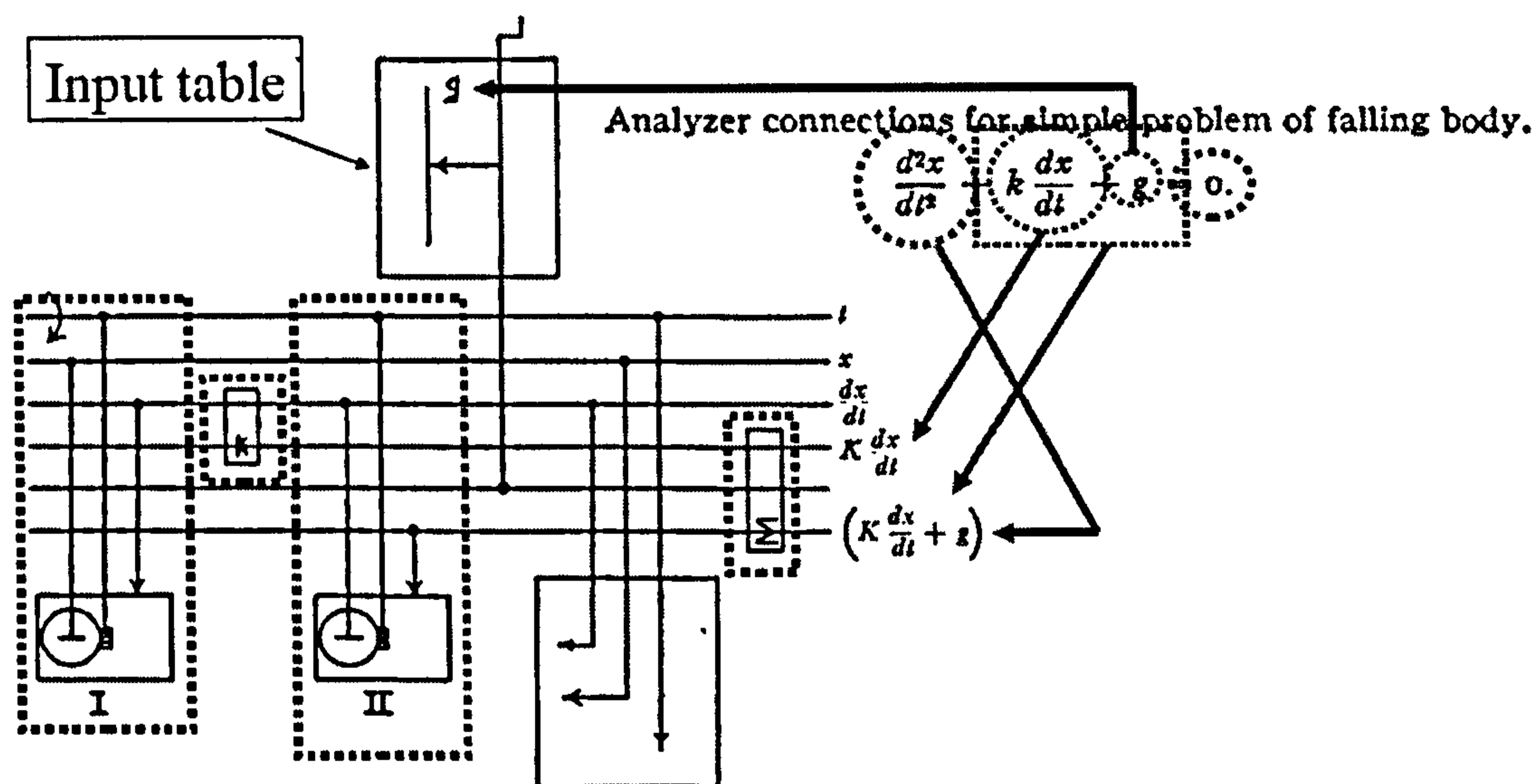


Figure 2.11: A 'program' for the differential analyser of a free-fall problem. Each linkage between shafts corresponded to a different mathematical operator in the original equations.

centres across the world. During the late 1930s, MIT received funding from the Rockefeller foundation to construct a larger and more accurate machine. The Rockefeller analyser still employed mechanical integrators, but used servo mechanisms to speed up the programming of the machine.⁶² As an icon of mathematical mechanisation, the differential analyser became a central focal point in the formation of early computing culture.⁶³

In an address to the American Mathematical Society, Vannevar Bush presented the differential analyser as an instrument that provided a 'suggestive auxiliary to precise reasoning'.⁶⁴ His belief was that there was significant cognitive support for mathematical work and he fully expected 'instrumental analysis' to become a driving force in mathematics. In his autobiography he described the differential analyser's educational dimension, which allowed the calculus to be communicated in mechanical terms. Here, both the referent and analogy were

⁶²See Owens (1996); Mindell (2002) pp. 170–173.

⁶³In an introductory article to the first issue of the *Journal of the ACM*, Samuel Williams, the fourth president of the Association of Computing Machinery (ACM) referred to the 1945 MIT conference where the Bush-Caldwell differential analyser was first publicised as the 'first meeting of those interested in the field'. For Williams, the differential analyser was central in the formation of the 'automatic computing' community. See Williams (1954) p. 1; Care (2007b)

⁶⁴Bush (1936) p. 649.

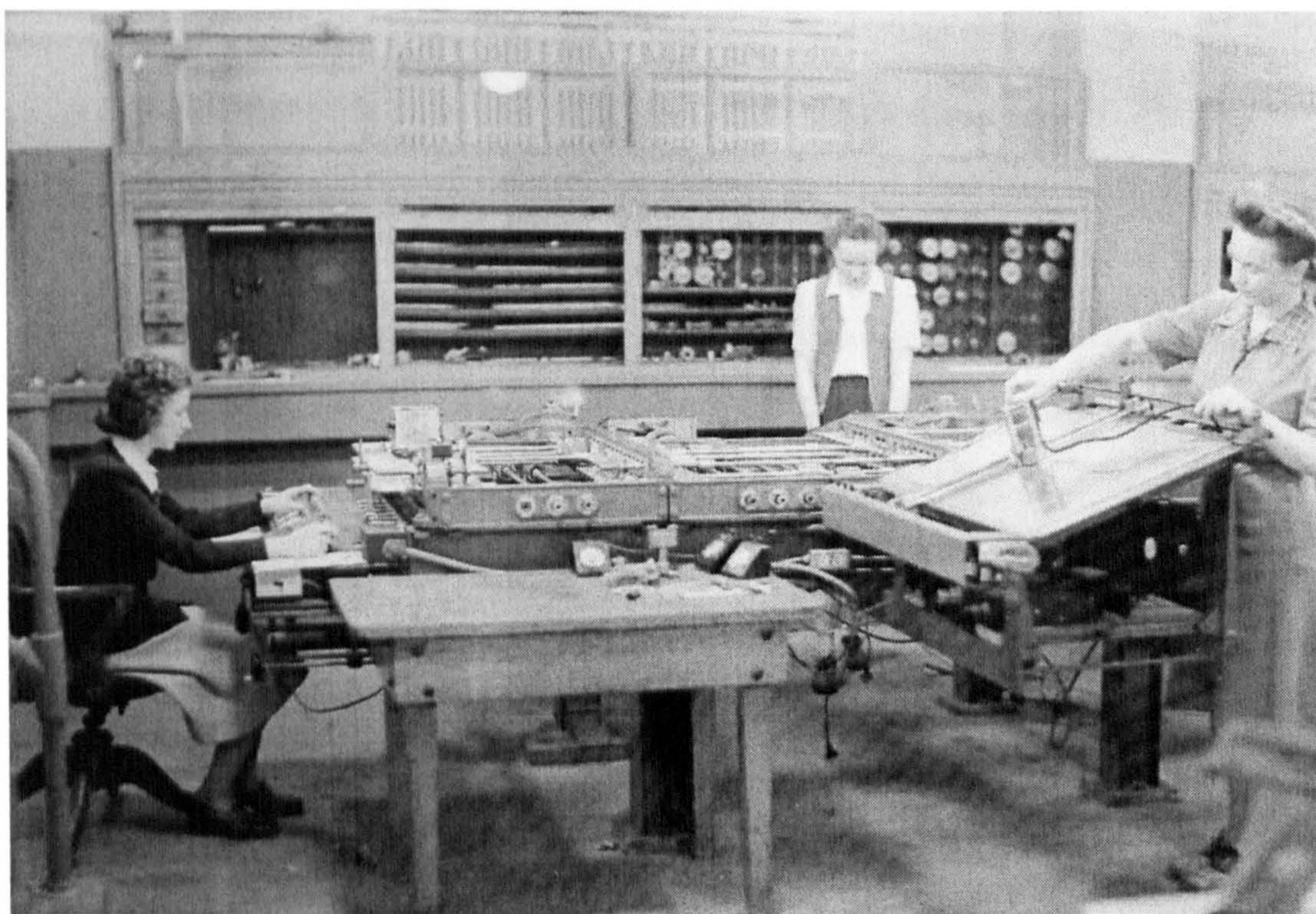


Figure 2.12: The differential analyser in use

so well accepted that the set-up began to communicate knowledge about the relationship between them. For Bush's 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.⁶⁵

'Differential analyzer' was an interesting name to choose for the machine, and

⁶⁵Bush (1970), p. 262.

a number of other prominent members of the computing community have questioned this choice of terminology. In January 1938, Douglas Rayner Hartree gave a talk to the Mathematical Association where he said that the name of the Differential Analyser was 'scarcely appropriate as the machine neither differentiates nor analyses, but, much more nearly, carries out the inverse of each of these operations.'⁶⁶ Similarly Hollingdale and Toothill (1970) wrote that the name was 'unfortunate':

The name 'differential analyzer' is unfortunate on two counts: the operation of differentiation is very uncommon, and the problems are set up on the machine by building up mathematical expressions term by term, which is hardly a process of analysis. A counter-proposal is 'integrating synthesizer', but it is too late to carry pedantry this far. It is better to reserve the name 'differential analyzer' for the mechanical computer, and to disallow it for the more modern electrical analog computers.⁶⁷

⁶⁶Hartree did however concede that since it was Bush's 'child', he had 'the right to christen it'. See Fischer (2003) p. 87.

⁶⁷Hollingdale and Toothill (1970) pp. 79–80. This shows that in thinking about the nature of computing, the distinction between analysis and synthesis was deemed important. Philbrick also observed that not all computing was analysis, advocating synthesis as part of his 'lightning empiricism'.

Second thematic time-line – From analogy to computation: the development of electrical modelling

As previously described, there are two main aspects to analog computing: continuous representation and physical analogy. In the first time-line, the history of the mechanical integrator gave us a story of the continuous calculating machine. In this time-line, we turn to the tradition of analog computing that emphasises the construction of analogies.

In a sense, analog computers based on analogy are more closely related to natural science experimentation than to the history of calculating machines. Scientists have for generations constructed models to illustrate theories and to reduce complex situations into an experimental medium. Since the mid-nineteenth century, the technology available for creating models (or analogies) gradually became part of the history of computing: developing from ad-hoc laboratory set-ups and evolving into sophisticated, general purpose tools.

1845–1920: The development of analogy methods

During the nineteenth century, model construction embraced the new medium of electricity. Using electrical components offered improved flexibility and extended the scope of what could be represented in a machine. In many ways, the history of the development of modern computing is the ongoing attempt to manage an electrical (and later electronic) modelling medium.

In the context of direct analog computing, this modelling medium took two forms: analogs were either based on circuit models, of which the Network Analyser became an archetype; or alternatively, an analog was established by exploiting the physical shapes and properties of a conducting medium such as conducting paper or electrolytic tanks.⁶⁸ Electrolytic tanks offered a continuous conductive

⁶⁸As well as tanks and networks, other novel media were employed, for instance the Hydrocal, a research analog developed at the University of Florida around 1950, was based on pipes and

medium while resistance networks had a necessarily discrete representation of the flow space.⁶⁹ Together, these techniques became grouped under the umbrella of electrical analogy: models first being referred to as ‘electrical analogies’, and then later as ‘electrical analogues’. It was during this period that the experimentalist culture of the laboratory was replaced by more generic technologies, laying the foundations for physical analogy to become a *computing* technology.

Tracing field lines, field analogies and electrolytic tanks

A whole class of analog computing was dedicated to the modelling of field potentials. These analogs were typically used for solving problems that would otherwise have required the solution of partial differential equations. They employed the principle that heat flow, aerodynamic flow, and a whole class of other problems governed by Laplace’s equation, could be investigated through the analogous distributions of electrical potential in a conductive medium such as conductive paper or an electrolytic tank. The identification that lines of electrical flux could represent flow dates back to early work by the German physicist, Gustav Robert Kirchhoff. In 1845 Kirchhoff used conducting paper to explore the distribution of potential in an electrical field. The so-called ‘field plot’ turned an invisible phenomena into a visual diagram and allowed scientists to begin exploring the analogy between fluid flow and electrical fields.⁷⁰

In 1876, in the same volume of the *Proceedings of the Royal Society* that Kelvin published his account of the use of integrators to solve differential equations, a different form of modelling technology was communicated to members of the Royal Society. This was an electrolytic tank developed by the British scientist

tanks of fluid (Anon., 1951b, p. 864). Typically, the applications that employed an indirect computer moved to digital more quickly because the problems were already in a mathematical form that could be programmed. For direct analog computers, the transition took longer because a suitable and trustworthy digital representation had to be established.

⁶⁹Note that this starts to frustrate certain clear-cut definitions of analog computing. Contemporary actors were using the labels ‘discrete analog’ and ‘continuous analog.’

⁷⁰Small (2001) p. 34. As well as conductive electrolyte, conductive ‘Teledeltos’ paper was also used extensively during the 1950s and 1960s.

William Grylls Adams, the younger brother of the astronomer who co-discovered the planet Neptune. Adams spent most of his academic career at King's College, London, where he established its Physical Laboratory (1868) and actively pursued the teaching and research of experimental physics.⁷¹ Initially part of the material culture of experimental physics, electrolytic tanks would later become an important technology of analog computing.

Adams' electrolytic tank further contributed to the visualisation of electrical field lines. The apparatus consisted of a wooden tank containing water, two fixed metal electrodes, and two mobile electrodes. Connecting a power source to the fixed electrodes established an electrical field which could be explored with the mobile electrodes (see Figure 2.13). A galvanometer connected in series showed the difference in electrical potential between the two mobile electrodes, and this allowed these roaming probes to be used to find points of equal electrical potential (signified by a zero displacement of the galvanometer needle).⁷² In this way gradient lines of an electrical field could be mapped, a process not dissimilar to surveying depth contours at sea by taking soundings.

Miniature power networks and resistor-capacitor models

In the 1880s Thomas Edison, the inventor of the light bulb, employed a research assistant to build scale models of power networks. These, over a number of years, evolved from special purpose laboratory experiments towards more general purpose set-ups. Following a development from the specific to the generic,

⁷¹Adams joined King's College, firstly as a lecturer, and subsequently held the chair of natural philosophy between 1865 and 1905. This position had been previously held by James Clerk Maxwell. Adams was an active member of the London scientific scene. He was elected fellow of the Royal Society in 1872 and was a founding member of the Physical Society of London (now the Institute of Physics) for which he acted as president between 1878 and 1880. During 1898 Adams served on the council of the Royal Society and in 1884 was president of the Society of Telegraph Engineers and Electricians (later the Institution of Electrical Engineers). In 1888, Cambridge University awarded him a DSc. See Anon. (1897b); Anon. (1915); G.C.F. (1915); Anon. (1897a); Anon. (1888). His emphasis on experimental methods is an interesting link with other actors in this history such as the engineers Vannevar Bush and George Philbrick, as well as the meteorologist, Dave Fultz.

⁷²See Adams (1876).

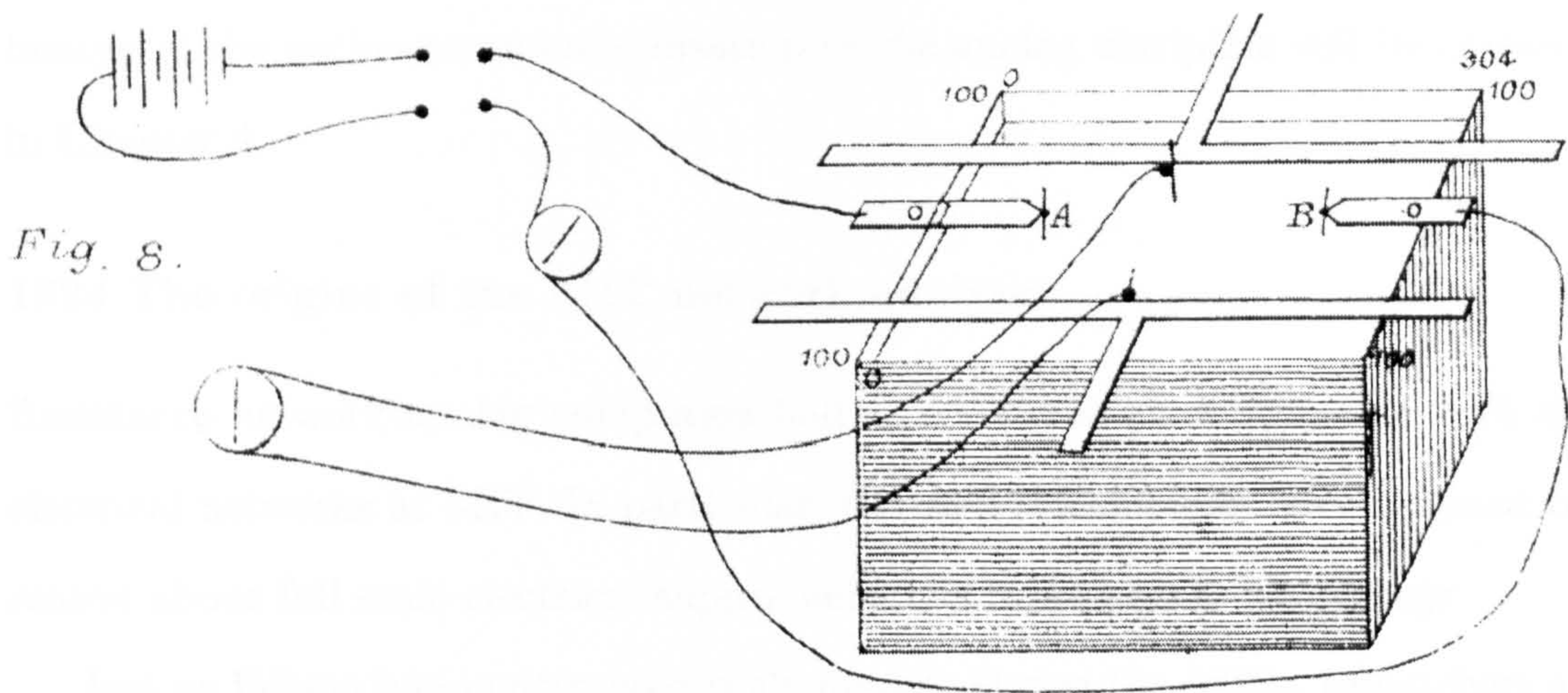


Figure 2.13: A diagram of Adams' electrolytic tank from his original paper. The fixed electrodes are marked A and B, the mobile electrodes are connected to the T-shaped handles. Source: Adams (1876).

experiments evolved into lab-based modelling set-ups, which in turn developed into special purpose electrical analogs. Subsequently, these electrical analogs were replaced by programmable analog computers before a final transition to programmable digital computers was made during the 1960s and 1970s.

1920–1946: Pre-digital analog modelling

It was during the 1920s that electrical analogy became properly established as a modelling medium and a number of contemporary publications regard an early paper by the engineer Clifford A. Nickle as a seminal development. In this paper, Nickle articulated a general approach to developing electrical models of complex systems, initiating the uptake of electrical analog methods in engineering.⁷³ It was around this time that analog culture was beginning to stabilise, allowing the discipline of electrical analogy to become enclosed and established. As a result, electrical network analogs became part of the literature of computing.⁷⁴ The

⁷³Nickle (1925); Karplus and Soroka (1959).

⁷⁴This is shown in the annual subject indexes of the *Review of Scientific Instruments*, a journal published by the American Institute of Physics during this period. Between 1947 and 1950, the number of articles classified under 'computer devices and techniques' grew to encompass both electrical networks and more conventional analog computers. The growth of this section is not simply due to advances in the technology. Instead we can see that there is an enclosure of the identity of 'computing technology' – the older classifications of 'electrical network' and 'counter

history of the enclosure and stabilisation of the analog discipline will be covered in Chapter 4.

1924 The origins of the MIT network analyser

Resistance network analog computers had their origins in the pre-war work on electrical networks at MIT. In particular, the *network analyser* was designed to reason about full scale electrical supply networks in miniature by analogy.

Just as Edison had constructed scale models during the 1880s, researchers at MIT began to build special purpose models to assist with the design of new power distribution networks.⁷⁵ Developing an individual model for each network was not very flexible and researchers realised that they needed a more generic tool. The network analyser occupied a large room and through its patch panels it allowed a user to quickly set up a specific network. Initially the analyser was used just to reason about electrical supply networks in miniature; however, its users soon developed techniques for wider modelling applications, representing more exotic referents such as hydraulic systems within the framework of resistor-capacitor networks.⁷⁶

Resistor-capacitor circuits could also be harnessed to directly solve mathematical equations. For instance, during the early 1930s, the Cambridge scientist Rawlin R. M. Mallock devised an electrical device to solve simultaneous equations. Using transformer winding ratios to mirror relationships in a set of mathematical equations, Mallock was able to directly extract a solution through measurement. Mallock developed an experimental machine in 1931 and the construction of a full-size machine (capable of solving ten simultaneous equations) was completed

circuits' that existed in 1947, being either reduced in size, or removed by the early 1950s.

⁷⁵This was in part due to the expansion and amalgamation of American regional power grids during the 1920s. The complexities of large scale transmission networks caused unstable black-holing in the power grid. See Akera (2007) p. 31.

⁷⁶Bush identified the network analyser as an instrument in which whole equations mapped to a particular set-up. By contrast, the differential analyser established analogies between the machine and individual components of a differential equation. See Bush (1936).

in 1933.⁷⁷

Because it modelled mathematical equations, the Mallock machine is a fine example of the kind of analog device known as ‘indirect’. Each equation was modelled by a circuit connecting a number of transformers; the number of transformers corresponding to the number of variables in the equation.⁷⁸ Vannevar Bush was impressed with the technique of using transformers, and used it as a starting point for further work in circuit models.⁷⁹ Although Mallock’s machine was intended as an indirect equation-solver, Bush would make significant use of its principles in the development of methods for structural analysis, an example of direct analog computing. This blurring of the two types of analog computation was typical of Bush, and at MIT the two perspectives of analysis and synthesis were managed within one research program.⁸⁰ We will return to this blurring in the third thematic time-line; but first we need to look at the history of the analogy-making technologies that were later enrolled into computing discourse.

Techniques using resistance networks were particularly useful in geographical modelling (such as hydrological planning) because the layout of the problem could physically map to the geography of the real-world problem. The co-evolution of network analysers and machines based on integrators came together in the research at MIT, where both the network and differential analysers were developed. These developments marked the beginning of the entwinement between analogy and calculation; a mixture of mathematics and experiment that would

⁷⁷A patent application was submitted in 1931, and granted in March 1933 (Mallock, 1933/1931). Later that month Mallock submitted a paper describing the machine in the *Proceedings of the Royal Society* (Mallock, 1933).

⁷⁸The coefficients of each variable were ‘programmed’ by the number of windings connecting that transformer to the others – clockwise windings for positive coefficients, and anti-clockwise for negative. Through applying an alternating current supply to one of the coils, the electrical circuits would reach a steady state corresponding to the equations’ solution.

⁷⁹See Bush (1934).

⁸⁰Mindell (2002) describes how Bush’s two perspectives of ‘modeling’ and ‘calculation’ were held in tension, indicating that this was the beginning of an entwinement between the empirical approaches of analogy making, simulation, and modelling; and the analytical approaches of calculation, theory and mathematics. Bush had a natural leaning towards the use of analogies. This can be seen in his earlier work on gimbal stabilisation (Bush, 1919). See Mindell (2002) pp. 149–150; Akeru (2007) pp. 31–32; Owens (1986); Wildes and Lindgren (1985) pp. 86–87.

become blended in ‘analog computing’. The two types of analyser represented different activities – two perspectives of use – sub-dividing the analog computing class. Small described them as competitive technologies that ‘maintained distinct lineages, but nevertheless shared a similar conclusion; their displacement by electronic digital computers.’⁸¹

1932 Le Laboratoire des Analogies Electrique: electrolytic tanks in France

During the 1930s the French mathematician Joseph Pérès (1890–1962) became well-known for his use of electrolytic tanks to model physical systems.⁸² In 1921 Pérès was appointed Professor of Rational and Applied Mechanics at Marseilles where he was inspired by the analog modelling of his colleague J. Valensi, who had solved a fluid dynamic problem by employing an analogy between streamlines of fluid flow and potentials in an electrical field.⁸³

By 1930, Valensi and Pérès had founded the Institute of Fluid Mechanics at Marseilles and over the following years, applied electrolytic tanks as a computing technology. Around 1932 Pérès accepted a Chair at the Université Paris-Sorbonne where, with his researcher Lucian Malavard, he established a Department of Electrical Analogy (Le Laboratoire des Analogies Electriques) within the Paris Faculté des Sciences. In Paris, Pérès and Malavard began to develop various refinements to electrolytic tank methods. In particular they developed applications using tanks of various depths, a technique that had been employed within British aeronautical research. The outcome of the work was the Wing Calculator, a tank that could solve the equations governing a lifting wing. The calculator was used by a

⁸¹Small (2001) p. 40.

⁸²Pérès came from an academic family and for his doctorate had studied permutable functions under the supervision of the Italian mathematician Vito Volterra. Pérès’ thesis *Sur les fonctions permutable du Volterra* was submitted in 1915.

⁸³In 1924, the same year that Valensi used an electrical analog to represent flow and the MIT network analyser was unveiled, similar work was done by E. F. Relf. A future fellow of the Royal Society (elected in 1936), Relf held the position of superintendent of NPL’s Aeronautics Division between 1925 and 1946. He also established the College of Aeronautics at Cranfield. See Pankhurst (1970); Taylor and Sharman (1928).

number of aircraft manufacturers until 1940 when the outbreak of war in Europe prompted the laboratory to be dispersed and the remaining research destroyed.⁸⁴

The uptake of electrolytic analog methods in Britain might have been greater had the work of Pérès and Malavard not been interrupted during the war years. The re-opening of communication post-war saw British users of the electrolytic tank rapidly increase in number. The use of tanks in aeronautical research is considered in Chapter 7.

1935 George Philbrick and the Polyphemus: Development of electronic modelling at Foxboro

The major developments of post-war analog computing utilised electronics. The popular class of machine referred to as the ‘General Purpose Analog Computer’ (or GPAC), was the electronic version of the differential analyser. Many pioneers of electronic analog computers were people who had previously undertaken research in control systems analysis or similar fields. One pioneer of electronic analog computing was George Philbrick (1913–1974), a Harvard-educated communications engineer involved in the construction of early electronic analog computers at the Foxboro Corporation.⁸⁵ At Foxboro Philbrick developed the Automatic Control Analyzer (ACA) simulator (nicknamed ‘Polyphemus’), an early electronic computer.⁸⁶

During World War II, Philbrick worked for the US government as a fire control

⁸⁴Pérès (1938); Mounier-Kuhn (1989) p. 257.

⁸⁵Mindell (2002) p. 307; Holst (1982). His obituary describes how he completed the Harvard undergraduate program in ‘record time’, entering the school in 1932 and receiving his degree in 1935. He worked for Foxboro between 1936 and 1942, under the eminent control engineer Cleson E. Mason. Mason was awarded the Rufus Oldenburger Medal for his work on automatic control in 1973. See Paynter (1975) and Anon. (2005b).

⁸⁶Similar activities were going on in other engineering contexts. In 1939 Helmut Hoelzer was working on early analog computing as part of German missile research, and in Britain a team developing radar crew trainers at the Telecommunications Research Establishment (TRE) constructed an analog simulator using electro-mechanical integrators, which they called ‘the velodyne’. The TRE was central in laying the foundations of post-war analog computing research. Another significant research program was American research into operational amplifiers for computing at Bell labs, from which came seminal papers from Ragazzini, Randall, and Russell, whom John McLeod referred to as the ‘three-Rs’ of simulation. These three had also been involved with the wartime NDRC analog culture. See Small (2001) pp. 66–67, 69–71; McLeod (1968) p. 15.

researcher within Division 7 of the National Defense Research Council (NDRC). During this period he met several, later eminent, engineers who were involved in the early seminal work on control electronics and servomechanisms.⁸⁷ Once his wartime research was completed, Philbrick had intended to enrol at MIT as a graduate student and develop a high-speed analog computer. However, this project was indefinitely put on hold when he was approached to design a special purpose simulator for the Wright Aeronautical Corporation. He successfully constructed the simulator in his spare bedroom and, as a result, set up his own company: George A. Philbrick Researches, Inc. (often abbreviated to GAP/R). GAP/R were the first company to manufacture and market a commercial operational amplifier.⁸⁸

1942 William A. Bruce and the modelling of oil reservoirs

An interesting example of analog computing as a modelling medium is the application of electrolytic tanks and resistive networks to the modelling of oil reservoirs. This application dated back to the 1930s when researchers for large petroleum corporations began to develop electrical models of the hydrodynamics of subterranean oil reservoirs. Within reservoir engineering literature, the first well-known application of analog computing to such problems is attributed to William A. Bruce, a researcher of Carter Oil. He invented his 'analyzer for subterranean fluid reservoirs' in 1942, demonstrating that the dynamics of an underground oil reservoir could be represented by electrical circuits.⁸⁹

Throughout the following two decades, large numbers of patents for reservoir analysers were granted. Initially, Bruce made no reference to analog, analogy or computing: throughout his 1945 patent application the circuit was described as

⁸⁷See Mindell (2002) p. 199–200. Mindell lists a number of important names who worked within this research team throughout the wartime period, including the famed J. R. Ragazzini and G. Stibitz.

⁸⁸Alongside these activities, Philbrick continued to act as a consultant to Foxboro. See Holst (1982) p. 156.

⁸⁹Peaceman (1990) pp. 106–108; Bruce (1947/1943).

an 'electrical counterpart of a reservoir'. Later, reservoir analysers would employ the conceptual label of 'electrical analogies' and thus become part of the discourse of analog computing. Their story is told in Chapter 6.

Third thematic time-line – Analog computing and the entwining of calculation and modelling

It was only after the emergence of the digital computer that it became necessary to assemble these various technologies under the umbrella term of ‘analog computing’. In the formation of an analog identity, the two concepts of continuity and analogy were blended together, entwining the chronologies of calculation and modelling into a coherent body of technology and practice.

1940: The emergence of analog computing as a technical label and class of machine

According to the *Oxford English Dictionary* the earliest use of the word ‘analog’ to describe a class of computers occurs in an article in *Nature*.⁹⁰ The article, authored by Douglas Hartree, states that the classification was established on the other side of the Atlantic.⁹¹ It is assumed that Hartree was introduced to the analog-digital classification during his visits to the Moore School of Electrical Engineering at the University of Pennsylvania. This was possibly from ENIAC pioneer John W. Mauchly who is known to have used the classification in communication with John Vincent Atanasoff (another pioneer) in 1941.

Mauchly and Atanasoff’s usage is the earliest explicit reference to analog as a class of computer technology. Indeed, in an autobiographical article, Atanasoff claimed to have first used the classification a year earlier. He recollected that the distinction between the two classes of computer ‘came from [his] own mind’ and identified a paper describing a digital computing technique (Atanasoff, 1940) as

⁹⁰‘analogue, *n.*, and *a.*’, *The Oxford English Dictionary*. 2nd ed. 1989. *OED Online*. Oxford University Press. Accessed 1st September 2006. <http://dictionary.oed.com/cgi/entry/50007887>.

⁹¹He wrote that ‘the American usage is analogue and digital machines’, (Hartree, 1946, p. 500). Hartree actually preferred to use ‘calculating machine’ for digital and ‘calculating instrument’ for analog, a distinction which he derived from the *Encyclopaedia Britannica* where the ‘two classes of equipment [were] considered in different articles.’ (Hartree, 1949, p. 1). These were, the articles on ‘calculating machines’ and ‘mathematical instruments’ respectively. See also Hartree (1947).

the earliest record of his usage.⁹² In this paper he wrote:

About seven years ago the writer [Atanasoff] began to investigate the feasibility of mechanizing this solution. He was aware of the possibility of using a mechanical or electrical analogue but discarded this *method*, as being too inaccurate and cumbersome when many equations are to be solved, in favor of a method employing direct calculation of the results desired.⁹³

Atanasoff's use of the word 'analogue' refers to a *method* of computation, rather than a particular class of device, subtly weakening the claim that his publication had been the first reference to analog as a class of computer. However, the terminology appears to have crystallised during early 1941, and within a couple of months Atanasoff was communicating to Mauchly a definition of analog computing far more recognisable as what would later become mainstream. The dialogue between Atanasoff and Mauchly began when they first met in December 1940 and resulted in Mauchly visiting Atanasoff in the summer of 1941.⁹⁴ On his return, Mauchly prepared some notes in which he described two classes of computing. In these notes attention is drawn to the principle of analogy, and the limited accuracy of analog technology:

Computing machines may be conveniently classified as either 'analog' or 'impulse' types. The analog devices utilize some sort of analogue or analogy, such as Ohm's Law or the polar planimeter mechanism, to effect a solution of a given equation. The accuracy of such devices is obviously subject to limitations; at times the attainable is more than sufficient, but there is increasing need for more computational aid not so restricted. Impulse devices comprise all those which 'count' or operate upon discrete units corresponding to the integers of some number system. There is no theoretical limit to the accuracy

⁹²Atanasoff (1984) p. 234. Although he acknowledges that 'others may previously have had the same idea' about the separation of computers into two classes, Atanasoff (1984) claimed that he had been 'the first to use the word *analog* for computers ...the term I devised at the time I made this distinction and used in my 1940 manuscript (spelled there *analogue*)'. Even the originality of 'analogue' is questionable. David Mindell noted that while Atanasoff 'may have been the first to specifically apply the term *analog* to a computing machine', others were using analogy to refer to earlier circuit models (Mindell, 2002, p. 387). Although used for calculation, such circuits would have not been called computers, so perhaps the real contribution of this 1940 paper was the connection between the linguistic labels 'analogue' and 'computer'.

⁹³Atanasoff (1940) p. 316, emphasis added.

⁹⁴Mauchly (1984) pp. 125–126.

to which such devices will work; practical limitations on the bulk or cost or convenience of operation provide the only restrictions. The usual mechanical computing machine, utilizing gears, pauls, etc, are examples of impulse calculators.⁹⁵

For Mauchly and Atanasoff, the technology was primarily an analog, a machine or set-up which maintained a correspondence or analogy between two physical systems, the continuous nature of the machine was coincidental.⁹⁶ A similar emphasis was made by Douglas Hartree who considered measurement to be a central aspect of his analog *instruments*, the technology that operated by ‘...translating numbers into physical quantities of which the numbers are the measures... finally measuring some physical quantity to give the result.’⁹⁷

1945–1960 The development and stabilisation of computer technology

World War II was a scientific war, and large research funds were distributed to develop computing aids for the science and engineering underpinning the war effort. Due to rapid innovation, and secrecy of projects, various different technological paths were pursued, some analog, some digital.

One of the major technical benefits of the wartime research was the major improvements in electronics. During the years after 1945, analog computers were constructed using electronic components, the mechanical integrators being re-

⁹⁵Mauchly (1941) – this usage was attributed to Atanasoff. A facsimile of the first page of these notes is provided in Appendix B. While Mauchly made no direct reference in these notes to the relationship between analog computing and the continuous representation of variables, he was aware of the connection. Note his spelling of ‘analog’ for the category, and ‘analogue’ for the concept.

⁹⁶Even forty years on, Atanasoff retained an emphasis on measurement rather than continuity: ‘In analog computers, a number is represented by a physical quantity in the machine as measured by some system of units’ (Atanasoff, 1984, p. 234). This can provide insight into his use of the phrase ‘direct calculation’ which is central to Atanasoff’s understanding of the distinction. Digital computers allow the computation to work with numbers directly whereas analog computing manipulates measures that represent numbers. Atanasoff’s use of *direct* should not be confused with the two categories of analog computers – direct and indirect – that later emerged.

⁹⁷Hartree (1947) pp. 7–8. Hartree did refer to continuous data, but not as a defining feature of analog computing. He wrote that ‘Analogue machines can be designed to handle continuous variables, and in particular can handle integration as a continuous process’ (p. 8).

placed with capacitor charging circuits. Small notes that the replacement of the mechanical with electronic was itself 'neither unproblematic nor swift'. These electronic components often had a lower accuracy than the precision engineering of mechanical integrators, but were considerably cheaper and could be used at higher speeds.⁹⁸ High speed components facilitated a new type of analog computing which supported repetitive operation (or rep-op), where the computer calculated many solutions per second, supporting parameter variation and explorative modelling. Rep-op allowed problems to be time-scaled, supporting problems to be solved via parameter variation. As a piece of contemporary sales literature put it:

Time itself becomes the servant, not the master, enabling protracted processes to be repeated many times in a minute or disturbances too fast for the human mind to be examined at leisure.⁹⁹

The development of electronic differential analysers

Now unified under 'analog computing', analog computers came to be classified as either direct or indirect. The indirect analogs were essentially the developments of the equation solving tradition. Pioneering work in the development of electronic versions of the differential analyser emerged from the wartime work on control systems, which had developed the electronic amplifiers needed to construct an electronic integrator. One such example of a high speed electronic analog computer was developed by Macnee (1949). Similarly research machines were developed in various universities and research establishments. In America most post-war analog computing was organised by the Office of Naval Research (ONR), which organised a number of large projects and symposia. Similarly, in the UK most research was done in relation to aeronautics, the large TRIDAC machine becoming operational in 1954.¹⁰⁰

⁹⁸Small (2001) pp. 54-56.

⁹⁹EMI (Undated).

¹⁰⁰Small (2001) pp. 181-182.

On the other hand, the development of direct electronic computing followed the same path as it had before the war. Much of the work on resistive networks and electrolytic tanks was focused on specific application domains such as engineering structures and power system analysis. These techniques were used extensively for quick, explorative investigations. Examples include the flutter simulators and electrolytic tanks used in aeronautics (see Chapter 7), resistance analogs used in hydrology and ground water research (see Chapters 5 & 6), and modelling electric transmission networks.

Early digital computers as the evolution of analog architectures

Earlier we referred to John Mauchly. Mauchly was a member of the team at the Moore School who constructed ENIAC, the first programmable electronic digital computer.¹⁰¹ Although fundamentally a digital machine, ENIAC was in many ways an extension of the analog culture that had existed previously. The choice of acronym (standing for Electronic Numerical Integrator and Computer) emphasises the link. While a major application of analog computers was mechanising the calculus; the ENIAC was intended to solve problems that had previously been undertaken by the differential analyser. An insightful quote from the ENIAC patent (submitted in 1947) shows that making an analog computation was understood as akin to conducting a laboratory experiment. The digital ENIAC offered a 'cleaner', more mathematical alternative:

It may be noted that much of the present experimental work consists essentially of the solution of mathematical problems by analogy methods. If one had a computing machine of sufficient flexibility the necessity for these experiments would be obviated. Our invention makes available such a machine.

In discussing the speed of computing machines it is desirable to distinguish between so-called continuous variable and digital machines.

¹⁰¹ENIAC ran its first successful program in 1946. It should be noted that deciding which machines were 'first' relies largely on personal definition and is often a contested issue amongst historians.

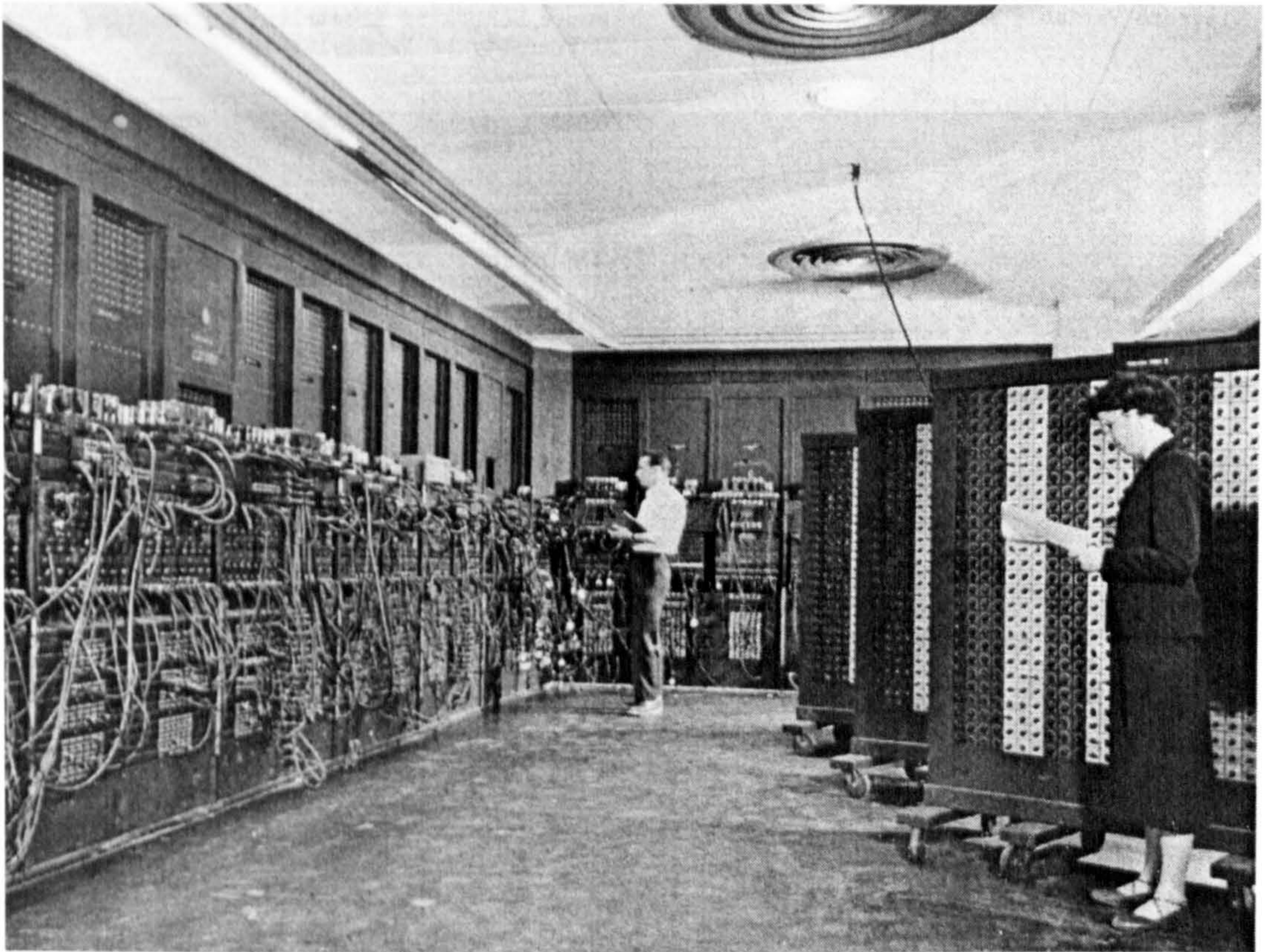


Figure 2.14: The ENIAC, a technical evolution of the differential analyser: Source Wikipedia Commons

Although existing continuous variable machines such as the differential analyser and the AC network analyser are exceedingly rapid, the class of problems which they can solve is limited.¹⁰²

As can be seen from the quote, the 1940s was the period when the concept of the analog computer was introduced to encompass both of the traditions explored in our first two time-lines. Here Eckert and Mauchly separated the technical concept of continuous variables, (a defining characteristic of continuous calculating machines), and the conceptual idea of analogy, characteristic of modelling technologies.

When John Brainerd, the original supervisor of the ENIAC project, recollected the background developments to building the ENIAC, he stressed the importance of the Moore School's prior experience with the differential analyser.¹⁰³ Further-

¹⁰²Eckert and Mauchly (1964/1947) col. 3.

¹⁰³Brainerd (1976) p. 483.

more, recent scholarship by Burks (2002) proposes an interesting theory behind the process of innovation of the early digital computers. Drawing a parallel between the developments of Atanasoff and Travis in their journey from analog to digital, Burks' investigations into this causal sequence of design shows how the architecture of the ENIAC mirrored the differential analyser, whereas experience with a different analog – the Laplaciometer – led Atanasoff to his different approach to building a digital computer.¹⁰⁴

Analog techniques on digital hardware: The digital differential analyser

While the ENIAC was partly inspired by the analog computers that preceded it, another technical evolution from the analog was the Digital Differential Analyser (or DDA). The principle of the DDA was that the analog integrators could be replaced by integration software running on a simplified digital computer. This underlying software would be built into the machine, and the computer would be 'programmed' by constructing circuits of feedback between summers, integrators, and others just as on a differential analyser or GPAC. In this sense, the DDA was an attempt to separate analog approaches from analog technology.

One example of a DDA is the MADDIDA computer constructed by engineers at Northrop aircraft.¹⁰⁵ During the early years of the cold war, Northrop were managing two important projects for the US military. These were the Snark missile, an intercontinental missile designed to deliver a nuclear warhead; and the 'flying wing' nuclear bomber. Both of these projects required sophisticated computing technology, both in the design stages (calculation perspective), and also in the air as embedded control systems. Because of the novel design of the flying wing, complex stabilisation controls were required. In the case of the Snark, a computer was required to perform celestial navigation functions. The Snark was

¹⁰⁴Burks (2002).

¹⁰⁵Northrop were an important early user of computing technology. To signify their importance, Ceruzzi referred to them as the 'midwife of the computer industry' (Ceruzzi, 1989, p. 19).



Figure 2.15: Launch of a Snark missile. The challenge to develop a fully automatic navigation system for the Snark missile was not simply a problem of data processing. Such hardware was needed to represent the world and the human process of navigation in a machine. Source: http://en.wikipedia.org/wiki/Image:Snark_rocket.jpg.

to fly independently, making its own celestial observations to navigate.

Ceruzzi described how in their search for automatic navigation technology, the researchers at Northrop turned to the EDVAC project.¹⁰⁶ They commissioned the BINAC, a smaller digital computer prototype manufactured by the Eckert-Mauchly Computer Corporation. However, the BINAC was too large to be used as an airborne system, and this led to the MADDIDA project, a special-purpose digital computer designed to work in a similar way to an analog differential analyser.¹⁰⁷

¹⁰⁶EDVAC (Electronic Discrete Variable Computer) was the first stored-program computer developed by the digital computer pioneers at the Moore School, Pennsylvania.

¹⁰⁷Ironically, the MADDIDA was still too large for use in the Snark, so the final guidance system was fully analog.

Invented in 1949, the main success of the MADDIDA was the demonstration that through sacrificing generality when it was not required, a digital computer could be significantly reduced in size. This was a computer that was able to travel to conferences and be assembled in a hotel bedroom.¹⁰⁸ By 1951, Northrup were marketing the machine as a tool ‘...for general use in science and industry’, with the first production model being sold to the Experimental Towing Tank research facility at the Stevens Institute of Technology, New Jersey. This installation was used for modelling the stability of torpedoes, submarines and ships.¹⁰⁹

By the mid-1950s a variety of other DDAs had been developed, for instance, the DART computer built through a collaboration between the US Air Force and the Naval Ordnance Laboratory.¹¹⁰ In describing the set-up of a computer centre of the day, Cozzone suggested that a facility comprising of an IBM digital machine and a MADDIDA could support the computing needs of an engineering department.¹¹¹ In Britain, DDAs were referred to as ‘incremental computers’ and over the following decade, they became a popular technology for on-board computation. For instance, in December 1960, engineers from a British aircraft firm presented a new DDA to a guided weapons forum of the Society of British Aircraft Constructors (SBAC). They wrote:

The present state of the art allows incremental computers to be constructed which are adequate for most airborne applications. For simulations, they are at present at a speed disadvantage, when compared with analogue computers, although this situation would alter when improved response times can be achieved.¹¹²

Spicer (2000) described the MADDIDA as a ‘bridge between worlds’, the concept of the digital differential analyser crossing the boundary between analog and

¹⁰⁸Eckdahl et al. (2003); Tropp (1987) pp. 266, 357.

¹⁰⁹Anon. (1951a). For a technical overview of the DDA, see Donan (1952); Sprague (1952).

¹¹⁰Meissner (1954) pp. 134, 137.

¹¹¹See Cozzone (1952). Cozzone is also mentioned in a series of short accounts of IBM 701 users (Various, 1983).

¹¹²Rowley (1960) p. 9. The computer described had been developed by AV Roe and Co. at their Chertsey research laboratories. The applications of such research fell into two categories: on-board navigation and basic use in simulation.

digital. Here was a digital machine that employed the benefits of numerical representation, and yet organised its computing like a differential analyser. For many contemporary engineers, blending of analog and digital approaches appeared to be the logical direction in which the technology would develop. However, eventually general purpose digital computers became small enough to compete without having to sacrifice generality. Commenting on the history of DDAs, Maurice Wilkes wrote that:

...compared with the digital computers then being built, the MAD-DIDA was on an impressively small scale. It lost some of its simplicity, however, when adequate input and output devices were added, and in the end, competition from general purpose digital computers proved too much for it. The MADDIDA and its descendants did not, therefore, have the bright future in scientific computation that was predicted for them.¹¹³

1950–1965: The commercialisation of the analog computer, and the invention of hybrid computing

During the years after 1950, the analog computer became a commercial product. Engineering and scientific firms began to install pre-bought computers rather than developing their own. Small (2001) offers an excellent and detailed study of the commercialisation that occurred in Britain and the US, with US analog manufacturers eventually dominating the market, both in America and Europe. Electronic analog computers were typically used for three major applications: solving differential equations, modelling complex systems, and simulating control systems. In Chapter 5 we will return to these three types of application and show that the history of analog computer use in British Academia followed different trajectories for each.¹¹⁴

The demise of the analog computer was a gradual process and it went through one more stage of innovation before disappearing. This was the development of

¹¹³Wilkes (2000) p. 538.

¹¹⁴For Small, the commercialisation of analog computers began in America in 1948 and in Britain in 1953. See Small (2001) p. 179.

hybrid computing. Although the DDA was a form of hybrid, there were various other types. These ranged from conventional analogs whose patchboard and control circuits were managed by a digital computer, through to computers where analog-to-digital converters were installed to allow analog variables to be stored in memory and manipulated by a digital computer. The analog part of the computer would typically handle differential equations, and the digital would manage special numerical operations such as function generation or the extraction of a logarithm.

During the 1960s most analog applications were in decline. This was the result not just of the ever-improving digital technologies which were becoming faster and cheaper, but also due to the development of new mathematical methods, such as the introduction of the Discrete Fourier Transform (DFT). Allan Newell described the DFT as 'penetrating the major bastion of analog computation'.¹¹⁵ The qualities of new digital software laid analog's traditional qualities of speed, cost, and ease of use, to one side. As one commentator put it:

By the late 1970s it was obvious that soon digital solutions would be faster – and considerably more accurate and convenient to use... The old axiom that '...when digital computers are programmed to solve equations as fast as analogs, they are less accurate and when programmed to be as accurate, digital computer are much slower,' was no longer true.¹¹⁶

Despite the demise of analog computers, there was a continuation of analog culture. In a similar vein to the DDA projects, the next stage of evolution was the simulation of analog computers, not with digital hardware (as with the DDA), but with software. Various simulation languages were proposed, allowing the users of analog computing to transfer their 'programming knowledge' from the old technology to the new. It is tempting to frame the transition from analog to digital as a clear cut example of success and failure, however the invention of such software and the fact that existing installations of hybrid and analog computers

¹¹⁵Newell (1983) p. 196.

¹¹⁶Holst (2000) p. 59.

were not immediately decommissioned, resulted in a mixture of both analog and digital computers being used during the late 1960s and early 1970s.

It is because of this gradual demise that we see the inclusion of the module ‘Analog and Hybrid Computing’ in *Curriculum 68*, a document published by the Association of Computing Machinery outlining the Computer Science curriculum in 1968. Suggested as a way to introduce analog simulation languages such as ‘MIDAS, PACTOLUS and DSL/90,’ the module was ‘...concerned with analog, hybrid, and related digital techniques for solving systems of ordinary and partial differential equations, both linear and nonlinear.’ The writers of the curriculum imagined that ‘a portion of the course should be devoted to digital languages for the simulation of continuous or hybrid systems’.¹¹⁷ The future was digital, but the ideas, techniques and language of analog would persist. Today, engineering modelling and simulation still speaks the language of integrators, summers and other analog computing components. This is best exemplified in the graphical interface to the popular MATLAB Simulink.¹¹⁸

Conclusions

This chapter has proposed a chronology of landmark themes in the development of analog computing. Such an analysis cannot be complete, nor do justice to the rich stories behind each technology. One of the purposes of preparing this chronology was to demonstrate the wide variety of technologies that are relevant to the history of analog computing and to highlight that defining ‘analog computing’ is a challenging problem. This is mainly because the majority of the history covers periods when the dichotomy analog-digital did not exist.

Through investigating analog’s identity, it becomes evident that there were two key aspects to analog computers: the use of continuous representation (reflecting the modern analog/digital classification), and the application of *analogy*

¹¹⁷ACM (1968) p. 159.

¹¹⁸Atherton (2005) p. 67; Bissell (2004b) pp. 7–8.

(visible in the etymology of 'analog(ue)'). While clearly interrelated, these two aspects of continuity and analogy belong to two separate (albeit closely inter-related) histories of technology. Each of these histories became entwined when computer pioneers began to refer to the concept of an 'analog computer' in the 1940s. Although the dual-meaning of analog is implicit in much of the previous work, authors have tended to mix their discussions of continuity and analogy. In this chapter, the history of analog computing was structured around this dual-meaning. Thus the contribution of this chapter is not just its content, but also its organisation. This chapter has argued that it is only once analogous modelling and continuous calculation were enrolled into the discourse of computing, that: (a) they became recognised as two different approaches of the same 'whole'; and (b) that the need arose to name this 'whole'. This convergence appears to have begun during the 1930s, and came to fruition with the widespread acknowledgement of 'analog computing' during the early 1940s.

Previous research on the history of analog computing has tended to focus on those artefacts that are more easily understood within a trajectory of information processing. For many scholars, that is enough, as analog computing provides a background context for the history of early digital computers and their invention.¹¹⁹ In this sense, the first thematic time-line has been well researched. However, focusing solely on this part of the history emphasises analog as a precursor to digital, but not as an alternative. This resulted in a number of scholars attempting to revisit the post-war analog history, questioning why analog computers were in use well into the 1970s. The work of James Small is the largest contribution to this literature and revisits post-war developments of general purpose analog computing.¹²⁰

Small's study focused on those machines that were manufactured in large quantities: the descendant technologies of the differential analyser. However,

¹¹⁹See for example, Croarken (1990), pp. 9–12, 47–60.

¹²⁰Small (2001).

there has been less research into those technologies described in the second time-line. The technologies that came to be classified direct analogs were novel computing tools which provided visual experimental modelling environments. These were not just used for information processing, but also for *modelling*. Modelling is an important type of computer use, and in Chapter 3, we turn our attention to how a history of computing can account for the computer as a modelling machine. Later, Chapter 4 returns to the relationship between electrical analogy and analog computing, exploring how analog culture emerged.

Having looked in detail at the history of analog devices of the first time-line, we can now move on from the stories of differential analysers, planimeters, and integrators – the analog equation solvers. The rest of this thesis concentrates on those technologies detailed in our second time-line, and their development into the post-1940 period (when they became part of the third time-line). This is a story of electrolytic tanks, resistance networks, and other, more direct, analog modelling techniques.

Chapter 3

Modelling technology and the history of analog computing

Today, computability (what is computable, how is it computable) is pretty much settled. In fact, the digital paradigm is now so pervasive that challenges to it are also framed (and won) in its terms. Analog machines do not start from the same point. As such, they allow us to ask fundamental questions about what one wins and loses with computation. It has been argued that technology has strong benefits because it is good to think with. Analog machines take this one step further. They offer us a new way to reconsider what we have come to take for granted – how we model and how we think about objects in the world.

James Nyce¹

As discussed in Chapter 2, the concept of an analog computer emerged during the mid-twentieth century to capture a class of computing technology whose popularity had gathered momentum during the 1930s. However, what the inventors of analog computing were doing in the late nineteenth and early twentieth centuries was not entirely new. They were following a tradition of modelling that has a long heritage in the history of science. What *was* new was the application of computer technology to provide generic environments for modelling.

Chapter 2 highlighted the need to narrate analog chronology in terms of both calculation and modelling, and through considering the computer as a modelling machine, this chapter investigates the wider modelling culture surrounding analog

¹Nyce (1996) p. 3.

computing. As the opening quote from anthropologist James Nyce indicates, the bias and perspective of current computing culture heightens difficulties in understanding analog in context. Analog computing as understood by its contemporary users is different from modern computing. This variance can be explained in terms of modelling. Modelling is a major use of computer technology that until recently had received little attention by historians of computing.

Analog computing must be situated within a history of computing informed by both information processing and modelling. While analog computers were not solely used for modelling, this chapter suggests that a historiography of models and modelling is necessary to provide a coherent view of the history of analog computing. Building on the thematic chronology of the last chapter, a modelling historiography emphasises the importance of those underlying themes that developed out of the second thematic time-line. This chapter first takes a step back from analog computing and discusses the wider relationship between computing and modelling. It then focuses on how the theme of modelling fits within the history of analog computing.

Modelling: a variety of definition and association

The success of the computer as a modelling tool is salient in most contexts of use. From the spreadsheet and simulation software of Operational Research, to the computer-aided-design or finite-element packages employed by engineers, modelling is central. Indeed, the use of computer-based models now underpins much of the research in the natural sciences, to the extent that methodologies are often framed in terms of computer modelling.²

²A shift emphasised in the title of a recent textbook on computer modelling: *Modeling Reality: How Computers Mirror Life*. With the rise of computational science, 'modelling of reality' through software has become an increasingly important area of scientific method (Bialynicka-Birula and Bialynicka-Birula, 2004). The development of computational science and the centrality of models and simulations are considered at length by Humphreys (2004) ch. 3–4; Hartmann (1996); and Galison (1997) ch. 8. From a historical perspective Yood (2005) gives an account

In its intuitive, everyday sense, modelling is the activity of developing models in a particular representation or medium. The purpose of creating such models is to represent an idea, concept, or situation, usually in a form that facilitates further analysis. The more malleable and flexible the modelling medium, the more powerful and exciting the modelling. With modern computers, technology has now provided virtual environments, re-defining the boundaries of what it is possible to create. Computers provide management of an inherently flexible and vast medium of electronic state, and by enabling ‘creating’ and ‘making’ with this state, the technology effectively becomes a modelling medium.

Models have a rich and varied tradition of use in the physical sciences, so much so that they have become the topic of attention for a significant body of literature in the philosophy of science. Like ‘analog’, the word ‘model’ is a slippery term, having multiple meanings and associations. A number of scholars in the history and philosophy of science have worked on unpicking the nature of models and modelling; a quick survey of the literature reveals an assortment of definitions so varied that they appear to defy classification. As philosopher Nelson Goodman put it:

Few terms are used in popular and scientific discourse more promiscuously than ‘model’. A model is something to be admired or emulated, a pattern, a case in point, a type, a prototype, a specimen, a mock-up, a mathematical description – almost anything from a naked blond to a quadratic equation – and may bear to what it models almost any relation of symbolization.³

of the development of computational science at the American Argonne National Laboratory.

³Goodman (1969) p. 171. Goodman’s response to this was to pursue alternative concepts such as diagrams and maps. This quote is also reproduced in McCarty (2005) p. 27. See also McCarty (2004) p. 257.

Modelling as a meta-narrative for the history of computing

The predominant thematic framework for considering the history of computing during the last twenty years has been that of information processing. Dominated in particular by business data processing, narratives begin with technologies such as the Hollerith census machines and other early ‘information technologies’ such as filing systems and cash registers.⁴ As Campbell-Kelly (2002) describes, it can be fruitful to view modern computers as the ‘latest technology’ in a much longer history of technical development:

There is now a bigger vision in the history of computing. Up to about 1990, the focus was on the computer as an artefact. Today the focus is on information processing. An analogy might help. There was (and still is) a flourishing history of railways, with a focus on artefacts and railway companies. But since the 1970s, there has been a much stronger interest in systems building, and transport is now viewed as a continuum starting with the stagecoach, evolving through the railways, and going on to air transport. Similarly, there has been a long evolution in the history of information systems, and the computer is now perceived as simply the latest example of the technology of information processing. This history is not just about computers, but about what came before them: punch-card machines, typewriters and office machinery, manual data processing systems, and even going back to encyclopedias – now viewed as information storage mechanisms.⁵

The information technologies described by Campbell-Kelly were the first generation products of the office machine industry. Companies from this industry, such as IBM, NCR and Burroughs, later turned their attention towards digital computing, entering the landscape of computer manufacture from the direction of the (American) office, and shaping the use of computer technology accordingly. The significance of prior technologies is understood in terms of the computer’s

⁴Recent examples of computer history as information processing include Campbell-Kelly and Aspray (1996); Essinger (2004); and Cortada (2002). The narrative of information processing is particularly useful for filling the gap between Babbage and the development of the Harvard Mark I nearly a century later. Augarten (1985) referred to the Hollerith punched card technologies as a ‘bridge between two centuries’.

⁵Campbell-Kelly (2002).

use today: the tradition of information processing identifying a coherent narrative of technological development. Many important machines were not known as 'computers' in their own context, so the association of these artefacts is back projected.⁶

In the tradition of information processing, the main applications of the technologies that emerged before the programmable digital computer fall into two categories: machines for bulk data processing, and machines for presenting or communicating information. With bulk data processing, machines perform calculations on batches of data as a factory might make rivets in batches of metal.⁷ On the other hand, examples of presentation and communication technologies include the typewriter for document preparation and the telegraph for data communication. As demonstrated by the literature, these two types of use are central in understanding the development of business computing and the commercialisation of the digital computer.

However, analog computing does not fit well within this historiographical tradition. For its users, the analog computer was more like a scientific instrument, an experimental tool that guided their reasoning. Throughout the development of analog technology its users were motivated by a desire to model and understand the world. When historians emphasise data processing, nineteenth century analog machines are portrayed as a technological dead end – what L. J. Comrie called a 'dark age' of digital computing.⁸ Like our opening quotation from James

⁶In a review of a history of Turing's ACE, Kidwell (2006) highlights this issue. She writes that a 'general problem for present-day historians lies in the widening gulf between the computer, as experienced [then]..., and the consumer products known by that name today.' While the modern computer is primarily a technology of entertainment or communication, Kidwell points out that they were 'first designed to compute' (pp. 461–462).

⁷Such metaphors extend back to Babbage who wanted to 'calculate by steam'. Babbage had in turn been inspired by Gaspard de Prony, whose teams of human computers at the French Bureau du Cadastre were based on the principles of division of labour (Grier, 2005, pp. 35–40). Other examples of data processing include tabulating census returns with Hollerith punch card technology, or performing ballistics calculations with the ENIAC.

⁸See Campbell-Kelly and Aspray (1996) p. 51. If you only look at the history from an information processing perspective, it is perhaps correct that this period be perceived as a 'dark age'. However, a framework based solely on modelling would not illuminate the importance of technologies such as punched card machines.

Nyce, historian Aristotle Tympas has commented how changing perceptions of computational identity led to a technology being 'devalued.'

Moments of shift in the emphasis from (digital) calculating machines to (analog) analyzers have been moments when the computing labor crisis became apparent. We know little about these moments because the post-40s demarcation between the analog and the digital was *a posteriori* projected to the pre-40s history of computing. As a result, analyzers are now historiographically devalued, despite their importance during their period of use.⁹

It is because of the dominance of information processing that historians began to narrate only the early portions of analog history (namely, those belonging to the first thematic time-line of Chapter 2). In terms of pure information processing, studying post-1940s analog technology seemed irrelevant.¹⁰ This supplied the fuel for those scholars who during the 1990s were to re-address the history of analog computing. However, within their work, analog computing's relevance had to be presented through the framework of failure studies.¹¹ As the history of computing moves into a new generation of scholarship, the older historiography of calculating and information processing must be combined with new narratives of modelling, rhetoric, culture, and society.

Within a narrative of modelling, the history of analog computing is far broader than the chronology of those machines that were described as 'analog computers'. As shown in Chapter 2, it is a story of the evolution of both calculating and modelling devices that became entwined together. Thus alongside information processing, we should consider a second, more user-intimate, mode of computing (see Figure 3.1). As well as providing a means for manipulating and presenting information; computing technology can, and has, been used to *generate* knowledge.¹² In other words, users can approach the computer as a means to discover

⁹Tympas (2003) pp. 76-77.

¹⁰Ironically, it was only after 1940 that these machines were actually called 'computers'.

¹¹See Chapter 1, page 2, above.

¹²Computers help us make sense of the world when they allow us to develop connections between the facts available to us, or to follow the language of Gooding (1990), to facilitate the development of a construal.

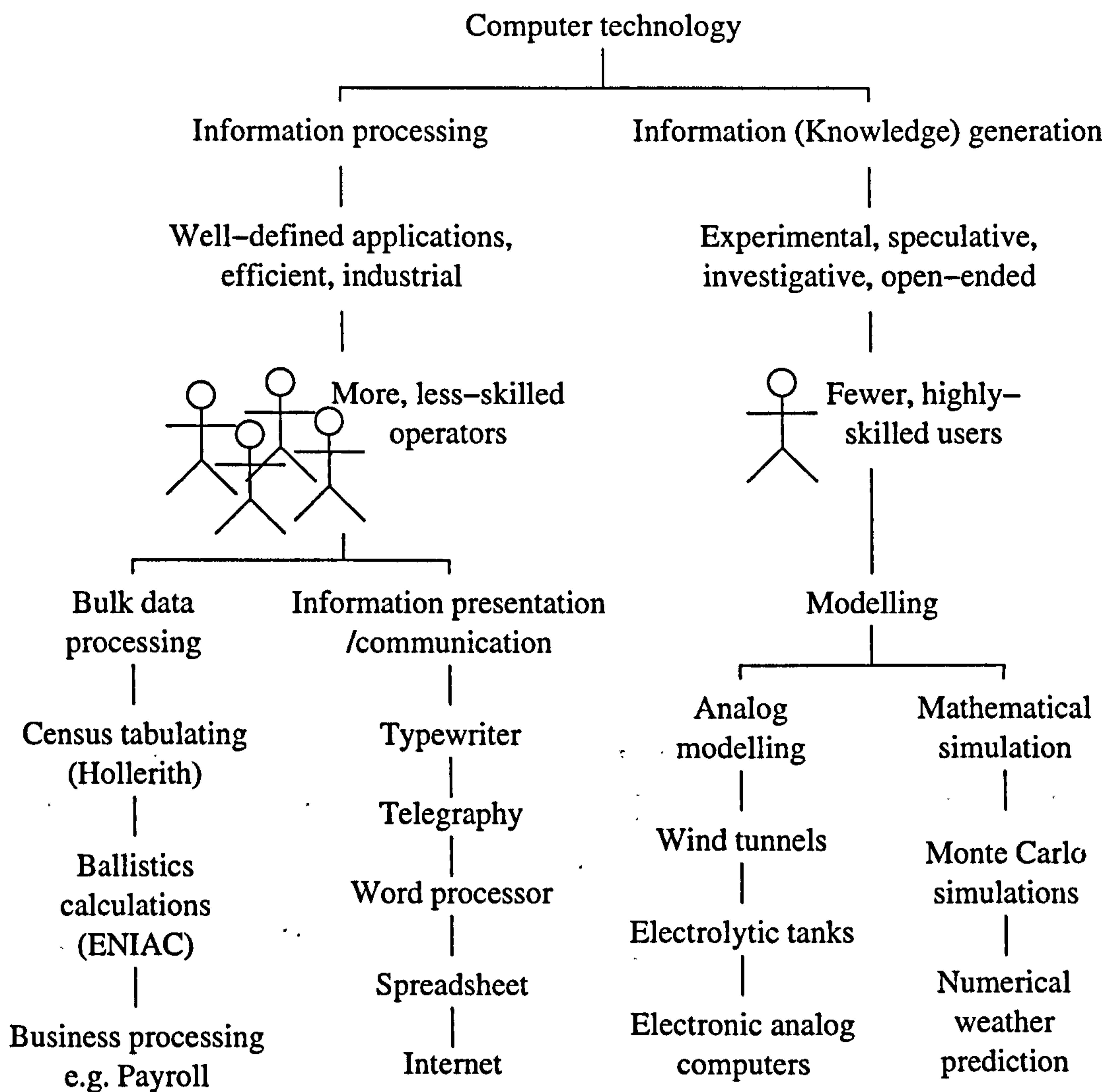


Figure 3.1: Information *processing* and information *generation* representing two fundamentally different approaches to computing. Computer history needs to account for both.

new knowledge, an activity of information generation rather than information processing, an activity of ‘modelling’.¹³

Just as considering the computer as an *information machine* has supported many fruitful studies (relating, in particular, to business applications), focusing on the computer as a *modelling machine* provides a useful perspective for considering the history of analog computing and its related technologies. In contrast to basing definitions on the continuous representation, using modelling as the meta-

¹³There is clearly an important philosophical distinction between knowledge and information that is beyond the scope of this thesis. Within the context of this work, developing knowledge requires human involvement, thus a computer when used as a modelling technology provides an environment through which a user can develop knowledge empirically.

Information-based historiography	Modelling-based historiography
Focus:	Focus:
<ul style="list-style-type: none"> • Office machines • Communication • Data processing 	<ul style="list-style-type: none"> • Modelling • Engineering design • Simulation • Analog computers
Theme:	Theme:
<ul style="list-style-type: none"> • Computer technology as information machine 	<ul style="list-style-type: none"> • Computer technology as modelling machine

Table 3.1: Modelling as a complementary perspective for computer history

narrative for analog computing encourages the consideration of the technology's users.¹⁴ Through exploring perspectives of use, this analysis provides a clearer picture of the development of analog computing than the idea of 'alternatives' proposed by Small (2001).¹⁵ The following sections consider the philosophical and historical issues behind such a perspective.

Support for thinking of the computer as a modelling medium

The computer is a composite technology, a point of convergence of various types of special purpose mechanisations. In a recent popular history entitled *Jacquard's Web*, James Essinger narrates such a story, the modern digital computer being: the latest communication tool in a succession from the telegraph; the latest document preparation technology (in a succession from printing presses and typewriters); and the latest calculation/accounting device – the spreadsheet being the modern equivalent of office accounting machines and mechanical calculators.¹⁶ In a history of convergent technology, each modern day application of the computer can be understood as having its own collection of predecessor technologies, and

¹⁴Those who worked with analog computing were typically engaged in developing models of physical systems. Much work on the history of computing has focused on technical considerations. However, it is also necessary to consider the more abstract theme of how technology is construed and understood. This is vital because it shapes expectations of use, and therefore the applications to which this technology was put.

¹⁵As discussed in Chapter 1, page 2, above.

¹⁶Essinger (2004). The work of Campbell-Kelly and Aspray (1996) follows a similar broad definition of computing.

with each application 'introduced' to the historiography of computing, a new set of technologies become part of its prehistory.¹⁷ In each case, the computer becomes the new genre of technology, embodying associations between machines and applications.

Because of this composite nature, the computer consolidates otherwise disparate activities. For instance, Nebeker (1995) claimed that computing was central in the formation of the modern discipline of meteorology, unifying the traditionally separate practices of forecasting, observation, and theoretical modelling.¹⁸ A similar theme can be drawn from Peter Galison's study of the emergence of Monte Carlo methods in the wartime nuclear research at Los Alamos.¹⁹ Galison shows that the history of such computing involves a diverse range of people, practices and locations. The one thing that unifies all the strands is the artefact itself, the computer.²⁰ Informed by the idea of the computer being a composite technology, analog computers are to be interpreted as the predecessor technology to the modern applications of computer modelling.

For scholars investigating the history or philosophy of science and technology, the issue of modelling is evidently a topic of increasing importance.²¹ Some justification for framing computing as modelling has already been given in Chapter 2 where two thematic traditions (calculation and modelling) were shown to be emergent from the historical sources. Interestingly, recent work on the history and philosophy of computing also supports situating computing within a trajectory of modelling technology. Before returning to the primary sources (the practice),

¹⁷Critiques of Essinger such as Ceruzzi (2006) doubt the precise linear account, but the idea that these information technologies are brought to fruition in the modern computer is fairly standard. See Campbell-Kelly and Aspray (1996).

¹⁸See Chapter 8, page 199, below.

¹⁹See Galison (1997), ch. 8.

²⁰The computer has essentially unified a plurality of disciplines. Obvious examples are communications, data processing, document preparation and calculation. With a modelling perspective, we can add modelling, simulation, and visualisation. Applications where, to paraphrase philosopher Paul Humphreys, the computer sits alongside other, more traditional, scientific apparatus as a technology used to 'extend ourselves' (Humphreys, 2004).

²¹A major collection of essays was edited by Morgan and Morrison (1999b). The history of systems modelling is considered by Edwards (2000), Monte Carlo simulations by Galison (1997), ch. 8.

it is helpful to consider these theoretical perspectives.

Theoretical support for a modelling perspective

With relation to modern computing, philosophical support for a modelling perspective can be found in Willard McCarty's contribution to the emerging discipline of Humanities Computing. From the perspective of an application-area dominated by large data banks and sophisticated search engines, McCarty cries out for a consideration that computers are not just tools of information management, mere storehouses of knowledge, but are also a technology through which users can create or develop knowledge, an activity which he describes as 'a process of coming to know':

...computational models, however finely perfected, are better understood as *temporary states in a process of coming to know* rather than fixed structures of knowledge... I conclude that although efficient access to data is an essential function of computing, the greater potential is for *computers as modelling machines, not knowledge jukeboxes*. To think of them as *only* the latter is profoundly to misunderstand human knowledge.²²

Similarly, in considering the history of scientific computing, Hughes (1999) situates his discussion of computer models within the context of both abstract mathematical models and physical models such as wind tunnels. Modern computer simulation is understood to relate to this modelling heritage.²³ Hughes makes a distinction between what he calls 'computer calculation' and 'computer simulation'. As an example of *calculation*, he describes an iterative process for solving a gravitational problem in physics, and suggests that this is '...just the kind of calculations that computers can perform more speedily than human beings.' On the other hand, his computer *simulations* are typically set up to provide

²²McCarty (2005) p. 27, emphasis in original. These pages do not offer space to address how computational theory should account for modelling. Of interest however, are theories of computing that consider analog computing. These include: Montague (1960), Davis (1964), Graça (2004), Piccinini (2004), and Velupillai (2004).

²³For Åström et al. (1998), analog computers were the first stage in a history of simulation technology. Similarly, Humphreys (2004) presents analog computers as a predecessor technology to modern computer simulation.

a 'mimetic function' of aspects of the world, and are often identified by their 'realist mode of description'.²⁴ Along with Morgan and Morrison (1999a), Hughes suggested that modelling technology has an instrumental quality. As objects of discovery, computer models function as a new kind of scientific instrument.²⁵

It is from these references to instruments and simulations that links between modern computing and analog computing begin to emerge. A number of philosophers of science²⁶ have considered the relationship between analog computers and scientific models – analog computers being positioned on the intersection of models and instruments.²⁷ One of the best summaries of various types of scientific instrument is given by Van Helden and Hankins (1994). They wrote:

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.²⁸

Besides the fact that both orreries and pendulums have been associated with analog devices,²⁹ as an instrument, analog computers correspond with two of Van Helden and Hankins categories. Firstly, in many applications of analog computing, users created computational artefacts that were 'models or analogies to

²⁴Hughes (1999) pp. 128–130. Hughes' example of a computer simulation is an investigation into the atomic effects of a nickel pin touching a gold plate. Quoting the scientist Fritz Rohrlach who published this experiment, he notes how the description of the investigation 'reads like a description of an actual physical process.' (p. 130). A close mapping to reality is central to the success of a simulation.

²⁵Numerous writers have presented computer technology as the pinnacle of scientific instrumentation technology. See Field (2000); Galison (1997) p. 692. However, as a technology, the computer can only function as an instrument when its users approach it as such.

²⁶See Hesse (1963) and Morgan and Morrison (1999b).

²⁷Recall how Hartree used 'calculating instrument' and 'calculating machine' to refer to 'analog' and 'digital'. See Chapter 2, page 58 note 91, above.

²⁸Van Helden and Hankins (1994) p. 4.

²⁹Bromley (1990) and Campbell-Kelly and Aspray (1996) refer to the orrery. Augarten (1985) refers to the pendulum in making a distinction between analog and digital.

nature'; secondly, just as the air-pump provided a new environment from which to explore phenomena, so the analog computer provided a new environment through which to think about and construct models of certain physical systems. In addition, analog computers were always 'the means of visual or graphic display'. Able to support dynamic models, analogs were able to support interactive visualisation long before their digital counterparts. Centres of analog computing research often developed expertise in visualisation technology.³⁰

As an instrument, the analog computer provided a generic modelling environment. For example, oil reservoir computers provided a way of generically modelling a number of oil fields. Each set-up created a new model of an oil field, but the computer itself provided the scope for many such set-ups.³¹ Every calculation on an analog computer can be considered an experiment with the computing mechanism, 'playing through' a sequence of actions analogous to a physical experiment.³² Essentially, the analog computer was an instrument that offered a rich modelling environment in which the symbols of an equation or the dynamics of a theory became physically situated and visually meaningful. For engineering culture, analog models faithfully represented reality:

As one learns to interpret the behavior of the computer, one begins to view it as the system itself rather than as some abstract analogue thereof. This resemblance between given and computer systems constitutes the fundamental characteristic which helps to endow the computer with its great value as a design and analysis tool.³³

³⁰It was in the context of analog computing that Donald MacKay described an early form of three-dimensional display (MacKay, 1949). When Mackay moved into neuroscience research he used his analog skills to develop novel display apparatus. See Chapter 5, page 135. Similarly, Macnee (1949) expected his all-electronic differential analyser to be: 'used, as a slide-rule is used, to give rapid solutions of moderate accuracy to the differential equations encountered by the engineer, physicist, and mathematician.' He wrote that '...the main advantage of the high speed of this analyzer is that it permits rapid exploration of a wide range of solutions.' (p. 1315).

³¹See Chapter 6, below.

³²With analog computing, the human operator was often guided towards the solution of the equation or system of equations that they were interested in. Computation was the result of an ongoing interaction.

³³Fifer (1961) vol. I, pp. 2-3.

Of course, it is not just analog computers that can provide experimental environments. Galison's study of Monte Carlo simulation gives an interesting account of how this modelling technology provided an experimental environment. A Monte Carlo model is based on probabilities and is solved through the successive generation of random numbers. Once established, the Monte Carlo physicists began to frame their world views in terms of the new paradigm, perceiving the Monte Carlo simulation as the closest mapping to the natural world. As Galison described:

One way of viewing the Monte Carlo was simply as another form of numerical approximation.... Even if later physics showed that there were underlying discontinuities in the physics, Einstein considered thermodynamics to reflect some fundamental truth about the world. Gilbert King saw things differently. As far as he was concerned, it was the partial differential equations that were the crutches, not the Monte Carlo. It was only the limitations of our calculating ability that had forced an over appreciation of continuum physics, and he saw the computer-driven Monte Carlo as a remarkable remedy. Now, with the Monte Carlo and the electronic computer, we could truly recreate the underlying, discontinuous reality that surrounds us.³⁴

Very quickly, the paradigms that we create to solve problems begin to shape the structure of the user community. In her article on war gaming technology, Ghamari-Tabrizi follows Galison, stressing how Monte Carlo simulations are essentially artificial experimental worlds. For those indoctrinated in the discipline, it was possible to apply the empirical method to the artificial, creating knowledge about the modelled phenomenon under study.³⁵ In essence, the modeller invests into the particular modelling paradigm to the point that the representation becomes a significant shaping-factor in their own natural outlook. For those who

³⁴Galison (1997) p. 742. Comparing these two outlooks, established physicists such as Einstein had a world view shaped by their confidence and familiarity of differential equations, whereas the modern 'stochasticivists' such as the industrial chemist Gilbert King understood problems in terms of Monte Carlo simulation.

³⁵She also identifies a second cultural view of such 'games of chance' – that they 'can be a direct analogue of the problem being studied', language that, thirty years previous, would have been reserved for physical modelling – Ghamari-Tabrizi quoting Herman Kahn in *Symposium on Monte Carlo Methods* [1956] (Ghamari-Tabrizi, 2000, p. 210). Kahn himself preferred the model to be an 'artificial construction'.

used analog computers, analogs appeared the ‘best’ way. Whether by analog or digital methods (such as Monte Carlo), there is a rich tradition of computers providing an empirical window on the world.

In sketching a history of computational environments used for modelling, the perspective of the user is central. In terms of analog computing, many users found the models they created to be inherently more flexible and trustworthy than those created on digital machines.³⁶ 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 analog computer provided an accessible environment through which to explore another system. To quote a textbook from the 1950s:

[T]he analog computer is more conducive to ‘experimental engineering.’ On an analog computer, each subunit or component has a direct significance in terms of the system under analysis. By programming the computer and by ‘playing around,’ for example, by varying electrical potentiometer settings, the engineer is permitted to gain an insight into the basic operation of the system.

By contrast, in the case of digital machines, the mathematical operations are performed as a sequence of arithmetic operations which generally bear no direct relationship to the system under study.³⁷

Individual experiment with the analog was central to the technology’s effectiveness. In their study of the Phillips economic computer, Morgan and Boumans (2004) identified that while mathematical theory can be used to calculate solutions, the analog computer can assist with ‘gaining knowledge of the economy through the mind’s eye’. Once a user was satisfied that the analog’s properties corresponded to their experience of the world, experiences of the referent and the analog began to merge.³⁸

³⁶Many such concerns related to familiarity, an issue explored with reference to aeronautical engineering in Chapter 7.

³⁷Karplus and Soroka (1959) pp. 3–4. In another text book Minorski (1947) wrote that ‘in a totally unexplored problem... the analogue will probably be preferable’ (p. 147).

³⁸This process is explained by Ihde (2004) with reference to a thermometer: after continued experience with a thermometer, the associations between length of mercury and temperature grow stronger. Ihde argues that the developing ‘embodiment relation’ allows an observer in

Historical support for a modelling perspective

Associations between computing and modelling are not just found in the philosophy of science, but also emerge from the history of computing. One example of this is found in the popular history of ‘mind expanding technologies’ published in 1985 by Howard Rheingold.³⁹ Although Rheingold is principally a journalist and not a historian, his book was based on field interviews with researchers at Xerox Parc, and so captures the mood of a significantly different community of computing practitioners.

In his lively narration of computer history, Rheingold’s text indicates that a significant innovation in the history of computing was not only the activities of Silicon Valley, but also the development of tools to support human reflection, writing, and communication. In particular, Rheingold was referring to the research agenda of J. C. R. Licklider, the famous pioneer who studied the relationship between humans and computers. Rheingold chose to frame his story of Licklider’s visionary perspective in terms of modelling. He suggested that in order to support the new kind of interaction Licklider required, the digital computer had to be re-invented⁴⁰ as a modelling technology:

Data processing involved certain constraints on what could be done with computers, and constraints on how one went about doing these things. Payrolls, mathematical calculations, and census data were the proper kinds of tasks. An arcane process known as ‘batch processing’ was the proper way to do these things...

But if you wanted to plot ten thousand points on a line, or turn a list of numbers into a graphic model of airflow patterns over an airplane wing, you wouldn’t want data processing or batch processing. You would want modeling – an exotic new use for computers that the aircraft designers were then pioneering.⁴¹

a warm room to experience something of the outside cold from the ‘immediacy of [the user’s] reading’ of the thermometer (p. 145).

³⁹Rheingold (2000/1985).

⁴⁰Re-invention is my concept for thinking of how a technology might move between different genres of use – for example, from information processing towards modelling and simulation. Although the computer is technically unchanged, the approach, expectations, and requirements of its users are transformed.

⁴¹Rheingold (2000/1985) p. 135. See also Rheingold (1991) ch. 3. Although ‘modelling’ is

Moving into more scholarly territory, further support for a modelling perspective is found in the work of David Mindell. In *Between Human and Machine*, he described the development of cybernetics in terms of the history of control and 'feedback culture'.⁴² Moving away from data processing, Mindell's analysis emphasised the importance of control, feedback and modelling; arguing that scholarship had 'not yet begun to understand the history and significance of analog computing, especially the relationship between digital and analog.'⁴³ Central to Mindell's study was the distinction between modelling and calculation, and the importance of both in the history of computing. Drawing on the context of computing at MIT, he stressed that for Vannevar Bush, there were two approaches to problem solving: physical (laboratory) modelling; and equation solving. Both approaches were present in Bush's research programmes at MIT, rearing their heads as two distinct technologies: the network analyser (modelling), and the differential analyser (equation solving).⁴⁴

Mindell's work is an important reminder that alternative narratives of computer history offer new insights into the limitations of current understanding.⁴⁵ He suggested that his study 'reconfigures our historical categories' exposing new themes in computer history:

The history of feedback, control, and computing before cybernetics not only chronicles these engineering developments but also reconfigures our historical categories. Until now, historians of computing have concentrated on hardware, biographies, institutions, and cultural representations. Now we might address modeling and simulation, ma-

Rheingold's language, his usage was derived from the computing cultures he studied. Rheingold's observation relates to the suggestion from Campbell-Kelly and Aspray that interactive computing, time-sharing, and the personal computer belonged to a distinct strand of computer history notably different from batch processing systems. See Campbell-Kelly and Aspray (1996) p. 185.

⁴²Mindell (2002) portrayed the history of computing in terms of human-machine systems, and was the first major study to develop these wider themes.

⁴³Mindell (2002) p. 10.

⁴⁴These technologies are exemplified in two papers from the early 1930s: 'Structural analysis by electric circuit analogies' (Bush, 1934), and 'The differential analyzer. A new machine for solving differential equations' (Bush, 1931). The distinction between the two classes were articulated in two keynote lectures – see Bush (1935); Bush (1936).

⁴⁵Mindell (2002) p. 10; Owens (2003) p. 843.

chine representation, ... , the importance of training, the evolution of user interfaces, the creation of the human operator.⁴⁶

The modelling focus employed in this thesis highlights the importance of the relationship between a user and his or her modelling technology, thus addressing a number of Mindell's themes. One area of common ground is how analog computing enabled rich mappings between machine representation and the world. Mindell described how engineers like Harold Hazen saw analog models as a favourable alternative to calculation and the abstractions of mathematical equations:

[Hazen] preferred machine representations with physical likeness to the world. Of course, analog computers also artificially represented the world in a machine. Hazen's own servomechanisms segregated data from their mechanical substrates, but always by substituting one physical quantity for another. Yet when symbolic representations (e.g., numbers or punched cards) replaced physical ones, Hazen became uncomfortable, he was simply unready to plunge headlong into a world where machines manipulated symbols that had no physical analogs to their referents.⁴⁷

Today, with a world dominated by digital computers, it is difficult to imagine research engineers exhibiting such a lack of technological trustworthiness. For engineers like Hazen, analog computing complemented their engineering practices, but digital computing would have to be re-invented as a reliable and trustworthy engineering tool. Essentially, this brings us back to the quote from James Nyce with which we began this chapter – arguments are now framed and won in terms of digital. This is why it made sense for James Small to present his history of analog computing in terms of alternatives.⁴⁸ By shifting the perspective from information processing to a narrative that incorporates modelling, we start to see the true benefits and deficiencies of analog technology as understood in context.

⁴⁶Mindell (2002) p. 321. In these views, Mindell is echoing Mahoney's call to consider 'how we have put the world into computers' – Mahoney (2005) as quoted in Chapter 1, page 11, above.

⁴⁷Mindell (2002) p. 163.

⁴⁸See Small (1994) and Small (2001).

Analog computing as a technology of modelling

Many computing applications belong to a family of modelling technology, and it is clear that analog computers were typically used for these applications before digital was cheap, popular, or fast enough. Armed with a modelling technology perspective, we can return to the history of analog computing. Looking back, the centrality of modelling as an application of analog is clear. However, what did analog users understand by modelling and simulation?

In his account of George Philbrick's ACA⁴⁹ simulator, Holst (1982) claimed that the terms 'modelling' and 'simulation' as used by Philbrick were relatively new, in particular, that the association of the word 'model' with electronic artefacts was a new technical concept.⁵⁰ While Holst's etymology might not be completely accurate, his identification of this shift in meaning does indicate a shift within his own technical culture at Foxboro. Holst was communicating that it was from Philbrick's invention of the Polyphemus that this richer notion of models and modelling became part of common technological discourse. Holst wrote:

A model categorizes a problem, relating its symptoms to causes, suggesting problem-solving approaches, and putting the system into the appropriate perspectives of environment and functional history. As such, a model is often incomplete, existing in its owner's head as an intuitive, often implicit extension of the owner's experience and insight, and relying on the assumption that the present situation is not dissimilar from others previously encountered.⁵¹

This idea of incompleteness resonates with the idea of computer experimentation introduced earlier. Computers were not just for well thought out activities,

⁴⁹See Chapter 2, page 55, above.

⁵⁰Holst describes that at the time when the Polyphemus was being planned, the word model was only used 'for small replicas (such as toy models) and to describe those persons who posed for artists and photographers.' This is not completely accurate. The OED defines one meaning of model to be 'a simplified or idealised description or conception of a particular system, situation, or process that is put forward as a basis for calculations, predictions, or further investigation.' The earliest recorded use of that particular meaning dates from the early 1900s. See 'model, *n.*, and *a.*', *The Oxford English Dictionary*. Draft revision, September 2002. *OED Online*. Oxford University Press. Accessed 1st October 2006. <http://dictionary.oed.com/cgi/entry/00313038>.

⁵¹Holst (1982) p. 144.

but could also be used for speculative investigation. Philbrick's own understanding of modelling is outlined in a short article written for *Instruments and Control Systems*, in which he explains that analog computers could be understood in terms of two kinds of electronic model: 'analyzers' and 'synthesizers'.⁵² Over a number of years he came to realise that his use of analog computing was bridging the gap between both 'modes of study'.

Computers may... be thought of as general-purpose flexible models or *synthesizers*, as well as *analyzers*. The question of names is a controversial issue, involving definitions rather than anything more fundamental, and is most happily resolved by recognition that the equipment under discussion is really a bridge between analysis and synthesis, bringing these two essential modes of study into closer collaboration.⁵³

Analysis and synthesis represented two different approaches to building knowledge. This links to the well established discussions of theory versus experiment: For instance, in the nineteenth century, Lord Kelvin had favoured the experience of creating an artefact or mechanical model that embodied the phenomena he was studying. This was what Philbrick understood as synthesis. Similarly, in a popular introduction to the computer published in 1970, Stuart Hollingdale and Geoffrey Toothill described computing as being either 'equation solving' or 'simulation'.⁵⁴ While they acknowledge both modes to be helpful, they offer a little caveat regarding equation solvers:

The disadvantages [with equation-solving] are the greater human effort required, the danger of introducing unwarranted assumptions, and the danger of introducing and overlooking important secondary aspects of the system.⁵⁵

⁵²Many early analogue computers were called analysers. In 1876 Kelvin developed the harmonic analyser for tides, in the early 1930s the network analyser and the differential analyser were developed at MIT. Although Philbrick's own 1950 patent was for a 'Process analyzer', he also understood the importance of synthesis.

⁵³Philbrick (1972b) p. 108.

⁵⁴Simulations involved an analog computer and were a study where 'there is no need for mathematical manipulation...quantities having a direct physical interpretation.' See Hollingdale and Toothill (1970) p. 80.

⁵⁵Hollingdale and Toothill (1970) p. 81.

So analog computers brought analysis and synthesis together. This is the ‘philosophical’ version of the technological story proposed in chapter 2. There we saw a technical entwinement of two types of machine to establish ‘analog’ technology in the 1940s. As an agent of unification, the computer provided a context in which the two conceptual ideas of analysing (processing) and synthesising (constructing, or making) came together into one concept – computing.

Conclusion

We have seen that the history of the computer is a composite of multiple technological trajectories. When it is used as a modelling medium, computers provide flexible manipulation of complex state. Computing is not solely about calculation or data processing, but also about constructing novel environments with the machine. This is why Rheingold identified Licklider’s vision as so important. The significance did not relate to calculating, but rather to technology with which to think, create, and build.

Analog computers were popular for the kind of applications that Rheingold naturally referred to as modelling. They found application in these areas because they supported novel visualisation and interaction – relating them to the history of scientific instruments. For example, they were a natural tool for the engineer to visualise air flow. During the 1950s, interactive modelling was the domain of analog, while information processing was the domain of digital. For digital to conquer the application domain of modelling, significant advances in visualisation and real-time systems were required. To understand the computer as a design, modelling, and simulation tool requires us to see the history in terms of a broader class of devices incorporating wind tunnels, electrolytic tanks, and analog computers. When Rheingold described modelling as an ‘exotic new use’, what was ‘exotic’ was the application of digital computing in this domain.⁵⁶ To

⁵⁶One of Rheingold’s examples was the use of computing for visualising airflow. However, the technology for this task had been established for over a century in the form of wind tunnels and

use Campbell-Kelly's idea of 'latest technologies': the digital computer, usually construed as the latest technology in the tradition of information processing, also became the latest development in the tradition of modelling technology. The digital computer effectively *became* a modelling machine.

Many factors needed to be in place for a particular application domain to make the transition to digital. From a technical perspective, factors such as speed and complexity dictated the point at which digital became the sensible progression of computing technology. Although this happened quite early on, analog continued to be used in certain applications. For basic calculation tasks, the digital computer quickly overtook the analog. Modelling however, was a far more complicated application and it took, in some cases, nearly thirty years for users to switch.

Digital became dominant principally because it was understood to be faster at equation solving, well-suited to data processing and applicable to time-sharing. However, it was not the tool of choice for modelling and in certain respects analog was superior. Digitalisation was partly the result of superiority in key application domains, perceived superiority, and the understanding that digital would eventually be able to catch up. Part II of this thesis will discuss what happened during that catch up.

analog electrolytic tanks. What was novel was the application of digital computing to replace these uses.

Chapter 4

Origins of analog: conceptual association and entanglement

This transfer of knowledge from one branch of science, electrical network theory, to another branch of science dealing with mechanical and electromechanical structures is one example of a long line of such interchanges that have been going on for over a hundred years. These interchanges are made possible by the fundamental analogies which exist between electrical and mechanical systems and which rest finally on the fact that electrical motions and mechanical motion satisfy the same type of differential equations... such analogies have been very productive in the past and are likely to continue to be so in the future...¹

Previous chapters have highlighted that the concept of an ‘analog computer’ was born around 1940 as a consequence of the conceptual entanglement of continuous computing and electrical analogy. However, it is clear that this pivotal moment was the result of a decade-long entwinement of these two themes. This chapter investigates the conceptual history of electrical analogy – looking at the processes of group formation and enclosure which clustered around this technical idea to establish analog culture.² The concept of ‘electrical analogy’ has an interesting history. During the mid-1920s it was common to talk about analogies between electrical and mechanical systems as a technique for rendering invisible electrical phenomena visible. A well established tradition within nineteenth

¹Mason (1941) p. 406.

²Whereas Chapter 2 focused on machines and the development of technology, this chapter explores the development of analog ideas and the enclosure of the discipline.

century physics, these physical analogies were used to facilitate explanation and understanding, but not to support quantitative modelling.

Electrical analogy evolved through four successive stages: firstly, it began with mechanical analogies of electrical systems (the ‘forward analogy’); secondly, actors reversed these relationships and identified electrical analogies of mechanical systems (the ‘reverse analogy’); thirdly, the terminology of ‘analog’ was introduced; and finally, the jargon shifted from ‘electrical analog’ (depicting a special-purpose set up) into ‘analog computer’ (a generic technology). These four stages were the conceptual foundations behind the emergence of ‘analog’ as a class of technology to be distinguished from digital. These form a story of analog’s enrollment into the technological frame³ of computing.

Once the communities researching electrical analogies had been enrolled into computing discourse, the discipline began to stabilise. In a shift from ‘radical use’ to ‘normal use’, textbooks were published and user communities began to emerge. However, within a decade, many applications of analog began to dry up, giving way to the ‘superior’ technology of digital.⁴ For applications that did not immediately shift to digital, the technology began to be redefined as non-computational.⁵ This initiated the dis-enrollment of analog users.

The establishment of ‘forward analogy’: historical influences from electrical theory

The modelling technique of analogy-making has a well established scientific pedigree.⁶ Central to this heritage was the development of so-called ‘mechanical models’, mental constructions that were popular in nineteenth century British physics.

³‘Technological frame’ is an idea coined by Bijker to capture the thematic whole that clusters around a technology. See page 109, below.

⁴As Small (2001) notes, although digital became the dominant technology, it was not always perceived as superior in every respect.

⁵These returned to being non-computational experimental set-ups.

⁶Hesse (1963), for instance, gives a full account of the use of analogies and models in the history of science.

Lord Kelvin, for instance, was famous for having put great value in the use of models for developing scientific theories. Mary Hesse, one of the first modern philosophers to seriously investigate scientific models, identified their importance as tools that explained the unknown in terms of the known. She notes how Kelvin had employed the ideas of heat flow, an established theory, to model the field theory of electrostatics. Similarly, billiard-ball models of gases, and the 'model of gravitating particles' were used to account for electricity and magnetism in terms of well known macroscopic phenomena. While there is evidence of nineteenth century physicists using electrical systems as a model of, for instance, chemical theory, Hesse writes that: 'Mechanical models were on the whole preferred during the nineteenth century.'⁷

As an example of this 'culture of analogy', the following quotations from Kelvin's *Lectures on Molecular Dynamics*⁸ demonstrate the high profile he gave to analogies and models. In these lectures, he often spoke of the correspondences between electrical and mechanical systems and saw the existence of such a model as a demonstration of understanding:⁹

My object is to show how to make a mechanical model which shall fulfill the conditions required in the physical phenomena that we are considering.... At the time when we are considering the phenomenon of elasticity in solids, I want to show a model of that. At another time, when we have vibrations of light to consider, I want to show a model of the action exhibited in that phenomenon. We want to understand the whole about it; we only understand a part. It seems to me that the test of 'Do we or do we not understand a particular subject in physics?' is 'Can we make a mechanical model of it?' I have an immense admiration for Maxwell's mechanical model of electro-magnetic induction. He makes a model that does all the wonderful things that

⁷Hesse (1970/1962) pp. 22-23.

⁸The so-called *Baltimore Lectures*. This 'master class' of nineteenth century physics was delivered in 1884 at the Johns Hopkins University in Baltimore. It is from these lectures that some of Kelvin's most famous quotations on models derive, Kelvin actively employing both theoretical and concrete models throughout this series of twenty lectures. (Kargon, 1987, pp. 1-3).

⁹Equating modelling with understanding was a British trend that evoked criticism from the continental scientific method, particularly from the philosopher of science Pierre Duhem. Duhem was scornful that British physicists equated understanding with identification of a model. See Duhem (1954/1906) pp. 71-72.

electricity does in inducing currents, etc., and there can be no doubt that a mechanical model of that kind is immensely instructive and is a step towards a definite mechanical theory of electro-magnetism.¹⁰

I never satisfy myself until I can make a mechanical model of a thing. If I can make a mechanical model, I understand it. As long as I cannot make a mechanical model all the way through I cannot understand; that is why I cannot get the electro-magnetic theory... I want to understand light as well as I can without introducing things that we understand even less of.¹¹

As electrical theory became better understood and accepted, there was less need for understanding to be framed in mechanical terms. Indeed, those with a strong understanding of electrical circuits began to use electrical models to represent mechanical systems. So began an exploration of this reverse analogy, research which developed significantly around 1900. For example, in the eleventh edition of the *Encyclopaedia Britannica* (published 1911), Ludwig Boltzman¹² referred to the reverse analogy in his article on models and modelling, noting that models were not necessarily mechanical:

Sometimes... [non-mechanical] forces are at work in models for purposes of investigation and instruction. It often happens that a series of natural processes – such as motion in liquids, internal friction of gases, and the conduction of heat and electricity in metals – may be expressed by the same differential equations and it is frequently possible to follow by means of measurements one of the processes in question... we are able by measuring the electrical conduction in the model to determine at once the numerical data which obtain [sic] for the analogous case of internal friction, and which could only be ascertained otherwise by intricate calculations.¹³

Although such analogies were familiar to scientists at the turn of the century, it was not until around 1920 that engineers began to make clear reference to the

¹⁰William Thomson, *The Baltimore Lectures*, Lecture 11 (Thomson, 1987/1884, p. 111).

¹¹William Thomson, *The Baltimore Lectures*, Lecture 20 (Thomson, 1987/1884, p. 206). For Kelvin, Maxwell's electrical theory was lacking a suitable grounding in 'sensory reality' (Smith, 2004). Despite this, Maxwell's analogy was for many developers of analog computing the conceptual heritage of what they were doing. This was true for researchers working on electrolytic tanks.

¹²The contributors to the 1911 edition of the *Britannica* were the leading scholars of the day. Boltzman was a famous physicist.

¹³Boltzmann (1911) p. 640.

reverse analogy as part of their analytical tool kit. It was within the context of American engineering that applications of electrical analogy became established and stabilised.

Analogies in American science and engineering

The state of knowledge within the American scientific scene during the early decades of the twentieth century is captured in the pages of the *Journal of the Franklin Institute*. In terms of electrical analogies, one noteworthy paper is a 1908 article by Edwin Northrup, an American physicist and inventor of electrical instruments.¹⁴ Mirroring contemporary usage of models, Northrup's analogies were more educational than computational.

Northrup's discussion of analogies is interesting because he not only articulated the two-way nature of the analogy, but also assigned symbols to signify cross-domain equivalences (such as ' $\Omega = \text{Mass of Particle}$ '¹⁵) and tabulating the mappings of different analogies (see Figure 4.1). His work was key because it stressed the idea that an analogy could be based on equations (symbolic) rather than situated in the physical. As an instrument maker, Northrup was interested in practical science and engineering culture; his claim was that establishing analogies would result in 'brain economy', an improved 'management of the mental

¹⁴A physicist interested in electrical theory, Edwin Fitch Northrup (1866–1940) graduated from Amherst College in 1891 and from Johns Hopkins University in 1895 with a doctorate in the measurement of capacitance. His career followed an academic-industrial mix: beginning with an associate professorship at Texas before working as an engineer in the telegraph industry. In 1903, he joined the businessman and inventor, Morris E. Leeds, to establish Leeds & Northrup Co., a manufacturer of scientific instruments. In his role as vice-president, Northrup developed a number of electrical instruments and received a number of patents. It was while working at Leeds & Northrup that he published his ideas of electrical analogy. He left the firm in 1910 to take up a professorship in Physics at the University of Princeton where he researched motions of a liquid vortex. During the following decade, Northrup published two textbooks on practical physics – *Methods of measuring electrical resistance* in 1912 and *Laws of Physical Science* in 1917. In the late 1930s he published a science fiction novel about space travel and received a DSc. See Northrup (1895); Amherst College (1951) p. 73; Northrup (1912) preface; IEEE (2007); Northrup (1937).

¹⁵Northrup (1908) p. 17. Such statements highlight the idea that the symbol Ω , normally representing an electrical property could equally represent a particle's mass through exploiting the underlying analogy.

PHENOMENON	Ω	ϵ	a	μ	$\frac{d a}{d \mu}$	F_1	Π
Linear motion of a particle.	Mass of particle.	Linear distance.	Linear velocity.	Time.	Linear acceleration.	Constant force acting.	$F_1 \epsilon =$ work done by force.
Circular motion of a particle distant, r , about a center, O .	Moment of inertia about O .	Length of arc.	Angular velocity	Time.	Angular acceleration.	$Fr =$ Moment of force.	$F \theta r =$ work done by force.
Flow of electric current in a coil of wire that has no resistance.	Self-Induction of coil.	Quantity of electricity.	Instantaneous Value of Current.	Time.	Change in current with the time.	Constant E. M. F.	$E \int d e =$ work in moving Elec. in circuit.

Figure 4.1: A table of analogies between symbols in a differential equation system. Within a few years, many technical engineering papers would contain these representations as a popular way of conveying the idea and extent of an analogy. Source: Northrup (1908)

household'.¹⁶

[I]n studying physical science, a fruitful brain economy will best result by establishing the habit of mentally associating phenomena, belonging in groups and classes, according to their natural physical connections and the analogies that exist among them.¹⁷

Just like Kelvin, Northrup's principal use of analogies was to apply well-understood phenomena to shed light on the unknown. However, his ideas were not associated with mechanising calculations or replacing computing labour; it was not until the mid-1920s that these *computing* motivations would become common. In the meantime, the analogy drawn between an (unknown) electrical system and a (better known) mechanical system was central in electrical teaching. Much was written on the topic throughout the engineering literature of the day. For example, in 1926 *The Engineer* – the principal journal of British engineering – ran a weekly column on 'Models and analogies for demonstrating electrical

¹⁶Northrup (1908) p. 2.

¹⁷Northrup (1908) pp. 2–3.

principles'.¹⁸

Ultimately, teaching aids were all the forward analogy could offer. Around the same time that *The Engineer* was reviewing these various forward analogies, engineering culture was beginning to accept a new kind of analogy: reversing the familiar relationship between electrical and mechanical systems, and applying electrical systems to aid the investigation of mechanical systems.

Clifford Nickle and Vannevar Bush: modelling with the reverse analogy

The early uptake of electrical analogy as a modelling medium came from American engineers. This explains why analog computing became such an important tool for this user group. Salient amongst the famous engineers of this period is Vannevar Bush, from whose research programmes the network analyser and differential analyser – both archetypal analog computers – would emerge. Bush's own engineering approach favoured the employment of analogies alongside traditional analysis. During the 1930s he would begin to articulate the idea that both calculation and modelling were important and complementary approaches to what he called 'instrumental analysis'. This blend of empirical and mathematical was embedded into the research culture he directed at MIT.

Around 1920, the analog culture began to crystallise and Bush was at the centre of this.¹⁹ Before he went to MIT, he published an early example of his approach in an investigation on Gimbal Stabilization (Bush, 1919). His technique used an electrical system whose formulae were, for Bush, '...much more convenient' than those for the mechanical problem. His paper included equivalence tables like those used by Northrup, and presented analogies with a mix of dia-

¹⁸Anon. (1926). This series on 'models and analogies' ran for 19 weeks and covered a whole range of set-ups from simple analogs of current flow to models of electrical capacitance and resonance.

¹⁹As a student, Bush attended Tuft's college, a school that 'stressed the value of graphical representation and intuition rather than abstract rigour in mathematics and physics' (Small, 2001, p. 40).

grams and text.²⁰ Widespread acceptance of the reverse analogy as an alternative to engineering calculations occurred during the 1920s with the publication of a seminal paper by Clifford A. Nickle. Described in the following pages, Nickle's work extended previous modelling practices and proposed a coherent approach to using electrical knowledge as a problem solving tool.²¹

Establishing a modelling medium based on the reverse analogy: the work of Nickle and Doherty

Clifford A. Nickle was a quiet design engineer working at General Electric. Alongside a 'magnificent depth' of analytical insight, Nickle also had a photographic memory and a strong practical familiarity with electrical circuits.²² Within General Electric, he began working with R. E. Doherty, who was then researching circuit theory. Doherty had, a year previously, published a paper establishing what became known as his Theorem of Constant Flux Linkages, and between 1924 and 1933 he and Nickle made significant contributions to the emerging discipline of synchronous machine theory. Part of an empirical tradition in early electrical engineering, researchers such as Doherty and Nickle had to rely on technical insight and modelling approaches to complement the analytical methods they were developing. As Bewley (1963) put it:

[Doherty and Nickle] laid the ground work for the generalizations and refinements that would follow. Their procedures have been called 'brute force methods' because they plowed through to final results without benefit of general differential equations or the transformation of reference frame concepts or operational calculus or symmetrical components. But they got results! And no more advanced theory has yielded numerical values of much greater accuracy...

²⁰The analogies were derived by manipulating equations either side of a vertical line, the left hand side denoting the electrical and the right hand side denoting the mechanical. As Bush wrote: 'Considerable care must be used, in interpreting this result on the mechanical system, to obtain exact analogues.' Bush (1919) p. 202.

²¹See Nickle (1925).

²²Bewley (1963). Bewley wrote that Nickle was a 'quiet, unassuming and lovable man of many interests'. Alongside A. R. Stevenson, Nickle helped establish the General Electric's 'Advanced Engineering Course', a graduate program noted for its rigour. See Owen (1999) pp. 11-12. Nickle was also involved in the industrial colloquia for Electrical Engineering students held at MIT during 1927 and 1928. See Anon. (1927, 1928).

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V. BUSH.

[J. F. I.]

If I_1 is the vector current in the inductance, we may write the relation between I_1 and I by considering that I divides into parts proportional to the admittances of the two branches. That is

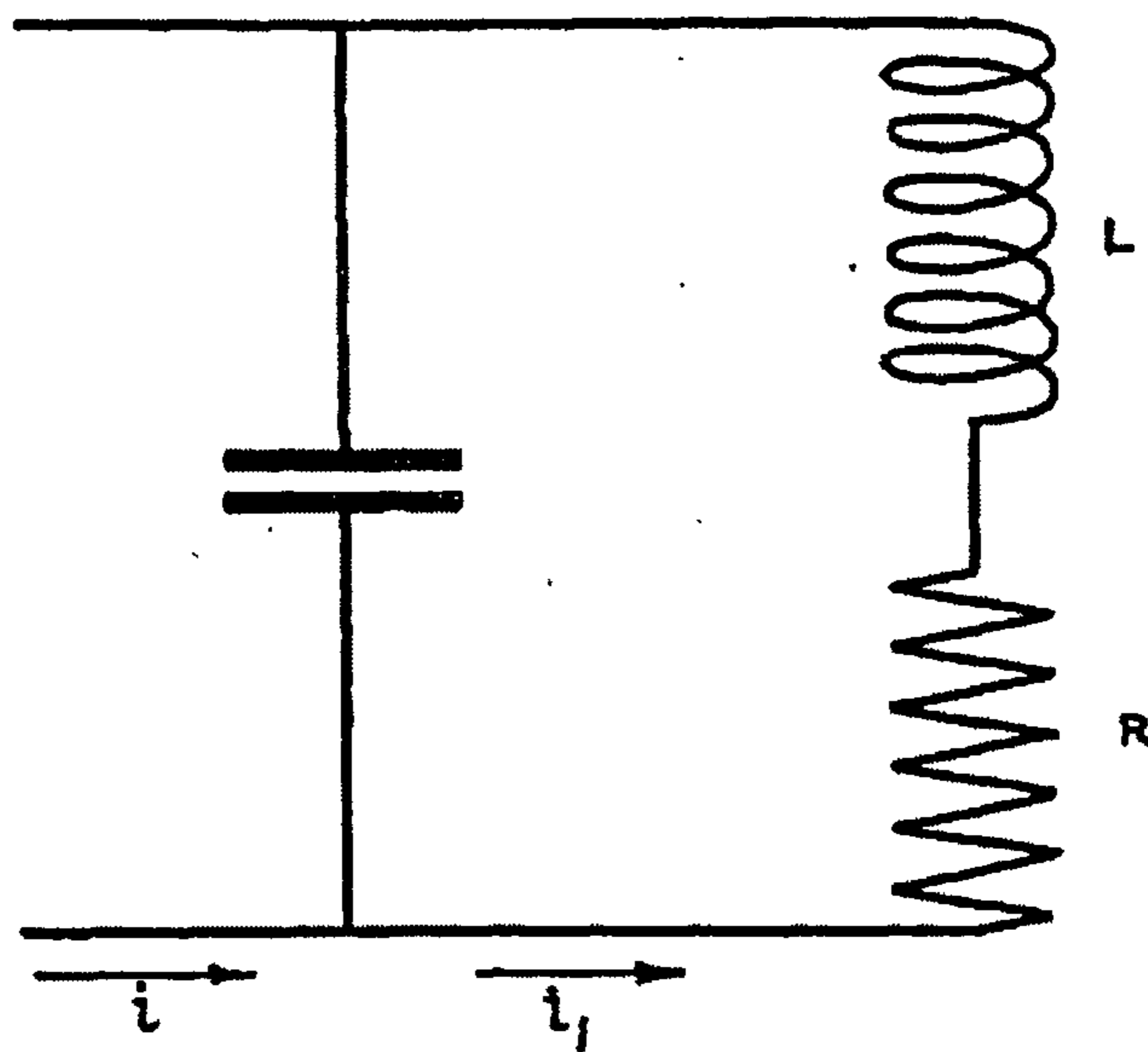
$$I_1 = I \frac{\frac{1}{jC\omega} + \frac{1}{R + jL\omega}}{R + jL\omega} = I \frac{1}{1 - LC\omega^2 + jRC\omega} = \frac{jQ\omega}{1 - LC\omega^2 + jRC\omega}$$

TRANSFER TO MECHANICAL SYSTEM.

Considerable care must be used, in interpreting this result on the mechanical system, to obtain exact analogues.

We have already set the maximum quantity Q analogous to

FIG. 3.



the maximum displacement A . Hence the current in the leads is analogous to $\frac{dx}{dt}$ or \dot{x} . If a displacement A is produced, and the centre of mass is simultaneously prevented from leaving the centre line, there will be, for a small angle θ , a back force produced equal to $\frac{mg}{b} A$, as can be seen from Fig. 4. Analogously in the electrical circuit if a charge Q is introduced through the mains, and the branch circuit is open so that this affects the condenser only, there will be a back electromotive force $\frac{Q}{C}$. We thus have C analogous to $\frac{b}{mg}$.

Figure 4.2: Extract from Bush (1919) showing the role of diagrams, equations, and description in the derivation of an analogy.

[Their approach included] relentless appeal to the underlying physics; a profound understanding of pertinent assumptions, relationships and interpretations; [and] a professional appreciation of the practicality of definitions, methods and results.²³

As part of this experimentalist culture, Nickle employed a variety of problem solving techniques and understood their limitations. In particular, he thought that existing graphical approaches for solving the complex mathematics of power systems were reaching their limits.²⁴ Harnessing technology to create and observe a model, his approach was to ‘have an “equivalent electrical circuit” solve the problem, and the oscillograph plot the solution.’²⁵ This seminal work presented an extensive set of example ‘equivalence circuits’, each modelling the different common classes of system, and made the clear claim that electrical analogies could be used as a generic problem solving tool.²⁶ Following traditions in earlier work by Bush, his contribution was to claim that an analogy could be not just an alternative to solving equations, but an alternative approach to problem solving – a methodology that allowed ‘the mathematical processes’ to be ‘eliminated altogether’.²⁷ An embryonic form of analog computing, Nickle’s development of the reverse analogy signified the acceptance that electrical circuits were a generic modelling medium. The approach was quickly adopted, and by the 1930s the use of electrical analogies was abundant in many areas of engineering research and began to expand into new domains.

Of course, Nickle was not the only pioneer of these techniques, and much appeared around the same time and in quick succession of his work. The scholarly climate of the late 1920s was a lively period with engineering becoming more and

²³Bewley (1963) cited in Owen (1999) p. 12.

²⁴He cites Bush and Booth (1925) as an example.

²⁵Nickle (1925) p. 854.

²⁶See Nickle (1925). Commenting on Nickle’s work, Karplus and Soroka (1959) speak of this being the ‘fundamental paper on the application of electrical circuits to the solution of problems’ from which the ‘field of experimental analysis was rapidly developed.’ (p. 265). Other citations by contemporaries such as Pérès (1938) confirm its significance.

²⁷Nickle (1925) p. 844.

more quantitative.²⁸ Essentially, Nickle's publication carved out a space within this territory for analogy methods and, within a few years, this approach became a hot topic from which the key-phrase 'electrical analog' would emerge.

An example of an enrolled technical culture is the use of 'electrical analogy' within sound and vibration research. Previously, this field had used its own descriptive categories but during the late 1920s, publications began to refer to 'electrical analogy' by name. For instance, in a lecture given to the Physical Society's Annual Exhibition of 1928, one actor claimed that the design of the gramophone 'owe[d] much to the theory derived from analogies between mechanical and electrical systems'.²⁹ As another example of this convergence of terminology, two years later, another researcher writing in the *Review of Scientific Instruments* would highlight the importance of 'analogous relations' in the study of vibrating systems:

The progress in recent years has been largely due to a clear understanding of the analogous relations which exist between mechanical and electrical vibrating systems, and to the application of already known electrical theory modified to suit the mechanical case. Inductance, capacity and resistance in electrical systems are analogous to mass, reciprocal stiffness and resistance in mechanical systems.³⁰

Thus 'electrical analogy' had become a focal point around which a variety of different research programs could associate with. Between 1925 and 1935, the field of electrical analogy was developed from scattered research pursuits into an enclosed discipline.³¹ Engineers could now refer to an 'electrical analogy' as a concrete technique of investigation. For example, in 1939, S. B. Bailey submitted an MSc thesis in engineering to the University of London entitled: *A method of finding frequencies of torsional vibration using an electrical analogy*.³²

²⁸In his investigation of analog computing and engineering culture, Small notes the centrality of shifting priorities of mathematics in the negotiation of the analog's place.

²⁹See Whitaker (1928) p. 41.

³⁰Oliver (1930) p. 318.

³¹Other examples of enclosure include the work of Clark (2002). The idea of a key concept initiating an enclosure has been explored in the social sciences by Dyer (2001) and the same can be seen in the physical sciences – see Caron (1988).

³²His thesis was a collection of various investigations using analogous circuits (Bailey, 1939).

Another example is Pérès and Malavard in Paris. Their decision to establish a Department of Electrical Analogy (Le Laboratoire des Analogies Electriques) in 1932 demonstrates that electrical analogy had become a discipline in its own right.³³

By the late 1930s, the reversal of the electrical-mechanical analogy was well established, initiating the process which would lead to the formation of 'analog computing' around 1940. As enclosure progressed, the discipline gathered momentum, actively enrolling scattered disparate research programmes into the discipline of electrical analogy.

Stabilising the field: Bush's classification schemes and their enrolling function

While Nickle had established the point of convergence, it was Bush's enthusiasm that resulted in the enrollment of his MIT Programme and other research projects into this new discipline.³⁴ When Bush began organising his research in terms of electrical analogy, others followed suit.³⁵

By 1934, Bush was articulating a clear idea of electrical analogy. He explained that there were three 'principal methods': mathematical investigation, physical modelling (he gave the example of a shaking table); and thirdly 'an analogous electrical circuit.'³⁶ To study structural strain of a bridge, he derived correspondences between the structural stresses and the physical behaviour of an electrical network using transformer winding ratios to program the relationships between vertical and horizontal stresses. Later that year, he gave a keynote address at the Fourth International Congress on Applied Mechanics, in which he set down a taxonomy of computing machines and a clear articulation of analogy. At this

³³Malavard (1947) p. 247. See Chapter 2, page 54, above.

³⁴Akera (2007) notes how Bush had realised that after the success of the differential analyser, computing machines could become research programmes in their own right (pp. 30–33).

³⁵This occurred through a series of high profile papers in the mid-1930s. It was in these papers that Bush heralded Nickle's work as seminal, directing the reader to the work of Nickle and also a 'friction analogue' developed by Skilling. See Bush (1934) p. 291.

³⁶See Bush (1934) p. 289.

point, Bush distinguished between his general purpose differential analyser for solving ordinary differential equations and the special purpose analogy methods for solving partial differential equations.

[The differential analyser] has now been in successful use for several years in the solution of ordinary differential equations. Devices for solving partial differential equations in a general manner are completely lacking, although they would be enormously useful. The only representatives of this class apply to special equations, usually with special boundary conditions. These are ‘analogy’ devices, that is, they enable the study of one system by setting up an easily measured analogous system controlled by the same equations. All equation solvers partake somewhat of this nature.³⁷

The following year, Bush was invited to deliver the American Mathematical Society’s Josiah William Gibbs Lecture.³⁸ In this lecture, he explored his idea of ‘instrumental analysis’, further developing his taxonomy of computational aids. These taxonomies give us a real insight into how pioneers perceived the structure of their discipline. Bush’s taxonomy was based on analogy rather than continuity. However for the American physicist John Atanasoff, these two facets of analog became entwined and conflated.³⁹ These associations shaped the perception that electrical analogies were not just a modelling medium, but were a generic problem solving technology. It therefore makes sense that by the late 1930s, people were seeking generic analogs. For instance, Myron Pawley, a faculty member of the Colorado School of Mines, aimed to establish generic analogies. His work

³⁷Bush (1935) p. 6.

³⁸See Bush (1936). The Gibbs lecture discusses the applications of mathematics and has been delivered by many eminent speakers. A year earlier, the lecture was given by Albert Einstein (Anon., 2007b).

³⁹Recall that in 1941, Mauchly would attribute his analog-impulse distinction of computer technology to Atanasoff. Following Atanasoff’s classification, Mauchly concluded that an analog had to employ ‘some sort of analogue or analogy, such as Ohm’s Law or the polar planimeter mechanism to effect the solution of a given equation’. Here ‘analogue’ merges the idea of electrical analogy and a continuous calculating device. Atanasoff was familiar with electrical analogy. In the early 1930s he developed an instrument called the Laplaciometer intended to solve Laplace’s equation – in particular he was working with his graduate student Lynn Hannum. The Laplaciometer consisted of a cube of wax which was shaped to model the problem. See Burks (2002); Murphy and Atanasoff (1949). Atanasoff began to move towards digital technology during the second half of the 1930s (Randell, 1982, p. 294).

suggested a notation for representing the analogies between generic systems of mechanical components and networks of electrical components.⁴⁰

At this point the word 'analogue' was still very much a descriptive adjective rather than a classifying noun. While some research was published under the banner of 'electrical analogy', it remained common for alternative jargon such as 'electrical equivalent', or 'equivalent network' to be used. For instance, one paper describing a resistance-network model does not refer to analog or analogy but instead to 'setting up the electrical equivalent.'⁴¹ Similarly an article describing how Wheatstone bridge circuits could be used as a 'computing device' (Ergen, 1947) contained no reference to analogy or to two classes of computer. However, the emergence of the electronic digital computer during the 1960s triggered a re-labelling of the older technologies.⁴²

Positive association with computing – computational rhetoric and analog oddities

The adoption of the label 'analog computing' created a technical genre into which other technologies could be enrolled. One example of this is the Bruce reservoir analyser (described in Chapter 6). When William A. Bruce, an American physicist, first developed this analyser in 1943, he described it as an 'electrical counterpart'.⁴³ It was only after successive analysers had been invented and associated with analog computing that the Bruce analyser was labelled an electrical analog and later an analog computer.⁴⁴ A history of Petroleum Engineering written in

⁴⁰Behind his motivation for finding a mechanical analogy for the 'general linear electrical network' was the idea that engineers knowledgeable in the theories of electrical networks would be able to 'recognize and analyze' mechanical systems through studying networks. See Pawley (1937).

⁴¹Hughes and Wilson (1947), p. 103.

⁴²As described in Chapter 2, it was in the context of the ENIAC's unveiling in 1946 that Douglas Hartree would first refer to analog and digital (Hartree, 1946, p. 500). With the subsequent unveiling of the EDSAC in 1947, the EDVAC in 1949, and the publication of early monographs, the analog-digital classification became foundational terminology. See Hartree (1947); Hartree (1949); Murray (1948)

⁴³See (Bruce, 1947/1943, col. 2).

⁴⁴Patents for subsequent analysers described the technology as an electrical analog – see Aronofsky (1958/1951); Loofbourrow et al. (1957/1952). By the 1950s reservoir analysers were

1961 described the Bruce analyser as an analog computer (Carter, 1961, p. 1097). Thus what had begun as a physicist's electrical model had, through redefinition, become computational.

As a result of this redefinition into the technological frame of computing, analog computing projects benefited from being part of the 'computer age'. For a variety of reasons, ranging from funding to marketing issues, a whole variety of devices started to be labelled 'computers'. This led to a number of analog oddities. The Phillips machine and the Jerie computer fall into this category. These technologies were quite different from other mainstream analog computers of the time in that they were not electronic and were used more as visual aids. Instead of being calculating aids in a classical sense, their connection to analog computing can seem a little loose. However, both were identified by contemporary actors as analog computers, so these devices are analog by association.

Like many of the analog computers described so far in this account, the machine developed by the economist A. W. Phillips provided a physical embodiment of a system of differential equations. The difference between his machine and others is that he represented variable quantities as levels of fluid.⁴⁵ In the Phillips machine, the flow of money around an economy maps to the flow of liquid around the machine. Proportions of liquid could be routed off into storage vessels representing, for instance, national savings; government borrowing was modelled by drawing liquid from a reserve tank.⁴⁶

Another example of an enrolled technology is a 'computer' developed for photo-

routinely being classed as analog computers (Montague et al., 1956, p. 12). When Birks, a BP reservoir engineer, summarised the development of reservoir analysers he introduced them as analog computers. See Chapter 6, 160, below.

⁴⁵Phillips (2000); Morgan and Boumans (2004); and Hally (2005) pp. 185–205.

⁴⁶Although it is frequently cited as an analog computer, recent scholarship has questioned whether this is really a computer in a general sense (Swade, 2000). But we need to hold this in tension with those actors who understood it as computational in context. If it were construed a computer in context, then it should be considered part of the discourse of computer history. The purpose of this invention was to produce an illustrative model of Keynesian economics. See Chapter 4, page 107, below. Swade (2000) described how the Phillips machine (or MONIAC) is perhaps not a computer at all (owing to it being more a dynamic illustration than an artefact for computation).

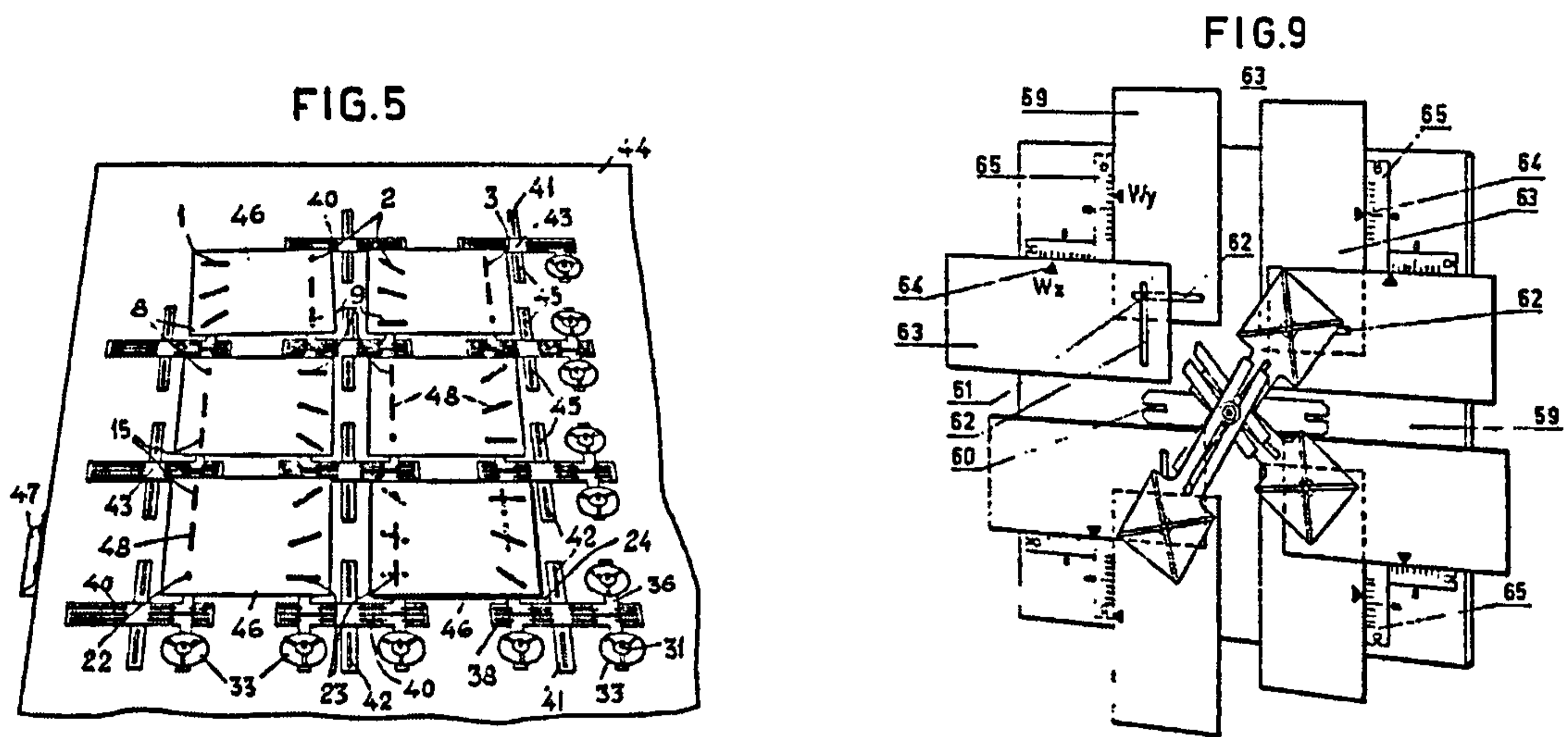


Figure 4.3: Illustrations of the Jerie Analogue Computer. Source: Jerie (1960/1958). The Jerie computer used a mechanical design in which the unknowns of the equations were represented by elastic links between plates (See also Jerie, 1965/1960). The various aerial photographs were transferred on to overlapping plates and the control points of each plate anchored together. The plates were free to move within the constraints of their elastic connections, eventually stabilising on a solution that best satisfied the positional constraints.

togrammetry in the 1950s and designed to resolve geometrical constraints. Photogrammetry is the application of photography to support mapping and surveying and was first pioneered during the late nineteenth century. The key principle is that a set of aerial photographs can be used to create a map if they share a common set of identifiable 'control points'. Matching up these control points requires the solution of a large system of simultaneous equations. The analog computer proposed by Professor H. G. Jerie of the International Training Centre for Aerial Survey (ITC) in Delft, the Netherlands, was a special purpose, mechanical device for solving these problems. The computer (see Figure 4.3) was patented by the ITC and was marketed and manufactured with reasonable success.⁴⁷

⁴⁷Jerie (1957-1958); ITC News (2001); Jerie (1960/1958); Jerie (1965/1960).

Formation of an analog user culture

So far we have described the evolution of analog computing's surrounding culture, and to account for these observations, the technological theory proposed by Bijker is helpful. In his historical study of Bakelite, Bijker suggested a 'theory of invention' revolving around his idea of a 'technological frame'. Each social group has its own technological frame, an aggregate of theory, practice, artefacts, and expectations of use.⁴⁸ In terms of his frames, periods in the history of a technology map to one of three types of situations. Firstly a situation where no social groups or technological frames are dominant; secondly a situation where one group is dominant; and finally, a third where two or more social groups compete for dominance.⁴⁹

These phases offer some useful explanation of the development of analog culture described so far. Initially, we saw how there was no core identity surrounding the devices which later became members of analog computing's technological frame. This is a type I situation, where there was a disparate group of calculation and modelling devices, and the co-existence of the two identities of analogy and continuity. Bijker notes that innovation in this type of situation is often 'radical redefinition' (anything is open to change because there is no central identity restricting classification). In the period between 1910 and 1930 we see a movement towards a Bijker phase II. This period begins with two established genres of technology (representing analogy and continuity) that were entwined into a single technological culture. It is in the 1930s that we can see this computing culture develop, leading to what Mindell described as 'analog's finest hour', a period where analog faced little competition.⁵⁰

⁴⁸This approach is appealing because the 'meanings attributed to an artefact' are pivotal in the technological story. As the members of a community attribute meanings to technology, they shape the practices of other group members. For Bijker, this 'interactional nature' is fundamental in the formation and disappearance of technological frames. See Bijker (1992).

⁴⁹Although there is a logical progression between these situations or phases, Bijker demonstrates that the precise journey through them often differs from technology to technology.

⁵⁰Mindell (2002) p. 231.

However, with the emergence of digital technologies, there became a need to identify analog computing as something distinct and different from the rest of the field. Thus, around 1940, a period of analog and digital computing was established. In this (type III) phase, there emerged two types of computing, each with various merits that (in a certain sense) were portrayed as competing technological solutions. This third type of phase explains why James Small chose to frame his history of post-war analog computing with the controversies between analog and digital. Eventually, the history progressed to a state where digital technology would become dominant, but as we shall see below, this in turn initiated a redefinition of analog's identity.

Up until this point, users and inventors were seldom distinguished: the people involved in the modelling, simulation, or computation were also those developing improved techniques or technology. During the 1950s analog computers started to be manufactured commercially, creating a new community of analog users.⁵¹ In understanding what this analog culture looked like, textbooks and technical newsletters offer some interesting insights. One interesting user community is GAP/R and their trade publication *The Lightning Empiricist* (published aperiodically between 1952 and 1971).

⁵¹A useful indicator of the developing analog culture is the emergence of textbooks which began to appear around 1950. Popular early texts on analog computing included Korn and Korn (1956/1952), Johnson (1956), and Soroka (1956). Michael E. Fisher, an analog research student of the 1950s, commented that prior to 1953 'the art of analogue computing had already reached quite an advanced state.' And that 'at least one textbook had been published' (Korn and Korn). However, by the completion of his thesis in 1957, there were many textbooks he could cite, and in the early 1960s he contributed his own. See Fisher (1957) p. 1.1. Initially these texts were geared to electrical engineers, detailing the inner workings of the computer circuits. Later – in a trend towards programming – the texts became more mathematically focused, presenting analog computing to the general scientific user. For example, one of the last successful textbooks (Charlesworth and Fletcher, 1974) replaced computing components with black boxes, and also encouraged the use of abstract 'machine units' rather than voltages to represent numbers. The use of machine units (MUs) meant that an analog 'program' could be easily transferred between different types of machine.

George Philbrick and Lightning Empiricism: an exemplar of analog culture

In a recent textbook entitled *Analog Circuit Design: Art, Science and Personalities*, Williams (1994) included a reprint of a 1960s article by George Philbrick. This reprint, with its wordy title of ‘Analog Yesterday, Today and Tomorrow Or: Metaphors of the Continuum’, was originally published in a trade journal named *The Lightning Empiricist*.⁵² By way of explanation of this article’s inclusion, Williams wrote that it would be ‘difficult to imagine a *real* guide to analog design without George Philbrick’.⁵³ This sentiment is echoed across the history of electronic analog design.⁵⁴

Philbrick’s technical career had its origins in the simulation and control culture of the Foxboro Corporation where he had simulated mathematically complex systems with causal feedback loops. This background meant that Philbrick was an advocate of high-speed analog computing applications supported by repetitive operation. In order to provide a modelling system which could be assembled in a highly customised fashion, GAP/R components were sold as individual ‘black boxes’.⁵⁵

Perhaps most significant were Philbrick’s (often rhetorical) writings describing his perspective on the relationship between modelling, computing, and simulation.

⁵²This was an extended version of a shorter piece published in the journal *Simulation*. See Philbrick (1963) p. 3.

⁵³Williams (1994) p. 1.

⁵⁴Holst (1982) described Philbrick as a ‘truly innovative and goal-oriented engineer’ who was ‘still remembered by old-timers as a unique, creative personality’, and Paynter (1975) identified him as ‘the father of modern operational amplifiers and analog computing’. Elsewhere he was described as ‘one of the most far-sighted engineers of our time’ (Philbrick, 1972a, ed. comm.), and in 2002, the magazine *Electronic Design* included him in their fiftieth anniversary ‘Hall of Fame’ (Anon., 2002a). See also the writing by Dan Sheingold in editorial articles of *Analog Dialogue*, the trade publication of Analog Devices Inc., available <http://www.analog.com/analogdialogue/>; and the material on the Philbrick Archive website (managed by Jo Sousa) <http://www.philbrickarchive.com/>.

⁵⁵Philbrick pursued what Holst would later describe as a ‘maverick’ approach to industry: GAP/R carried on with alternating-current-coupled computing units even though the ‘industry norm’ became direct-current-coupled; they also pursued the view that the analog computer should be a fully modular set of black boxes rather than the ‘patchboard-oriented’ computers offered by other manufactures. See Holst (1982) p. 156. Holst described these black boxes as ‘flexible and effective engineering analysis tools’ (Holst, 2000, p. 58).



Figure 4.4: George Arthur Philbrick. Source: http://www.philbrickarchive.org/george_arthur_philbrick.htm.

Philbrick and his colleagues coined the term *Lightning Empiricism* to convey the rapid experiential quality of their application of these high speed, modular components. GAP/R began publishing *The Lightning Empiricist* as an aperiodical trade journal through which they could voice their ideas and communicate with other 'devotees of high-speed analog computation, those enthusiasts for the new doctrine of Lightning Empiricism'.⁵⁶ The first issue was dated June 1952 and distributed free of charge to interested parties. A number of issues were produced in the 1950s and it was published quarterly between 1963 and 1965 (before disappearing again until 1969).⁵⁷

The central aspect of this particular approach (or 'doctrine' as Philbrick called it) was that inexpensive electronic models could be constructed to explore phenomena and that their physicality would provide a rich platform upon which to work through certain ideas:

But the biggest advantage of operational modelling, even at the maximum level of abstraction in this theoretical stage, is that of Reality. Many a promising principle – or group of principles – may be found wanting by such representation, with the result of large savings in development cost and time. This is, of course, what we have chosen to call Lightning Empiricism.⁵⁸

GAP/R were the first company to manufacture a commercial operational amplifier with their K2-W model. Although the concept of the operational amplifier had already been invented, Philbrick appears to have arrived at the same basic concept independently. Reflecting on this, Philbrick understood the development of this component as an extension of his modelling activity:

I might as well admit immediately that I do not claim to be the original inventor of the operational amplifier. It is true, however, that I

⁵⁶Frontmatter. *The Lightning Empiricist*, 1(1), 1952.

⁵⁷Anon. (1969). For many years the editor was Dan Sheingold, a Vice President of GAP/R, who in later years edited the trade publications of Analog Devices Inc. and in particular, their magazine *Analogue Dialogue*. Although few of the articles in *The Lightning Empiricist* were attributed to an author, Sheingold's distinctive writing style can be seen throughout the publication record.

⁵⁸Philbrick (1969) p. 24.

The Lightning Empiricist

A journal for devotees of high-speed analog computation, those enthusiasts for the new doctrine of Lightning Empiricism, publishable aperiodically and distributed without charge by Geo. A. Philbrick Researches, Inc., 230 Congress Street, Boston 10, Mass. and offering items of interest and value on such computational topics as applications, techniques, and new or improved components.

ISSUE NO. 1

GAP/R

JUNE, 1952

AN EXEMPLARY APPLICATION

One of the many purposes of this journal shall be to offer its readers, in each issue, an important and authoritative article on the use of high-speed analog equipment to further some particular area of knowledge.

These treatments shall be contributed by outstanding thinkers in each field of application, so that we shall serve such fields fundamentally and not merely publicize the computer per se.

In this issue we are proud to present the first of a series on the dynamics of governing. The author, a recognized expert, is Dr. Henry M. Paynter, Assistant Professor of Hydraulic Engineering at Massachusetts Institute of Technology.

The Analog in Governor Design, I A Restricted Problem

by Prof. Henry M. Paynter

A prime-mover governor like other control mechanisms should possess the twin qualities of rapid response and stability. Ideal governors would operate in a power system so as to maintain constant frequency under changes in the electrical load. Of course this is not attained in practice, since all the governors operate from a frequency or speed error and it is only possible to adjust their settings so that the prime movers will reach a new equilibrium as rapidly as possible after a change in load. In the governing problem, then, the basic error signal is the change of prime mover speed which is detected by a flyball mechanism. This error signal is fed into a series of hydraulic valves and servos to produce a change in throttle valve or gate position of the prime mover. While for proper operation the governor assemblage must be sensitive to small changes in speed, and the control relays very quick, the response must not be such that the governor will overshoot the new equilibrium or even cause a steady hunting of the generating unit.

This tendency toward instability is remedied by introducing a stabilizing element into the governor, which in most American practice is a restoring mechanism. With no water inertia, in the case of hydro units, and without boiler lags in steam units, only slight restoration (feedback) between gate or throttle opening and pilot valve position is required

Continued on page 3, Col. 1

LANDSLIDE FOR LITTLE BLACK BOXES

BOSTON, June 12 — As anticipated, the votes of right-thinking technologists everywhere have elected and kept in office (and laboratory) the entire slate of GAP/R Computing Components, in triumph over the misrepresentations of unhappier rivals. From the theoretical abstractions of top-level planning right down to the grass roots of practical computing accomplishments, these faithful servants are ushering in a new epoch of analogical progress.

Shown here in the glow of victory are your friends and mine: A, C, and J.

COMPONENTS K3-A, K3-C, AND K3-J,
FOR ADDING, PROPORTIONING,
AND INTEGRATING



These incumbents and their functional co-workers will never confound or confuse you, nor otherwise equate your intelligence to zero. Climb on the mathematical bandwagon with this dynamic team, and join the crusade against ignorance and brute force!

Tabulated hereinafter are the three solid planks of the platform on which these candidates have been chosen:

To Subscribers

Any reader of this journal who is impressed by it so deeply as to want to receive future issues may assure that outcome by writing to The Lightning Empiricist, c/o Geo. A. Philbrick Researches, Inc., at the address given above.

To Contributors

The welcome sign is out to fellow empiricists. We shall be glad to consider items for publication, long or short, and will guarantee full credit (of course).

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1. BASIC SIMPLICITY — We feature individual component types which are chosen to afford the most fundamental sort of *unit operations*, linear & non-linear, thus enabling preparation of close-to-Nature block diagrams which may be embodied immediately in an actual computer of similar configuration. Such computing structures may be set up either from equations or from a physical situation directly, and will serve simultaneously the varying purposes of analysis, synthesis, the building of models, and the exploration of hypotheses. The modular construction of the computing units has been worked out to give compactness, flexibility, and convenience.

2. LIGHTNING SPEED — This property applies to overall computing time, and includes setup (or "programming") and parametric adjustment, as well as the *faster-than-thought* solutions themselves. Fast operation brings exclusive benefits in a number of ways. Typically, in problems where optimum adjustments for stability are sought, or if the criticality of a set of parameters is to be minimized, one must study the effects of experimental variation among many parameters; hardly a spot for a sluggish computer! Responses on the CRO may readily be traced or photographed (courtesy of Dr. Land) whenever a record is required for posterity. Note further that the CRO is capable of at least as much accuracy as a low-speed mechanical recorder.

3. PROGRESSIVE ECONOMY — Our policy is to get the most out of up-to-date electronics: staying ahead with the latest techniques and employing precision parts which are in large scale production. The GAP/R system of interchangeable components is adaptable to every budget, yet permits growth at any rate or to any extent. We have striven to avoid over-emphasis on any one refinement at the expense of others, and have tried to show good engineering sense in *balancing the design* of our computers. The result is maximum useful analog accuracy, maximum computing value for your dollar, and minimum obsolescence with the coming of still newer methods. Indeed, a number of interesting innovations are now in preparation, and will be promulgated soon.

Figure 4.5: 'The Lightning Empiricist: A journal for devotees of high-speed analog computation, those enthusiasts for the new doctrine of Lightning Empiricism...', issue 1. Source: <http://www.me.utexas.edu/~lotario/paynter/hmp/LITENING.pdf>

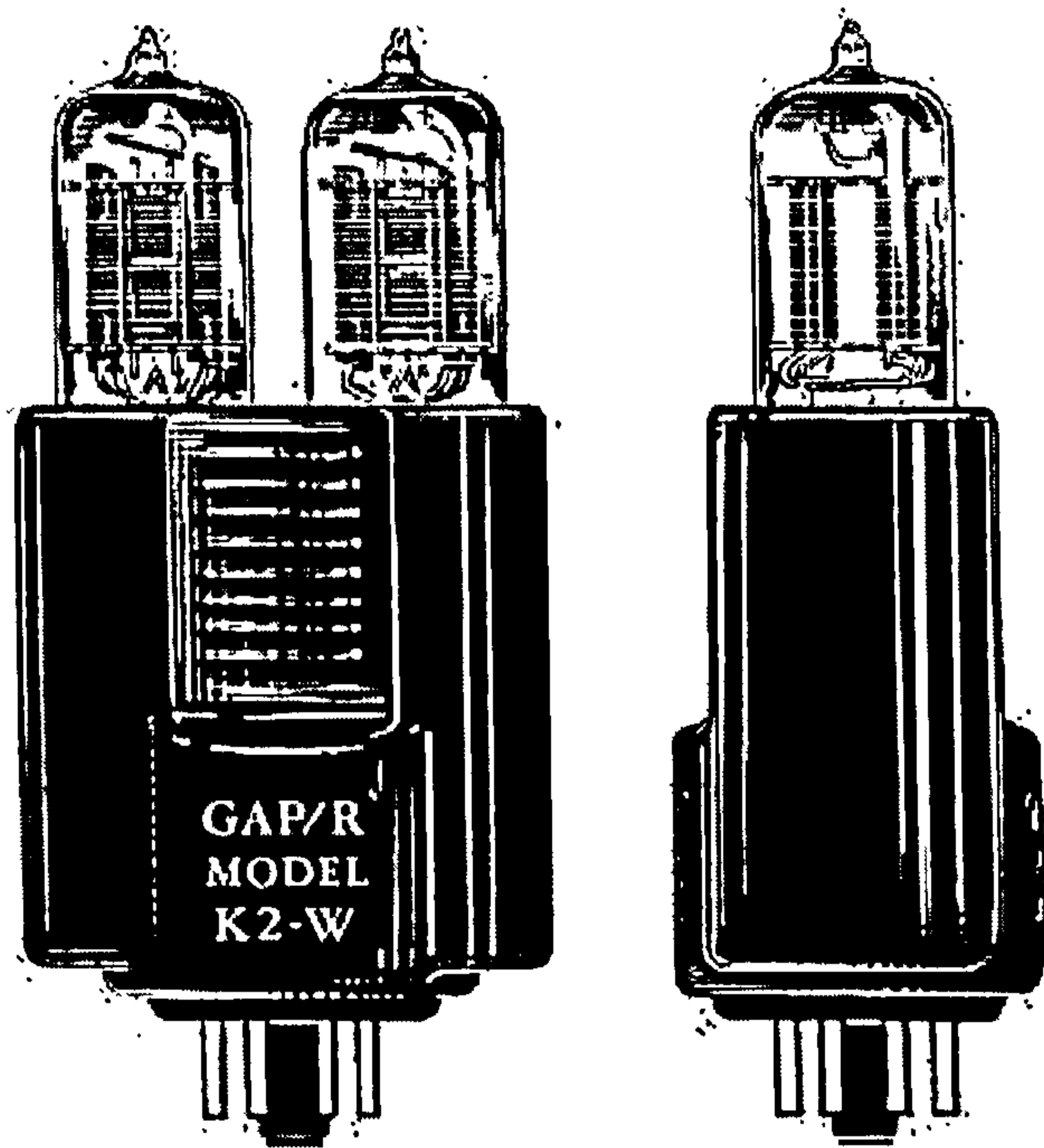


Figure 4.6: GAP/R's first operational amplifier was known as the K2-W and consisted of two electronic tubes in a Bakelite shell. Source: *Model k2-W Operational Amplifier*, sales sheet K2W357.

did build some of them more than four years before hearing of anyone else's and that their purpose was truly simulative. These amplifiers were indeed DC feedback units, used to perform mathematical operations in an analog structure, but the very first such amplifier *itself* began as a model of a mechanical control amplifier. Thus my role as a model builder, even at that stage, loomed larger than my possible role as inventor, and I have been dealing continually with models and analogs ever since.⁵⁹

The rep-op technologies underpinning the Lightning Empiricist philosophy provided a significantly improved quality of interaction where experimentation was on a 'safe' system and also had an immediacy of feedback: '[T]he general principles of Lightning Empiricism... [being] reducing the epochs of trial and error, and learning by experience under conditions where mistakes are not traumatic, and where the results of tentative questions and actions are evident before their purposes have been forgot.'⁶⁰

...the point is that models and analog procedures generally can add in-

⁵⁹Philbrick (1963)

⁶⁰Philbrick (1969) p. 24.

spiration to instruction, especially when they can be constructed and operated by the Learner himself in gradual and simple, yet meaningful stages. Talk is fine, symbols on paper are nice, but they are no meaningful substitute for tangible experience with working mechanism. There is also no respect to compare with that which one holds for what one has built up personally and brought to life. For these purposes the [Operational Amplifier] holds a position almost unique as a basic component.⁶¹

Just as Bush's texts exposed the modelling culture of 1930s engineering, Philbrick's writings provide a handle on analog computing's user culture of the 1950s and 1960s. Throughout the issues of *The Lightning Empiricist*, there always appears to be a subtext that public attention is not focused on the most exciting form of computing. For those involved in the analog industry, the future was one of decreasing attention, increasing competition and so, not surprisingly, some fought their ground and claimed that their technology was the advanced one. By volume 11, the journal carried the motto 'Advocating electronic models, at least until livelier instrumentalities emerge'.⁶²

With the practicality of a theoretical proposal established in principle, the experimental stage is entered. In this phase of development there may simply be a filling of detail, or a reduction in the level of abstraction which was maintained on the theoretical plane. This may entail the assemblage and study of more elaborate representing structures: more operational circuits; more OAs [Operational Amplifiers] fetched from the stock room. In general, however, a new combination will be involved, with electronic modelling means coupled into actual or simulated apparatus of other physical forms. The search then proceeds for optimum characteristic and conditions, and conversely for adverse situations to be avoided.

Certain criteria for design will be expected to emerge from the experimental phase, if indeed the development project has survived examination so far. Among the valuable information which model-building can supply are those kinds of data which tell how *bad* things may be permitted to be. Rather than being flippant, as this last remark may

⁶¹Philbrick (1969) p. 22.

⁶²*The Lightning Empiricist* vol. 11. The titles of articles in *The Lightning Empiricist* were elaborate and elegant, positioning themselves as something a bit different from the main-stream electronics and computer literature. Titles such as 'Intentionally unconventional analoguery', or 'Modularity, medieval and modern' had an almost poetic adaptation of conventional terminology. See Anon. (1963a,c)

seem to be, we are speaking of a very serious matter. By including adjustable imperfections in the circuits of the electronic representation, one finds out rapidly how critical the developing design may be to them. It is obvious that an impossibly close tolerance is to be avoided at any point within a system under development; merely that a model may warn of such a disaster could make it worthwhile. It is less obvious that a good design is characterized, in part, by its permitting the most liberal tolerances throughout. In view of the number of parameters which not infrequently are involved, the attainment of this desirable state can be a formidable task, however praiseworthy the goal, especially without simulative techniques. Electronic modelling does not eliminate the need for ingenuity, but it can serve as a valued and uncomplaining partner in the demanding work of design.⁶³

Through these publications we can trace an ongoing analog rhetoric comparing the beautiful, sophisticated and elegant analog to the clunky, unimaginative and lossy digital. To understand the contribution of Philbrick and others at GAP/R we need to understand that rhetoric, a discourse that led to many wonderful engagements between the followers of analog and the enthusiasts of digital. This reminds us that the users of technology can be both resistive and promotive agents of change. It was not just technological progress driving analog use, but also the surrounding technical culture.

Dis-enrollment of analog computing and the redefinition of analog culture

Bijker's theory offered some useful insights into how enrollment fuelled the analog-digital debates of the 1940s and 1950s. However, to explain what happened afterwards is to account for the social *deconstruction* of analog computing: its dis-enrollment.⁶⁴ As is well documented by history of computing literature, between 1950 and 1960 digital became the dominant technology. In terms of Bijker's phases, the growing importance of digital corresponds to a shift back to a type II phase, and as a result analog culture began to be dis-enrolled.

⁶³Philbrick (1969) p. 16.

⁶⁴Dis-enrollment, as a tool for getting a handle on evolving technical cultures, is discussed in Maggie Mort's history of the Trident submarine (Mort, 2002).

During the 1960s, digital developed to become more dominant over both analog and hybrid, initiating a devaluing of analog application. It is at this point that James Small's work is particularly useful. Small describes how analog-digital debates developed and continued through the period. These debates were the attempts of the analog actor-network resisting marginalisation. One significant attempt was to pursue hybrid computing, essentially inventing a third technological frame. However, as a consequence, analog and hybrid became further linked, initiating a process of redefinition in which: analog hardware issues became part of electrical engineering; direct analog computers became redefined or dis-enrolled into special purpose analog modelling; and indirect analog computing was redefined into a software concern leading to the development of analog simulations, analog compilers, and analog languages.

The translation into electrical engineering created new sub-disciplines of 'analog electronics' and 'analog control' and analog simulator software evolved into modern modelling and simulation software. While some applications went straight to digital (an example of technological absorption); some applications went through this redefinition process and became part of a new technological frame.⁶⁵ These were later independently enrolled into the digital computing frame.

Conclusion

Between 1920 and 1930, new disciplines such as 'applied mechanics' had their founding conferences, and pioneers like Bush were key in enrolling these communities into computing culture. It was from these early computing cultures that early digital technology emerged and comparisons between the two classes of machine were made. These comparisons, made during the 1930s, led to the adoption

⁶⁵An example is the application of electrical analogs to hydroscience. During the 1960s, modelling ground water systems was a well-known application of resistance networks and other electrical circuits. Analog remained a significant modelling tool in this domain, but actors stopped referring to these setups as 'computers'. A technology that had previously been computational had returned to being a physical model. See Prickett (1975) for examples of non-computational analog computing – what he calls 'electrical models'.

of the words ‘analog’ and ‘digital’ around 1940. During the 1940s analog referred to both continuity and analogy, strengthening the widespread adoption of the analog-digital classification in the 1950s. However, the late 1950s also saw a shift towards ‘analog’ conveying just continuity, a meaning that stabilised during the 1960s. After this, analog computers began to disappear and the analog-digital dichotomy was exported into new domains such as signal processing.

This chapter emphasised that analog computing is broader than its technology, theory, or practice. Development of technologies and theories about technologies do not develop in a vacuum, but instead are intimately linked to activities of the technology’s users. However, these users do not work in isolation either. They take on the discourse of a technology: the jargon, classifications, assumptions, and these inform their practices. The next chapters are about the users of analog computing in context – how the communities around this tool perceived the position of the technology, and how they shaped its history.

Earlier, reference was made to a Philbrick reprint appearing in a modern engineering textbook. On the cover of this book is a photograph of its author’s workbench, a cluttered desk full of wires and patch panels, a discarded packet of ‘potato chips’ and accompanying cola drink can.⁶⁶ On the desk sits an oscilloscope, and alongside sits a label, jokingly bearing the words ‘Analog CAD’⁶⁷. The tinkering spirit, the hands on ‘engineering feel’, and the rhetoric of the 1950s analog culture still exist today: the difference is that the discipline has been re-defined. No longer computational, the modelling culture of analog computing evolved into the design culture of analog electronics.

⁶⁶See the cover images of Williams (1994).

⁶⁷Computer Aided Design.

Part II

Analog computing in use: a selection of contexts

Chapter 5

Analog computers in British higher education

The previous chapters have argued for a history of computing centred on the user activity of modelling. By examining groups of users and their contexts, this chapter considers analog computing within British higher education, a case study that highlights the importance of different modes of use, as well as the consequences of classification in the funding of analog machines.

During the 1950s and 1960s, British higher education consisted of traditional universities and colleges of advanced technology. Analog computing research was the domain of the universities, whereas the technical colleges were teaching courses more aligned to industry. For example, at the Bristol College of Science and Technology (subsequently the University of Bath), the analog laboratory had strong links with Rolls-Royce and ran an annual summer school to educate their new trainee engineers in analog computing.

Much like the history of digital computing in higher education, analog use falls into two periods: firstly a prototyping phase where analog computers were developed in-house, followed by a second phase of commercialisation where analogs (now products rather than prototypes) were manufactured and sold to university departments.¹ In-house development was standard practice for the first

¹In his description of analog computing at Manchester between 1956 and 1962, Derek Atherton recalled that the research machine, occupying 'around 400 square feet' of floor space, was developed in-house with a custom design even at component level, due to a lack of cheap com-

generation of electronic analog computers built during the 1950s. However, by 1960, universities were tending to purchase their computers from a manufacturer. With this shift, analog research focused less on innovating hardware and turned its attention towards developing techniques and applications for the commercial analogs.² Generally, university requirements were on a lower scale to industry, with computers being used to illustrate the principles of analog modelling rather than simulating complex systems.³ Popular educational manufacturers were Solartron, EMI and EAL, and a number of these companies also released smaller machines for classroom use.⁴

Analog computing was applied as a research tool in various application areas: for instance, of the 200 theses published between 1950 and 1979 relating to analog computing (see Figure 5.1), 40% belong to disciplines outside computing.⁵ These range from experimental psychology to mechanical engineering. This chapter therefore presents an explanation of analog demise framed in terms of a shift from *radical* use to *normal* use. In Britain, a number of universities were innovative in developing digital computing prior to the 1960s, but also remained significant users of analog until the late 1970s. When digital computers replaced analog, academics often redefined their analog expertise into (digital) simulation skills.

The story of analog computing presented by previous scholarship in the history of British computing hinges on the pre-war differential analysers at Manchester

mercial parts – the cheapest available amplifier (manufactured by GAP/R) cost four times more than their own and ‘was technically inferior’ (Atherton, 2005, p. 66).

²Small (2001) p. 205. Small showed how companies and institutions progressed through three categories. These were ‘developer/users’, who constructed analog computers in-house to support their own computing needs; ‘user/manufacturers’ who developed machines for their own in-house needs which subsequently became products; and finally ‘non-user/manufacturers’ who were typically electronics companies producing computer equipment for retail.

³Atherton (2005) p. 66.

⁴For instance, Solartron launched its ‘Analog tutor’ in 1957, EMI produced an educational version of the EMIAC II in 1965, and during the same period, a desktop version of the EAI PACE computer was marketed. See EMI (1965a) p. 9; Small (2001) pp. 189 & 202. The popularity of Solartron and EMI was due to the Ministry of Technology’s ‘buy British’ policy (see page 145, below). The American firm *Electronic Associates Incorporated* (EAI) later became a dominant player in the British market when it started manufacturing machines through its UK subsidiary (EAL).

⁵Based on an analysis of data from the *Index to Theses* (Theses, 2007). Prior to 1950, it is difficult to identify applications of analog computing due to a lack of stabilised terminology.

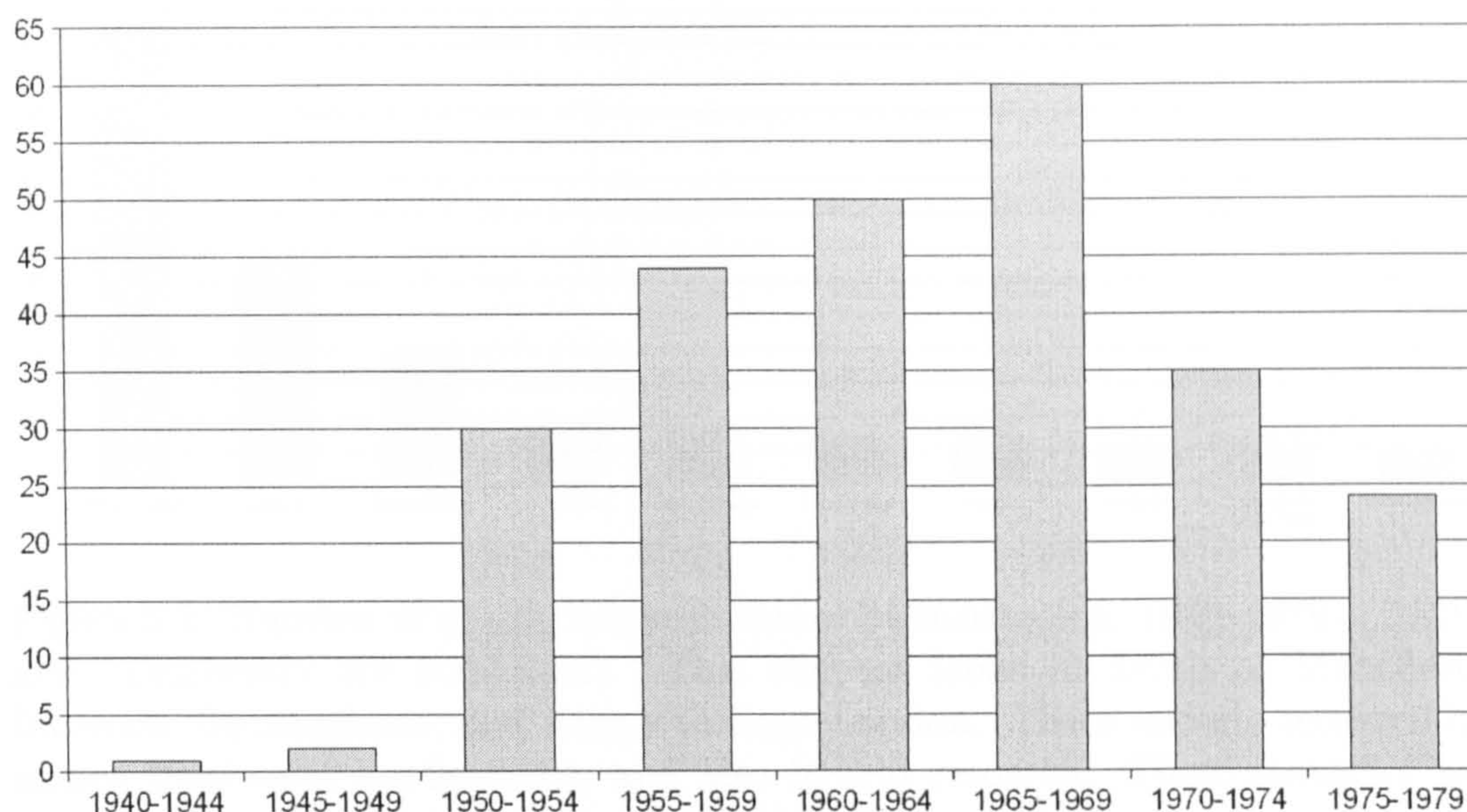


Figure 5.1: Number of analog research theses by year, 1940–1979. These include research into analog hardware, applications, and also hybrid research. Data from before 1950 is sparse because it was only after 1946 that ‘analog computer’ became common terminology. The graph concludes with 1979 as only two theses were submitted in that year followed by very few in the 1980s. These statistics were compiled using the British *Index to Theses* (Theses, 2007).

and Cambridge: machines that were replaced by early digital machines. However, analog computing was widely used after 1950. As an indication of its popularity, Figure 5.1 shows the growth of research theses published between 1940 and 1979. We can see that there was significant activity in analog research well into the 1970s. Figure 5.2 shows the top 10 institutions contributing to these statistics.

Radical innovation and normal application: perspectives of analog use

As noted in the previous chapter, it was in America that the culture of ‘electrical analogy’ first crystallised. In fact, there was little British interest in the development of analog devices during the 1930s.⁶ As a result, most of the suc-

⁶Mary Croarken noted that analog computing devices developed in Britain during the 1920s and 1930s were not the ‘main interest of the inventors.’ (Croarken, 1990, p. 49). This was also observed by Bowles (1996) who described a ‘British technological scepticism’ (p. 5). British engineers were interested in getting the job done rather than advancing the computing technol-

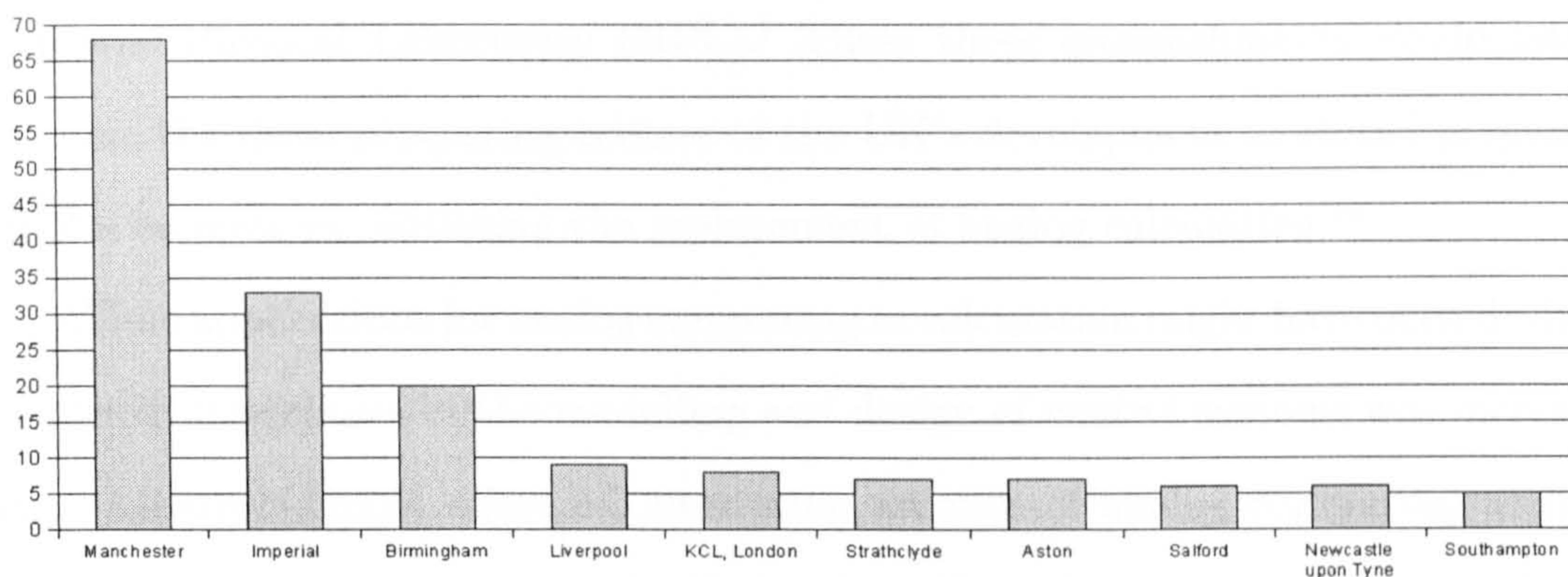


Figure 5.2: Number of analog research theses by institution, 1940–1979. (UMIST and Manchester are combined). This chapter looks in depth at Manchester, Imperial, Birmingham, and King’s College London. These include research into analog hardware, applications, and also hybrid research. These statistics were compiled using the British *Index to Theses* (Theses, 2007).

Successful analog installations were technologies ‘imported’ from American research. One importer of computing technology was the Manchester applied mathematician Douglas Hartree who, in a 1933 visit to MIT, had used Bush’s differential analyser as a research aid.⁷

Inspired by his experience with the differential analyser, Hartree decided that he too should have access to the technology. Once back at Manchester, he constructed a small version with his research student, Arthur Porter using Meccano (a popular British construction toy, similar to the American toy ‘Erector Set’). In the following years, Hartree encouraged other academics to develop Meccano analysers⁸ and the success of these home-grown computers motivated the manufacture and installation of full size copies at Manchester, Cambridge, and the

ogy for its own sake. An exception to this was the electrical analog devised by Mallock which inspired the later work on transformer analogs. See Chapter 2, page 52, above.

⁷Croarken (1990) pp. 47–48 & 50–51. During the 1940s, Hartree made a further visit to the United States and was introduced to the ENIAC electronic computer. The article he subsequently published in *Nature* on the ENIAC was one of the first English publications to refer to an analog-digital classification. See Chapter 2, page 58, above.

⁸In the late 1940s, H. E. Rose, a reader in Mechanical Engineering at King’s College London, gave a lecture on differential analysers to the Institution of Mechanical Engineers. He had been guided by Douglas Hartree to investigate the applications of the technology and was constructing his own Meccano analyser. See Rose (1948) pp. 46 & 54; Anon. (1948) pp. 62–80. At Cambridge, J. B. Bratt constructed a copy of the Hartree/Porter model in 1935. Other models were built at the University of Birmingham, the General Electric Corporation, and the Queen’s University of Belfast. See Robinson (2005) pp. 78–80; Croarken (1990) p. 51; Croarken (1992) p. 10; Bromley (1990) p. 184; Wood (1942) pp. 71–73.

National Physical Laboratory (NPL).⁹ These three establishments would later become the three pioneering centres of the UK's development in stored program digital computers, initiating the replacement of analog calculation.¹⁰

While applications for analog computing in calculation might have been drying up, their importance in the modelling and design of control systems was increasing. Atherton (2005) offers an interesting account of analog computing within the engineering department at the University of Manchester, a department whose research programme in control systems would employ analog for many subsequent years. Because of this mix of applications, the history of analog computing in universities is really a history of three major themes: calculation, modelling, and control.

Calculation, modelling, or control: three different uses, three different histories

Analog computing was an interdisciplinary technology, applicable to many different classes of technical problem. It typically had three main uses, calculation, modelling, and control.¹¹ A *calculation* use of analog computing corresponds to Hartree's involvement with differential analysers during the early 1940s. Users like Hartree had specific equation-driven problems to solve, and thus when digital computers became available, they jumped on to the bandwagon of these 'even better' calculators.¹² Alternatively, a modelling use relates to the explorative modelling that technologists such as George Philbrick had advocated. Developing

⁹The Cambridge and Manchester differential analysers were purely mechanical like the original Bush analyser. However, the NPL machine was not installed until the 1950s and was far more elaborate, boasting automatic servos and controllers like the Rockefeller analyser at MIT. See Pyatt (1982) p. 156.

¹⁰These early machines were the EDSAC (Cambridge), the Pilot ACE (NPL), and the Manchester 'Baby' computer.

¹¹Calculation refers to equation solving, modelling to set-ups that modelled a dynamic system, and control to the simulation and design of analog controllers. In terms of the multi-stranded chronology proposed in Chapter 2, applications in modelling and control were included within the second thematic time-line.

¹²Croarken (2005) notes how the 'common denominator' of Hartree's career was his involvement with the solution of differential equations (p. 859).

a complex, dynamic system – perhaps with a visual interface – was an application particularly suited to analog. Thirdly, certain analog computing components were used to simulate control systems.¹³

University applications of analog computing followed this threefold scheme of use, each strand having its own trajectory and ‘heyday’ (as demonstrated by Figure 5.3). For instance, applications in scientific computing dried up before those in modelling or simulation. However, most scholarship in the history of analog computing has related to the use of analog computing in calculation. This explains why the majority of previous narratives focus on the very early users of analog computing such as Manchester or Cambridge. Because the Manchester Baby and the EDSAC machines led a rapid decline in the role of analog as a *calculator*, it is easy to think that both Cambridge and Manchester made the transition to digital early on. In fact both institutions had engineering departments actively designing and modelling analog controllers, and continued to install and maintain analog (and later hybrid) computers for many subsequent years.¹⁴

While the differential analysers installed at Cambridge and Manchester remain the principal landmarks of analog calculation, the post-WWII developments of analog computing are the landmarks of analog modelling and control. Of the three uses, control was the most resistant to digitalisation – analog control systems were still frequent use in the 1970s.¹⁵ Furthermore, even after the introduction digital controllers, it was common for a controller’s test rig to be an analog computer model. The following sections outline the history of analog computing as used for simulation and modelling at a number of key institutions. The most signifi-

¹³This thesis only touches on control systems, the interested reader is directed towards Mindell (2002) or Bennett (1979). These three uses actually represent different engineering practices and although there is a close relationship between the technologies of analog modelling and control, the people engaged with these technologies would have belonged to quite different communities.

¹⁴Small describes how UMIST, Cambridge and Imperial were all selected in the mid-1960s to become centres of excellence for control engineering and therefore received extra support from the Science Research Council. This funding provided for new hybrid computers at Cambridge and UMIST (Small, 2001, p. 211).

¹⁵See, for instance, Bonnor (1997).

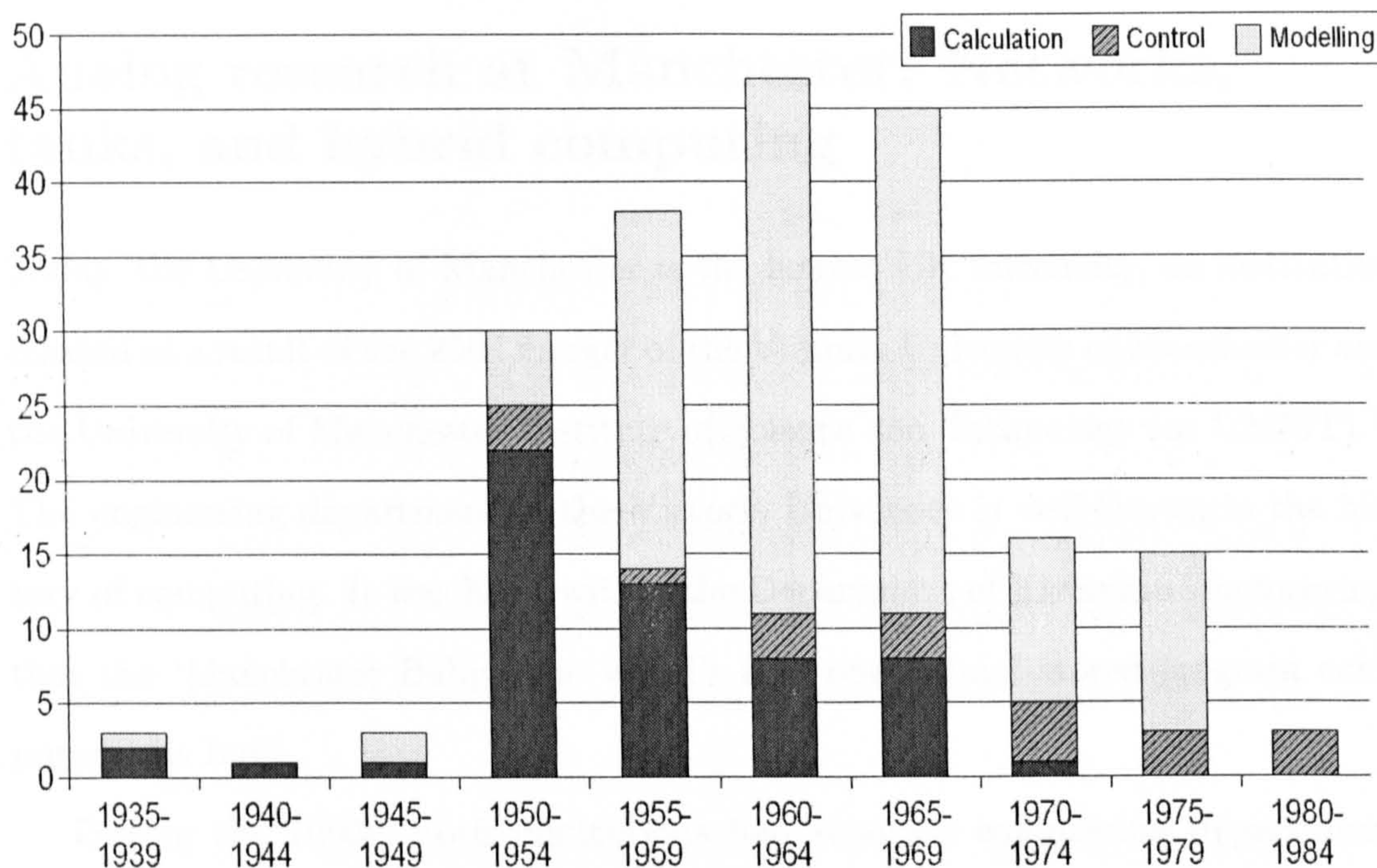


Figure 5.3: British theses sub-divided by type of application. The graph clearly identifies a different 'heyday' for each type of application. Analogs for calculation were being replaced in the late 1960s, while there was significant application of analogs for modelling lasted into the late 1970s. These statistics do not include theses relating solely to the development of analog hardware (such as curve followers or function generators), or to those relating to hybrid computing.

cant institutions were the two universities in Manchester and Imperial College in London. Also of interest is the work at King's College London that had a slightly smaller, but more focused research programme developing high-speed computing. Finally, we also discuss the Bristol College of Science and Technology (now the University of Bath) to investigate the story from the perspective of a technical college.

Analog research at Manchester: Networks, tanks, and hybrid computing

Today, the University of Manchester is the largest UK university, an institution created as a result of the 2004 merger of the Victoria University of Manchester and the University of Manchester Institute of Science and Technology (or UMIST).¹⁶ The engineering department of the Victoria University is well-known in the history of computing. It was here, within the Department of Electrical Engineering, that the 'Manchester Baby', the world's first operational stored-program computer, was built.

During the 1950s, both institutions had separate engineering departments actively pursuing analog research. Compared to the Victoria University, UMIST (then called the Manchester College of Science and Technology) had a slightly more industrial focus, and analog computers were in wide use. On the other hand, engineers at the Victoria University, already pioneers of digital calculation, were mainly using analog computing for control engineering problems.¹⁷

At the College of Science and Technology, students were using analog for cal-

¹⁶These institutions have an entwined history. In 1905, the forerunner of UMIST became known as the Faculty of Technology and was administratively part of the Victoria University. Even when UMIST became an independent university in the mid-1950s, the two universities maintained close links until their eventual merger (McCall, 2006); (University of Manchester, 2007).

¹⁷At Victoria, the principal technology was general purpose (and so indirect) analogs. An exception to this was the research of J. Potts, who submitted a thesis describing a special purpose computer developed for use in the servomechanisms lab, however, this is an example of normal analog use, rather than 'radical' analog development. See Potts (1953).

ulation, simulation, and control.¹⁸ The major research focus was, however, the development of network analysers for simulation and modelling. Under the supervision of Professor Eric Bradshaw and Colin Adamson, a number of projects investigated their application and developed bespoke hardware to extend them.¹⁹ During the late 1950s, the department also developed transformer network analogs, machines similar to network analysers but utilising AC transformer windings to represent quantities.²⁰ Researchers were also developing electrolytic tanks: for instance, in the department of mechanical engineering, J. K. Royle and H. Naylor used them to investigate fluid flow in pipes.²¹ Similarly, within the electrical engineering research group, an 'automatic field mapper' was invented to allow the electrical field of an electrolytic tank to be automatically visualised.²² The series of research projects undertaken within this context confirm that analog computing was an established research field.

Researchers at UMIST also undertook some early investigations into hybrid computing, connecting a network analyser to a small digital computer and assembling the appropriate analog-digital converters.²³ As well as investigating hybrid computing, the 1960s saw many researchers make the transition into new domains

¹⁸For instance, as an example of calculation, in 1951 a young researcher named Baida Paul constructed an electronic differential analyser for equation solving. See Paul (1951).

¹⁹See for instance Durrani (1953) who constructed a network analyser and Atkinson (1954) who developed improved inductance units. Watkins (1952) developed hardware to model the characteristics of the 'swing curve' of real-world alternators, which was used to accurately model electrical generation on the network analyser (p. iv-v). Prof. Bradshaw was an important character within the Electrical Engineering community. He had a PhD from the University of Glasgow, and was the founding editor of the *Bulletin of Electrical Engineering Education*. See Hartley (1998).

²⁰In 1958 Salah El-Sobki, an Egyptian graduate student, submitted a PhD thesis describing improvements and applications of a transformer analog. Inspired by the Mallock Machine, transformer analogs were based on a generic computer designed by Blackburn (who demonstrated how a pair of 3-winding transformers could represent a complex variable). See El-Sobki (1958) pp. 1-2, 290-292.

²¹See Naylor (1956).

²²By using a cathode ray tube as the base of an electrolytic tank, the field mapper made it possible to automatically drive a visual display (on a second tube) which reflected the real-time potentials in the tank. For the field mapper developed by Burt under the supervision of J. Willis, in 1954, the display was updated 25 times a second. See Burt (1954); Burt and Willis (1957).

²³Ghoshal (1956) refers to a 'Network-Analyser-Digital Computer' belonging to the Power Systems Laboratory of the College of Technology (p. 2).

such as digital simulation. For instance, the lecturer Michael G. Hartley, who had previously taught analog computing (and published *An Introduction to Electronic Analogue Computers*) would later supervise academic research into digital road traffic simulation.²⁴ This is indicative of how analog computing culture evolved into the digital world. By redefining analog computing expertise into simulation expertise, there was a continuity of practice.

Analog research at Imperial College: Networks and tanks as engineering tools

Under the supervision of Sir Willis Jackson (1904–1970, FRS 1953), then chair of Electrical Engineering, graduate researchers at Imperial also developed network analyser technology.²⁵ Like Manchester, a particular research interest was the development of transformer analogs, research that resulted in a simpler design which was later manufactured commercially.²⁶ Alongside this work, A. J. Boothroyd and Edward Colin Cherry were developing electrolytic tanks, and using them to model electrical circuits.²⁷

Jackson left the department in 1953 but research in analog computing continued.²⁸ Most studies involved some application of digital computing. For example Blackman (1957) developed an early hybrid computer in which an analog resis-

²⁴Hartley (1965); Saleeb (1964); Saleeb (1967).

²⁵This resulted in a number of PhDs: Jackson supervised Abou-Hussein (1950), Boothroyd (1951), and Ismail (1955). Humphrey Davies, then a reader in the department, was also involved in this research and supervised Faragalla (1954).

²⁶In 1955, the General Electric Company assembled a machine with 208 computing units based on this design, as did the British Thomson-Houston Company (BTH), and also Metropolitan Vickers. These computers were smaller, and used to design induction motors – the BTH machine had 9 computer units. See El-Sobki (1958) p. 2.

²⁷While Boothroyd was still a PhD student, the Boothroyd-Cherry tank design was applied to electrical circuit modelling by one of Cherry's MSc. students (Makar, 1950). Cherry had previously taught at the University of Manchester and later became renowned for his work on cognitive science.

²⁸Jackson moved into industry to manage the research of Metropolitan Vickers. He also held a number of civil service advisory roles and spent a period on the University Grants Committee (UGC). In 1967 he returned to Imperial's department of electrical engineering where he remained for the rest of his life. See Brown (2004).

Year	Researcher	Degree	Department	Supervisor	Technology
1950	M. S. M. Abou-Hussein <i>An A.C. network analyser using transformers.</i>	PhD.	Elect. Eng.	Willis Jackson	Network analyser
1950	R. Makar <i>The use of an electrolytic tank in circuit analysis and synthesis.</i>	MSc	Elect. Eng.	E. Colin Cherry	Electrolytic tank
1951	A. R. Boothroyd <i>The electrolytic tank as an aid to electric network design and its application to filter synthesis.</i>	PhD.	Elect. Eng.	Willis Jackson	Electrolytic tank
1952	J. N. Holmes <i>The design and use of a correlation function computer for the analysis of speech waveforms.</i>	MSc	Elect. Eng.	-	-
1952	S. L. Chen <i>An harmonic analyser for non-linear circuit analysis.</i>	MSc	Elect. Eng.	-	-
1952	J. H. Westcott <i>The synthesis of electrical networks with particular reference to servo-mechanisms</i>	PhD	Elect. Eng.	-	Network analyser
1953	S. K. Ip <i>An electrolytic tank as an analogue computing machine for factorising high degree polynomials.</i>	MSc	Elect. Eng.	E. Colin Cherry	Electrolytic tank
1953	D. O'Kelly <i>The development and application of a transformer analogue network analyser.</i>	MSc	Elect. Eng.	-	Network analyser
1955	M. K. E. Ismail <i>Development of the transformer analogue analyser and its application to electrical machines.</i>	PhD	Elect. Eng.	Willis Jackson	Network analyser
1955	F. F. Faragalla <i>A synchronous machine analogue and its application to power system dynamical analysis.</i>	PhD	Elect. Eng.	Humphrey Davies	Network analyser
1956	C. P. Kuriakose <i>Stability investigations with dynamic network analysers.</i>	PhD	Elect. Eng.	-	Network analyser
1957	N. G. Davies <i>A low frequency analogue multiplier.</i>	MSc	Elect. Eng.	-	Network analyser
1957	P. F. Blackman <i>A computer combining analogue and digital principles to investigate network functions...</i>	PhD	Elect. Eng.	J. A. Westcott	Hybrid
1958	A. A. El-Shirbini <i>Study of turbulent flames by electric analogue.</i>	PhD	Mech. Eng.	-	-
1958	S. Saha <i>An experimental investigation of analogue methods for computing gravity and magnetic effects.</i>	PhD	Geophysics	-	-
1959	W.R. Atkins <i>Pulse width modulation and analogue multiplication with transistor circuits</i>	MSc	Elect. Eng.	-	-
1960	T. Kovattana <i>Networks of non-linear resistors and their application as analogues...</i>	PhD	Elect. Eng.	J. R. Barker	Network analyser
1960	S. Rudzinski <i>The analogue representation of the two-axis commutator machine</i>	MSc	Elect. Eng.	-	-
1961	A. A. K. El-Bahadli <i>The electric analogue for turbulent flame studies: an investigation of its validity.</i>	PhD	Mech. Eng.	-	-
1961	C. Lemyre <i>Study by analogue means of base charge properties of junction transistors...</i>	PhD	Elect. Eng.	-	-
1961	C. J. Bland <i>An analogue computer for the investigation of the trajectories of cosmic ray particles...</i>	PhD	Physics	-	-
1962	W. F. Fincham <i>A study of the mechanism regulating the composition of the human blood...</i>	PhD	Elect. Eng.	-	-
1963	N. H. Gillon <i>An RC analogue for eddy current problems.</i>	MSc	Elect. Eng.	-	Network analyser
1964	B. P. Apaydin <i>Study and analogue simulation of the dynamic behaviour of transistors for small signals.</i>	PhD	Elect. Eng.	-	-
1964	D. N. Davies <i>Approximately optimal control of a non-linear system by means of an analogue computer.</i>	MSc	Elect. Eng.	-	-
1964	P. C. Hedgecock <i>An analogue computer study of cosmic ray threshold rigidities.</i>	PhD	Physics	-	-
1965	R. E. Parking <i>An investigation of the transmission properties of distributed resistance-capacitance networks</i>	PhD	Elect. Eng.	-	Network analyser
1965	M. J. Short <i>The conjoint use of a network analyser and analogue computer...</i>	PhD	Elect. Eng.	D. G. O. Morris	Network analyser
1966	D. P. Deziel <i>Applications of analogue computers in operational research.</i>	PhD	Business	-	-
1976	C. B. Giles <i>The development of a hybrid simulator for power system control investigations.</i>	PhD	Elect. Eng.	-	Hybrid
1977	N. L. Shore <i>Hybrid computer simulation and on-line digital computer control of D.C. link.</i>	PhD	Elect. Eng.	-	Hybrid
1978	A. Nava-Segura <i>Hybrid computer simulation of HVDC systems.</i>	PhD.	Elect. Eng.	-	Hybrid

Table 5.1: Analog research dissertations at Imperial 1950–1979.

tive network was combined with digital.²⁹ Other studies were more comparative, for instance, one PhD student investigated the relative merits between numerical methods, graphical approaches and electrolytic tanks for solving physical problems.³⁰ Network analysers continued to be researched as tools for modelling power system stability. In the early 1960s, the department collaborated with the Central Electricity Generating Board (CEGB) to investigate grid stability problems, PhD researchers being jointly funded by the DSIR and the CEGB.³¹

King's College London: Analog computing at 'ultra-high speed'

Work at the University of London's King's College was not on such a grand scale as at Manchester or Imperial, but is interesting because it focused on high speed analog computing. Of particular significance was the research initiated by Donald MacKay (1922–1987) in the departments of physics and electrical engineering.³² MacKay had joined the physics Wheatstone Laboratory during the late 1940s and started building high speed analog computers.³³

Similar to the vision of George Philbrick in America, MacKay's research aimed to develop a reliable and accurate machine utilising repetitive operation, a goal MacKay later articulated as 'computing at ultra-high speed'.³⁴ At the time, most

²⁹The digital circuits provided the storage and automated capture of analog quantities while also facilitating the extraction of logarithms.

³⁰See Kovattana (1961).

³¹See Short (1965) acknowledgements. In his study of network analysers, Short considered both analog and digital techniques, concluding that 'the digital approach can, in itself, hardly be appropriate to basic investigations. An analogue, or simulator, approach is more suitable, because the logical steps in the solution need not be stated at the outset...' (Short, 1965, p. 60).

³²King's College has one of the oldest engineering schools in Britain – the Department of Engineering and Applied Sciences was established from an existing department of applied science in 1874. In the twentieth century, King's established separate departments of civil, mechanical, and electrical engineering. Civil engineering was closed in 1989, with mergers of the remaining departments into what would later evolve into the Department of Electronic Engineering (KCL, 2003).

³³MacKay spent the war years working on Radar within the Admiralty Signals Establishment (Anon., 2007/1987). It was during this wartime work that he became interested in computing circuits, particularly from their use in gun directors – he cites (Hale, 1945).

³⁴MacKay was well-read in information theory, as well as having an interest in physical experimentation (MacKay, 1950, p. 289). For MacKay the desire to provide a novel experimental

analog computers did not operate at high speeds and the transition from the higher accuracy 'single-shot' machines to the lower accuracy, but faster, rep-ops would support an interactive, more visual, mode of computing.³⁵ Describing the flexible parameter variation offered by rep-op, one of MacKay's research students later wrote:

[MacKay's] computer offered a wide scope for the rapid solution of trial-and-error problems, and striking possibilities for studying the effects of continuous parameter changes, and also of tackling more complicated problems, such as partial differential equations.³⁶

The computer MacKay developed in 1950 was capable of calculating between 1,500 and 25,000 solutions each second, and would form the basis for a decade of analog research at King's.³⁷ Upon graduating from his doctorate in 1951, MacKay became a lecturer of physics, supervising further work into high speed computing techniques and components. During his PhD, MacKay had collaborated with E. M. Deeley, another physics research student who was awarded his doctorate in 1950 (a year before MacKay).³⁸ Their research focused on computing units for function storage and multiplication, employing 'Williams tubes'.³⁹ MacKay had detailed some preliminary investigations into the use of these tubes in his thesis and by 1950 had prepared a patent submission for a function gener-

environment as well as attempts to maximise the information-theoretic capacity of a computer led, quite naturally, to developing high speed analog computing.

³⁵See Chapter 2, page 61. Fisher wrote that before he began his PhD research in 1953, there had only been two earlier high speed machines developed (Fisher, 1957, p. 1.1). One was MacKay's computer which he then extended; and the other was a high speed machine that had been invented across the Atlantic by A. B. Macnee (Macnee, 1949). An earlier consideration of repetitive computing elements for control systems modelling is given by Williams and Ritson (1949), describing wartime work.

³⁶Fisher (1957) pp. 1.1-1.2. Rep-op provided the perfect environment for MacKay to experiment with using cathode ray tubes as projective three-dimensional displays, see MacKay (1949).

³⁷Anon. (2007/1987). The computer is detailed in MacKay (1951) and MacKay (1955).

³⁸MacKay also made use of Deeley's measuring system in developing his computer (Fisher, 1957, p. 2.1) (MacKay, 1951, p. 6.9). After his doctorate, Deeley became a Nuffield research fellow in that department, and by the mid-1960s he became a full-time academic within the Department of Electrical Engineering. See Deeley (1955) p. 263; Harris (1963), introduction; Okon (1966), introduction.

³⁹Williams tubes were an important memory device based on a cathode-ray tube, pioneered by the Manchester research engineer F. Williams, and most famous for their use in the memory modules of the Manchester 'Baby' computer.

ator.⁴⁰ The function generator and memory unit for MacKay's analog computer went through several subsequent developments, being further refined by his first graduate student G. D. Bergman who submitted his PhD in 1955.⁴¹

During 1953, MacKay took on a second research student, Michael E. Fisher, who had recently graduated with first class honours in physics from King's. Fisher became equally passionate about high-speed computing, and over the following years, he and MacKay would work closely together. As a physicist, Fisher framed his research around applications, and his thesis discusses how high speed analogs could aid the theoretical physicist.⁴² Shortly after completing his PhD, he too became a full-time member of the Wheatstone Laboratory, joining as a lecturer in 1958, with subsequent promotion to reader in 1962 and professor in 1965.⁴³ While MacKay's interest in high speed analog computing had been active since 1946, during the 1950s he became increasingly interested in the relationship between computers and the brain. In 1960, he moved to the newly formed University of Keele to become Professor of Communication and establish a department of communication and neuroscience.⁴⁴ This did not, however, immediately terminate his involvement with analog computing, nor his collaboration with Fisher. In 1962, they co-authored *Analogue computing at Ultra-High speed*, a work combining their respective theses.⁴⁵ Despite his shifting research interests, MacKay's

⁴⁰MacKay (1951) p. 10.02. The device employed a light source and card mask to project a function curve on to the surface of a cathode ray tube, which, in turn, drove a circuit mapping projected light to electrical voltage. These devices were clearly a hot-topic, and the same idea was devised by D. J. Mynall at the British Thomson-Houston Company. Mynall, who had also submitted a patent specification, was further developing the apparatus to act as a high speed multiplier unit. See MacKay (1947) pp. 406–407; Mynall (1947) p. 743. Across the Atlantic, Macnee (1949) wrote about the same idea, and also had an operational multiplier in 1947. Building on Mynall's work, Deeley and MacKay also developed a high speed multiplier for their computer, an account of which was published in *Nature* in 1947. See Deeley and MacKay (1949) p. 650.

⁴¹See Bergman (1955) p. 1.1.

⁴²Fisher (1957) p. 1.2. Investigating the application domain of theoretical physics was partly a result of Fisher's own expertise, and partly due to an observation that its problems had 'received relatively little attention from the analogue computing practitioners' (p. 1.2).

⁴³A year later, he moved to Cornell to become Professor of Mathematics and Chemistry. He was elected FRS in 1971. (Anon., 1962c, 1965, 1971), (Fisher, 2007), (Royal Society, 2006).

⁴⁴Now renamed the 'MacKay Institute of Communication and Neuroscience' in his honour.

⁴⁵MacKay and Fisher (1962).

early innovations in computing were significant in shaping his later work: his obituary records that: 'expertise in electronics and high-speed analogue computing enabled him to develop brilliantly elegant display and recording equipment'.⁴⁶

The analog research going on in universities during the 1950s focused on developing the actual hardware. However, by 1960, analog research had shifted towards applying the established technology to scientific modelling and engineering design. Analog computing would no longer be technologically innovative (i.e. 'radical'), but rather a 'normal' research tool.⁴⁷ Analog computing at King's College was an active blend of radical and normal: Deeley, Mackay and Fisher all developed both hardware and techniques. However, elsewhere the technology was also being employed in normal usage. For instance, within the King's civil engineering department, analog computing was applied to problems such as investigating stresses and strains in concrete, or studying soil seepage and groundwater flow.⁴⁸ These examples were not innovative developments of technology, but were research studies exploring the technology's potential application.

Analog computing at Birmingham

A major location for research *using* analog computing was the departments of electrical engineering and civil engineering at the University of Birmingham.⁴⁹

⁴⁶Anon. (2007/1987). It was through developing the analog computer that MacKay developed early three-dimensional projective displays, see MacKay (1949). A projective display uses coordinate mapping creates a three-dimensional effect.

⁴⁷By the 1960s research into analog computing hardware was limited to the development of peripheral hardware or improvements in speed. In general, the majority of such investigations occurred within the laboratories of manufacturers rather than universities; university research focused on techniques and application.

⁴⁸In 1950, John W. Bray explored a variety of analog models including electrolytic tanks which he found inferior to resistive networks. His large resistor networks were encased in perspex to protect against dust or moisture, and photographs of his set-ups are included in his thesis (Bray, 1950). In 1958, under the supervision of Nash (a reader in Civil Engineering), research student Gordon Brooke completed an MSc dissertation on investigating soil seepage using an electrolytic tank (Brooke, 1950).

⁴⁹Analog techniques were also applied to mechanical engineering research. For instance, around 1950 a number of students undertook research projects investigating analog models. See for instance Amos (1959) or Loosemore (1960). Interestingly these studies did not refer explicitly to computing (referring instead to 'resistor-capacitance analogues' or 'resistance-inductance analogues'), but still referenced texts within what was understood as the analog computing

Year	Researcher	Degree	Department	Supervisor	Technology
1950	J. W. Bray	PhD.	Civil Eng.	Prof. A. D. Ross	Electrical tanks and networks
					<i>An electrical analogue for the estimation of temperatures in the mass-concrete structures.</i>
1950	E. M. Deeley	PhD.	Physics	–	GPAC
					<i>Electro-dynamical methods of computation.</i>
1951	D. M. MacKay	PhD.	Physics	Coulson	Rep-op GPAC
					<i>The application of electronic principles to the solution of differential equations in physics</i>
1955	G. D. Bergman	PhD.	Physics	D. M. MacKay	Rep-op GPAC
					<i>Application of the principles of electronic storage to the solution of equations in physics.</i>
1957	M. E. Fisher	PhD.	Physics	D. M. MacKay	Rep-op GPAC
					<i>The solution of problems in theoretical physics by electronic analogue methods.</i>
1958	G. Brooke	M.Sc.	Civil Eng.	J. K. T. L. Nash	Electrolytic tank
					<i>Analysis of seepage in soil using an electrolytic tank.</i>
1963	G. F. Harris	PhD.	Electrical Eng.	Grieg; E. M. Deeley	Rep-op GPAC
					<i>A study of a cathode ray tube multiplier for analogue computation.</i>
1966	E. E. Okon	PhD.	Electrical Eng.	E. M. Deeley; Grieg	Rep-op GPAC
					<i>Computation of inductance and alternating current resistance by analogue and digital methods.</i>

Table 5.2: Analog research dissertations at King's College, London

Within the Department of Electrical Engineering, the application of analog computing techniques was directed by Professor A. Tustin, who throughout the 1950s supervised research students in control engineering and electrical system design.⁵⁰ During the second half of the decade, the department's technicians built a rep-op machine to support the research of Cecil J. Pengilley, a PhD student who was modelling the characteristics of electrical systems.⁵¹ Analog research within this department came to an end around 1960.

Within the Department of Civil Engineering, a research programme evolved that would favour analog computers based on resistive networks and apply them to various aspects of civil and aeronautical engineering. The programme was mobilised by Professor S. C. Redshaw, and investigated the applications of resistive network analogs to solving engineering problems such as heat flow, structural stability and aerodynamics.⁵² Redshaw was a major contributor to the development of resistance network analogs. During WWII he had worked with Bolton

literature.

⁵⁰Because much of this work was of a prototyping nature, each of Tustin's research students constructed (or rather, had technicians construct) an analog computer from basic components.

⁵¹The high speed analog computer followed the techniques developed by Macnee and incorporated the work of MacKay and Fisher at King's College. The computer also incorporated high speed curve-following techniques using a cathode-ray-tube set up. More detail into Pengilley's work is detailed in his doctoral thesis which contains a photograph of the set-up (Pengilley, 1957, p. 58).

⁵²As we will see in Chapter 7, there were two major approaches to solving problems relating to fluid flow in aeronautics: tanks or networks. Redshaw's department favoured networks.

Aircraft developing electrical analog techniques for aircraft design, and held a patent for the improved network analyser he invented.⁵³ Over the following two decades, the group made numerous studies in electrical analog methods, particularly favouring the use of resistance networks, and received funding from a variety of sources including the Ministry of Supply (MoS), the Department of Scientific and Industrial Research (DSIR), and the Civil Engineering Research Council.

While the research undertaken by Redshaw and his research students was applicable to a wide range of applications, the Ministry of Supply provided funding for a number of projects to focus on aeronautics. One of the researchers to be funded under this program was Kenneth Rushton, who under Redshaw's supervision received a PhD in 1960.⁵⁴ After receiving his PhD, Rushton became a full-time member of academic staff, eventually becoming a professor of Civil Engineering.⁵⁵ His doctoral research involved improving the techniques of using Redshaw's 'fine mesh resistance network', to investigate stresses in metal plates and the effects of extension and flexure – issues vital for the design of aircraft (see Chapter 7).⁵⁶ This work made extensive use of 'negative resistances' (see Figure 5.4).⁵⁷ The benefit of using these negative resistances was that problems that had previously required a combined resistor-capacitor or resistor-inductor network could be accomplished with a pure resistor network.

In Rushton's initial years as a lecturer, his main responsibility was to manage the analog laboratory, and in this capacity he took an active role in assisting

⁵³One of his research students described how he had devised a 'novel method' for constructing large networks based on a mesh of resistance ribbon (Copson, 1957, p. 9).

⁵⁴Rushton (1960). A number of Redshaw's research students (Anne Copson, Kenneth Rushton, and H. Ward) were applying networks and other electrical analogs to aerodynamics. Ward (1962) compared tanks and networks. He described that the electrolytic tank offered 'a rapid and accurate means of calculation for the lifting surface problem.' (p. ii) He also used the Birmingham resistance network to investigate and model the airflow at leading edge of a delta wing and progressed onto cambered wings, demonstrating that resistance networks could be employed as 'a design method for any given cambered wing.' (p.iii).

⁵⁵Rushton received a DSc for his collected papers in 1971 (Rushton, 1970).

⁵⁶Rushton (1960). Rushton's thesis is full of photographs of set-ups on the Birmingham network analyser, each a spaghetti of wires for solving different problems of varying complexity.

⁵⁷In an electrical circuit, electrical resistance determines the electrical current. Rushton's 'negative resistance' circuit induced a current in the opposite direction, hence giving the impression of a negative resistance.

Year	Researcher	Degree	Department	Supervisor / Assistance	Technology
1951	D. R. Holloway	MSc	Elect. Eng.	A. Tustin	Analog control
	<i>Some aspects of control system analysis and an electronic simulator...</i>				
1953	E. Hofstetter	MSc	Elect. Eng.	A. Tustin; J. G. Henderson	GPAC
	<i>The design and applications to linear system analysis of an analogue computer for product integrals.</i>				
1957	C. L. Pengilley	PhD	Elect. Eng.	J. G. Henderson; A. Tustin	?
	<i>An investigation into the application of correlation and analogue techniques...</i>				
1957	A. R. Copson	MSc	Civil Eng.	S. C. Redshaw	Network analyser
	<i>An investigation into the use and accuracy of electrical resistance analogues...</i>				
1958	R. J. Churchill	MSc	Elect. Eng.	J. C. Cluley	?
	<i>An analogue computer for a nuclear power reactor.</i>				
1959	J. D. Amos	MSc	Mech. Eng.	B. Mills	?
	<i>An electrical analogue for the solution of vibration problems in engineering.</i>				
1959	G. P. Loosemore	MSc	Mech. Eng.	B. Mills	Network analyser
	<i>An A.C. network analyser for the study of mechanical vibrations.</i>				
1960	K. R. Rushton	PhD	Civil Eng.	S. C. Redshaw	Network analyser
	<i>The solution of elastic plate problems by direct current electrical analogues.</i>				
1962	H. S. Ward	PhD	Civil Eng.	S. C. Redshaw	Network and Tank
	<i>The application of electrical analogues to the solution of some aerodynamic problems.</i>				
1962	K. S. Chan	PhD	Civil Eng.	S. C. Redshaw	Network analyser
	<i>Electrical analogue solution of heat conduction in solids.</i>				
1962	J. B. Menzies	PhD	Civil Eng.	S. C. Redshaw	Network analyser
	<i>The analysis of thin shells by electrical analogues and scale models.</i>				
1965	B. D. McManus	MSc	Civil Eng.	S. C. Redshaw and K. R. Rushton	Network analyser
	<i>The analysis of pipe networks by means of a pure resistance electrical analogue.</i>				
1965	M I Webbe	PhD	Civil Eng.	S. C. Redshaw	Network analyser
	<i>An electrical analogue for the stress analysis of arch dams.</i>				
1966	R. Herbert	PhD	Civil Eng.	S. C. Redshaw	Network analyser
	<i>Analogue computers to study ground water flow.</i>				
1966	C. A. T. Harden	PhD	Civil Eng.	K. R. Rushton	Network analyser
	<i>The solution by electrical analogue of certain elastic plate problems.</i>				

Table 5.3: Analog research dissertations at Birmingham

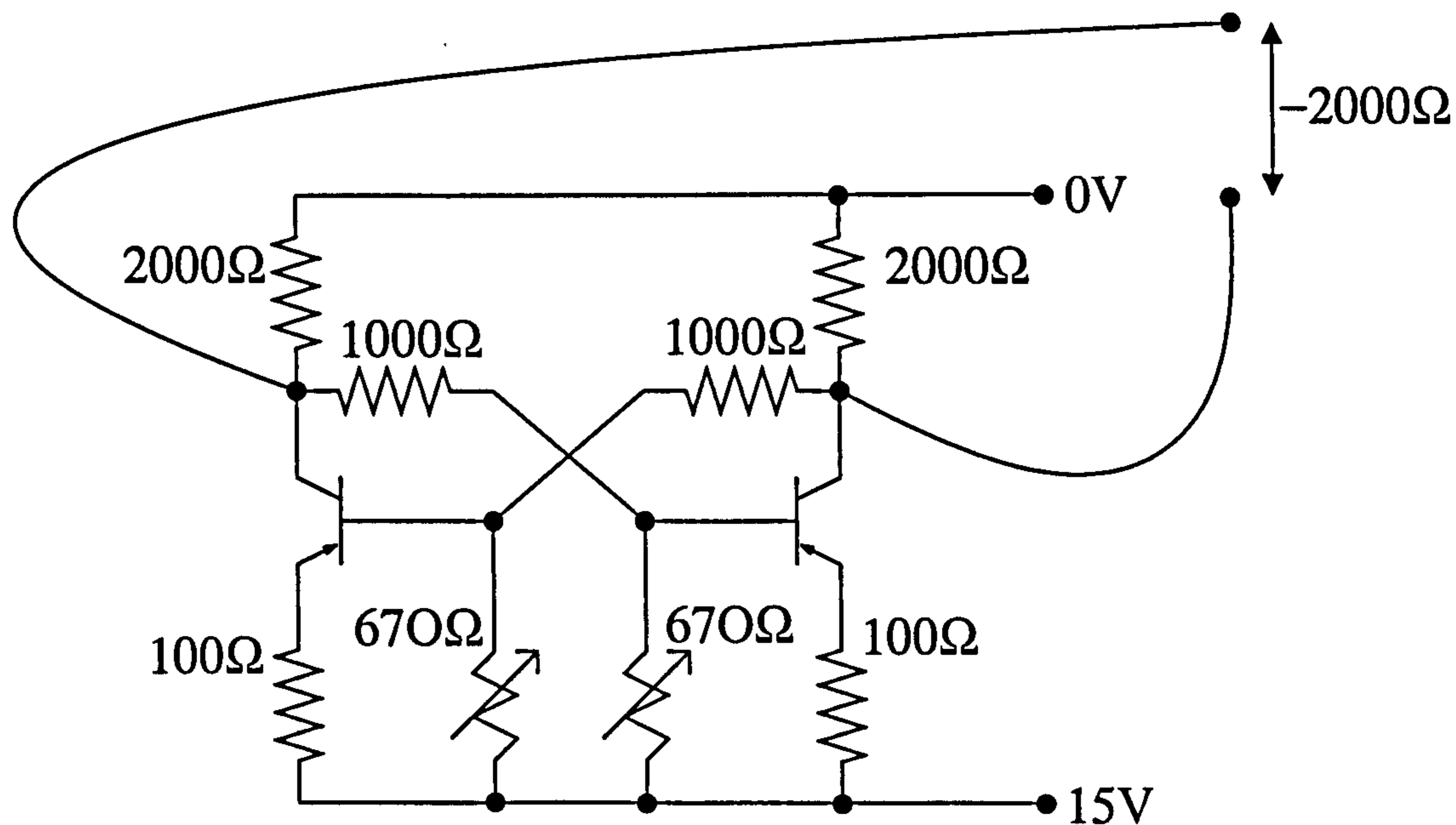


Figure 5.4: The negative resistance circuit employed by Rushton in his investigations into elasticity. The component values shown correspond to a negative resistance of -2000Ω . Driven by an individual battery the adjustment of a particular negative resistance (using the variable resistors) avoided interference with the settings of other negative resistors in the network. Redrawn from the original in Redshaw and Rushton (1961b).

Redshaw's later students, and subsequently supervised many of his own.⁵⁸ From these investigations, Rushton applied the techniques developed from elasticity research to flow problems, both airflow (investigating the wall interference in wind tunnels), and water flow (studying groundwater flow and 'multi-well dewatering systems').⁵⁹ Subsequently, Rushton and Redshaw co-authored a number papers and a book on hydraulic flow.⁶⁰

Analog computing at the University of Bath: an example of a technical college

At the University of Bath analog laboratory, which was established in the early 1960s (first as the Bristol College of Science and Technology, and then as the University of Bath) analog computers were bought-in from industrial manufacturers.⁶¹ Equipped with 12 teaching machines, its analog laboratory had responsibility for teaching analog computing techniques to mathematics and engineering undergraduates. As a result of being situated within a mathematics department, they developed a different approach to teaching analog computing – evident in the publication of their textbook on analog *programming* which became one of the standard works for teaching analog computing in Britain. Moving away from

⁵⁸See Harnden (1966) p. 156; Rushton (1970) pp. 2–4. Rushton assisted McManus with the investigation of pipe networks, and they undertook a design study on the water network of the Corporation of Coventry, proposing the analog method as a simple and cost effective solution (McManus, 1965, introduction). He also assisted Chan looking at heat conductance problems (Chan, 1962, p. 203). With Herbert he investigated ground water flow (Herbert and Rushton, 1966) and subsequently assisted Harnden who further investigated the stresses of plates, extending the analysis to plates of variable thickness, and comparing both analog and digital methods (Harnden, 1966, p. 156). After Redshaw's departure, he supervised Lucy M. Laing who was undertaking wind tunnel studies, and was still using analog techniques in 1970. See Rushton (1970), item 30.

⁵⁹Rushton (1967); Herbert and Rushton (1966); Rushton (1970) pp. 2–3.

⁶⁰They published a number of collaborative papers derived partly from the work detailed in Rushton's PhD thesis – see Redshaw and Rushton (1960, 1961a,b). Their book, published after Redshaw had retired was entitled *Seepage and Groundwater Flow* (Rushton and Redshaw, 1979).

⁶¹First from the manufacturer Solartron, and later from the Anglo-American firm Electronic Associates Limited. Electronic Associates produced the high quality PACE machines and became the dominant provider of commercial analog and later hybrid computers. As well as manufacturing computers, EAL also ran a successful analog computing centre at Burgess Hill. See Small (2001) pp. 201–202; Anon. (1956–1958).

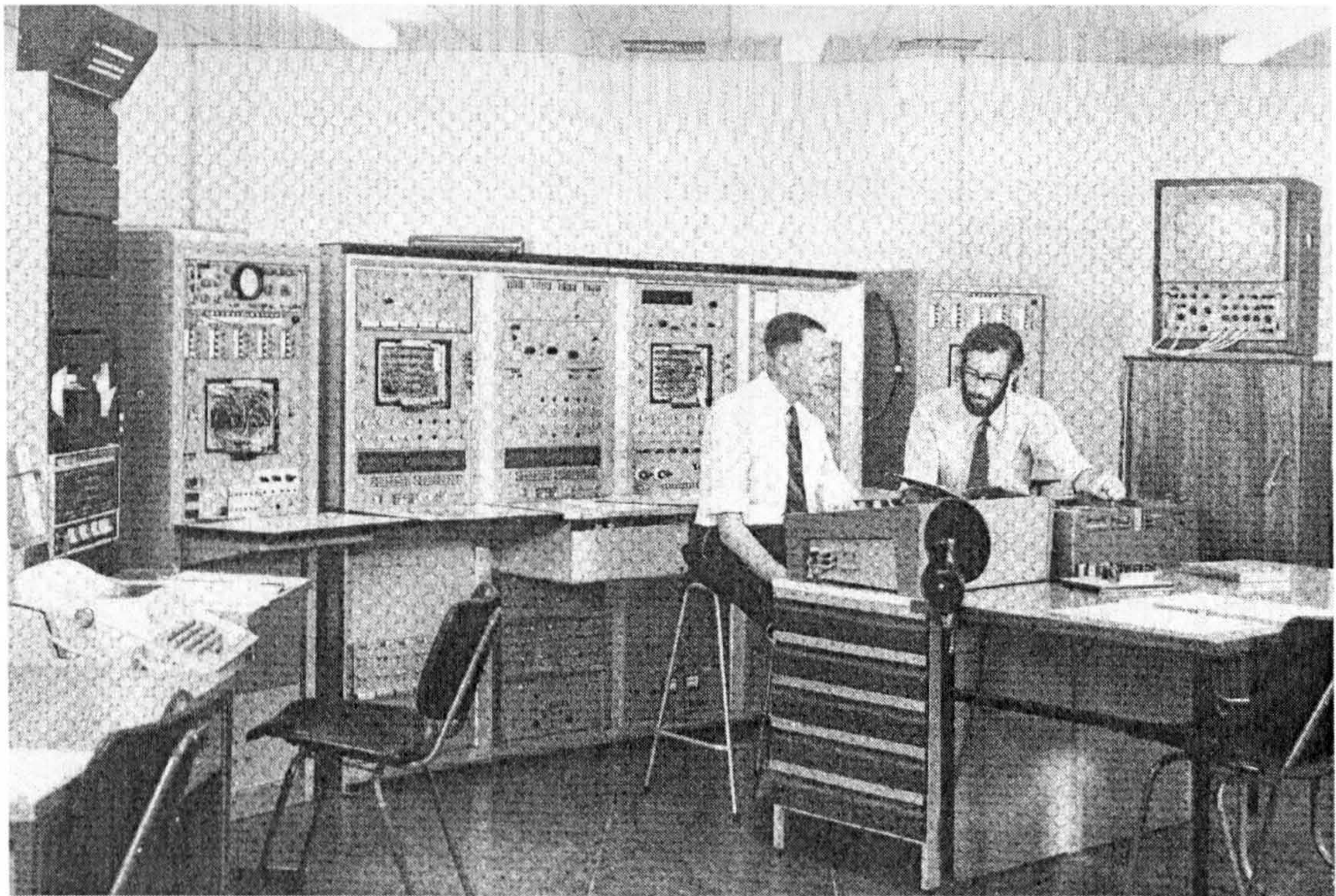


Figure 5.5: The analog/hybrid lab at the University of Bath. Source: Charlesworth and Fletcher (1974)

the traditional ‘electrical engineering’ presentation of analog computing, their textbook contained fewer circuit diagrams, presenting the analog computer as a mathematical machine.⁶²

Alongside these undergraduate teaching commitments, the academic staff ran a number of short courses focused on industrial users. In particular they would run a week long course for Rolls-Royce engineers to teach analog programming. They also undertook contract simulation studies, including investigations of the effect of earthquakes on buildings. As such, the Bath laboratory was an example of normal analog computing that used commercial analogs as tools. In the next section we will see how a funding request for one of their teaching machines became stuck within a political analog-digital debate.

⁶²The textbook, *Systematic analogue computer programming*, presented a method, whereas previous texts introduced the technology from an electronic engineering perspective. As well as this ‘black-box’ approach, the text pushed for the machine unit programming of an analog computer, allowing particular GPAC problems to be re-used on the analog computers of other manufacturers (Charlesworth and Fletcher, 1974).

The work at Bath finally came to an end in the late 1970s.⁶³ Anecdotally, the final crunch is said to have come when a mathematics professor decreed: ‘they look old, I will have none of them.’⁶⁴ The staff then had to transfer into new disciplines. For example, Alan Charlesworth, their ‘senior hybrid programmer’, became an expert in relational databases. It was because of the department’s involvement with hybrid computers that analog had been able to persist this long, the machines co-existing with digital.⁶⁵

The Flowers report and the funding of analog computing

Through looking at a number of academic contexts, we have seen how the analog applications of calculation, simulation, and control were disparate in activity but associated in name. This association meant that the subtle differences between analog and digital became critical for funding bodies in determining whether or not to award grants. In an article discussing the provision of digital computers for UK universities, Agar (1996) noted three rounds of funding opportunities, culminating in the publication of the Flowers Report. This report was a major landmark in the public funding of computers, and as a policy, accelerated the transition from analog to digital.

The recommendations of the committee chaired by Brian Flowers, a professor of physics at Manchester University: the Flowers Report set out guidelines for funding university computing. To quote Agar, it recommended ‘at least one

⁶³Although still used up until this period, the focus on the analog technology had been diminishing with the introduction of digital process controllers. Toward the end of the 1970s engineers began to learn about digital controllers rather than analog ones, and the analog computers were used to simulate the controlled environment so that the digital controllers could be tested.

⁶⁴Alan Charlesworth, interview.

⁶⁵When interviewed, Alan Charlesworth recalled how the research team at Bath had once ‘tuned’ the circuits of an analog computer to musical notes, and then used a digital computer to play Christmas carols. Like MacKay’s developments of computer visualisation technology, an understanding of both analog and digital was helpful for experimenting with multimedia applications.

computer per university and a budget commitment over twice that imagined a year before.⁶⁶ In identifying the key needs for the following five years, it was perhaps appropriate that the committee had decided to focus on digital machines.⁶⁷ However, in doing so, the policy makers failed to leave room for the users of analog. As a consequence of increasing the funding of digital, analogs were left without a funding category and became the 'poor relation' of computing.

Within the University Grants Committee, the responsibility of processing the requests for computers fell on to the civil servant Donald F. E. King. For King, analog-digital issues were of everyday concern. One request causing difficulty was from the Bristol College of Science and Technology for an analog computer costing £13,100. Submitted in early 1965, around the same time that the Flowers Committee was formed, this application's review and assessment was delayed while King's team awaited the guidance of the report's conclusions.⁶⁸ With the Treasury allocating the funds to underwrite the extra investment proposed by Flowers, it became increasingly difficult for computational equipment to be provided outside the remit of the Flowers budget. Frustrated by the conflicting situation of a report not covering analog, and a treasury wanting centralised computer spending, King was in a difficult position. In June 1965 he wrote to Sir Willis Jackson, then a member of the UGC, seeking guidance as to how analog computers should be treated.⁶⁹ King was concerned as to whether they should even be considered computers:

We have... an application outstanding from Bristol C.S.T. for an analogue costing £13,100. Your Committee did consider it but asked for it to be referred back to the College to enquire whether the work

⁶⁶Agar (1996) p. 642.

⁶⁷The report records how they '...decided that the review should concentrate on general facilities for digital computing and should exclude consideration of analogue computers.' (HMSO, 1966, para. 34).

⁶⁸See UGC (1952–1953). The committee was established in March 1965 at the request of the Frank Cousins, the Minister of Technology.

⁶⁹A decade previous, Willis Jackson had held the Chair of Electrical Engineering at Imperial and supervised analog computing research. After leaving Imperial he held a number of industrial and civil service positions, before returning to Imperial in the mid-1960s. He was a member of the UGC between 1955 and 1965. See Brown (2004).

could not be done on their digital machine... All this has been held up by Professor Flower's activities but the College is getting restive, and now we know that Professor Flowers decided not to deal with analogues.

...the Treasury's present wish is to include analogues in the money to be made available for digital machines arising from the Flowers Report. We [the UGC] feel that this is wrong in principle and that were analogue computers called e.g. 'simulators', as they might well be, they would be regarded as ordinary equipment.⁷⁰

While King wanted to argue that analog computers were essentially quite different from digital computers and so not within the Flowers remit, or budget, he needed 'an authoritative statement of the difference between analogue and digital computers.'⁷¹ Agreeing with King, Jackson responded and suggested that he approach Professor G. Black of Manchester University. Black was one of the members of the Flowers Committee and was asked to supply a better definition between analog and digital.⁷² Black was, in Jackson's opinion, an 'anti-analogue computer man'⁷³, but in a written reply, he provided King with a fair account and an interesting taxonomy. Distinguishing between differential analysers and 'simulators', he emphasised the importance of analog computers in solving engineering problems:

Simulators are analogue machines fitted up to illustrate the workings of a physical system and are called Simulators to distinguish them from the general purpose analogue machine which is used to solve a branch of mathematical problems – differential equations.

...

Digital machines are generally favoured by physicists and mathematicians who are prepared to tackle problems like integration step by step-wise. The numerical analysis of such computations can be sometimes quite intricate and delicate. Analogues are favoured by mechanical and electrical engineers because they like the idea of substituting

⁷⁰Letter from D. F. E. King to W. Jackson, 29th June, 1965 (UGC, 1952–1953).

⁷¹Letter from D. F. E. King to W. Jackson, 29th June, 1965 (UGC, 1952–1953).

⁷²There were nine members of the Flowers Committee. The others were: Prof. B. H. Flowers, Dr R. F. Churchouse, Dr B. Collinge, Dr K. V. Roberts, Prof. M. J. Seaton, F. J. M. Laver, Dr A. V. Cohen, and Dr D. W. Tanner. See HMSO (1966) para. 33.

⁷³Memorandum to King regarding phone call from Jackson, 1st July, 1965. (UGC, 1952–1953).

electrical quantities – things they can imagine and measure for the quantities they are thinking about.⁷⁴

Black described how engineers and physicists fell into distinct analog and digital ‘types’ and that there was a higher proportion of ‘analogue types’ in the CATs (Colleges of Advanced Technology) than in the universities. He acknowledged that analog computing was useful for speculative investigation and felt that the Bristol machine should be granted due to a lack of suitable digital facilities in the Bristol area. While analog was not cutting edge, the case for the Bristol machine was also stronger by virtue of it being ‘of reasonable cost’:

The problems that they mention... are all solvable on a digital computer if it were big and fast enough... but they can be solved only if they are very clear about precisely what they want to do. My feeling is that they are not and want an analogue machine which they can understand, to play with.

...

By modern analogue standards what they have asked for is quite small. We would need to have much better evidence in support of a ‘hybrid’ machine which would be 5 or 10 times as expensive.⁷⁵

Conscious of not wanting to set a precedent to fund analog, Black suggested that teaching machines, which he expected to cost around £5,000, should be considered as laboratory equipment. He noted that while there were no procedures in place to deal with the research machine requests, he felt that ‘the machinery which is recommended in the Flowers report should be quite capable of dealing with the few research analogue applications.’⁷⁶ This was an optimistic view. King thanked Black for his assistance, and decided that analog computing would be billed as general purpose teaching equipment.

During the following months, the UGC discussed these issues with representatives from the Ministry of Technology (MinTech). Eventually, the Ministry agreed

⁷⁴Letter from Prof. Black to D. F. E. King, 10th July, 1965 (UGC, 1952–1953). ‘Modern digital computers’, Black wrote, ‘are an extremely sophisticated abacus; they simply add, subtract, multiply and divide extremely rapidly when “told” to do so.’ In contrast he explained that analog ‘cannot and does not count. Rather it measures.’

⁷⁵Letter from Prof. Black to D. F. E. King, 10th July, 1965 (UGC, 1952–1953).

⁷⁶Letter from Prof. Black to D. F. E. King, 10th July, 1965 (UGC, 1952–1953).

to allocate analog, hybrid and digital-differential analysers within the provision of 'normal equipment', but limited funding to British machines costing less than £10,000. Any analog requests not following this 'buy British' policy or costing more than the threshold required further authorisation.⁷⁷ Bristol's application along with similar applications from Manchester and other technical colleges remained unresolved. In a memo dated January 1966, King wrote:

Bristol C.S.T's application for an analogue computer got put on one side during the period when the Flowers Report was being prepared and later when it was under consideration. We are awaiting a letter from the Department about money for analogue computers and until we get this we can make no progress with Bristol C.S.T's application. As soon as the lines are clear, however, we ought to get expert advice on the machine and clear with the Ministry of Technology, if necessary.⁷⁸

And finally, by late March 1966, about a year after the college's original application:

...agreement has now been reached with the Treasury that analogue computers, hybrid digital-analogue computers and incremental computers, should all be treated as ordinary equipment and charged against the universities' normal non-recurrent grants.⁷⁹

So we can see how the complexities of technical definition and classification shaped the funding policies of the period. Although the success of the digital computer is founded upon generality, accuracy, and speed; its dominance is not just the result of applicability. Here we have seen how analog-digital classification and rhetoric were key factors driving the shaping of funding decisions. Effectively, the treasury wanted to fund all computers from the same 'pot', and the UGC wanted to process applications quickly and fairly. On the other hand,

⁷⁷Letter from D. M. Dell to D. F. E. King, 12th January, 1966 (UGC, 1952-1953). At a meeting on the 17th January, King put forward his proposal to treat hybrid in the same way as analog, feeling that 'these computers would probably have a very limited range [of application] and might therefore be treated as analogues.' See UGC (1952-1953), minutes of meeting on the 17th January 1966.

⁷⁸Memorandum from D. F. E. King to E. M. Church, 11th January, 1966 (UGC, 1952-1953).

⁷⁹Letter from H. B. Jay (Department of Education And Science) to E. M. Church (UGC), 7th April 1966 (UGC, 1952-1953).

the Flowers Committee were a technical group with a bias towards digital machines. Not wanting to set precedents about analog procurement, they placed analog computing out of scope, describing small analogs as 'laboratory equipment' and large analogs as unnecessary. This acted in tension with the university departments who wanted specific machines to pursue their research and teaching agendas. The result of this pushing and pulling was the eventual 'separation' of analog computing from mainstream computing. Analog devices had previously been enrolled into a discourse of computing, and in riding this bandwagon had benefited from the association with digital. Analog was now the poor relation of computing and the association had turned sour.

Conclusion

This chapter demonstrated that not only were analog computers used for different applications, but the historical trajectories for each were different. Thus analog's calculation use became insignificant quite early on. This is exemplified in the way the differential analysers of Manchester and Cambridge often appear in the narratives as leading on to subsequent digital developments. While this strengthens Small's argument that post 1950s analog computing was downplayed, it proposes a different explanation of *why*. Rather than being downgraded, the analog use that remained significant was the modelling and simulation applications (and control applications lasted even longer). This is a clear example of how these different interpretations of 'computing technology' have been shaped through different usage, and so need separate historiographic narratives.

A history of use covers not just the technologies, but also the people. In the accounts of the various institutions, one commonality is that it became necessary for academics who researched and taught analog computing to redefine their expertise. In the accounts of Imperial and Manchester, we saw analog experts redefining themselves into simulation experts. Some analog pioneers moved into

new fields. For instance, MacKay applied prior knowledge of information theory, analog computing and control, in his neuroscience research, his analog background allowing him to develop novel visualisation techniques. At Bath, Charlesworth used the digital expertise gained through his hybrid research to make a transition into digital database work.

Another example of this academic redefinition is seen in the story of the Department of Electrical Analogy founded by Pérès and Malavard in Paris (discussed in Chapter 7). As analog computing began to be replaced, this department redefined itself, and through expertise in hybrid computing, evolved into a research centre renowned for speech recognition, computer graphics and fluid dynamics.⁸⁰ Expertise in hybrid computing equipped its users with a broad range of transferable skills for a career in computing. Indeed, many people thought that hybrid computing would be the way forward. However, as we have seen, funding schemes – like those governed by the Flowers Report – badly managed the analog-digital classification, and the result was that only small teaching installations were procured. Had such funding initiatives been more open to analog computing, the digital computer would still have become dominant, but we might have seen more development of hybrid computing along the way.⁸¹

In summary, this chapter highlighted the need for user-centric history based on multiple perspectives of use. In considering users it noted how analog users evolved into digital users in a process of redefinition, and how certain application areas of simulation, modelling and visualisation were common ways of redefining analog expertise into the digital world. In this story of redefinition, higher edu-

⁸⁰See Chapter 7, page 194, below.

⁸¹For instance, in 1962, *Time Magazine* announced a new hybrid research programme proposed by John E. Gibson (Purdue University). It reported: ‘Gibson is preparing to “mate” an analogue computer, which solves mathematical problems in a flash, with a digital computer, which possesses a superior “memory.” Gibson’s belief is that when the combined machines encounter a strange situation, they will be able to reason out a solution for it on the strength of their recorded memory of experiences with related problems in the past. The Purdue crew anticipates that the coupled computer systems will be working together well enough to tackle practical problems by late 1964.’ (Anon., 1962b). For the computer community of the 1960s, it was expected that future progress would involve a mixture of both analog and digital.

cation provides an interesting window on the issue of analog association. While the 1940s had seen electrical analogies become enrolled into computing discourse (and thus receive funding benefits deriving from the modern status of computers), the late 1950s and early 1960s saw the situation swing the other way. Now the poor relation of computing, analog became excluded from computer funding schemes, and analog people became redefined into modelling people.

Chapter 6

Analog computers and oil reservoir modelling

OILFIELD STUDIES BY COMPUTER

Oil engineers will soon be able to feed back information concerning oil reservoir structure and oil well behaviour from various parts of the world to the BP research centre at Sunbury-on-Thames, where an EMIAC II analogue computer will synthesize the data and make it possible to predict optimum operating conditions.

The Times, 1962¹

For many industries, the period 1950–1960 saw an increasing dependence on computational support to manage commercial activities. The petroleum industry was at the forefront of these developments, with BP (British Petroleum) being one of the first British companies to purchase a large digital computer.² Within this context of extensive digital computer use and investment, it is interesting that in November 1962, an analog computer (or analyser) was installed to aid the work of BP's Exploration Research Division. As well as providing support to BP, Exploration Research offered consultancy services to other oil companies, and it was for this work that the reservoir analyser was most useful.

Earlier we referred to electrolytic tanks, and an interesting example of analog computing as a modelling medium is the application of these tanks (and also

¹Anon. (1962a) p. 20.

²BP installed an English Electric DEUCE in 1956 to perform refinery related calculations, but the machine was extensively applied to solve Operational Research problems. See Bamberg (2000) pp. 398–399.

resistor networks) to the modelling of oil reservoirs. This application dated back to the 1930s when researchers working for large petroleum corporations began to develop electrical models to model the hydrodynamics of subterranean oil reservoirs.³ The analog computer installed at BP allowed reservoir engineers to simulate an oil field reservoir through the creation of an electrical analog that could be studied in a laboratory setting. Through exploring the effects that various oil production strategies had on this model, the computer could be used to predict the optimum operating conditions of an oil well. It was manufactured by EMI Electronics Ltd to the custom specification of BP engineers and installed at the BP Research Centre in Sunbury-upon-Thames.

Based on reservoir modelling techniques developed by two American companies – Carter Oil and Sun Oil – the BP computer was the first installation of its kind in the UK.⁴ For the engineers who prepared the specification of the BP machine, analog computing was not a technology ‘on the way out’, but rather a technique that was still being developed and explored; distinct, and yet complementary to digital computing. By mixing the techniques developed at Sun and Carter, the BP analyser was a novel application of high speed analog computing. Using BP as a context of use, this chapter explores the history of the analog reservoirs that inspired the BP installation, and then investigates the story of the BP computer.

Despite their use of analog computing, the engineers at BP did not actively engage with the analog-digital debate. Located within an industrial setting, the BP engineers pursued analog techniques because other oil companies were deriving useful results from them. The story of the BP analyser questions the validity of understanding analog as a predecessor technology, or even as an alternative, to digital. At BP, analog and digital were *complementary* technologies of computing.

³The link between electrical models and computers was forged as the inventors of reservoir analysers began to patent and publish their work, as well as incorporating the early analog technology developed by electrical engineers. Through such associations, the electrical analyser became known as an analog computer. See for instance Murty (1964) vol. II, pp. 14–21.

⁴BP Newsletter (1961b). Carter were a subsidiary of the Standard Oil Company.

Production management and the application of analog computing

Industrial oil production revolves around a cycle of licensing concessions on areas of land or seabed and exploring them for oil; once a reservoir is discovered, suitable techniques are applied to extract the oil. Throughout the history of this industry, petroleum engineers have developed various techniques to maximise oil production and different strategies need to be applied to different oil fields. Since badly made production decisions can render large volumes of crude oil unobtainable, predicting the long-term effects of a production strategy is important.⁵ During the early twentieth century, petroleum companies became increasingly aware of the need to reliably predict reservoir behaviour, and this initiated research programs to develop mathematical models of pressure gradients and fluid flow.⁶ However, due to the mathematical complexities associated with this theory, reservoir engineers turned to analog models – physical systems with behaviours analogous to the reservoir.⁷

The main purpose of the early reservoir analysers was to predict the pressure changes due to the effects of water influx. Most oil reservoirs are surrounded by porous water-bearing rocks known as the aquifer, and because these exert hydraulic pressure on the reservoir, variations in aquifer pressure determine production rates.⁸ As a dynamic model, the reservoir analyser became an important tool for long term production management.⁹

⁵Production research offered significant improvements in oil production. Barger and Schurr (1972) estimated that in the early years of petroleum production the total recovery of a well was only in the region of 10–20 percent of the total amount of oil present. By the 1970s this proportion had increased to between 70 and 80 percent (p. 204).

⁶Carter (1961) notes that prior to the mid-1920s, there was no significant or organised production research with a long-term perspective. What was going on was ‘sporadic and unorganised’ and ‘primarily for immediate utility’ (p. 1098). For Constant (1989) it was not until the end of World War II that reservoir engineering was fully developed into a ‘mathematically rigorous, well formulated body of esoteric knowledge.’ (p. 444).

⁷Carter (1961) pp. 1026 & 1097.

⁸See, for example, Craft and Hawkins (1959) p. 205.

⁹Such decisions were not only important for obtaining the maximum output of a reservoir, but also assisted with the conservation of natural resources. In their company periodical, Carter Oil asserted that their analyser could ‘[forecast] the production future of an oil field in

The first widely reported application of analog computing principles to oil reservoir calculations is the work of William A. Bruce, a researcher for the Oklahoma-based company Carter Oil. His invention of an 'analyzer for subterranean fluid reservoirs' in 1942 showed that the dynamics of an underground oil reservoir, and in particular the hydraulics of water bearing rocks, could be represented by electrical circuits.¹⁰

Modelling hydraulic pressures with electricity: William A. Bruce and the Carter analyser

Bruce had trained as a physicist, receiving a PhD from the University of Washington in 1938. His thesis investigated X-Ray scattering studies of zinc crystals, and shortly after graduation he joined the research team at Carter.¹¹ In line with his training as a materials physicist, Bruce was involved in investigating the effects of arc welding on the 40ft cylindrical tubes used to encase oil wells.¹² However, during the following years, Bruce turned his attention away from materials research and began developing the reservoir analyser, modelling an oilfield's aquifer region using a network of electrical components.

The analyser consisted of two sections, one an electrical analog of the reservoir and the other a resistor-capacitor model of the aquifer.¹³ The reservoir was represented by a tank with a conductive edge containing a low conductivity electrolyte (see Figure 6.1). By representing the water drive into a reservoir as a

the interest of conservation'. (May 1946 issue of *The Link*).

¹⁰Earlier analog models of reservoirs were developed during the 1930s. A history of Petroleum Engineering published in 1961 referred to the work of Wyckoff, Botse and Muskat. Published in 1933, this work used an electrolytic tank to model reservoir pressures. See Carter (1961) p. 1097; Soroka (1956) p. 364. A number of engineers were also developing scale modelling techniques to represent reservoirs.

¹¹Only three months passed between his last publication to acknowledge the University of Washington and the first to mention an affiliation to Carter. See Bruce (1938); Jauncey and Bruce (1938) p. 163; Severinghaus (1939) p. 594.

¹²See Severinghaus (1939) p. 594; Bruce (1939) p. 578.

¹³Bruce modelled the hydraulic pressures in the aquifer and reservoir by simulating water-influx (in-flow) and representing oil production (out-flow) with electrical current. The basic variables of the model were hydraulic pressure in the reservoir (in particular the 'well bottom-hole' pressure), inward pressure at the interface between the aquifer and the reservoir, and oil flow out of producing wells.

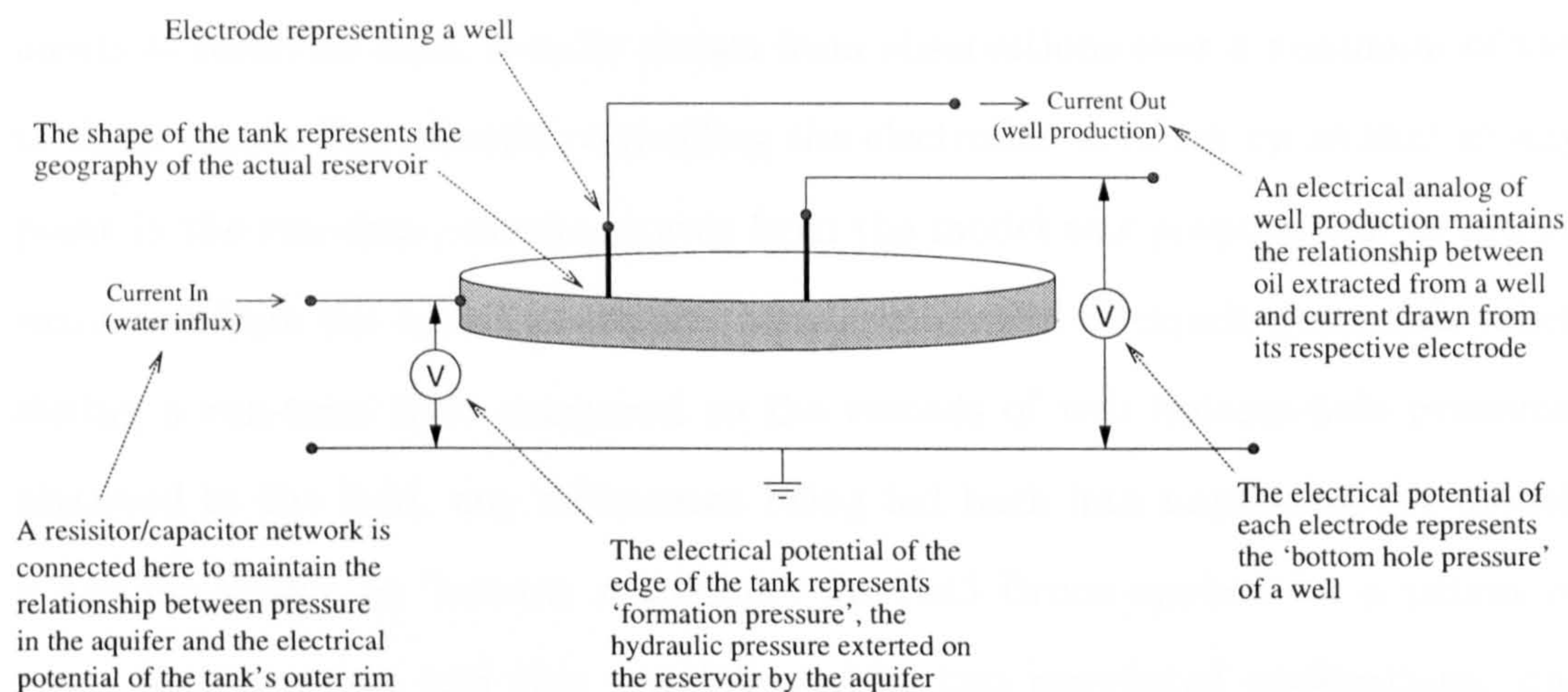


Figure 6.1: The main features of the Bruce reservoir analyser, interpreted from his 1947 patent. The reservoir is modelled with an electrolytic tank, with electrodes representing wells. Current flow into the tank is controlled by a model of the aquifer. The flow of current out of a given electrode is proportional to the production flow of the corresponding well.

Actual Reservoir (hydraulic)		Reservoir Analyzer (electrical)
Hydraulic capacitance of aquifer	\iff	Electrical capacitance in model
Hydraulic permeability of aquifer	\iff	Electrical resistance in model
Aquifer pressure	\iff	Electrical potential of tank's rim
Reservoir pressure	\iff	Electrolyte potential
Well bottom-hole pressure	\iff	Electrode potential
Oil produced from a well	\iff	Current drawn from electrode

Table 6.1: The hydraulic-electrical analogies employed in the Bruce analyser.

source of electrical power, the analyser enabled an analogy to be drawn between hydraulic pressures in the reservoir and its surrounding rocks, and electrical potentials in the electrolyte and its surrounding circuits. In an actual reservoir, water influx is caused by hydraulic pressures from the adjacent aquifer; on the Bruce analyser, the electrical potential of the reservoir's outer rim was determined by the output voltage of a resistor-capacitor network modelling the aquifer. The hydraulic-electrical analogies of the Bruce analyser are detailed in Table 6.1.

The Bruce analyser was 'programmed' for a particular oil field by adjusting the positions of wells, and also by adjusting the settings of variable resistors and capacitors to correspond to geographical features of the reservoir. After the initial setting up, the user would refine this model by 'playing through' past measure-

ments of reservoir data, usually drawn from observations over a minimum of two to three years. The circuits controlling the electrodes were set up so that at any point in the run-time, current drawn from the model was proportional to the oil extracted from the actual reservoir. Measurements of electrode potentials taken during a run-time were compared to the records of well bottom-hole pressures observed in the field, any differences being fed back into improving the model, a process known as 'historic matching'. In 1943 Bruce applied for a patent to cover his invention, and this was followed by two associated applications: one a refined model of the well and the second a tool for automating data input.¹⁴ A diagram from Bruce's analyser patent (reproduced as Figure 6.2) shows the variable capacitors (labelled 12) and resistors (labelled 14) that modelled the aquifer.

Following from the work of Bruce at Carter, a number of American petroleum companies invested in analog computer research, and by the mid-1950s reservoir analysers were in common use.¹⁵ The patent records show that other significant players were the Sun Oil Company, the Texas Company and Union Oil.¹⁶ The main improvements made by these companies in their patents often related to the user interface, providing, for example, the facility to manipulate the model dynamically.

Incorporating repetitive operation: the reservoir analysers developed by the Sun Oil Company

The second major influence for the BP analog computer was the series of analysers developed by Omar L. Patterson and other researchers based in Sun Oil's physical

¹⁴See Bruce (1947/1943); Bruce (1949/1945a); Bruce (1949/1945b).

¹⁵A contemporary paper (Odeh et al., 1956) commented on how the method had become 'an accepted procedure.' (p. 200.)

¹⁶In particular, a number of features of the Sun analyser (such as the roaming probe) were developed from the inventions of Texas Co. A detailed history of the different research projects is beyond the scope of this chapter.

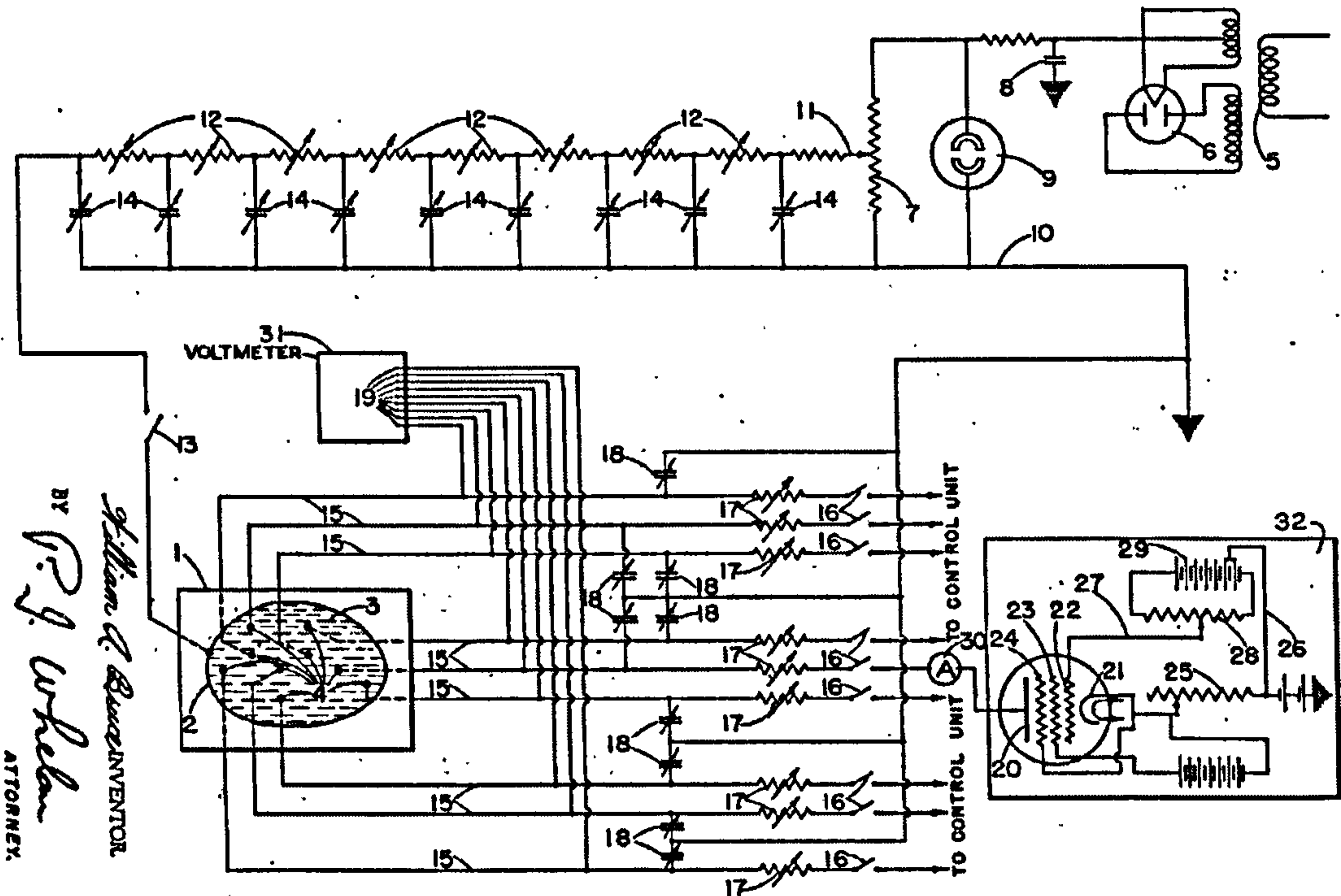


Figure 6.2: The diagram of the Bruce analyser in the issued patent. The array of capacitors and resistors at the top of the diagram make up the electrical model of the aquifer and are connected to the edge of the electrolytic tank by closing switch 13. The representation of the reservoir in the bottom-right of the drawing (labelled 1) is shown from above and comprises nine electrodes (illustrated by black dots) each modelling an oil well. Each of these electrodes is connected to the voltmeter (labelled 31) so that the bottom hole pressures can be measured. To model the production history of each well, each electrode is connected (via switch 16) to a control unit 'programmed' so that at any instant, the current drawn is proportional to the production flow of the oil well being modelled. One such control unit is shown in the bottom left of the diagram (labelled 32). Source: Bruce (1947/1943).

laboratory in Dallas.¹⁷ One of the early innovations from this group was the incorporation of an analog of a reservoir's gas cap, another important feature of subterranean reservoirs.¹⁸ These analysers were not just used for oil reservoirs but patented as generic analog simulators for solving problems defined by Laplace's equation. They also employed electronic techniques used in more mainstream applications. For instance, in his history of operational amplifiers, Walter Jung identified the analyser described in Patterson's 1951 patent application as an early use of a non-inverting amplifier circuit.¹⁹

The Sun analysers differed from those of Carter Oil in their use of repetitive operation, a technique popular in mainstream analog computing.²⁰ Bruce's analyser was a single shot computer and although time was scaled so that the model progressed much faster than the actual reservoir, analyser-time still moved slowly enough to allow the user to make measurements and compare analyser plots with trends observed in the field. In contrast, rep-op computers provided a technology for on-line analysis.

Utilising rep-op, the Sun analyser designed by Patterson incorporated time-scaling with fifty years represented by an analyser run-time of two milliseconds.²¹ Patterson's analyser used a roaming probe to take measurements and this made the recording circuits simpler than in the Bruce analyser (which had measuring

¹⁷Between 1949 and 1953, Sun Oil filed six patent applications for technologies relating to reservoir analysers, three of which were assigned to Omar L. Patterson. It is in this work that we can see the developing association between the reservoir analyser and analog computation, two of the patents being entitled *Analog Computer or Analyzer* (Patterson, 1955/1949, 1957/1950). Initially, Bruce had not made reference to analog, analogy or computer, and throughout his 1945 patent application had described his circuits as an 'electrical counterpart of a reservoir' (Bruce, 1947/1943, col. 2). Later analysers would be described as electrical analogs, marking the beginning of their enrollment into the discipline of analog computing.

¹⁸The gas cap analog was incorporated into a patent filed in 1950 and an account was published in 1951. See Patterson (1957/1950); Patterson et al. (1956) p. 79.

¹⁹Patterson (1958/1951); Jung (2005) p. 782.

²⁰See Chapter 2, page 61.

²¹While this allowed the historic matching to be completed on-line, the downside of the increased speed was that it became impossible for a user to make measurements directly. Many general purpose rep-op computers solved this problem by replacing user measurements and paper plots with the dynamic graphical output of an oscilloscope. However, Patterson used a different technique of 'pulse marking'. This involved using a synchronising circuit to trigger measurements and provided a means for 'a stroboscopic view of a recurrent phenomenon' to be captured. See Patterson (1955/1949) col. 2.

lines and recording circuits for each individual electrode). One major benefit of Patterson's roaming probe setup was that it became possible to investigate the pressure gradient between wells.²² To support the roaming probe, the analyser substituted the electrolytic tank of Bruce's machine for a solid model coated with conducting paint, the whole set up fitting onto a tabletop. The position of the probe was controlled by a pantograph mechanism: by moving a pointer to a given location on a paper diagram of the reservoir, the probe was positioned in the corresponding location on the reservoir model.²³ Rep-op would be used in all subsequent analysers developed at Sun Oil.

Further developments in the Sun analysers also saw a complete departure from representing the oil reservoir with an electrolytic tank or conductive model. Around 1950, Sun were managing the production of the Holt-Bryant reservoir in Louisiana, and investigations into this complex field exposed a weakness with the older analysers. Previously, all the analog models had all assumed that a reservoir could be accurately modelled as one single pool of oil; the Holt-Bryant study demanded the invention of a 'multi-pool' analyser permitting the reservoir to be treated as three separate pools.²⁴ As a consequence of these improvements in generality, the extra complexity of the multi-pool analyser initiated a transition towards rack mounted resistance networks. The reservoir analysers thus evolved to resemble a conventional network analyser installation. While this was appropriate for most applications, the original visual interactivity and continuity of the

²²Although this was of limited use in historic matching due to a lack of real-world observations from arbitrary locations in the actual reservoir.

²³Patterson (1955/1949). Other models mounted the probe on a carriage above a tank (Yetter, 1958/1952). The use of a roaming probe and pantograph mechanism had already been used to effect by Alexander Wolf and Burton Lee, researchers working for the Texas Oil Company (later renamed Texaco). Lee was the assistant director of the Geophysical Laboratory at Texas Co. and his team made a variety of improvements to reservoir analysers between 1945 and 1951. See Wolf (1951/1947); Wolf and Lee (1951/1947); Lee (1951/1947); Lee (1948); Lee and Herzog (1951/1949); Stelzer and Herzog (1954/1949); Stelzer and Herzog (1957/1951); Loofbourrow et al. (1957/1952); Stelzer (1961/1956).

²⁴This analyser also saw the incorporation of extra analog computing components (mainly integrators) for solving the material balance equation that maintained the correspondence between oil, water and gas production rates. In previous analysers this had been pre-calculated manually and input at run time. The Holt-Bryant reservoir was discovered in 1944 and was yielding oil by 1948. See Patterson et al. (1956) p. 74.

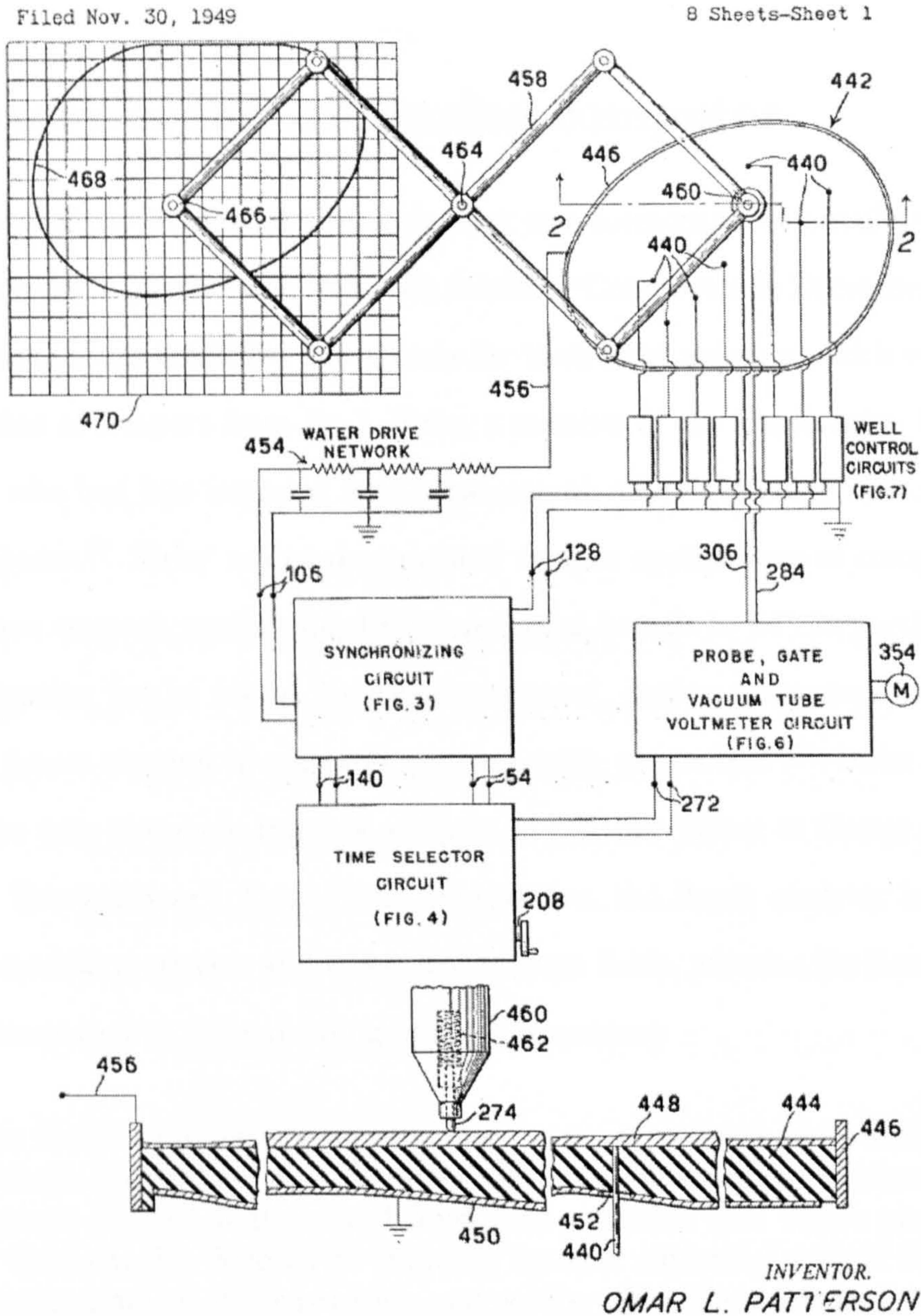


Figure 6.3: Schematic diagram of an analyser designed by Omar Patterson of the Sun Oil Company. The pantograph mechanism connecting the paper plot and electrolytic model of the reservoir is clearly visible. At the bottom of the diagram is a side-on drawing of the solid reservoir model constructed from a non-conductive material covered by conducting paint. Source: Patterson (1955/1949).

electrolytic tank was lost. It was for this reason that the BP engineers would later decide that their reservoir analyser should combine 'the fast, repetitive techniques of the Sun analyser with the areal representation of the Carter-type.'²⁵

The story of the BP analog computer

The origins of the BP installation date back to a memorandum circulated to the members of BP's Exploration Research Advisory Committee in December 1956.²⁶

The memorandum identified the agenda for their next meeting which was to be a discussion of a report from Dr J. Birks, a member of the Exploration Research Division who had just returned from a two month tour of research centers in the United States.²⁷ Birks' report documented various applications of computers in exploration research, and outlined their potential benefit to BP. In particular, he drew attention to the use of 'reservoir analysers', analog computers that could 'predict future changes in reservoir pressure with production'.²⁸ Birks recorded that there were two main types of analyser in use, the 'Bruce or Carter analyser' and the 'Sun analyser'. From Birks' perspective, the Bruce analyser involved a lengthy modelling process and was suited to large fields, whereas the Sun analyser was better suited to the modelling of simpler systems:

The Bruce analyser is generally used for large reservoir units such as Kirkuk, Burgan and the Aramco fields where there is a considerable amount of core analysis and fluid data available and where plenty of time can be devoted to building up and adjusting a large scale electrical model of the reservoir and aquifer. The Sun analyser is best used for small reservoirs or ones which can be treated as a few units

²⁵BP Exploration Research Minutes (1958) p. 2. See also page 161, below.

²⁶This committee met quarterly and provided a link between the research personnel of BP's Exploration Research Division and M. H. Lowson, the division's technical manager (see Figure 6.4). BP's research program had originally begun in 1917 in the basement of an old country house, but by 1960 the operation had developed into a 19 acre research centre at Sunbury-on-Thames, a facility employing over 1300 personnel. The exploration research team were located within the Sunbury complex. See BP Newsletter (1961c); (Matthews, 1962, p. 9).

²⁷A chemist by training, Birks had obtained a PhD for research into evaporation from the University of Leeds in 1949. See Birks and Bradley (1949).

²⁸Birks (1956) p. 2.

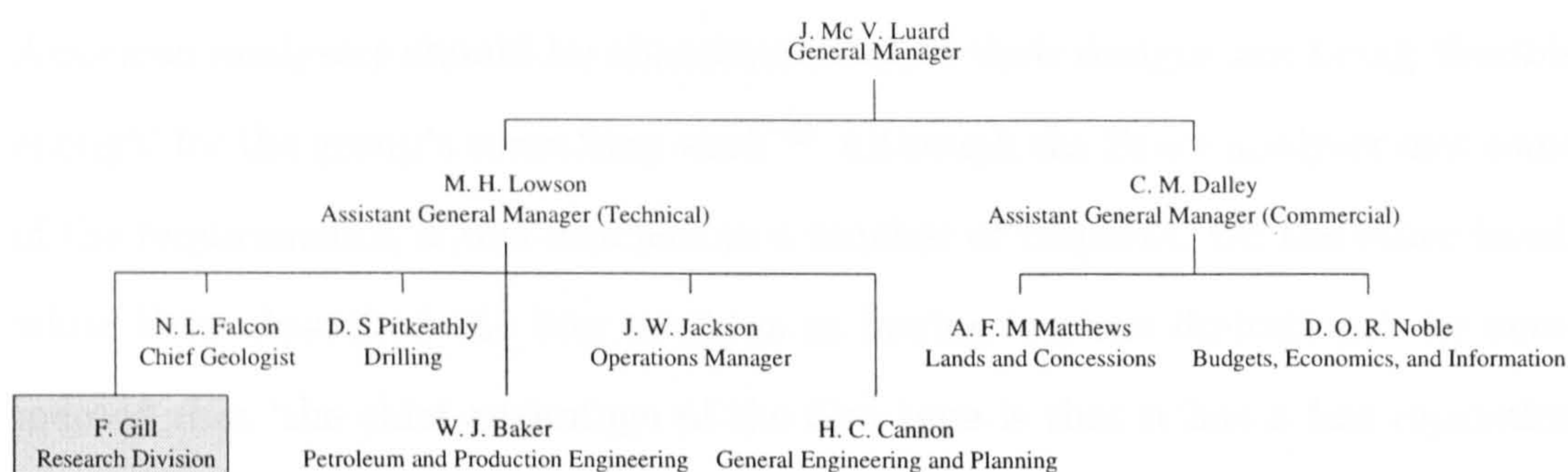


Figure 6.4: The management structure of BP's Exploration Division. Highlighted is Mr F. Gill, the head of the division's research team based in Kirklington Hall and later Sunbury. The Exploration Research Advisory Committee provided communication between Gill's researchers and Lawson, their technical manager in London. Source: based on information from BP internal literature (Matthews, 1962).

since it is much easier to use and gives a visual display of the pressure decline curve.²⁹

Birks concluded his discussion by recommending that BP should purchase a Sun analyser and send a reservoir engineer to Sun Oil's Dallas laboratory for three months of training. He also recommended that a small digital computer be purchased. Both machines were approved for purchase by the advisory committee, although it was decided that a reservoir engineer be trained on the Sun analyser first, and that this training should inform the choice between purchasing a Bruce or a Sun analyser.³⁰ During the following year, a detailed investigation was undertaken to select between the two American machines. The study was done by both Birks and another member of the Exploration Research team, Dr K. R. Keep.³¹ They considered the particular strengths and weaknesses of the Sun and Bruce analysers and their relative suitability for BP's particular work. In 1958 Keep prepared a report of their findings.

Keep's report outlined the need for the analog computer and provided a technical specification. Keep suggested that the original plan of purchasing one of the

²⁹Birks (1956) p. 2.

³⁰BP Exploration Research Minutes (1958) p. 4.

³¹It can be assumed that it was Keep who was sent to Dallas for training as he became the central expert and motivator for the BP installation, taking a leading role in the specification of the required machine.

American analysers should be abandoned due to their designs not being 'flexible enough' for the group's consulting work.³² Although the Bruce analyser met some of the requirements, it was deficient in a number of respects. On the other hand, while Keep described the Sun machine as having 'serious limitations', he commented that 'the chief advantage of the Sun type is that it has a fast repetition rate and uses some excellent electronic techniques.'³³ In order for the purchase of the analyser to be worthwhile, the computer would need to be applicable to all the field problems for which the group provided consultancy. For this, BP would need a custom design:

In view of the limitations of the existing types of analogue, it was considered that any future instrument should combine the advantages of previous models and at the same time attempt to reduce the disadvantages to a minimum. The suggested specification therefore combines the fast, repetitive techniques of the Sun analyser with the areal representation of the Carter-type. For this purpose, about 40 condenser and 70 resistance units would be required to simulate an oil pool subdivided into 10 layers and 4 areas.³⁴

Outsourcing development to EMI Electronics

Unlike the American research groups who developed their own analysers in-house, BP commissioned a third party to do the design work. The advisory committee approved a six month 'development study contract' with EMI Electronics costing £4,000. This was followed by the purchase of a full computer for around £40,000.³⁵ EMI Electronics, a subsidiary of the entertainment company *Electrical and Musical Industries* (EMI), was formed around 1957 to bring together EMI's various interests in electronic goods.³⁶ EMI was a regular supplier of bespoke hardware to BP, and had recently completed a development contract for an in-

³²Keep (1958) p. 1.

³³Keep (1958) p. 3.

³⁴BP Exploration Research Minutes (1958) p. 2.

³⁵BP Exploration Research Minutes (1958) p. 1.

³⁶Anon. (1959a) p. 22; Hamilton (1997) p. 82. EMI were pioneers of a number of electronic products including medical scanners, computers, radar, and domestic television.

strument to investigate rock formations.³⁷ Since BP wanted to design the analog computer within a similar business process, it made sense to use a company who they knew could produce a successful custom product.

EMI decided to develop the reservoir analyser around the technology of their commercial analog computer, the EMIAC II.³⁸ The EMIAC was a reasonably popular product marketed throughout the British Commonwealth. Important users of the EMIAC were firms undertaking missile research and designing aircraft controls.³⁹ The EMIAC, like other analog computers of the period, had a modular design. The basic computer was a single module consisting of 18 computing components, and extra modules could be connected to allow more complex problems to be solved. Within each module the selection of computing components installed was fully configurable: each component was encased in a removable tray, or 'C Box' which could be swapped with relative ease and allowed the computer to be customised for a particular problem.⁴⁰ To implement BP's requirements, EMI assembled 18 EMIAC II rack mounted modules providing 324 C Box locations (see Figure 6.5). EMI also developed some special purpose hardware to provide a network-analyser to model the reservoir's aquifer.⁴¹ Most of this hardware was built into a central control console (visible in Figure 6.5) and this was similar to another contemporary EMIAC customisation which provided a resistance network analog for EMI's own Power Tube Division (see Figure 6.6).

³⁷EMI (1961) p. 8.

³⁸The name EMIAC was an acronym for *EMI Analogue Computer*. Similarly, EMI's range of digital computers were labelled EMIDEC.

³⁹EMIAC users included De Havilland Propellers, Whitworth Gloster, Hobson Ltd, and the Australian Government Aircraft Factory. Units were also sold to a number of university engineering departments at UMIST, Oxford University, Cranfield and Witwatersrand University of Johannesburg. See EMI (1959b, 1962a,b, 1963c, 1965b); Bennington (1964). The installations at de Havilland Propellers in Hatfield, and Armstrong-Whitworth in Coventry were also, like the BP analyser, large arrays of EMIAC II modules, the installations costing £52,000 and £55,000 respectively. See Anon. (1959b) p. 35.

⁴⁰For example, if a user required more integrators than normal, C Boxes containing other components could be removed and replaced by integrator components. A full range of boxes incorporating all the common analog computing components were available. The computer featured removable patch panels so that problems could be 'patched up' away from the computer. For a detailed technical description of the EMIAC see EMI (1963b).

⁴¹Anon. (1963b) p. 151; EMI (1963a) p. 14.

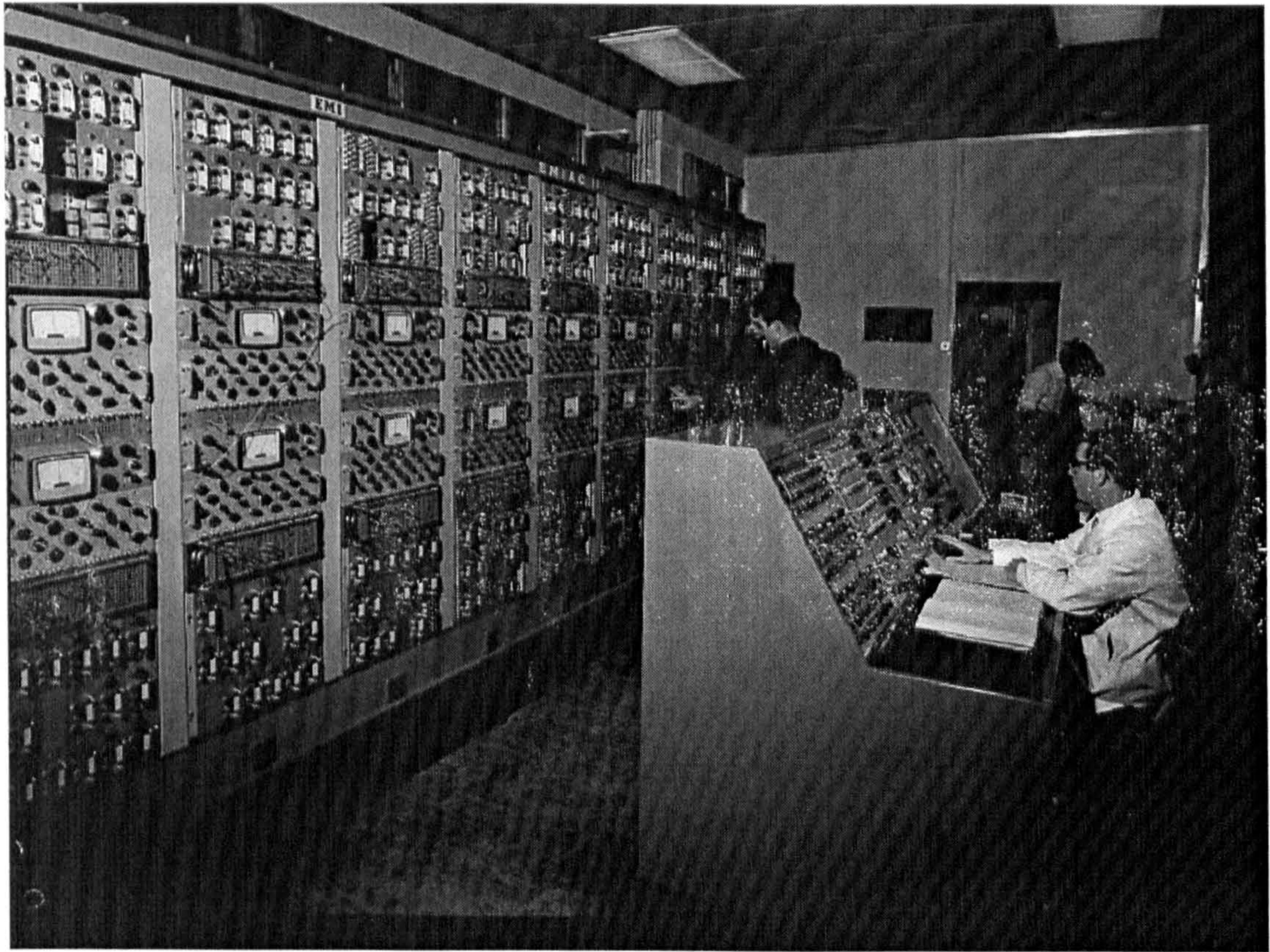


Figure 6.5: The EMIAC II installed at Sunbury. EMI designed extra hardware specific to the reservoir modelling problem, most of which was built into the central console. The central console allowed the user to manage the timing circuits and the resistance networks which modelled the reservoir.

Source: BP Archive: reference EMIAC II 7331.1 © BP plc

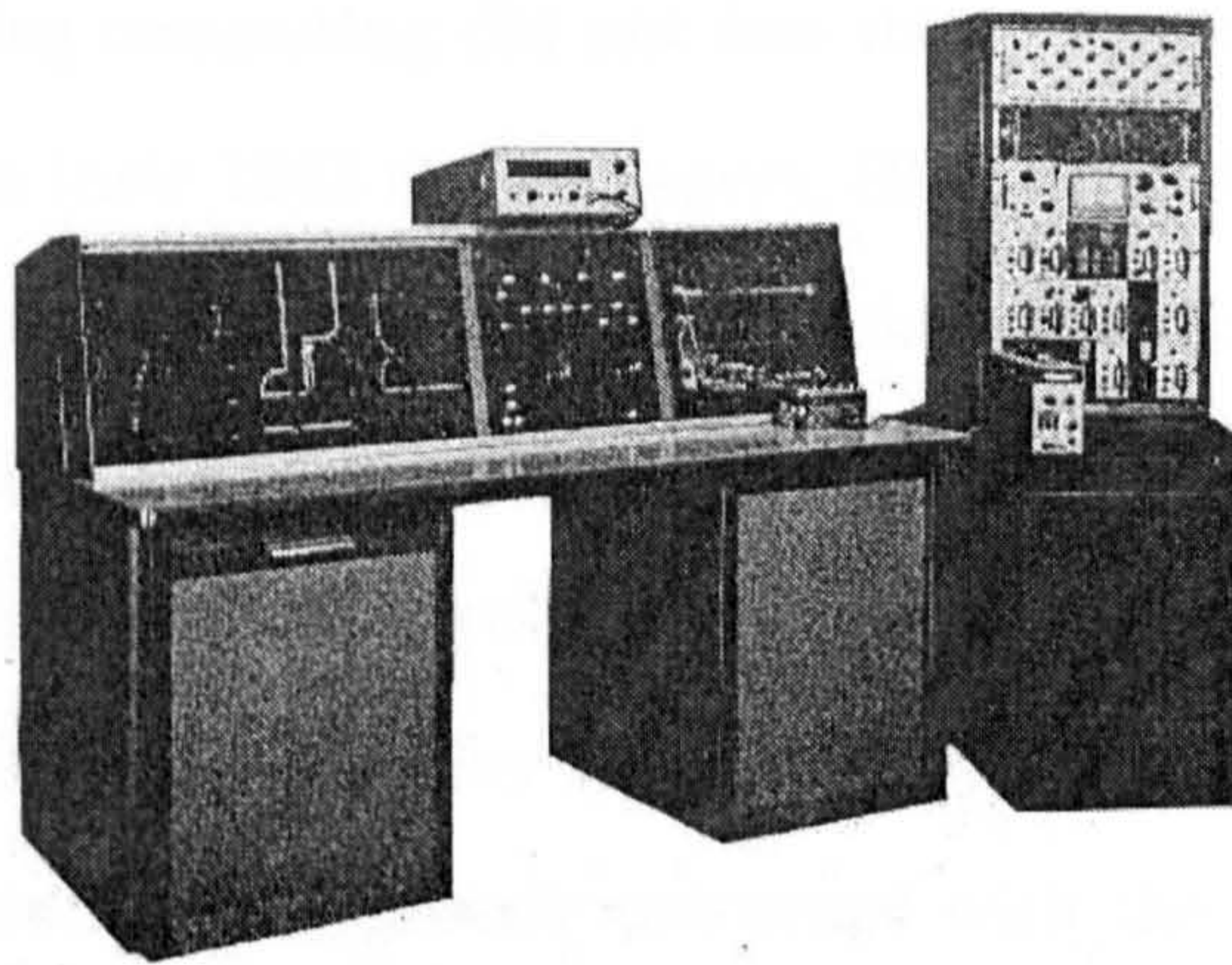


Figure 6.6: An EMIAC module connected to extra hardware. This image is of a resistance network analog computer used by the Power Tube Division of EMI. The computer consists of an EMIAC II module connected to a console containing the patch panel and control components used to build resistance networks. The connection between the hardware and the computer is through a special C Box which extends out of the computer further than the other 17 boxes. When EMI designed special purpose hardware for BP it was encased in a similar setup. Source: Harvey (1968).

The BP analyser in use

As the first, and perhaps only, reservoir analyser to be installed in the UK, the computer was a ‘state of the art’ piece of equipment. It is interesting to explore to what extent it gave BP a commercial advantage and to understand why BP invested time and money into developing a computer superior to the American machines installed at Carter and Sun Oil.

The decision to purchase the analyser required a long-term view of the group’s activities, since the principal benefit related to the group’s expanding consultancy skills rather than analysis of BP’s own fields. Experience in reservoir simulation would improve their competitiveness in external contracting:

It was pointed out in the discussion that possession of such a computer would result in Kirklington Hall obtaining a wider experience of field problems; at the moment these problems are dealt with in their entirety by American companies.⁴²

Furthermore, during the five years between the identification of a need and

⁴²BP Exploration Research Minutes (1957) pp. 1–2.

EMI's delivery, analog computing did not lose its applicability to reservoir engineering problems. In their 1963 annual report, BP heralded the analog computer as a successful addition to their research establishment and although there are few references to the use of the computer after its installation, those that exist indicate that it was a profitable procurement. For example, during 1963 Gill requested extra staff for his Sunbury research team and this was in part due to their technical assistant being 'mostly concerned with the computer.'⁴³ The use of the computer at that time included a contract modelling Iranian oil fields that was worth £20,000 annually, and Gill expected work of this kind to 'continue and increase in the next few years.'⁴⁴ Even with financing the machine's running costs, the salary of one technical assistant, and the occasional input of a reservoir engineer, an annual income of half the analyser's value on one contract⁴⁵ indicates that the analyser was indeed a successful purchase and that there was a market for BP's consultancy services.

The BP archives do not record when the computer was decommissioned, but by 1975 most analog computer applications and installations had disappeared due to the faster speeds and lower costs of digital machines. While the computational difficulties associated with early numerical reservoir modelling had been the original motivation behind Bruce's electrical analyser, digital developments would herald a return to numerical modelling. A brief history of digital reservoir simulation has been written by Donald Peaceman, a pioneer in that field, who worked for the Humble Oil and Refining Company.⁴⁶ At Humble, Peaceman experienced a mixture of physical and mathematical modelling techniques. He described how the types of problem that the researchers could solve was largely dependent on the types of calculating machine available:

⁴³Gill (1963) p. 3.

⁴⁴Gill (1963) p. 3.

⁴⁵The budgeted price of the EMIAC II was £40,000 (see above).

⁴⁶Peaceman published several papers (detailed in his account) and also a book on numerical reservoir simulation (Peaceman, 1977). Like Carter, Humble was another subsidiary of Standard Oil.

We had nothing that you could call a computer. We did have access to some accounting machines that the accounting department would let us use, but only at night. Henry Rachford had come to work a year before me and was already playing with an accounting machine called the IBM 604. He, along with the managers of the Production Research Division of Humble, had the vision to see that digital computation was going to be the way to do reservoir modeling and... could overcome the limitations of the analytical methods.⁴⁷

Peaceman's account emphasises how the successful development of numerical prediction was not as simple as having the vision for digital use. In developing numerical reservoir prediction techniques, Peaceman and his colleagues had to develop their own numerical methods. In programming their problems, they often came up against limitations of computer hardware. As a result of this digitalisation, reservoir engineering textbooks began to present the problem of reservoir simulation in terms of software simulation and mathematical models, instead of introducing the concepts of the hydraulic analogy behind the Bruce analyser.⁴⁸ If we assume that BP followed the rest of the industry in replacing analog with digital, then the computer would have had a working life of between five and ten years, a reasonable lifetime for any computational tool.

BP and the analog-digital debate

In his history of analog computing, Small (2001) referred to an 'analogue versus digital debate'. The BP story offers a chance to reconsider how end-users engaged with this debate. In this, we can make two observations: firstly, at the local level, the BP engineers did not feel committed to a particular approach but procured analog machines because they were cheaper than digital and did the job. On a corporate level, we see that the BP press office saw no embarrassment in the installation of an analog computer; any installation of a technology bearing the

⁴⁷Peaceman (1990) p. 108. Rachford and Peaceman would become well-known for developing what is now called the 'alternating direction implicit' (or ADI) mathematical method. See Usadi and Dawson (2006).

⁴⁸Compare Craft and Hawkins (1959) pp. 205–210; and Peaceman (1977) pp. 1–2.

name 'computer' was employed to advertise innovative practice at BP.

Analog-digital issues at the local level

In considering analog-digital issues, both an application and research outlook can be identified.⁴⁹ While those with a *research outlook* were debating the merits of these two distinct technologies, the engineers at BP had an *application outlook* where different computers were evaluated in terms of their practical and observed suitability (rather than a theoretic suitability derived from a machine's internal design, architecture, or data representation.)

Of major concern in discussions surrounding the merits of these two technologies is the issue of general-purpose: digital computing being more appropriate since it could be used to solve a wider class of problems. For instance, one common milestone in the wider history of computing is when, in 1946, Jay Forrester decided to use a digital rather than an analog computer as the central technology of Project Whirlwind.⁵⁰ However, this again is an example drawn from the world of research rather than of application.⁵¹ For those without the deep budgets of a defence contract, analog computers were the tool of choice well into the early 1970s. For the successful evolution of digital computing, it was important that such projects existed, but BP's interest was not to significantly develop computing technology. Rather, BP's need was for *normal computing*.

⁴⁹A research outlook represents those involved in computer research and development – the communities that actually created the distinctions between the technologies. For example, John Mauchly and other digital computing pioneers at the Moore School that were among the first to articulate a clear distinction between analog and digital. See Chapter 2, page 58, above. To develop the language with which to discuss the emerging technology of computers, it was necessary for pioneers to identify classifications and types between different machines, approaches and representations.

⁵⁰Whirlwind was a project initiated by the US military to develop a general-purpose flight simulator, and evolved to develop the powerful real-time computer at the heart of the SAGE air defence system. See Campbell-Kelly and Aspray (1996) pp. 143–145; Augarten (1985) p. 196.

⁵¹The Whirlwind project exceeded both its allocation of time and funding and took on a far more research based approach to real-time computing. Although Forrester is correctly credited with having the foresight that general purpose digital computers were far more powerful and versatile tools, his design choice was only possible because of quite exceptional funding. Project Whirlwind proved that digital computers could be constructed to work in real-time and so take on tasks that analog computers had previously been used for. However, affordable digital alternatives to analog computing were much slower in coming to the application community.

While the BP engineers were aware of the generality of digital computing and knew that many problems could be solved on digital machines, they also knew that a digital computer for reservoir analysis would come with extra expense and size, and be time consuming in operation. When comparing affordable computers, digital machines were just not fast enough:

[Mr Docksey] queried, however, whether a digital computer [sic] could not be used for these studies but later agreed with Dr Birks that there was a strong case for the analogue approach, the studies being both awkward and time-consuming when carried out on the large digital computer which would be required.⁵²

There was also concern amongst the committee that despite analog computing being much cheaper than digital, BP's requirement of a customised design would result in a cost of '[perhaps] several times that of those at present available'.⁵³

However, one of the engineers commented:

The economies which can be effected by good reservoir computations make the differences in price insignificant. The primary concern should be whether a more advanced type of machine is required and if so, the aim should be to produce a good workable machine, size being relatively unimportant.⁵⁴

As an engineer with an application perspective, Birks understood the technology in terms of the business' needs. The language of his proposals did not presuppose that digital was better than analog, neither did it represent a view that analog was always more appropriate than digital. This is best illustrated by the fact that alongside his proposal for the analog computer, he also drew attention to the importance of acquiring access to a digital computer, and even suggested that the digital procurement should be given priority.⁵⁵ For Birks,

⁵²BP Exploration Research Minutes (1958) p. 3.

⁵³BP Exploration Research Minutes (1958) p. 3. Recall that there was an English Electric DEUCE available, however the reservoir engineers needed continual access to a computer over the modelling study. Their work did not fit within the batch process model.

⁵⁴Docksey quoted in BP Exploration Research Minutes (1958) p. 3.

⁵⁵The digital computer facilities were a priority because of their general purpose nature, the machine being applicable to 'any type of numerical calculation and not only for petroleum engineering problems'. See BP Exploration Research Minutes (1957) pp. 1-2.

however, the issue of priority was always grounded in the specific business application: the analog being less urgent because its immediate use was for external consultancy rather than internal BP contracts. In contrast, the digital was needed to help with the group's current work.

In summary, BP needed a 'good workable machine' to give them an industrial advantage. Investing in analog would open new opportunities for consultancy in the long term and significantly extend the group's skills-base. Analog techniques had already proved suitable in other oil companies and the expense was thus deemed recoverable. The group simply opted for the portfolio of technology that best suited their needs. In the case of the reservoir analyser, this was a custom analog machine based on the American techniques.

Analog-digital issues at the corporate level

So at a local level, there was not excessive concern about whether a procurement should be analog or digital. Similarly, at the corporate level, press releases relating to both types of computer were used to strengthen the image of BP as a modern technology-enhanced company. BP appeared to be equally proud of both their digital and analog machines and this can be seen in the 1963 annual report where the reservoir analyser and the ATLAS (a new digital machine) were both announced and given reasonably equal prominence:

On the computer side our effort was concentrated on preparing for the commissioning of the large [Ferranti] ATLAS computer which is coming into use in 1964.

...

The exploration and production side of our business has been much helped by research, in particular from the installation of an analogue computer.⁵⁶

⁵⁶'Report on the activities of the Research and Engineering Department' in *BP Annual Report* (BP, 1963, p. 31). The ATLAS installation was actually owned by the University of London. BP provided a quarter of the funding and received a portion of computing time for five years. See BP Newsletter (1961a).

In the context of the late 1950s, announcing the installation of a computer was an indicator of business success. Of course, compared to the costs of the ATLAS computer (upward of £2.5 million), the expense of the reservoir analyser would have been quite small. The inclusion of the analog machine in the annual report indicates that the installation of any computer had publicity value. There was no embarrassment associated with installing an analog computer, it was no different to any other tool. The technology's ability to deliver results, and the fact that BP had one, was still worth broadcasting.

Conclusion

The BP story offers a window on the use of analog computing for industrial problems. We have seen that it was commercially viable in 1958 for a global company to invest in an analog computer and that the engineers in this industrial setting were happy to accept a special-purpose or limited-purpose machine. Always driven by a need for accurate reservoir predictions, they did not seek the generality of digital computation or become involved in developing digital methods. This analog computer was an example of *normal* computing, and this explains why there was no need for BP to engage in the analog-digital debate. Discussions around technical suitability were grounded in practical business benefits. Thus, analog and digital were complementary – not because of anything inherent in the technologies, but because a mixture of the two types of computer were an effective and cost efficient solution for BP's needs in exploration research.

The beginning of the chapter identified that for BP analog and digital were complementary rather than opposites. In explaining this, we identified that BP had an application perspective rather than a research perspective. This is linked to the idea of normal and radical use introduced earlier in Chapter 5.⁵⁷ The reservoir analyser was employed as a normal tool and so there was no need for

⁵⁷See Chapter 5, page 135.

the BP engineers to engage with issues of classification and analog-digital debate.

When Bamberg (2000) wrote the history of BP for this period, he included a chapter on computer use within the company. However, in this chapter no reference to the EMIAC II was made. This is not surprising since the narrative focused on the development of Operational Research (OR) methods and the use of digital computing in business management. Some computer historians might claim that this is an example of ‘presentist’ history – the ignorance of analog computer history in the light of digital computing and its dominance today. However, here this is not the case. Bamberg’s excellent account is centrally about the company’s business activities and the changes and developments in the management of global oil during the latter-half of the twentieth century.⁵⁸ While the development of OR clearly links with the global business, a small research tool in Sunbury was more a *cog-in-the-machine* than a revolutionary aspect of the business process. What makes studying this computer interesting is what was earlier identified as the application perspective, the engineering culture that sought and used analog computational assistance. In a sense, the importance of this installation to the history of computing is its normality. The analog technology, although no longer cutting edge, was used in *normal* computing applications.

Returning to the BP context, the ‘cog-in-the-machine’ metaphor identifies more than just the status of the analog computer, but is indicative of the status of the personnel who worked around it. When requesting extra staff, Gill described the team as:

...a small but very active group working on a project which is elsewhere receiving a great deal of effort and attention. The group requires (and deserves) support in order to be able to make its own adequate contribution, and to gain and maintain a place for BP in the Petroleum Geochemistry field.

In Geophysics and especially in seismic theoretical fields, and laboratory (model) work, we do not think the quantity and quality of the output receives wide or adequate recognition within the Company

⁵⁸See the review article by Pratt (2001). In fact, Pratt identified that this chapter ‘stray[ed] from the thematic coherence’ of the rest of the text (p. 825).

partly because of its specialised and mathematical, and also its long term nature.⁵⁹

Exploration research played an important but often forgotten role in the large commercial activity of exploration, production and refining of oil. Because of its slight independence, senior management did not force the reservoir engineers down a certain computational route and limited budgets dictated that the most cost effective solution be bought. When a new analog computer was installed, the group achieved recognition by corporate level public relations, however, the analog computer quickly became forgotten as its use slipped into the quiet and ordinary activities of the Iranian research contracts. The exploration researchers had specific work to deliver and to do this, they relied on the special purpose technology of the analog computer. Compared to the, then radical, technology of digital computing, analog was normal, ordinary, and used to get the job done.

⁵⁹Gill (1963). p. 2.

Chapter 7

Analog-digital decisions in British aeronautical research

...the relationship between aeronautics/guided weapons and analogue computing is such that it is difficult to overstate the influence of these fields of study on the development of the electronic analogue computers... several of the commercial electronic analogue computer systems originated in programmes to develop military aircraft and guided weapons.

James Small¹

Throughout the past two centuries, the science of flight has evolved through a large body of experimental and theoretical research. Like many other technical disciplines, aeronautics began as a primarily experimental activity and later became more mathematical through the establishment of the 'engineering science' of aerodynamics.² This 'scientification' is visible in the transformation of aeronautical research from field experiments based on trial-and-error towards laboratory-based methods. This laboratory setting motivated the invention of a whole series of standardised experimental environments; modelling technologies including wind tunnels, direct and indirect analogs and software packages for

¹Small (2001) p. 57.

²Walter Vincenti shows that there is a '...fundamental difference between engineering as the creation of artefacts and science as the pursuit of knowledge.' See Vincenti (1990) p. 112. Alongside the development of these modelling technologies evolved the mathematical theory. Beginning with the work of George Cayley, applied mathematicians began to develop models of fluid flow, initiating the development of the discipline of fluid dynamics. However, the mathematical theory created equations that were difficult to solve, leading to the development of model environments whose behaviour was analogous to that of the equations (an indirect analog).

digital computers.

The computer is central to the history of aviation technologies and this chapter focuses on the use of analog computers in the design of aerodynamic structures.³ Prior to 1950, analogs were vital computing aids for this field. Throughout the following decade, the increasing availability of digital computers stimulated debate over which technology was most appropriate. The first half of this chapter reviews the use of analogs in this field, with the second investigating an analog-digital debate which took place within the computation panel of the UK's Aeronautical Research Council (ARC), a government-supported advisory organisation.⁴

Analog computing for aeronautics

Two major types of analog computing were used in British aeronautics. Direct analogs were used to model airflow and structural stability, and indirect machines supported the solution of differential equations – vital for modelling or simulating flight. Most of the early British developments of general purpose (indirect) analog computers were carried out by the Royal Aircraft Establishment (RAE) in Farnborough.⁵ Between 1948 and 1954, RAE developed a series of indirect

³The aerospace industry was a key agent in bringing computing out of the laboratory and into the wider world of industry. Cerruzzi explains that the aerospace industry was 'accustomed to complex machines that needed long break-in periods' and were therefore well suited to developing the technology. See Ceruzzi (1989) pp. 13–14. Ceruzzi is referring here principally to the digital computer, but aeronautical applications also drove the development of analog computing.

⁴Founded in 1909, the ARC (then called the Advisory Committee for Aeronautics) had been set up to provide the government with advice surrounding aeronautical research and was instrumental in establishing an aerodynamics department at NPL. Prior to its inception, aeronautical research was fairly ad-hoc with no overarching research direction. Ward (1962) described the establishment of the Advisory Committee for Aeronautics as marking 'the beginning of an intensive experimental and theoretical approach to aerodynamics.' (p. 3). Until it was disbanded in the early 1970s, the council provided an interface between the closed world of government establishments and the work undertaken at universities. The ARC was structured by special interest sub-committees, on which sat security cleared academics, civil servants and government researchers. Historian Andrew Nahum described this set-up as 'an ingenious mechanism... for peer review of secret work.' (Nahum, 2002, p. 55). Of the various sub-committees within the organisational structure, two were related to important uses of computers. These were the Fluid Motion sub-committee and the Oscillation sub-committee.

⁵This was a consequence of the centralisation of guided weapons research at RAE in 1945. See Small (2001) pp. 180–181.

computers, culminating in TRIDAC. A large analog occupying two purpose-built buildings, TRIDAC simulated the flight characteristics of guided weapons.⁶

Alongside indirect analog computers based on summers, integrators, and other mathematical components, direct analog computers such as resistance networks and electrolytic tanks were used to represent the complex mathematics associated with aerodynamic flow and structural flutter. The use of these technologies form part of a wider history of modelling: encompassing analogs based on rubber membranes and even soap bubbles – techniques that can appear far removed from modern computing. At an application level, there are strong similarities between direct analogs and modern approaches such as digital finite element analysis.⁷ Direct analogs were the modelling technology of choice during the 1920s and 1930s, and were often used for experimental and visual simulations. From the perspective of modern computing, they can appear a semi-computational technology, but as problem solving technologies, they were the predecessors of modern computational modelling.⁸

Soap film models as analog computers

One important example of a semi-computational technology is the use of soap bubbles as analog computers, the physical behaviour of a soap film being used to solve complex problems. As a computational aid, these were included within

⁶Symbolising the climax of electro-mechanical analog computing in Britain, this machine employed a mixture of electronics and hydraulic servo-mechanisms to accurately model the complexities of flight. For contemporary descriptions of this machine, see Anon. (1954); Gait (1955a); Gait (1955b). TRIDAC was also the last computer of its kind to be developed in-house: during the following decades, institutions like RAE began to buy in commercially manufactured indirect analogs. Installed at various aircraft manufacturers, commercial analog computers were used for modelling guided weapons. For instance a large EMIAC II analog computer was installed in the factory of Armstrong Whitworth in Coventry to support their work on the Seaslug surface to air missile (EMI, 1962b).

⁷Finite element analysis divides a large system into a grid and models the interactions between adjacent cells. This is commonly used for simulating structural strain or heat flow. Like direct analogs, this approach exploits the physical structure of a problem.

⁸Electrical analogs were important tools because they were much faster to operate than environments such as the wind tunnel and had the added benefit of being smaller and cheaper. They were typically used to get a quick result or to identify trends, often as preliminary studies to wind tunnel tests.

the technical discourse surrounding electrical tanks and networks. For instance, as one textbook published in 1961 described:

Two of the most interesting, if not the most accurate, methods for obtaining solutions to the Laplace equation are the soap-film and rubber-sheet analogues. Particularly, the soap-film analogue has been applied to the problem of torsion in uniform bars of non-circular cross section. The stress function, in terms of which the shear-stress components are given... satisfies Poisson's equation.

...

The soap-film analogy entails the following procedure. An opening is made in a sheet of metal and the edge of the opening is distorted in such a manner as to make the shape of the opening similar to the cross-sectional area of the bar in torsion... If a soap film is stretched across the opening, the distance of any point... satisfies the Laplace equation.⁹

Evidence of the use of soap films in aeronautical research can be seen in the publications of the ARC and also of the American National Advisory Committee for Aeronautics (NACA).¹⁰ In these applications, soap film was used to calculate the torsion of the structural bars of aircraft structures.¹¹ To use this technique, a frame specific to the given problem would be dipped in soap solution, the soap film immediately taking the spatial form representing an optimal solution – determined by measuring distances on the film with a micrometer.¹²

⁹Fifer (1961) pp. 770–1 (vol. 3). Others have identified this technique as computational. For instance, Cyril Isenberg, who popularised the use of soap film in education, described them as an analog computer. He wrote: 'The advent of digital computers in the 1950s and their rapid growth in the 1960s and 1970s has resulted in the neglect of analogue computers and analogue methods', and continued, 'analogue computers usually have one advantage: they provide a speedy visual solution to a problem. One of the simplest and most impressive analogue methods is based on a physical property of soap films... these methods can be used to solve mathematical minimization problems.' (Isenberg, 1976, p. 514). See also Isenberg (1975a); Isenberg (1975b); Isenberg (1992).

¹⁰The NACA was the forerunner organisation of NASA, the American space agency.

¹¹See Batchelor (1996) p. 118, n1.

¹²The micrometer point could cause the film to burst, however this was usually prevented by limiting the size of the opening and thus strengthening the bubble. The bubbles had to be particularly strong and persist long enough for in-depth measurements to be taken. The soap solution used for industrial research was a mixture of 'sodium oleate, glycerin, and water', and could form bubbles lasting up to twenty-four hours (Fifer, 1961, p. 772). An alternative, but similar, approach for solving these problems was to apply fixed constraints to a flexible rubber sheet and then allow the sheet to find a stable equilibrium. For instance, in 1929, the physicists Marcus Oliphant and Philip Moon investigated electrical discharge tubes using a rubber sheet analog.

The first application of soap films to aeronautics is attributed to Ludwig Prandtl (1875 – 1953) who used them to represent torsion as part of his doctoral research (completed in 1900).¹³ In 1914, a similar result was discovered by G. I. Taylor and A. A. Griffith, working within the Royal Aircraft Factory (which would later become the RAE) and published in a series of papers during 1917 and early 1918.¹⁴ This research was welcomed by many eminent scientists of the day, and Taylor and Griffith were awarded the Thomas Hawksley gold medal by the Institution of Mechanical Engineers for their 1917 paper entitled ‘The use of soap-films in solving torsion problems’.¹⁵ During the 1920s soap film analogs continued to be used, both in British and American aeronautics.¹⁶ As an analogy method, soap films were just one of a whole family of techniques being used. Of these, analogs based on electrical media would become the most prominent, electrical modelling offering stability and scalability. As G. I. Taylor wrote in 1922:

The reason why I never pursued [the soap film method for calculating stream lines] was that I could see no way in which a soap film big enough to represent the whole length of the channel could be constructed... [this] made me think that an electrical method would be better than the soap film method.... The aerofoil would be represented by a block of copper of suitable shape. The potential of this could be maintained at any given value by some potentiometer device and the equipotential lines (representing stream lines) could be plotted by the ordinary null method.¹⁷

What Taylor here describes as an ‘electrical method’ would evolve into one of the most important forms of direct analog computing for aeronautics: the electrolytic tank.

¹³Busemann (1960) p. 194.

¹⁴See Taylor and Griffith (1917b); Taylor and Griffith (1918); Taylor and Griffith (1917a). Griffith went on to research brittle fracture and later designed turbojet engines at Rolls-Royce. He was the pioneer behind the ‘flying bedstead’, a prototype of vertical take-off and landing (King’s Norton, 2004).

¹⁵Rubbra (1964) p. 118.

¹⁶On the British side, the aerodynamics committee of the ARC were discussing the use of soap films for mapping air flow (Southwell, 1922). In US aeronautics the NACA were also using them for structural investigations (Trayer and March, 1930).

¹⁷From a technical note by G. I. Taylor, appended to Southwell (1922) pp. 1–2.

The electrolytic tank as a table-top wind tunnel

As an experimental space, industrial wind tunnels offered designers the cost-saving of non-destructive testing and provided an increased speed of experimentation. However, with only a limited number of tunnels available, and their high cost of use, research engineers began to use analogs to model airflow.¹⁸ Through exploiting the analogy between electrical fields and airflow, electrolytic tanks offered an alternative experimental space.

As described in Chapter 2, the history of the use of electrolytic tanks dates back to early work by Adams who, following Kirchhoff, used a tank to trace field lines in the 1870s.¹⁹ During the 1920s tanks were first applied to aeronautics by E. F. Relf. Working in the National Physical Laboratory, Relf used them to measure the streamlines of airflow over an aerofoil section. Despite this early British research, it was in France, with the work of Joseph Pérès and Lucien Malavard, that the electrolytic tank became a particularly popular computing medium for aeronautics. In their Parisian *Laboratoire des Analogies Electrique*, they designed and implemented a Wing Calculator that solved the fundamental equation of the lifting wing. The wing calculator was used successfully by a number of aircraft manufacturers until 1940, when the onset of World War II and advancing German troops prompted the equipment in the laboratory to be broken up.²⁰

During the war years, Pérès and Malavard's work on tanks was isolated from Britain, and as a consequence, British aerodynamic researchers would come to favour resistance networks for modelling airflow. However, after the liberation of France, the Paris laboratory was re-established and Malavard became its director. With peace came new opportunities for knowledge sharing and collaboration between France and Britain. In September 1945, four months after the end of the

¹⁸One contemporary article estimates that during the 1940s the aircraft models used in wind tunnel investigations were costing as much as £100,000 (Bollay, 1947, p. 106).

¹⁹See Chapter 2, pages 49–50

²⁰Mounier-Kuhn (1989) pp. 257–258.

war in Europe, a group of engineers met in the Library of the Royal Aeronautical Society to hear a lecture from Malavard describing the work of the Paris laboratory.²¹ The uptake of these principles in Britain after the war is notable. A number of aircraft companies installed 'Electric tanks' and RAE and NPL both make extended use of the technology.²²

Although Malavard's laboratory continued to pursue generic electrolytic tanks, the majority of their work was aeronautical calculations. The research was jointly directed by both the CNRS (Centre National de la Recherche Scientifique), who funded one theoretical researcher and three technicians, and the ONERA (Office National d'Etudes et de Recherches Aeronautique), who funded two theoretical researchers and five technicians. On top of this, technical personnel from aircraft design companies would visit the group to use the electrical tanks, of which there were 'about a dozen'.²³

One example of an industrial application of Malavard's approach was within the research facility of Saab, an engineering firm who decided in 1948 to install a tank to aid their aeronautical research. Saab used this prototype to evaluate 'existing principles of measurement', and as a result, constructed their own modified design, first operational during 1949.²⁴ The Saab 'gradient tank' was made of glass allowing individual cartesian components of the electrical potential gradient to be easily measured, a process corresponding to measuring different components

²¹This lecture was an attempt to re-establish scientific links between France and Britain 'helping...', to quote the then Superintendent of aeronautical research at the National Physical Laboratory (NPL), '...to forward the understanding between England and France'. The meeting had been organised by a Lieut. Col. J. Valensi, himself a Frenchman and expert on analog computing who had escaped from France in 1942. Fleeing to England, Valensi had shared his scientific expertise with the allied forces, 'joining the common struggle by working at the NPL.' After the liberation of France, he continued to work in England and became the 'Liaison Officer for Aeronautical Research' facilitating scientific dialogue between the two countries. Valensi would later return to an academic post in France. See introductory comments in Malavard (1947) p. 247.

²²Hargest (1952); Kuchemann and Redshaw (1954). While the electrolytic methods had existed on a small scale during the war based on those of Relf and Taylor, reports published after 1950 reference both the English and French work. This indicates that so-called 'scientific mission' to share research with France was successful.

²³Hartshorn (1948) p. 1.

²⁴After 1970, Saab would develop digital controllers for fire control. See Persson (1999).

of velocity in a wind tunnel.²⁵ In an article published in 1949, Lennart Stenström described how their tank was used. To investigate the tail portion of an aeroplane, a model was constructed out of moulded Bakelite and placed in the tank. Being an electrical insulator, the Bakelite model distorted the electrical field in the same way that an actual plane would distort airflow. Once an initial study on a model had been undertaken in the tank, extra superstructure was added to the model with modelling clay.²⁶ The effects of this change could then be seen immediately by re-investigating the model in the tank and comparing the two distributions. In terms of reducing wind tunnel experimentation time, the electrolytic tank was a great success. The Saab researchers enjoyed the tank's flexibility, simplicity, and cost saving:

The great advantage of the gradient tank as compared with wind tunnels lies in the simplicity of the tank models. At every measuring point on a wind tunnel model intended for measuring the distribution of pressure, a small pressure pipe must be drawn out. The model is expensive and the programme of measurements must be partly known before the model can be constructed. On the other hand, a gradient tank model requires no pressure pipes and is consequently cheap and can be easily subjected to modifications. The gradient can be measured at every point on and outside the model without previous preparation.

The programme of measurements can be arranged freely and can subsequently be revised without difficulty when measuring results are gradually being available. Thus, it is possible with the help of the gradient tank to vary the shape of the aeroplane parts progressively until a favourable pressure distribution is obtained.²⁷

The hands-on engineering feel that the electrolytic tank offered was a different form of computing that was incremental in its approach. Engineering design demands these kind of qualities. Engineers, like those at Saab and elsewhere prized the flexibility that supported incremental design and experiment. Modern

²⁵The method was only useful for studies of velocities below the speed of sound because the analogy ceases to hold at higher speeds.

²⁶Producing the accurate non-conductive model required special techniques. The approach taken at Saab was to create a mould using cross-sections – a technique similar to the analog cam construction described by Mindell (2002) pp. 96–97.

²⁷Stenström (1949) p. 21.

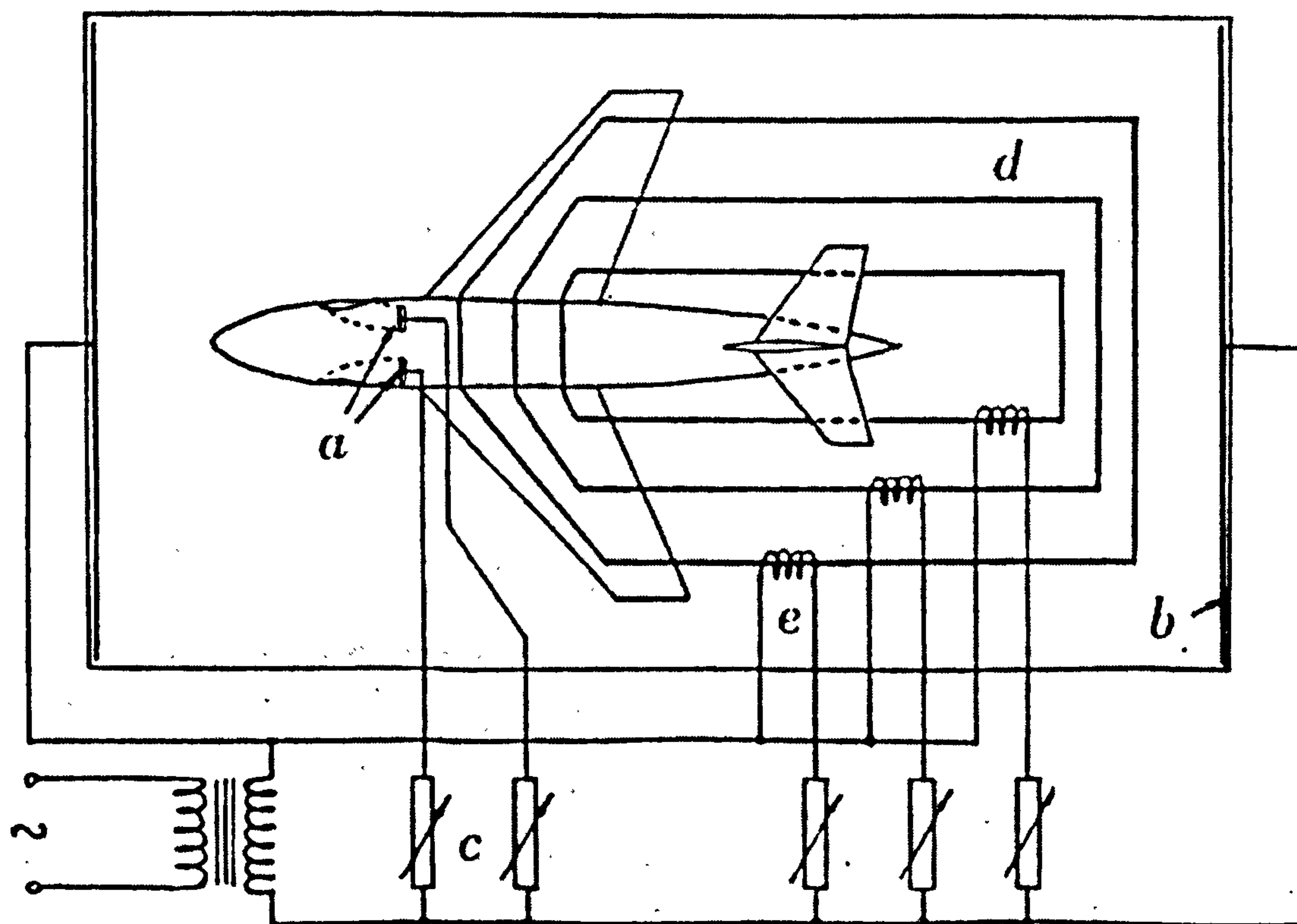


Figure 7.1: Diagram of an aircraft model in the Saab electrolytic tank. The diagram shows the circuits added to model the aircraft's air intakes (labelled a), and the cyclic circuits (labelled d) for generating circulation around the wing. Source: Stenström (1949)

design software now provides this experimental quality but in 1950 it was direct analogs that provided interactive modelling.

Aerodynamic calculations, British aircraft designers and the ARC computation panel

In post-war Britain, the rising importance of aviation can be seen in British military policy.²⁸ Guided weapons and a nuclear deterrent were to become the principal technologies to defend the British Isles, resulting in a multitude of military aerospace research. Along with an increasing demand for domestic flight, this put tremendous strain on the British aircraft manufacturing firms who were suffering from a lack of suitably trained design engineers. As Brigadier Hinds of

²⁸Edgerton (1991, 2006); Nahum (2002); Twigge (1993, 2002).

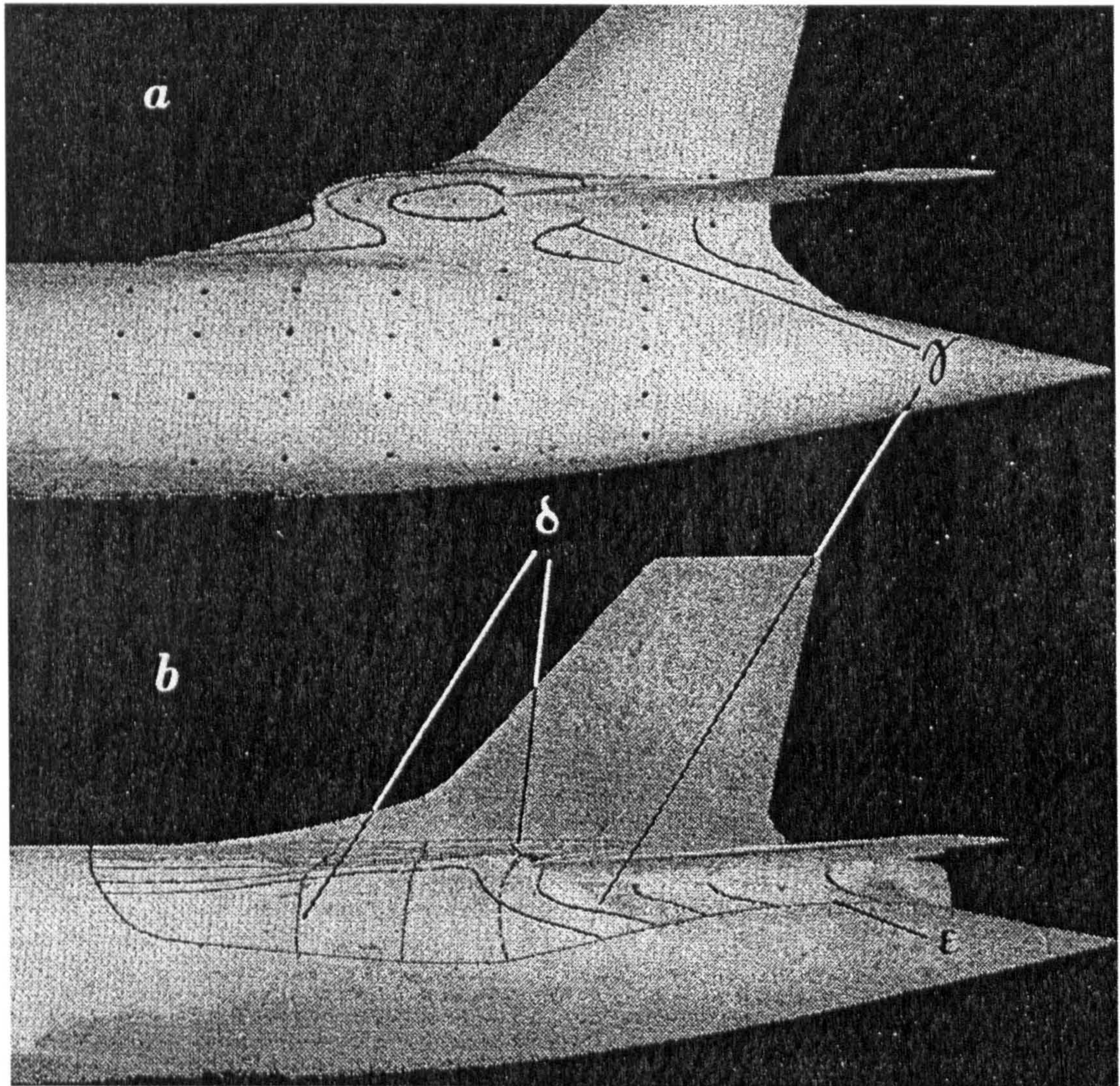


Figure 7.2: Incremental modelling with an electrolytic tank. This image shows how an initial model (labelled **a**) was modified by adding modelling clay, experimentation with the tank informing the process. Source: Stenström (1949)

the Ministry of Supply commented: 'there was a lack of design engineers because so many were required for stress calculations, and it was hoped that better methods of calculating would improve the position.'²⁹ The government, aware of this problem, looked to computing technology for a solution.

During 1951, two government researchers, Stuart H. Hollingdale of the Royal Aeronautical Establishment and E. T. (Charles) Goodwin from the National Physical Laboratory, surveyed the computing needs of aircraft firms.³⁰ They visited a number of the major companies and found that 'appallingly crude methods of computing were used'.³¹ What they discovered was a low-quality workforce of dedicated human computers:

The level of skill and initiative expected by the firms of their [human] computers is not high. It was suggested that the introduction of one or two computers of higher calibre would pay handsome dividends. In particular, computing activities should be in the charge of a capable officer, who would not only plan and lay out the work, but would keep abreast of development in outside centres, such as NPL and RAE.³²

As a consequence of these findings, the ARC decided to establish a 'Computation Panel'.³³ Chaired by S. C. Redshaw, an analog computing expert from

²⁹Brig. Hinds as quoted in Minutes of the 1st meeting of the ARC computation panel. See ARC (1952–1953), 21st November 1952, p. 2.

³⁰Both Hollingdale and Goodwin were mathematicians by training and had been contemporaries at Cambridge University. After graduating from the mathematical tripos in 1932, Hollingdale pursued postgraduate study at Imperial College and submitted a PhD thesis entitled 'Stability and configuration of the wake behind a body moving through a fluid' in 1936. On leaving Imperial, he joined the Aerodynamics department at Farnborough where he remained throughout the wartime period. Goodwin remained at Cambridge and obtained a PhD on: 'The quantum theory of surface phenomena' before joining the NPL. See Anon. (1932); Hollingdale and Toothill (1970), preface; Theses (2007).

³¹Goodwin as quoted in Minutes of the 1st meeting of the ARC computation panel. See ARC (1952–1953), Meeting 1, 21st November 1952, p. 2.

³²Goodwin and Hollingdale (1952). The key problem was that undertaking the calculations required not only mathematical expertise, but also engineering competence. For instance, as one contemporary source notes: 'If the young mathematician... has little supplementary training in physics or engineering, he may find a position in the aircraft industry as a computer or supervising a group of computers; however, his possibilities for advancement are limited. For he does not ordinarily know sufficient mathematics to be useful in solving problems of applied mathematics; nor does he know sufficient physics or engineering to make a competent engineer.' (Bollay, 1947, pp. 106–107). It was these higher levels of expertise that were lacking in the British Industry.

³³The panel was established in November 1952, was re-established as the computation *sub-committee* in February 1954, and was disbanded in late 1958. By 1958, the network of com-

the University of Birmingham, the panel had a broad membership including the digital computer pioneers Maurice Wilkes and F. C. Williams.³⁴ Representing the Government was Brigadier G. H. Hinds, then the Director of Weapons Research for the Ministry of Supply.³⁵ Only half of the members were digital pioneers, the other half being either analog experts or users of both technologies. Goodwin and Hollingdale were both members, each representing their respective establishments.³⁶

By bringing in experts from the main centres of British computer research, the panel's remit was to promote the use of efficient computing techniques, advising other ARC sub-committees (focusing on topics such as oscillation, structures, and aerodynamics) on the best technologies and methods for particular problems. Throughout their early meetings their greatest concern was the lack of computer knowledge in industry, and they considered assembling an introductory handbook, and running short courses.³⁷ At their first meeting one member of the panel felt that:

...only a few people in the Aircraft Industry realised the need for efficiency in computation and many were content to take months over work that could, and had, been done in a few days.³⁸

puting expertise was sufficiently established to warrant a more ad-hoc approach to discussing computing issues. See ARC (1954–1958), Meeting 21, 17th October 1958.]

³⁴Wilkes and Williams had led pioneering computer projects at the universities of Cambridge and Manchester respectively.

³⁵Hinds had served in the British Army during the Second World War, and received an OBE in the 1946 New Year's Honours List. After the war, he began working in Whitehall. In 1957 he left his post as Director of Weapons Research to take up an appointment as Electronics Advisor for the British Transport Commission. See Anon. (1946, 1957). Wilkes oversaw much of the development of the Cambridge EDSAC but had also previously used a differential analyser as part of his PhD.

³⁶While Hinds and Wilkes were keen on digital, others in the group had a more open-minded view to analog-digital issues and while there was an analog-digital debate, there were no hostilities between the two camps.

³⁷At Wilkes' suggestion, the panel decided to promote Hartree's *Calculating Instruments and Machines* and maintain a bibliography of relevant research papers.

³⁸Although minuted, the statement is unattributed. ARC (1952–1953), Meeting 1, 21st November 1952, p. 2.

The computation panel: reviewing appropriate methods and technology

The panel considered the whole range of computer technologies including direct analogs, indirect analogs, and digital. One of their main outputs was to build a collection of important reports, papers and other documentation relating to their field of interest.³⁹ Two major analog applications were discussed by the panel. The first was the application of resistance networks and electrolytic tanks for aerodynamic modelling; the second, the provision of analogs for modelling aircraft flutter.

Tanks versus networks

With electrolytic tanks becoming more popular within the aeronautical research community, the panel needed to make decisions about which technology, tank or network, should be recommended to British aircraft manufacturers.⁴⁰ During 1954, they reported on the use of electrical analogies for aviation, discussing the relationship between Redshaw's resistance network methods at the University of Birmingham and Malavard's electrolytic tanks.⁴¹ Their conclusions were that there was need for both types of analog:

Two principal electrical analogies for the study of flow problems were those of the electrical resistance network and the electrolytic tank, the former giving essentially a discrete point representation and the latter a continuous one. The two methods were complementary rather than alternatives and each had its particular advantages and limitations. In both cases the advantage over ordinary computation procedures lay in the ease of altering parameter and direct reading of solutions.⁴²

³⁹During its seven years of existence, they indexed around 150 documents. No complete list of these publications exist within the archival holdings of The National Archives, however, through the various references in the minutes, I have reconstructed an almost complete list (see Appendix D) which should assist further research into the computing panel.

⁴⁰This was an important issue, because not only did the ARC have significant influence over the technologies in use in research establishments and industry, their choices would also directly impact on which university research programmes the Ministry of Supply would fund.

⁴¹Kuchemann and Redshaw (1954).

⁴²ARC (1955)

Discussion of this kind tended to conclude that both methods should be recommended for different work. Electrical networks were still favoured however, perhaps because Redshaw, the chair of the panel, led the largest network analog research programme in the UK.

This was all set against the backdrop of increasing digital computer use. For example in 1947, R. A. Fairthorne, an engineer from the RAE, introduced the electrical tank as an intermediate technology between network analysers, which were slow to set up, and digital computers which were still not fast enough:

The tendency during the past ten years in electrical analogy methods has been to make networks, and [Fairthorne] felt that the tendency had gone much too far. The network apparatus which had been developed and used in the United States since 1934 had reached an incredible degree of complexity, so much so that he would guarantee that the ordinary calculating machine would require less time to calculate numerically than would be required to set up the network apparatus.

In M. Malavard's type of analogy the network was of an infinitesimally small mesh, which they could not hope to handle by numerical methods or by the network apparatus.⁴³

The electrolytic tank was a computational medium that simply did not exist in the digital world. It was an experimental apparatus, more like the wind tunnel, where the user was encouraged to get close to the computational problem. The system under study was modelled using the immediate analogy between displacement in the model and displacement of the aircraft or missile. During the 1950s, digital computers were operated in batch mode by computer operators, the engineer would not be involved in the actual computing process. Unlike a digital computer which generated a solution, the electrolytic tank provided an environment for exploring solutions. This is captured in a report on aeronautical analog computers dating from 1953:

The analogue machine, on the other hand, is more convenient where the problem is itself tentative and experimental; that is, where the

⁴³Fairthorne as quoted in Malavard (1947).

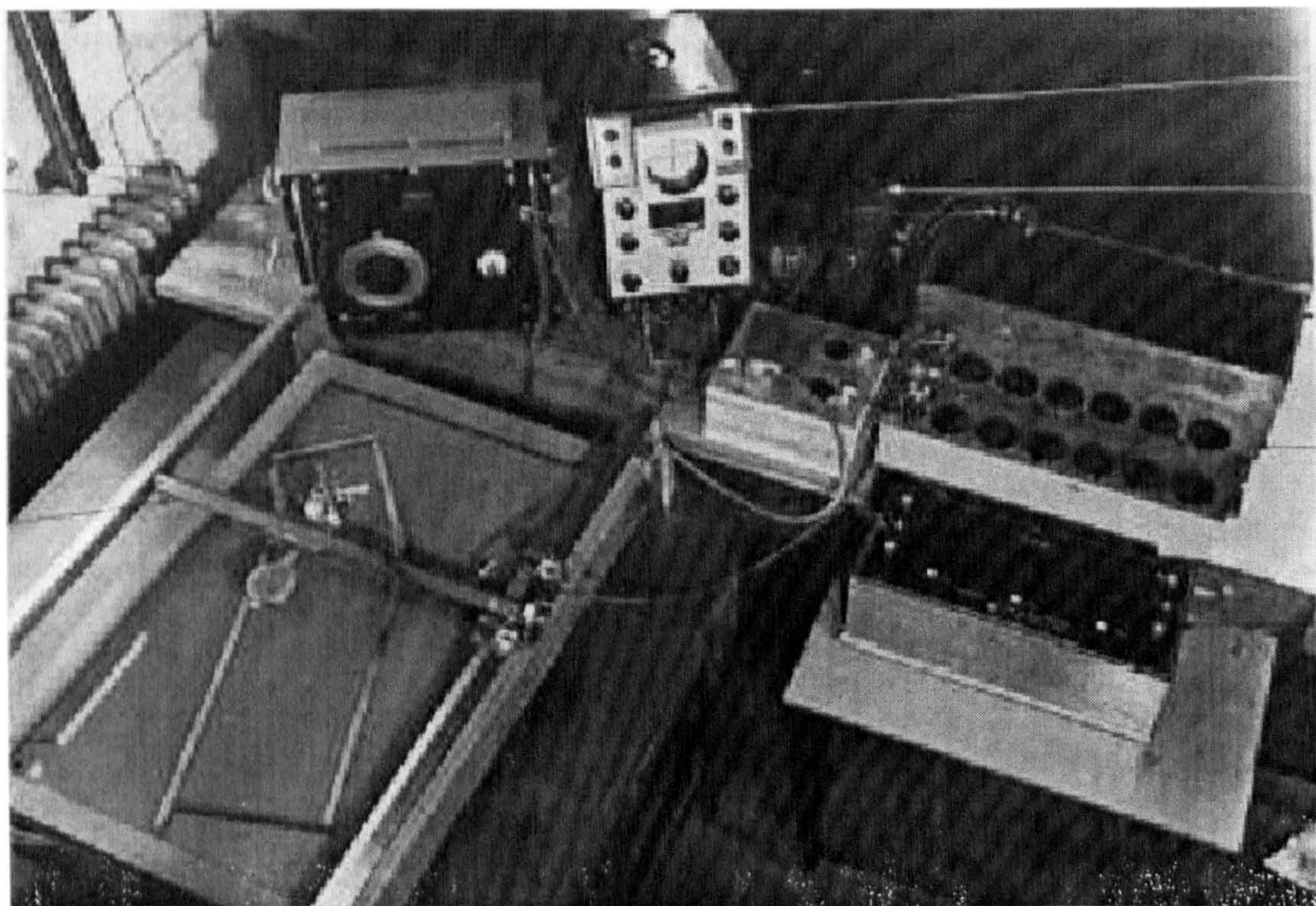


Figure 7.3: An electrolytic tank used in British aeronautical research. Source: Hargest (1952)

choice of later calculations may depend on the results of earlier ones, not in a definite mathematical way, but by the intervention of human intelligence.⁴⁴

Deciding between analog and digital: the case of flutter

While the discussion between types of analog are interesting, more pertinent for the engineers like those on the computational panel was how to decide between analog and digital. During this period, a major problem within aircraft design was the problem of flutter: planes becoming unstable and even disintegrating due to unstable structural vibrations.⁴⁵ Flutter was one of the key computational

⁴⁴Hollingdale and Diprose (1953) p. 1.

⁴⁵The first documented case of flutter was experienced by a bomber aircraft designed by Handley-Page during 1916. During the early half of the twentieth century, the common approach to designing flutter-free structures was through experimental test-flights. However by the late 1930s, the threat of serious accidents such as the crash of a Junkers aircraft during such an experiment resulted in engineers turning to ground-based analysis. This involved both theoretical consideration of the aerodynamics, which required the solution of complicated equations, and ground-based experiments involving wind tunnels. See Rodden (1992) pp. 223–224.

problems in the design of high-speed supersonic aircraft, and a complex problem for which analog computing was commonly used.

Solving flutter equations was the major computational problem facing aircraft designers.⁴⁶ In a RAE technical note dated 1955, H. Templeton, an aerodynamic researcher wrote that it had 'become an increasingly serious problem due to the combination of higher aircraft speeds and thinner wings and tail surfaces.'⁴⁷ This was further complicated by the introduction of swept and delta wings for high speed aircraft. Templeton understood this increasing complexity as a motivation for analog computer application:

...calculations have to cover more degrees of freedom, and the effects of variations in the aerodynamic and structural parameters need to be investigated to a greater extent. The final result has been that the flutter calculations required on a modern aircraft are usually beyond the scope of a desk calculating machine, and high speed computational aids have become a necessary adjunct to flutter prediction.⁴⁸

In this quotation, 'high speed computational aids' actually refer to analog computing machines. RAE constructed two 'flutter simulators' both of which were installed at Farnborough and made available for aircraft manufacturers to use. There was some digital work done by Goodwin on NPL's Pilot ACE to solve the same equations as the flutter simulators, and while the technique proved viable, this was not seen as particularly practical. Goodwin was certain that 'digital machines would finally prove a better proposition', but the ARC concluded that at the time, digital computers were not sufficiently advanced for this application.⁴⁹

Historians of computing have identified flutter as a key mathematical application of the early digital machines. See Aris (2000) p. 10; Neukom (2005) p. 17.

⁴⁶Of all the calculations of aeronautical engineering, Paul Ceruzzi described flutter as 'the most urgent' (Ceruzzi, 1989, p. 33). He noted that theory had surpassed what could be computed easily by hand. It was flutter that encouraged Northrop to develop the Maddida DDA and also inspired the IBM CPC computer – Ceruzzi described Northrop as a midwife of computer application (see below). He notes that a principal use of the CPC was parameter variation which is more like employing the computer as a modelling tool than as a calculating tool.

⁴⁷Templeton (1955) p. 1.

⁴⁸Templeton (1955) p. 1.

⁴⁹ARC (1952–1953), Meeting 2, 16th December 1952, p. 3.

Solving a flutter problem was a three stage process. The first two steps were preparatory,⁵⁰ formulating a system of equations which were then solved. RAE's first flutter simulator (FS I) was designed to assist the third stage of the process and was developed in-house, beginning service in 1949. The FS I was a prototype machine, supporting only two degrees of freedom and was soon followed up with the FS II which became operational in January 1952 and could solve problems involving six degrees of freedom. By 1955 it was becoming clear that an even larger machine would be required to 'satisfy the demand for some time to come'.⁵¹ The FS III which was in the planning stages in 1955, would work with twelve degrees of freedom.⁵²

Since solving flutter equations was such an important application, large aircraft firms began to think about developing their own flutter calculators. Reducing duplicated effort was one of the ARC's key objectives and the computation panel had already expressed concerns about individual firms designing and developing their own machines. It was the hope of RAE, and of the computation panel, that users in the aircraft industry would either use the Farnborough machine or construct their own to the RAE design.⁵³

While it was agreed that an economic saving would be made if every company were to adopt the same machine, the jury was still out over what that technology would be. There was a preference amongst the government engineers that the RAE flutter simulator should be used, some members of the panel suggested that a more general purpose machine, perhaps a digital computer, might be better still. The suggestion of a digital computer came from Wilkes and was supported by Hinds. As a digital computing pioneer, Wilkes was aware of the benefits of

⁵⁰Firstly determining the 'normal modes of oscillation', and then calculating the structural and aerodynamic coefficients.

⁵¹Templeton (1955) p. 6.

⁵²Alongside the modelling of the mathematical equations, RAE also developed smaller analog computers to complete stages 1 and 2. Stage 1 was served by NOMAD – a 'Normal Mode Analogue Computer', and stage 2 by a combination of INCA (Integral Calculator) and MAYA (Matrix Multiplier). Thus even in the mid-1950s, RAE was developing an entire end-to-end special purpose analog computing process. (Templeton, 1955, pp. 4–8).

⁵³ARC (1952–1953), Meeting 3, 23rd January 1953, p. 1.

digital computing. On the other hand, as a MoS representative, Hinds gravitated towards the economic benefits of having one generic type of machine to purchase and maintain. Based on the assumption of general-purpose being desirable, Hinds gave the digital computer as the way to provide this goal. However, the idea of a general-purpose tool did not seem popular with the engineers; and such a goal only seemed sensible if the digital route was chosen. Half of the attraction of analog was that it could be encapsulated into fairly inexpensive, well-targeted installations. For example, Redshaw, the chair of the panel, saw the special-purpose nature of the flutter simulator as its main strength, thinking that a more generic analog would 'defeat its own purpose'. Diprose, an RAE engineer, echoed this by pointing out:

...that an analogue flutter simulator would be preferred by the people working on flutter because an all-purpose machine could be used for other computations and therefore would not be for exclusive use.⁵⁴

While pioneers like Wilkes could see the benefits of digital, the technical, engineering communities were resistive to change. This was most likely due to analog being the technology that they had been trained and educated in. In the same meeting, Prof. Pugsley, the renowned structural engineer from Bristol and an established member of the ARC remarked that:

...the popularity of analogue machines was due to the fact that firms already employed staff trained in electronics and servomechanisms who could be used to service such machines. Digital machines required more specialised servicing teams and some training schemes would be required to provide the necessary staff.⁵⁵

⁵⁴ARC (1952-1953), Meeting 2, 16th December 1952, p. 2.

⁵⁵ARC (1952-1953), Meeting 2, 16th December 1952, p. 3.

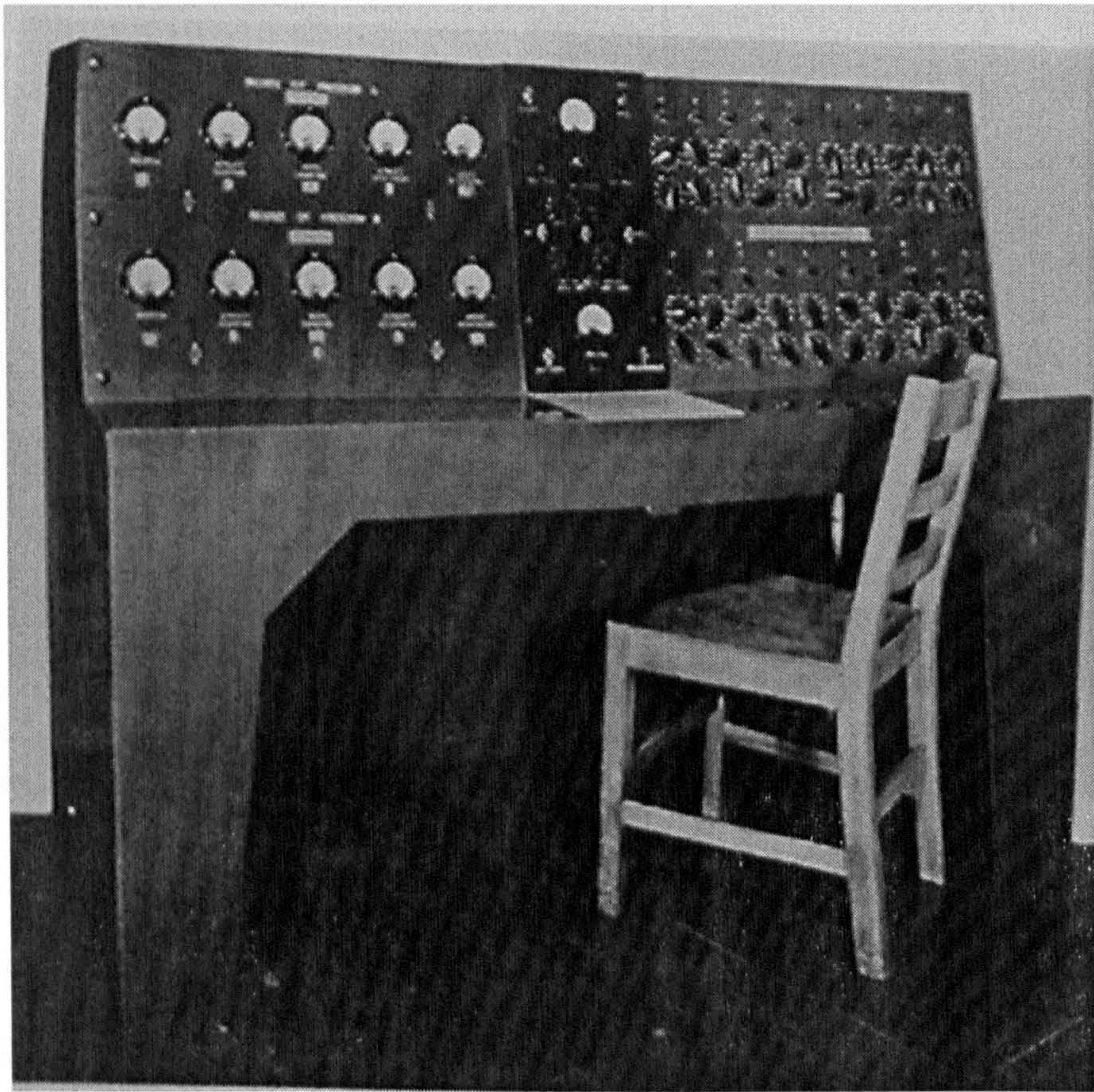


Figure 7.4: The first RAE Flutter Simulator (FS I) Source: Smith and Hicks (1950)

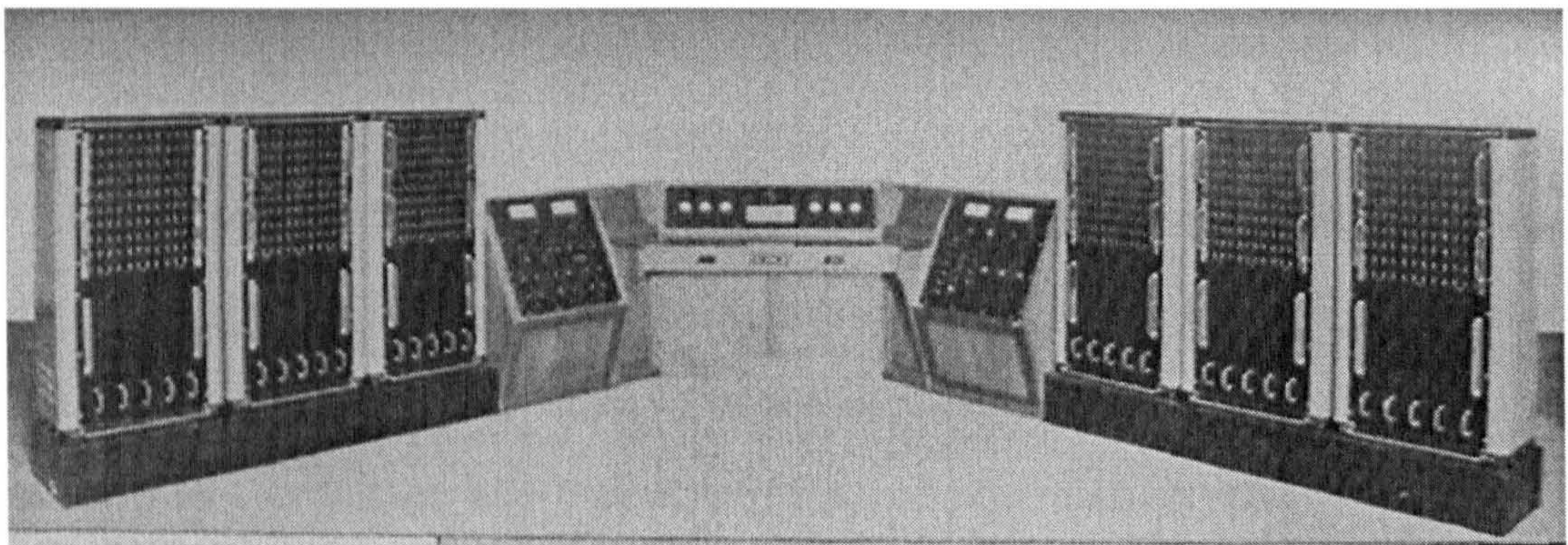


Figure 7.5: Front view of the main RAE Flutter Simulator (FS II) Source: Smith and Hicks (1953).



Figure 7.6: Close up of the FS II control desk Source: Smith and Hicks (1953).

Thirty year persistence: the shortcomings of digitalisation

Despite a realisation early on within the panel that digital computers were the more general purpose and would become the technology of the future, analog computing remained central to their discussions. A look at the papers circulated towards the end of this series show that research on analog computing was still commonplace in the mid to late 1950s. In the wider context, there was significant use of analog computers by the aeronautical community well into the late 1960s.

A major difficulty was training engineers to formulate their problems for the digital computer. In organizing the digital computer, users had a choice, either the aeronautical engineer could write the program himself, or it could be outsourced to a dedicated and trained professional programmer. Once written, the program would be submitted to a computer centre, and the results brought back to the engineer. However, engineers were not trained in programming as a primary activity, so formulating their own problems for the computer was difficult.

If it was undesirable for engineers to learn the new skill of programming, they could avoid it by employing a programmer, just as they had in the past employed human computers to do calculation, or secretaries to prepare documentation.

Alongside the issue of programming, the engineers in the computation panel were unsure whether the design process should be adapted to fit with the new technology. Previously, and especially with analog computers – since the very nature of analog computing meant that there was such a close mapping between the system and its computer representation – engineers did not separate the calculations from the design work. The introduction of digital methods led to a policy of closed shop computing where all problems needed to be framed in a batch processing model.⁵⁶ Engineers liked the idea of having their own machine with a real-time response. Digital computing created a new culture of waiting for results.⁵⁷

Another concern of the aeronautical engineers was the trustworthiness of digital software. Because engineers had framed their problems in terms of physical phenomena with analog computing, there had previously been less need to worry about the verification of their models. This tension between the analog engineering culture and the emerging digital computing culture is exemplified by a short discourse between Diprose and Wilkes at an early meeting of the computation panel.

Mr Diprose viewed with alarm the implied tendency to build up large

⁵⁶In a review paper on 'The Role of Analogue Computing in the Aircraft Industry', Hollingdale and Diprose suggested that digital should be used for problems that suited batch processing and analog for the experimental problems. See Hollingdale and Diprose (1953). Hollingdale had a broad perspective when it came to computing. With his mathematical background, he saw the merits of the digital computer. However, through working at RAE, he also understood the importance of analog. In 1965 he co-authored a popular introduction to computers entitled *Electronic Computers*. In this text (and in the second edition published in 1970) the authors described both analog and digital. There was no rhetoric in this book about the relative merits of the two technologies, the authors preferring to emphasise their complementary roles. For example, the authors noted Hartree's involvement with the differential analyser and the ENIAC as 'an excellent early example in avoiding narrow specialisation on either analog or digital computers.' (Hollingdale and Toothill, 1970, p. 80).

⁵⁷This would be relieved by the introduction of time-sharing systems, minicomputers and later personal workstations. This explains why engineers were not fully dis-enrolled from analog until the 1970s.

programmes and so have the arithmetical processes divorced from the physical problem.

Dr Wilkes said there was less danger of this happening with automatic digital computers than with a team of hand computers. The machine would employ no short cuts or approximations which the programmer did not put into his coding...⁵⁸

The best solution appeared to be to get engineers to do the programming themselves, at least for simple problems. But this, ironically, fuelled the same problem that had initiated the group's formation, that design engineers were not doing enough design work and were distracted by calculations.⁵⁹

The replacement of analog and the redefinition of skills

Of course, the digital computer did eventually replace analog techniques. To return to the story of Pérès and Malavard in Paris, their analog facility evolved into a centre of hybrid computing, and later a centre of expertise for digital modelling.

By the 1960s advances in digital computing meant that applications of analog computing technology began to diminish. Mounier-Kuhn (1989) describes how Malavard responded to this by reorienting the focus of the laboratory towards hybrid-computing. This subtle adjustment in research direction allowed the laboratory to maintain a strong position in fluid dynamics and their other application specialisms without being restricted to a particular technology. Hence when the laboratory became the LIMSI (Laboratoire d'Informatique pour la Mécanique et les Sciences de L'Ingénieur) in 1972, the researchers were able to apply their expertise in hybrid systems to emerging application areas in multimedia technology.

As historian Pierre Mounier-Kuhn wrote:

⁵⁸ARC (1952–1953), Meeting 3, 23rd January 1953, p. 3. Diprose was, at this time, employed by the RAE.

⁵⁹In their original suggestion that engineering calculations should be organised by means of division of labour, Hollingdale and Goodwin had noted that 'this policy has proved successful in U.S.A.' However, with respect to British engineering culture, the story was different and many engineers wanted to continue to manage the calculations themselves (Goodwin and Hollingdale, 1952).

Since its first trials of speech synthesis on a CAB 500, LIMSI has remained as one of the leading French laboratories for fluid mechanics calculations, computer graphics, and speech recognition by computer.⁶⁰

While the influence of analog computing as a technology was fading out, it is important to realise that the analog culture remained. The communities that had been specifically involved with digital computing were focusing on algorithm design, programming languages and machine hardware but those involved in analog and hybrid computing started to develop more exotic peripheral hardware involving sound, graphics and other analog (continuous) electronics. This mirrors what we observed in Chapter 5. In the context of aeronautics, the development of digital visualisation and modelling was key to provide a replacement for analog.

Conclusion

In contributing to a history of use, this chapter emphasises how the preferences of contemporary actors form part of a mutual shaping of technology. Employing a modelling perspective helps show the rich story of analog use in aeronautics. By considering the heritage of analogy, we have included technologies such as soap bubbles and electrolytic tanks, both of which were referred to as analog in context. These technologies offered a more interactive form of computing than the digital technology of the day. In order for digital to fully replace analog, modelling software had to provide the same levels of flexibility, interactivity and visualisation.

Within the ARC computation panel digital advocates such as Wilkes or Hinds were advocating digital primarily due to its generality. While they both understood the economic and technological benefits of this, the engineers were quite happy with special purpose technology. We saw how one engineer felt that employing a digital machine would make the tool 'not for exclusive use' and reduce

⁶⁰Mounier-Kuhn (1989) p. 258.

its availability to its users. Within a context such as aeronautics the rhetoric of generality was not as strong and was even thought to 'defeat its own purpose'. When we look at the decisions surrounding analog versus digital, we see that the digital pioneers were taking a modelling activity, exploring what could be automated, and transforming it into information processing. The aeronautical engineers were not as interested in automation. Instead they wanted tools that they could think with. In Chapter 3, we referred to Howard Rheingold's discussion of Licklider's vision of interactive computing. One of the examples Rheingold gave of this new type of computing (which he called modelling) was the visualisation of airflow. A modelling perspective helps explain the complexity of the transition to digital.

This chapter demonstrates the popularity of analog computing within the aeronautical community. We saw how engineers were concerned about the trustworthiness of digital representation, and that they liked having control of their own computing. In Chapter 5, we identified a three-way split in calculation, modelling, and control. The indirect analogs (being primarily equation solvers) were the first to be transferred to digital. However, because of the need to establish this trust, it was direct analog computing (such as tanks and networks, which did not have a clear mathematical representation) that took longer to become trustworthy.

None of these problems posed a direct barrier to digitalisation, and in fact, engineering practice did adapt to the batch processing model. However, concerns such as engineering trust were factors in slowing down the uptake of digital. There is a consensus that it was not until the mid 1970s that modelling applications of analog computing were completely displaced, a whole generation away from the efforts of the digital pioneers of the 1940s. The people engaged with computing in this period were *users* rather than inventors. The computational medium of analog computing held their trust and supported their professional credibility. It took a generation for the credibility of digital to become fully established.

Chapter 8

Physical modelling and numerical calculation in meteorology

During the twentieth century, the discipline of meteorology evolved significantly. In particular, there were major advancements in the application of numerical modelling, computers enabling the science of numerical weather prediction to flourish. Historian Amy Dahan-Dalmedico notes that meteorology was ‘one of the first scientific disciplines where the advent of numerical methods transformed the mathematical practices of its scientists’.¹

Digital computing is therefore hugely significant in the history of meteorology. But what about analog computing? This chapter takes a look at this application area and finds that where analog devices were used, they were not always referred to as computers. In particular we will see how Lewis Fry Richardson – a pioneer of digital modelling – used physical modelling techniques to complement numerical processing. This chapter offers the chance to employ the broader theme of modelling technology, and explore a context where analog computing existed, but was not so called.

¹Dahan Dalmedico (2001) p. 396. In a recent history of numerical forecasting, Kristine Harper described numerical weather prediction as ‘the major advance in 20th-century meteorology’ (Harper, 2003, p. 690).

Computation and the history of meteorology

One of the major studies of the history of meteorology is Frederik Nebeker's *Calculating the weather*, an investigation that stresses the centrality of the computer in the development of twentieth century meteorology.² Nebeker explained that modern meteorology is the amalgamation of three distinct strands of activity: the empirical activity of recording and observing the weather; the theoretical tradition of attempting to explain current weather; and the practical tradition of predicting (or forecasting) future weather.³

While all three traditions of meteorology shared common motivations, they each had their own culture and type of activity. The void between the two traditions which Nebeker described as empirical and theoretical cannot be understated. Commenting on the history of American forecasting, Kristine Harper noted that most of the American theorists 'had never made a forecast in their life [and] certainly not one for anyone outside of their immediate family.'⁴ The result was that empiricists rarely drew on meteorological theory, and the theorists made little use of observational data. The forecasters, whom Nebeker presented as a third, more practical, tradition, 'based their predictions on only a small amount of data and hardly any theory at all', and were therefore perceived as unscientific by the observers and theoreticians.⁵

During the nineteenth century calculation had a secondary role, but during

²Historiographical consensus is that computational influences are pivotal in the history of twentieth century meteorology. Edwards (2000) states that '[b]y the 1960s, increasing computer power made possible detailed simulations of the general circulation of Earth's atmosphere. This, in turn, allowed scientists to simulate weather and climate...' (p. 222).

³Nebeker (1995) p. 1. Nebeker supports his argument of this three-fold separation with a quote from Napier Shaw, a contemporary British Meteorologist (pp. 10, 195). In fact Nebeker's three-way analysis closely mirrors Shaw's history of meteorology (Shaw, 1926, p. 320). Nebeker describes how the three distinct fields emerged during the nineteenth century, the increasing numbers of active researchers encouraging specialism into disparate cultures.

⁴Harper (2003) p. 669. The traditional method of forecasting required a vast amount of weather data to be tabulated and indexed so that a forecaster could match the current weather and make predictions.

⁵Before pioneers like Richardson developed mathematical models that could be used to 'compute' the weather, the activity of forecasting was based on comparing observed weather conditions against historical data. In his book, Richardson presented this activity as highly inexact and unscientific. See Richardson (1922b), preface.

the early twentieth century, each of the three traditions experienced a different force that directed them to computational technology. Firstly, the empiricists began to draw on wider data sources and so created a demand for information processing. Secondly, meteorological theorists began to develop complex mathematical models and so had to do extensive calculation in order to verify theory. Thirdly, in an attempt to become more scientific, the forecasters left their activity of ad-hoc pattern matching, and developed procedures involving significant number crunching. Each tradition was drawn towards computing technology, and thus the computer *unified* the discipline.

However, crediting the computer with such agency is perhaps too simplistic. In a review of Nebeker's work, Agar (1997) notes that it is quite rare for a technology to have such a pivotal role in history.⁶ Indeed, Agar questions such strong technical determinism, suggesting that the idea of automating numerical weather prediction was not obvious or necessarily welcome to the meteorological community. He highlights how this opposition might have come from alternative approaches, perhaps including analog computing:

...Nebeker gives no account of opposition to the numerical transformation of the discipline. He notes that 'the new style of meteorology required skills different from those meteorologists traditionally possessed', and histories of other disciplines would suggest this would be enough for conflict. Indeed, Nebeker mentions elsewhere that the formerly influential Bergen School 'benefited hardly at all from the new computational power'. Another possible site of conflict could have been with users of analogue computers (declared as quickly 'obsolete' by Nebeker as part of the abandonment of other computational aids in the face of the digital computer). We know, through the work of James Small, that analogue computers should not be seen as a wrong turning in technological evolution... The analogue computer offered speed (cited by Nebeker as one reason why digital electronic computers were adopted) and hands-on interactivity (surely invaluable in modelling and simulating a complex system such as the weather).⁷

⁶Agar acknowledges that Nebeker identifies 'the interplay between theory, observation, and organisation.' For example: 'the development of equations connected to designs of practical Meteorological Office organization, new ways of gathering data, and, completing the circle, further theory development'. Agar (1997) p. 119.

⁷Agar (1997) p. 118.

Following Agar's call to consider non-digital computational influences, a closer look at this domain shows that there were technologies which elsewhere would have been called analog. In particular, there was a physical modelling tradition in meteorology that bore resemblance to analog computing, but was not called 'analog'. It appears that for meteorological applications, analog models were not enrolled into computing culture.⁸

Non-digital approaches to meteorology

Two early movers in trying to bridge the divide between meteorological theory and practice were the Norwegian scientist Vilhem Bjerknes and the British meteorologist Lewis Fry Richardson, both working during the first two decades of the twentieth century. These pioneers believed that it was possible to bring together the growing wealth of observational data and the theoretical research derived from the laws of physics.⁹ As described below, Richardson proposed a highly parallel computing technique for modelling the world's weather. Unlike Richardson, Bjerknes did not persevere with developing a mathematical approach; he did not consider the equations to be easily solvable.¹⁰ Working around 1903, Bjerknes came to develop (with his colleagues at Bergen, and later at Leipzig) a set of qualitative approaches that still made use of the underlying physics. The methods of the Bergen school became widely accepted during the 1930s and were used extensively until numerical prediction became dominant.

In terms of computing aids, analog technology was mainly used in early meteorological applications as an equation solver. For instance, during the late nineteenth century, a copy of Kelvin's harmonic analyser had been installed and was used for 'daily work' at the Meteorological Office.¹¹ Similarly, Nebeker refers

⁸Edwards (2000) p. 248; Nebeker (1995) p. 181.

⁹Woolard (1922) p. 173.

¹⁰Bjerknes was called into practical forecasting work during the aftermath of war and therefore favoured those methods that would deliver results quickly. Hunt (1998).

¹¹Shaw (1885) p. 164; Scott and Curtis (1886) pp. 382–383.

to an electronic calculating device developed by Seymour Hess at Florida State University for determining the two-dimensional Laplacian from a map, and John Mauchly used an analog computer to show the relationship between solar observations and weather.¹² Although analog computers were employed as calculating aids in these examples, the historiography indicates that meteorology never became a major application area for electrical analog technology.

Richardson's forecast factory and his suggested analog alternative

One of the most interesting characters in the history of numerical weather prediction was Lewis Fry Richardson. Well known to meteorologists, he pioneered numerical techniques for forecasting during the early twentieth century.¹³ In a seminal work entitled *Weather Prediction by Numerical Process* (WPNP) published in 1922, he outlined techniques which, according to recent scholarship, is 'essentially the method used today.'¹⁴ Within the history of computing, Richardson is best remembered, and most frequently cited, for his idea of a forecast factory: a fantasy human computing organisation which he lightheartedly described in the final pages of *Weather Prediction by Numerical Process*.¹⁵ In this imaginary factory, the efforts of 64,000 human 'computers' would be combined to predict the world's weather in a parallel fashion.¹⁶

Richardson's forecast factory was an intelligent musing of how to mobilise the computation required to numerically model the Earth's weather. In a room built

¹²Nebeker (1995) p. 168; Merzbach (1970) p. 12. See also Hess (1957); Gierasch (1982).

¹³Boulding (1985) wrote that Richardson 'laid the foundations for the theory behind [modern] computerized weather predictions' (p. 461). Today, both a number in turbulent fluid theory and an annual prize awarded by the Royal Meteorological Society bear his name.

¹⁴Lynch (2006) frontispiece.

¹⁵Bailey (1993) pp. 77–78; Descriptions of the forecast factory can be found in Campbell-Kelly and Aspray (1996) pp. 54–57; Williams (1999); Grier (2005) pp. 142–144.

¹⁶Richardson managed the calculations by splitting them up by region, a technique known commonly today as 'domain decomposition' (Lynch, 2006, p. 247). Bailey (1993) likens the forecast factory to a modern parallel computer with a large number of individual processing units passing information to their neighbouring units (p. 77).

to correspond to the globe, teams of human computers would work in parallel to calculate the weather of particular regions, communicating their forecasts to neighbouring teams. While Richardson did not pose this as a practical proposal, he had clearly given much thought to the problem.

After so much hard reasoning, may one play with a fantasy? Imagine a large hall like a theatre, except that the circles and galleries go right round through the space usually occupied by the stage. The walls of this chamber are painted to form a map of the globe. The ceiling represents the north polar regions, England is in the gallery, the tropics in the upper circle, Australia on the dress circle and the Antarctic in the pit.

A myriad computers are at work upon the weather of the part of the map where each sits, but each computer attends only to one equation or part of an equation. The work of each region is coordinated by an official of higher rank. Numerous little 'night signs' display the instantaneous values so that neighbouring computers can read them. Each number is thus displayed in three adjacent zones so as to maintain communication to the North and South on the map.

From the floor of the pit a tall pillar rises to half the height of the hall. It carries a large pulpit on its top. In this sits the man in charge of the whole theatre; he is surrounded by several assistants and messengers. One of his duties is to maintain a uniform speed of progress in all parts of the globe. In this respect he is like the conductor of an orchestra in which the instruments are slide-rules and calculating machines. But instead of waving a baton he turns a beam of rosy light upon any region that is running ahead of the rest, and a beam of blue light upon those who are behindhand.

Four senior clerks in the central pulpit are collecting the future weather as fast as it is being computed, and dispatching it by pneumatic carrier to a quiet room. There it will be coded and telephoned to the radio transmitting station. Messengers carry piles of used computing forms down to a storehouse in the cellar.

In a neighbouring building there is a research department, where they invent improvements. But there is much experimenting on a small scale before any change is made in the complex routine of the computing theatre. In a basement an enthusiast is observing eddies in the liquid lining of a huge spinning bowl, but so far the arithmetic proves the better way. In another building are all the usual financial, correspondence and administrative offices. Outside are playing fields, houses, mountains and lakes, for it was thought that those who compute the weather should breathe of it freely.¹⁷

¹⁷Richardson (1922b) pp. 219–220.

There is much to say about this often-quoted passage. From an industrial and technical perspective, we can see that Richardson understood the key features of an efficient information clearing house. The division of computing labour is well thought out, as is the supporting infrastructure of telephone and radio communication.¹⁸ From a social perspective, the description also highlights Richardson's ethics.¹⁹ What is particularly interesting for our purposes is the surprising reference to physical modelling. In the final paragraph, Richardson described a research and development laboratory developing what could be considered an analog computer. The actual analogy is not specified, but Richardson intended the behaviour of eddy currents in a spinning bowl to correspond to atmospheric flow patterns. Most importantly, Richardson presents this set-up as a possible alternative to the 'myriad of [human] computers', and therefore as an alternative calculating technology.

In previous chapters, we have been employing a pragmatic approach to defining analog computing; Richardson's rotating tank is a physical model conceived to replace conventional calculation, and could therefore be considered a direct analog. Actually, this 'huge spinning bowl' is a reference to a class of experiment that would later be reinvented in the 1950s. Known as a 'rotating dishpan', the experiment was used to model atmospheric Coriolis forces caused by the rotation of the Earth. The rotating bowl technique represented atmospheric flow with fluid flow in the model, providing a scaled experimental environment.

Richardson's depiction of such an experiment indicates that he was open to the idea that an arithmetical approach might not always prove 'the better way', high-

¹⁸While the forecast factory was always given as a fantasy – 'Richardson's dream' to quote Peter Lynch – the reality of human computing organization based on factory economics was a reality. The Oxford English Dictionary records that original usage of 'computer' refers to humans engaged in calculation or reckoning. There is now a significant literature surrounding the topic of 'human computers', see Grier (2005). In developing his mathematical method, Richardson hoped that the weather could be computed with the same reliability as the British Nautical Almanac, another successful large scale (human) computing project (Aspray, 1990b, p. 127).

¹⁹Richardson was a Quaker, and his insistence in the creation of an idyllic environment around the forecast factory where workers could benefit from fresh air is clearly inspired by the tradition.

lighting that the relative merits between numerical and physical were not always clear cut. Richardson experimented with this idea while serving on the Western Front in early 1918, constructing a 'working model' of the atmosphere using a basin of water on a rotating gramophone turntable.²⁰ Being a celebrity character in the history of mathematical forecasting, the literature portrays Richardson as a forward thinker, a pioneer of the mathematical method. As such, it is unclear why he would have considered developing an analog device.²¹

Although Richardson did not develop the experiment further, a copy of his research notes were passed on to the experimental meteorologist Dave Fultz of the University of Chicago, who around 1950 was developing similar models of atmospheric motion.²² We will return to the history of rotating fluid analogs later in the chapter, after investigating the context behind Richardson's experiment, and understanding his gentle assertion: 'but so far the arithmetic proves the better way'.

Richardson: mathematician, experimentalist, Quaker

Richardson was born in 1881 in Newcastle-upon-Tyne, the seventh child of a Quaker family. All of the Richardsons were well educated and he attended a well-regarded Quaker school in York, followed by Durham College of Science in Newcastle, and subsequently King's College, Cambridge.²³ After leaving Cambridge, Richardson entered a wilderness period, frequently moving between vari-

²⁰Ashford (1985) p. 71. Thus, we can see in this quote two sides of Richardson's character: firstly Richardson the pioneer of the numerical method and the need for almost unimaginable computational power, and Richardson the quiet experimenter, working on a physical model.

²¹Richardson's whole career can be interpreted in terms of the application of mathematical modelling. This is a theme clear in the recent review of his work by Hunt (1998). Nicholson noted that through all of his work ran the common theme of mathematical analysis and 'rigorous statistical methods' (Nicholson, 1999, p. 542).

²²We can assume that Fultz became aware of this early work from the description of the forecast factory; Oliver Ashford, then Richardson's biographer-to-be, supplied Fultz with a copy of Richardson's manuscript notes (Fultz et al., 1959, p. 4).

²³He graduated in 1903 with first class honours in part I of the natural sciences tripos. See Anon. (1903).

ous teaching and research posts.²⁴

Between 1905 and 1907, he worked in the peat industry, mathematically modelling water drainage. In 1907 he became an assistant to Karl Pearson at University College London, and afterwards returned to NPL to join the newly founded meteorology department. After a year at NPL he spent another spell in industry before accepting a teaching post at Manchester College of Technology (later UMIST). Once again, he was to stay there only a year, finally accepting the position of superintendent of Eskdalemuir observatory in Scotland, an appointment within the Meteorological Office. Richardson remained at Eskdalemuir until 1916 when he resigned his post to take up a role in the Friends (Quakers) Ambulance Unit (FAU), his Quaker beliefs preventing him from either enlisting in the Military or sitting out the war in the comparative safety of Scotland. Within the FAU he worked as an ambulance driver attached to the *Section Sanitaire Anglaise*, a unit based on the Western Front in Champagne.²⁵ On his return to England, he rejoined the Meteorological Office, working on numerical forecasting. A keen experimentalist, he also developed instruments and techniques to aid meteorological observation.²⁶ In 1920 he became head of physics at Westminster Training College, and in 1929 was appointed principal of Paisley Technical College where he remained until his retirement in 1940.²⁷

Richardson was a profoundly practical man: at school he was taught natural

²⁴His first position after graduation was as an assistant in the metallurgy department of the National Physical Laboratory (NPL), and he remained there for a year before becoming a junior demonstrator at University College, Aberystwyth. Ashford (1985) would later write that 'he drifted from job to job, with little sense of continuity.' (p. 19). While Richardson was certain that he wanted to be a researcher, he was still discovering the areas in which his interests lay. In this sense, Hayes (2001) likens Richardson's first decade of work with the experience of the modern post-doctoral fellow, a career path dominated by many short-term contracts (p. 10).

²⁵His experiences on the Western Front would later motivate him to develop mathematical models of war, although these investigations did not receive significant scholarly recognition until after his death. See Richardson (1957); Hunt (1998); Nicholson (1999). Nicholson explained that it was natural for Richardson to develop mathematical accounts of his experience: 'Wilfred Owen, Siegfried Sassoon, Robert Graves and other *littérateurs* wrote poems, autobiography and autobiographies disguised as novels; Richardson wrote equations' (p. 544).

²⁶Examples include a technique to measure wind direction and speed by projecting spheres into the air, and various work on weather balloons.

²⁷Lynch (2006) p. 254; Ashford (1985); Anon. (1953); Anon. (1929); Gold (1953); Hayes (2001) p. 10.

science by J. Edmund Clark, a member of the Royal Meteorological Society; at Cambridge, he had been instructed by eminent empirical physicists such as J. J. Thomson and G. F. C. Searle.²⁸ This inspired Richardson to develop his keen experimentalist attitude, which manifested itself in a variety of improvements to instruments. For example, his Royal Society obituary describes how David Brunt, then a student at Aberystwyth and later an eminent meteorologist, recalled this innovative nature:

...he [Richardson] was keenly interested in designing a planimeter. He carried his model around in his pocket, and would take it out and test and modify it in any free moment. He remained in my memory as a quiet friendly man, always ready to help in any difficulty with an experiment.²⁹

Even in the stress and strain of the Western Front, Richardson's passion for research and experiment did not wane.³⁰ Herbert Morrell, another member of the SSA ambulance unit, recalled that he 'spent a lot of his time setting up meteorological instruments and taking readings: we thought nothing of seeing him wandering about in the small hours checking his instruments.'³¹ Another example of Richardson's practical and experimental nature derives from his time at Westminster College, where he developed innovative teaching aids, including a set-up to demonstrate electromagnetism using bicycle wheels and an electric motor.³² Referring to this period, Ashford wrote that Richardson was 'a skilled practical experimenter... [who] made much of his own apparatus'.³³

²⁸Hayes (2001) p. 10; Searle is noted for his emphasis in experiment; especially its use in the education of physics. See Woodall and Hawkins (1969); French (2006).

²⁹Sir David Brunt quoted in Gold (1954).

³⁰Hunt (1998) observes that Richardson was fairly unique in not having stayed home to undertake scientific research as part of the War effort: 'This was the first major war in which leading scientists were called on by the armed forces and used to great effect, particularly in aerodynamics (G. I. Taylor at Cambridge, L Prandtl at Göttingen), ballistics (J. E. Littlewood at Cambridge), and the chemistry of explosives and gases (C. Weizmann at Manchester).' (p xix - xx).

³¹Herbert Morrell quoted in Ashford (1985) p. 57.

³²Described by Ashford (1985) p. 113, and published as Richardson (1922a).

³³Ashford noted how in later life Richardson had repaired a galvanometer at Paisley College when the laboratory technician's poor eye sight prevented him from doing it. He also managed all of his own weather instruments. (Ashford, 1985, p. 16).

We can therefore identify three major factors that shaped Richardson's life and career: firstly, a passion for research in the mathematical sciences, particularly expressing complex systems as formulae (exemplified by his work on water flow in peat, numerical weather prediction, and his later studies on mathematical theories of war). A second dominant feature of his approach was an innovative and experimentalist nature (consider his experimental background, the planimeter developed at Aberystwyth, the instruments he devised and maintained at Eskdalemuir, and the teaching experiments developed at Westminster). Always, these two characteristics were held in tension with the strong pacifist views that accompanied his religious life as a Quaker.³⁴ Through understanding Richardson's strong background in both experiment and mathematics, and his flexible and inter-disciplinary interest in research, we can begin to understand how both a physical analog and mathematical computation could be considered part of the forecast factory dream.

Richardson's rotating fluid experiment and the tension between experiment and mathematics

The research behind *Weather Prediction by Numerical Process* spanned two very different periods in Richardson's life: firstly his employment as the superintendent of a Scottish observatory, and secondly his wartime role as an ambulance driver on the Western Front.³⁵ Before he left Eskdalemuir, Richardson communicated a draft of his monograph – then called *Weather Prediction by Arithmetical Finite Differences* – to the Royal Society.³⁶ However, Richardson's desire to add a prac-

³⁴Richardson's interests in experiment and mathematics initiated his career in meteorology, while his pacifism, combined with first hand experience of the Western Front between 1916 and 1919, later directed his research towards the mathematical modelling of war. See Richardson (1957) p. 301; Lynch (2006) pp. 254–255; Ashford (1985) p. 71.

³⁵Lynch (2006) describes how the idea of applying the numerical methods he had devised in 1910 to meteorology had come to him gradually and that the first record of a specific connection is in a letter to Pearson dated 1907, but serious investigations on numerical forecasting began during his employment at Eskdalemuir.

³⁶The text was well received by Napier Shaw who proposed that the society fund the book's publication. Ashford (1985) p. 49; (Lynch, 2006, p. 254).

tical example meant that the whole project would be delayed until after the First World War. While in France he produced an example forecast demonstrating his methods.

It was in France that he conducted his spinning fluid experiment. In archive material now held in the special collections of Cambridge University Library, two pages of hand written notes describe the experiment he conducted on the 25th February 1918.³⁷ Using the limited technology around him, Richardson attempted to model rotations of the atmosphere with a bowl of water driven by a gramophone. His results showed promise, and he estimated that with a larger bowl and a steady water-powered motor, a 'very fair representation' of atmospheric currents could be constructed.³⁸ Using the bowl he experimented, without success, with the effects of heating, mimicking the temperature variations on earth between the polar and equatorial regions. This experiment was a rough-and-ready prototype, but Richardson detailed improvements in his notes: while his model only gave a representation of a single hemisphere, he suggested that adding a second parabolic shell within the main bowl would provide a model of winds that crossed the equator. With a water surface on both sides (see Figure 8.1) each side of the shell would act as a model of one of the Earth's hemispheres. Richardson noted that 'a special optical device' would be needed to view the rotating surface, perhaps a camera that revolved as part of apparatus.³⁹

There is no evidence to suggest that Richardson ever extended his initial study. Certainly, the scope for further experiment was limited in France⁴⁰, and by the time he returned to England, the two major topics on his mind were

³⁷Alongside his numerical studies he undertook many experiments while in France, investigating weather balloons, thermometers, and this basic dishpan experiment. Richardson was not a man to specialise, note that he maintained two different research careers throughout his working life, only turning to peace studies full-time in retirement. It is not surprising that Richardson had multiple research agendas within meteorology.

³⁸Richardson (1916–1919). Richardson's notes are reproduced in Appendix C.

³⁹Richardson (1916–1919). Also see Ashford (1985) p. 71.

⁴⁰Ashford (1985) noted that '[t]he facilities available in France were obviously inadequate for Richardson himself to follow up these ideas.' (p. 71).

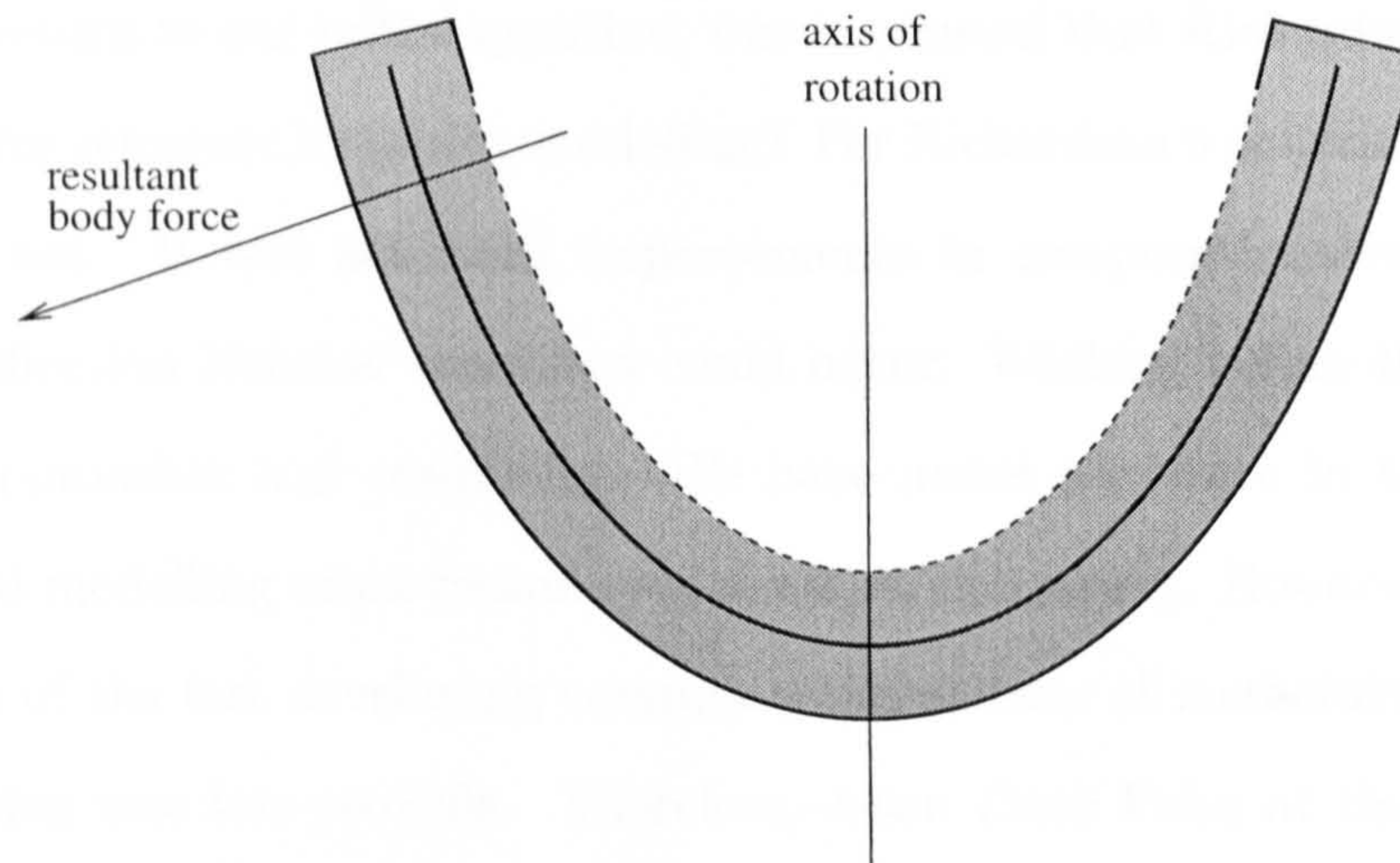


Figure 8.1: A sketch of Richardson's double rotating bowl for modelling the atmospheric interactions between two hemispheres. One parabolic shell (black curve) is shown within another; the liquid (shaded) represented the atmosphere, and the inner shell, the earth's surface. Source: redrawn from original in Richardson's own hand (Richardson, 1916–1919).

the completion of WPNP, and the design of weather balloons.⁴¹ The dishpan experiment would not become a serious avenue of his meteorological research.

As already discussed above, the expectation was that as a pioneer of numerical weather prediction, Richardson's own activities would be firmly in the digital camp; his reference to analog computing therefore appears an oddity. It is, however, possible to account for Richardson's involvement in terms of the three major driving forces in his career: practical experiment, mathematical modelling, and Quaker theology. His background in experiment would have inspired the rotating tank experiment; his arithmetical process deriving from a desire to develop mathematical models. While in hindsight we can see that these experimental investigations are not related to numerical weather prediction – the significant thread of chronology, we cannot assume that Richardson would have perceived them as 'digressions' from his research goal. It was not that simple for Richardson; he clearly tried many different avenues in meteorological research, and found

⁴¹In other notes dating from this period, Richardson was developing various instruments for use with weather balloons. His interest in weather balloons was presumably motivated by the data he required in order to further the research into numerical forecasting.

it very natural to be an experimentalist.⁴²

To return to our initial question, was it unusual that Richardson should have made this reference to analog modelling? For Richardson's empirical background, it was not. It was not until improvements in computation had arrived that the unification Nebeker described could occur. Working before this unification, both approaches had credibility. We have noted elsewhere in this thesis that physical modelling often became redefined as computing. However, by 1950, the culture of the fast developing computational science of meteorology meant that an analog was less credible. Therefore, when Dave Fultz at the University of Chicago began to develop his 'rotating dishpans', he maintained the separation between computers and his experimental technology. The justification for the existence of his methods would be that small-scale experiment could highlight new ideas: in other words, Fultz would describe his set-ups as a complementary approach. Empirical meteorology based on analog models could no longer be an *alternative* to computational meteorology.

Dave Fultz and the experimental tradition of meteorology

In 1951, the American Meteorological Society published the *Compendium of Meteorology*, a collection of over a hundred articles that covered the significant topics in the field, aiming 'to take stock of the present position in meteorology... and to

⁴²The relative merits of the two approaches are themselves complex, however we can identify a number of factors that were key to Richardson as he was working in 1918. Firstly, there is the matter of practicality. Working close to the front line, paper-based numerical investigations were far easier to manage. Richardson described his wartime office as 'a heap of hay in a cold rest billet' (Richardson, 1922b, p. 219). However, the adoption of numbers came at a price. Recent scholarship by Lynch estimates that Richardson must have spent the majority of two years working through his sample forecast (Lynch, 1993, p. 69). Lynch noted that for 'useful and timely predictions, the calculations would need to go several times faster than the atmosphere... the establishment of a 'practical' forecast-factory would have reduced the ranks of the unemployed by over a million' (Lynch, 2006, p. 261). Within that context, the idea of creating a 'working model of the atmosphere' to simplify predictions would have been very attractive.

indicate the avenues of further study and research.⁴³ Divided into 24 categories, its coverage ranged from topics in the physical properties and dynamics of the atmosphere, such as atmospheric electricity, cloud physics, and atmospheric dynamics, through to meteorological optics and climatology. Practical issues were covered including a substantial section of weather forecasting and a small section on the design of meteorological instruments.

Towards the end of this 1,300 page volume can be found a collection of three articles under the heading of 'Laboratory Investigations'. The first paper in this section is an article by Dave Fultz entitled 'Experimental Analogies to Atmospheric Motions'.⁴⁴ Fultz opened his article by claiming that 'one of the very old dreams of meteorologists and other scientific observers... has been that of solving some problems... by means of experimental work on a small scale.'⁴⁵ He wanted to establish an experimental approach to meteorology:

In recent times the increasingly far-reaching successes of model experimentation in aerodynamics, hydraulics, oceanography, and other fields have given renewed impetus to efforts at serious work on meteorological questions by this means.⁴⁶

According to Edward Lorenz, Fultz was the first to develop a physical atmospheric model to 'bear fruit'.⁴⁷ Working at the University of Chicago, Fultz

⁴³Malone (1951) p. v. The project was directed by a committee of seven prominent meteorologists and chaired by H. G. Houghton.

⁴⁴The latter two articles considered modelling techniques in meteorological research and experimental investigations into cloud formation, and were written by the American engineer Hunter Rouse and the British meteorologist Sir David Brunt (Brunt, 1951; Rouse, 1951). Rouse was involved extensively in analog methods (particularly tanks), see Hubbard (1949); Brunt retired the same year from his professorship at Imperial, and developed a second career in civil administration, leading the Electricity Supply Research Committee and continuing with chairing the Brunt Committee who advised the DSIR on high speed computing. Agar (1996).

⁴⁵Fultz (1951) p. 1235.

⁴⁶Fultz (1951) p. 1235.

⁴⁷Lorenz (1995/1993) p. 87. A number of recent publications on the use of models in scientific culture have made reference to Dave Fultz. Paul Krugman uses Fultz as an example of physical modelling in his analysis of modelling in economics (Krugman, 1994). In particular he noted how modelling involves a reduction, and that the challenge of the modeller is managing that reduction. In his study of the Phillips Machine (see Chapter 4 page 107, above), Vines (2000) likened the Phillips and the dishpan in terms of the technical insight 'provoked' by the analogy built into the machine. In particular he highlighted how such speculative experiments could help understand how a mathematical model could be constructed (p. 41). He described both as a Kuhnian 'progressive model' (p. 58).

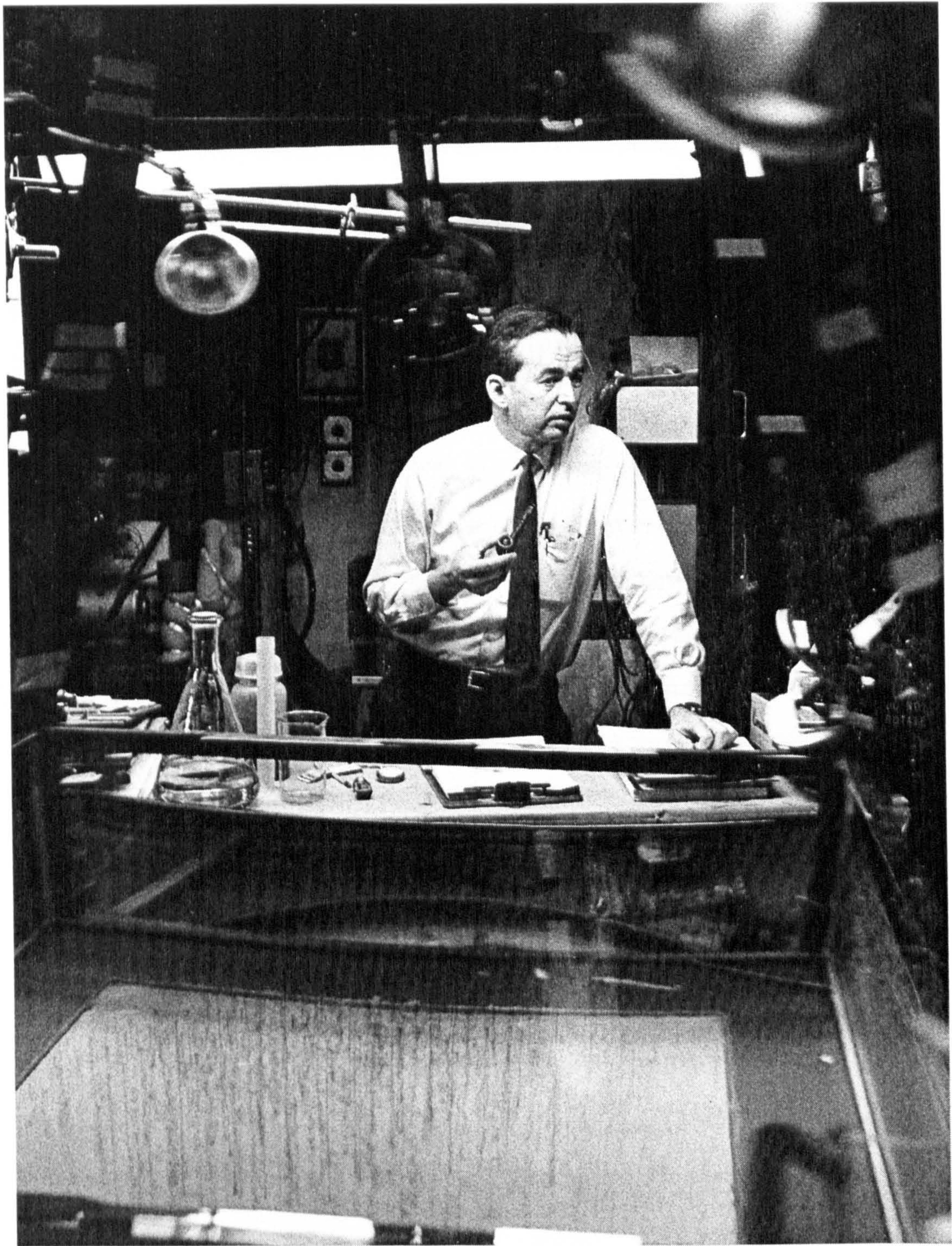


Figure 8.2: Dave Fultz in a laboratory setting. Source: University of Chicago press office, <http://www-news.uchicago.edu/releases/photos/fultz/fultz-lab.jpg>. Last accessed 20th April 2008.

constructed a set-up with a cylindrical bowl cooled in the centre and heated at the rim to represent the temperature gradient between the polar and equatorial regions of the atmosphere. Heating was first by Bunsen burner and later by electric coils for greater control, cooling was managed by an upward jet of cold water in the centre of the bowl. Placed on a motorised platform, the bowl was spun to model the Earth's rotation.

Just as Richardson had suggested in 1918, Fultz collected data with a camera that rotated with the bowl. He used sprinkled aluminium particles or coloured dye to visualise the flow patterns. Using extended-exposure photography, the images would capture movements of the aluminium particles as streaks. While the total cost of his set-up was around \$40,000, the basin of water was supposedly just a regular kitchen dishpan, and so the name 'dishpan experiment' caught on. In fact, a whole series of seemingly unrelated rotating liquid experiments were undertaken by meteorological researchers in the nineteenth and twentieth centuries.

The first well-known application of a rotating fluid experiment is attributed to F. Vettin, a German working in the 1880s, mainly experimenting with the effects of heating and cooling on fluids (experimenting with a rectangular tank). He then went on to investigate rotating systems using a cylinder containing air to which he applied heating and cooling. He used his rotating tanks to model the effects of mountain barriers on circulation, and attempted to show their relationship to equatorial calms.⁴⁸ It was only after 1940 that the models could be measured to derive quantitative data; early models were purely qualitative.⁴⁹ Between Vettin's investigations and the 1940s, several passing (and seemingly independent) references are made to fluid models, including James Thomson who wrote:

The apparatus would consist mainly of a horizontal circular tray kept revolving around a vertical axis through its center. The tray would be filled to some suitable depth with water. Heat would be applied

⁴⁸Fultz et al. (1959) p. 4.

⁴⁹Fultz et al. (1959) noted that it was not until Ferguson Hall working at the University of Chicago constructed a laboratory model of a 'hurricane-like vortex' with an aluminium dishpan, that useful quantitative measurements began to be made (p. 3).

round its circumference at the bottom, and cold would be applied or cooling would be allowed to proceed in and around the central part at or near the surface. Under these circumstances I would expect that motions would institute themselves, which would be closely allied to those of the great general currents supposed under the theory to exist in either hemisphere of the Earth's atmosphere.

...

By various trials with variations in these respects I think it likely that the phenomena expected could be made manifest.⁵⁰

The dishpans are an example of the value of physical modelling. Another example of experimental environments is Prandtl's rotating room (Karrussell), a three metre diameter space in which experiments were conducted. Prandtl is also reported as having attempted a dishpan experiment in a rotating room but the behaviour was deemed 'too irregular and ill-defined'.⁵¹ Developing these models provided a visual handle on what was otherwise poorly understood. An ex-graduate student of Fultz recalls just how innovative this was:

Before the advent of sophisticated numerical modeling, Dave cleverly devised and systematically exploited a number of laboratory analogs to gain insight into many complex atmospheric processes, most significantly the atmospheric general circulation. His 'dishpan' experiments provided tangible examples of otherwise poorly understood physical processes.⁵²

Lorenz notes that similar work was being undertaken by Raymond Hide, a British scientist working at Cambridge University. His investigations related to modelling the motions of the Earth's magnetic core, and he collaborated with

⁵⁰James Thomson 1892, as cited in Fultz et al. (1959) p. 4. Fultz et al. note that a similar comment was made by C. Abbe in 1907 and that Bigelow writing in 1902 indicated that he had seen a rotating experiment. Richardson's experiment was undertaken in 1918, but not followed up. Another independent investigation was undertaken by F. M. Exner in the 1920s. Exner's pan was 1 metre in diameter (15 cm deep) and was heated by a ring of gas flames. He used a block of ice as a cold source (with ink frozen into the ice to trace the cold water.) Its period of rotation was 3–7 seconds. In 1929, Rossby at the US Weather Bureau undertook a similar experiment using a salt solution with coloured dyes to investigate thermal currents. His pan was 2 metres in diameter and rotated at 3–4 rpm.

⁵¹Fultz et al. (1959) p. 5. Prandtl was noted for emphasising the importance of both experimental and theoretical research, and helped establish practical laboratories for investigating aerodynamics. See Busemann (1960) p. 197.

⁵²Tom Spence (a geoscience researcher and one-time graduate student of Fultz) quoted in Anon. (2002b).

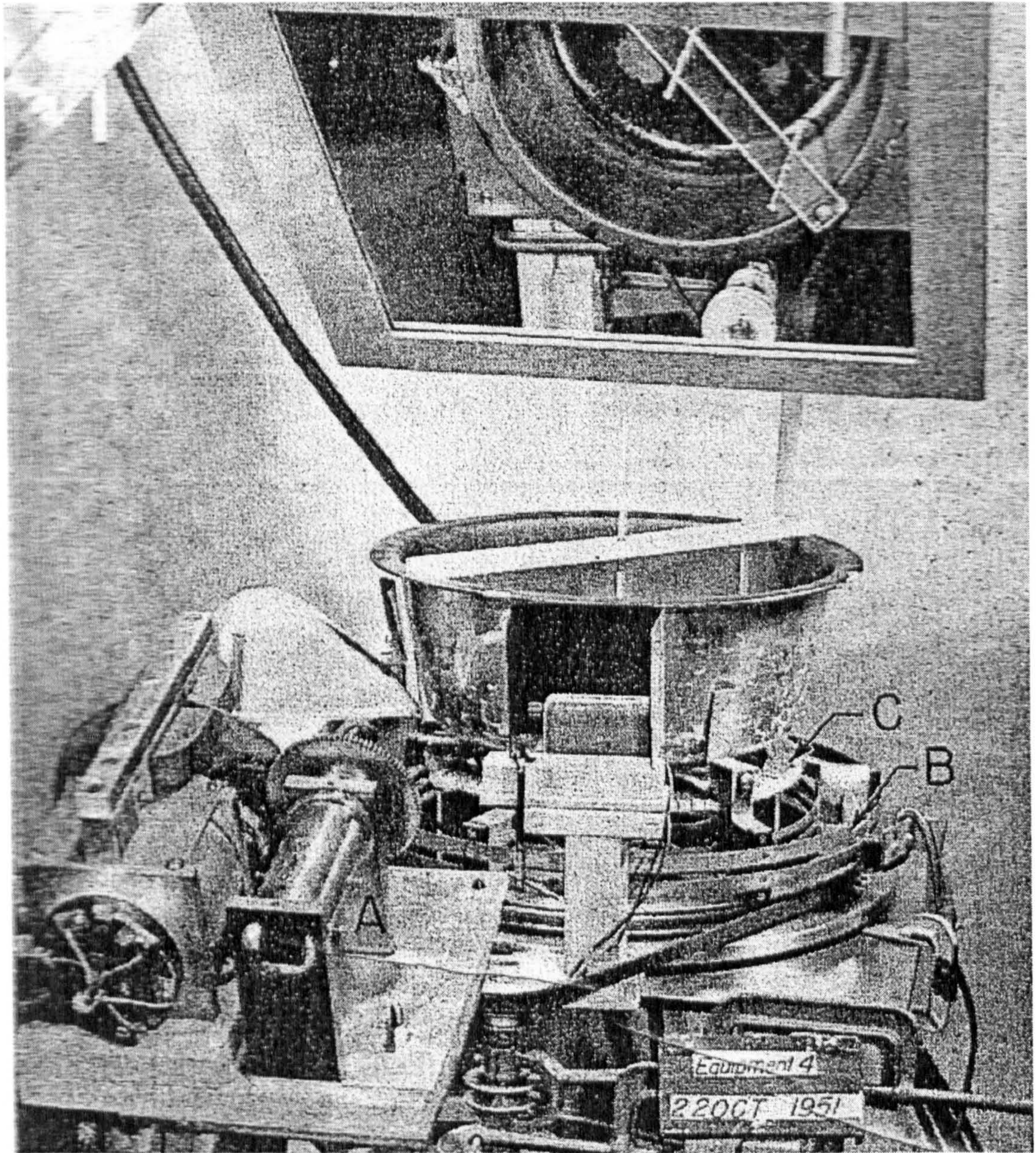


Figure 8.3: Fultz's dishpan apparatus. In the centre of the image is the metal rotating metal bowl filled with water. Above the bowl is a mirror to reflect the view from above, and in the foreground is a camera directed at this mirror to capture the changes in flow. Source: Fultz et al. (1959) p. 6.

Fultz. Hide's apparatus was more similar to Richardson's proposed setup, the liquid being held in a ring between two cylinders. After this approach was established by Fultz, a number of other scientists pursued similar modelling experiments.⁵³ One large dishpan was installed at Woods Hole Oceanographic Institution, an independent U.S. research laboratory founded in 1930, which became a major centre of defence research during World War II.⁵⁴ This had a diameter of eight feet, and was able to reproduce more interesting phenomena such as cold and warm fronts.⁵⁵

Conclusion

Apart from brief analog side stories such as experimental dishpans and the non-computational practices of the Bergen school, the history of twentieth century meteorology is dominated by the development of the mathematical approaches that Richardson pioneered, and which paved the way for numerical weather prediction. As Lynch and Nebeker have reviewed, numerical weather forecasting was one of the early application domains explored by the pioneers of the ENIAC, an early electronic computer.

However, for meteorologists like Fultz, experimental culture was a vital complement to the development of mathematical theory. His position was that in the study of large-scale geophysical and meteorological systems, experiment was complementary to mathematics:

[further developments are]... likely to broaden the study of these geophysical problems in a very fundamental way; namely, to bring about much more of the sort of interplay between experiment, theory, and observation that continually revitalises the growth of such sciences as physics and chemistry.⁵⁶

⁵³Lorenz, p. 92.

⁵⁴Anon. (2007a).

⁵⁵Lorenz, p. 92.

⁵⁶Fultz (1961) p. 2.

Fultz had a practical approach to meteorological problems. Although these were physical rather than mathematical, they were none the less important for knowledge discovery. Through these experiments he was able to discover interesting chaotic properties in atmospheric flow.⁵⁷

When dishpans became a serious research activity they were not portrayed as computing aids, but rather as modelling tools for investigating atmospheric theory. However, for Richardson, they were clearly interrelated – emphasising that in terms of problem solving, physical modelling and mathematical calculation were alternative technologies. Hence Richardson's comment 'but so far the arithmetic proves the better way'. This chapter has shown that within meteorology the physical analogs and experimental culture that elsewhere were enrolled into a discourse of analog computing were separate. Separate from computing, experimentalists such as Fultz did not have to compete for computing funding, but neither did their efforts become entwined with the history of computing. This emphasises the role of theoretical classifications in shaping history. In previous work on the history of computing, meteorology is perceived as a stronghold of digital application, however by looking at the practice, we see that the boundaries between computational and non-computational differ from context to context.

⁵⁷A nice account of Fultz's experiments are given in Edward Lorenz's popular science book: *The Essence of Chaos* – Lorenz (1995/1993).

Chapter 9

Conclusion

This study opened with two main observations of analog computing. The first related to technological classification and the complexity of defining ‘analog computing’. The second noted that the major use of analog computers was for modelling, indicating that the technology should be situated within a wider history of modelling technology. The first was an observation about analog identity, the second was a more practical observation regarding analog use.

Inspired by the first observation, the early chapters of this thesis investigated the theory and identity of analog computing, discussing the origin of its classification and the evolution of its culture. Investigation into the analog-digital classification showed that the labels ‘analog’ and ‘digital’ originated in the classification of computational technology. To understand analog computing, the two key themes of continuity and analogy are important. Following these two conceptual themes, Chapter 2 demonstrated that two perspectives of use – equation solving and modelling – were emergent from the sources. Chapter 3 took this further and considered how analog computing fits within a historiography of modelling.

In identifying the two parallel histories of equation solving and modelling, it became clear that most scholarship had considered analog computing as a calculating machine. Hence there was far less coverage of early analogs (often called ‘electrical analogies’) such as electrolytic tanks and resistance networks.

Within the theme of information processing, direct analogs (being special purpose devices) can appear insignificant. However, the meta-narrative of modelling developed in Chapter 3 helps explain why users often needed this technology.

An important pre-history of analog modelling is the use of electrical analogies during the early twentieth century. Tracing the formation of the culture of electrical analogy during the 1920s, Chapter 4 demonstrated that direct analogs had rich connections with experimental practice and visual reasoning – applications that were popular with engineers and took longer to become digitalised. The chapter showed that a community began to develop around the key phrase of ‘electrical analogy’, forming a discipline that would later be enrolled into computing. This is an example of theory (the various associations between key words, users, and technologies) shaping practice.

To narrate the story of analog computing and its use as a modelling technology, the second half of the thesis focused on investigating its use in a number of contexts. It became evident that in these application areas information generation was just as important as information processing. Chapters 5 and 6 discussed the various research applications within British universities, and explored the context behind BP’s analog oil reservoir simulator. These studies explored the role of analog-digital classifications in procurement decisions, and drew a distinction between ‘normal’ and ‘radical’ computing. Chapters 7 and 8 discussed the relative merits of analog and digital, identifying the qualities that made analog popular and considering the tension between numerical and experimental approaches.

Using the framework of modelling developed in Part I, the case studies in Part II differ from previous analog historiography by focusing on modelling (the application), rather than analog (the technology). They discuss the broader technologies that existed before electronic analog computers, and start to show what happened as each application turned to digital. Within each case study the original observations of classification and application are central. Analog classifications shaped the formation of user communities as well as informed analog-digital

decisions over procurement and funding. In terms of use, different analog applications followed different historical trajectories, and each application domain fuelled discussions of the technology's suitability and applicability. The framework of modelling has been particularly fruitful in guiding this work.

The thesis: three conclusions

The conclusions of this thesis can be summed up in three broad themes: first, that multiple perspectives of use call for multiple historical trajectories; second, that both theoretical classification and social associations played an important role in the construction and deconstruction of the analog community; and third, that where analog-digital debates existed, concerns of analog users related to their approach rather than the technology's merits.

Multiple perspectives of use informing multiple historical trajectories

One of the major contributions of this thesis has been to acknowledge the importance of multiple perspectives of use in the history of computing. In Chapter 2 we observed that analog computing could be separated into the two themes of calculation and modelling.¹ Similarly in Chapter 3 it was argued that analog computing should be interpreted within a context of 'computer as modelling machine'. Furthermore, Chapter 5 suggested that the three main applications of analog computing were calculating, modelling, and control – digitalisation occurring in separate stages for each application type.²

Multiple perspectives of use help explain the persistence of analog computing.

For instance, the BP computer could be perceived as a 'backward technology'

¹Distinguishing between these two themes was shown to assist with confusing definitions over the scope of 'analog computing', one example being the disagreement over analog identity being continuity or analogy – as exemplified in Small (2001)'s critique of Campbell-Kelly and Aspray (1996) (see Chapter 1 page 7, above.)

²Analog use for calculating and equation solving was replaced first, then analog computing for modelling and simulation, and finally analog components for control systems.

in the pathway to digitalisation. However, in terms of its users' expectations, this machine was fit for purpose. The tendency of computer history to focus on innovative developments is overcome by considering analog in normal use. An example of normal computing, analog computing was a popular tool that many users did not need to displace. Thus although digital might have been superior, analog was still in use due to cost, simplicity, and general user expectations. Technological advancement from analog to digital computing lasted a significant period, and this was partly because digital techniques had to be individually developed and popularised for each application domain.

As shown in Chapter 2, the history of computing is a history of convergence. The variety of applications run on modern computers is a common point in a number of histories of technology. Emphasising multiple perspectives of use is effectively a call for historians to untangle the modern web of associations, and explore these parallel histories of the computer in the pre-converged period. Perspectives of use encourage us to 'follow the actors'. Through applying the framework of modelling introduced in Part I, Part II of this thesis demonstrated how user culture shaped the theory and classification of analog computing.

The importance of classifications and social associations in the construction and deconstruction of the analog community

If multiple perspectives of use (the practice) were shown to have shaped the theory, this thesis has also demonstrated that the theory and associations derived from technical classifications also shaped analog use.

The history of analog computing is a complex web of multiple histories of use. Thinking about associations, keywords and classifications provides a framework for demonstrating how analog culture were enrolled into (and subsequently dis-enrolled from) computer discourse. The enrollment of 'electrical analogies' into the discourse of computing created theoretical associations between technologies

that subsequently guided its users. In Chapter 2 we saw how positive association permitted the enrollment of devices like the Phillips machine and the Jerie analog. In Chapter 4, it was shown how analog culture evolved around the developing associations between technologies, concepts, and use. The activity of users and technologies being enrolled and dis-enrolled in and out of analog culture has left a legacy of inconsistent definition. This mirrors Mindell's observation that the pathway from analog to digital was 'neither instant, obvious, nor complete'.³

In Part II, we saw the importance of these associations in various contexts. At BP, there was a positive association – both digital and analog technologies were 'computers' and announced in corporate press releases. On the other hand, a look at meteorology in Chapter 8 showed that a domain dominated by digital did use direct analogs, but that these devices were not classed as computers. For BP, analog and digital were part of a coherent modelling culture. Within meteorology, analog set-ups were not computational.

In Chapter 5, we also observed the consequences of classification within the university setting. While early analog computing had flourished through its positive association with digital, over time the associations turned negative. With digital becoming the preferred form of 'computer', it was difficult to fund analog technology as computers. The result was that associations began to break. Analog's link with computing remained strong in contexts where computational investment had a reasonably short pay back (such as BP). However, in the university context, the analog became the 'poor relation' of computing.

In terms of analog culture, the analog experts within higher education began to redefine their expertise, moving into new fields of research. Those who were involved in analog (and particularly hybrid) research were in a perfect position to become the leaders in audio/visual peripheral computer technology, advanced visualisation techniques, or digital simulation and modelling. These applications were not dependent on analog computing, but required expertise and interest in

³Mindell (2002) p. 10.

analog electronics, digital computing, and programming. It was analog laboratories that had this blend of interests, equipment and personnel.

By incorporating labels and classifications into the history of analog computing, we see the relationships between classification and use. Through associations embedded into classifications such as analog-digital, a technology's theory creates structures that, in turn, shape its practice and use.

Analog-digital debates were application based not technologically based

Throughout the thesis, we have seen a variety of analog-digital debates. In the chronology of continuous calculating machines, we identified an early analog-digital exchange between Hele-Shaw and Henry Babbage. Similarly, Chapter 4 visited the work of George Philbrick and the rhetoric of his 'Lightning Empiricism'. In Chapter 5, we witnessed discussions over how analog computers should be funded for higher education, analog being aligned as backward despite the universities wanting them. Within the context of meteorology there was no obvious analog debate, but there was an empirical-computational debate over the role of physical modelling versus numerical computation.

However, the cultural split between analog and digital was not always evident. For instance, at BP the engineers did not engage with analog-digital rhetoric. Any perceived importance of digital over analog was always grounded in terms of concrete application and business benefit. When we think of a range of applications supported by a variety of technologies, analog and digital are better understood as complements. When engineers opted for analog computers, this was not a complete commitment, but application specific; certain application areas being suited to digital and others to analog. This accounts for the extensive hybrid activity that was going on between 1955 and 1970. Most users were employing a mix of technologies and practices to get on with their day-to-day work.

Although analog computing was replaced by digital, it is evident that there

was a continuity of practice through a process of redefinition: analog users evolving into digital users. Thus, as well as understanding the distinctions, a broader account of use must consider the coherence between analog and digital. Hence this thesis has tried to explore the coherence between the two technologies. By considering computers like the MADDIDA,⁴ which borrowed technological principles from both analog and digital, it becomes possible to separate ‘analog thinking’ from ‘analog technology’. This introduces the idea of partial failure: superseded technology, but common approaches and practice. These analog-digital debates relate primarily to the applications supported by analog.⁵ Technical enthusiasm was not based on the technology, but on the type of use it afforded. Because analog methods evolved into digital techniques, digitalisation was only a partial ‘failure’ of analog computing.

Further work

Within the theoretical theme of understanding analog computing, this thesis has successfully shown that associations between technologies and concepts were central in shaping analog culture.

Although this thesis has gone some way to explaining the formation of analog culture, it has only begun to discuss the issues surrounding user dis-enrollment. Earlier we identified how university researchers redefined their analog expertise into digital modelling and simulation. Future work should look in more depth as to how analog users were retrained in digital methods. We also identified the importance of analog’s trustworthiness. It would be interesting to investigate how this trust in these methods was established. When did users reach the consensus that digital would provide a better and cheaper solution?

One area that would particularly benefit from further scholarship is the story of hybrid computing. For many contemporary users of analog computing, hy-

⁴Chapter 2, page 64, above.

⁵Analog technology supporting a high quality of interaction and visualisation.

brid technology was the preferred way to blend the merits of analog and digital. Although this thesis and previous work discuss hybrid computing, it would be interesting to understand more about its use within academia and industry. Future work could extend the work on the university funding and describe the role of Government policy on the uptake of hybrid methods.

However, one of the key contributions of this thesis was to re-organise the history to reflect multiple types of use. Any future work relating to analog computing should be informed by taxonomies of use instead of the confusing technical classifications of analog-digital. Orthogonal to the main direction of this thesis, the case studies of Part II touched on many important applications areas relating to modelling. In particular, this thesis has undertaken significant archival research into the histories of reservoir modelling, aeronautical modelling, and meteorological modelling. Each of these investigations could have expanded into an entire thesis and would provide an interesting topic for future research. By approaching these contexts from the perspective of modelling technology (instead of analog computing) future investigation could show how a history of modelling technology sits across the analog-digital boundary.

Concluding remarks

In the centuries prior to 1900, analog has its own history of development. A history that during the twentieth century became entangled with that of the digital computer. It was through this entanglement that analog and digital computers received the linguistic labels to which we now refer to them, and became understood as separate classes of computing technology.

Through thinking about use and modelling, analog-digital becomes a less important classification. By exploiting the framework of modelling, this study has been able to look at the users of analog computing in a different way. We saw that these actors needed a technology to think with rather than a technology to

process data. This shed new light on the importance of direct analog computers, and helps explain the context of analog-digital debates occurring during the 1950s and 1960s.

It is hoped that these case studies, along with the investigations into the technical and conceptual origins of the analog-digital dichotomy will assist future scholars understand the history of computer modelling. Although physically-based models can seem a little distant from modern computing, the applications of these technologies are represented in modern simulation software. The perspective of users, the issue of trust, and analog culture all transcend the modelling medium and still exist today.

Perhaps the findings of this thesis imply that analog computing should no longer be an independent area of scholarship. We see that the issues are not so much analog versus digital, but rather modelling versus equation solving. Just as the pioneers of analog computing started to consider a distinction between analysis and synthesis, so must the history of computing. Once we have a history that accounts for computer environments for synthesising, modelling, and constructing, we will be able to see the strong correspondences between the use of analog computing and the use of digital modelling and simulation.

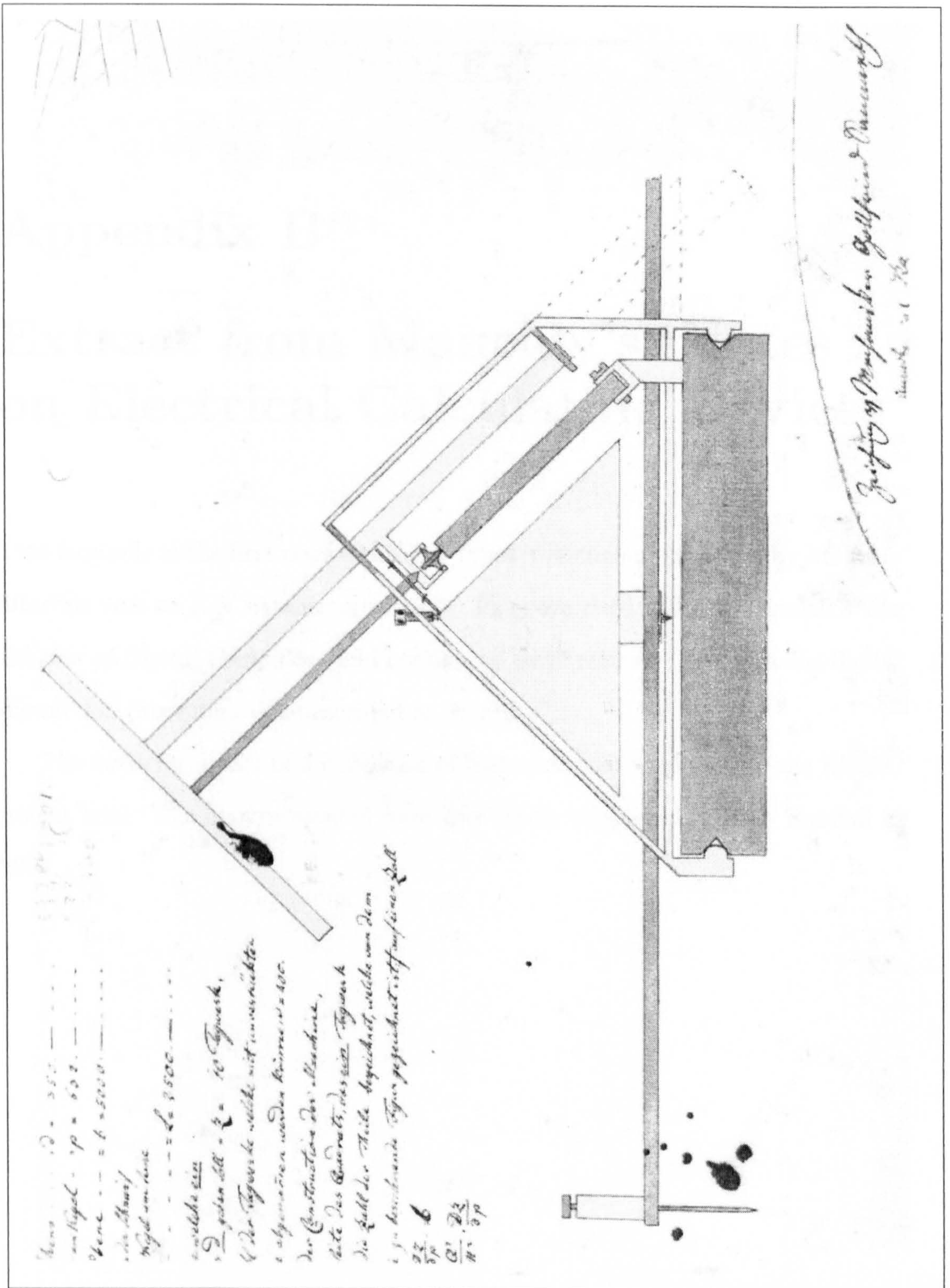
In Chapter 1, we discussed Michael Mahoney's call to consider 'software as medium of thought and action' and 'how we have put the world into computers'.⁶ The challenge to the next generation of scholarship is not to consider analog and digital as separate technologies, but to consider the continuity of practice that spanned the two. It is only then that we will fully understand the history of computer modelling.

⁶Mahoney (2005) pp. 107-108.

Appendix A

Facsimile of a diagram of the Hermann planimeter

This diagram is a side-on elevation of the Hermann planimeter, printed on an A4 page it is roughly at full-size scale.



Appendix B

Extract from Mauchly's 'Notes on Electrical Calculating Devices'

This facsimile is the first page of a short typeset document prepared by Mauchly after his visit to J. V. Atanasoff in 1941. They are cited in Brian Randall's *The Origins of Digital Computing* and contain an early reference to an analog-digital distinction (here digital is described as 'impulse').

The notes form part of a collection of materials that were used in the ENIAC patent trial. The copy presented here was kindly supplied by Brian Randall in 2004.

PLAINTIFF'S TRIAL
EXHIBIT
No 847

---1--- Analog versus impulse types ---

Computing machines may be conveniently classified as either "analog" or "impulse" types.* The analog devices utilize some sort of analogue or analogy, such as Ohm's Law or the polar planimeter mechanism, to effect a solution of a given equation. The accuracy of such devices is obviously subject to limitations; at times the attainable is more than sufficient, but there is increasing need for more computational aid not so restricted. Impulse devices comprise all those which "count" or operate upon discrete units corresponding to the integers of some number system. There is no theoretical limit to the accuracy ^{to} which such devices will work; practical limitations on the bulk or cost or convenience of operation provide the only restrictions. The usual mechanical computing machine, utilizing gears, pulleys, etc., are examples of impulse calculators.

* I am indebted to Dr. J.V. Atenasoff of Iowa State College for the classification and terminology here explained.

No further attention will be given to the analog type here, for although differential analyzers and other analog machines are now ^{used} and will continue to be used for some problems, it is in the field of impulse machines that major improvements in speed and accuracy are to be expected and sought for.

---2--- For speedy (and noiseless) operation, vacuum tubes and associated circuits are the obvious answer. There are no essential difficulties in designing V.T. apparatus to do the job of ordinary mechanical calculators - - - but after taking care of stability, freedom from error, ease of servicing, etc., one might conceivably wind up with a design too costly to build. But economically feasible designs are possible. At present it may not be possible to build a commercial competitor for the desk-type mechanical computer, but larger machines for more involved, more lengthy, or more specialized jobs are practical. In some cases it is possible to materially decrease the number of tubes and circuits required in a large machine by having many similar operations performed by one and the same

Appendix C

L. F. Richardson's notes on a rotating dishpan model

The following notes were made by Richardson in France after conducting an experiment on rotating fluid. Such experiments became popular 30 years later when they were developed by the Meteorologist Dave Fultz working in Chicago who called them 'rotating dishpans. Fultz's work was independent of Richardson, but through Oliver Ashford (Richardson's colleague and biographer) he received as copy of these notes.

The notes are typeset from an original manuscript in Cambridge University Library entitled 'Working Models of Atmosphere', the diagram is redrawn from Richardson's original sketch.¹

¹'Working Models of Atmosphere', 25th February 1918, in Richardson (1916–1919).

Working Models of Atmosphere

25 Feb 1918

Made an experiment with a basin placed on a gramophone disk, which revolved about once per second. The water surface assumed a radius of curvature of say $\frac{1}{2}$ metre, so that with a paraboloidal bowl about a metre diameter & $\frac{1}{2}$ metre deep, we should have obtained a very fair representation both of the variation of the normal component of rotation with latitude and of the term $\frac{\tan\phi}{a}v_n$. There may possibly be some exact correspondence between the equations for the sphere & for the paraboloid.

There were ripples on the surface which I attribute to the axis of rotation not having been perfectly vertical. It is very necessary to avoid all disturbance and so the apparatus should have a concrete bed, levelling screws, and a long greased journal bearing.

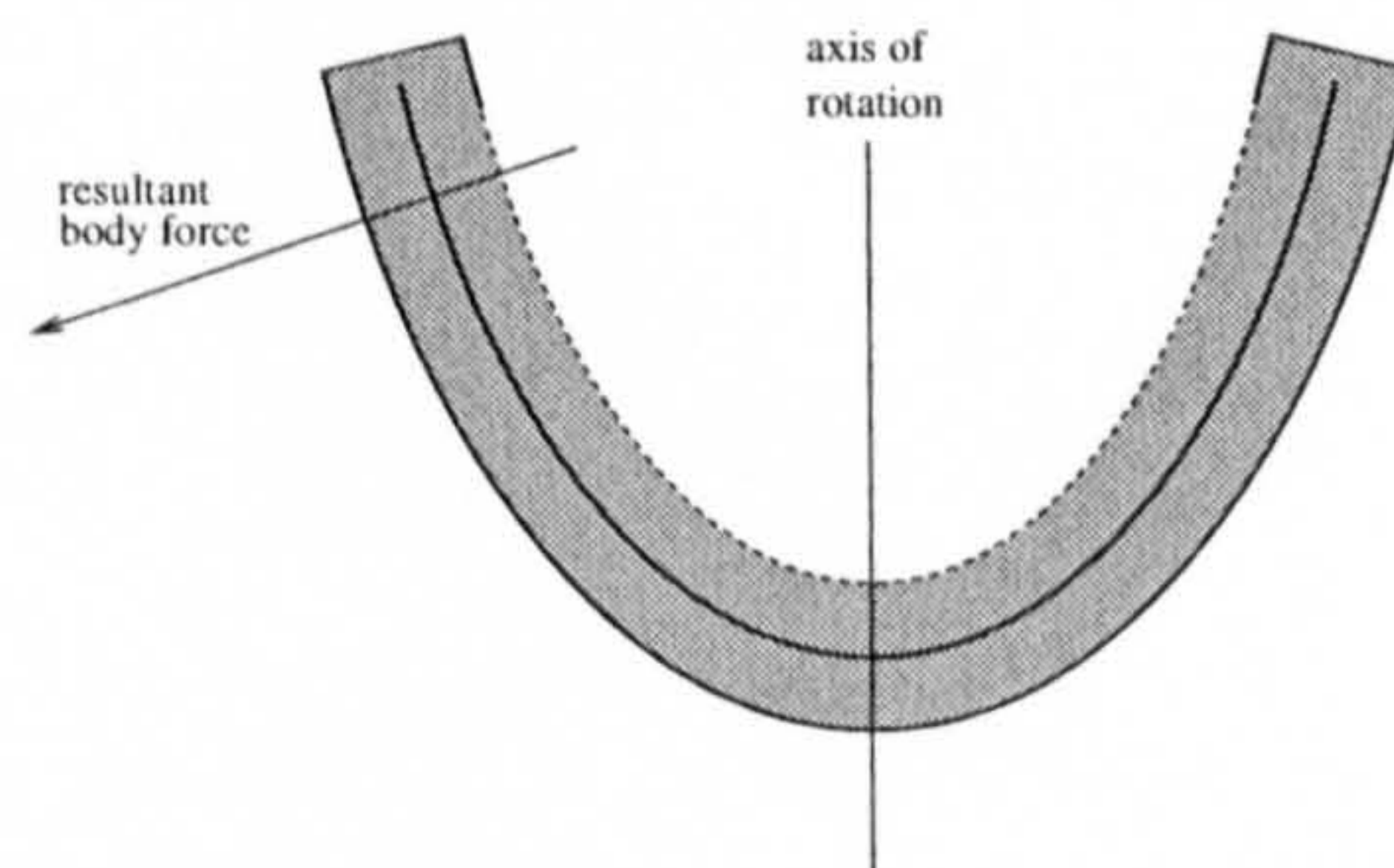
To prevent disturbance the rotatory motion should not vary by more than a fraction of a turn in a quarter of an hour. To attain this one might use a small water motor driven from a special cistern which would be kept full by a float valve. A considerable head of water is necessary for Pelton wheel motors. L. H. G. Davies's type at Eskdalemuir would probably be more convenient. With the gramophone motor, when kept fully wound by hand, the motion was fairly steady.

Tried with the gramophone motor the effects of heating, but there were too many disturbances.

When the bowl is moving rapidly it is difficult to observe the motion relative to the bowl. A special optical device is desirable; for instance look vertically down the axis of rotation at a mirror which revolves with the bowl. In the mirror one sees spinning, but not translating, one portion of the surface. Now let a shutter close the field of view except at one portion of the revolution. Then one sees the map in glimpses but always the same way up. Or photograph the motion by a camera which revolves with it.

Even winds crossing the equator might be modelled by having two paraboloidal shells one inside the other, as in the sketch. The water surface is indicated in green & the water is shaded in the same colour.

Now the inner metal paraboloid is regarded as the earth's surface for both layers of water so that the rotation along a line drawn normally from the surface is opposite in the two layers, as it should be. Only as the paraboloidal free surface is never vertical, there is a discontinuity in $\sin\phi$ at the rim of the double basin which represents the equator.



Appendix D

Documents indexed by the ARC Computation Panel

This appendix contains a list of the documents indexed by the Computation Panel (later the Computation Sub-committee) of the Aeronautical Research Council. During its seven years of existence, it indexed around 150 documents. The records of the whole council now reside within the National Archives (series AVIA 23). However, no complete list of computation documents exist within these archival holdings. Through going through the various references in the records and minutes of the council, the following list has been created. This should assist future research into the panel.

Index Reference	ARC reference	Title / Author	Year	Meeting (and paragraph) where discussed	Type of technology
1	15320	Draft terms of reference and membership of the computation panel			n/a
2	15154	Mechanical Computation with relation to aeronautical engineering	1951		Both
3	15118	Computing problems. Report on visit of Dr E. T. Goodwin (NPL) and DR S. H. Hollingdale (RAE) to two aircraft firms to discuss their computing problems (9th January 1952, 13th August 1952)		1.5	Both
4		Computing machines in aircraft engineering / Charles R. Strang (Douglas Aircraft Co.) Communicated by H B Howard MOS (12 December 1951)		1.5	Both
5	15209	A photo-electric curve follower / R. H. Forest and K. H. Treweek (Appendices by J.A. Roberts)	1952	1.5	Analog
6					
7					
8	15399	Organising a computer center / F. P. Cozzone	1952	2	Both
9	13864	Application of high speed computing in aeronautical research / Dryden			Digital
10		First report of the computation sub-committee			Both
11					
12					
13					
14					
15					
16	15335	Electrical analogues for the solution of problems concerning the extension and flexure of flat elastic plates / S. C. Redshaw	1952	4.19	Analog
17	15535	The role of analogue computing in the Aircraft Industry / S. H. Hollingdale and K. V. Diprose		3.14	Analog
18	15550	The technique of Flutter investigations / H. Templeton		3.13	Analog
19					
20	15601	The numerical solution of fourth order differential equations / L. C. Woods	1952	4.19	Digital
21		The formulation of biharmonic problems / D. N. de G. Allen and S. C. R. Denis	1953	4.19	Digital
22		Note on some methods of finding the stress in arbitrary flat plates / K. V. Diprose	1953	4.19	
23					
24	15637	The use of digital computers in aircraft design / Dr. B. V. Bowden	1953	4.23	Digital

Index Reference	ARC reference	Title / Author	Year	Meeting (and paragraph) where discussed	Type of technology
25		The determination of the pressure distribution over an aerofoil surface by means of an electrical potential analyzer / Prof. S. C. Redshaw	1952	5.27	Analog
26		Second report of the computation panel	1953	1.10	Digital
27					
28		The RAE Hollerith Punched Card Installation		6.32	Digital
29		Function Generators based on linear interpolation with applications to analogue computing / Burt and Lange		1.4	Analog
30	16187	A General Purpose Analogue Computer (Shorts)		6.34	Analog
30a		Notes on the production (Mark II) version of the Short general purpose analogue computer		1.10	Analog
31		Approximate solution of simultaneous equations... / Langefors		1.3	Digital
31a		Comments on "Approximate solution of simultaneous equations" / Woodger			Digital
32		The Philbrick Electronic Analog Computer, and its use for the solution of the dynamical equations of an aircraft-plus-autopilot		7.41	Analog
33		Survey of computing facilities in the United Kingdom / Reiners		3.41	Both
34		Calculation of latent roots of matrices / J. H. Wilkinson		7.39	Digital
35		An example of a complete flutter calculation on ACE		7.37	Digital
36		W.R.(D) List of abstracts (computing) no. 25		7.41	n/a
37		W.R.(D) List of abstracts (computing) no. 29		7.41	n/a
38		W.R.(D) List of abstracts (computing) no. 31		7.41	n/a
39		W.R.(D) List of abstracts (computing) no. 35		7.41	n/a
40		Circular announcing the MoS computing library		7.41	n/a
41		A cyclic progressive, binary-coded-decimal system of representing numbers / Petherick		1.5	Digital
42		Third report of the computation panel		1.10	Both
43		Proposals for RASCAL, a small sequence-controlled calculator based on cold-cathode valves / Petherick		1.6	Digital
44	16521	The RAE electronic simulator for flutter investigations in six degrees of freedom or less / F. Smith and W. D. T. Hicks		1.10	Analog
45		W.R.(D) List of abstracts (computing) no. 25A		2.17	n/a

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46		W.R.(D) List of abstracts (computing) no. 29A		2.17	n/a
47		W.R.(D) List of abstracts (computing) no. 31A		2.17	n/a
48		Chebyshev polynomials and their use in automatic computation		2.14	Digital
49		The use of an automatic calculating machine to obtain the general performance of a turbo-jet aircraft from standard test or estimated data / Spillman and Harvey		2.14	Digital
50		Design of Tridac, part I		2.17	Analog
50a		Design of Tridac, part II			Analog
50b		Design of Tridac, part III			Analog
51		Note on training and qualifications of computers [letter to Nayler]		2.13	Digital
52		Cambridge diploma in numerical analysis [letter]		2.13	Digital
53	16660	Recent developments in the structural approach to aeroelastic problems / Williams		3.21	
54		W.R. (D) Computing and data reduction abstracts no. 5			n/a
55		First report of the computation sub-committee		4.28	Both
56		W.R. (D) Computing and data reduction abstracts no. 6			n/a
57		The automatic electronic digital computer as a potential aid to air traffic control / M. H. Johnson		5.31	Digital
58		Air traffic control by "Electronic Brain" / M. H. Johnson		5.31	Digital
59		The limitations of computing equipment [Copy of letter from secretary of the council to the chairman of the computation sub-committee]		5.34	Digital
60		Tests of some methods for the approximate calculation of inviscid flow past infinite cylinders / Frazer		10.60	Analog
61		A high speed electro-mechanical multiplier / C. A. A. Wass and D. W. Allen		5.34	Analog
62		Calculation of chord and spanwise loadings on three thin wings / Klanfer		5.34	
63		Catalogue of the MoS Computing library		5.34	n/a
63a		MoS Computing and Data Reduction library catalogue part II - classified amendments 1			n/a
63b		MoS Computing and Data Reduction library catalogue part II - classified amendments 2			n/a
64	17045	Experiments with an electrical analogue for the solution of problems concerning the extension and flexure of flat plates / P.J. Palmer and S. C. Redshaw		7	Analog

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65	17078	Some Problems in aerodynamics and their solution by electrical analogy / D. Küchemann and S. C. Redshaw		6	Analog
66		The solution of plane elastic problems in complex and hypercomplex form / Stahl		9.54	
67	17112	On the approximate calculation of steady viscous flow past infinite cylinders by the method of boundary retardation / Frazer		10.60	
68	17222	The solution of biharmonic problems / D. N. de G. Allen and C. M. Wilson		7.42	
69	17229	Second report of the computation sub-committee			Both
70	17235	The solution of plane stress problems by an electrical analogue method / Liebmann		7	Analog
71					
72		Training and careers for computers			n/a
72a		Training and careers for computers, copies of correspondence			n/a
73		On structural fatigue under random loading		8.47	
74		On the analysis of linear and non-linear dynamical systems from transient response data / Shibrot (NACA 3288)		12.76	
75		Relaxation methods applied to determine the motion. In two dimensions, of a viscous fluid past a fixed cylinder / D. N. de G. Allen and R. V. Southwell		9.53	Digital
76	17409	The solution of linear simultaneous equations my matrix iteration		13.83,16.103	Digital
77		Hypercomplex variables and plane elastic problems [note by prof G. Temple]		11.66	Digital
78					
79					
80		Draft third report of the computation sub-committee		12.74	Both
81		Theory of lifting surfaces / Acum		14.87	
82		W.R. (D) Computing and data reduction abstracts no. 8		12.76	n/a
83	17951	Computational aids for the solution of flutter problems / H. Templeton		13.80	Analog
84		W.R. (D) Computing and data reduction abstracts no 7		12.76	n/a
85		A general method (depending on the aid of a digital computer) for deriving the structural influence coefficients of aeroplane wings / D. Williams		12.72	Digital
86					
87		Contratants: A new method for the numerical evaluation of determinants / R. H. Macmillan		12.73	Digital

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88	17388	Solution of a load diffusion problem by relaxation methods / G. Vaisey and Prof. W. S. Hemp		13.81	Digital
89	18194	Recording and processing flight test data by digital methods		13.83	Digital
90		The analogy between electrical networks and structural frameworks / E. Melan		14.90	Analog
91		A set of orthogonal exponential functions / Mansfield		14.88	Digital
92		Electrical analogies: A survey of their use in the United Kingdom / A. J. Knight		14.90	Analog
93		On the solution of problems of dynamic plane elasticity / Radok		16.107	
94		Relative accuracy of deflections and bending moments (or stresses) derived by the methods of RAE report (Structures 168) / D. Williams			Digital
94a		Notes on paper by D. Williams / L. Fox and E. T. Goodwin		16.107	Digital
95		Third report of the computation sub-committee		14.87	
96		Catalogue of the MoS Computing and data reduction library		15.98	n/a
96c		MoS Computing and Data Reduction library catalogue		15.98	n/a
97		W.R. (D) Computing and data reduction abstracts no 9			n/a
98		The calculation of the spanwise loading of sweptback wings with flaps or all-moving tips at subsonic speeds / Brebnre and Lemaire		15.98	
99		A note on kinetic heating / Hunn		15.95	
100		A method for the numerical evaluation of an integral / T. Nonweiler		15.98	Digital
101		Report on Savin's "Stress concentration around holes", Moscow 1951 (part I)		15.98	
102		W.R. (D) Computing and data reduction abstracts no 10		15.98	n/a
103		Problems involving transient heat flows [Copy of letter to the chairman of the computation sub-committee from secretary engineering-physics sub-committee]		15.95	n/a
104		Fourth report of the computation sub-committee		16.107	
105		Forces on a rectangular wing oscillating in a stream of high subsonic Mach number / W. E. A. Acum		16.107	
106		Solution of the problem of the cantilever square plate by the use of influence coefficients and a high speed digital computer / D. Williams and P. C. Birchall			
107		The flutter problem / C. Strachley (1956)		16.102	Digital
107a		Some matrix problems arising from the consideration of flutter in aircraft/ C. Strachley		16.102	Digital

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108		Analysis of a loaded cantilever plate by finite difference methods / Livesley and Birchall		16.101	Digital
109		Notes on the practical application of the method of (RAE Structures 168)		16.101	Digital
110		D.W.R. Computing and data reduction abstracts no. 11		17.116	n/a
111		A survey of computing facilities in the U.K. (second edition) / A. J. Knight		17.116	Both
112		Investigations into the use of an electrical resistance analogue for the solution of certain oscillatory flow problems / P. J. Palmer, Anne R Copson and S. C. Redshaw		19.130	Analog
113		Australian reports (Nov 1955 - Sep 1956)		18.124	n/a
114		Note on "Power spectral methods of analysis and their applications to problems in airplane dynamics" by Press and Tukey / Zaremba		19.128	Analog
115		Note on boundary conditions in the problem of the clamped plate/ E. T. Goodwin		17.113	
116		The recovery of an airplane from a high speed dive / Yound and Neumark		17.112	
117		An analogue computer for convective heating problems/ H. G. R. Robinson		17.111	Analog
118		Report on Savin's "Stress concentration around holes", Moscow 1951 (part II)		18.124	
119		Notes on the use of Monte Carlo methods [letter from G. Temple to the chairman of the computation sub-committee]		18.124	Digital
120	19139	Numerical solution of a second order linear differential equation with time dependent coefficients		20.137	Digital
121		List of Australian Reports on structures, aero-elasticity, computational methods and machines issued during the period 1 st October to 31 st December 1956		19.132	n/a
122		S.A.U Computing and Data reduction abstracts no 12		18.124	n/a
123		Calculation of forces on wings oscillating with finite frequency in a high-subsonic stream		18.119	
124		Numerical aspects of unsteady lifting-surface theory at supersonic speeds / H. C. Garner		18.119	Digital
125		Loading on an oscillating wind of infinite aspect ratio in subsonic stream / Wilkinson		18.119	
126		5 th report of the computation sub-committee		19.132	
127					
128		S.A.U Computing and Data reduction abstracts			n/a
129		Power spectral methods of analysis and their application to problems in airplane dynamics / Harry Press and John W. Tukey			

Index Reference	ARC reference	Title / Author	Year	Meeting (and paragraph) where discussed	Type of technology
130	9593,19756	Wall corrections for wings oscillating in wind tunnels of close rectangular section / Acum (2 parts) (2 nd 130a)			
131		A note on some integrals in aerodynamics / D.E. Williams		19.132	Digital
132		Methods of solution of the basic equations in the theory of elasticity / Marguerre		19.132	Digital
133		A new method for obtaining lower limits for the solutions of 'eigenvalue' problems for beams and plates / D. Williams		19.132	Digital
133a		A formal proof of the proposition put forward in RAE Report Structures		20.141	Digital
133b		Notes on "A formal proof..." [133a] by L. Fox			
134		On the finite difference methods in eigenvalue problems / E. H. Mansfield	1957	19.132	Digital
134a		On the use of finite difference methods in eigenvalue problems / L. Fox			Digital
135		Copy of a letter from Dr G. K. Batchelor to Mr M. Woodger, Secretary, Computation sub-committee		19.128	Analog
136					
137		Bibliography of computing No. 1	1957	19.132	n/a
138		A report of SBAC Computer sub panel	1957	20.141	n/a
139		A routine method of approximating to the transient response of a linear system from its frequency responses / K. R. Rushton		20.141	Analog
140	20046	Applications and proposals for a digital differential analyser suitable for computation in real time . L. Owen			Hybrid
141		Automatic data reduction equipment for wind tunnels r Rey		20.141	Digital
142		A Short survey of problems worked upon by SBAC Computing Panel over the past five years		20.136	n/a
143		The relaxation method in the statics of shells / Fluegge		20.141	Digital
144		6 th Report of the computation sub-committee [draft]			
145		A note on the approximate solution of eigenvalue problems / D. C. Belinfante and H. G. Hopkins	1958	21.148	Digital
146		Proposal to wind up the computation sub-committee - "Computation sub-committee. Copies of correspondence"	1958	21.144	n/a
147					
148					

Index Reference	ARC reference	Title / Author	Year	Meeting (and paragraph) where discussed	Type of technology
149		Seventh Report of the Computation Sub-Committee	1959		

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